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Climate Change and San Francisco Bay–Delta Tidal Wetlands

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ABSTRACT

Climate change will affect tidal wetlands with higher rates of sea-level rise and higher concentrations of salt in brackish and freshwater tidal systems, in addition to causing increases in atmospheric CO_2 concentration, warmer temperatures, and shifts in precipitation. In the San Francisco Bay–Delta, the areas most likely to be affected—brackish and freshwater tidal wetlands—are also the sites with the majority of endemic plant species and the greater biodiversity and productivity. Effects on the San Francisco Bay–Delta estuary are complex and difficult to predict, but a few things are clear. Biodiversity of the tidal wetland system in the San Francisco Bay–Delta region will decline, with subsequent effects on ecosystem functioning and services. Altered plant production, physiological tolerances, and shifts in rates of mortality will modify wetland plant communities in ways not yet predictable. Lower ecosystem productivity from salinity increases will affect both primary and detrital-based food webs. Such changes will cascade via the food webs into invertebrate, bird, and pelagic systems. Tidal wetlands are especially sensitive to processes that climate change will alter. Several of these altered processes are exacerbated by water diversions from the Delta.

KEY WORDS

Brackish tidal wetlands, climate change, freshwater tidal wetlands, salinity, salt marshes, sea-level rise, Mediterranean climate

INTRODUCTION

Climate change will have significant global impacts on tidal wetland ecosystems. In addition to responses to changes in CO_2, temperature, and precipitation that all biotic communities will experience, tidal marshes also will experience shifts in salinity and sea level. The root causes of these global changes are increases in atmospheric greenhouse gases such as CO_2 (Meehl and others 2007; Richardson and others 2009). Plants will experience both direct effects from CO_2 increases as well as the indirect effects of CO_2-mediated climate change (Hayhoe and others 2004; Meehl and others 2007; Church and others 2008). For example, increases in CO_2 concentrations—because of its role as a plant resource—might favor some wetland species at the expense of others because of different physiological adaptations (e.g., C3 over C4 species, Drake and Rasse 2003; Rasse and others 2005).

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CO_2-influenced climate change will affect plant respiration, rates of decomposition, soil carbon storage, soil nutrient cycling, mycorrhizal symbionts, and herbivory. By itself, increases in sea level will account for some losses of tidal wetlands, and, globally, estimates range from a 22% to 70% loss of coastal wetlands (Nicholls and others 1999; Najjar and others 2000; but see Hughes 2004). As a consequence, the San Francisco Bay–Delta estuary is predicted to change dramatically under every scenario of future climate change and sea-level rise.

We will examine current patterns of global change in more detail as the context for analyzing potential future changes in tidal wetlands in the San Francisco Bay–Delta (Cayan and others 2008a, 2008b). We will first consider scenarios of how California's climate and other processes are suggested to change in the near future. Using those changes as a framework, we will then examine potential plant responses. Wetland vegetation will respond in a complex manner to these shifting processes, but an underlying lack of knowledge about most plant species means that we have great uncertainty about any projection of climate-change related effects. Some species favored by increases in atmospheric CO_2 concentration, for example, may not respond well to temperature increases in the growing season, while others may respond favorably. Productivity and survival of other species certainly will be reduced simply by salinity increases. Overall, there will likely be significant shifts in wetland composition, especially in the brackish and freshwater portion of the estuary.

CURRENT PATTERNS OF TIDAL WETLAND VEGETATION

The salinity gradient formed by the mixing of freshwater from the San Francisco Bay–Delta watersheds and saltwater from the Pacific Ocean form the template for the distribution of a variety of wetland types. In freshwater areas, sites are dominated principally by large and very productive plants such as *Schoenoplectus acutus* and *Salix lasiolepis*. These wetlands are quite high in annual net productivity, exceeding 2,000 to 2,400 gm m^{-2} yr^{-1} (Atwater and others 1979; Parker and others, unpublished data). Species richness is also quite high in freshwater tidal sites and we have found up to 58 different plant species in as few as ten, 0.1-ha plots at Sand Mound Slough near the mouth of the Delta (Vasey and others, submitted).

At the other end of the salinity gradient, salt marshes contain few species, and the marsh plains are dominated almost exclusively by *Sarcocornia pacifica* (formerly *Salicornia virginica*). Species such as *Spartina foliosa* are found in low marsh sites or restricted to channel or upland edges, or both, such as *Grindelia stricta* var. *angustifolia*, *Jaumea carnosa,* or *Distichlis spicata*. For example, a comparable random sample of ten, 0.1-ha plots at China Camp State Park, a remnant salt marsh in lower San Pablo Bay, and part of the San Francisco Bay National Estuarine Research Reserve, yielded just ten tidal marsh species (Vasey and others, submitted). Annual net productivity is low compared to freshwater wetlands of the bay-delta, ranging from 400 to 1,200 gm m^{-2} yr^{-1} depending on site conditions (Mahall and Park 1976).

Between the salinity and freshwater extremes are a range of brackish marshes with intermediate and variable species richness and productivity that depend on patterns of salinity and inundation. Many of the endemic species of the San Francisco Bay–Delta, such as *Lathyrus jepsonii* and *Cirsium hydrophilum* var. *hydrophilum*, are restricted to brackish wetlands. All the tidal wetlands also connect with adjacent terrestrial and pelagic systems as a resource base for food webs in those ecosystems. Consequently, because of cross-boundary ecosystem subsidies (Polis and Hurd 1996; Harding 2002), the influence of climatic change is likely to be critical not only to tidal wetlands but also to the adjacent systems with which they are linked.

CHANGES IN THE COMPOSITION OF THE ATMOSPHERE AND SUBSEQUENT EFFECTS

In the last 20 to 30 years, concentrations of CO_2 and other greenhouse gases have increased dramatically (Meehl and others 2007; Richardson and others 2009). Current levels of greenhouse gases are already believed to have affected global climates (Meehl and others 2007). Models indicate these gases may increase in the future; depending on assump-

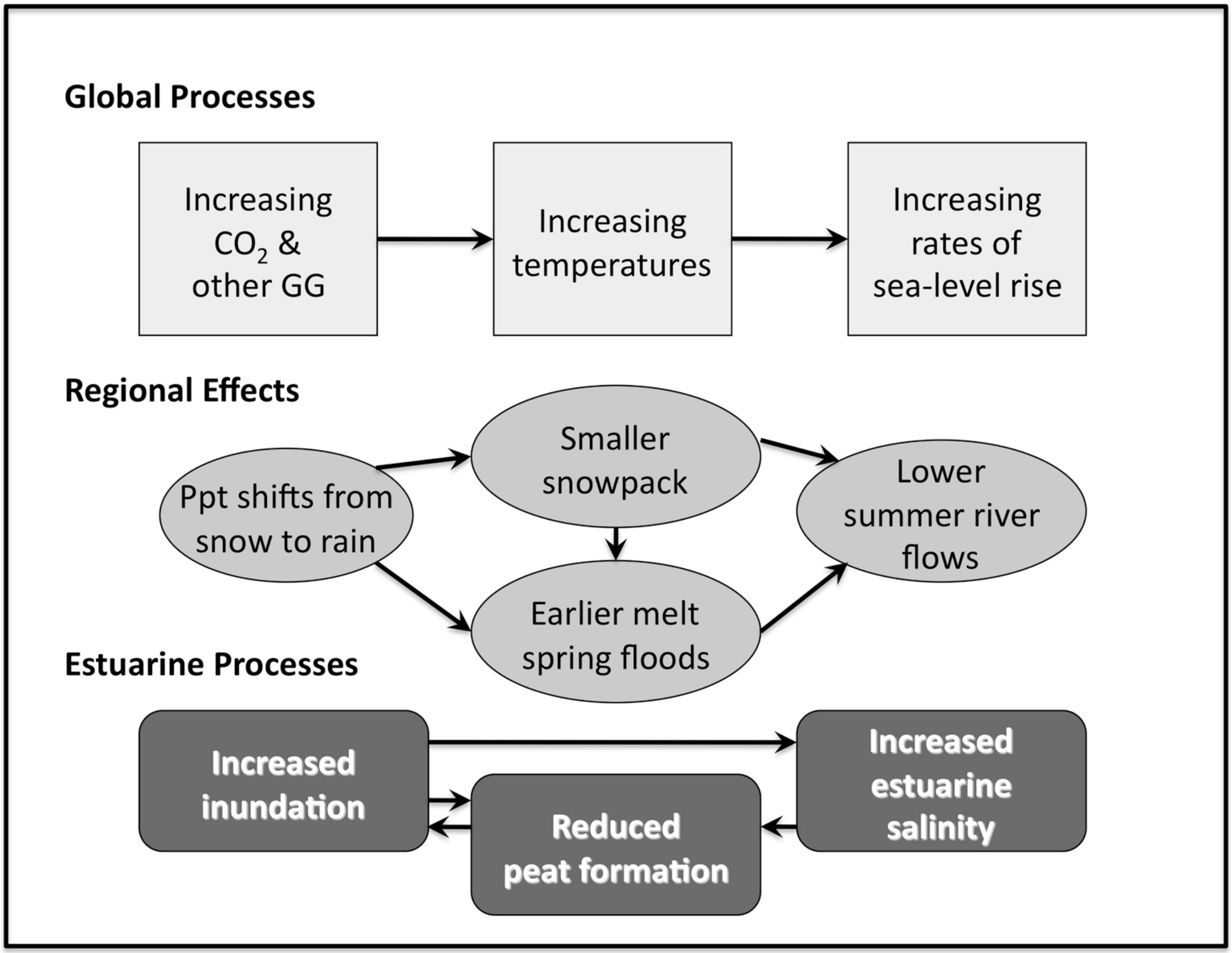

Figure 1 Principal processes governing effects of climate change on the San Francisco Bay–Delta estuary. The first level containing CO_2 and greenhouse gases, increasing temperature, and sea-level rise represent global processes. Below that are regional processes that are either the result of direct or indirect effects of global processes on the Sacramento–San Joaquin watershed. The final level indicates processes within the estuary in addition to the global and regional processes that will directly affect tidal vegetation.

tions, by 2100 CO_2 will increase to 400 ppm or up to nearly 1,000 ppm (Meehl and others 2007; Cayan and others 2008b). Current rates of increase in CO_2 concentration are on a pace to reach the higher values (Richardson and others 2009). Such increases will facilitate continued and dramatic climate change. For example, in California, models suggest that temperatures may rise significantly during the 21st century, from 1.5° to 7 °C for a variety of scenarios that involve increases in greenhouse gases (Dettinger 2005, 2006; Cayan and others 2008b).

Directly or indirectly, the changes resulting from increases in greenhouse gases will affect the physical dynamics of tidal wetlands, plants and their interactions within these wetlands, and animals that live in them or depend upon them. Most predicted changes for northern California—including increases in temperature, unpredictable effects on precipitation, major losses in watershed snowpack, shifts in runoff patterns, and increases in the rate of sea-level rise—will all affect tidal wetland dynamics. Taking these processes together, critical changes in tidal wetlands will result in eventual increases in wetland salinity and duration of inundation (Figure 1). The rest of this paper examines these probable effects in the context of the San Francisco Bay–Delta estuary and its tidal wetlands.

EFFECTS OF RISING TEMPERATURES ON THE BAY–DELTA ESTUARY: SEA-LEVEL RISE AND SALINITY

Increasing temperatures will act globally, regionally, and locally to affect wetlands (Figure 1). For example, temperature increases that drive both thermal expansion of the world's oceans and melting of terrestrial ice sheets are believed to be primarily responsible for increases in rate of global sea-level rise, which has been close to 2 to 3 mm yr^{-1} over the last few decades (e.g., Stevenson and others 2002; Meehl and others 2007; Church and others 2008). Historical rates before 1930 were generally less than 1 mm yr^{-1}, rising to 2 mm yr^{-1} between the 1930s to the 1950s, and declining during the 1960s and 1970s due to increases in global volcanic activities (Church and others 2005). Increases in rates of sea-level rise are reported in most parts of the world (Cazenave and Nerem 2004; Holgate and Woodworth 2004; Hughes 2004; Church and White 2006), and recent re-evaluations of global data suggest even faster rates (Richardson and others 2009). Since approximately 1992, rates are now over 3 mm yr^{-1} (Holgate and Woodworth 2004; Beckley and others 2007; Church and others 2008). The IPCC estimated sea-level rise to be 10 to 59 cm by 2100, but later raised estimates to 18 to 79 cm (Meehl and others 2007). The higher range would be more than a doubling of current rates, even though these rates are quite conservative because the IPCC did not include changes in the melting rates of large ice sheets like Antarctica or Greenland. Melting has increased in the last decade (Rignot and Kanagaratnam 2006); therefore, rates of sea-level rise actually may increase much more than predicted (Rahmstorf 2007; Vermeer and Rahmstorf 2009). The most recent estimates of sea-level rise are suggesting more than a meter increase by 2100 (Richardson and others 2009; Vermeer and Rahmstorf 2009); process models attempting to account for ice sheet melting are just beginning, and bring uncertainty to these rates, which could be significant under-estimates (Richardson and others 2009; Vermeer and Rahmstorf 2009).

Historical rates of sea-level rise in the bay-delta have been similar to global averages, with the exception of localized regions or time periods of high subsidence rates, and future increases are also likely to mirror global predictions (Cayan and others 2008a). Models of sea-level rise for the San Francisco Bay–Delta, however, are complicated by other forces. For example, during the negative phase of the Pacific Decadal Oscillation (PDO), climate change effects on the rate of sea-level rise will be slowed, while a shift to the positive phase may result in an accelerated rise (Ramp and others 2009; Largier and others 2010). Combined with other processes (e.g., El Niño Southern Oscillation [ENSO]), fluctuations in sea-level rise may have a greater effect on wetlands than a steady increase.

Locally, other influences from increased average temperatures will be just as great on estuarine wetlands (Figure 1). The primary effects will result from several changes. One is the shift in precipitation toward an increase in rain at the expense of snow in the Sierran watershed (Lettenmaier and Gan 1990; Knowles and Cayan 2002; Miller and others 2003; Hayhoe and others 2004; Knowles and others 2006; Cayan and others 2008b). These changes in snowpack storage will shift the timing of freshwater flows into the estuary, increasing flows in winter with potential flooding (Knowles and Cayan 2002; Miller and others 2003; Hayhoe and others 2004). The remaining smaller snowpack (Hayhoe and others 2004; Cayan and others 2008b), will lead consequently to reduced summer river flows entering the estuary. Lower flows will shift the freshwater–marine mixing interface eastward, progressively encroaching upon the Delta, and increasing salinity in brackish regions of the Napa River, Suisun Bay and potentially up into the western Delta (Goman and Wells 2000; Byrne and others 2001; Stahle and others 2001; Malamud–Roam and others 2007). Current water-management actions have not changed the net climatic influence on estuary salinity, and likely will not influence even greater future effects (Enright and Culberson 2010). The net result of all of these changes will be an estuary with higher mean sea level, increased duration and frequency of inundation, and higher salinities.

Bay–delta wetlands also are affected by Mediterranean-style summer droughts. Porewater in high-marsh areas in salt marsh and brackish tidal wetlands significantly increases in salinity during the warmer, rainless growing season. Our monitoring of wetland soil salinities across the estuary indicates that by late summer salinity only a few meters away from channels is two to three times its concentration in adjacent estuarine waters (unpublished data). Increasing average temperatures (Meehl and others 2007; Richardson and others 2009), increased frequency of heat waves (Cayan and others 2008b), and additional salt inputs from sea-level rise will exacerbate these summer rises in high-marsh salinity. As a consequence, gradual increases in salinity in the San Francisco Bay–Delta estuary will promote the conversion of brackish wetlands to salt marshes, and intruding brackish waters, affecting areas that are currently fresh.

CLIMATE CHANGE EFFECTS ON BAY–DELTA WETLAND VEGETATION

Among wetlands, freshwater and brackish tidal systems will exhibit the greater sensitivity, with large shifts in plant composition and productivity in response to elevated salinity levels—effects that will likely cascade into terrestrial and pelagic food webs. Currently, brackish wetlands are most prominent up the Napa River and in much of the Suisun region. These brackish wetlands transition to freshwater tidal systems farther up the Napa River and into the Delta. Because so many processes are changing simultaneously, however, these tidal systems are likely to change dramatically with multiple species increasing or declining unpredictably.

The San Francisco Bay–Delta system currently experiences seasonal and annual variation in salinity (Fox and others 1991; Peterson and others 1995), and, historically, the brackish zones have shifted across parts of the estuary (Atwater and others 1979; Goman and Wells 2000; Byrne and others 2001; Malamud–Roam and others 2007). More recently, the brackish zones have experienced increased salinity from water diversions upstream, with subsequent shifts in plant composition (Stahle and others 2001; Malamud–Roam and others 2007). Such a historical perspective leads to confidence that wetlands have some resilience in the face of global changes. The changes that will be experienced in the future, however, will be accompanied not only by increased salinity in the system, but also by shifts in CO_2 concentrations, higher temperatures, accelerated sea-level rise, and increasing water diversions—all within the context of a highly urbanized estuary.

Decreases in summer–fall watershed freshwater flow and sea-level rise will shift the saltwater–freshwater mixing zone inland up the estuary, expanding saline influences and increasing wetland soil salinities through time (Figures 1 and 2). Temperature increases will accelerate rates of evapotranspiration, further escalating soil salinities in areas not flushed daily by tides and further influenced by the dry-summer Mediterranean climate compared to many temperate regions (Figure 2). Brackish wetland plant communities will shift toward plants with greater salinity tolerance, for example, *Sarcocornia pacifica*, *Spartina foliosa*, and *Distichlis spicata* (Mall 1969). The latter two, however, are C4 plants and may be at a metabolic disequilibrium with C3 plants that have some salinity tolerance. Further, these changes will be occurring simultaneously in the context of other globally shifting processes, such as increased frequency and duration of inundation due to sea-level rise (Figures 1 and 2). We have found that *S. pacifica* produces biomass at very different rates throughout the northern Bay wetland system, depending on frequency and duration of inundation along a salinity gradient (Schile and others 2011). In well-drained areas, *S. pacifica* seems indifferent to changes in soil salinity, and produces relatively high amounts of biomass. In poorly drained areas, plants are sensitive to salinity, and decrease in productivity with increases in salinity. An estuary with increasing salinity will shift to more salt-tolerant species such as *S. pacifica*, but if inundation frequency and duration increase from a rising sea level, salt marshes in the lower bay-delta may actually be lost, and overall estuarine productivity could decline considerably.

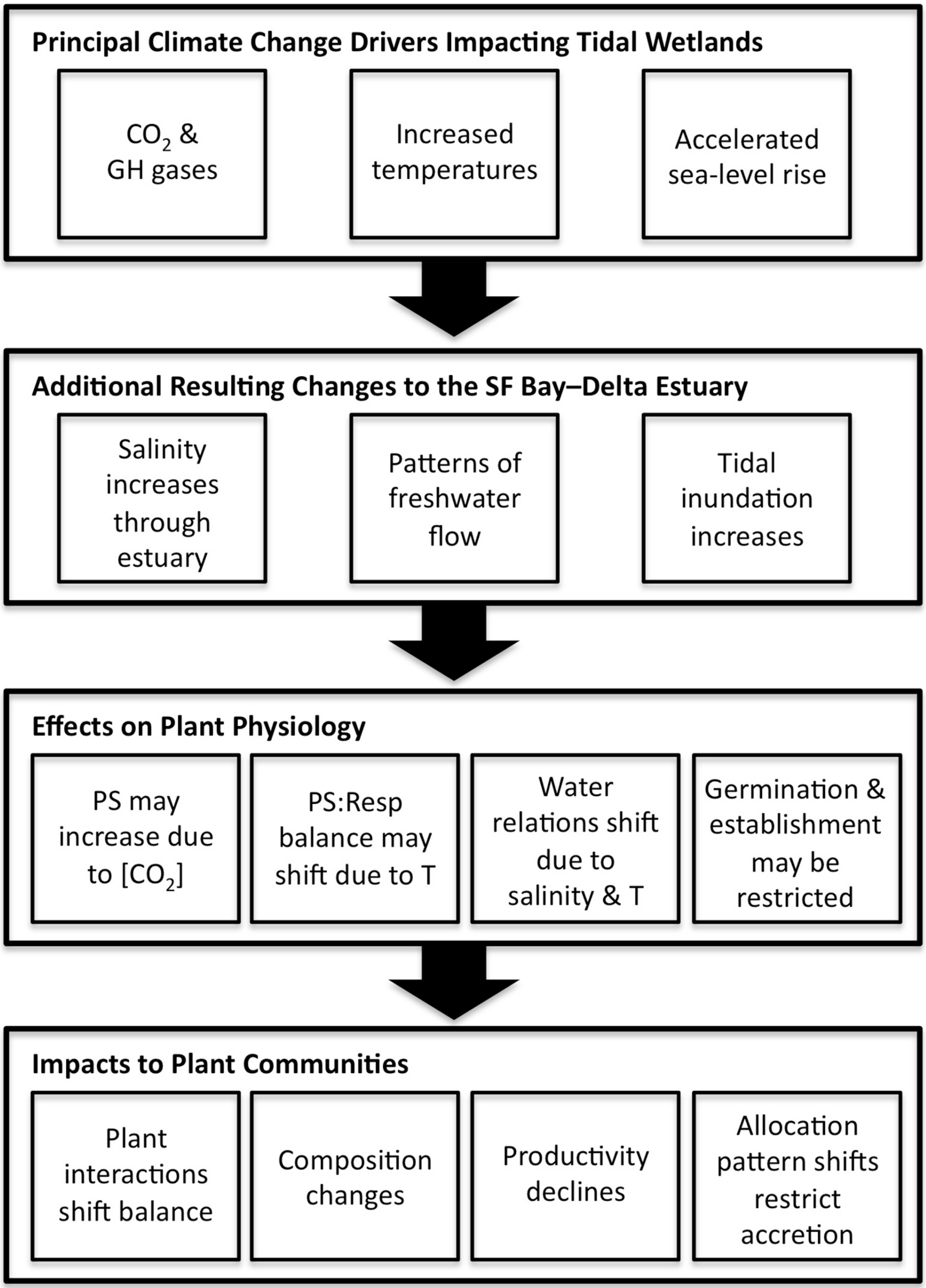

Figure 2 Cascading effects of global climate change processes on tidal wetlands. Effects of increased concentration of carbon dioxide (CO_2) and other greenhouse gases (GH), increased temperature (T) and accelerated sea-level rise (SLR) will directly and indirectly influence plant physiology and stress. Subsequently, changes will occur in the outcome of plant interactions resulting from shifts in physiological performance, for example, of photosynthesis (PS) and cellular respiration (RESP). Composition of wetlands will change, productivity will decline, and these changes may restrict the organic component of vertical accretion.

These environmental shifts will not affect all species within tidal marshes equally. Changes in hydrology, salinity, and other effects of climate change will shift interactions among plants. CO_2, temperature, and increased inundation and soil salinity will strongly influence plant metabolism (Figure 2). CO_2 is an essential plant resource required for photosynthesis (Figure 2). Long-term studies, particularly in the Chesapeake Bay, indicate that a number of ecosystem processes will be affected by increased concentration of CO_2 alone, including photosynthesis, carbon storage and cycling and soil nitrogen fixation and nitrogen dynamics (Drake and others 2003; Johnson and others 2003; Rasse and others 2003; Pendall and others 2004; Hungate and others 2005, 2006; Marsh and others 2005; Rasse and others 2005). Changes in the carbon composition of plants and their structural characteristics may reduce herbivore attack or their effects (Stiling and others 2003; Cornelissen and others 2004).

Experimental studies indicate that overall increases in CO_2 seem to differentially favor plants with C3 photosynthesis at the expense of those with a C4 metabolism (Rasse and others 2005). While these studies found that some acclimation occurred, not all plants fully acclimated, and, some still revealed increased rates of photosynthesis or plant density even after 17 years (Rasse and others 2005). Other wetland research focused on C4 plants found that salt marshes are resilient to modest warming and large shifts in precipitation, although they conclude that interactive effects of multiple changes resulting from climate change may strongly affect wetland composition and function (Charles and Dukes 2009). While most of the species in the San Francisco Bay–Delta wetlands are C3 plants, *Spartina foliosa* and *Distichlis spicata* are C4 plants that are dominant in some parts, and are likely to become comparatively less competitive.

At the same time, increasing temperatures will have both direct and indirect effects. Metabolic systems for any plant ecotype are adapted to limited ranges of temperatures, and enzymes involved in photosynthesis, respiration and other metabolic processes change in efficiency as temperature shifts away from their optimum. Generally, as temperature increases, photosynthesis and respiration rates both increase in an individual plant. At some point, photosynthetic enzymes reach a peak, and photosynthesis declines past that threshold while respiration continues to increase (Figure 3). This will first affect productivity and later plant survival as increasing respiration rates consume stored carbon. Most studies of climate change effects on ecosystems have focused more on CO_2 concentration than temperature (e.g., Rasse and others 2005). Yet long-term research suggests that the shift in the balance between photosynthesis and respiration is already decreasing forest productivity (Clark and others 2003). Unlike increases in CO_2, temperature shifts are more likely to favor C4 plants over C3, complicating our ability to predict the overall response of wetland vegetation to climate changes. Additionally, future climate scenarios suggest up to 7 °C average temperature increases for California, significantly greater than average global increases (Dettinger 2005, 2006; Cayan and others 2008b). Such extreme increases are more likely to reduce

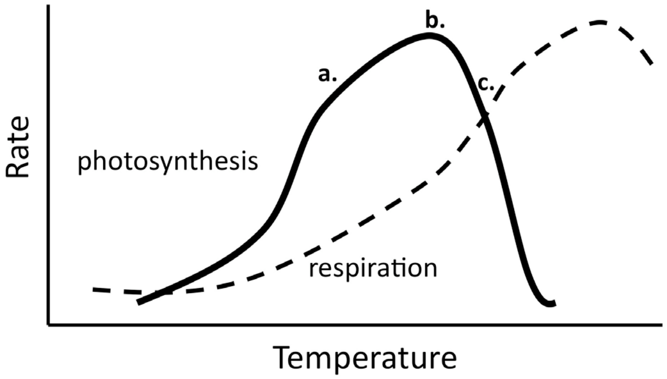

Figure 3 The potential effect of increasing temperatures on the relative balance between photosynthesis and respiration in wetland plants. Depending on their current temperature optima, any particular species might have a different balance in these metabolic rates. For example, if these processes are currently at temperature "**a**," then the balance between photosynthesis, and respiration will be weighted in favor of photosynthesis and further increases in temperatures in the short term will maintain or increase that ratio. At temperature "**b,**" photosynthesis will have peaked, and further increases in temperature means a decrease in plant productivity, as photosynthesis declines but respiration continues to increase. Finally, at temperature "**c**," the rate of respiration now exceeds that of photosynthesis, and mortality will occur after carbon reserves are used.

growth and increase mortality rates in wetland plant species.

Historically, wetlands maintain themselves against sea-level rise by both accretion and upland retreat. A number of uncertainties exist about future rates of sea-level rise, such as estimates of glacial and icepack melt input (Meier and others 2007; Vermeer and Rahmstorf 2009). The most recent model of estimated rates of sea-level rise for the San Francisco Bay–Delta indicate that the estuary has had historical rates equivalent to the global average (Cayan and others 2008a). If the San Francisco Estuary continues to parallel global averages, this suggests a conservative estimate of a rise of 11 to 79 cm by 2070 to 2099 (Meehl and others 2007), with the real possibility of a 1-m to nearly 2-m rise by 2100 (Richardson and others 2009; Vermeer and Rahmstorf 2009). While wetland accretion in the San Francisco Bay–Delta has generally kept up with increases in sea level during the last several thousands of years (Goman and Wells 2000; Byrne and others 2001; Orr and Williams 2003; Malamud–Roam and others 2007), the amount of suspended sediment in bay-delta water suggests that accretion rates may not be able to keep up with accelerated sea-level rise, and upland retreat is blocked by levees or development in many places. Clearly, the relationship among marsh accretion, inundation, and salinity will have variable impacts on tidal marsh species that are difficult to predict (Watson and Byrne 2009).

The future of tidal wetlands in this context of predicted sea-level rise is challenging (Stralberg and other 2011). Because of human development on or near the Bay and Delta, areas for wetland retreat are limited, wave energy will increase, and wetlands are likely to erode in a shoreward direction (e.g., Crooks 2004). While wetlands likely could keep pace with moderate increases in sea level of up to 6 mm yr^{-1} (Patrick and DeLaune 1990; Orr and others 2003), this may not occur with higher rates of sea-level rise that other researchers suggest may occur (Meier and others 2007; Church and others 2008; Richardson and others 2009; Vermeer and Rahmstorf 2009). Suspended sediment in estuary waters may be insufficient for compensatory wetland accretion after a threshold rate of sea-level rise is reached (Orr and Williams 2003); past that threshold, only the organic contribution by plant growth remains as the driving mechanism for wetland accretion. Current models suggest that wetlands have a lag in response to rising sea level, with a significant variation in productivity. Wetlands appear to be stable when the wetland surface is above the optimal elevation (Morris and others 2002). Unless belowground plant productivity compensates with large increases in biomass production, the result will be increases in the frequency and duration of tidal inundation (Figure 2), leading to increased plant stress. Existing low-marsh areas would be converted to mudflats, and low-marsh plants would migrate into areas previously dominated by marsh plain vegetation (e.g., Donnelly and Bertness 2001). Depending on conditions along the wetland–upland border, wetlands will migrate inland. In many cases around the Bay–Delta, however, migration will be restricted by adjacent dikes and development‹a process often referred to as coastal squeeze (Titus 1991; French 2001). Finally, many wetlands have been converted to islands and lack any chance for migration. Increased rates of sea-level rise will differentially affect the viability of restoration projects in the bay-delta region by reducing the opportunity for plants to establish in newly restored wetlands (see Table 1 in Callaway and others 2007).

Another effect that is poorly understood is the combination of (1) increases in estuarine salinity, (2) rates of sea-level rise, and (3) reductions in plant productivity on the dynamics of physical–biological processes that create substrates within wetlands. Specifically, wetland substrates change in tandem with the salinity gradient. Within freshwater tidal regions, the substrate is highly organic. These substrates become increasingly mineral in more saline areas, such that the salt marsh substrates have lower organic content than freshwater wetlands and are dominated by fine clays (e.g., Nyman and others 1993). As the estuary increases in salinity and plant productivity declines, including in the rooting zone, even greater rates of mineral sediment inputs will be required for wetlands to remain stable with sea-level rise, because of the reduction in belowground productivity and corresponding decrease in the organic composition of substrates.

In addition to altered growth rates as a result of climate shifts, other types of effects will occur (Jin 2008, Figure 2). Increases in soil salinity and inundation will differentially affect germination and the physiological limits of species. For example, the salt marsh shrub *Grindelia stricta* var. *angustifolia*, while tolerant of high salinities, requires a considerable reduction in salinity for germination; complete inhibition of germination occurs by salinities at or above 23 ppt (Wayne 1995). Six years of drought in the late 1980s to early 1990s and corresponding salinity increases during germination resulted in more than a 90% reduction in population size at China Camp salt marsh (V. Thomas Parker, unpublished data). Such effects on germination and survival will result in a shift in species composition through time, regardless of how environmental changes affect productivity. In salt marshes within the bay-delta, wetland productivity will only decline slowly without large composition or structural changes. However, in brackish and freshwater tidal marshes, changes in salinity of a few parts per thousand will have considerable effects because the growth, productivity, and survival of most species are highly sensitive to any salinity. Small changes in salinity could significantly affect the diversity and composition of these wetlands.

Lastly, as part of the California Floristic Province, the bay-delta presents relatively high levels of local species endemism, particularly in the brackish marshes of San Pablo Bay, Suisun Bay, and the lower Delta. As highlighted by Loarie and others (2008), local endemic species are highly susceptible to the forces of rapid climate change, particularly in cases where their dispersal is likely to be constrained by impermeable barriers. Endemic flowering plant species in the bay-delta (e.g., *Cirsium hydrophilum*) could be particularly susceptible to the kinds of changes described above.

CONCLUSIONS AND IMPLICATIONS

In summary, global climate changes are differentially affecting tidal wetlands compared to temperate terrestrial ecosystems (Nicholls and others 1999; Ellison 2000; Stevenson and others 2002) and may already be shifting these ecosystems into novel states (Donnelly and Bertness 2001). Effects on the San Francisco Bay–Delta estuary are complex and difficult to predict, but a few points are clear. Biodiversity of the tidal wetland system in the San Francisco Bay–Delta region will decline, with subsequent effects on ecosystem functioning and services (e.g., Hooper and others 2005). Changes in concentrations of carbon dioxide—as well as increased temperatures—will affect plants directly and their direct and indirect effects (Figure 1) will alter plant production, physiological tolerances, and rates of mortality (Figure 2). The result of shifting tolerances and the changes in the balance among plant interactions will lead to altered wetland plant communities. The earliest recognizable changes in estuary wetlands will be from salinity increases, because even with current levels of water management, climate patterns govern shifts of salinity in the estuary (Enright and Culberson 2010). As summer temperatures rise and Sierra snowmelt decreases, we should expect saline ecosystems to increase both in distribution and in area upstream, with losses principally in brackish and freshwater tidal wetlands and their local endemic species, leading to overall lower ecosystem productivity. Increases in sea-level rise will further shift plant distributions, with an increase in species that are more tolerant of inundation (e.g., *Spartina foliosa*, *Schoenoplectus* spp., *Typha*) at moderate rates of sea-level rise and outright loss of wetlands at higher rates. These changes will affect both primary and detrital-based food webs, and cascade via these food webs into invertebrate, bird, and pelagic systems (e.g., Galbraith and others 2002; Hughes 2004).

What is also clear is that under current policies and social perspectives, long-term and appropriate management of the estuary will conflict with other resource demands of California. The San Francisco Bay–Delta estuary is beginning to reverse a century of tidal wetland loss through large-scale wetland restoration projects across the estuary (Callaway and others 2007, 2011), but current bay-delta development at low elevation, and increasing demands on freshwater supply, will emerge as major threats to the estuary, as will shifts in the overall sediment budget of the estuary. Globally, a consensus is emerging that policies need to accommodate and adapt to changes that will accompany climate change. Attempts to maintain and defend estuarine and coastal developments inevitably will become increasingly costly (Crooks 2004), at the expense of the estuarine ecosystem and the ecological services provided.

Great uncertainties underlie much of the modeling that suggests the future scenarios for the San Francisco Bay–Delta estuary. We did not consider predicted extreme events, such as longer series of hot or cold years, large earthquakes, severe storms, normal shifts in precipitation patterns, increased frequencies in flooding, or other changes that will occur as temperatures and sea-levels rise (Cayan and others 2008b). Changes in wetland vegetation will not follow simple gradient shifts because of these extreme events, but rather change opportunistically following episodic droughts or heat waves that result in large diebacks or reduced growth after thresholds in salinity or heat tolerances are reached. These will undoubtedly have major effects on the system as well. For example, a brief heat wave early in the spring 2001 growing season caused a temporary setback in the restoration of a newly formed marsh on the Petaluma River (Tuxen and others 2008). Other uncertainties are more global, for example, rates of melting of Greenland or the Antarctic, disruptions of the Atlantic thermohaline circulation, shifts in decadal processes such as the El Niño–Southern Oscillation, or other “tipping points” that may cause rapid disruptions in the estuary (Lenton and others 2008).

At present, we need more research into a number of issues to fully understand how climate change will affect the San Francisco Bay estuary, so that appropriate policies and management actions can be developed (e.g., Sutherland 2004). Clearly, new wetlands need to be restored rapidly so that their development will not be inhibited by the increased erosive energy that will result from future increases in sea-level rise. Once established, restored marshes with well-developed vegetation are more likely to resist the effects of sea-level rise or other environmental changes. However, restoration priorities need to focus on sites not subjected to potential coastal squeeze, or else site barriers need to be modified to retreat along with the wetland restoration. In addition, a number of issues not discussed here need further research, such as the effect of invasive species. Changes in precipitation or temperature have already helped to spread wetland invasive species (Minchinton 2002; Loebl and others 2006). Invasive invertebrates are eroding marshes in southeastern Britain at relatively rapid rates, and the increased temperatures of climate change may stimulate that process (Hughes 2004); ironically, the bay-delta has any number of plant and invertebrate invasive species that will potentially synergize with climate change to create an even greater effect on this ecosystem in the future. We are unsure exactly how dominant wetland species will respond to the range of changes resulting from climate change. We lack information on the links between biodiversity in brackish and freshwater tidal wetlands and ecosystem functioning. Finally, we do not know the effectiveness of current conservation measures and policies governing human development and potential paths for biotic retreat in areas increasingly threatened in the near future. Natural ecosystems such as the bay-delta provide too many ecological services to society to be ignored or reduced in priority.

The San Francisco Bay–Delta estuary embodies a nexus of natural ecosystems and socio-economic policies that have come into conflict in the face of rapid environmental change. This iconic region is at risk, as is the economic health and vitality of the human society that depends upon it. As we shift toward mitigating greenhouse gas emissions, we also must embrace adaptating to the suite of potential ecological changes described above. Innovative use of water storage and flows, land use policies that favor corridors and refugia to accommodate wetland migration, restricted infrastructure in or adjacent to wetlands, and many other measures will be needed to break the traditional pattern of sacrificing ecosystems for short-term gain. The manner in which we face this challenge realistically and act accordingly, will determine the ecosystem’s—and our—continuing vitality.

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