Estuaries and Coasts
DOI 10.1007/s12237-013-9585-4

Implications for Future Survival of Delta Smelt from Four Climate Change Scenarios for the Sacramento–San Joaquin Delta, California

Larry R. Brown · William A. Bennett · R. Wayne Wagner · Tara Morgan-King · Noah Knowles · Frederick Feyrer · David H. Schoellhamer · Mark T. Stacey · Michael Dettinger

Received: 12 July 2011 / Revised: 12 November 2012 / Accepted: 3 January 2013

Abstract Changes in the position of the low salinity zone, a habitat suitability index, turbidity, and water temperature modeled from four 100-year scenarios of climate change were evaluated for possible effects on delta smelt *Hypomesus transpacificus*, which is endemic to the Sacramento–San Joaquin Delta. The persistence of delta smelt in much of its current habitat into the next century appears uncertain. By mid-century, the position of the low salinity zone in the fall and the habitat suitability index converged on values only observed during the worst droughts of the baseline period (1969–2000). Projected higher water temperatures would render waters historically inhabited by delta smelt near the confluence of the Sacramento and San Joaquin rivers largely uninhabitable. However, the scenarios of climate change are based on assumptions that require caution in the interpretation of the results. Projections like these provide managers with a useful tool for anticipating long-term challenges to managing fish populations and possibly adapting water management to ameliorate those challenges.

L. R. Brown (✉) · T. Morgan-King · D. H. Schoellhamer
US Geological Survey, Placer Hall, 6000 J St.,
Sacramento, CA 95819, USA
e-mail: lrbrown@usgs.gov

W. A. Bennett
Center for Watershed Sciences, Bodega Marine Laboratory,
University of California, Davis, PO Box 247,
Bodega Bay, CA 94923, USA

R. W. Wagner
Department of Civil and Environmental Engineering,
University of California, Berkeley, 205 O'Brien Hall,
Mail Code 1712, Berkeley, CA 94720-1720, USA

M. T. Stacey
Department of Civil and Environmental Engineering,
University of California, Berkeley, 665 Davis Hall,
Mail Code 1710, Berkeley, CA 94720-1710, USA

N. Knowles
US Geological Survey, Bldg 15, McKelvey Building,
345 Middlefield Road,
Menlo Park, CA 94025-3561, USA

F. Feyrer
Bay Delta Office, US Bureau of Reclamation, 801 I Street,
Sacramento, CA 95814, USA

M. Dettinger
US Geological Survey, Scripps Institute of Oceanography,
University of California, San Diego, 9500 Gilman Drive,
La Jolla, CA 92093-0224, USA

Keywords Delta smelt · *Hypomesus transpacificus* · San Francisco Estuary · Sacramento–San Joaquin Delta · Climate change · Delta · Estuary

Introduction

Assessments of climate change effects on aquatic resources are increasing in relevance and importance as methods for downscaling global scenarios to ecologically relevant scales improve. This sharper resolution for scenarios provides increased opportunities for understanding the effects of climate change on aquatic resources. For example, projections of the likely effects of climate change on fish populations are moving from basin-scale oceanic and regional freshwater assessments (e.g., Beamish 1995; Roessig et al. 2004; Chu et al. 2005; Perry et al. 2005) to projections for specific river systems (Yates et al. 2008; Wiley et al. 2010).

Published online: 17 January 2013

However, relatively few assessments have focused on specific estuarine systems and their aquatic resources, presumably because of the inherent challenges in projecting likely changes occurring across multiple tributary watersheds and the dynamic estuarine environment where inflowing fresh water mixes with the near-shore ocean (Wood et al. 2002; Peterson 2003; McClusky and Elliot 2004; Moyle et al. 2010; Cloern et al. 2011).

The San Francisco Estuary (hereafter, Estuary) (Fig. 1) is the largest estuary on the West Coast of North America and is arguably one of the best studied (e.g., Conomos 1979; Hollibaugh 1996; Feyrer et al. 2004). The native aquatic organisms of the estuary and watershed have been affected by multiple interacting factors since European settlement, including habitat alteration, water diversion, flow regime alteration, and invasive species (Bennett and Moyle 1996; Brown and Moyle 2005; Sommer et al. 2007; Moyle et al. 2010). Presently, six native fishes that use or pass through the Estuary are listed as threatened or endangered under state or federal statutes. Water diverted from the Sacramento–San Joaquin Delta (hereafter, Delta) at the southeastern margin of the Estuary (Fig. 1) supports a multibillion dollar agricultural economy and provides drinking water to more than 20 million Californians.

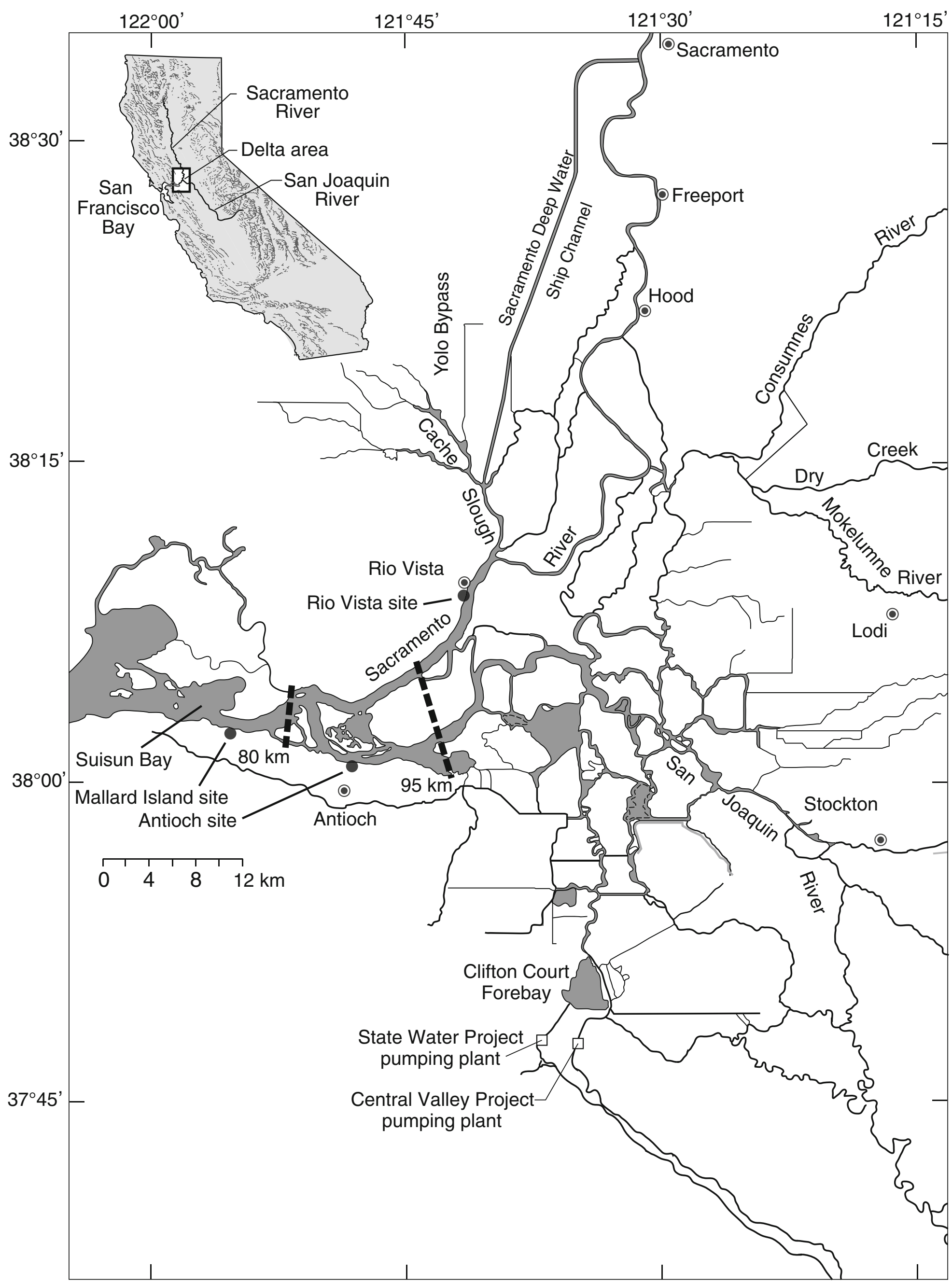

Fig. 1 Map of the Sacramento–San Joaquin delta and Suisun Bay. Sites are indicated by *black dots*. The *dashed lines* indicate X2 values (distance of the salinity 2 isohaline from the Golden Gate) that bound all but a few of the X2 values expected under the climate change scenarios

The delta smelt *Hypomesus transpacificus* is endemic to the upper San Francisco Estuary, primarily the Delta and Suisun Bay (Fig. 1) and is one of the six species listed as threatened or endangered under state or federal statutes. Because of its limited range, the delta smelt may be the most vulnerable to climate change of the native fishes that use the Estuary. After years of gradual decline and a recent steep decline (Sommer et al. 2007; Thomson et al. 2010), there is a growing concern that the delta smelt is in danger of extinction. Like many estuarine species, thresholds of water temperature, salinity, and turbidity are important elements of the physical habitat utilized by delta smelt (Bennett 2005; Sommer et al. 2007; Feyrer et al. 2007, 2010). These factors are not only influenced by changes in climate, but water management practices as well. Current water management practices intended to benefit delta smelt and other listed species often involve limitations on quantity and timing of water exports and are thus inexorably linked to water resource policies and allocation throughout California.

The delta smelt is primarily an annual species with a small percentage living for 2 years (Bennett 2005). Maturing delta smelt move from Suisun Bay into the freshwater regions of the Delta during the winter, where they continue to develop. Water temperatures during spawning have not been measured in the wild, but larval survival in aquaculture and occurrence of larvae in the estuary suggests that the majority of successful spawning occurs within a window of 15–20 °C (Bennett 2005). After hatching, larval delta smelt gradually move seaward toward Suisun Bay (Dege and Brown 2004) as water temperatures in the Delta approach 20 °C. Juvenile delta smelt largely rear in the low salinity zone (about 1–6 salinity), which is generally located from Suisun Bay to the confluence of the Sacramento and San Joaquin Rivers (Fig. 1) depending on Delta outflow. However, recent sampling in the northern Delta suggests that some portion of the population may inhabit freshwater for the entire year, specifically the Sacramento River to Rio Vista and then northward to the region around the Sacramento Deepwater Ship Channel (Sommer et al. 2011). Based on hatchery studies, delta smelt growth seems to be optimal at about 20 °C with unlimited food (Bennett et al. 2008). Catches of delta smelt in the estuary decrease at temperatures above 20 °C (Bennett 2005; Feyrer et al. 2007; Nobriga et al. 2008) with delta smelt rarely captured at temperatures exceeding 25 °C. Recent studies have linked delta smelt distribution in the summer and fall with turbidity levels within the suitable ranges of salinity and temperature (Feyrer et al. 2007, 2010; Nobriga et al. 2008). Delta smelt are rarely captured in clear water (<12–18 NTU); larval delta smelt require turbidity for successful feeding in laboratory culture experiments (Baskerville-Bridges et al. 2004a, b).

In this paper, we assess possible effects of four scenarios of climate change for the present century on the Delta and likelihood of persistence of delta smelt under these scenarios. Specifically, we use model projections of changes in water temperature, salinity, and turbidity to assess the possible effects of climate change on delta smelt. These results add to previous analyses by Cloern et al. (2011) that considered only two scenarios and only one metric of possible effects on delta smelt. Recent declines in delta smelt abundance almost certainly resulted from many interacting factors (Sommer et al. 2007; NRC 2012), including changes in physical habitat features and other factors we do not address in this paper (e.g., food availability, predation, and entrainment by water diversions; Sommer et al. 2007; NRC 2012). However, changes in the availability and distribution of suitable habitat define the arena within which complex ecological processes occur. We stress that these scenarios are possible futures rather than quantitative predictions. Furthermore, the scenarios assume that no major changes in infrastructure or water management practices will occur, which is unlikely over the long term as California grapples with its water supply issues (Lund et al. 2010).

Methods

General Modeling Approach

Here, we briefly outline our general modeling approach (Fig. 2). Details are presented in separate sections below. Our general approach is the same as that followed by Cloern et al. (2011). We selected two very different scenarios of climate change from those included in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (2007) and two intermediate scenarios (Table 1). The global climate model (GCM) projections of precipitation and air temperature were then downscaled to the regional level, specifically the San Francisco Estuary and watershed, using the same approach as Dettinger (2012). The VIC model (Cherkauer et al. 2003; Liang et al. 1994) was then used to project runoff in the major river systems of the watershed, all of which have major storage reservoirs. The CALSIM II water management model (Draper et al. 2004) was used to simulate water project operations, which partially determine discharge into the Delta and outflow from the Delta to San Francisco Bay. Outflow from the Delta toward San Francisco Bay determines the location of the low salinity zone with is indexed by X2, the distance from the Golden Gate (km) of the salinity 2 near-bottom isohaline (Jassby et al. 1995). X2 can be used to estimate the extent of habitat considered suitable for delta smelt with respect to salinity and turbidity based on a habitat suitability index created by Feyrer et al. (2010).

We developed a simple turbidity model for the Rio Vista location to evaluate the turbidity component of the habitat

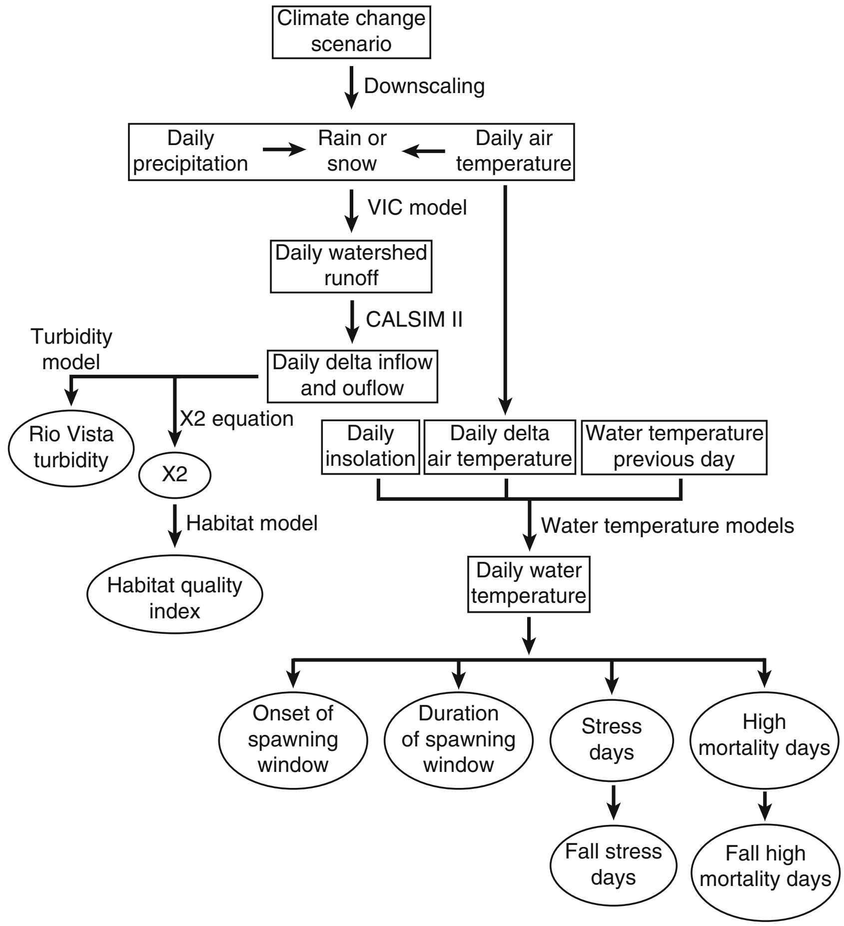

Fig. 2 Flow chart of modeling strategy. See text for details

suitability model, which assumes no change in the relationship of turbidity to flow. We calculated future turbidity under two alternative assumptions. First, we assume only changes in flow based on the CALSIM II output. Second, we also assume decreasing turbidity based on the calculation of Cloern et al. (2011) of a 1.6 % annual decrease based on data collected from 1975 to 2008. Turbidity modeling was based on statistical models of the relationship between river inflow and turbidity measured near Rio Vista (Fig. 1).

Statistical models of daily water temperature were developed for monitoring stations in the Delta with sufficient length of record (Wagner et al. 2011). These models are based on air temperature, water temperature the previous day, and daily insolation. Based on the available delta smelt life history information and outputs from the available models, we selected a variety of metrics as indicators of delta smelt habitat quality (Table 2).

Similar to Cloern et al. (2011), there are multiple sources of uncertainty in our study; however, the complexity of the San Francisco estuary and watershed and the detailed environmental variables evaluated make a full sensitivity analysis of the entire suite of models used in this study

Table 1 Climate change scenarios used to assess the potential effects of climate change on delta smelt in the upper San Francisco Estuary

Scenario	Definition	Descriptive outcome
PCM B1	Parallel Climate Model assuming a future where greenhouse-gas emissions level off by the end of the century	A modestly warmer (~ +1.5 °C end of century) future with no change in precipitation
PCM A2	Parallel Climate Model assuming a future where greenhouse-gas emissions continually increase through the century	A moderately warmer (~ +2.5 °C) future with little change in precipitation
GFDL B1	Geophysical Fluid Dynamics Laboratory CM2.1 model assuming a future where greenhouse-gas emissions level off by the end of the century	A moderately warmer (~ +2.7 °C) future with moderate declines (−10 %) in precipitation
GFDL A2	Geophysical Fluid Dynamics Laboratory CM2.1 model assuming a future where greenhouse-gas emissions continually increase through the century	A much warmer (~ +4.5 °C) and drier (−20 %) future

The descriptive outcome is based on the downscaled data for the San Francisco Estuary watershed described in the text

Table 2 Metrics used to assess the potential effects of climate change on delta smelt in the upper San Francisco Estuary (see the text for details)

Metric	Definition	Significance
Fall X2	X2 is the distance of the salinity 2 isohaline from the Golden Gate, measured near bottom. Fall X2 is the mean of the monthly values from September to December	Indicator of the location of the low salinity zone favored by juvenile delta smelt
Habitat suitability index	The index is derived from a model that considers delta smelt occurrence relative to salinity and turbidity and the areal extent of suitable habitat	Indicator of the extent of physical habitat available for delta smelt to utilize
Number of days in spawning window	Number of days during the period beginning with 5 consecutive days of water temperature >15 °C and ending with 5 consecutive days of water temperature >20 °C	Indicator of the length of the spawning season
Mean date of the spawning window	The Julian date of the midpoint of the spawning window as previously defined	Indicator of the timing of the spawning season
Stress days	Cumulative number of days of daily average water temperature >20 °C	Indicator of sublethal physiological stress
High mortality days	Cumulative number of days of daily average water temperature >25 °C	Indicator of increased mortality due to acute temperature stress
Stress days in Fall	Number of stress days from 1 September to 14 December. This time period coincides with the time period for Fall X2 and the Habitat Index	Indicator of sublethal physiological stress during the Fall
High mortality days in Fall	Number of high mortality days from 1 September to 14 December. This time period coincides with the time period for Fall X2 and the Habitat Index	Indicator of increased mortality due to acute temperature stress during the Fall
Percentage of time turbidity <18 NTU	The percentage of the year when the regression model predicts turbidity <18 NTU based on average daily flow	Indicator of unfavorable turbidity for delta smelt

prohibitively difficult. One of the largest sources of uncertainty is represented in the spread of projected temperature and precipitation changes among the model outputs used in the IPCC's Fourth Assessment Report (IPCC 2007). Our general approach was to select scenarios that bracketed the likely range of future conditions, specifically with regard to temperature and precipitation changes. A general tendency of GCM projections over northern California is toward little precipitation change from models with smaller warming trends and less precipitation from models with greater warming (Dettinger 2005; Brekke et al. 2008). By selecting two models from near the two extremes of this tendency and two different emission scenarios (Table 1), we cover a wide range of possible conditions, to reflect the uncertainties in GCMs and emissions of greenhouse gases. By then evaluating responses of selected environmental variables and their possible effects on delta smelt, we capture a wide range of possible effects on the species.

We limit our assessments to three locations that bracket the confluence of the Sacramento and San Joaquin Rivers (Fig. 1). This geographic region can comprise a large portion of suitable delta smelt habitat when X2 is located in the Antioch region and landward. Delta smelt also reside in freshwater in the Cache Slough region and deepwater ship channel north of Rio Vista (Sommer et al. 2011). Tidal exchange of water from this area with Rio Vista is substantial because the deepwater ship channel is much deeper than the Sacramento River channel upstream of their confluence. Thus, water temperature and turbidity conditions at Rio Vista can be considered indicative of conditions in this northern area. Water clarity and water temperature conditions are already unfavorable for delta smelt in the central and southern Delta during the summer (Nobriga et al. 2008; Sommer et al. 2011).

Baseline Conditions

Understanding the effects of climate change requires establishment of a baseline for evaluation of changes. We established a baseline condition for each of our environmental metrics. The baseline was then compared to 90 years of data from each scenario (2010–2099). Baseline conditions for mean X2 (September–December) were hindcast for the period 1968–2000 using the same modeling setup used to produce the future scenario values of X2 (described below). While actual data for X2 are available for this period (Dayflow data base, http://www.water.ca.gov/dayflow/), we wanted to produce a baseline for X2 that reflected both historical hydro-meteorological variability and the same modeling assumptions present in our future X2 scenarios. Therefore, we used historical hydrological simulations of reservoir inflows to drive the CALSIM II model, which was configured exactly as in the 2010–2099 runs except that freshwater demands in the model correspond to a 2000 level of development (as opposed to a 2020 level of development in the future scenarios). Thus, any differences between baseline and scenario values can be attributed to climate change and to the change between the year 2000 level of development and the projected 2020 level of development rather than to differences from observations caused by model assumptions. A consequence of this, however, is that our baseline data calculated using this model "hindcast" approach, while more useful in allowing an "apples-to-apples" comparison with future scenarios, do not faithfully reproduce the observed historical variability, particularly with regard to any trends that may have resulted from changes in management strategies and capabilities over the historical baseline period. However, the use of historical meteorology permits at least some reasonable comparisons with observed historical behavior, as opposed to "historical" GCM runs, which correspond to actual historical behavior only in terms of greenhouse gas forcings and not year-to-year variability.

The resulting model-based estimates of historical Delta outflow were used to calculate baseline X2 as detailed below. Mean fall (September–December) X2 was then determined and used to calculate the habitat suitability index for the baseline period. Baseline water temperatures were also obtained by hindcasting for the same reasons discussed above (to generate a baseline based on the same models used to produce future scenarios, allowing more meaningful comparisons) and because water temperature has not been monitored at all sites over the entire baseline period. Baselines for the water temperature metrics (1969–2008) were calculated from historical air temperature values. Similar to X2, hindcasts of turbidity were conducted using the CALSIM II calculated daily flows for 1968–2000 to drive the turbidity model detailed below.

Climate Change Scenarios

Projected scenarios of daily air temperatures and flow were derived from simulations of twenty-first century climate by two GCMs under each of two future global greenhouse-gas emissions scenarios (Table 1). The GCMs used were the Geophysical Fluid Dynamics Laboratory (GFDL) CM2.1 coupled ocean–atmosphere GCM (Delworth et al. 2006) and the National Center for Atmospheric Research Parallel Climate Model (PCM) coupled ocean–atmosphere GCM (Washington et al. 2000). The GFDL model is considered strongly sensitive to greenhouse-gas emissions among those considered by the IPCC (2007) and produces larger changes in climate compared to other models with the same change in greenhouse-gas emissions. The PCM model is considered to have low sensitivity to greenhouse-gas emissions, producing smaller changes in climate than other models for the same change in greenhouse-gas emissions.

We considered two scenarios of greenhouse-gas emissions available from the IPCC (Nakicenovic et al. 2000). The A2 scenario assumes a very heterogeneous world economy with high population growth and resulting greenhouse-gas emissions that accelerate through the remainder of the century. We selected this scenario because it represented a reasonable estimation of a worst case scenario. Subsequently, Raupauch et al. (2007) showed that during the past decade, emissions have actually exceeded those represented by A2. Thus, our results may underestimate the most extreme possible effects on delta smelt. The B1 scenario assumes a more resource efficient future with lower population growth resulting in emissions leveling off by the end of the century.

Climate data from simulations by these two models, under A2 (continually increasing) and B1 (leveling by mid-century) greenhouse-gas emissions scenarios, were obtained from the Program for Climate Diagnosis and Intercomparison at the Lawrence Livermore National Laboratory (Meehl et al. 2007). As explained earlier, these scenarios were chosen to largely bracket the range of recent climate-change projections for California, with the GFDL A2 scenario being near the warmer and drier end of current projections and the PCM B1 scenario being near the less-warm and less-dry end of projections (Cayan et al. 2009) (Table 1). These climate change scenarios are included in several recent assessments of climate change for California (Cayan et al. 2008, 2009), which should allow for integration of our results with climate change planning for the state.

Downscaling

The GCM simulations were made on global grids with spatial resolutions of about 2–3° latitude and longitude (about 250 km at the latitude of the Delta). The GCM outputs were "downscaled" onto a one-eight-degree grid over the conterminous US by the method of Constructed Analogues (Hidalgo et al. 2008; Maurer et al. 2010; data available at http://tenaya.ucsd.edu/wawona-m/downscaled/) under the direction of one of the authors (MDD). The data for our study area was then extracted from this larger coverage. Downscaling refers to the transformation of simulated climate variables from the spatial scale of GCMs to estimates of climate at smaller spatial scales. Briefly, Constructed Analogues is a statistical approach to downscaling in which the coarse gridded depiction of a day's climate (weather) from a GCM is matched to a set of days, in the same season of the year, with closely matching historical, observed climate patterns (weather maps) at the same spatial scale. The best linear combination of the historical weather maps that fit the model pattern is then determined by linear regression. The resulting regressions are then used to interpolate climate variables at finer spatial scales between the GCM grid points. The Constructed Analogues approach yields particularly realistic temperature and precipitation relations across areas with sharp geographic gradients (Cayan et al. 2009) like the near-coastal areas of California. The method was applied to climate simulations spanning the period from 1950 to 2100, to obtain daily, gridded temperature and precipitation patterns of twenty-first century climate over California. Greater detail on the application of the method to California is available in Dettinger (2012). Plots of air temperature and precipitation for the GFDL A2 and PCM B1 scenarios are available in Cloern et al. (2011).

VIC Model

Downscaled precipitation and air temperature from the climate change scenarios were used to drive the VIC watershed model (Cherkauer et al. 2003; Liang et al. 1994). This model has been applied in several prior studies of the Sacramento River and San Joaquin River watersheds (Barnett et al. 2008; Cayan et al. 2008; Maurer et al. 2010). We use the same model configuration and parameters used in those studies. The VIC model is a surface water energy balance model intended for large-scale applications. It considers land cover within each gridded cell of the model. Within each land cover vegetation class, the model considers spatial variability of infiltration and simulates runoff generation, using a variable infiltration curve (Cherkauer et al. 2003). We used the model to calculate unimpaired runoff for each of the major headwater basins of the Delta's watershed at inflows to the major reservoirs. Cloern et al. (2011) simulated unimpaired runoff using two separate models—VIC and the independently derived Bay-Delta Watershed Model (Knowles 2000; Knowles and Cayan 2004). The latter is a distributed soil-moisture accounting model of unimpaired hydrology for the watershed. Results from the two models are very similar, indicating that our results are robust with respect to choice of hydrologic model. Plots of projected unimpaired runoff for GFDL A2 and PCM B1 scenarios are available in Cloern et al. (2011).

CALSIM II

Because all of the major headwater basins in the Sacramento–San Joaquin watershed include dams, storage reservoirs, and diversions, water management activities must be considered when estimating inflow to the estuary from runoff in the watersheds. We did this using unimpaired runoff at major reservoir inflow points from the VIC model to drive the CALSIM II model. The CALSIM II model is used to help plan operations of the State Water Project and the federal Central Valley Project, given existing water allocations, regulatory commitments, and annual runoff conditions (Draper et al. 2004). The model is also used to assess future water demand given scenarios of future development.

CALSIM II is a management optimization model (Draper et al. 2004). Given reservoir inflows, a set of water management actions (e.g., reservoir releases) is derived that optimally satisfies operational goals (e.g., water diversions) and constraints (e.g., water quality requirements). The results are estimates of managed freshwater flows at established points throughout the watershed. CALSIM II has been applied to a number of other climate-change studies in California (Brekke et al. 2004; Dracup et al. 2005; Vicuna et al. 2007; Anderson et al. 2008; Brekke et al. 2009; Cloern et al. 2011).

CALSIM II has several shortcomings that must be considered when interpreting results. When surface water supplies are insufficient to meet demands, the model implements additional groundwater withdrawals. When the mismatch is great enough, groundwater withdrawals can exceed sustainable levels. In reality, such high withdrawals could eventually lead to depletion of aquifers, and to avoid this, reductions in surface-water deliveries would be likely, and the ability to repel salinity intrusion could be affected.

CALSIM II also works at a monthly time step, producing monthly averaged streamflow. As described in Cloern et al. (2011), monthly flows were disaggregated to daily flows by selecting from daily flow records at key locations where water is released below dams. For each future month, an optimally matched historical month was selected based on comparisons of historical and projected inflows to the reservoir. Matches were based on a combined root-mean-square error and correlation coefficient metric. The daily flows at the downstream location for the historical month were then scaled to match the projected CALSIM II monthly flow. This approximation of daily flow was designed mainly to represent rainy-season flow peaks and is largely superfluous during the months of September–December examined in this study for fall X2 and the habitat suitability index—in a separate analysis, there was very little difference between monthly mean values of X2 (see below) calculated using daily flow and those calculated directly using interpolated monthly averaged flows.

Many aspects of California's freshwater management system are in flux and changing economic conditions will likely have major effects on projected demand (Lund et al. 2010). Given these uncertainties and the inability to run simulations for a wide range of water management and future demand scenarios, we based our projections of a 100-year period (2000–2100) on projected water demand for the year 2020 and the operational criteria as of 2006, when we obtained the CALSIM II model from the California Department of Water Resources. The water demand for 2020 level of development had already been determined as part of a California Department of Water Resources planning study. The implications of these modeling limitations are addressed in "Discussion."

The output of the CALSIM II model, which includes monthly flow for all inputs to and outputs from the Delta, were disaggregated to daily values as described above. It is important to note that while the CALSIM II model's assumption of present-day management priorities in the future is a limitation, the model treats X2 control as one of its top priorities. This means that the model may take unrealistic measures (such as unsustainable levels of groundwater extraction) to repel salinity, with the result that salinity intrusion is, if anything, underestimated in the present approach. This is even more the case because sea level rise effects are not included in this analysis (see below).

X2 and Habitat Index

The location of the low salinity zone, as indexed by X2, in the estuary during the spring has been linked with the abundances of a number of species of aquatic organisms (Jassby et al. 1995), although the actual mechanisms underlying these relationships are poorly known (Kimmerer 2002a, b). The low salinity zone, defined as salinity 1–6, represents the optimal salinity for delta smelt in the summer and fall based on species occurrence (Feyrer et al. 2007; Nobriga et al. 2008). We used the estimates of daily outflow to calculate X2 according to the autoregressive model of Jassby et al. (1995): $X2_{(t)}=10.16+0.945\ X2_{(t-1)}-1.487\ LQ_{(t)}$, where $X2_{(t)}$ and $X2_{(t-1)}$ are the positions of salinity 2 at day (t) and ($t-1$), and LQ is the $\log_{10}$ of daily mean net Delta outflow. We then calculated the mean monthly X2 for the period September through December. These months represent the sampling period for the Fall Midwater Trawl (FMWT), which is the primary survey used to index the size of the delta smelt population each year. These months represent the period when juvenile delta smelt develop into preadults and acquire the energy resources necessary for maturation and production of gametes. Current regulations apply to X2 position during spring to maintain salinities <2 for a given number of days per month at one of three locations in Suisun Bay according to the amount of freshwater storage and outflow to the Estuary.

Feyrer et al. (2010) developed an index for delta smelt habitat suitability during the fall (September–December) based on X2. Habitat suitability was considered a function of the surface area of the Estuary with suitable values of specific conductance (from which salinity can be calculated) and Secchi depth (a measure of water transparency related to turbidity). Abiotic habitat was defined using a generalized additive model of the probability of occurrence of delta smelt at a site based on specific conductance and Secchi depth. Model development was based on a 40-year record at 73 sites sampled by midwater trawl on a monthly basis from 1967 to 1988 (no sampling in 1974, 1979 and only October and November in 1976). A habitat index was then developed that accounted for both the quantity (surface area) and quality (probability of occurrence). A relationship between habitat suitability and X2 was then modeled using locally weighted-regression scatterplot smoothing (LOESS regression). For the model, X2 was calculated as the mean X2 over the September to December sampling period. The final generalized additive model explained 26 % of the variation in delta smelt occurrence. The habitat index shows a sigmoidal increase in habitat suitability for delta smelt with decreasing X2 (Fig. 3). The regression explained 85 % of the variance in the relation between X2 and the habitat index. The habitat index ranged in value from 1,932 to 8,982 over the 42-year period of sampling and has shown a declining trend (Fig. 3). Feyrer et al. (2010) applied the index to assess future habitat conditions based on a different set of climate change scenarios than we consider here.

Calculation of the habitat index for future scenarios assumes that the associations of salinity and turbidity with X2 and the physical configuration of the delta remain unchanged as climate change proceeds. It is highly unlikely that this will be the case for salinity. Cloern et al. (2011) estimated sea-level rise of about 80 and 125 cm for the PCM B1 and GFDL A2 scenarios, respectively, which would tend to increase saltwater intrusion into the Delta. Cloern et al. (2011) also utilized the Uncle–Peterson box model of

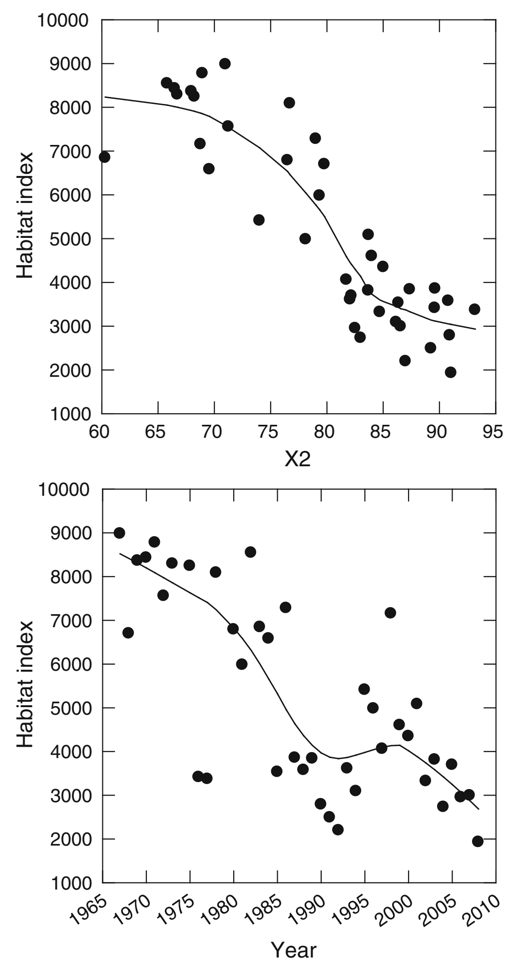

Fig. 3 Relationship of habitat index with X2 and changes in habitat index over time. Modified from Feyrer et al. (2010)

salinity as applied in previous studies (Peterson et al. 1995; Knowles et al. 1998) combined with short-term, two-month applications of a Delft3D hydrodynamics model (Lesser et al. 2004) to estimate a median increase in salinity in the northern Estuary of about 0.33 and 0.46/decade for the two scenarios, respectively. However, the present study relies on estimates of X2, which the Uncles–Peterson model is not well-suited to estimate. This is especially true when X2 is in the lower Delta, which is highly idealized in the Uncles–Peterson model and strongly influenced by the upstream model boundary. The results of Cloern et al. (2011) concerning the influence of sea level rise on salinities in the northern San Francisco Bay could therefore not be translated into corresponding X2 changes in the Delta. Our results concerning the habitat index, which is based in part on X2 estimates, likely underestimate the effects of climate change because sea level rise effects are not included, and because one of the top priorities in CALSIM II is the prevention of saltwater intrusion, which degrades the quality of exported water. It is likely that excessive groundwater extraction in the CALSIM model to compensate for changes in freshwater availability due to upstream hydrometeorological changes (see Cloern et al. 2011) allows for more efficient repulsion of saltwater than would occur in reality. Testing the constant turbidity assumption is considered in the next section.

Turbidity Model

The habitat index will also be sensitive to changes in turbidity over time. Sediment delivery from the Sacramento River watershed to the San Francisco Bay has decreased by about one half during the period of 1957–2001 (Wright and Schoellhamer 2004). As these changes in sediment delivery have occurred, turbidity within the Sacramento–San Joaquin River Delta during the last four decades has decreased by approximately 50 % (Jassby et al. 2002; Jassby 2008). We limit our analysis of turbidity to the Rio Vista station because freshwater discharge from the Sacramento River is a primary driver for the fluctuations in turbidity at Rio Vista and Rio Vista is centered within a critical delta smelt habitat corridor. Our analysis describes the Sacramento River corridor portion of the Delta. Turbidity processes at Antioch and Mallard Island are complicated by tidal exchange between sites and with Suisun Bay where wind resuspension of deposited sediment is common. Juvenile and adult delta smelt appear to prefer turbidities above about 12–18 NTU (secchi depth of 40–50 cm) presumably to reduce predation risk (Feyrer et al. 2007, 2010; Nobriga et al. 2008).

We determined the portion of time that turbidity is less than 18 NTU at Rio Vista as a function of Sacramento River discharge. Turbidity time series data (15-min event data) for the Sacramento River at Rio Vista from 2008 to 2010 were obtained from the California Department of Water Resources Environmental Monitoring Program (data available at http://cdec.water.ca.gov/). Sacramento River discharge data was obtained from the US Geological Survey and is the daily sum of Sacramento River at Freeport (USGS station 11455420) and the Yolo Bypass at Woodland (USGS station 11447650) (data available at http://waterdata.usgs.gov/ca/nwis/). A group average technique (Glysson 1987) was applied to overcome two common problems in relating discharge and turbidity: (1) suspended-sediment concentrations and thus turbidity are often not linearly related to discharge and (2) regression analyses are often influenced by a mass of point at the low discharges with one slope and fewer points at higher discharges with a different slope. Discharge bins were created based on equal increments between the minimum and maximum of the log transformed discharge values. A percentage of time (days) with turbidity <18 NTU was then calculated for each discharge bin (Fig. 4). For each scenario, each value for daily discharge in a year was assigned to the appropriate bin and the corresponding percentage applied to calculate the percentage of time each year with turbidity <18 NTU. We calculated two possibilities for the annual percent time turbidity <18 NTU for each of the four climate scenarios: (1) assuming that the relationship of turbidity to discharge was constant and (2) assuming that turbidity would continue to decline at the 1975–2008 rate of 1.6 % per year (Cloern et al. 2011).

Water Temperature Models

Details of the water temperature models are available in Wagner et al. (2011). In short, we calculated daily average water temperature from a regression model for each location (Rio Vista, Antioch, and Mallard Island, Fig. 1) of the general form:

$$T(n) = aT_{\mathrm{a}}(n) + bT(n-1) + cR(n) + d$$

where T represents modeled water temperature, n is the day for which the temperature is being calculated, T_{a} is the

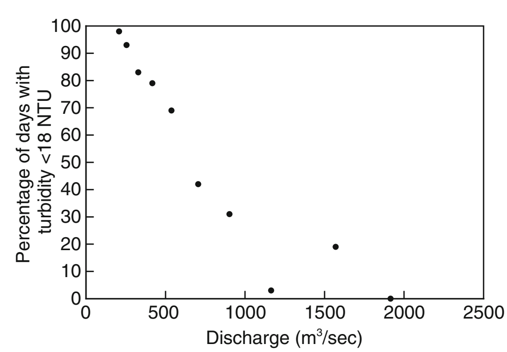

Fig. 4 Relationship of the percentage of days with turbidity <18 NTU with discharge (m^3/s) at Rio Vista

current day's air temperature, a is the coefficient of the current day's air temperature, b is the coefficient of the previous day's water temperature, c is the coefficient on the current day's insolation, and d is a constant offset. Thus, the predicted water temperature on a particular day depends on air temperature, insolation, and water temperature the previous day. Each location has a separate set of coefficients (Wagner et al. 2011). Developing the models depended on the availability of a minimum of 1 year of daily water temperature data. The models for the three sites used in this study performed well with $R^2>0.93$ for calibration and verification data sets.

Downscaled average daily air temperatures from the climate change scenarios were subsampled for the Delta region and then averaged to produce Delta daily average temperature 2000 through 2100. The climate projections did not provide insolation, so Wagner et al. (2011) estimated the average daily insolation from historical data, assuming that insolation will be constant over the century. These data values were then used to generate daily average water temperature for each of the climate change scenarios. An example plot of a single year of output data from the GFDL A2 scenario is shown in Fig. 5.

Delta Smelt Temperature Metrics

Increasing water temperatures are likely to affect many aspects of delta smelt life history. Both the timing and duration of the spawning window might influence delta smelt spawning success. As explained earlier, delta smelt spawn in the spring within a temperature window of approximately 15–20 °C (Bennett 2005). We determined two metrics for spawning, the Julian date of the midpoint (mean) of the spawning window and the duration in days of the spawning window (Table 2, Fig. 5). Water temperature continues to increase in the spring when juvenile delta smelt are present in the Delta. Catches decline rapidly as temperatures increase from 20 to 25 °C and delta smelt are rarely captured at water temperatures >25 °C (Bennett 2005; Feyrer et al. 2007; Nobriga et al. 2008). We presume that this decline in catches indicates avoidance by delta smelt, and we include the number of days with water temperatures of 20–25 °C as a metric of increasing temperature stress (Table 2, Fig. 5). This interpretation is supported by histopathological evidence from field specimens captured in this temperature range, primarily glycogen depletion and liver abnormalities (Bennett et al. 2008). Water temperatures above 25 °C seem likely to cause high mortality. This temperature (25 °C) was determined as the acute lethal limit of delta smelt when acclimated to 17 °C (Swanson et al. 2000). Moreover, recent observations of control groups of delta smelt held as part of mark–recapture studies (Castillo et al. 2010) indicated that exposure of well-fed, unstressed, hatchery-reared delta smelt to ambient water temperatures >25 °C for several days resulted in poor survival. The observed mortality was not reversed when ambient water temperature declined below 25 °C, suggesting irreversible physiological impairment. Thus, number of days with water temperatures >25 °C is one of our metrics (Table 2, Fig. 5). We also calculate stress days and high mortality days (Table 2, Fig. 5) from 1 September to 14 December each year. This is the period that corresponds to the fall midwater trawl and the habitat index. In general, this is the time period when somatic growth declines and production of reproductive products, primarily eggs and sperm, increases. Increased stress or mortality during this time period will affect reproductive output of the population.

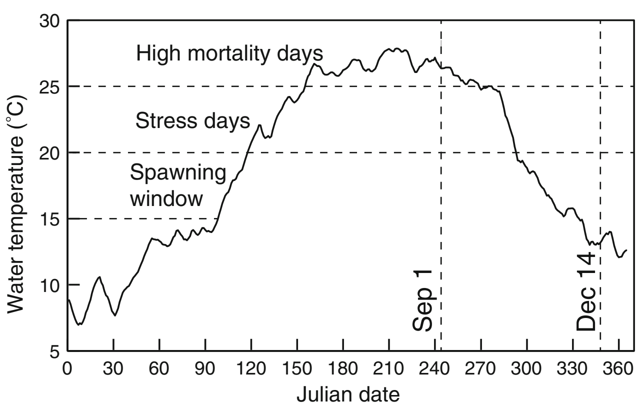

Fig. 5 Daily average water temperature for 2090 at Rio Vista. *Dashed lines* depict temperature values used to calculate the metrics listed in Table 2. The fall midwater trawl, the major survey used to index the delta smelt population, occurs from September (*Sep*) 1 to December (*Dec*) 14

Statistical Analyses

We evaluated trends in the metrics using the Mann–Kendall test (Helsel and Hirsch 2002). The Mann–Kendall test is an application of Kendall's tau to time series data. The overall trend slope is computed as the median of all slopes between data pairs. We chose a nonparametric test because we had no expectation for the shape of any of the relationships. The main question of interest is whether there was a consistent trend. Trend lines presented in figures are based on locally weighted regressions (LOWESS) (Systat 11 2004). For clarity of presentation, we did not graph individual data points for the temperature metrics from each scenario. For temperature metric baseline data without trends, we graphed a band representing the 95 % confidence interval of the mean. For baseline data with statistically significant but relatively minor trends, we graphed a band representing the 95 % confidence interval of the mean of the final 20 years of the series. Note that the beginning of a particular time series will not necessarily fall within the 95 % confidence interval of the baseline mean. To further explore observed patterns in X2 and habitat index, we compared the variances and values of the baseline and the scenarios, using an *F* test and Mann–Whitney *U* test, respectively.

Results

X2 and Habitat Index

A striking result for fall X2 was the loss of variability compared to the baseline period (Fig. 6). The scenarios had lower variance in fall X2 (*F* test, all $P<0.001$) and higher fall X2 values (Mann–Whitney *U* test, all $P<0.001$) than the baseline series. However, care must be taken in interpreting this shift, as it is due in part to behavior inherent in the models used. This is addressed further in "Discussion." There was no trend in fall X2 for the baseline period (Mann–Kendall, $P<0.05$). Of the climate scenarios, only the GFDL A2 scenario exhibited a trend (slight positive trend; Mann–Kendall, $P<0.05$). Mean values of fall X2 increased by about 7 km, and standard deviations for the scenarios were half or less of the standard deviation for the baseline period (Table 3). The mean fall X2s for the scenarios were generally near Antioch (Fig. 1).

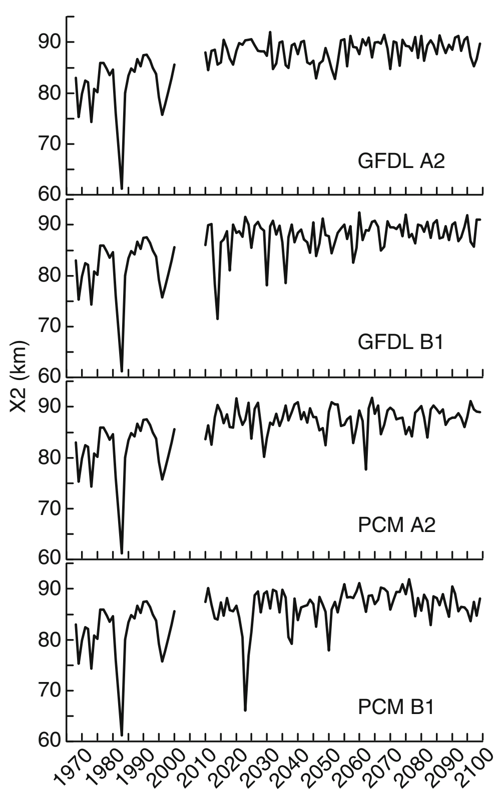

Fig. 6 Values of X2 (distance of the salinity 2 isohaline from the Golden Gate) for the baseline period and each scenario. See Table 2 for scenario definitions

Because fall X2 is used to calculate the habitat index, it is not surprising that the habitat index also exhibits a loss in variability (Fig. 7). The habitat index values for the scenarios had lower variance (*F* test, all $P<0.001$) and lower values (Mann–Whitney *U* test, all $P<0.001$) than the baseline series, especially beyond about 2050 (Fig. 7). The loss of variance was even more striking for the habitat index because fall X2 was generally >85 km and the slope of the relationship between fall X2 and the habitat index is much shallower in this range of values compared to X2 values <80 km (Fig. 3). There was no trend in the fall habitat index for the baseline period (Mann–Kendall, $P<0.05$). Only the PCM A2 scenario exhibited a significant trend (slight negative trend; Mann–Kendall, $P<0.01$). Mean fall habitat index values were approximately 70 % of the baseline value with standard deviations of half or less of the baseline value.

Turbidity

There were significant trends in the percentage of days with turbidity <18 NTU for all scenarios at the Rio Vista station when the trend of declining turbidity was projected into the future (Fig. 8). During the last 20–40 years of each scenario, the percentage of days with turbidity <18 NTU was centered above 90 %. There was a significant trend during the baseline period for the percentage of days with turbidity <18 NTU (Fig. 8), but this was not surprising given that observed turbidity within the Sacramento–San Joaquin River Delta has decreased by approximately 50 % during the last four decades (Jassby et al. 2002; Jassby 2008).

For the scenarios, when we assumed no change in the flow–turbidity relationship at the Rio Vista station, there was a significant trend in the percentage of days with turbidity <18 NTU only for the GFDL A2 scenario (Fig. 8). The positive trend was likely due to a series of years near the end of the scenario with a high percentage of days with low turbidity. The annual mean (±SD) percentage of days with turbidity <18 NTU ranged from 63±13 % (PCM B1) to 69±11 % (GFDL A2) among the four scenarios. Minimums ranged from 19 % (PCM B1) to 49 % (GFDL A2) and maximums ranged from 88 % (GFDL B1) to 91 % (GFDL A2). The annual mean (±SD) percentage of days with turbidity <18 NTU during the final 20 years of each scenario ranged from 60±7 % (PCM B1) to 76±11 % (GFDL A2).

Spawning Window

The duration of the spawning window exhibited little response to climate change. There were trends in the length of the spawning window only for the GFDL A2 scenario in which all sites exhibited significant trends (Fig. 9). The actual changes were relatively modest with a maximum difference of about 10–15 days between the minimum and

Table 3 Mean (±SD) of selected metrics for the baseline period and four scenarios of climate change

Metric Site	Baseline	GFDL A2	GFDL B1	PCM A2	PCM B1
Fall X2 (km)	81±9	88±2	88±3	88±3	87±4
Habitat suitability index	4,655±1,497	3,157±205	3,306±756	3,241±476	3,414±829
Mean number spawning days					
At Antioch	58±18	52±13	54±16	52±13	52±12
At Mallard Island	60±17	53±15	58±12	60±15	56±14
At Rio Vista	54±17	46±12	48±13	51±15	49±14

maximum length of the spawning window. There were slightly more spawning days each year during the baseline period compared to the scenarios (Table 3).

The mean date of the spawning window was more responsive to climate change than duration with the spawning window generally occurring earlier over the course of the scenarios (Fig. 10). There were no trends evident for the baseline periods. Overall, the trends are very similar among the three sites, with mean dates at Antioch approximately ten days earlier than at Mallard or Rio Vista each year. Over the entire length of each scenario, the mean spawning date occurred about 10 days earlier for GFDL B1 and PCM B1, about 15 days earlier for PCM A2, and about 20–25 days earlier for GFDL A2. Scenarios GFDL A2 and PCM A2 appeared to produce the greatest departures from the baseline period (Fig. 10).

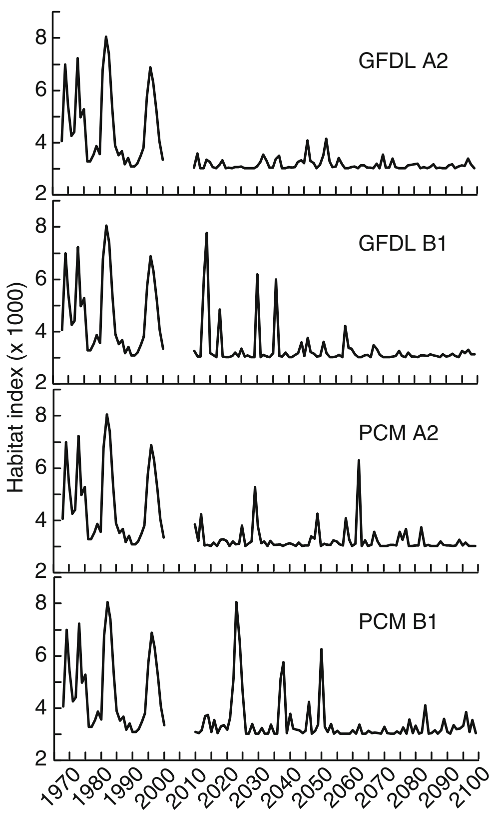

Fig. 7 Values for the delta smelt fall habitat suitability index (Feyrer et al. 2010) for the baseline period and each scenario. See Table 2 for scenario definitions

Stress and High Mortality Days

The trends for total number of stress days tended to stay flat or decline (Fig. 11), while total number of high mortality days (Fig. 12) increased for all scenarios. There were no trends during the baseline period at any site. Overall, the

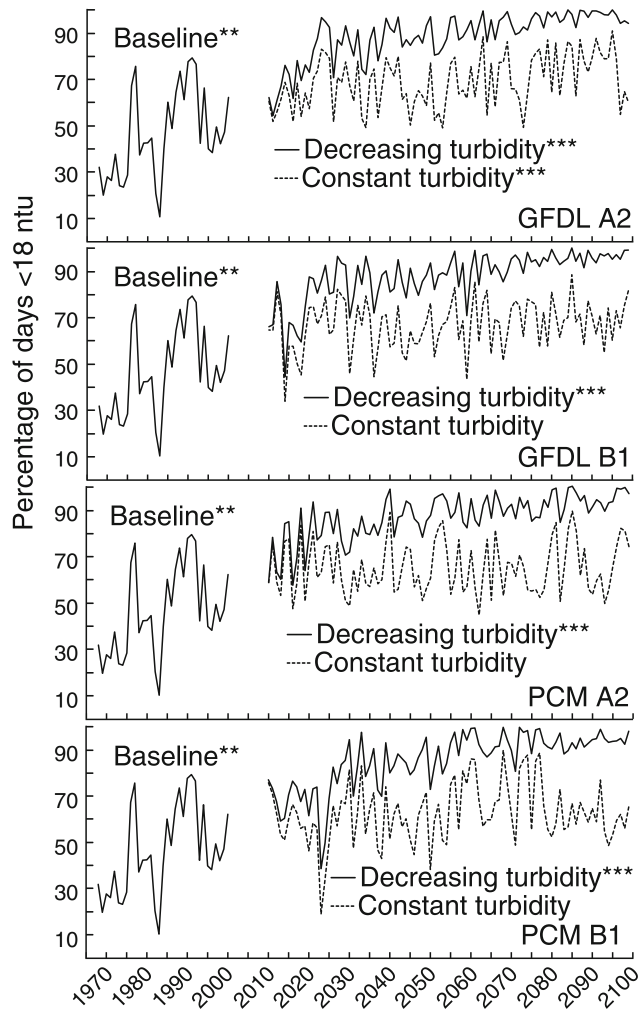

Fig. 8 Percentage of time with turbidity <18 NTU for the site at Rio Vista for each scenario. Values were calculated assuming a constant flow–turbidity relationship and assuming turbidity declining at the current rate. Statistically significant trends based on the Mann–Kendall test are indicated by *P<0.05, **P<0.01, and ***P<0.001. See Table 2 for scenario definitions

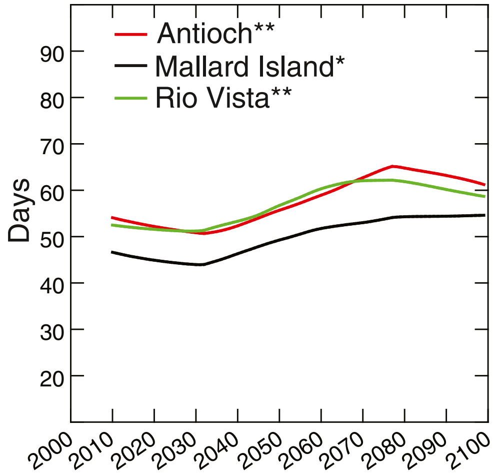

Fig. 9 Trends (LOWESS smooths) for the number of days in the spawning window (15–20 °C) for the GFDL A2 scenario for each site. Statistically significant trends based on the Mann–Kendall test are indicated by *P<0.05, **P<0.01, and ***P<0.001. See Table 2 for scenario definitions

baseline number of high mortality days was low. During the baseline period, high mortality days occurred in 20 of 40 years at Antioch (5±7, range=2–25 days), in 7 years at Rio Vista (1±2, range=1–10 days), and in 1 year with 7 high mortality days at Mallard Island.

In the scenarios, the trends at the Antioch site were generally negative for stress days and positive for high mortality days. At Mallard Island, there was only a significant decline in stress days for the GFDL A2 scenario, but all scenarios exhibited a positive trend in high mortality days. The increase was especially great for the latter third of the GFDL A2 and PCM A2 scenarios, increasing by about 100 and 40 days, respectively. The patterns at Rio Vista were similar to those observed at Mallard Island, except that the increases in high mortality days were somewhat greater, especially for the B1 scenarios. The trends in stress days were not far outside the range of the 95 % confidence interval of the mean for the baseline period (Fig. 11) except for Mallard Island and the GFDL A2 scenario at all three sites. The values for high mortality days rapidly exceeded even the maximum observed during the baseline period at each site.

During the fall period, water temperature projections are particularly appropriate because X2 is bracketed by the Mallard Island and Rio Vista sites with Antioch located in the mid-range of the projected values (Fig. 1). This means that the projected temperatures are occurring in the area where delta smelt are most likely to occur. Significant trends in number of stress days in the fall were sporadic (Fig. 13).

At the Antioch site, there was no trend during the baseline period, but there was a negative trend for the GFDL A2 scenario. There was a positive trend for PCM A2 although the data actually showed an increase and then a decrease (Fig. 13). Only the GFDL A2 scenario had a trend that

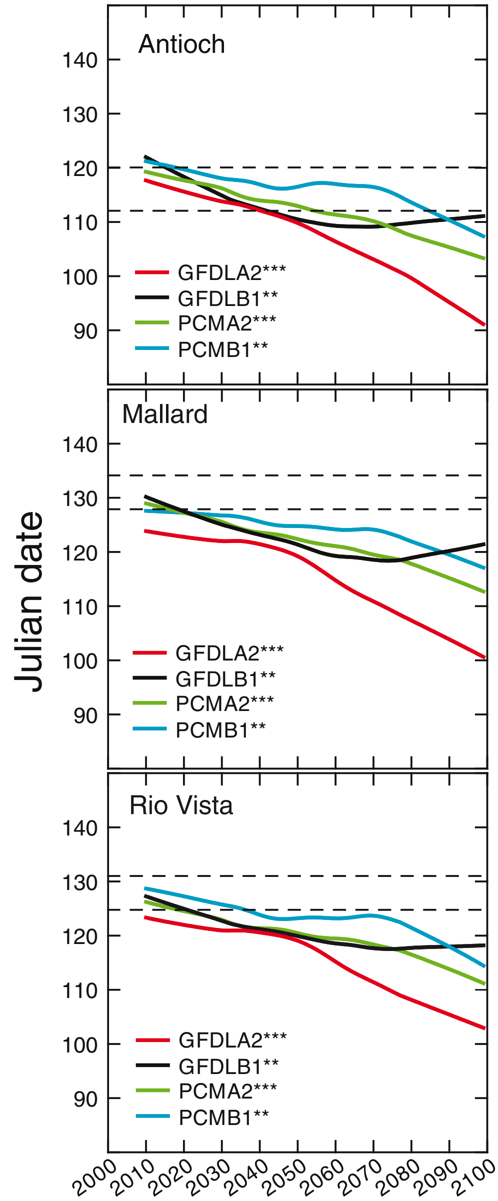

Fig. 10 Trends (LOWESS smooths) in the mean Julian date of the spawning window for each site. The *dashed lines* represent the 95 % confidence interval for the mean of the baseline data. Statistically significant trends based on the Mann–Kendall test are indicated by *P<0.05, **P<0.01, and ***P<0.001. See Table 2 for scenario definitions

deviated substantially from the baseline period. At Mallard Island, there was a positive trend in number of stress days in the fall during the baseline period (not graphed). During the first half of the baseline period the mean value was 36± 8 (range=22–49). During the second half, the mean value was 45±9 (range=30–67). There were significant positive trends for GFDL B1 and PCM A2 (Fig. 13); however, neither scenario appeared to deviate substantially from the baseline. Similar to Mallard Island, at Rio Vista there was a positive trend in number of stress days in the fall during the

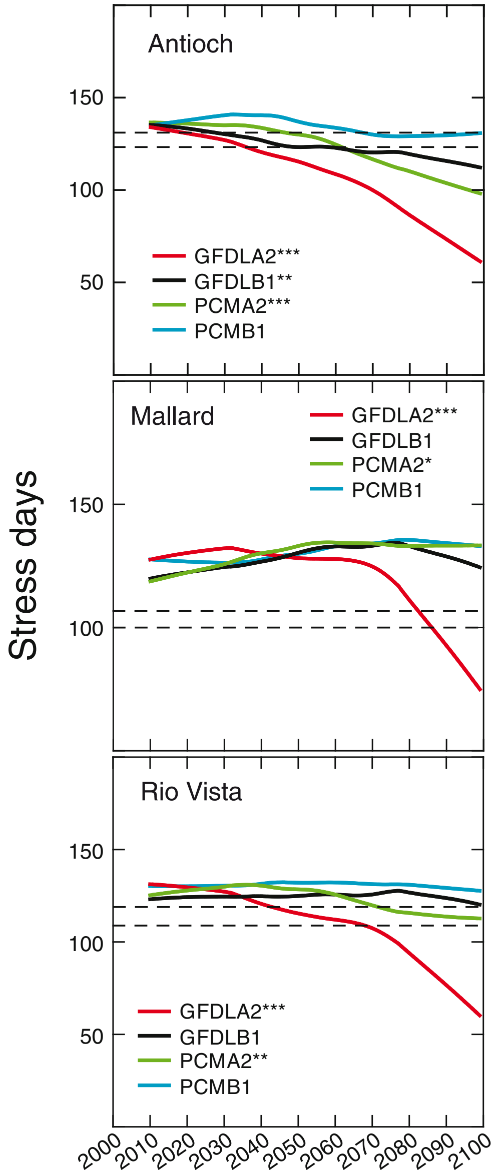

Fig. 11 Trends (LOWESS smooths) in the number of stress days (20–25 °C) for each site. The dashed lines represent the 95 % confidence interval for the mean of the baseline data. Statistically significant trends based on the Mann–Kendall test are indicated by $*P<0.05$, $**P<0.01$, and $***P<0.001$. See Table 2 for scenario definitions

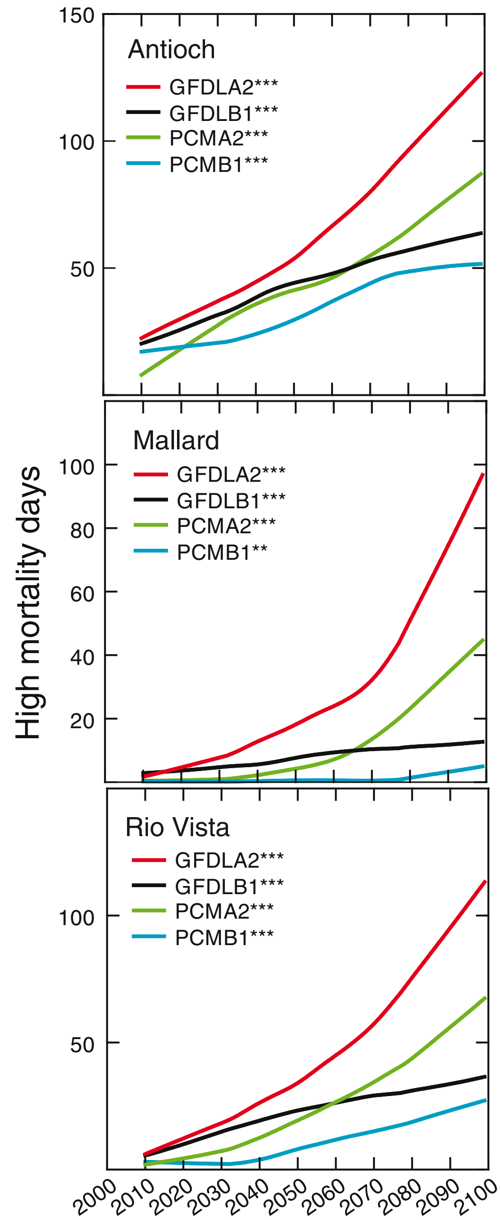

Fig. 12 Trends (LOWESS smooths) in the number of high mortality days (>25 °C) for each site. Mean baseline values are all near 0. Statistically significant trends based on the Mann–Kendall test are indicated by $*P<0.05$, $**P<0.01$, and $***P<0.001$. See Table 2 for scenario definitions

baseline period (not graphed). During the first half of the baseline period the mean value was 39±8 (range=22–50). During the second half, the mean value was 48±9 (range=31–67). There was a significant positive trend for PCM A2 (Fig. 13); however, the trend did not appear to deviate substantially from the baseline. The trend for scenario GFDL A2 was not statistically significant by the Mann–Kendall test; however, there did seem to be a negative trend developing after 2070 (Fig. 13).

High mortality days during the FMWT period were rare during the baseline period but generally showed slight to strongly positive trends during the scenarios (Fig. 14). During baseline, there were no high mortality days at Mallard Island and only two high mortality days at Rio Vista in 1996. High mortality days occurred during 3 years at Antioch with a maximum of 6 days. There were significant positive trends for all four scenarios at Antioch (Fig. 14). The most substantial increase in more than 30 days occurred for GFDL A2. A change of about 15 days occurred for PCM A2. At Mallard Island and Rio Vista, only the GFDL A2 scenario exhibited trends with changes of more than 10 days. Overall, the changes were most substantial for

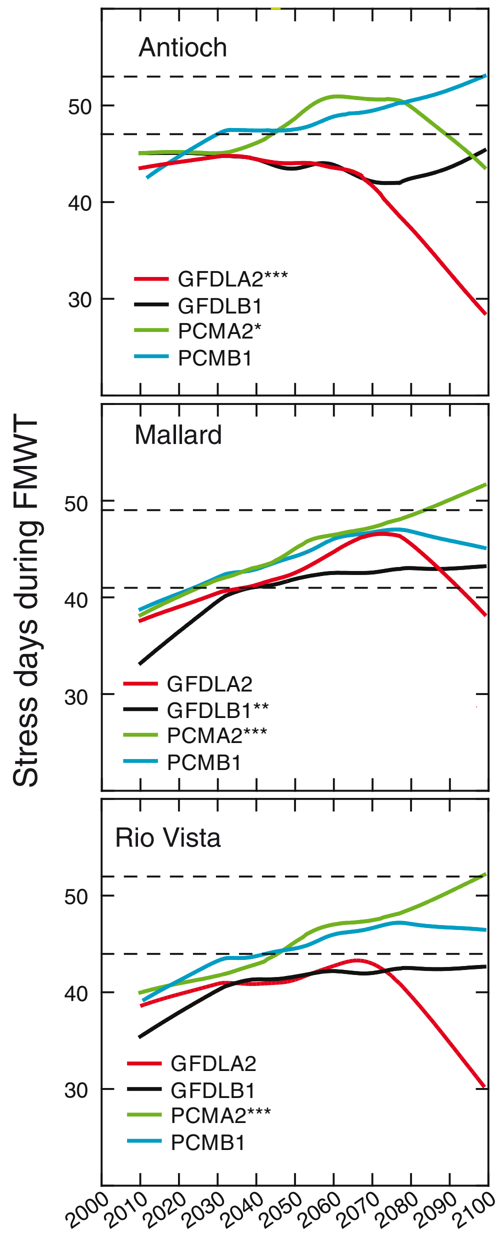

Fig. 13 Trends (LOWESS smooths) in the number of stress days (20–25 °C) for each site during the fall midwater trawl survey (FMWT; 1 September–14 December). The *dashed lines* represent the 95 % confidence interval for the mean of the baseline data. Statistically significant trends based on the Mann–Kendall test are indicated by $^{*}P<0.05$, $^{**}P<0.01$, and $^{***}P<0.001$. See Table 2 for scenario definitions

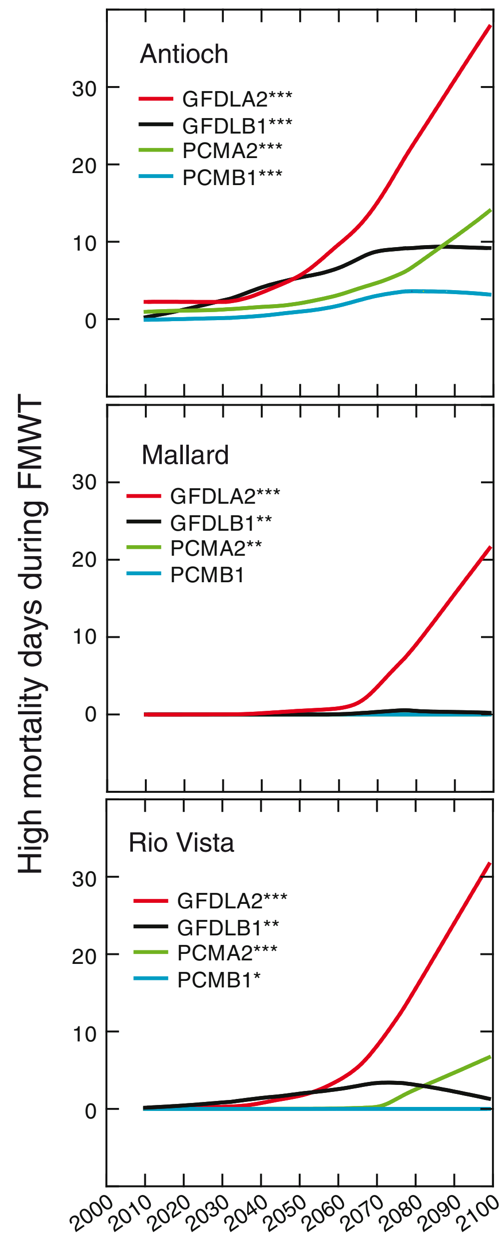

Fig. 14 Trends (LOWESS smooths) in the number of high mortality days (>25 °C) for each site during the fall midwater trawl survey (FMWT; 1 September–14 December). Mean baseline values are all near 0. Statistically significant trends based on the Mann–Kendall test are indicated by $^{*}P<0.05$, $^{**}P<0.01$, and $^{***}P<0.001$. See Table 2 for scenario definitions

GFDL A2, which exhibited a sharp increase in high mortality days at all three sites. The other scenarios did not show substantial differences from the baseline period.

Discussion

Numerous studies have assessed the possible effects of climate change on California water resources (e.g., Knowles and Cayan 2002, 2004; Knowles et al. 2006; Dettinger et al. 2009; Cloern et al. 2011); however, the effects of climate change on aquatic organisms have not been addressed in detail, with a few exceptions (e.g., Yates et al. 2008; Feyrer et al. 2010). Our results suggest that climate change could have important effects on habitat conditions for delta smelt in the Delta with respect to the position of the salinity field and water temperature. Turbidity could also change; however, this is more related to concurrent declines in sediment transport rather than climate change. This does not diminish the importance of possible changes in turbidity and highlights the fact that climate change will occur within a framework of other human-caused changes to the environment. Considering all such interventions poses a major challenge for projecting possible conditions in the future. In short, our results suggest that Delta waters could become warmer and clearer, and the salinity field may move further upstream and become less variable in the fall. Such conditions are considered undesirable for delta smelt and other native fishes (Moyle and Bennett 2008; Moyle et al. 2010) and could affect a large portion of remaining habitat.

Based on our projections, there will be substantially less physical habitat (as defined by salinity, temperature, and turbidity) available for delta smelt as climate change occurs through the end of the current century. The fall salinity field moves east to almost 90 km from the Golden Gate in all scenarios. This is roughly equivalent to an X2 observed only during the worst droughts experienced during the baseline period (1976–1977 and 1987–1992) (Fig. 6), during which delta smelt abundance was low (Bennett 2005). Because the calculation of the habitat index is based on X2, it also converges on low values associated with droughts during the baseline period (Fig. 7). The lack of variability may be particularly important. Moyle et al. (2010) suggest that increased spatiotemporal variability in salinity over current conditions will decrease abundances of key invasive species and likely increase abundances of delta smelt and other native species. The situation with turbidity is less clear with trends ranging from no change to continued decline, depending on our assumption about future sediment supply to the estuary.

The habitat index model incorporates turbidity values from the baseline period, but does not account for the likelihood of future declines in turbidity. Although high turbidity is still expected during the winter and spring during high outflows, the habitat index applies during the fall, when low turbidity conditions could occur >90 % of the time. Thus, fall habitat quality could be further compromised. Water temperatures likely to cause high mortality of delta smelt could occur during the summer at all sites. In the region bracketing X2, water temperatures increase to levels likely to cause delta smelt mortality as do water temperatures in the freshwater portions of the northern Delta, as represented by the Rio Vista site. Higher water temperatures may also extend into the fall, rendering the waters near Antioch and Rio Vista, traditionally the center of delta smelt fall distribution, less suitable or even uninhabitable (GFDL A2 scenario) for the species by mid-century. Thus, delta smelt may be restricted to Suisun Bay where tolerable temperatures are more likely to occur (Wagner et al. 2011), but at higher salinities than optimal.

The possible combined effects of degraded habitat conditions in summer and fall with an earlier spawning window could present an extremely challenging set of circumstances for an annual fish. Delta smelt would be forced to grow under more stressful conditions during summer and fall with less time to mature because of an advanced spawning season. Such conditions could result in a decrease in size of maturing delta smelt. Because fecundity of delta smelt is dependent on length (Bennett 2005), smaller mean length would result in lower reproductive output of the population. Such a decrease in mean length was noted in the 1990s, possibly a result of changes in food availability (Bennett 2005). In addition, recent field data indicate that delta smelt can produce at least two clutches of eggs under favorable conditions (L. Damon, California Department of Fish and Game, unpublished data), supporting earlier observations made during laboratory culture (Bennett 2005). A decreased time for maturation and storage of energy reserves could decrease the probability of multiple clutches, as well as the proportion of females able to mature each year. Thus, future changes in environmental conditions may alter the timing of the delta smelt life cycle with possible effects on reproductive success. Moreover, further declines in sediment loading may reduce turbidity levels during spring and summer. High turbidity is assumed to provide a refuge from predators and provide a cue for upstream movement of mature adults (Grimaldo et al. 2009; Sommer et al. 2011). In spring, the suspended sediment particles causing turbidity may be important for enhancing early feeding and survival of larvae, based on laboratory studies (Baskerville-Bridges et al. 2004a, b).

We chose to target potential changes that are likely to be relevant for delta smelt because it is an endangered species that will continue to be a major focus of management actions. However, other species in the Estuary and watershed could also be affected by climate change (Yates et al. 2008). Threatened and endangered races of Chinook salmon and steelhead rainbow trout *Oncorhynchus mykiss* must move through the Delta on their way to and from spawning grounds as do Pacific lamprey *Lampetra tridentata* and river lamprey *L. ayersi*. Water temperatures of 20–22 °C can be lethal to migrating adult Chinook salmon (McCullough 1999), and water temperatures above 20 °C can inhibit smoltification of outmigrating juvenile salmon (McCullough 1999), which can delay migration or reduce survival as they move into salt water. Thus, changes in survival or disruption of natural migration timing could occur. White sturgeon *Acipenser transmontanus* and threatened green sturgeon *A. medirostris* must move through the Delta to spawn in the Sacramento River. The upper temperature tolerance for white sturgeon is considered to be 25 °C (Israel et al. 2009). The clearer, warmer conditions that may occur would likely favor an array of freshwater invasive fishes over the native fishes (Moyle and Bennett 2008), which prefer cooler water than the invasives (Moyle 2002). Habitat restoration efforts should therefore consider the role of climate change. It is possible that the positive benefits of habitat restoration efforts for native species in the Delta could be reduced by water temperatures exceeding those needed for maintaining desirable species during much of the year. Such restoration efforts may simply increase habitat for invasive fishes if they do not specifically address measures to provide cool-water refugia.

The scenario evaluations presented here incorporate a number of underlying assumptions and methodological limitations, which require caution in the interpretation of our results. For one, the apparent reduction in variability of the X2 and habitat indices must be interpreted carefully, as it can be partially an artifact of the approach used. As described earlier, historically based gridded meteorological data were used to drive the hydrologic and CALSIM models for the baseline period, while downscaled GCM data were used for the future projections. The difference in these approaches contributes to the apparent shift in variability differently for each scenario. For example, the GFDL model tends to have substantially reduced precipitation variability (which ultimately contributes to X2 variability) compared to the historical record. However, PCM tends to have only slightly smaller precipitation variability than the historical record, suggesting that other factors are also playing a role in the trend toward reduced variability evident in Figs. 6 and 7.

Another factor contributing to a shift toward reduced variability in the future scenarios of X2 relative to baseline conditions is the different "levels of development" (LOD) used in the baseline and future runs (2000 and 2020 LODs, respectively). The LOD incorporates projections of future population and agricultural demands to estimate future freshwater demand. The increase in freshwater demands in the 2020 LOD over the 2000 LOD, due primarily to a projected population increase, has the effect of increasing competition for the freshwater supply among the various uses. In the CALSIM model (and likely in reality if the current regulatory goals were unchanged), this means just enough water is released to keep X2 near the regulatory limits, with little "excess" flow. The end result is an apparent abrupt shift in X2 variability and, to a lesser degree, in its position, between the 2000 LOD baseline and the 2020 LOD future scenarios. While the abruptness of this shift is an artifact of the modeling approach, the factors behind it, and its occurrence in a less abrupt manner, are not unrealistic outcomes. Indeed, our use of the 2020 LOD throughout the twenty-first century means that our projections past 2020 very likely underestimate freshwater demand, rendering our results conservative in the sense that freshwater availability for the purpose of salinity (X2) repulsion is likely to be overestimated. The fact that CALSIM II resorts to unrealistic levels of groundwater pumping to compensate for reduced surface-water availability only magnifies this conclusion, particularly in very dry scenarios such as GFDL A2.

Feyrer et al. (2010) also evaluated the effects of climate change (through 2040) on delta smelt habitat and obtained results similar to ours with declines in habitat and decreased variability. As in our results, conditions converged on drought conditions during dry and critically dry years. Feyrer et al. (2010) also depended on CALSIM II results for projection of habitat and they noted many of the same issues we note above.

We also did not consider sea level rise in these analyses even though various studies indicate that sea level is currently rising and will have substantial effects on the San Francisco Estuary (Knowles 2010; Lund et al. 2010) and delta smelt habitat (Feyrer et al. 2010). Such effects include increased salt water intrusion into Suisun Bay and the Delta (Cloern et al. 2011) and increasing likelihood of levee failures and flooding of areas around Suisun Bay, within the Delta, and in peripheral areas of the Delta (Mount and Twiss 2005; Knowles 2010; Lund et al. 2010). Although some modeling studies have assessed the effects of sea level rise on inundation of marshes (Orr et al. 2003; Strahlberg et al. 2011), they did not address salinity intrusion in a quantitative way. Feyrer et al. (2010) included one climate change scenario incorporating sea level rise (0.33 m and 10 % increase in tidal range) in their study and found no significant saltwater intrusion; however, their scenarios were based on CALSIM II output assuming *only* sea level rise without the interactive effects of climate change. Brekke (2008), the source of the data for Feyrer et al. (2010), noted that a 0.33 m sea level rise combined with the drier climate change scenarios would lead to decreases in mean-annual water deliveries and end-of-September carryover storage. Fleenor et al. (2008) also considered the effects of sea level rise but restricted their analysis to historical data at existing monitoring stations and did not consider climate change interactively with sea level rise. They did consider the effects of flooded islands and various configurations for a new water diversion canal around the periphery of the Delta (peripheral canal). The results were complex and depended on assumptions, but sea level rise increased Delta salinity when considered alone and contributed to salinity increases associated with the other factors. Moyle et al. (2010) used modeling by Fleenor et al. (2008) to estimate that salinity, measured as X2, would intrude an additional 5 km for each 0.3 m of sea level rise. Unfortunately, the regression model for calculating the habitat suitability index does not extend beyond an X2 of 95 km (Fig. 3) and extrapolation into the complex channel network of the Delta seems unwise. In short, there is evidence to suggest sea level rise will increase salinity intrusion into the Delta, changing the distribution of physical habitat for delta smelt, but we do not yet have the tools to quantitatively describe such changes.

Our temperature models are statistical in nature and may no longer be applicable if there are major changes in infrastructure. The temperature models are based on data from fixed shore stations that do not sample the entire water column. There are important lateral and vertical variations in temperature that might preserve some areas of cooler water as climate change proceeds (Wagner 2012).

Finally, our study makes the obviously unrealistic assumption that freshwater management strategies and infrastructure will remain unchanged for the rest of the century. Therefore, it is our hope that these results, representing potential changes to the environment, be used as a guide for designing future management capabilities and strategies. Well-designed human modifications of Delta management and infrastructure (e.g., intentional flooding of interior islands) or changes in water management may well mitigate some of the anticipated outcomes from climate change, including projected increases in water temperature. There have been numerous suggestions made for reconfiguring the Delta to meet the needs of the ecosystem and water supply, including habitat restoration, flooding islands, and construction of a tunnel or peripheral canal for water diversions (e.g., Lund et al. 2010; Moyle et al. 2010, 2012); however, a final plan for implementing such changes has not yet been finalized (see http://deltacouncil.ca.gov/delta-plan/current-draft-of-delta-plan). Once such decisions are made, understanding the quantitative effects of changes in Delta infrastructure, landscape, and water management on variables like delta smelt physical habitat (e.g., salinity, water temperature, and turbidity) will require complex hydrodynamic, water management, and habitat models. In addition, these models will have to be applied for multiple scenarios of climate change and water management. Such models are currently being developed but the modeling challenges are formidable.

Given that our results could be interpreted to imply that the Delta is unlikely to provide suitable habitat for delta smelt in the future, we caution that we are presenting plausible scenarios of climate change and not quantitative predictions. Clearly, there are still many uncertainties associated with assessments of the potential effects of climate change in the San Francisco Estuary. However, our results suggest that the potential effects could be substantial. This is especially sobering given that our most extreme scenario for greenhouse gas emissions (A2) is already below observed emissions and is increasingly considered to reflect the midrange of possible futures (Raupach et al. 2007). Uncertainty will be reduced as models improve; however, we suggest that actions being considered to improve habitat for native organisms should also carefully consider the potential effects of climate change over a range of possible scenarios. Actions that provide a range of future options for conserving (or even relocating) these species are most desirable because they will help prevent investments with short-term benefits that are lost over the long term as factors such as water temperature change over the coming decades. The problems posed by climate change are not unique to the San Francisco Estuary and will provide challenges to resource managers and researchers across the globe.

Acknowledgments We thank Michael Meador, Matthew Miller, and several anonymous reviewers for comments that enhanced the clarity and quality of the paper. Funding for this work was provided by the Computational Assessments of Scenarios of Change for the Delta Ecosystem (CASCaDE) project. CASCaDE is supported by a grant from the CALFED Science Program and the Priority Ecosystems Science program of the US Geological Survey. This is contribution number 27 from the CASCaDE project.

References

Anderson, J., F.I. Chung, M. Anderson, L. Brekke, D. Easton, et al. 2008. Progress on incorporating climate change into management of California's water resources. *Climatic Change* 87(suppl. 1): 91–108.

Barnett, T.P., D.W. Pierce, H.G. Hidalgo, C. Bonfils, B.D. Santer, T. Das, G. Bala, A.W. Wood, T. Nozawa, A.A. Mirin, D.R. Cayan, and M.D. Dettinger. 2008. Human-induced changes in the hydrology of the western United States. *Science* 319: 1080–1083.

Baskerville-Bridges, B., J.C. Lindberg, and S.I. Doroshov. 2004a. The effect of light intensity, alga concentration, and prey density on the feeding behavior of delta smelt larvae. *American Fisheries Society Symposium* 39: 219–228.

Baskerville-Bridges, B., J.C. Lindberg, J.V. Eenennaam, S.I. Doroshov. 2004b. Delta smelt research and culture program 5-Year Summary, 1998–2003. Final report to CALFED Bay-Delta Program, Sacramento, CA, USA

Beamish, R.J. (ed.). 1995. Climate change and northern fish populations. Canadian Special Publication in Fisheries and Aquatic Sciences 121.

Bennett, W.A. 2005. Critical assessment of the delta smelt population in the San Francisco estuary, California. Online San Francisco Estuary and Watershed Science 3(2). http://repositories.cdlib.org/jmie/sfews/vol3/iss2/art1

Bennett, W.A., and P.B. Moyle. 1996. Where have all the fishes gone? Interactive factors producing fish declines in the Sacramento San Joaquin Estuary. In *San Francisco Bay: the ecosystem*, ed. J.T. Hollibaugh, 519–542. San Francisco: Pacific Division American Association for the Advancement of Science.

Bennett, W.A., J.A. Hobbs, and S.J. Teh. 2008. Interplay of environmental forcing and growth-selective mortality in the poor year-class success of delta smelt in 2005. Final report to the POD Management Team of the Interagency Ecological Program for the San Francisco Estuary, Sacramento, CA, USA

Brekke, L. 2008. Sensitivity of future Central Valley Project and State Water Project Operations to potential climate change and associated sea level rise. US Bureau of Reclamation, Final report. Appendix R of OCAP biological assessment on the continued long-term operations of the Central Valley Project and State Water Project. http://www.usbr.gov/mp/cvo/ocapBA_2008.html

Brekke, L.D., M.D. Dettinger, E.P. Maurer, and M. Anderson. 2008. Significance of model credibility in projection distributions for regional hydroclimatological impacts of climate change. *Climatic Change* 89: 371–394.

Brekke, L.D., E.P. Maurer, J.D. Anderson, M.D. Dettinger, E.S. Townsley, et al. 2009. Assessing reservoir operations risk under climate change. *Water Resources Research* 45: W04411.

Brekke, L.D., N.L. Miller, K.E. Bashford, N.W.T. Quinn, and J.A. Dracup. 2004. Climate change impacts uncertainty for water resources in the San Joaquin River Basin, California. *Journal of the American Water Resources Association* 40: 149–164.

Brown, L.R., and P.B. Moyle. 2005. Native fish communities of the Sacramento–San Joaquin watershed, California: a history of decline. *American Fisheries Society Symposium* 45: 75–98.

Castillo, G., J. Morinaka, J. Lindberg, R. Fujimura, B. Baskerville-Bridges, J. Hobbs, G. Tigan, and L. Ellison. 2010. *Pre-screen loss and fish facility efficiency for delta smelt at the south Delta's State Water Project California*. Sacramento: Final report to CALFED Science Program.

Cayan, D., M. Tyree, M. Dettinger, H. Hidalgo, T. Das, E. Maurer, P. Bromirski, N. Graham, and R. Flick. 2009. Climate change scenarios and sea level rise estimates for California, 2008 Climate Change Scenarios Assessment. California Energy Commission Report CEC-500-2009-014-D, Sacramento

Cayan, D.R., E.P. Maurer, M.D. Dettinger, M. Tyree, and K. Hayhoe. 2008. Climate change scenarios for the California region. *Climatic Change* 87(Suppl. 1): 21–42.

Cherkauer, K.A., L.C. Bowling, and D.P. Lettenmaier. 2003. Variable infiltration capacity cold land process model updates. *Global and Planetary Change* 38: 151–159.

Chu, C., N.E. Mandrak, and C.K. Minns. 2005. Potential impacts of climate change on the distributions of several common and rare freshwater fishes in Canada. *Diversity and Distributions* 11: 299–310.

Cloern, J.E., N. Knowles, L.R. Brown, D. Cayan, M.D. Dettinger, et al. 2011. Projected evolution of California's San Francisco Bay-Delta-River System in a century of climate change. *PLoS One* 6 (9): e24465. doi:10.1371/journal.pone.0024465.

Conomos, T.J. (ed.). 1979. *San Francisco Bay: the urbanized estuary. Investigation into the natural history of San Francisco Bay and Delta with reference to the influence of man*. San Francisco: Pacific Division American Association for the Advancement of Science.

Dege, M., and L.R. Brown. 2004. Effect of outflow on spring and summertime distribution and abundance of larval and juvenile fishes in the upper San Francisco Estuary. *American Fisheries Society Symposium* 39: 49–66.

Delworth, T.L., A.J. Broccoli, A. Rosati, R.J. Stouffer, V. Balaji, J.A. Beesly, W.F. Cooke, K.W. Dixon, J. Dunne, K.A. Dunne, J.W. Durachta, K.L. Findell, P. Ginoux, A. Gnanadeiskan, C.T. Gordon, S.M. Griffies, R. Gidgel, M.J. Harrison, I.M. Held, R.S. Hemler, L.W. Horowitz, S.A. Klein, T.R. Knutson, P.J. Kushner, A.R. Langenhorst, H.-C. Lee, S.-J. Lin, J. Lu, S.L. Malyshev, P.C.D. Milly, V. Ramaswamy, J. Russell, M.D. Schwarzkopf, E. Shevliakova, J.J. Sirutis, M.J. Spelman, W.F. Stern, M. Winton, A.T. Wittenberg, B. Wyman, F. Zeng, and R. Zhang. 2006. GFDL's CM2 global coupled climate models, Part I: Formulation and simulation characteristics. *Journal of Climate* 19: 643–674.

Dettinger, M.D. 2012. Projections and downscaling of 21st Century temperatures, precipitation, radiative fluxes and winds for the southwestern US, with focus on Lake Tahoe. *Climatic Change* 116: 17–33. doi:10.1007/s10584-012-0501-x.

Dettinger, M.D. 2005. From climate-change spaghetti to climate-change distributions for 21st Century California. Online San Francisco Estuary and Watershed Science, 3(1), http://escholarship.org/uc/item/2pg6c039

Dettinger, M.D., H. Hidalgo, T. Das, D.R. Cayan and N. Knowles. 2009. Projections of potential flood regime changes in California. California Energy Commission Report CEC-500-2009-050-F, Sacramento

Dracup, J.A., S. Vicuna, R. Leonardson, L. Dale,and M. Hanneman. 2005. Climate change and water supply reliability. California Energy Commission, PIER Energy-Related Environmental Research. CEC-500-2005-053

Draper, A.J., A. Munevar, S.K. Arora, E. Reyes, N.L. Parker, F.I. Chung, and L.E. Peterson. 2004. CalSim: Generalized model for reservoir system analysis. *Journal of Water Resource Planning and Management* 130: 480–489.

Feyrer, F., L.R. Brown, R.L. Brown, and J.J. Orsi (eds.). 2004. *Early life history of fishes in the San Francisco Estuary and Watershed, American Fisheries Society Symposium 39*. Bethesda: American Fisheries Society.

Feyrer, F., K. Newman, M. Nobriga, and T. Sommer. 2010. Modeling the effects of future outflow on the abiotic habitat of an imperiled estuarine fish. *Estuaries and Coasts* 34: 120–128.

Feyrer, F., M. Nobriga, and T. Sommer. 2007. Multi-decadal trends for three declining fish species: habitat patterns and mechanisms in the San Francisco Estuary, California, U.S.A. *Canadian Journal of Fisheries and Aquatic Sciences* 64: 723–734.

Fleenor, W., E. Hanak, J. Lund, and J. Mount. 2008. Delta hydrodynamics and water quality with future conditions. In *Comparing futures for the Sacramento–San Joaquin Delta. Technical Appendix C*, ed. J. Lund, E. Hanak, W. Fleenor, W. Bennett, R. Howitt, J. Mount, and P.B. Moyle. San Francisco: Public Policy Institute of California.

Glysson, D.G. 1987. Sediment–transport curves. US Geological Survey Open File Report 87-218.

Grimaldo, L.F., T. Sommer, N. Van Ark, G. Jones, E. Holland, P. Moyle, B. Herbold, and P. Smith. 2009. Factors affecting fish entrainment into massive water diversions in a tidal freshwater estuary: Can fish losses be managed? *North American Journal of Fisheries Management* 29: 1253–1270.

Hidalgo, H., M. Dettinger, and D. Cayan. 2008. Downscaling with constructed analogues—Daily precipitation and temperature fields over the United States. California Energy Commission PIER Final Project Report CEC-500-2007-123, Sacramento

Helsel, D.R., and R.M. Hirsch. 2002. *Statistical methods in water resources techniques of water resources investigations, Book 4, chapter A3*. Reston: US Geological Survey.

Hollibaugh, J.T. (ed.). 1996. *San Francisco Bay: The ecosystem*. San Francisco: Pacific Division American Association for the Advancement of Science.

IPCC. 2007. *Climate change 2007—impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the IPCC*. Cambridge: Cambridge University Press.

Israel, J., A. Drauch, and M. Gingras. 2009. *Life history conceptual model, white sturgeon (Acipenser transmontanus). Delta Regional Ecosystem Restoration Implementation Plan*. Sacramento: California Department of Fish and Game.

Jassby, A.D. 2008. Phytoplankton in the upper San Francisco Estuary: recent biomass trends, their causes and their trophic significance. Online San Francisco Estuary and Watershed Science 6(1). http://escholarship.org/uc/item/71h077r1

Jassby, A.D., J.E. Cloern, and B.E. Cole. 2002. Annual primary production: patterns and mechanisms of change in a nutrient-rich tidal ecosystem. *Limnology and Oceanography* 47: 698–712.

Jassby, A.D., W.J. Kimmerer, S.G. Monismith, C. Armor, J.E. Cloern, T.M. Powell, J.R. Schubel, and T.J. Vendlinski. 1995. Isohaline position as a habitat indicator for estuarine populations. *Ecological Applications* 5: 272–289.

Kimmerer, W.J. 2002a. Physical, biological, and management responses to variable freshwater flow into the San Francisco Estuary. *Estuaries* 25: 1275–1290.

Kimmerer, W.J. 2002b. Effects of freshwater flow on abundance of estuarine organisms: Physical effects or trophic linkages. *Marine Ecology Progress Series* 243: 39–55.

Knowles, N. 2010. Potential inundation due to rising sea levels in the San Francisco Bay region. Online San Francisco Estuary and Watershed Science 8(1). http://escholarship.org/uc/item/8ck5h3qn

Knowles, N. 2000. Modeling the hydroclimate of the San Francisco Bay-Delta estuary and watershed. PhD dissertation, Scripps Institution of Oceanography, University of California, San Diego, La Jolla.

Knowles, N., and D.R. Cayan. 2004. Elevational dependence of projected hydrologic changes in the San Francisco Estuary and watershed. *Climatic Change* 62: 319–336.

Knowles, N., and D.R. Cayan. 2002. Potential effects of global warming on the Sacramento/San Joaquin watershed and the San Francisco Estuary. *Geophysical Research Letters* 29: 38-1–38-4.

Knowles N, D. Cayan, D.H. Peterson, and R.J. Uncles. 1998. Simulated effects of delta outflow on the Bay: 1998 compared to other years. Interagency Ecological Program Newsletter 11:29–31.

Knowles, N., M.D. Dettinger, and D.R. Cayan. 2006. Trends in snowfall versus rainfall in the western United States. *Journal of Climate* 19: 4545–4559.

Lesser, G.R., J.A. Roelvink, A.A.T.M. van Kester, and G.S. Stelling. 2004. Development and validation of a three dimensional morphological model. Coastal Engineering 51:883–915.

Liang, X., D.P. Lettenmaier, E. Wood, and S.J. Burges. 1994. A simple hydrologically based model of land surface water and energy fluxes for general circulation models. *Journal of Geophysical Research* 99: 14415–14428.

Lund, J.R., E. Hanak, W.E. Fleenor, W.A. Bennett, R.E. Howitt, J.F. Mount, and P.B. Moyle. 2010. *Comparing futures for the Sacramento–San Joaquin Delta*. Berkeley: University of California Press.

Maurer, E.P., H.G. Hidalgo, T. Das, M.D. Dettinger, and D.R. Cayan. 2010. The utility of daily large-scale climate data in the assessment of climate change impacts on daily streamflow in California. *Hydrology and Earth System Sciences* 14: 1125–1138.

McClusky, D.D., and M. Elliott. 2004. *The estuarine ecosystem: Ecology, threats, and management*. Oxford: Oxford University Press.

McCullough, D.A. 1999. *A review and synthesis of effects of alterations to the water temperature regime on freshwater life stages of salmonids, with special reference to Chinook salmon. EPA 910-R-99-010*. Seattle: US Environmental Protection Agency, Region 10.

Meehl, G.A., C. Covey, T. Delworth, M. Latif, M. McAvaney, J.F.B. Mitchell, R.J. Stouffer, and K.E. Taylor. 2007. The global coupled model dataset: A new era in climate change research. *Bulletin of the American Meteorological Society* 88: 1383–1394.

Moyle, P.B. 2002. *Inland fishes of California. Revised and expanded*. Berkeley: University of California Press.

Moyle, P.B., and W.A. Bennett. 2008. The future of the Delta ecosystem and its fish. In *Comparing futures for the Sacramento–San Joaquin Delta. Technical Appendix D*, ed. J. Lund, E. Hanak, W. Fleenor, W. Bennett, R. Howitt, J. Mount, and P. Moyle. San Francisco: Public Policy Institute of California.

Moyle, P., W. Bennett, J. Durand, W. Fleenor, B. Gray, E. Hanak, J. Lund, and J. Mount. 2012. *Where the wild things aren't, making the Delta a better place for native species*. San Francisco: Public Policy Institute of California.

Moyle, P.B., W.A. Bennett, W.E. Fleenor, and J.R. Lund. 2010. Habitat variability and complexity in the upper San Francisco Estuary. Online San Francisco Estuary and Watershed Science 8(3). http://escholarship.org/uc/item/0kf0d32x

Mount, J. and R.Twiss. 2005. Subsidence, sea level rise, seismicity in the Sacramento–San Joaquin Delta. Online San Francisco Estuary and Watershed Science 3(1). http://www.escholarship.org/uc/item/4k44725p

Nakicenovic, N., J. Alcamo, G. Davis, B. de Vries, J. Fenham, S. Gaffin, K. Gregory, A. Grubler, T.Y. Jung, T. Kram, E.L. La Rovere, L. Michaelis, S. Mori, T. Morita, W. Pepper, H. Pitcher, L. Price, K. Riahi, A. Roerhl, H.H. Rogner, A. Sankovsk, M. Schlesinger, P. Shukla, S. Smith, R. Swart, S. van Rooijen, N. Victor, and Z. Dadi. 2000. *Special report on emissions scenarios*, 599. Cambridge: Cambridge University Press.

Nobriga, M.L., T. Sommer, F. Feyrer, and K. Fleming. 2008. Long-term trends in summertime habitat suitability for delta smelt, *Hypomesus transpacificus*. Online San Francisco Estuary and Watershed Science 6(1). http://escholarship.org/uc/item/5xd3q8tx

NRC (National Research Council). 2012. *Sustainable water and environmental management in the California Bay-Delta. National Research Council*. Washington: The National Academies Press.

Orr, M., Crooks, S., and Williams, P.B. 2003. Will restored tidal marshes be sustainable? Online San Francisco Estuary and Watershed Science 1(1). http://www.escholarship.org/uc/item/8hj3d20t

Perry, A.L., P.J. Low, J.R. Ellis, and J.D. Reynolds. 2005. Climate change and distribution shifts in marine fishes. *Science* 308: 1912–1915.

Peterson, M.S. 2003. A conceptual view of environment–habitat–production linkages in tidal river estuaries. *Reviews in Fisheries Science* 11: 291–313.

Peterson, D., D. Cayan, J. Dileo, M. Noble, and M. Dettinger. 1995. The role of climate in estuarine variability. *American Scientist* 83: 58–67.

Raupach, M.R., G. Marland, P. Ciais, C. Le Quéré, 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* 104: 10288–10293.

Roessig, J.M., C.M. Woodley, J.J. Cech, and J. Hansen. 2004. Effects of global climate change in marine and estuarine fishes and fisheries. *Reviews in Fish Biology and Fisheries* 14: 251–275.

Sommer, T., C. Armor, R. Baxter, R. Breuer, L. Brown, M. Chotkowski, S. Culberson, F. Feyrer, M. Gingras, B. Herbold, W. Kimmerer, A. Mueller-Solger, M. Nobriga, and K. Souza. 2007. The collapse of pelagic fishes in the upper San Francisco Estuary. *Fisheries* 32(6): 270–277.

Sommer, T., F. Mejia, M. Nobriga, F. Feyrer, and L. Grimaldo. 2011. The spawning migration of delta smelt in the upper San Francisco Estuary. Online San Francisco Estuary and Watershed Science 9 (2). http://www.escholarship.org/uc/item/86m0g5sz

Stralberg, D., M. Brennan, J.C. Callaway, J.K. Wood, L.M. Schile, D. Jongsomjit, M. Kelly, V.T. Parker, and S. Crooks. 2011. Evaluating tidal marsh sustainability in the face of sea-level rise: a hybrid modeling approach applied in San Francisco Bay. *PLoS One* 6(11): e27388.

Swanson, C., T. Reid, P.S. Young, and J.J. Cech Jr. 2000. Comparative environmental tolerances of threatened delta smelt (*Hypomesus transpacificus*) and introduced wakasagi (*H. nipponensis*) in an altered California estuary. *Oecologia* 123: 384–390.

Systat 11. 2004. SYSTAT for Windows, Version 11. SYSTAT Software Inc., Richmond

Thomson, J.R., W.J. Kimmerer, L.R. Brown, K.B. Newman, R. Mac Nally, W.A. Bennett, F. Feyrer, and E. Fleishman. 2010. Bayesian change-point analysis of abundance trends for pelagic fishes in the upper San Francisco Estuary. *Ecological Applications* 20: 181–198.

Vicuna, S., E.P. Maurer, B. Joyce, J.A. Dracup, and D. Purkey. 2007. The sensitivity of California water resources to climate change scenarios. *Journal of the American Water Resources Association* 43: 482–498.

Wagner, R.W. 2012. *Temperature and tidal dynamics in a branching estuarine system. PhD dissertation*. Berkeley: University of California.

Wagner, R.W., M. Stacey, L.R. Brown, and M. Dettinger. 2011. Statistical models of temperature in the Sacramento–San Joaquin Delta under climate-change scenarios and ecological implications. *Estuaries and Coasts* 34: 544–556.

Washington, W.M., J.W. Weatherly, G.A. Meehl, A.J. Semtner Jr., T.W. Bettge, A.P. Craig, W.G. Strand Jr., J.M. Arblaster, V.B. Wayland, R. James, and Y. Zhang. 2000. Parallel climate model (PCM) control and transient simulations. *Climate Dynamics* 16: 755–774.

Wiley, M.J., D.W. Hyndman, B.C. Pijanowski, A.D. Kendall, C. Riseng, E.S. Rutherford, S.T. Cheng, M.L. Carlson, J.A. Tyler, R.J. Stevenson, P.J. Steen, P.L. Richards, P.W. Seelbach, J.M. Koches, and R.R. Rediske. 2010. A multi-modeling approach to evaluating climate and land use change impacts in a Great Lakes River Basin. *Hydrobiologia* 657: 243–262.

Wood, R.J., D.F. Boesch, and V.S. Kennedy. 2002. Future consequences of climate change for the Chesapeake Bay ecosystem and its fisheries. *American Fisheries Society Symposium* 32: 171–184.

Wright, S.A., and D.H. Schoellhamer. 2004. Trends in the sediment yield of the Sacramento River, California, 1957–2001. Online San Francisco Estuary and Watershed Science 2(2). http://escholarship.org/uc/item/891144f4

Yates, D., H. Galbraith, D. Purkey, A. Huber-Lee, J. Sieber, J. West, S. Herrod-Julius, and B. Joyce. 2008. Climate warming, water storage, and Chinook salmon in California's Sacramento Valley. *Climatic Change* 91: 335–350.