A Place To Call Home:

A Synthesis of Delta Smelt Habitat in the Upper San Francisco Estuary

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Abstract. We used a combination of published literature and field survey data to synthesize the available information about delta smelt *Hypomesus transpacificus*, a declining native species in the San Francisco estuary. Delta smelt habitat ranges from San Pablo and Suisun bays to their freshwater tributaries, including Delta and the Sacramento and San Joaquin rivers. In recent years, substantial numbers have colonized habitat in Liberty Island, a north Delta area which flooded in 1997. The species has more upstream distribution during spawning periods and a more downstream distribution during wetter years. Delta smelt are most common in low salinity habitat (<6 psu) with high turbidities (>12 ntu) and moderate temperatures (7-25^{o}C). They do not appear to have strong substrate preferences, but sandy shoals may be important for spawning. The evidence to date suggests that they generally require at least moderately tidal habitats. Delta smelt also occur in a wide range of channel sizes, although they seem to be rarer in small channels (<15 m wide). Nonetheless, there is some evidence that open water habitat adjacent to long residence time areas (e.g. tidal marsh, shoal, low order channels) may be favorable. Other desirable features of delta smelt habitat include high calanoid copepod densities, and low levels of submerged aquatic vegetation and the toxic algae *Microcystis*. While enough is known to plan for large scale pilot habitat projects, these efforts are vulnerable to several factors, most notably climate change, which will change salinity regimes and increase the occurrence of lethal temperatures. We recommend a "bet hedging" approach coupled with extensive monitoring and adaptive management. An overall emphasis on ecological processes rather than specific habitat features is also likely to be most effective.

Introduction

The San Francisco Estuary is one of the prominent features of the California coastline. The estuary is both unconventional and complex, supporting diverse habitats ranging from marine bays to brackish marshes and tidal freshwater wetlands. Given the extreme level of urbanization and hydrologic alteration of the estuary, it is therefore not surprising that identifying and protecting the habitats of endemic plants and animals has become one of the major resource management issues in the San Francisco Estuary (Figure 1). Habitat increasingly has become a target of management and restoration as a result of declines in multiple trophic levels. Of the various declines, the highest-profile has been the collapse of the pelagic fish community of the upper San Francisco estuary (Sommer and others 2007). Indeed, few regional fisheries issues have generated as much debate as the habitat requirements of delta smelt *Hypomesus transpacificus,* a native osmerid that occurs only in the low salinity zone of the system. The population has declined precipitously over the past decade, leading to major legal and regulatory actions to try and improve its status (Service 2007; Sommer and others 2007). The species is currently listed as Threatened under the Federal Endangered Species Act and Endangered under the California Endangered Species Act (USFWS 2008).

This annual species is confined to a single estuary, so maintenance of the population depends in part on habitat conditions in the Sacramento-San Joaquin Delta (herein referred to as the *Delta*), the upstream region of the San Francisco Estuary from which the species gets its name (Figure 1). The hydrodynamics of the Delta's highly interconnected channels are especially complex and highly altered, with major changes to key parts of the distribution of delta smelt. One of the biggest hydrologic changes over the past century has been the construction of the large Central Valley Project (CVP) and State Water Project (SWP) water diversions, which supply water to about 25 million California residents and a multi-billion dollar agricultural industry (Grimaldo and others 2009).

Given its legal status, there has been substantial progress in understanding the life history of this species (Moyle and others 1992; Bennett 2005; Nobriga and Herbold 2009). The typical pattern is for delta smelt to inhabit the oligohaline to freshwater portion of the estuary for much of the year until late winter and early spring, when they migrate upstream to spawn (Sommer and others 2011a). Following hatching, their young subsequently migrate downstream in spring towards the brackish portion of the estuary (Dege and Brown 2004). Some of the key physiological and environmental requirements are understood based on laboratory studies and analyses of field data (Swanson and others 1998, 2000; Baskerville-Bridges and others 2004; Feyrer and others 2007; Nobriga and others 2008).

The primary objective of this paper was to synthesize the available information about the habitat of delta smelt and to provide insight into what may happen in the future. Although there are multiple definitions of habitat, we have chosen to consider delta smelt habitat as the physical, chemical, and biological factors in the aquatic environment of this species (Hayes and others 1996). Moreover, we assume that the maintenance of appropriate habitat quality is essential to the long-term health of delta smelt (Rose 2000; Peterson 2003). <u>We emphasize that this does not mean that this report assumes that habitat is the primary driver of the delta smelt population</u>. To the contrary, there is substantial evidence that delta smelt are controlled by a complex set of multiple interacting factors (Sommer and others 2007; Baxter and others 2010; MacNally and others 2010). Therefore, it should not be assumed that providing good habitat conditions now or in the future will guarantee delta smelt success. In ecological terms, this issue is often considered in terms of the *realized* versus *fundamental* niche of a species. Having lots of suitable habitat creates the potential for delta smelt to occupy a large area (i.e. *fundamental niche*), but the *realized* distribution may be much smaller because other factors (e.g. predators) limit their ability to use all of the available area. In other words, habitat is a necessary but not sufficient condition to support delta smelt. Habitat is, nonetheless, unique in that it not only directly affects the species of interest (delta smelt), but all affects other population drivers including “top-down” and “bottom-up” effects. As such, it provides an excellent useful starting point for evaluating the ecological status of species and potential restoration options.

A key point in evaluating delta smelt habitat is that it needs to be considered in two different ways. First, it can be considered in a geographical context based on fixed regions of the delta that seem to be important for delta smelt such as the west Delta, Suisun Bay, and Cache Slough Complex. Because the estuary is strongly tidal and delta smelt are a pelagic fish strongly associated with distinct salinity ranges (Dege and Brown 2004; Feyrer and others 2007; Kimmerer and others 2009), its habitat must also be considered as constantly shifting in position along the axis of the estuary. In physical science terms, the former is the Eulerian frame of reference, while the later is the Lagrangian frame of reference.

For the purposes of this study, we focused on the following major questions: 1) what are the basic physical, chemical, and biological requirements for delta smelt habitat? 2) What geographic areas currently provide these conditions? 3) What habitat types support delta smelt? 4) Given factors such as climate change, will the upper estuary provide suitable conditions in the future? With respect to the last question, a second major objective of the study was to identify which areas and habitat features will improve the survival chances of delta smelt. Hence, our analysis was clearly targeted at providing direction for large scale restoration efforts being considered under programs such as the Bay Delta Conservation Plan (BDCP) and recent Biological Opinions (FWS 2008).

Because of the limited nature of the data available on delta smelt, our study was not intended as a "bible" for their habitat. Specifically, our synthesis does not provide detailed description of what delta smelt require for any single factor, habitat, or geographic area. Moreover, we focus on the direct habitat needs of delta smelt, but do not substantially address the role of subsidies across habitats that this fish do not necessarily occupy (e.g. tule marsh contributions to the smelt food web). Our goal was therefore to provide a basis for generating testable hypotheses for future restoration and research projects. Given the rarity of delta smelt and associated constraints on field collection, we also hoped that our analyses of existing data would help to set priorities for future studies.

Methods and Materials

Assessing habitat needs of delta smelt is especially challenging because the fish is very small (usually <100 mm FL), fragile, increasingly rare, and has a protected legal status (Moyle 2002; Bennett 2005). A related issue is that the San Francisco estuary is vast and spatially complex, with multiple tributaries, embayments, and braided channels (Figure 1). High turbidity levels in the estuary present major challenges to direct observations of habitat use. As noted previously, the need to evaluate smelt habitat in both Lagrangian (moving flow field) and Eulerian (fixed locations) frames of references complicates the interpretation of the available data. Finally, observational data on different habitats can yield ambiguous or even misleading results. For example, juvenile Chinook salmon densities are consistently higher along the narrow rip-rapped edge of the Sacramento River than in the broad expanses of the adjacent Yolo Bypass floodplain (Ted Sommer, California Department of Water Resources, unpublished data). In other words, care must be used to correct observational data for habitat availability.

Several of these issues meant that currently it is not feasible to use traditional habitat assessment techniques such as telemetry, mark-recapture, or visual observation. We therefore relied on a combination of published literature, data analyses from long- and short-term fisheries surveys, and the expert opinion of colleagues to synthesize the available information with delta smelt. There is no question that our approach has a higher uncertainty than direct observational methods; however, the information represents the best available given the many constraints. Although our synthesis does not follow the format of a traditional scientific paper, similar efforts to integrate multiple information sources have proven useful to guide subsequent research and restoration (e.g. Moyle and others 2004).

Data Sources

Literature: We focused on peer-reviewed literature, the majority of which was from the San Francisco estuary and about delta smelt. For topics with no journal publications, we also included some agency reports and unpublished manuscripts.

Long-term surveys: The following describes several of the key Interagency Ecological Program monitoring surveys that collect delta smelt. Several of the descriptions are from Sommer and others (2011a) and are presented approximately in ontogenetic order starting with larvae.

Initiated in 1995, the California Department of Fish and Game (DFG) 20 mm survey typically samples larvae during each neap tide between March and July (Dege and Brown 2004). A total of 48 sites have been sampled continuously and include freshwater to mesohaline habitats of the estuary. Three 10-min oblique tows are conducted at each location using a 5.1-m long, skid mounted net with a 1.5 m^2 mouth, a 1.6 mm mesh body and a removable 2.2 L cod end jar. Zooplankton tows were collected simultaneously using a Clarke-Bumpus net (0.160 mm mesh nylon cloth, outer mouth diameter of 12.5 cm, 76 cm length with a cod-end screened with 0.140 mm mesh) Volume was recorded with a General Oceanics model 2030 flow meter. Zooplankton samples were preserved in 10% formalin with Rose Bengal dye. Preserved samples were concentrated in the laboratory by pouring them through a sieve screened with 0.154 mm mesh wire, rinsed, then reconstituted to organism densities of 200-400 per milliliter. A 1 milliliter subsample was then extracted and counted and identified in a Sedgewick-Rafter cell. For the purposes of this study we focused on counts of calanoid copepods, a key food source for delta smelt (Nobriga 2002; Bennett 2005).

The Summer Townet Survey (TNS) has been conducted annually by DFG 1959. The survey was designed to index the abundance of age-0 striped bass, but also collects delta smelt data that have been used to analyze abundance, distribution, and habitat use (Kimmerer 2002; Bennett 2005; Nobriga and others 2008). The TNS samples up to 32 stations using a conical net (1.5 m^2 mouth; 2.5 mm cod-end mesh) towed obliquely through the water column.

The DFG fall midwater trawl (FMWT) samples fishes in open-water and other offshore habitats monthly each September to December at 116 stations throughout the northern region of the estuary. The survey at each location takes a 10 to 12-minute tow with a 13.4 m^2 midwater trawl of variable meshes starting with 20.3 cm mesh at the mouth of the net and 1.3 cm mesh at the cod end (Feyrer at al. 2007). The survey represents one of the best long-term fishery data sets for the San Francisco estuary and covers the majority of the range of delta smelt. The FMWT samples delta smelt distribution and relative abundance during the period leading up to, but not including their spawning migration. Thus, it provides a long-term dataset on where delta smelt are distributed in the estuary. The survey has been conducted since 1967 with the exception of 1974 and 1979.

The DFG Spring Kodiak Trawl survey (SKT) has been conducted since 2002 as a survey to assess the distribution of adult delta smelt during the time they ripen and spawn (Source: http://www.delta.dfg.ca.gov/data/skt/). It samples 39 locations from Napa River upstream though Suisun Bay and the Delta (Figure 1). The survey has been conducted every 2-4 weeks in winter and spring starting in January or February. At each location, a single 10 minute surface sample is taken by two boats that tow a 7.6 m wide by 1.8 m high Kodiak trawl (mesh ranges in dimension from 5.1 cm knotted stretched mesh at the mouth and decreases by 1.3 cm through a series of 5 panels to 0.6 cm knotless stretched mesh at the cod-end).

The USFWS Beach Seine Survey uses a 12-meter long by 1.2 meter high seine to collect inshore fishes from areas generally less than one meter deep (Brandes and McLain 2001). Seine hauls are conducted year-round at 57 current sampling stations from San Francisco Bay upstream to the lower Sacramento and San Joaquin Rivers. Unlike most other surveys, basic substrate data is collected for this program. In addition to the core USFWS, we examined data from special surveys in Liberty Island, a flooded tidal wetland in the Cache Slough Complex. The surveys during August 2002-October 2004 used similar methods as the regular USFWS Beach Seine program at ten core sites located around the periphery of the lower portion of the island (Figure 2).

Short-term and geographically-limited studies: One of the key studies used to identify habitat use by delta smelt was the DFG Delta Resident Fishes Survey (Brown and Michniuk 2007). This survey used an electrofishing boat to sample 200-m reaches of shoreline spread across several delta regions. The timing of this survey has been sporadic, with sampling that collected delta smelt in 1981-1982, 1995-1997, and 2001-2003.

Another source of data about delta smelt use of small channels was the California Department of Water Resources Yolo Bypass study, which includes larval sampling and rotary screw trapping. This sampling occurred near the base of Yolo Bypass in a 40 m wide perennial channel. Methods for the two surveys are summarized in Sommer and others (2004a) and Feyrer and others (2006).

Data Analyses: Delta smelt are a relatively rare and patchy fish, so most survey data were summarized based on presence-absence data. To summarize the general locations of delta smelt habitat by life stage, we summarized the upstream and downstream distribution limits for each of the major surveys: FMWT, SKT, 20 mm, and TNS. The center of distribution was calculated for each survey (Sommer and others 2011b). Data were summarized separated for wet and dry years using all years since 1995, when all four surveys were conducted.

For several analyses, we calculated the percentage of samples with delta smelt present for under different conditions (e.g. substrate, geographic locations). Where possible, we did statistical analyses. For example, we used this approach for USFWS beach seine data to compare delta smelt habitat use in Liberty Island as compared to concurrently collected data from the core west and north Delta station region where the population is often centered (Sommer and others 2011a; Figure 3). We focused on six west and north Delta stations (Sandy Beach SR012W; Stump Beach SR012E; Rio Vista SR014W; Brannan Island TM001N; Eddo's SJ005N; Sherman Island MS001N; Antioch Dunes SJ001S) that commonly catch delta smelt. Differences in percent of samples with delta smelt were compared for the Liberty Island (Figure 2) and the core Delta sites during the same sampling period (2002-2004) using a Kruskal-Wallis test. The USFWS beach seine data for the core Delta stations were also used to evaluate substrate use. Only data after 1993 were used because they included substrate information (mud, pavement, vegetated, sand, gravel). We did a Chi-square test comparing the number of samples in which delta smelt were captured on each substrate type to the total samples (i.e. effort) on each substrate type. However, we acknowledge that fixed stations are not an optimal approach to habitat use. One concern about the use of fixed stations is that salinity-induced shifts in the distribution of delta smelt along the axis for the estuary, which may “push” delta smelt away from or towards certain substrate types.

Food was analyzed for the 20 mm survey, the only IEP sampling program which collects data simultaneous with fish at each station. As others have shown, generalized additive models (GAMs) can be used to examine the associations between fish occurrence and habitat variables such as salinity, temperature, and turbidity (Stoner and others 2001; Feyrer and others 2007; Kimmerer and others 2009). We examined whether adding food availability improved the model predictions for delta smelt. The technique uses smoothers to describe the empirical relationships between predictor and response variables and therefore does not assume particular relationships between the two. We used the GAM function in the MGCV package of the statistical program R (R Development Core Team 2011;Wood 2011) with a logit link function to determine whether there were significant relationships between four response variables (mean temperature; mean EC; mean secchi depth; mean calanoid copepod density) and the presence of delta smelt in 20 mm samples for 1995-2009. The variables were tested both individually and in combination with each other. We analyzed the GAM results in two ways. First, we examined whether the smoothed results were congruent with expected responses based on laboratory tests and ecological literature. Specifically, we expected that delta smelt would show a unimodal response to temperature and salinity, a declining occurrence relatively to Secchi (Feyrer and others 2007), and an increasing or saturating response to food availability (e.g. Holling 1959). Second, we assessed statistical significance of the GAM outputs using an approximation of the ability of each variable to reduce null deviance in the models (Venables and Ripley 1997; Feyrer and others 2007).

Delta Smelt Habitat: A Synthesis

Basic Habitat Requirements

Salinity: Salinity is the main factor that defines an estuary, so understanding salinity requirements is an essential in describing the habitat of estuarine organisms. Because of the ease of measurement, salinity is often represented based on electrical conductivity. The two units are not strictly interchangeable because of variation in the ionic composition of different regions of the San Francisco estuary (e.g. oceanic salts vs. agricultural salts in the San Joaquin River).

More so than any other delta smelt habitat variable, salinity has been the subject of intense research and debate. Higher flow levels shift the salt field downstream, as commonly represented by X2, the distance of the 2 psu salinity isohaline from the Golden Gate Bridge (Jassby and others 1995; Kimmerer 2002). There are no long-term trends in the salinity of the upper estuary for most months (Jassby and others 1995; Enright and Culberson 2010); however, there have been salinity increases during fall (Feyrer and others 2007), when the issue has become most controversial.

Delta smelt are strongly associated with the low salinity zone, typically <6 psu or <10,000 uS/cm (Feyrer and others 2007; 2010; Kimmerer and others 2009). Our GAM results for the 20 mm survey showed a similar pattern (Figure 4; Table 1). The distribution of delta smelt is therefore affected by salinity at multiple life stages. For example, Dege and Brown (2004) found that the center of distribution of young delta smelt during spring was determined by the location of the salt field, with a more downstream distribution during wetter years. Similarly, Sommer and others (2011a) found that the center of distribution of older delta smelt was consistently associated with the location of the salt field (X2) during all months. As will be discussed below, this does not mean that all smelt are confined to a narrow salinity range since fish occur from fresh water to relatively high salinities.

The effects of salinity on habitat area vary seasonally and therefore by life stage. Kimmerer and others (2009) found that X2 had a negative association with habitat area (i.e. higher flow = more area) for all surveys analyzed, but the effect was strongest in spring and summer. They suggest that earlier life stages were more responsive to salinity changes because they tend to occupy fresher water than older delta smelt. Despite a clear effect of estuarine salinity on habitat area, Kimmerer and others (2009) did not observe strong effects on abundance. Feyrer and others (2010) also found a negative effect of X2 on habitat area during the fall. Feyrer and others (2007) report a long-term decrease in habitat area based on the combined effects of salinity and turbidity (as indexed by Secchi depth), and a weak effect of fall conditions on juvenile production the following summer. The significance of these results has been the source of intense debate as part of legal challenges to the USFWS (2008) Biological Opinion for delta smelt, which included new requirements to change X2 during the fall of wet years.

Tides and Flow: There have been occasional collections of delta smelt upstream of the tidal zone north of Sacramento (USFWS Juvenile Salmon Survey, unpublished data). All of these occurred during the winter and spring spawning season. Despite these rare exceptions, the habitat of delta smelt is focused entirely in the tidal zone. It is not known if delta smelt can survive in areas without consistent tidal flows as may be the case for some areas in the future with sea level rise (see below).

Delta smelt currently are found in the small channels such as the Yolo Bypass Toe Drain, where tidal flows are periodically less than +/-4 m^3/sec during months when smelt are present (Lisbon Gauge, Department of Water Resources, unpublished data), to areas with stronger tides such as Chipps Island, where representative summer tidal flows are +/-9400 m^3/sec (DWR 1993). It is highly likely that delta smelt use some form of tidal surfing to change their location in the estuary (Swanson and others 1998; Sommer et al. 2011a). Bennett and others (2002) provide evidence that young longfin smelt (*Spirinchus thaleichthys*) use tidal surfing to maintain their position in the estuary, so it is reasonable to assume that a close relative like delta smelt does the same. Sommer and others (2011a) used a particle tracking model to show that apparent upstream migration rates of adult smelt were consistent with simulations based on a simple tidal surfing behavior.

Velocity: Closely related to tides and flow is water velocity. This variable may be much less relevant to fishes in the highly tidal upper San Francisco estuary than for species that live in riverine systems. Even in a tidal environment, it is likely that delta smelt respond to covariates of velocity such as turbulence, so velocity should not be ignored as a habitat feature.

The effects of water velocity on delta smelt are understood primarily from laboratory studies. Swanson and others (1998) showed that maturing delta smelt probably can swim for long periods at rates of 1-2 body lengths per second, representing about 6-12 cm per second. Critical swimming velocities were around 28 cm/second. These rates were comparable or somewhat lower than similar-sized fishes for the same temperature range.

Turbidity: Important progress in our understanding of the habitat needs of delta smelt is that the species requires turbid water. Traditionally, fisheries biologists have viewed high turbidities as a detriment to fish based on extensive evidence that high sediment loads degrade the quality of salmon habitat (Newcombe and Macdonald 2011). This has led to widespread regulations for logging and construction projects along the Pacific Coast to limit sediment loading to rivers. However, Feyrer and others (2007) found that delta smelt are strongly associated with turbid water. Their results showed that during fall delta smelt are only present at locations where Secchi depth is less than 1 meter deep. This finding is consistent with Grimaldo and others (2009a), who found that the occurrence of delta smelt at the SWP salvage facilities was linked, in part, with high turbidities. Specifically, delta smelt were not present when turbidities were less than about 12 ntu. This results are consistent with our GAM analyses of the 20 mm data set, which showed that young delta smelt are strongly associated with lower Secchi depths (Figure 4: Table 1).

The specific mechanism by which delta smelt require high turbidity is not known. An obvious potential function of turbidity is that it may help delta smelt avoid visual predators (Baskerville-Bridges and others 2004; Feyrer and others 2007; Nobriga and Herbold 2009). Light apparently plays a role in feeding ecology as laboratory studies show that consumption is low in clear water ((Mager 1996; Baskerville-Bridges and others 2004). It is possible that turbidity helps create a contrasting background for delta smelt to locate their prey.

One of the most disturbing long-term changes in for delta smelt has been the increase in water clarity in the upper estuary (Jassby and others 2002; Wright and Schoellhamer 2004; Feyrer and others 2007). Moreover, modeling by Schoellhamer (2011) suggests that there has been a sudden recent (1999) increase in water clarity as the sediment balance shifted. In contrast to other habitat variables such as salinity, these trends are not driven by hydrology (Jassby and others 2002). As noted in Baxter et al. (2010), the primary mechanisms suggested to explain the increasing water clarity are: 1) reduced sediment supply due to dams in the watershed (Wright and Schoellhamer 2004); 2) major flood events (e.g 1982-1983) that washed out large amounts of sediment (Baxter and others 2010); and 3) biological filtering by submerged aquatic vegetation (Brown and Michniuk 2007, Hestir and others In review). Whatever the mechanisms, this change appears to have had a serious effect on habitat quality for delta smelt during both summer (Nobriga and others 2008) and fall (Feyrer and others 2007).

Temperature: Upper temperature limits for delta smelt habitat have been relatively well-studied in both the laboratory and using field data. Interpretation of the laboratory results is somewhat complicated as temperature limits can be affected by various factors including acclimation temperature, salinity and feeding status. The general pattern is that delta smelt cannot tolerate temperatures higher than 25^{o}C (Swanson and others 2000), a level that is highly consistent with field collections of young smelt (Nobriga and others 2008) and our GAM results for the 20 mm data set (Figure 4; Table 1). Hence, the 25^{o}C is currently used at the general guideline to assess the upper limits for delta smelt habitat (Wagner and others 2011; Cloern and others 2011).

The lower limit to water temperature has not yet been evaluated in detail. However, Bennett and Burau (2010) analyzed the occurrence of adult in the Spring Kodiak Trawl based on three water quality variables. Their preliminary results suggest that delta smelt are rare below about 7^{o}C. Note, however, that temperatures below 10^{o}C are uncommon in the estuary (Kimmerer 2004; Nobriga and Herbold 2009).

Depth: Like velocity, the relevance of depth to a pelagic fish in a tidal estuary is open for debate. Landscape variables such as depth are, nonetheless, clearly important features that define tidal dynamics such as velocities, excursion, and frequency of inundation. Unfortunately, depth is not recorded for many of the pelagic trawls in the upper estuary making it difficult to evaluate this variable. Some data are available for littoral surveys, but delta smelt catch is generally too low for a rigorous statistical analysis. While generally regarded as a pelagic fish (Moyle 2002), delta smelt are clearly caught in shoal and shallow inshore areas such as Suisun Bay and Liberty Island (Moyle and others 1992; Nobriga and others 2005; Sommer and others 2011a). Aasen (1999) found that juvenile smelt densities can actually be higher in shoal areas than adjacent channels. However, delta smelt use of shallow areas apparently varies with tide (Aasen (1999) and they probably do not substantially use the shallowest tidally dewatered edge areas (Matt Nobriga, USFWS, unpublished data). There does not appear to be an obvious maximum depth for delta smelt as the fish are commonly captured along the Sacramento Deep Water Ship Channel (Grimaldo and others, In prep; DFG Spring Kodiak Trawl:

http://www.dfg.ca.gov/delta/data/skt/DisplayMaps.asp), which has most of the deepest habitat in the upper estuary.

Channel size: Most data has been collected in large channels, making it difficult to evaluate what types delta smelt prefer. It is likely that channel width itself is not a constraint; instead, delta smelt are likely to be cued into related habitat features such as tidal excursion, velocity, temperature, and turbidity. There does not appear to be a clear upper limit for channel width as the FMWT and TNS data show that delta smelt are common in large channels including broad bays that are several km wide. For example, some of the most numerically important areas for delta smelt catch are Cache Slough, a 200-280 m wide channel (20mm station 716, TNS & FMWT stations 716 and 721) and the Sacramento Deep Water Ship Channel, with a 170-200 m wide channel (TNS and FMWT stations 719 and 797).

The lower limit to channel size for delta smelt has still not been addressed. In the Delta, the smallest channels that we are aware of where delta smelt have been collected are around 45 m wide. One example is a small perennial channel of the Yolo Bypass—both adult and larval stages seasonally were collected there in many years (Sommer and others 2004). Another narrow channel with regular catches of delta smelt larvae is Miner Slough at 45-50 m wide (20 mm station 726). Downstream of the Delta, the smallest channel where adults and juveniles have been reported is Spring Branch Slough in Suisun Marsh, which averages about 15 meters near the sampling area of the UC Davis Suisun Marsh Survey (Meng and others 1994; Matern and others 2002). These fish are most commonly caught during winter, usually January to March (Teejay Orear, UC Davis, unpublished data).

Food: Even if physical and chemical requirements are met, delta smelt will not survive if habitat does not contain enough food to support basic metabolic needs. The food source of delta smelt is fairly specialized, relying primarily on calanoid copepods such as *Eurytemora affinis* and *Pseudodiaptomus forbsi* (Nobriga 2002; Moyle 2002). There has been a long-term decline in zooplankton in the upper estuary (Winder and Jassby 2010), which partially may account for the reduction in the mean size of delta smelt in fall (Sweetnam 1999; Bennett 2005). Overall, food limitation remains a major stressor on delta smelt (Baxter and others 2010). The importance of this variable is supported by Kimmerer (2008), who showed that delta smelt survival from summer to fall is related to biomass of copepods in the core range of delta smelt. These relationships have led to the recognition that food availability should be included in life cycle models of delta smelt (Maunder and Deriso 2011).

There is evidence of substantial spatial and temporal variation in copepods in the estuary. The most extensive database for zooplankton of the upper estuary is the IEP's Environmental Monitoring Program (http://www.water.ca.gov/iep/activities/emp.cfm), which includes stations in Suisun Bay, Suisun Marsh, and the West and South Delta. *P. forbesi* and *E. affinis* both frequently show their highest densities in the south Delta and Suisun Marsh (Hennessy 2009; Anke Mueller-Solger, unpublished data). *P. forbesi* is most abundant during summer to fall, while E. affinis largely disappears from the EMP sites in summer and fall.

From a restoration perspective, one of the more important recent findings has been that food resources are often more abundant around the periphery of the upper estuary. In the brackish zone, the smaller channels of Suisun Marsh frequently show relatively high levels of chlorophyll *a* and copepods (Schroeter 2008; Anke Mueller-Solger, Delta Science Program, unpublished data). Similarly, studies by Benigno and others (In review) show that the channels of the Cache Slough Complex consistently have higher chlorophyll *a* levels than Delta EMP stations. The data suggest that calanoid copepod levels may be enhanced during key months for delta smelt. Longer residence times are likely a major contributing factor to increased food web production in these regions (Lucas and others 2009).

Food thresholds for delta smelt have not yet been established, although our GAM analyses provide some insights for spring. The GAM results of the 20 mm data set suggested that temperature, salinity, Secchi depth, and calanoid copepod density were all significantly associated with occurrence of young delta smelt (Table 1; Figure 4). However, the smoothed GAM results for calanoid copepods (Figure 4) did not follow the expected increasing or saturating responses (e.g. Holling 1959). Instead, the smoothed response suggested a questionable decline in delta smelt abundance at high calanoid copepod densities. An additional issue is that models that incrementally added each of the environmental variables indicated that adding calanoid copepods to the model explained only a small additional amount of deviance (2%) as compared to models with just the three physical variables (Table 1). These results suggest that calanoid copepod density was not a meaningful predictor of young delta smelt in the 20 mm survey. This does not mean that food is unimportant to young delta smelt; rather, the data may not be at a sufficient scale to detect associations.

Substrate: Most fish surveys in the upper Estuary do not record substrate, making it difficult to evaluate the importance of this variable to delta smelt. The relevance of substrate in the deep channel habitat of delta smelt is questionable; for example, young smelt are typically in the middle or upper portion of the water column, particularly during day time (Rockriver 1994; Grimaldo and others, In review). Nonetheless, substrate may be relevant when delta smelt venture into littoral areas. Delta smelt catches are typically quite low in inshore areas, making it hard to analyze the data in any rigorous way.

The best available data about substrate use are from the USFWS beach seine survey (Table 2). The results suggest at least modest differences between observed and expected habitat use (Chi square = 29.15; DF = 3; $p<0.001$). Delta smelt were never collected in vegetation, despite 167 samples in such habitats. Habitat use was also much lower than expected at paved locations (boat ramps), but somewhat higher than expected over gravel, mud, and sand.

Another example is the DFG Resident Fishes Survey, which used electrofishing to sample nearshore areas during the early 1980s, mid-1990s, and early 2000s (Brown and Michniuk 2007). The survey did not have high enough catch of delta smelt to warrant statistical analysis. The 1981-1982 data collected delta smelt in 5% of 360 samples over the following substrates: rip-rap 41% of fish; mud bank 59% of fish. These proportions were very similar to the distribution of sampling effort among all sites. Sampling effort was much greater in later years (5,645 samples); however, delta smelt were collected in only 0.4% of samples. These fish were collected over rip-rap (38%), mud bank (47.6%), and sand beach (14.3%), which was somewhat different than the overall sampling effort for all sites (rip-rap 60%; mud bank 33%; sand beach 3%; mud flat 4%).

In general, these data suggest that delta smelt do not have particularly strong substrate preferences, which is not surprising given their niche as a pelagic fish. Nonetheless, substrate may be an important issue during spawning. The substrate preferences of delta smelt are not known; however, many other smelts are known to favor sandy substrate for spawning (Bennett 2005). This substrate is relatively common in inshore areas of the west Delta (e.g. Sherman Island) and north Delta (e.g. Liberty Island and Sacramento Deep Water Ship Channel).

Other Water Quality Factors: The current state of knowledge about the effects of water quality problems including contaminants on delta smelt and other pelagic fishes has recently been summarized by Brooks and others (2011). The evidence to date indicates that although acute contaminant toxicity is not a likely cause for the population declines, sublethal stress from multiple factors including metals, nutrient-rich effluents, toxic algal blooms, and pesticides all degrade the habitat of delta smelt. For example, sublethal contaminant exposure can impair immune function and swimming ability of delta smelt (Connon and others 2011). Delta smelt distribution is known to overlap with several key contaminants (e.g. Kuivila and Moon 2004; Brooks and others 2011) and effects can be substantial depending on the level of exposure (Connon and others 2009).

The highest profile water quality issue has been inputs of ammonium to the Delta, primarily from municipal discharges. The largest source of ammonium to the system is the Sacramento Regional Wastewater Treatment Plant (Jassby 2008). There is no evidence yet of direct effects on delta smelt, but there are concerns about food web effects based on the finding that phytoplankton growth may at times be inhibited by high ammonium concentrations in the Delta and Suisun Bay (Wilkerson et al. 2006, Dugdale and others 2007; Glibert 2010; Glibert and others 2011). This could directly reduce primary productivity and alter phytoplankton species composition, which may in turn affect the zooplankton community that delta smelt rely upon (Glibert and others 2011).

Another emerging and related concern for delta smelt is that there are periodic blooms of the toxic blue-green alga *Microcystis aeruginosa* during late summer, most commonly August and September (Lehman and others 2005). These blooms typically occur in the San Joaquin River away from the core summer distribution of delta smelt (Figure 3), but some overlap is apparent. Results by Lehman and others (2010a) indicate a strong likelihood that delta smelt are exposed to microcystins, which may in turn affect their habitat use (Baxter and others 2010). Laboratory studies demonstrate that the blue-green alga is toxic to another native fish of the region, Sacramento splittail *Pogonichthys macrolepidotus* (Acuna and others 2012). Indirect effects are also a major concern as Microcystis blooms are toxic to the primary food resources of delta smelt (Ger and others 2009; 2010a; 2010b).

Pesticide effects are less well understood, although effects may be substantial given that agricultural, commercial, and urban purchases of pesticides within the Delta and the upstream watershed averaged 21 million kg annually from 1990 to 2007 (Brooks and others 2011). Intermittent toxicity has been reported for *Ceriodaphnia dubia* an invertebrate surrogate for Delta prey species (Werner and others 2000) and *Hyalella azteca*, a common invertebrate bioassay species (Weston and Lydy 2010; Werner and others 2010).

Geographical Range of Habitat

A common misconception is that the habitat of delta smelt only occurs in the Delta. The monitoring data indicate that center of distribution for the population commonly occurs in the Delta during spring (Dege and Brown 2004) and fall (Sommer and others 2011a). However, the overall distribution of delta smelt habitat is much broader. To illustrate this point, we summarized survey data for different seasons and water year types by life stage (Figure 3). The survey data show that delta smelt habitat is often located well downstream of the Delta, commonly in Suisun Bay. Their habitat also varies substantially by life stage and water year. The habitat tends to be most landward (upstream) for adults (SKT survey) and most seaward for the other life stages (20 mm, TNS, FMWT). As expected based on their strong association with salinity (Dege and Brown 2004; Sommer and others 2011a), the habitat for younger life stages shifts landward in drier years (Figure 3).

Following the listing of delta smelt in the early 1990s, one of the most surprising initial discoveries was the presence of delta smelt in the Napa River, a tributary to San Pablo Bay (Figure 1). While they are generally caught in wet years (Figure 3), the fact that delta smelt can periodically use this downstream habitat is significant. Hobbs et al. (2007) found that use of habitat in this region results in a unique chemical signature in the otoliths of delta smelt and revealed that the portion of fish that use Napa River can be substantial (e.g. 16–18% of population in 1999).

Another key finding was that delta smelt heavily use the Cache Slough Complex (Sommer and others 2011a). As reported in Sommer and others (2011a), at least some delta smelt occur year-round in the region. Although it is unclear what percentage of the population occurs in this region, survey data suggests that this area sometimes seasonally supports the majority of the delta smelt catch. To illustrate the importance of the Cache Slough Complex, FWS beach seine surveys during 2002-2004 show that delta smelt apparently occur year-round in Liberty Island (Figure 5) and were present in all stations sampled (Figure 2). Similarly, expanded efforts of the 20-mm, TNS and FMWT surveys into the Sacramento Deepwater Ship Channel found delta smelt June through October, the warmest months of the year (Baxter and others 2010). Delta smelt use of the Cache Slough complex appears to be substantial as the frequency of occurrence in Liberty Island habitats was comparable to FWS beach seine stations located in their core Delta habitat during 2002-2004 (Figure 6). These findings were relatively unexpected as the general assumption at the time was that delta smelt leave the north Delta after larval stage (Sommer and others 2011a). Moreover, flooded islands were generally considered poor-quality habitat for delta smelt in other parts of the Delta (e.g. Grimaldo and others 2004; Nobriga and others 2005).

Although the Napa River and Cache Slough Complex studies provide some cause for optimism with regard to the status and extent of delta smelt habitat, it is important to note one of the most troubling changes over the past four decades, the loss of the south Delta as year-round habitat for delta smelt. As noted by several studies (Nobriga and other 2008; Sommer and others 2011a), the historical data show that many delta smelt remained in the south Delta throughout the summer. While delta smelt still seasonally occur in the south Delta during winter and spring (Figure 3; Sommer and others 2011a), they are now absent in summer. Nobriga and others (2008) suggest that this is due to major habitat changes including the proliferation of aquatic weeds and associated declines in turbidity.

Habitat Types

The general habitat use by delta smelt is basically a function of the features described in the previous sections. Table 3 provides a synthesis of some of the major types based on some fairly broad habitat classifications. The summary is not intended to reflect the temporal and spatial variability in delta smelt distributions within a given habitat; rather it is designed to demonstrate relative patterns among habitat types. Note also that historical collections of delta smelt in any one of these types does not guarantee that future habitat projects will support this species. Any one of a number of physical (e.g. turbidity; temperature), chemical (e.g. contaminants), and biological factors (e.g. food, competitors, predators) may limit the ability of delta smelt to colonize new areas.

The Future of Delta Smelt Habitat

There is widespread consensus among scientists that the upper San Francisco estuary will be quite different in the future (Knowles 2010; Cloern and others 2011). Studies by Mount and Twiss (2005) predict that there is a high probability of massive levee failure in the foreseeable future. This will radically change the salinity distribution along with the types and locations of different habitats (Lund and others 2007; Moyle 2008). As a consequence, it is especially challenging to use observations on current delta smelt habitat to predict future changes. There have at least been efforts to model habitat based on future flow conditions through the present landscape. The results are fairly discouraging, with predictions of reduced area of low salinity habitat as soon as 50 years in the future (Feyrer and others 2011). Even more disturbing is the finding that within

100 years the number of lethal temperature days for delta smelt will greatly increase and that turbidities will decrease (Wagner and others 2011; Cloern and others 2011). At the same time major biological community changes are inevitable, along with very different physical and chemical regimes (Lund and others 2007; Cloern and others 2011). These issues raise the question of whether delta smelt will be able to persist with climate change. At the very least, the analyses help show that current habitat conditions are not sustainable (Lund and others 2007), making it critical to begin planning for ways to react to long term changes.

Management Implications

The available information suggests a high degree of uncertainty about many aspects of delta smelt habitat (e.g. Brown 2003). This is to be expected given the relatively rare status of this species and the difficulty in directly measuring habitat use in a highly variable and turbid environment. This does not mean, however, that there is insufficient information to examine some of the management issues with delta smelt habitat. Some basic ideas are provided below. Note that we do not specifically address the issue of how much habitat would be required to generate a measurable increase in the population of delta smelt. Such analyses are notoriously difficult and uncertain, even for better-studied fishes such as salmonids (Roni and others 2010). A major part of the problem is that habitat often is not the only factor controlling fish abundance, likely the case for delta smelt (Sommer and others 2007; MacNally and others 2008; Baxter and others 2010).

We know enough to attempt some large scale habitat projects.

While there is not sufficient information to fully design delta smelt habitat, enough is known to attempt major projects to evaluate some of the key questions. For example, the salinity, turbidity, temperature, and food requirements provide a basic description of some of the most important habitat features. Moreover, the large unintentional flooding of Liberty Island and subsequent colonization by delta smelt suggests that there is some potential to expand and improve the habitat of this imperiled species. Indeed, the status of delta smelt is so dire, that we cannot simply hope that the species will be able to recover without several different types of active management. It therefore seems prudent to proceed with one or more large scale projects provided that there is an intensive field monitoring and adaptive management process.

Since much of the proposed habitat restoration activities will likely occur in Suisun Marsh and the north Delta, we propose that new habitat projects try and emulate key aspects of these regions. Based on our analyses, some general suggestions are provided in Table 4. Note that these habitat features are not intended as the sole design criteria for this species. A given project will fail if the constructed habitat if it is subject to periodic water quality issues such as low dissolved oxygen, pesticides, and toxic algal blooms, or high levels of predators or invasive species. In general, maintaining high levels of variability and complexity has been suggested as a key approach to promote native fishes (Moyle and others 2010).

Habitat restoration is highly vulnerable to several factors.

The vulnerability of habitat restoration to future climate change was discussed above. However, even under limited climate change there are many factors than can undermine the value of habitat for delta smelt. Of primary concern is the effect of alien species, given the high level of invasions in the estuary (Cohen and Carlton 1998). Submerged aquatic vegetation such as Egeria can quickly colonize shallow areas of the Delta (Brown and Michniuk 2007), covering shallow open water areas that provide part of the habitat for delta smelt. A notable local example is Decker Island, where a restoration project was constructed next to a known “hot spot” for delta smelt, yet the small dendritic channels were rapidly choked with Egeria. SAV is especially attractive to invasive predators (Grimaldo and others 2004; Brown and Michniuk 2007), that create mortality risks for delta smelt. However, SAV is not necessary for predator colonization as recently-created open water areas such as Liberty Island now support large numbers of striped bass and inland silverside. In addition, it is possible that new habitat projects may be subject to harmful algal blooms or localized runoff problems. The bottom line is that delta smelt habitat restoration may be hard to achieve since there are many pitfalls. Careful site selection and design coupled with intensive monitoring will be needed to minimize these risks.

Bet hedging is critical

Our review of the habitat needs of delta smelt reveals substantial uncertainty about specific features that will support this fish. Given the high level of uncertainty, a sensible approach is to adopt a "bet hedging" strategy coupled with intensive monitoring and evaluation. Of particular importance is the development of habitat projects in more than one geographic area that include multiple habitat types. This is critical given the projection for future climate change (Wagner and others 2011; Cloern and others 2011), the vulnerability of the Delta to floods and earthquakes (Mount and Twiss 2005; Moyle 2008), and the apparent diversity of delta smelt life histories. An emerging story is that the delta smelt do not undergo uniform upstream migration of adults followed by downstream migration of juveniles into the low salinity zone (Sommer and others 2011a). The year-round presence of delta smelt in the north Delta region is evidence of divergent migration pathways (Sommer and others 2011a). Indeed, new otolith research by Hobbs (2010) suggests that the range of life histories includes freshwater spawning/freshwater rearing, freshwater spawning/brackish rearing, brackish spawning/brackish rearing with multiple variations in the specific timing. Again, this means that a single habitat type or region should not be the focus of habitat restoration for delta smelt.

Processes may be more important than specific habitat features

Habitat restoration projects typically try and maximize the specific features that the target species prefers. Obviously, this is a key first step as fishes like delta smelt cannot colonize a habitat unless its basic environmental needs are met. Unfortunately, this can result in over-engineering of habitats, something that may not be justified given the high level of uncertainty about delta smelt habitat and the future of the delta. We propose that an increased emphasis on processes may be more successful that the construction of well-engineered "gardens". Key processes include sustainability and food web subsidies across habitats.

With regard to sustainability, habitats need to be designed to accommodate anticipated changes that will occur over the next century and beyond. Key changes include a declining sediment load (Wright and Schoellhamer 2004) that will strongly affect accretion and degradation rates of delta habitats, and sea level rise which is expected to eventually submerge many lower elevation sites. Careful selection of sites to progressively accommodate sea level rise is therefore a high priority. The declining sediment load is more problematic, but locating restoration areas is sites with relatively higher sedimentation or re-suspension rates may help to alleviate problems.

Although most of the carbon inputs to the food web appear to be from riverine inputs (Jassby and Cloern 2000; Kimmerer 2004), there is a growing ecological recognition that there may be substantial localized inputs across adjacent habitats. This is certainly the case with Yolo Bypass, which exports primary and secondary production to downstream areas (Schemel and others 2004; Sommer and others 2004b). Liberty Island may also export production during some seasons (Lehman and others 2010b). However, some areas such as SAV habitat in other parts of the Delta show evidence of being trophically decoupled from offshore food webs (Grimaldo and others 2009b), so few subsidies are expected across these habitats. The degree to which tidal marsh habitat may subsidize adjacent pelagic habitat remains unclear (Brown 2003), but there is some evidence that marsh exports could be important. In general, phytoplankton and zooplankton levels are higher in small channels surrounded by dense emergent vegetation in Suisun Marsh (Rob Schroeter, UC Davis, unpublished data). This may be more a function of longer residence time in these low order channels, but marsh subsidies are also likely. In any case, it seems wise to consider habitat projects in locations where trophic subsidies are most likely (Jassby and Cloern 2000).

Several key studies are needed

As suggested previously, delta smelt habitat restoration will not succeed unless there is a sufficiently high level of monitoring and research. Moreover, these types of studies are needed immediately in order to learn from existing habitat use by delta smelt, and to develop baseline data and methodologies to evaluate project success. With respect to habitat use, we have learned quite a bit about the basic needs of delta smelt from long-term monitoring and laboratory studies, but we expect that much more information would be gained from efforts designed specifically to assess habitat use. Specifically, stratified randomized sampling methods are a more statistically defensible way to assess habitat use than fixed stations and can be customized to evaluate habitat types and features not covered by the existing monitoring network. Such surveys would be a useful supplement to the existing long term monitoring conducted in the estuary. Initial efforts should be focused on locations such as Suisun Marsh and the Cache Slough Complex, the two major target areas for restoration and existing "hot spots" for delta smelt.

An ongoing issue for the study of delta smelt habitat has been that this listed species is rare and fragile, so "take" is generally a concern. This means that we are unlikely to be able to greatly increase our sampling efforts in areas where delta smelt are common. A major priority is therefore the development of improved telemetry, marking and imaging techniques to minimize take of delta smelt. In the short term, perhaps the most promising method is the use of underwater cameras. There are currently studies investigating the use of a towed net fitted with a camera at its (open) cod end (Baxter and others 2010). The camera and associated image processing software were successfully used in fall 2011 to identify and record delta smelt in several locations of the low salinity zone. Such methods may allow much more intensive sampling of different habitats without incurring high mortality. Better use of samples from the existing monitoring program using novel approaches such as otolith microchemistry may provide additional insight into delta smelt habitat use and migration patterns (Hobbs and others 2007; Hobbs 2010).

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Table 1: Generalized additive modeling (GAM) delta smelt results for the 20 mm survey including Temperature (T), Specific Conductivity (C), Secchi depth (S), and Calanoid Copepod Density (F). The variances in each model were all statistically significant ($P<0.00001$) based on approximate Chi square tests.

Model	Residual Deviance (Percentage of total explained in parentheses)
T	5158 (7.1)
T + C	4876 (12.2)
T + C + S	4640 (16.4)
T + C + S + F	4514 (18.7)

Table 2: Substrate use by delta smelt as sampled by six core USFWS beach seine stations in the west Delta since 1993 (see text for details). The Chi-square analysis excluded vegetated substrate because it included no catch, which violates the assumption of that test.

Substrate	Samples with delta smelt	Total samples (effort)
Gravel	6	338
Mud	39	2483
Pavement	6	2508
Sand	116	6945
Vegetation	0	183

Chi square = 29.15, DF = 3, p<0.001 (Excluding vegetation)

Table 3: Habitat types in which delta smelt have been collected: *= rare; **=periodic, *** = common. As noted in the text, historical observations do not ensure that newly created habitats will support delta smelt.

Region	Habitat	Present	Comments	Sources
Marine Examples: Lower Napa River, San Pablo Bay	-Bay -Channel -Marsh	* * **	Generally only during high flow events. Collections adjacent to Napa marshes.	Bennett (2005); Hobbs and others (2007); DFG Bay Study & Townet Survey.
Brackish Examples: Suisun Bay, West Delta	-Bay -Channel -Marsh	*** *** **	Core habitat. Core habitat. Collections adjacent to Suisun Marsh.	Moyle and others (1992); Aasen (1999); Bennett (2005); Feyrer and others (2007); Dege and Brown (2004); Sommer and others (2011a); UCD Suisun Marsh Survey (unpubl).
Freshwater Examples: Sacramento River, Cache Slough, Sacramento Deep Water Ship Channel.	-Non-tidal -Tidal channel -Littoral -Emergent marsh. -SAV	* *** *** ? *	Rare, highly seasonal. Primarily North Delta. Primarily North Delta. Little sampling. Collections adjacent to SAV.	Aasen (1999) Grimaldo and others (2004); Nobriga and others (2005); Sommer and others (2011a); DFG Fall Midwater and Kodiak Trawls; FWS Juvenile Salmon & Liberty Surveys (unpubl); This Report.

Table 4: Suggested habitat features for pilot delta smelt restoration projects. See text for details.

Habitat Feature	Comments	Citations
Low salinities • Typically <6 psu	The best-studied variable that defines the habitat of delta smelt.	Bennett (2005) Feyrer and others (2007) Kimmerer and others (2009)
Moderate temperatures • *7-25^{o} C*	The upper temperature limits appear consistent for laboratory and field studies, but tolerance is strongly affected by food availability and acclimation conditions. Lower limits have not been studied in detail, but stress from very low temperatures is likely.	Swanson and others (2000) Bennett (2005) Nobriga and others (2008) Bennett and Burau (2010)
High turbidity • *>12 ntu*	Regions with shoal habitat and high wind re-suspension may help maintain high turbidities.	Feyrer and others (2007) Grimaldo and others (2009a)
Sand-dominated substrate	May be useful as spawning substrate.	This report.
At least moderately tidal	Delta smelt are only rarely observed outside tidal areas.	This report.
High copepod densities	Delta smelt survival appears to be linked to higher levels of calanoid	Nobriga (2002)

	copepods in the low salinity zone.	Moyle (2002) Kimmerer (2008b)
Low SAV	The absence of delta smelt in most SAV sampling indicates that submerged vegetation degrades habitat value.	This report. Grimaldo and others (2004) Nobriga and others (2005)
Low Microcystis	The absence of delta smelt in areas with periodic Microcystis levels indicates that these blooms degrade habitat values.	Baxter and others (2010) Lehman and others (2010) This report.
Open water habitat adjacent to long residence time habitat (e.g. low order channels; tidal marsh).	This concept has not been tested statistically, but the frequent occurrence of delta smelt in these habitats suggests that it may be important.	Aasen (1999) This report.

Figure Legends

Figure 1. The San Francisco estuary including key landmarks noted in the text. The Delta is the area between Chipps Island, Sacramento, and just south of Stockton.

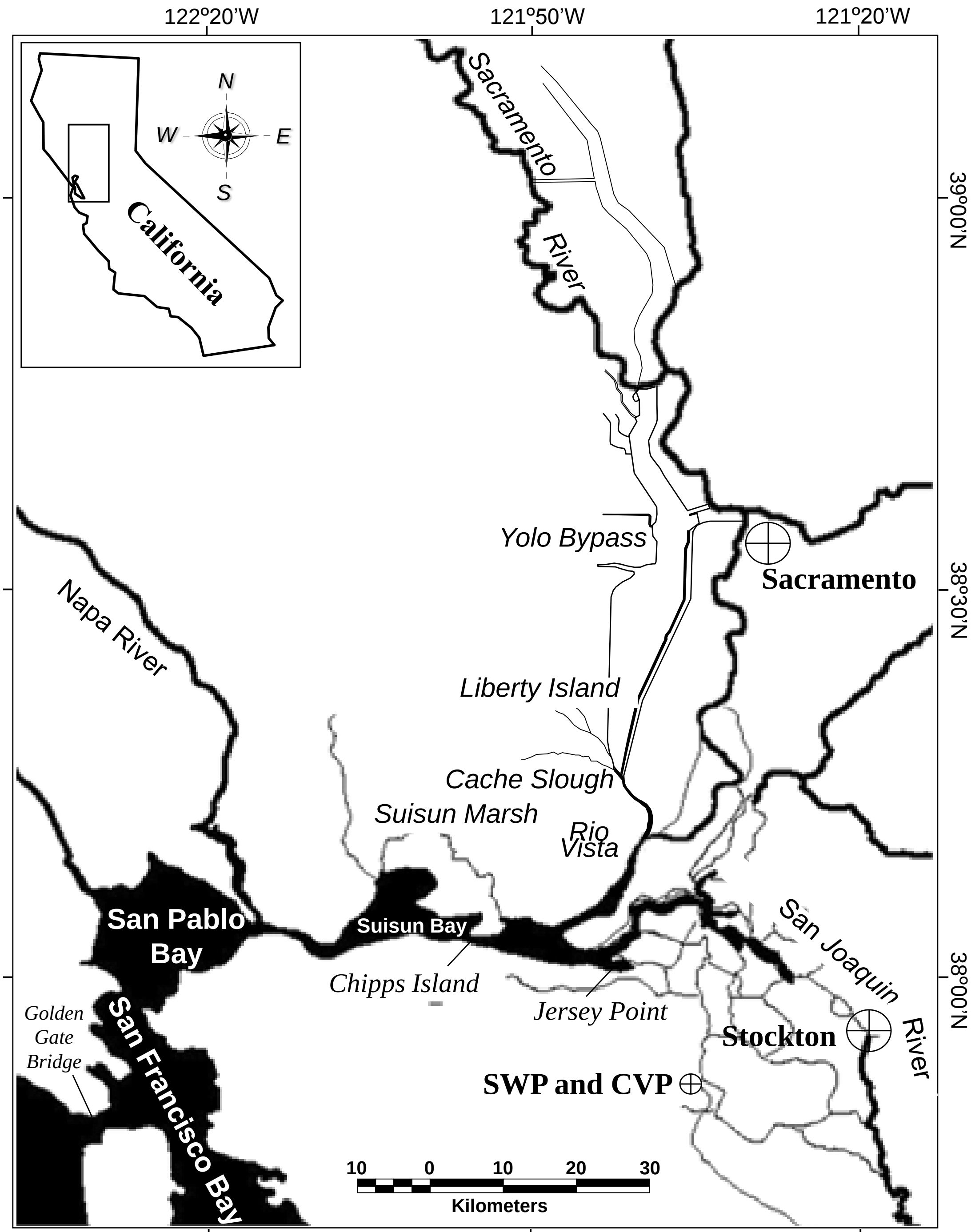
Figure 2. Locations of USFWS beach seine sampling in Liberty Island. The stations starting counter clockwise from the southeast corner of the site are: Liberty Island East #1-5 and Liberty Island #1-5. The data show the percentage of samples with delta smelt in different parts of Liberty Island based on data from August 2002- October 2004 (n = 607 hauls).

Figure 3. Summary of the extent of delta smelt habitat for four surveys: FMWT, SKT, 20 mm, and TNS. The data are for 2002-2010, when all surveys were conducted. The lines show the upstream and downstream limits of catch for wet (left panel) and dry (right panel) years based on the distance from the Golden Gate Bridge. The circles represent the center of distribution for each survey (see text and Sommer and others 2011a). Note that the surveys do not include inshore habitat or locations around the periphery of the estuary (e.g. Liberty Island, upper Deep Water Ship Channel).

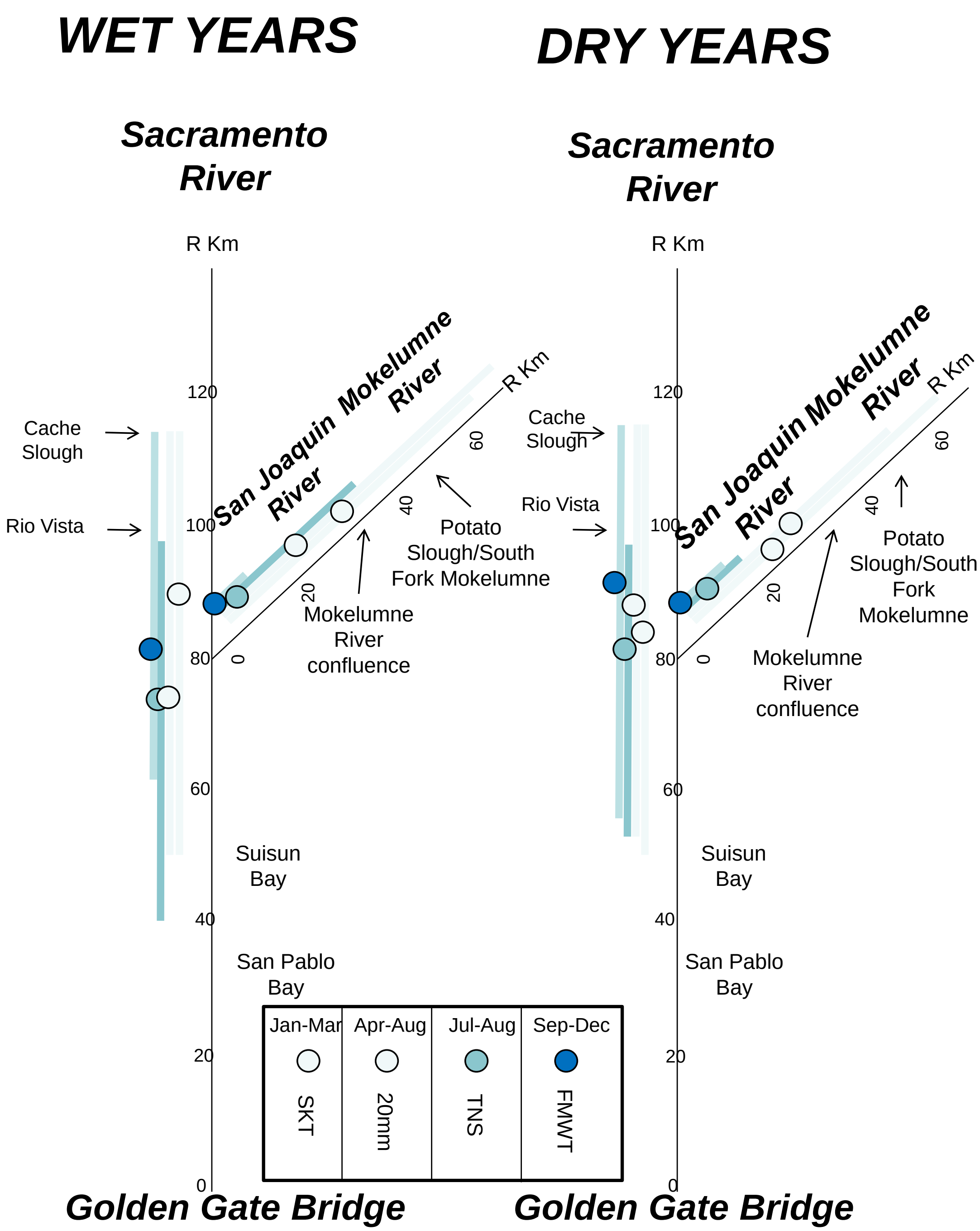
Figure 4. Generalized additive (GAM) model predictions of delta smelt occurrence in the 20 mm survey (based on all four habitat variables) verses the habitat variables for: a) water temperature; b) specific conductivity; c) Secchi depth; and d) calanoid copepod density.

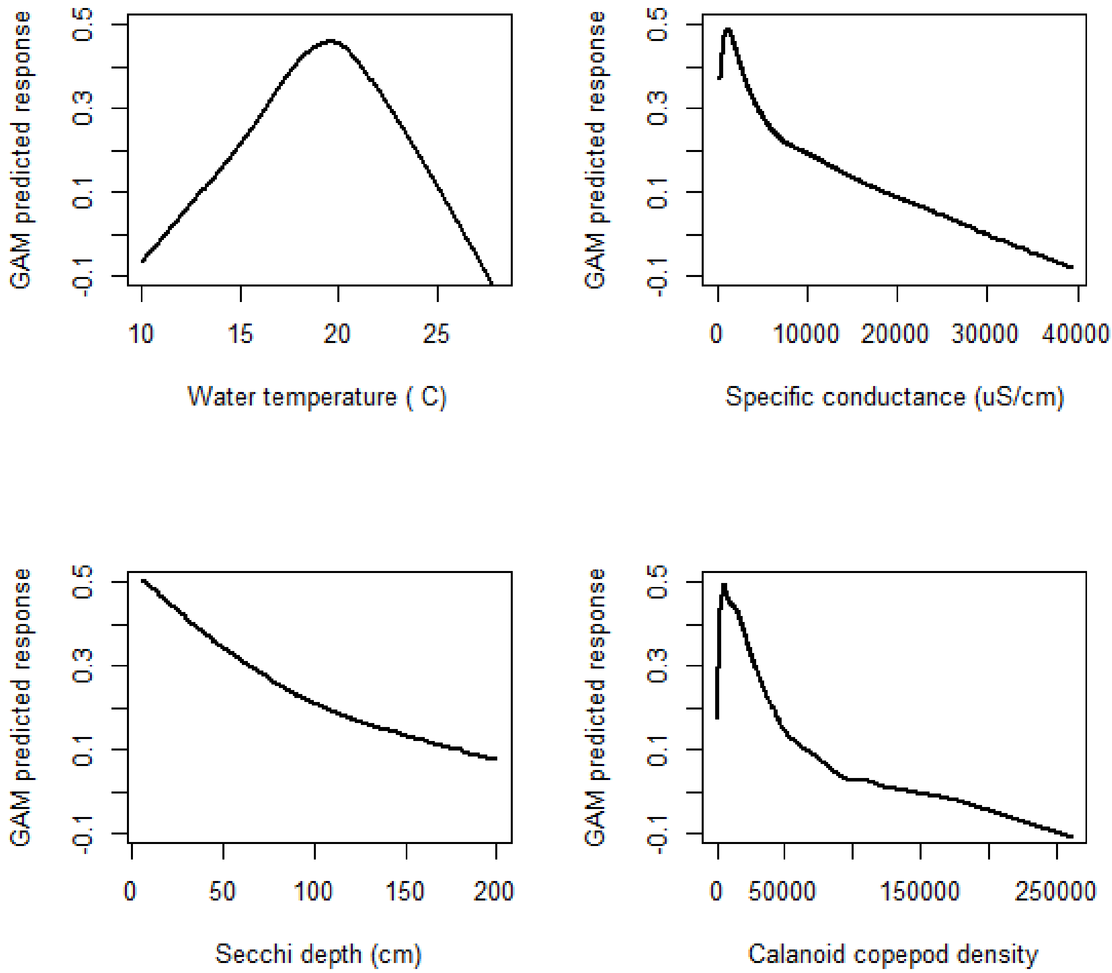
Figure 5. Distribution of catch of delta smelt across seasons in Liberty Island based on USFWS beach seine data from August 2002- October 2004 (n = 93 fish).

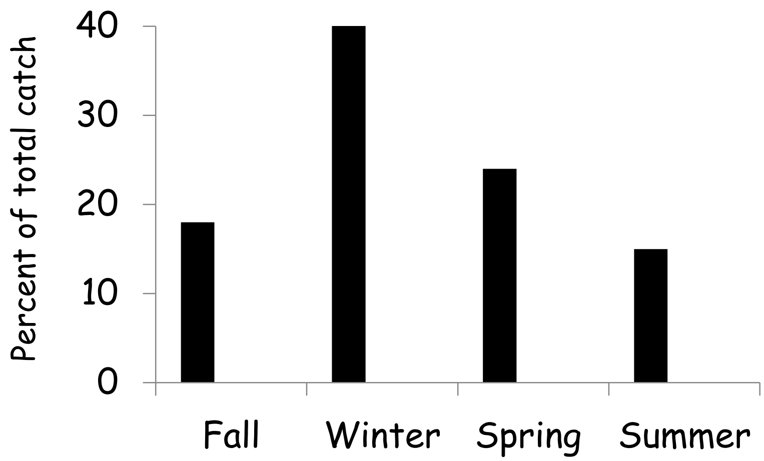
Figure 6. Percentage of beach seine samples with delta smelt in different parts of Liberty Island (ten “LI” stations) as compared to five core west and north Delta sites. Analyses are based on USFWS beach seine sampling in these locations during August 2002- October 2004. The locations of the Liberty Island stations are shown in Figure 2. The differences between the Liberty Island and core Delta stations were not significantly different based on a Kruskal-Wallis test (p=0.065).

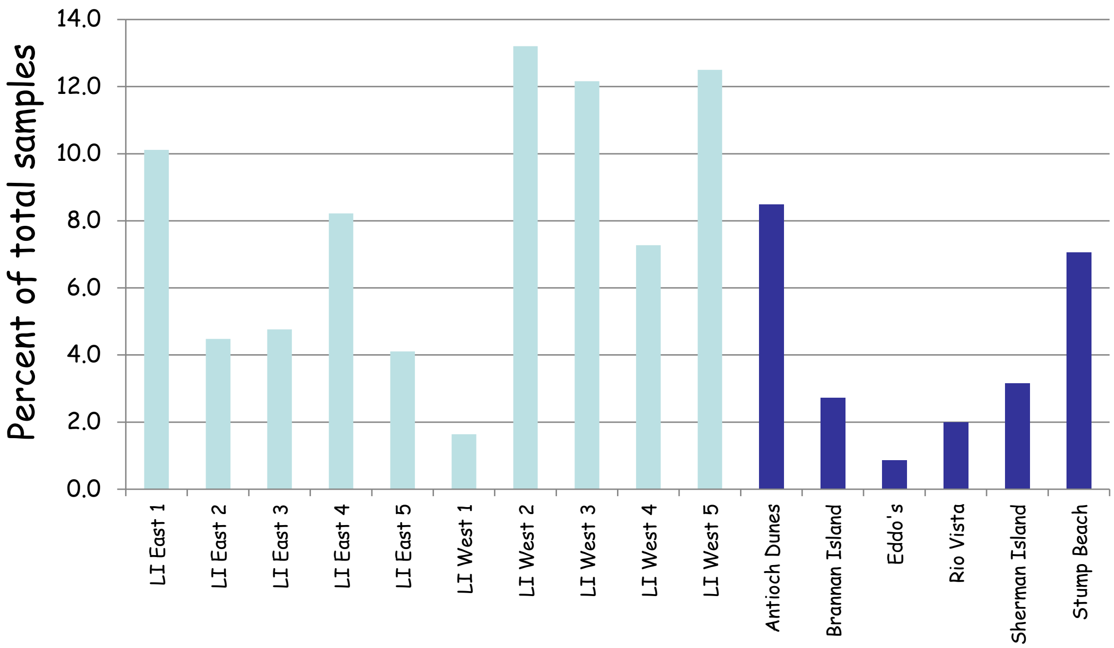

122°20'W
121°50'W
121°20'W
39°00'N
38°30'N
38°00'N
N
W
E
S
California
Sacramento
River
Yolo Bypass
Sacramento
Napa River
Liberty Island
Cache Slough
Suisun Marsh
Rio
Vista
San Pablo
Bay
Suisun Bay
Chipps Island
Jersey Point
San Joaquin
River
Stockton
Golden
Gate
Bridge
San Francisco Bay
SWP and CVP
10 0 10 20 30
Kilometers


2%
4%
13%
8%
12%
5%
7%
4%
13%
10%


WET YEARS
DRY YEARS
Sacramento River
Sacramento River
R Km
R Km
San Joaquin River
Mokelumne River
San Joaquin River
Mokelumne River
R Km
R Km
Cache Slough
Rio Vista
Cache Slough
Rio Vista
Potato Slough/South Fork Mokelumne
Mokelumne River confluence
Potato Slough/South Fork Mokelumne
Mokelumne River confluence
120
100
80
60
40
20
0
0
20
40
60
Suisun Bay
San Pablo Bay
Suisun Bay
San Pablo Bay
Jan-Mar
Apr-Aug
Jul-Aug
Sep-Dec
SKT
20mm
TNS
FMWT
Golden Gate Bridge
Golden Gate Bridge


GAM predicted response
-0.1
0.1
0.3
0.5
10
15
20
25
Water temperature (C)
GAM predicted response
-0.1
0.1
0.3
0.5
0
10000
20000
30000
40000
Specific conductance (uS/cm)
GAM predicted response
-0.1
0.1
0.3
0.5
0
50
100
150
200
Secchi depth (cm)
GAM predicted response
-0.1
0.1
0.3
0.5
0
50000
150000
250000
Calanoid copepod density


Percent of total catch
40
30
20
10
0
Fall
Winter
Spring
Summer


Percent of total samples
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
LI East 1
LI East 2
LI East 3
LI East 4
LI East 5
LI West 1
LI West 2
LI West 3
LI West 4
LI West 5
Antioch Dunes
Brannan Island
Eddo's
Rio Vista
Sherman Island
Stump Beach