Chapter 17 Technical Assistance for Longfin Smelt

Longfin Smelt Biology and Population Dynamics

General Biology

Longfin smelt populations occur along the Pacific Coast of North America. Hinchinbrook Island, Prince William Sound, Alaska represents the northernmost documented population and the San Francisco Estuary represents the southernmost population (Lee et al. 1980). Individual longfin smelt have been caught in Monterey Bay (Moyle 2002) but there is no evidence of a spawning population south of the Golden Gate. In California, the largest spawning population is in the San Francisco Estuary. The existence of other spawning populations has been documented or suspected in Humboldt Bay, the Eel River estuary, the Klamath River estuary, the Van Duzen River, the Eel River drainage, and the Russian River (Moyle 2002, Pinnix et al. 2004); most of these populations are small and perhaps ephemeral, if they exist at all. Longfin smelt are periodically caught in nearshore ocean surveys (City of San Francisco 1985). It is possible that longfin smelt individuals may emigrate from or immigrate to the San Francisco Estuary. The degree of demographic and genetic interaction between coastal populations is unknown; however, given their small size and short life span, it is unlikely that the San Francisco Estuary's population size or genetic diversity are supported by regular emigration from other California coastal populations (which are all ephemeral, small, or distant). Longfin smelt are widespread within the San Francisco Estuary and, historically, they were found seasonally in all of its major open water habitats and Suisun Marsh.

In San Francisco Estuary, longfin smelt adults are generally 90-110 mm standard length (SL) at maturity, but some individuals may be up to 140mm SL (Baxter 1999; Moyle 2002). Longfin smelt can be distinguished from other California smelts by their long pectoral fins, incomplete lateral line, weak or absent striations on the opercular bones, low number of scales in the lateral series, low number of scales in the lateral series (54-65) and long maxillary bones. The lower jaw projects forward of the upper jaw when the mouth is closed. Small, fine teeth are present on both jaws, tongue, vomer and palatines. The sides of living fish appear translucent silver while the back has an olive to iridescent pinkish hue. Mature males are usually darker than females, with enlarged and stiffened dorsal and anal fins, a dilated lateral line region, and breeding tubercles on the paired fins and scales (Moyle 2002).

Longfin smelt generally occur in Suisun, San Pablo, and San Francisco bays as well as in the Gulf of the Farallones, just outside San Francisco Bay. Longfin smelt is anadromous and spawn in the Delta in freshwater. Longfin smelt spawn at 2-years of age. Female longfin smelt may live a third year but it is not certain if they spawn again. Most spawning takes place from February through April. The larval longfin smelt move downstream with the tides until they reach favorable rearing habitat near X2 and, later, downstream into Suisun and San Pablo bays. Larger longfin smelt feed primarily on opossum shrimps *Neomysis mercedis* and *Acanthomysis* spp (Feyrer et al. 2003). Copepods and other crustaceans can also be important food items, especially for smaller fish (DFG unpublished).

Legal Status

The San Francisco Estuary population of longfin smelt was recently advanced to candidacy as an endangered species by the California Department of Fish and Game. As a candidate species, it is afforded all of the protections as formally listed species until a decision has been rendered by the Fish and Game Commission on its status. Longfin smelt is also currently proposed for listing under the federal Endangered Species act.

Distribution, Population Dynamics, and Baseline Conditions

Distribution

Longfin smelt in the San Francisco Estuary are broadly distributed both temporally and spatially, and interannual distribution patterns are relatively consistent (Rosenfield and Baxter 2007). Seasonal patterns in abundance indicate that the population is at least partially anadromous (Rosenfield and Baxter 2007). This is indicated by a decrease in density and distribution in San Francisco Bay up to Suisun Marsh after the first winter of the longfin smelt life cycle, which cannot be attributed solely to mortality because both density and distribution increased during the second winter of the life cycle, just before the spawning season. Sampling by the City of San Francisco during several years in the early 1980s detected longfin smelt in the Pacific Ocean, providing additional evidence that some part of this population migrates beyond the Golden Gate Bridge (City of San Francisco and CH2M Hill 1985). Anadromous populations of longfin smelt occur elsewhere in their range, but the duration of this anadromous phase of their life cycle is unstudied as are the ecology and behavior of longfin smelt in marine environments. However, the detection of longfin smelt within the estuary throughout the year suggests that anadromy is just one of potentially several life history strategies or contingents in this population.

There is also a consistent pattern of bathymetric distribution in that postlarval longfin smelt are associated with deep-water habitats (Rosenfield and Baxter 2007). Longfin smelt in the Lake Washington population also display a depth-stratified distribution (Chigbu et al. 1998; Chigbu 2000). Longfin smelt concentration in deepwater habitats combined with migration into marine environments during summer months suggests that longfin smelt may be relatively intolerant of warm waters that occur seasonally in this estuary.

Longfin smelt migrate upstream to spawn in freshwater during late autumn through winter. The general spawning region is believed to be downstream of Rio Vista on the Sacramento River and downstream of Medford Island on the San Joaquin River Sacramento River, to just downstream of the confluence of these two rivers (Moyle 2002). Limited spawning may also periodically occur in the south Bay (DFG unpublished). Larvae are most abundant in the water column usually from January through April (DFG unpublished), and are one of the most common and abundant species encountered during the 20mm Survey (Dege and Brown 2004). The vertical distribution of longfin smelt larvae is highly associated with the upper portion of the water column (DFG unpublished) The geographic distribution of longfin smelt larvae is closely associated with the position of X2; the center of distribution varies with outflow conditions but not with respect to X2 (Dege and Brown 2004). The center of distribution is consistently seaward of X2 (Dege and Brown 2004). This pattern is consistent with juveniles migrating downstream to low salinity habitats for growth and rearing.

Population Abundance Trends

The population size of longfin smelt in the San Francisco Estuary is measured by indices of abundance generated from different sampling programs. The abundance of age-0 and older fish is best indexed by the Fall Midwater Trawl and Bay Study, while the abundance of larvae and young juvenuiles is best indexed by the 20mm Survey (Figure 17-1). The relationship between these indices and actual population sizes are unknown. Furthermore, basic life-history information (mortality and growth rates) and ecological patterns (e.g. the extent, duration, and outcomes of marine migrations) for this population have received little study. As a result, a quantitative assessment of population viability (i.e., with extinction thresholds and probabilities) has not developed.

The abundance of longfin smelt in the Estuary has fluctuated over time but has exhibited a sharp decline since the early 1980’s, and was particularly low during the drought of the early 1990’s and recent wet years (Figure 17-1) (Rosenfield and Baxter 2007; Sommer et al. 2007). This decline has also been reflected in a reduction in the percent of trawls that catch longfin smelt throughout the Estuary (Rosenfield and Baxter 2007). Thus, longfin smelt have apparently decreased in abundance and are also less common than they have been historically. Also, whereas the Suisun Marsh sampling program commonly caught small numbers of age class 2 longfin smelt in the late-fall and winter, that program has caught very few spawning-age adult longfin smelt since 1990 (Rosenfield and Baxter 2007). More concerning, the 2007 Fall Midwater Trawl index was the lowest (13) recorded since the survey began in 1967. The recent decline in longfin smelt numbers and those of other pelagic fish species such as delta smelt has become known as the Pelagic Organism Decline (Sommer et al. 2007).

Note that in Figure 17-1 the panels from top to bottom are: fall midwater trawl, 20mm survey, bay study midwater trawl, and bay study otter trawl. Values exceeding the vertical scale on the fall midwater trawl are (in chronological order) 81,740, 59,350, 31,184 and 62,905. There is no fall midwater trawl index for 1974, 1976, or 1979. The 20mm survey started in 1995, and the bay study started in 1980. Error bars for the 20mm survey and bay study are one standard error.

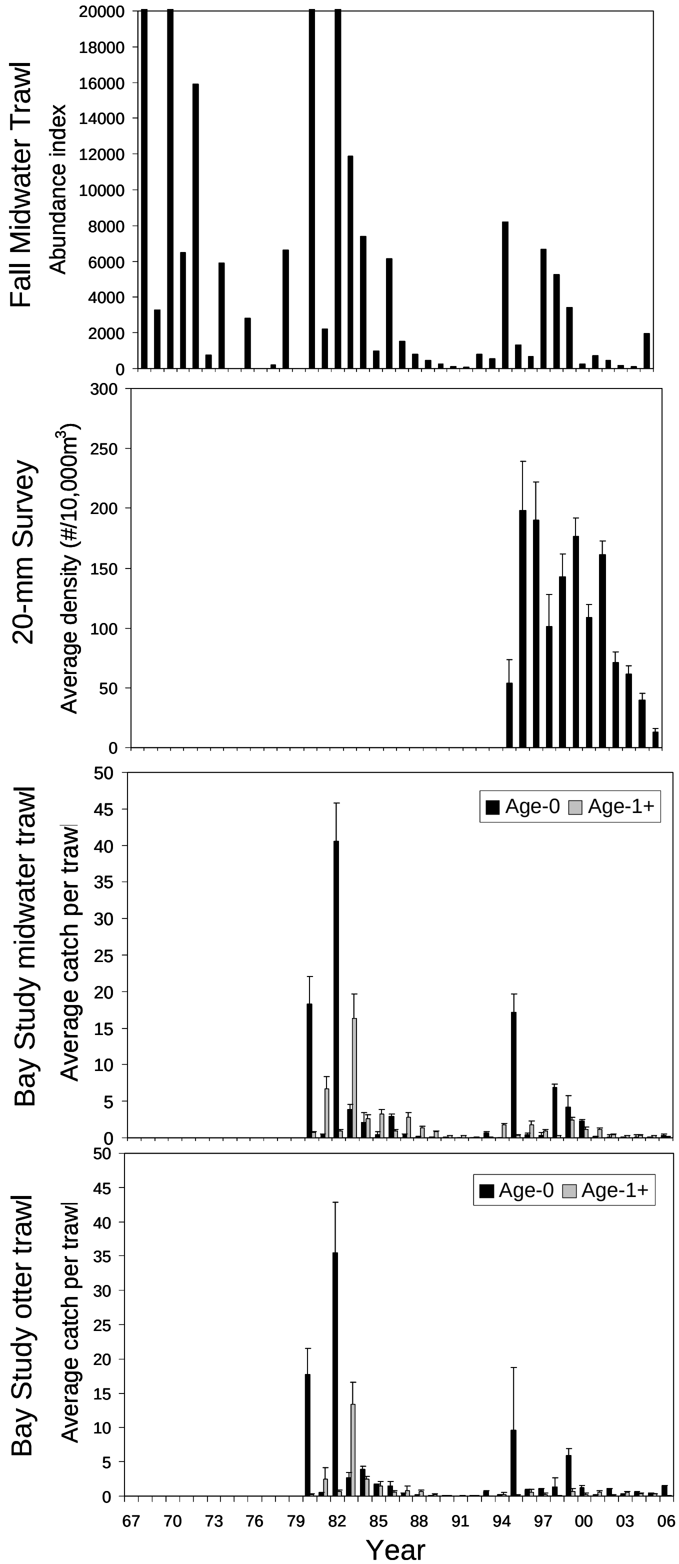

Figure 17-1 Four separate "indices" of longfin smelt abundance in the San Francisco Estuary through 2006.

The Pelagic Organism Decline

The term "Pelagic Organism Decline" (POD) denotes the sudden, overlapping declines of San Francisco Estuary pelagic fishes since about 2002. The POD species include delta smelt, longfin smelt, threadfin shad, and (age-0) striped bass, which together account for the bulk of the pelagic fish biomass in the upper Estuary. The year 2002 is often reckoned as the start of the POD because of the striking declines of three of the four POD species between 2001 and 2002. The POD declines became clearly evident against the high background variability in these species in early 2005, when analysis of the third consecutive year of extremely low numbers in these species made them statistically clear.

Post-2001 abundance indices for the POD species have included record lows for longfin smelt, delta smelt and age-0 striped bass, and near-record lows for threadfin shad. Abundance improved for each species during 2006, but levels for all have remained relatively poor since 2002 for all four species. Low abundance levels have been especially remarkable in that winter and spring river flows into the estuary have been moderate or very wet (2006) during recent years. Moderate to wet conditions have historically usually been associated with at least modest recruitment of most pelagic fish species. Longfin smelt is perhaps the best example of this point as the species shows a very strong relationship with delta outflow. The introduction of the overbite clam (*Corbula amurensis*) in 1986 and associated changes in the food web reduced the magnitude of the response of longfin smelt without altering its slope (Kimmerer 2002). Specifically, the grazing effects from Corbula are thought to have resulted in a substantial decline in phytoplankton and calanoid copepods, the primary prey of early life stages of pelagic fishes. As a consequence, comparable levels of flow did not generate the expected levels of fish biomass (as indexed by abundance) after 1986. During the POD years, the abundance indices for longfin smelt deviated substantially from both the pre-and post-Corbula relationships with outflow. The situation is similar for age-0 striped bass, which has a historical abundance association with outflow that was also altered by *Corbula*, whereas the recent abundance indices were well below expected levels based on outflow. Hence, it appears that the response of these pelagic fishes to environmental conditions has fundamentally changed since the POD (Sommer et al. 2007).

Because of its many management implications, the POD has been the subject of an intensive analytical effort by the Interagency Ecological Program since the POD was recognized in 2005. The POD investigation has greatly improved our understanding of the ecology of pelagic fishes in the Estuary. Content of this chapter and in the formulation of the longfin smelt effects analysis largely reflect changes in our understanding of longfin smelt biology that have emerged from the POD investigation. While mechanisms responsible for POD-era declines of the species probably vary by species, it appears very unlikely that they are independent of one another. Consequently, some of the discussion in the remainder of this chapter involves species other than longfin smelt. This chapter borrows heavily from the text of the 2007 POD Synthesis Report (IEP 2008).

Factors That May Influence the Abundance and Distribution of Longfin Smelt

Numerous factors are hypothesized to have influenced historical population dynamics of longfin smelt (Moyle 2002). Some of these factors (e.g., climatic influences on the physical environment) are thought to exert strong, consistent influences, while others are thought to exert more subtle influences (e.g., factors affecting growth rates), or to be important only under certain conditions (e.g., entrainment losses). Historically, the evidence brought to bear on most mechanistic hypotheses has been based on statistical correlations of abundance and/or survival with environmental variables (Jassby et al. 1995; Moyle 2002; Kimmerer 2002; Sommer et al. 2007; IEP 2007).

For organization we will use the four categories described in the simple conceptual model presented in the POD 2007 Synthesis Report (IEP 2007). Where the POD Team used the model to describe possible mechanisms by which a combination of long-term and recent changes to the ecosystem could produce the observed pelagic fish declines, we use it simply to organize mechanisms that affect abundance and distribution. The conceptual model is rooted in classical food web and fisheries ecology and contains four major components: (1) prior fish abundance, including low-abundance effects that may reduce juvenile production (e.g. stock-recruit effects); (2) habitat, including physical and chemical variables, disease, and localized toxic algal blooms that affect survival and reproduction; (3) top-down effects, including predation, entrainment, and other processes that cause juvenile and adult mortality; (4) bottom-up effects, including food web interactions that affect growth, reproduction, and, indirectly, survival.

Prior Abundance

The relationship between numbers of spawning fish and the numbers of young subsequently recruiting to the adult population is known as a stock-recruit relationship. Stock-recruit relationships have been described for many species and are a central part of the management of commercially and recreationally fished species (Myers et al. 1995). Different forms of stock recruit relationships are possible, including density-independent, density-dependent, and density vague types. The latter refers to situations where there is not a statistically demonstrable stock recruit relationship observable in available data. In any form of a stock-recruit model, there is a point at which low adult stock will result in low juvenile abundance and subsequent low recruitment to future adult stocks even under favorable environmental conditions while the stock 'rebuilds' itself.

There has been no demonstrated stock-recruit relationship for longfin smelt in the San Francisco Estuary.

Habitat

Aquatic habitats are the suites of physical, chemical, and biological factors that species occupy (Hayes et al. 1996). The maintenance of appropriate habitat quality is essential to the long-term health of aquatic resources (Rose 2000; Peterson 2003). A key point is that habitat suitability affects most or all other factors affecting abundance and/or distribution. This is because changes in pelagic habitat, to take an example, affect not only affect delta smelt and other pelagic fishes but also their predators and prey.

Habitat for longfin smelt is open water, largely away from shorelines and vegetated inshore areas except perhaps during spawning. This includes large embayments such as Suisun Bay and the deeper areas of many of the larger channels in the Delta. More specifically, longfin smelt habitat is water with suitable values for a variety of physical-chemical properties, especially including salinity, turbidity, and temperature, suitably low levels of contaminants, and suitably high levels of prey production to support growth. Thus, longfin smelt habitat suitability in the estuary can be strongly influenced by variation in freshwater flow (Jassby et al. 1995; Bennett and Moyle 1996; Kimmerer 2004). Several of the POD fishes, including longfin smelt, use a variety of tidally assisted swimming behaviors to maintain themselves within open-water areas where water quality and food resources are favorable (Bennett et al. 2002). The four POD fishes also distribute themselves at different values of salinity within the estuarine salinity gradient (Dege and Brown 2004), so at any point in time, salinity is a major factor affecting their geographic distributions.

Physical Habitat

Changes in longfin smelt habitat quality in the San Francisco Estuary can be indexed by changes in X2. The abundance of many local taxa has tended to increase in years when flows into the estuary are high and the 2 psu isohaline is pushed seaward (Jassby et al. 1995), implying that over the range of historical experience the quantity or suitability of estuarine habitat increases when outflows are high.

Currently, X2 (which is controlled by both climate and water operations) is a strong predictor of the longfin smelt Fall Midwater Trawl index, which suggests flow and its affect on habitat are strong determinants of year class strength for longfin smelt. This is particularly important considering there is no demonstrated stock-recruit relationship for longfin smelt.

Although similar work has not yet been completed for longfin smelt, there has been a long-term decline in fall habitat environmental quality for delta smelt (Feyrer et al. 2007). The long-term environmental quality declines for delta smelt are defined by a lowered probability of occurrence in samples based on changes in specific conductance and Secchi depth. Notably, delta smelt environmental quality declined recently coinciding with the POD (Figure 7-8). The greatest changes in environmental quality occurred in Suisun Bay and the San Joaquin River upstream of Three Mile Slough and southern Delta (Figure 7-9). There is evidence that these habitat changes have had population-level consequences for delta smelt. The inclusion of specific conductance and Secchi depth in the delta smelt stock-recruit relationship described above improved the fit of the model, suggesting adult numbers and their habitat conditions exert important influences on recruitment. Additional discussion pertinent to delta smelt is provided above in the chapter covering delta smelt biology. Given the status of longfin smelt, similar work evaluating their habitat should be initiated immediately.

Contaminants and Disease

In addition to habitat changes from salinity, turbidity and invasive aquatic vegetation such as E. densa, contaminants can change ecosystem functions and productivity through numerous pathways. The trends in contaminant loadings and their ecosystem effects are not well understood. We are currently evaluating direct and indirect toxic effects on the POD fishes of both man-made contaminants and natural toxins associated with blooms of M. aeruginosa (a cyanobacterium or blue-green alga). The main indirect contaminant effect we are investigating is inhibition of prey production.

Although a number of contaminant issues first during the POD years, concern over contaminants in the Delta is not new. There are long standing concerns related to mercury and selenium in the watershed, Delta, and Bay (Linville et al. 2002; Davis et al. 2003). Phytoplankton growth rate may occasionally be inhibited by high concentrations of herbicides (Edmunds et al. 1999). New evidence indicates that phytoplankton growth rate may at times be inhibited by ammonium concentrations in and upstream of Suisun Bay (Wilkerson et al. 2006, Dugdale et al. 2007, Dugdale et al unpublished). Toxicity to invertebrates has been noted in water and sediments from the Delta and associated watersheds (e.g., Kuivila and Foe 1995; Giddings 2000; Werner et al. 2000; Weston et al. 2004). Undiluted drainwater from agricultural drains in the San Joaquin River watershed can be acutely toxic (quickly lethal) to fish and have chronic effects on growth (Saiki et al. 1992). Evidence for mortality of young striped bass due to discharge of agricultural drainage water containing rice herbicides into the Sacramento River (Bailey et al. 1994) led to new regulations for discharge of these waters. Bioassays using caged fish have revealed DNA strand breakage associated with runoff events in the watershed and Delta (Whitehead et al. 2004). Kuivila and Moon (2004) found that peak densities of larval and juvenile delta smelt sometimes coincided in time and space with elevated concentrations of dissolved pesticides in the spring. These periods of co-occurrence lasted for up to 2-3 weeks, but concentrations of individual pesticides were low and much less than would be expected to cause acute mortality. However, the effects of exposure to the complex mixtures of pesticides actually present are unknown.

The POD investigators initiated several studies to address the possible role of contaminants and disease in the declines. Their primary study consists of twice-monthly monitoring of ambient water toxicity at fifteen sites in the Delta and Suisun Bay. In 2005 and 2006, standard bioassays using the amphipod Hyalella azteca had low (<5%) frequency of occurrence of toxicity (Werner et al. unpublished data). However, preliminary results from 2007, a dry year, suggest the incidence of toxic events was higher than in wetter previous years. Parallel testing with the addition of piperonyl butoxide, an enzyme inhibitor, indicated that both organophosphate and pyrethroid pesticides may have contributed to the observed 2007 toxicity. Most of the tests that were positive for H. azteca toxicity have come from water samples from the lower Sacramento River. Pyrethroids are of particular interest because use of these insecticides has increased (Ameg et al. 2005, Oros and Werner 2005) as use of some organophosphate insecticides has declined. Toxicity of sediment-bound pyrethroids to macroinvertebrates has also been observed in watersheds upstream of the Delta (Weston et al. 2004, 2005).

Larval delta smelt bioassays were conducted simultaneously with a subset of the invertebrate bioassays. The water samples for these tests were collected from six sites during May-August of 2006 and 2007. Results from 2006 indicate that delta smelt is highly sensitive to high levels of ammonia, low turbidity, and low salinity. There is some preliminary indication that reduced survival under low salinity conditions may be due to disease organisms (Werner, unpublished data). No significant mortality of larval delta smelt was found in the 2006 bioassays (Werner 2006), but there were two instances of significant mortality in June and July of 2007 (Werner, unpublished). In both cases, the water samples were collected from sites along the Sacramento River and had relatively low turbidity and salinity and moderate levels of ammonia. It is also important to note that no significant H. azteca mortality was seen in these water samples. While the H. azteca tests are very useful for detecting biologically relevant levels of water column toxicity, interpretation of the H. azteca test results with respect to fish should proceed with great caution. The relevance of the bioassay results to field conditions remains to be determined.

POD investigators have also monitored blooms of the toxic cyanobacterium *Microcystis aeruginosa*. Large blooms of *M. aeruginosa* were first noted in the Delta in 1999 (Lehman et al. 2005). Further studies (Lehman et al. in prep.) suggest that microcystins, the toxic chemicals associated with the algae, probably do not reach concentrations directly toxic to fishes, but during blooms, the microcystin concentrations may be high enough to impair invertebrates, which could influence prey availability for fishes. The *M. aeruginosa* blooms peak in the freshwaters of the central Delta during the summer at warm temperatures (20-25°C; Lehman et al. in prep). Delta smelt and longfin smelt are generally not present in this region of the Delta during summer (Nobriga et al. in press; Rosenfield and Baxter 2007) so *M. aeruginosa* toxicity is not likely a factor in their recent decline. However, in the low flow conditions of 2007, blooms of this cyanobacterium spread far downstream to the west Delta and beyond during summer (Lehman, unpublished data), so toxicity may have been a much broader issue than in other years.

The POD investigations into potential contaminant effects also include the use of biomarkers that have been used previously to evaluate toxic effects on POD fishes (Bennett et al. 1995; Bennett 2005). The results to date have been mixed. Histopathological and viral evaluation of young longfin smelt collected in 2006 indicated no histological abnormalities associated with toxic exposure or disease (Foott et al. 2006). There was also no evidence of viral infections or high parasite loads. Similarly, young threadfin shad showed no histological evidence of contaminant effects or of viral infections (Foott et al. 2006). Parasites were noted in threadfin shad gills at a high frequency but the infections were not considered severe. Thus, both longfin smelt and threadfin shad were considered healthy in 2006. Adult delta smelt collected from the Delta during winter 2005 also were considered healthy, showing little histopathological evidence for starvation or disease (Teh et al. unpublished). However, there was some evidence of low frequency endocrine disruption. In 2005, 9 of 144 (6%) of adult delta smelt males were intersex, having immature oocytes in their testes (Teh et al. unpublished).

In contrast, preliminary histopathological analyses have found evidence of significant disease in other species and for POD species collected from other areas of the estuary. Massive intestinal infections with an unidentified myxosporean were found in yellowfin goby *Acanthogobius flavimanus* collected from Suisun Marsh (Baxa et al. in prep.). Severe viral infection was found in inland silverside *Menidia beryllina* and juvenile delta smelt collected from Suisun Bay during summer 2005 (Baxa et al. in prep.). Lastly, preliminary evidence suggests that contaminants and disease may impair striped bass. Ostrach et al. (in prep.) found high occurrence and severity of parasitic infections, inflammatory conditions, and muscle degeneration in young striped bass collected in 2005; levels were lower in 2006. Several biomarkers of contaminant exposure including P450 activity (i.e., detoxification enzymes in liver), acetylcholinesterase activity (i.e., enzyme activity in brain), and vitellogenin induction (i.e., presence of egg yolk protein in blood of males) were also reported from striped bass collected in 2006 (Ostrach et al. in prep.).

Much of the previous discussion about how physical conditions and water quality affect delta smelt and other fishes is also relevant to other aquatic organisms including plankton and the benthos. It is important to keep in mind that river flows influence estuarine salinity gradients and water residence times. The residence time of water affects both habitat suitability for benthos and the transport of pelagic plankton. High tributary flow leads to lower residence time of water in the Delta (days), which generally results in lower plankton biomass (Kimmerer 2004), but also lower cumulative entrainment effects in the Delta (Kimmerer and Nobriga in press). In contrast, higher residence times (a month or more), which result from low tributary flows, may result in higher plankton biomass. This can increase food availability for planktivorous fishes; however, much of this production may be lost to water diversions under low flow conditions. Under extreme low flow conditions, long water residence times may also promote high biological oxygen demand when abundant phytoplankton die and decompose (Lehman et al. 2004; Jassby and Van Nieuwenhuyse 2006). Recent particle tracking modeling results for the Delta show that residence times in the southern Delta are highly variable, depending on Delta inflow, exports, and particle release location (Kimmerer and Nobriga, in press). Very high inflow leads to short residence time. The longest residence times occur in the San Joaquin River near Stockton under conditions of low inflow and low export flow.

Salinity variation can have a major effect on the benthos, which occupy relatively "fixed" geographical positions along the gradient of the estuary. While the distributions of the benthos can undergo seasonal and annual shifts, benthic organisms cannot adjust their locations as quickly as the more mobile pelagic community. Analyses of long-term benthic data for four regions of the upper San Francisco estuary indicate that two major factors control community composition: species invasions, and salinity (Peterson et al. in prep). Specifically, the invasion of the clam *C. amurensis* in the late 1980s resulted in a fundamental shift in the benthic community; however; the center of distribution of *C. amurensis* and other benthic species varies with flow and the resulting salinity regime. So at any particular location in the estuary, the benthic community can change substantially from year to year as a result of environmental variation and species invasions (Figure 7-10). These changes in the benthos can have major effects on food availability to pelagic organisms, including delta smelt.

Few studies have directly addressed how toxic chemicals, disease, and parasites affect longfin smelt. One of the few that does is an unpublished study by Scott Foott (CDFG), who summarizes the work as follows.

> Larval and 0+ juvenile Longfin smelt (LFS) and Threadfin shad (TFS) were collected in 2006 and 2007 from April – November. Over 400 fish / yr were assayed for virus using up to 4 different cell lines. Other fish were processed for histological examination (Davidson's fixative, 6µm paraffin sagittal sections, H&E or PAS stain) of 10 target tissues (gill, liver, kidney, acinar tissue, intestinal tract, heart, brain, eye, olfactory organ, and epidermis). The histological sample set in 2006 was composed of 15 TFS and 142 LFS while 118 TFS and 86 LFS histological specimens were examined in 2007.
>
> Trematodes and cestodes were observed in 8-16% of intestines without associated tissue damage. Varying degrees of hepatocyte vacuolation was observed in a majority of LFS livers (July – November 2006 and 2007). PAS stain showed little glycogen and we speculate the vacuoles primarily contain fat. Fatty change can be associated with contaminate exposure. Interpretation is complicated by signs of tissue hypoxia in many specimens (outcome of capture stress prior to fixation?).
>
> Summary: no significant health problem was detected in either TFS or LFS juveniles in 2006 or 2007. No virus was isolated in over 800 samples and the low incidence of parasitic infection was not associated with tissue damage or inflammation. In both 2006 and 2007, hepatocyte vacuolation was seen in many juvenile LFS livers from fish collected primarily in the fall. It is unknown whether fatty liver is normal for LFS or associated with toxic insults.

Climate Change

There are several reasons we expect future climate change might have negative long-term influences on pelagic habitat suitability for the POD fishes. First, there has been a trend toward more Sierra Nevada precipitation falling as rain earlier in the year (Roos 1987, 1991; Knowles and Cayan 2002, 2004). This increases the likelihood of winter floods and may have other effects on the hydrographs of Central Valley rivers and Delta salinity. Altered hydrographs interfere with pelagic fish reproduction, which is usually tied to historical runoff patterns (Moyle 2002). Second, sea level is rising (IPPC 2001). Sea level rise will increase salinity intrusion unless sufficient freshwater resources are available to repel the seawater. This will shift fish distributions upstream and possibly further reduce habitat area for some species. Third, climate change models project warmer temperatures in central California (Dettinger 2005). As stated above, water temperatures do not currently have a strong influence on POD fish distributions. However, summer water temperatures throughout the upper estuary are fairly high for delta smelt. Mean July water temperatures in the upper estuary are typically 21-24C (Nobriga et al. in press) and the lethal temperature limit for delta smelt is reported to be 25C (Swanson et al. 2000), though entrainment of juvenile delta smelt in spring 2007 continued until central Delta temperatures approached 28C. Thus, if climate change were to result in summer temperatures in the upper Estuary substantially exceeding current levels, suitable habitat during those months could be reduced or, in the worst case, eliminated in some years.

Top-Down Effects

The two most prominent top-down influences on pelagic fishes are entrainment into various water diversions and predation by piscivorous fishes. Major water diversions in the delta include the SWP and CVP export facilities, power plants, and agricultural diversions. The CVP and SWP water export operations include upstream reservoirs, the DCC, the SMSCG, the North Bay Aqueduct facilities (NBA), the Contra Costa Canal facilities (CCC), CCF, the Banks Pumping Plant/Skinner Fish Facilities (hereafter SWP), the South Delta Temporary Barriers (SDTB) and the Jones Pumping Plant/Fish Collection Facilities (hereafter CVP). The description and operation of these facilities was covered in the “Project Description” section of this Biological Assessment.

Water export operations occur primarily at SWP and CVP, with far smaller amounts of water diverted at NBA and CCC. Because of their size, and because of evidence implicating water project operations as contributing causes of the POD, the discussion of them below borrows heavily from the POD analysis.

As described in the “Project Description”, the NBA diversions have fish screens designed to FWS criteria for delta smelt protection. In addition, a larval delta smelt monitoring program occurs each spring in the sloughs near NBA. This monitoring program is used to trigger NBA export reductions when delta smelt larvae are nearby. Because the FWS deems these NBA measures to be adequately protective of delta smelt, the NBA will not be considered further.

Water is also temporarily diverted by two power plants located in the western Delta at Antioch and Pittsburgh. Nonconsumptive water use may reach 3200 cfs during full operation of both plants, which might be enough to create a substantial entrainment risk for fishes residing in the vicinity (Matica and Sommer, in prep.). Studies in the late 1970s indicated that losses of pelagic fishes during such operations can be very high. In recent years these plants have not been operated frequently, and their use appears to be restricted to supplying power only during periods of extreme demand. They are discussed in more detail below.

Entrainment

Because large volumes of water are drawn from the estuary, water exports and inadvertent fish entrainment at the SWP and CVP export facilities are among the best-studied top-down effects in the San Francisco Estuary (Sommer et al. 2007). The export facilities are known to entrain most species of fish in the upper Estuary (Brown et al. 1996), and are of particular concern in dry years, when the distributions of young striped bass, delta smelt, and longfin smelt shift closer to the diversions (Stevens et al. 1985; Sommer et al. 1997). As an indication of the magnitude of the effects, approximately 110 million fish were salvaged at the SWP screens and returned to the Delta over a 15-year period (Brown et al. 1996). However, this number greatly underestimates the actual number of fish entrained. It does not include losses at the CVP. Even for the SWP alone, it does not account for mortality of fish in Clifton Court Forebay and the waterways leading to the diversion facilities, larvae < 20 mm FL are not collected by fish screens, and losses of fish > 20 mm FL that because of inefficiencies are not removed by the louver system.

One piece of evidence that export diversions played a role in the POD is the substantial increases in winter CVP and SWP salvage that occurred contemporaneously with recent declines in delta smelt and other POD species (Grimaldo et al. in review). Increased winter entrainment of delta smelt, longfin smelt and threadfin shad represents a loss of pre-spawning adults and all their potential progeny. Similar increases in the salvage of littoral species including centrarchids and inland silverside were observed during the same period. The littoral species are less influenced by flow changes than the POD fishes. However, the increases in salvage for centrarchids may be at least partially a result of the range expansion of *Egeria densa*, which provides favored habitat. This hypothesis is supported by the observation that the greatest increases in centrarchid salvage occurred at the CVP. The intake of the CVP is located in an area with significant areas of *E. densa* nearby. Nonetheless, the increase in entrainment of both groups of fishes suggests a large change in the hydrodynamic influence of the export diversions during recent winters. Note that winter salvage levels subsequently decreased to very low levels for all POD species during the winters of 2005-2006 and 2006-2007, possibly due to the very low numbers of fish that appear to remain in the estuary.

In trying to evaluate the mechanism(s) for increased winter-time salvage, POD studies by USGS made three key observations (IEP 2005). First, there was an increase in exports during winter as compared to previous years, mostly attributable to the SWP (Figure 7-11). Second, the proportion of tributary inflows shifted. Specifically, San Joaquin River inflow decreased as a fraction of total inflow around 2000, while Sacramento River increased (Figure 7-12). Finally, there was an increase in the duration of the operation of barriers placed into south Delta channels during some months. These changes may have contributed to a shift in Delta hydrodynamics that increased fish entrainment.

These observations led to a hypothesis that the hydrodynamic change could be indexed using net flows through Old and Middle rivers (Figure 7-13), which integrate changes in inflow, exports, and barrier operations (Arthur et al. 1996; Monsen et al. 2007). Net or residual flow refers to the calculated flow when the effects of the tide are mathematically removed. An initial analysis revealed that there was a significant inverse relationship between net Old and Middle rivers flow and winter salvage of delta smelt at the SWP and CVP (P. Smith, unpublished). These analyses were subsequently updated and extended to other pelagic fishes (Figure 7-14, L. Grimaldo, in preparation). The general pattern is that POD species salvage is low when Old and Middle river flows are positive.

The hydrologic and statistical analyses suggest a reasonable mechanism by which winter entrainment increased during the POD years; however, the direct population-level effects of increased entrainment are less clear. As part of the POD investigation, Manly and Chotkowki (IEP 2005; Manly and Chotkowski 2006) used log-linear modeling to evaluate environmental factors that may have affected long-term trends in the Fall Midwater Trawl abundance index of delta smelt. They found that monthly or semi-monthly measures of exports or Old and Middle rivers flow had a statistically significant effect on delta smelt abundance; however, individually they explained a small portion (no more than a few percent) of the variability in the fall abundance index of delta smelt across the entire survey area and time period. Hence, there are other factors that dominate the relationship between exports and delta smelt fall abundance. Similarly, Kimmerer et al. (2001) estimated that entrainment losses of young striped bass were sometimes very high (up to 99%), but they did not find evidence that entrainment losses were a major driver of long-term striped bass population dynamics.

These results do not mean, however, that direct export effects can be dismissed as a contributing cause of the POD. There are two aspects of entrainment that explicitly were not addressed by Manly and Chotkowski (2006) and are not well understood: (1) the possibility that selective entrainment among a heterogeneous population of prespawning adults could produce consequences that do not become manifest until the following year (discussed in the next paragraph), and (2) larval entrainment. Very little is known about historical larval entrainment because larvae are not sampled effectively at the fish screening facilities. To address this shortcoming, Kimmerer and Nobriga (in press) coupled a particle tracking modeling with survey results to estimate larval entrainment. Kimmerer (in press) used data from several IEP monitoring programs to estimate entrainment of delta smelt. These approaches suggest that larval delta smelt entrainment losses could exceed 50% of the population under low flow and high export conditions. Because there are few reliable larval entrainment data, it is not possible to directly address the question of how important these losses were historically.

It has been proposed that losses of larger females and their larvae may have a disproportionate effect on the delta smelt population (B. Bennett, unpublished data). Bennett (unpublished data) proposes that larger females spawn earlier in the season and produce more eggs, which are of better quality, and survivability, as has been noted for Atlantic cod and other commercially harvested species (Marteinsdottir and Steinarsson 1998; Swain et al. 2007). As a consequence, winter and early spring exports, which have continually increased as described above (Figure 7-15), could have an important effect on reproductive success of early spawning female delta smelt. Bennett hypothesizes that the observed reduction in the mean size of adult delta smelt in the early 1990s (Sweetnam 1999) is a result of selective losses of earlier spawning adults and their larvae, thereby selecting for later spawned offspring (that have less time to reach maturity). Under this hypothesis, the most important result of the loss of early spawning females would manifest itself in the year following the loss, and would therefore not necessarily be detected by analyses relating fall abundance indices to same-year (or same-water year) predictors. This hypothesis is presently being evaluated by Bennett’s laboratory using otolith methods.

The CVP and SWP export operations are most likely to impact adult delta smelt during their upstream spawning migration between December and April. A significant negative correlation between November-February delta smelt salvage and the residuals from a FMWT index at year one vs. FMWT index at year two stock-recruit relationship is evidence for an influence of adult entrainment on delta smelt population dynamics (Brown and Kimmerer 2001). Delta smelt spawn over a wide area (much of the delta and some areas downstream). In some years a fairly large proportion of the population seems to spawn in or be rapidly transported to the central and southern delta. Presumably, entrainment vulnerability is higher during those years. Unfortunately, it is not currently known what cues decisions about where to spawn.

The CVP and SWP water operations are not thought to have any impact on delta smelt eggs because they remain attached to substrates. Shortly after hatching, larvae are vulnerable to entrainment at all points of diversion, but, as mentioned earlier, are not counted in SWP or CVP fish salvage operations. Juvenile delta smelt also are vulnerable to entrainment and are counted in salvage operations once they reach 20-25 mm in length. Most juvenile salvage occurs from April-July with a peak in May-June (Nobriga et al. 2001).

Salvage of delta smelt population has historically been greatest in drier years when a high proportion of YOY rear in the delta (Moyle et al. 1992; Reclamation and DWR 1994; Sommer et al. 1997; Figure 7-6). In recent years however, salvage also has been high in moderately wet conditions (Nobriga et al. 2000; 2001; springs of 1996, 1999, and 2000) even though a large fraction of the population was downstream of the Sacramento-San Joaquin River confluence. Nobriga et al. (2000; 2001) attributed recent high wet year salvage to a change in operations for the VAMP that began in 1996. The VAMP provides a San Joaquin River pulse flow from mid-April to mid-May each year that probably improves rearing conditions for delta smelt larvae and also slows the entrainment of fish rearing in the delta. The high salvage events may have resulted from smelt that historically would have been entrained as larvae and therefore not counted at the fish salvage facilities growing to a salvageable size before being entrained. However, a more recent analysis summarized in Figure 7-6 provides an alternative explanation. Delta smelt salvage in 1996, 1999, and 2000 was not outside of the expected historical range when three factors are taken into account, (1) delta smelt distribution as indexed by X2 position, (2) delta smelt abundance as indexed by the Townet Survey (TNS), and (3) the amount of water exported. Therefore, it is uncertain that operations changes for VAMP have influenced delta smelt salvage dynamics as strongly as suggested by Nobriga et al. (2000). Nonetheless, it is likely that actual entrainment has decreased since the initiation of the VAMP because of the improved transport flows it provides. In addition, “assets” from CALFED’s Environmental Water Account (EWA) are often used during this time of year to further reduce delta smelt entrainment. Although the population level benefits of these actions are unknown, they appear to have been successful at keeping delta smelt salvage under the limits set by FWS (1993) (Brown and Kimmerer 2002).

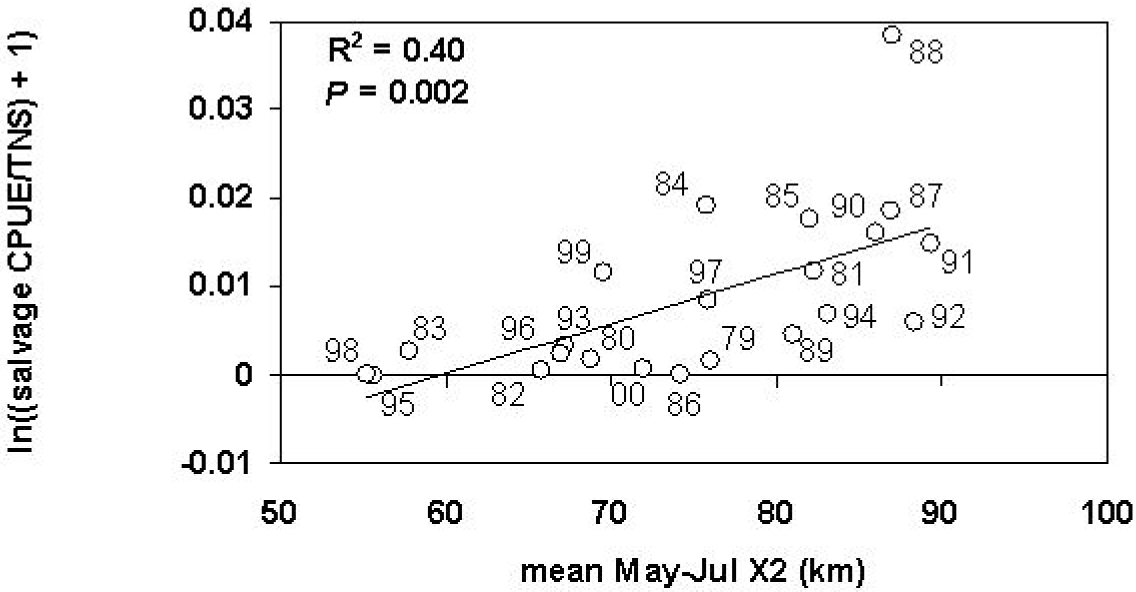

Figure 17-2 Water operations impacts to the delta smelt population.

Another possible effect on delta smelt entrainment is the SDTB. The SDTB are put in place during spring and removed again each fall (see the "Project Description" section of this Biological Assessment for more detail). Computer simulations have shown that placement of the barriers changes south delta hydrodynamics, increasing central delta flows toward the export facilities (DWR 2000). When delta smelt occur in areas influenced by the barriers, entrainment losses could increase.

Predation Effects

Predator-prey dynamics in the San Francisco Estuary are poorly understood, but are currently receiving considerable research attention by the IEP as part of the POD investigation. Studies during the early 1960s found delta smelt were an occasional prey fish for striped bass, black crappie and white catfish (Turner and Kelley 1966). This, coupled with the substantial decline in striped bass abundance has been taken as evidence that delta smelt are not very vulnerable to predation (Sweetnam and Stevens 1993). In recent years, it has become clear that the prey choices of piscivorous fishes switch as the relative abundances of species in the prey field change (Buckel et al. 1999). Even in the 1960s, delta smelt was rare relative to the dominant prey fishes of striped bass (age-zero striped bass and threadfin shad) (Turner and Kelley 1966). Therefore, there should have been no expectation that delta smelt would be commonly found in stomach contents samples. Because delta smelt are still rare relative to currently common prey fishes, the same holds true today (Nobriga et al. 2003). Because of the limitations of using stomach samples, IEP researchers are attempting to model potential impacts of striped bass on delta smelt using bioenergetics and individual-based approaches.

Bennett and Moyle (1996) proposed that inland silverside may be impacting delta smelt through predation (on delta smelt eggs and/or larvae) and competition (for copepod prey). This hypothesis is supported by recent statistical analyses showing negative correlations between inland silverside abundance and delta smelt TNS indices, and two indices of egg and/or larval survival (Brown and Kimmerer 2001). The hypothesis also is consistent with the analysis by

Kimmerer (2002) showing a change in the sign of the delta smelt X2-TNS relationship (described above) because inland silversides began to increase in abundance about the same time the relationship changed sign (Brown and Kimmerer 2001). It should be noted however that since the early 1980s, there also have been increases in other potential larval fish predators such as coded wire tagged Chinook salmon smolts released in the Delta for survival experiments (Brandes and McLain 2001) and centrarchid fishes (Nobriga and Chotkowski 2000). In addition, striped bass appear to have switched to piscivorous feeding habits at smaller sizes than they historically did following severe declines in the abundance of mysid shrimp (Feyrer et al. in press). We suspect that CWT salmon and centrarchid abundance, as well as the striped bass diet switch have covaried with the increase in inland silverside abundance and the declines in phytoplankton and zooplankton abundance mentioned above.

One hypothesis arising from the POD investigation holds that predation effects on delta smelt and other POD species have increased in all water year types as a result of increased populations of pelagic and inshore piscivores. In the pelagic habitat, age-1 and age-2 striped bass appear to have declined more slowly than age-0 striped bass (compare Figure 7-6 with Figure 7-16, CDFG, unpublished data). Adult striped bass abundance increased in the latter 1990s (Figure 7-17) so high striped bass predation pressure on smaller pelagic fishes in recent years is probable. Further, largemouth bass abundance has increased in the Delta over the past few decades (Brown and Michniuk 2007). While largemouth bass are not pelagic, their presence at the boundary between the littoral and pelagic zones makes it probable that they do opportunistically consume pelagic fishes. Analyses of fish salvage data show this increase occurred somewhat abruptly in the early 1990s and has been sustained since (Figure 7-18). The increase in salvage of largemouth bass occurred during the time period when *E. densa*, an introduced aquatic macrophyte was expanding its range in the Delta (Brown and Michniuk 2007). The habitat provided by beds of *E. densa* provide good habitat for largemouth bass and other species of centrarchids. Thus, the increased abundance of this introduced predator was likely caused by an increase in an introduced plant, which provided favorable habitat. The areal coverage of *E. densa* in the Delta continued to expand by more than 10% per year from 2004 to 2006, by infesting a greater portion of channels and invasion of new habitat (E. Hestir et al., U.C. Davis, unpublished data). This suggests that populations of largemouth bass and other species using submerged aquatic vegetation will continue to increase. Although none of the IEP surveys adequately tracks largemouth bass population trends, the Delta has become the top sport fishing destination in North American for largemouth bass, which illustrates the recent success of this species. Each year, lucrative fishing tournaments are held in the Delta to take advantage of the large number of trophy-sized bass in the region. Largemouth bass have a much more limited distribution in the estuary than striped bass, but a higher per capita impact on small fishes (Nobriga and Feyrer 2007). Increases in largemouth bass may have had a particularly important effect on threadfin shad and striped bass, whose earlier life stages occur in littoral habitat (Grimaldo et al. 2004; Nobriga and Feyrer 2007).

A change in predation pressure may, in part, be an effect of interactions between biotic and abiotic conditions. Natural, co-evolved piscivore-prey systems typically have an abiotic production phase and a biotic reduction phase each year (e.g., Rodriguez and Lewis 1994). Changing the magnitudes and durations of these cycles greatly alters their outcomes (e.g., Meffe 1984). Generally, the relative stability of the physical environment affects the length of time each phase dominates and thus, the importance of each. Biotic interactions like predation will have stronger community-structuring influence in physically stable systems (e.g., lakes). Historically in the estuary, the period of winter-spring high flow was the abiotic production phase, when most species reproduced. The biotic reduction phase probably encompassed the low-flow periods in summer-fall. Multi-year wet cycles probably increased (and still do) the overall 'abiotic-ness' of the estuary, allowing populations to increase. Drought cycles likely increased the estuary's 'biotic-ness' (e.g., Livingston et al. 1997), with low reproductive output and increased effect of predation on population abundance. Our managed system has reduced flow variation much of the time and in some locations more than others. This has probably affected the magnitudes and durations of abiotic and biotic phases (e.g., Nobriga et al. 2005). In other words, reduced flow variability in the estuary may have exacerbated predation effects. However, there is no clear evidence that such changes have been abrupt enough to account for the POD.

Agricultural Diversions

There are 2,209 agricultural diversions in the Delta and an additional 366 diversions in Suisun Marsh used for enhancement of waterfowl habitat (Herren and Kawasaki 2001). The vast majority of these diversions do not have fish screens to protect fish from entrainment. It has been recognized for many years that delta smelt are entrained in these diversions (Hallock and Van Woert 1959; Pickard et al. 1982). In the early 1980s delta smelt were the most abundant fish entrained in the Roaring River diversion in Suisun Marsh (Pickard et al. 1982), so it is possible the waterfowl diversions are detrimental. However, delta smelt may not be especially vulnerable to Delta agricultural diversions for several reasons. First, adult delta smelt move into the Delta to spawn during winter-early spring when agricultural diversion operations are at a minimum. Second, larval delta smelt occur transiently in most of the Delta. Third, Nobriga et al. (2002; in press) examined delta smelt entrainment at an agricultural diversion in Horseshoe Bend during July 2000 and 2001, when much of the YOY population was rearing within one tidal excursion of the diversion. Delta smelt entrainment was low compared to density estimates from the DFG 20 mm Delta Smelt Survey. Low entrainment was attributed to (1) offshore distribution of delta smelt, and (2) the extremely small hydrodynamic influence of the diversion relative to the channel it was in. Because Delta agricultural diversions are typically close to shore and probably take small amounts of water relative to what is in the channels they draw water from, delta smelt vulnerability may be low despite their modest swimming ability and their poor performance near simulated fish screens in laboratory settings (Swanson et al. 1998; 2002). It should be noted however that DWR screened five agricultural diversions around Sherman Island, an area consistently used by delta smelt of all life stages.

Antioch and Pittsburgh Power Plants

PG&E operates two power generation facilities within the range of delta smelt: Contra Costa Power Plant and Pittsburg Power Plant. Contra Costa Power Plant is about six miles east of the confluence of the Sacramento and San Joaquin rivers. Pittsburg Power Plant is on the south shore of Suisun Bay, in the town of Pittsburg. Each power plant has seven generating units that rely on diverted water for condenser cooling. Cooling water is diverted at a rate as high as about 1,500 cfs for the Contra Costa plant and 1,600 cfs for the Pittsburg plant, forming a thermal plume as it is discharged back into the estuary. Pumping rates are often significantly lower under normal operation. Potential impacts of the power plants fall into two categories - direct and indirect. Previous data on direct and indirect impacts of the power plants were summarized by Reclamation and DWR (1994). However, robust data analyses of population level effects of power plant operation on delta smelt and other fishes have not been performed. Briefly, the direct impact of the power plants comes from the removal of fish during diversion operations. Indirect effects stem from water temperature increases when the cooling water is returned to the estuary. Intakes at all units at both power plants employ a screening system to remove debris, but the screens allow entrainment of fish smaller than about 38 mm and impingement of larger fish.

Since the 1978–79 studies were completed, PG&E has implemented a resource management program to reduce striped bass loss. During the period of peak striped bass entrainment (May to mid-July), power generation units are operated preferentially, using fish monitoring data. This program has reduced entrainment losses of larval and juvenile striped bass by more than 75 percent (PG&E 1992a). Given its timing, this management program also may be beneficial to delta smelt.

In recent years, the plants have been operated only in a “peaking” capacity, and kept in a standby state when regional power consumption is not high. However, although they may not be routinely operated, the plants are most likely to be called into use during the summer, at a time when delta smelt are potentially close to the intake and discharge points, and thus vulnerable to entrainment and other adverse effects.

Bottom-Up Effects

The quality and availability of food may have important effects on the abundance and distribution of delta smelt. Food quality and availability have been highly historically variable, largely because of the lamentable history of exotic species introduction into the Estuary. In this section recent elements of that story are presented to develop the theme of dependency between delta smelt and its trophic support. Because a large part of this discussion has evolved only in the last few years as a result of the POD investigation, this account borrows heavily from the POD work.

Interconnected Recent Changes in Plankton and Benthos

Estuaries are commonly characterized as highly-productive nursery areas for a suite of organisms. Nixon (1988) noted that there actually is a broad continuum of primary productivity levels in different estuaries, which in turn affects fish yield. Compared to other estuaries, pelagic primary productivity in the upper San Francisco estuary is poor and a low fish yield is expected (Figure 7-19). Moreover, there has been a significant long-term decline in phytoplankton biomass (chlorophyll a) and primary productivity to very low levels in the Suisun Bay region and the lower Delta (Jassby et al 2002). Hence, low and declining primary productivity in the estuary is likely a principal cause for the long-term pattern of relatively low and declining biomass of pelagic fishes.

A major reason for the long-term phytoplankton reduction in the upper estuary is filter-feeding by the overbite clam (*Corbula amurensis*), which became abundant by the late 1980s (Kimmerer 2002). The overbite clam was first reported from San Francisco Estuary in 1986 and it was well established by 1987 (Carlton et al. 1990). Prior to the overbite clam invasion, there were periods of relatively low clam biomass in the upper estuary because the Asiatic freshwater clam (*Corbicula fluminea*) colonized Suisun Bay during high flow periods and the native marine clam *Mya arenaria* (also known as *Macoma balthica*) colonized Suisun Bay during prolonged (> 14 month) low flow periods (Nichols et al. 1990). Thus, there were periods of relatively low clam grazing rates while one species was dying back and the other was colonizing. The overbite clam invasion changed this formerly dynamic clam assemblage because the overbite clam, which is tolerant of a wide range of salinity, is now always the dominant clam species in the brackish water regions of the estuary and its grazing influence extends into the Delta (Kimmerer and Orsi 1996; Jassby et al. 2002) beyond the clam's typical range, presumably due to tidal dispersion of phytoplankton-depleted water.

According to recent research, shifts in nutrient concentrations may also contribute to the phytoplankton reduction as well as to changes in algal species composition in the San Francisco Estuary. While phytoplankton production in the San Francisco Estuary is generally considered light limited and nutrient concentrations exceed production limiting levels, nutrients may affect production during times when light conditions are more favorable and also affect species composition. Dugdale et al (2007) and Wilkerson et al (2006) found that high ammonium concentrations prevented the formation of diatom blooms but stimulated flagellate blooms in the lower estuary. Ammonium concentrations in the Delta and Suisun Bay have significantly increased over the last few decades due to increased loading from sewage treatment plants (Jassby, in press, Mueller-Solger, in prep.). Van Nieuwenhuyse (2007), on the other hand, found that a rapid reduction in wastewater total phosphorus loads in the mid-1990s coincided with a similarly rapid drop in phytoplankton biomass at three stations in the upper estuary.

Starting in the late 1980s, a series of major changes was observed in the estuarine food web that negatively influenced pelagic fish (including delta smelt) production. Major step-declines were observed in the abundance of phytoplankton (Alpine and Cloern 1992) and the copepod Eurytemora affinis due to grazing by the clam (Kimmerer et al. 1994). Northern anchovy abandoned the estuary's low salinity zone coincident with the overbite clam invasion, presumably because the sharp decline in planktonic food items made occupation of low-salinity waters unprofitable for this marine fish (Kimmerer 2006). There was also a major step-decline in mysid shrimp in 1987-1988, presumably due to competition with the clam for phytoplankton (Orsi and Mecum 1996). The mysid shrimp had been an extremely important food item for larger fishes like longfin smelt and juvenile striped bass; its decline resulted in substantial changes in the diet composition of these and other fishes (Feyrer et al. 2003). As described above, the population responses of longfin smelt and juvenile striped bass to winter-spring outflows changed after the overbite clam invasion. Longfin smelt relative abundance was lower per unit outflow post-clam (Kimmerer 2002b). Young striped bass relative abundance stopped responding to outflow altogether (Sommer et al. 2007). One hypothesis to explain these changes in fish population dynamics is that lower prey abundance reduced the system carrying capacity (Kimmerer et al. 2000; Sommer et al. 2007).

Several recent studies have shown that pelagic consumer production is limited by low phytoplankton productivity in the San Francisco Estuary (Sobczak et al. 2002, 2004; Mueller-Solger et al. 2002). However, in contrast to the substantial long-term declines in phytoplankton biomass and productivity (Jassby et al. 2002), phytoplankton trends for the most recent decade (1996-2005) are actually positive in the Delta and neutral in Suisun Bay (Jassby, in press). While this does not support the hypothesis that changes in phytoplankton quantity are responsible for the recent declines of delta smelt and other pelagic fishes, phytoplankton may nevertheless play a role via changes in species composition, as will be discussed in the food quality section below.

A notable finding for the POD is that *Pseudodiaptomus forbesi*, a calanoid copepod that has replaced *Eurytemora affinis* as the most common delta smelt prey during summer, continued to decline in the Suisun Marsh and confluence regions from 1995 to 2004, while its numbers increased in the southern Delta (Figure 7-20; Kimmerer et al. in prep., Mueller-Solger et al. in prep.). Although substantial uncertainties about mechanisms remain, this trend may be related to increasing recruitment failure and mortality in Suisun Bay and the western Delta due to competition and predation by the overbite clam, contaminant exposures, and entrainment of source populations in the Delta (Durand et al. in prep., Mueller-Solger et al. 2006). For example, overbite clam abundance and distribution in the Suisun Bay and the western Delta during 2001-2004 was greater than during the 1995-1999 wet period, but similar to abundance indices and distribution patterns during the 1987-1992 drought (IEP 2005, Peterson et al. in prep.). Further, in the two most recent years (2005 and especially 2006), *P. forbesi* has started to rebound substantially in the western Delta (Figure 7-21, Mueller-Solger et al. in prep., Jassby et al. in prep.).

There is also interest in a more recent invader, the cyclopoid copepod *Limnoithona tetraspina*, which significantly increased in the Suisun Bay region beginning in the mid-1990s. It is now the most abundant copepod species in the low-salinity zone (Bouley and Kimmerer 2006). It has been hypothesized that *L. tetraspina* is an inferior food for pelagic fishes including delta smelt because of its small size, generally sedentary behavior, and ability to detect and avoid predators (Bouley and Kimmerer 2006). Experimental studies addressing this issue are ongoing (Sullivan et al., unpublished). *Acartiella sinensis*, a calanoid copepod species that invaded at the same time as L. tetraspina, also reached considerable densities in Suisun Bay and the western Delta over the last decade. Its suitability as food for pelagic fish species remains unclear, but is also being investigated (Sullivan et al., unpublished).

Preliminary information from studies on pelagic fish growth, condition and histology provide additional evidence for food limitation in pelagic fishes in the estuary (IEP 2005). In 1999 and 2004, residual delta smelt growth was low from the Sacramento-San Joaquin confluence through Suisun Bay relative to other parts of the system. Delta smelt collected in 2005 from the Sacramento-San Joaquin confluence and Suisun Bay also had high incidence of liver glycogen depletion, a possible indicator of food limitation. Similarly, during 2003 and 2004 striped bass condition factor decreased in a seaward direction from the Delta through Suisun Bay.

Thus far, there is little evidence that the unusually poor growth rates, health, and condition of fishes from Suisun Bay and western Delta are due directly to the effects of toxic contaminants or other adverse chemical or physical habitat conditions. Therefore, our working hypothesis is that the poor fish growth and condition in the upper estuary are due to food limitation. Note, however that contaminant episodes may be contributing to poor phytoplankton growth (Dugdale et al. 2007) and invertebrate mortality (Werner unpublished data), which could exacerbate food limitation. If fishes are food limited in Suisun Bay and west Delta during larval and/or juvenile development, then we would expect greater cumulative predation mortality, higher disease incidence, and consequently low abundance indices at later times.

Fish Co-Occurrence with Food

The above patterns in fish food have generally been described at rather broad scales. Recently, interest has focused on determining patterns of co-occurrence of fish predators, particularly delta smelt, and their zooplankton prey. The assumption is that predators should co-occur with their prey. This idea was first explored by Nobriga (2002) who showed that delta smelt larvae with food in their guts typically co-occurred with higher calanoid copepod densities than larvae with empty guts. Recently, Kimmerer (in press), Miller and Mongan (unpublished data), and Mueller-Solger (unpublished data) used similar approaches to look at potential co-occurrence of delta smelt and their prey and its effects on survival. Kimmerer (in press) showed that there was a positive relationship between delta smelt survival from summer to fall and zooplankton biomass in the low-salinity region of the estuary (Figure 7-22). Miller and Mongan (unpublished data) have concluded that April and July co-occurrence is a strong predictor of juvenile delta smelt survival. Mueller-Solger (unpublished data) defined delta smelt habitat based on the environmental quality results of Nobriga et al. (in press) and prey spectrum more broadly (as all copepods) compared to Miller and Mongan (unpublished data) and found no long-term decline in the total biomass of copepods potentially available for consumption by delta smelt in midsummer, although species composition has changed considerably (Figure 7-21).

There are two shortcomings of co-occurrence analyses like those described above. First, it is difficult to characterize fish prey suitability. For instance, *E. affinis* and *P. forbesi* are generally believed to be “preferred” prey items for delta smelt (Nobriga 2002; Miller and Mongan unpublished). However, diet data show that delta smelt will actually feed on a wide variety of prey (Lott 1998; S. Slater, California Department of Fish and Game, unpublished; Figure 7-23). Thus, the question of prey co-occurrence involves questions of prey catchability (e.g., Meng and Orsi 1991) and profitability (energy per item consumed and nutritional quality of individual prey items). For example, *L. tetraspina* has a large biomass in the system but individual *L. tetraspina* are smaller and possibly more evasive than the larger calanoid copepods. The energy needed by an individual delta smelt to harvest a similar biomass of *L. tetraspina* compared to the energy needed to harvest a larger species could be very different, as suggested by optimal foraging theory (e.g., Stephens and Krebs 1986). Another major limitation of co-occurrence analyses is that IEP sampling programs sample fish and zooplankton at larger spatial and temporal scales than those at which predator-prey interactions occur. Both fish and copepods are likely to be patchy and the long tows required to collect sufficient numbers of organisms for counting would homogenize such patch structure. Moreover, it is unlikely that the (monthly or even twice monthly) “snapshot” of fish and prey co-occurrence in specific locations or even small regions provided by the IEP surveys is representative of feeding conditions actually experienced by fish on an hourly or daily basis.

The weight of evidence strongly supports bottom-up food limitation as a factor influencing longterm fish trends in the upper estuary. However, the bottom-up hypothesis is unlikely as a single mechanism for the recent pelagic organism declines. Specifically, it is unclear why there has been a substantial recent decline in some Suisun Bay and western Delta calanoid copepod species, but not in phytoplankton chlorophyll a concentration. Also, calanoid copepod densities (especially *P. forbesi*) rebounded substantially in 2006 (Mueller-Solger, unpublished data) while the POD fish abundance indices (especially for delta smelt) remained low. Second, recent *C. amurensis* levels are not unprecedented; they are similar to those found during the 1987-92 drought years, so it is unclear if and why benthic grazing would have a greater effect on the Suisun Bay food web during the POD years than during the earlier drought years. Finally, it is possible that the hypothesis that the San Francisco Estuary is driven by phytoplankton production rather than through detrital pathways (Sobczak et al. 2002, 2004; Mueller-Solger et al. 2002) may have been accepted too strictly. Many zooplankton are omnivorous and can consume microbes utilizing dissolved and particulate organic carbon. This has recently been demonstrated for several zooplankton species in the San Francisco Estuary (Gifford et al. 2007 and references therein). Thus, shifts in availability of phytoplankton and microbial food resources for zooplankton might favor different species. It is possible that a better understanding of shifts in phytoplankton and zooplankton community composition and perhaps related changes in the microbial food web in the Suisun Bay region could explain these apparent inconsistencies.

Food Quality

Studies on food quality have been relatively limited in the San Francisco Estuary, with even less information on long-term trends. However, food quality may be another limiting factor for pelagic zooplankton and their fish predators, including delta smelt.

At the base of the pelagic food web, food quality for consumers is determined by the relative contributions of different phytoplankton and microbial species and detritus to the overall organic particle pool available to primary consumers. For example, diatoms and cryptophytes are thought to be of good food quality for zooplankton, while the nutritional value of cyanobacteria such as *Microcystis aeruginosa* can be very low (Brett and Müller-Navarra 1997), particularly for toxic varieties (Rohrlack et al. 2005). Lehman (1996, 2000) showed shifts in phytoplankton species composition in the San Francisco Estuary from diatom dominated to more flagellate dominated communities. Mueller-Solger et al. (2006) found that in recent years, diatoms were most abundant in the southern San Joaquin River region of the Delta, and Lehman (2007) found greater diatom and green algal contributions upstream and greater flagellate biomass downstream along the San Joaquin River. To date, the *M. aeruginosa* blooms have occurred most intensively in the central Delta, thus POD species that utilize the central Delta such as threadfin shad, striped bass, and the poorly monitored centrarchid populations (largemouth bass and sunfish) would be most likely to suffer any direct adverse effects of these blooms.

In 2007, the *M. aeruginosa* bloom year was the worst on record in the Delta (P. Lehman, in prep.). The highest cell densities were observed near Antioch, i.e. considerably west of the previous center of distribution, and may thus have affected invertebrates and fishes in the confluence and Suisun Bay regions of the upper estuary. In general, phytoplankton carbon rather than the much more abundant detrital carbon are thought to fuel the food web in the San Francisco Estuary (Mueller-Solger et al. 2002; Sobczak et al. 2002, 2004); however, that does not mean the detrital pathways are not significant because many zooplankton are omnivorous and capable of utilizing both pathways. For example, Rollwagen- Bollens and Penry (2003) observed that while heterotrophic ciliates and flagellates were the dominant prey of *Acartia* spp. in the bays of the San Francisco Estuary, diatoms and autotrophic ciliates and flagellates also formed an important part of their diet during phytoplankton blooms. Calanoid copepod and cladoceran growth and egg production may often be limited by low levels of phytoplankton biomass. This appears to be true even for omnivorous calanoids such as *Acartia* spp. Kimmerer et al (2005) found a significant relationship between *Acartia* spp. egg production and chlorophyll a concentration in the San Francisco Estuary, suggesting that *Acartia* spp. likely also derived a large part of carbon and energy from phytoplankton. Bouley and Kimmerer (2006), on the other hand, reported that egg production rates of the cyclopoid copepod *L. tetraspina* were unrelated to chlorophyll a concentrations in the low salinity region of the San Francisco Estuary. *L. tetraspina* digestion rates were highest for ciliates, perhaps suggesting a greater importance of the detrital carbon pathway for this species.

In a study focusing on the nutrition and food quality of the calanoid copepods *E. affinis* and *P. forbesi*, Mueller-Solger et al (2006) found evidence for “trophic upgrading” of essential fatty acids by *E. affinis* and *P. forbesi*, confirming their importance as high-quality food for fish. They also found that *E. affinis* gained the greatest nutritional benefits from varied food sources present in small tidal sloughs in Suisun Marsh. *P. forbesi*, on the other hand, thrived on riverine phytoplankton in the southern Delta, especially diatoms. Diatoms are likely also an important food source for other calanoid copepod species. The relative decrease in diatom contributions to the phytoplankton community in the central Delta and Suisun Bay (Lehman 1996, 2000) is thus a concern and may help explain the declines in *P. forbesi* and other calanoid copepods in these areas.

Mueller-Solger et al. (2006) concluded that areas rich in high-quality phytoplankton and other nutritious food sources such as the southern Delta and small tidal marsh sloughs may be critical “source areas” for important fish prey organisms such as *P. forbesi* and *E. affinis*. This is consistent with results by Durand et al. (unpublished data) who showed that transport from upstream was essential for maintaining the *P. forbesi* population in Suisun Bay. It is possible that the increase in *P. forbesi* densities in the western Delta in 2006 could be related to greater San Joaquin River flows during this wet year, which may have reduced entrainment of *P. forbesi* source populations in the Delta.

As noted in earlier sections, the dichotomy between phytoplankton and detrital/microbial energy pathways supporting zooplankton has probably been applied more stringently than is appropriate. Both are likely important, with the balance between them in specific areas of the estuary likely having affects on the success of particular zooplankton species. Additional research into the detrital pathway might be useful in understanding the factors controlling zooplankton populations, which are critical food resources for pelagic fishes.

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