Interagency Ecological Program
2010 Pelagic Organism Decline Work Plan
and
Synthesis of Results

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List of Acronyms

Acronym	Definition
BDCP	Bay-Delta Conservation Plan
BEM	bioenergetic modeling
CCF	Clifton Court Forebay
CDFG	California Department of Fish and Game
CESA	California Endangered Species Act

CPUE	catch per unit effort
CSTARS	Center for Spatial Technology and Remote Sensing
CVP	Central Valley Project
CVRWQCB	Central Valley Regional Water Quality Control Board
DDT	dichlorodiphenyltrichloroethane
DO	dissolved oxygen
DRERIP	Delta Regional Ecosystem Restoration Implementation Plan
DSP	Delta Science Program
DWR	California Department of Water Resources
E/I	export to inflow
EDC	endocrine disrupting compounds
EQ	environmental quality
FESA	Federal Endangered Species Act
FMWT	Fall Midwater Trawl
IEP	Interagency Ecology Program
LC	Lethal Concentration
NCEAS	National Center for Ecological Analysis and Synthesis
OMR	Old and Middle rivers
OP	organophosphate
PBDEs	polybrominated diphenyl ethers
PBO	piperonyl butoxide
PCBs	Polychlorinated biphenyl
PCR	polymerase chain reaction
POD	Pelagic Organism Decline
POD-MT	POD Management Team
SAV	submerged aquatic vegetation
SFF	State Skinner Fish Protective Facility
SL	Standard Length
SPMDS	semi-permeable membrane devices
SRWTP	Sacramento Regional Wastewater Treatment Plant
SWP	State Water Project
SWRCB	California State Water Resources Control Board
TFCF	federal Tracy Fish Collection Facility
TL	total length
TMDL	Total Maxium Daily Load
TNS	Summer Townet Survey
USBR	US Bureau of Reclamation
USGS	US Geological Survey
VAMP	Vernalis Adaptive Management Plan

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Executive Summary

Abundance indices for four pelagic fishes in the upper San Francisco Estuary (the Delta and Suisun Bay) rapidly declined to record low levels starting in 2002. These fishes include native delta smelt (listed under federal and California Endangered Species acts) and longfin smelt (listed under the State Endangered Species Act) as well as introduced threadfin shad and juvenile (age-0) striped bass. Three of these species have also experienced more gradual long-term declines, but the recent rapid collapse of all four species to persistently low levels was unexpected given the relatively moderate hydrological conditions in the first half of this decade. In 2005, the IEP formed a Pelagic Organism Decline Management Team (POD-MT) to evaluate the potential causes of the declines.

The POD-MT has developed several conceptual models to guide work plan development and synthesize results. In this report we update previously developed conceptual models with new results and introduce a new conceptual model:

1. The "basic POD conceptual model" was introduced in 2006 and groups the effects of potential drivers of the POD into four categories (*previous abundance, habitat, top-down effects*, and *bottom-up effects*);
2. "Species-specific conceptual models" were introduced in 2008 and show how key population drivers presently affect each of the four POD fish species in each season;
3. A new conceptual model posits that the POD represents a rapid ecological "regime shift" that followed a longer-term erosion of ecological resilience. We present this conceptual model as a working hypothesis for future investigations.

Much has been learned about individual drivers and their effects on the POD species over the course of the POD investigation. An initial "triage" approach seeking to rule out individual drivers was unsuccessful – we now have evidence that all investigated drivers may have played a role in the POD. As in previous reports, we summarize new evidence for the effects of individual drivers and some of their interactions in the context of the basic POD conceptual model.

Results of the POD investigation discussed in the report, organized by the four components of the basic POD conceptual model, include:

1. ***Previous abundance.*** IEP fish monitoring provides population indices, not actual population size estimates. This complicates evaluation of the effects of previous abundance, i.e. stock-recruitment relationships. The delta smelt stock-recruitment relationship appears to be density–independent, particularly since the late 1970s. The fall abundance index for pre-spawning adults explains about half of the variation in the juvenile abundance index for the next summer over the period from 1978 to present. The juvenile to adult transition is influenced by density-dependent mechanisms and declining carrying capacity, especially during the POD years. For longfin smelt, preliminary analyses support a stock-recruitment relationship between adults approaching their second birthday and age-0 fall recruits. A significant stage-recruitment relationship (fall age-0 to fall age-1 abundance) also exists. There is little evidence for strong stock-recruitment or stage-recruitment relationships for threadfin shad. The adult striped bass

stock is currently not particularly low and total stock size is not likely a mechanism contributing to recent very low age-0 striped bass abundance. However, the effective spawning stock may have decreased due to a decline in number of females relative to males in the spawning runs.

2. ***Habitat.*** Changes in habitat drivers affect the amount and suitability of habitat available to the POD fishes. Habitat changes not only affect pelagic fishes, but also their predators and prey, which, in turn, can also have effects on the habitat they occupy. Changes in habitat suitability appear to be important in the long term declines of all of the POD species, but particularly delta smelt and age-0 striped bass. Key drivers are decreasing turbidity and changes in the salinity field. While these changes negatively affect the POD fishes, they appear to benefit other organisms such as the invasive aquatic weed *Egeria densa* and harmful bloom-forming algae such as *Microcystis aeruginosa*. Toxic chemicals are more likely to cause chronic effects than acute effects in the POD fishes, except in long-lived striped bass. Large female adult striped bass can transfer bioaccumulated compounds to eggs with negative effects on survival of embryos and larvae. Increasing total ammonia concentrations and *Microcystis* blooms are more likely to have effects through the food web than via direct toxicity to fish (see Bottom-up). Pyrethroid toxicity to invertebrates and endocrine disrupting compounds are of increasing concern in the estuary.

3. ***Top-down.*** In the basic POD conceptual model, top-down effects refer to mortality from predation and entrainment into water diversions. Piscivorous predators in the Delta include native pikeminnows as well as introduced largemouth bass, striped bass, and Mississippi silversides. Striped bass prey on all four POD species. While increasing in abundance, largemouth bass primarily consume littoral, not pelagic prey. New genetic evidence suggests that Mississippi silversides prey on larval delta smelt. Decreasing turbidity may be increasing the vulnerability of pelagic prey to predators. Mortality associated with the State Water Project (SWP) and Central Valley Project (CVP) water diversions is well-documented in the San Francisco estuary. However, mortality estimates based on fish caught in fish screens at these diversions (salvage) are underestimates because small larval fish are not collected at all, other small fish are caught inefficiently, and entrainment-associated mortality that occurs before fish are collected in the screens (pre-screen loss) is not regularly assessed. Shifting of more exports to winter has been accompanied by increased salvage for POD species and other Delta fishes. However, the population-level effects of increased entrainment remain unclear and may vary greatly within and among years and between species. Greater net flow through Old and Middle Rivers toward the SWP and CVP diversions rather than seaward is associated with greater salvage of adult delta smelt, longfin smelt, and striped bass. Overall, entrainment can affect multiple life stages of the POD fishes and often interacts with other drivers affecting the behavior and spawning success of the POD fishes.

4. ***Bottom-up.*** Compared to other estuaries, phytoplankton primary productivity in the San Francisco estuary is low and has experienced a long-term decline. The long-term decline has been linked to grazing by invasive clams and to shifts in nutrient ratios and

> concentrations, especially increasing ammonium concentrations. It has led to a decline in overall food availability for pelagic fishes. In addition, there have been substantial changes in phytoplankton and zooplankton community composition which led to changes in food quality. The now common cyanobacteria *Microcystis aeruginosa* are of particularly low nutritional quality for Delta zooplankton species, while nutritionally valuable diatoms have declined. Similarly, a nutritionally inferior, small copepod species is now the dominant zooplankton species in Suisun Bay and the western Delta. Overall, bottom-up food limitation is likely an important driver influencing long-term fish trends in the upper estuary. However, it is likely not the sole driver behind the recent POD decline for several reasons. First, phytoplankton and zooplankton declines preceded the POD. Second, while high, current clam abundance and biomass is not unprecedented. Finally, while phytoplankton production fuels the Delta food web, new research shows that many zooplankton species currently present in the estuary are omnivorous and can consume microbes utilizing dissolved and particulate organic carbon. Shifts in community composition at the base of the food web may be as important as declines in overall productivity, or perhaps even more important. The current composition may favor non-native over native consumers.

The emerging conclusion is that the POD was caused by multiple and often interacting drivers. The multi-driver origin of the POD is an important insight. However, it is not particularly helpful to policy makers and managers seeking guidance for management strategies aimed at reversing the POD declines. The POD-MT has thus used two other approaches to evaluating drivers.

The first approach focuses on how the major drivers differ for each of the four POD fish species, and how they differ in relative importance during different life history stages or seasons. The results are summarized in the species-specific conceptual models and may help policy makers and managers identify targeted management actions and guide further research studies for individual POD species.

The second approach seeks to understand the POD in the context of an ecological “regime shift” affecting the entire estuarine ecosystem and explores the effects of changing drivers through several historical periods leading up to the POD. In this conceptual model, drivers are distinguished based on their approximate rate of change and their importance to ecological resilience. We hypothesize that drivers that changed slowly over decades (“slow drivers”) contributed to the slow erosion of ecological resilience of the system. This made the system more vulnerable to the effects of drivers that changed more rapidly around the time of the POD (see basic POD conceptual model) and/or have greater species specificity (see species-specific conceptual models). In order of their hypothesized importance to the resilience of the system and approximate rate of change, the slow drivers we propose for the POD regime shift are 1) outflow, 2) salinity, 3) landscape, 4) temperature, 5) turbidity, 6) nutrients, 7) contaminants, 8) harvest. In this report, we summarize changes in these environmental drivers and provide hypotheses about their individual and combined effects on the biota and importance to ecological resilience and the POD regime. We also briefly mention other potential slow drivers. Finally, we describe the resulting new ecosystem regime for the pelagic, benthic, and littoral zones of the Delta and Suisun Bay regions. As it becomes more fully developed, the POD regime shift story may inform adaptive management strategies aimed at shifting the ecosystem into a more desirable state and improving long-term ecosystem resilience and adaptive capacity in the face of future threats.

The number of peer-reviewed POD publications has increased rapidly since 2005. However, many studies that will provide important POD information are still in progress. The 2010 POD work plan includes 39 continuing study elements and 32 new elements. The 2010 POD program is funded by DWR, USBR, and SWRCB (approximately $7,547,000). POD-related Delta (previously CALFED) Science Program grants are estimated at $3,019,000. We provide some preliminary results from these studies, but peer-reviewed products may not be available for some time. This report considers available information through about August 2010. We intend to publish a fully peer reviewed, final POD synthesis report in 2012–2013.

Introduction

The San Francisco Estuary (Figure 1) has been an area of importance to humans starting with Native Americans and continuing to the present day. Beginning with the California Gold Rush in the mid-1800s and subsequent rapid population growth, exploitation of resources broadened and accelerated. The resulting changes in land use from natural landscapes to agriculture and urbanization combined with development of an extensive water management infrastructure have been accompanied by declines in nearly all species of native fish (Moyle 2002; Brown and Moyle 2005). The construction and operation of two large water projects, the federal Central Valley Project (CVP), and the State Water Project (SWP) have been especially important. Mitigation for the potential effects of these projects on important fisheries has included salmon hatcheries below some dams and extensive fish screening facilities at the pumping plants in the Delta (Brown et al. 1996). Despite these efforts, populations of important fish species have declined in the San Francisco Estuary and its watershed, culminating in listings, under the Federal and California Endangered Species Acts (FESA and CESA), of a growing number of species since the 1990s, including winter-run and spring-run Chinook salmon *Oncorhynchus tshawytscha*, Central Valley steelhead *O. mykiss*, delta smelt *Hypomesus transpacificus*, Sacramento splittail *Pogonichthys macrolepidotus* (subsequently removed from listed status, but currently undergoing another status review), longfin smelt *Spirinchus thaleichthys* (only under CESA) and green sturgeon *Acipenser medirostris*. The petition to list the San Francisco Estuary longfin smelt population as a distinct population segment under FESA was denied, but a range-wide status review was initiated.

The four primary pelagic fishes of the upper estuary (delta smelt, longfin smelt, age-0 striped bass *Morone saxatilis*, threadfin shad *Dorosoma petenense*), have shown substantial variability in their populations, with evidence of long-term declines for the first three of these species (Kimmerer et al. 2000, Bennett 2005, Rosenfeld and Baxter 2007, Thomson et al. 2010). Against this backdrop of long-term decline, Fall Midwater Trawl (FMWT) abundance indices for these four pelagic fishes (Figure 2) appeared to decline sharply around 2000, despite hydrology expected to support at least modest fish production based on previous relationships (Sommer et al. 2007). Subsequent statistical analyses have supported the existence of “changepoints” in the early 2000s (Thomson et al. 2010). These species have remained at low levels through 2009 with record low values for delta smelt in 2009, age-0 striped bass in 2004, longfin smelt in 2007, and threadfin shad in 2009. These declines are collectively known as the Pelagic Organism Decline (POD). The POD is now a major policy and management issue in the context of California water resources (Sommer et al. 2007).

The POD Management Team (POD-MT) was established in 2005 by the Interagency Ecology Program (IEP) to evaluate the potential causes of the species declines (Sommer et al. 2007). The POD-MT organized an interdisciplinary, multi-agency research effort including staff and researchers from California Department of Fish and Game (CDFG), California Department of Water Resources (DWR), California State Water Resources Control Board (SWRCB) and Central Valley Regional Water Quality Control Board (CVRWQCB), U.S. Bureau of Reclamation (USBR), U.S. Fish and Wildlife Service (USFWS), U.S. Environmental Protection Agency (USEPA), U.S. Geological Survey (USGS), and the Delta Science Program (DSP) (formerly CALFED Science Program). Many POD research activities were also carried out by academic, non-profit, and private scientists.

At the core of the POD investigation has been a series of evolving, non-quantitative conceptual models about the declines. These conceptual models were developed to help organize, synthesize, and communicate existing and emerging information about the declines and to identify data gaps for the initiation of new studies. Particularly useful has been what has come to be known as the “basic POD conceptual model” (Figure 3, updated from Sommer et al. 2007). In addition to the basic model, the POD-MT has developed and refined species-specific conceptual models focusing on seasonal drivers of population dynamics of the four POD fish species (Figures 4–7, first introduced in Baxter et al. 2008) and a conceptual model placing the POD in the context of an ecological regime shift (Figure 8, the model is explained in later sections).

The POD investigation has taken place in a rapidly evolving water resource management, policy, and science landscape. This rapid change has been caused by growing concerns about the ability to meet the dual goals of water supply reliability for Californians and a functioning Delta ecosystem. These concerns grew even more pressing during the 2007–2009 drought. Additionally, California is currently facing a major economic crisis. Some of the major developments since the last comprehensive POD report (Baxter et al. 2008) include: (1) new Biological Opinions for the operation of the State and Federal Water Projects; (2) a new Federal California Bay-Delta Memorandum of Understanding and formation of a Federal Bay-Delta Leadership Committee; (3) a comprehensive water bill package by the California legislature establishing a Delta Water Master, Delta Stewardship Council, and a Delta Conservancy; (4) a new National Research Council committee on “Sustainable Water and Environmental Management in the California Bay-Delta;” and (5) intense work on a new Bay-Delta Conservation Plan (BDCP). Sound scientific information is regarded as a key ingredient to the success of these efforts. The IEP is one of the main providers of such information for the estuary and has been responding to the new demands by creating a new IEP Lead Scientist position, forming new technical work teams, and focusing new POD studies on emerging information needs. Future changes to the IEP may include new formal partnerships and initiatives that are currently under development by the IEP Coordinators.

Purpose

This report has three objectives:

1. Synthesize the information collected by the POD investigation through approximately August 2010,
2. Provide a basis for future syntheses and work plans, and
3. Present the 2010 POD work plan.

In previous reports, our approach was to synthesize this information in the context of our basic conceptual model (Figure 3; Sommer et al. 2007). In this report, we continue to use the basic conceptual model as an organizing principle, but we also present two additional types of conceptual models. The first type is the “species-specific” conceptual models (Figures 4–7) first introduced in Baxter et al. (2008). This type of conceptual model narrows the basic POD conceptual model to the level of individual POD fish species and shows how key population drivers presently affect the POD fish species in each season. We believe this approach increases the clarity of the presentation because not all new information necessarily applies to all POD species. The second type of conceptual model is new. It broadens the basic POD conceptual model to the ecosystem level and places it in a historical ecological regime shift context. In the regime shift conceptual model, the POD is part of a larger, fundamental change in structure and functions of the San Francisco Estuary ecosystem brought about by changes in multiple and often interacting environmental drivers. Some of these changes occurred slowly or decades ago, while others were more rapid or recent. In this report we describe our current understanding of the present state of the system, the changes that led to this state, and what this may mean for the resilience of the system in the face of future challenges such as global climate change and additional species invasions.

From the beginning, the POD investigation has been designed to assess the role of multiple drivers individually and in combination. Similar to Baxter et al. (2008) we rely on a *weight of evidence* approach (Burkhardt-Holm and Scheurer 2007, Linkov et al. 2009) to synthesize and interpret the many individual and in some cases conflicting lines of evidence emerging from the POD studies. In particular, we examined the multiple types of evidence to develop plausible linkages within our conceptual models. As a result, this report focuses on the linkages within the conceptual models and their contributions to the individual “fish species stories,” the overall “POD story,” and the emerging “regime shift story” provided in the final synthesis, rather than providing in-depth examinations of relationships between individual drivers and fish abundance.

As for previous reports, many of the POD study elements have not been completed or fully evaluated and we wish to emphasize that our conceptual models represent works in progress. We envision delivering a final comprehensive POD report in 2012–2013. The final POD report will synthesize all prior POD results, including the final analyses and insights resulting from an ongoing collaboration of the IEP with the University of California-Santa Barbara, initially with the National Center for Ecological Analysis and Synthesis (NCEAS). The present progress report was written by members of the IEP POD-MT. It has been reviewed by the IEP Agency Coordinators, but has not undergone any external, independent peer review.

This report is divided into several major sections. We first provide some basic background on the POD fishes. Second, we present the progression of scientific knowledge on specific topics within the context of the basic conceptual model for the POD that was developed in previous reports and publications (Sommer et al. 2007). Third, we refine the more detailed conceptual models for each of the POD fishes that were first presented in Baxter et al. (2008). Fourth, we present a new conceptual model about ecological regime shift that places the information presented in the general and individual species models in a broader ecosystem context. Finally, we describe how the 2010 work plan addresses information gaps associated with the three conceptual model types and what the next phase of this work might hold. Some material is repeated in several sections of the report to minimize the need for readers to search the entire report for pertinent supporting information.

This report has the same limitations as earlier reports from the POD-MT. Specifically, many studies initiated by the POD or initiated by others that will provide important POD information are still in progress. As explained in the 2009 Addendum to the 2008 POD Work Plan (Baxter et al. 2009), many POD study elements have also been delayed due to a December 2008 “Stop Work Order” for State bond funded projects that lasted eight months. In addition, there have been two to three mandatory furlough days for State employees which started in February 2009 and continue to the present, as of the writing of this report. Preliminary results from studies that are still in progress are provided whenever possible, but peer-reviewed products from these studies may not be available for some time to come. We rely as much as possible on peer-reviewed published literature. When such literature is not available we utilized agency reports and reports to the POD management team regarding POD funded research that are available to the public (POD study reports are available at http://www.science.calwater.ca.gov/pod). In some cases, we also include information from articles that have been submitted to scientific journals but that have not yet been accepted for publication; we cite them as “submitted.” All other information (e.g., posters, abstracts) is cited as unpublished data or personal communication with the exception of the IEP Newsletter. The IEP Newsletter is cited as a peer-reviewed publication, even though it is not rigorously peer-reviewed. Articles generally receive informal review before submission and are reviewed by an editor with local experience with San Francisco Estuary issues. Also, the IEP Newsletter publishes articles of intense local interest that may not be of interest to journal publishers. We encourage readers to be cautious when evaluating the relative importance of the hypotheses presented in this report. Hypotheses not based on peer-reviewed literature should be viewed with more skepticism. We present them because they represent the newest thinking on POD issues and may stimulate productive discussions and new research.

Species Background

The apparently simultaneous declines of four pelagic Delta fish species in the early 2000s (Sommer et al. 2007) were surprising because of the differences in their life histories and differences in how each species utilizes Delta habitats. These differences suggested one or more Delta-wide factors to be important in the declines. Thorough descriptions of the POD phenomenon and the early stages of the POD investigation are available in Sommer et al. (2007). Here, we briefly review the general life history of each of the four POD fish species based on descriptions in Moyle (2002) as ecological background for understanding the remainder of the report. Readers are referred to the papers cited in the remainder of this report and the species-specific conceptual models for additional details.

Delta smelt is a slender-bodied fish typically reaching 60–70 mm standard length (SL) with a maximum size of about 120 mm SL. Delta smelt is endemic to the upper San Francisco Estuary, primarily the Delta and Suisun Bay. Delta smelt is generally associated with the low salinity zone locally indexed by X2, which is the distance (in km) along the axis of the estuary from the Golden Gate to the 2 psu isohaline measured near the bottom of the water column (Jassby et al. 1995). Delta smelt feed primarily on planktonic copepods, cladocerans, and amphipods. Delta smelt is basically an annual species and spawns in freshwater in the Delta. Upstream migration of maturing adults generally occurs in the late fall or early winter with most spawning taking place from early April through mid-May (Bennett 2005). Larval delta smelt move downstream with the tides until they reach favorable rearing habitat in the low salinity zone. Some apparently remain in upstream reaches including the Cache Slough-Sacramento deepwater ship channel region and the central Delta region year-round (Julio Adib-Samii, CDFG, and J. Hobbs, UCD, unpublished data). A very small percentage of delta smelt is believed to live 2 years and spawn in one or both years (Bennett 2005). Delta smelt was listed as a threatened species by both the federal and state governments in 1993. Its status was changed to state endangered in 2009. A similar change to federal endangered status was recently determined to be “warranted but precluded” (USFWS 2010).

Longfin smelt typically reach 90–110 mm SL with a maximum size of 120–150 mm SL. In the San Francisco Estuary, 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 spawns at 2-years of age in freshwater portions of the Delta. A few fish over 110 mm SL are captured annually during spawning migrations, but it’s uncertain whether these are third-year fish or fast growing fish in their second year. Most spawning takes place from December through March. Incubation takes about a month and larvae are buoyant at hatching. Larval longfin smelt are transported downstream with outflow-generated surface currents. As they develop and can control their depth distribution, larvae move lower in the water column and probably remain in favorable rearing habitat in the low salinity zone and farther downstream. As juveniles grow and become more mobile they disperse downstream into Suisun, San Pablo and San Francisco bays. Longfin smelt feed primarily on mysid shrimp including the non-native *Hyperacanthomysis longirostris* and the native *Neomysis mercedis*. Copepods and other crustaceans can also be important food items, especially for smaller fish. Although other populations of longfin smelt occur on the Pacific Coast, the San Francisco Estuary population is the southern-most reproducing population and was recently proposed for listing under CESA, and as a distinct population segment of the species under FESA (The Bay Institute et al. 2007a, b). In April 2010, the California Fish and Game Commission listed longfin smelt as threatened. The USFWS determined that the longfin smelt in the San Francisco estuary did not meet the definition of a distinct population segment and the species was not listed (USFWS 2009).

Striped bass is native to the Atlantic Coast of North America. It was introduced to California in 1879. Striped bass is a large (> 1 m), long-lived (> 10 years) species. Striped bass juveniles and adults are widespread in the San Francisco Estuary watershed. The species can be found in the larger river systems downstream of impassable dams and in the coastal ocean. Striped bass is a generalist predator. Larval and small post-larval bass feed mainly on copepods. As the fish grow they consume larger invertebrates and fishes. Striped bass is an anadromous mass spawner. Females begin spawning at 4–6 years of age and can spawn every year depending on environmental conditions. In the Sacramento River, spawning occurs in the upper parts of the tidal portion of the river and lower portions of the riverine portion of the river. A small proportion of spawning occurs in the San Joaquin River within the Delta. Embryos and larvae drift into the Delta and larval striped bass are associated with the low salinity zone. As the juveniles grow, they disperse throughout the Delta and San Francisco Bay. Although an invasive species, striped bass supports a popular and economically important recreational fishery.

Threadfin shad was introduced to California in 1954 to provide forage for predatory fish in reservoirs. It was planted in the San Francisco Estuary watershed in 1959 and rapidly colonized all available habitat. Adult threadfin shad are typically less than 100 mm total length and primarily inhabit freshwater, where they are omnivorous filter feeders on phytoplankton, zooplankton, and detritus. They can also selectively sight-feed on individual organisms, primarily zooplankton. Most threadfin shad spawn as 2-year olds, although some may spawn at the end of their first year. Spawning occurs from April to August, but most occurs in June and July. Larval and juvenile threadfin shad are mainly found in the freshwater portions of the Delta. Threadfin shad is the most abundant pelagic fish in the upper estuary and is exceptionally important as prey for piscivorous species.

The apparently simultaneous declines of these four species of fish were surprising because of the differences in their life histories and differences in how each species utilizes Delta habitats. These differences suggested one or more Delta-wide factors to be important in the declines.

Conceptual Models

All conceptual models developed during the POD investigation revolve around natural and anthropogenic drivers that affect ecological change such as the observed pelagic fish declines. Drivers and stressors are events or processes involving environmental (natural or human) variables and the terms are often used interchangeably or with fluid boundaries. Some authors define drivers as larger-scale and/or external influences on ecosystems, while stressors are defined as smaller-scale, internal changes brought about by the larger-scale drivers (e.g. Ogden et al 2005). Others define stressors as drivers that “exceed the range of variation beyond which the current biological communities can survive (commonly taken as exceeding the long-term or reference range of variation” (Miller et al. 2010). Here, we make the somewhat arbitrary decision to refer only to drivers because the term “stressor” implies an adverse or “undesirable” changes in ecosystem structure and functions that may be directly responsible for the POD phenomenon. Given that two species might respond in opposite ways to the same stressor, the meaning of the term becomes confusing. The distinction between drivers and stressors has become more important in the most recent POD work on regime shifts and ecological thresholds, as will be described in later sections of this report.

Based on the observation that fish abundance indices declined abruptly after 2000, the POD-MT developed an initial conceptual model about drivers potentially responsible for the declines (IEP

2005). After the completion of the first set of studies in late 2005, alternative models were developed based on the results available at that time and the consensus of professional judgment of the POD-MT regarding the extent to which individual drivers were likely to have affected each species-life stage during recent years. The nine drivers evaluated were: (1) mismatch of larvae and food; (2) reduced habitat space; (3) adverse water movement/transport; (4) entrainment; (5) toxic effects on fish; (6) toxic effects on fish food items; (7) harmful *Microcystis aeruginosa* blooms; (8) C*orbula amurensis* effects on food availability; and (9) disease and parasites.

These earlier conceptual models provided a useful way to: (1) summarize understanding of factors that may have contributed to the POD and (2) design the initial suite of research studies; however, they had several shortcomings. They did not adequately reflect spatial and temporal variation in the nine drivers evaluated, new data showed several assumptions to be incorrect, and the initial models were relatively cumbersome.

The basic conceptual model developed in 2006 (Sommer et al. 2007) and species-specific models developed in 2007 (Baxter et al. 2008) represented an improvement over the earlier efforts, but still had numerous limitations. Many of the results and inferences were preliminary at the time they were developed and had not been peer-reviewed, so the models were considered preliminary. Moreover, the models may have been influenced by potential biases in the sampling programs. Changes in the size and distribution of the target species have the potential to change our perception of trends in abundances and distributions. This, in turn, would affect our conceptual models. Throughout this discussion we use indices of fish abundance such as the Fall Midwater Trawl and Summer Townet survey (TNS) indices or catch per unit effort (CPUE) as estimates of abundance. The relationship between these indices of abundance and the actual population size of any species are generally not known, but they are presumed to increase monotonically with each other. Modeling efforts along with sampling gear evaluation studies are underway to better understand these relationships (e.g., Newman 2008). The same caveats continue to apply to the refined and new conceptual models presented in this report.

We also recognize that the recent decline in pelagic fish species is superimposed over long-term declines for several of these species and their long-term relationships with other environmental variables. Initial change-point analyses (Manly and Chotkowski 2006) suggested that distinctly different statistical models might be appropriate for different time periods. A clear line divides the POD era from the years preceding it for some species. Bayesian change-point modeling indicated that there were long-term declines in all 4 POD species abundances related to long term changes in some environmental variables, such as water clarity. However, the step decline in abundance of the species in the early 2000s (Thomson et al. 2010) could not be explained by changes in those same environmental variables or any of the other variables considered in the analysis. There also appear to be multiple periods of decline within the historical record preceding the POD and the periods are not always the same across species. The basic and species-specific conceptual models explicitly focus on mechanisms that might have contributed to the decline of pelagic fishes during the POD era; however, the historical antecedents to the POD are a crucial part of the story. These historical changes are more explicitly acknowledged and explored in the new regime shift model; however, this model is still in the early stages of development and contains many uncertainties.

Note that none of the conceptual models are intended to exclude other explanations for the observed changes in fish abundance, nor are they designed to set priorities for resource management. Instead, they are intended as examples of how different drivers may be linked and produce ecological responses. Moreover, no single model component can explain the declines of all four species (Thomson et al. 2010, Mac Nally et al. 2010). We will continue to further develop and refine the models as additional data become available. In this report, as in previous reports, we use the basic conceptual model as an organizing principle for an examination of the historical development of thought on various topics we believe important to POD species. We use the individual species models to present the suite of drivers we think is important for that particular species. We use the regime shift model to put the POD into a more historical ecosystem context and set the stage for a new phase of the POD investigation.

Basic Conceptual Model

The basic conceptual model (Figure 3) is rooted in classical food web and fisheries ecology and contains four major components: (1) prior fish abundance, which posits that continued low abundance of adults leads to low juvenile production (i.e., stock-recruitment effects); (2) habitat, which posits that the amount of water (volume or surface area) with suitable conditions for a species has changed because changes in estuarine water quality variables, disease, and toxic algal blooms in the estuary affect survival and reproduction; (3) top-down effects, which posits that predation and water project entrainment affect mortality rates; and (4) bottom-up effects, which posits that consumable resources and food web interactions affect survival and reproduction. Each model component contains one or more potential drivers affecting the POD fishes. The overlap of the four model components indicates that they can affect the fish species simultaneously and can interact to produce synergistic or antagonistic effects. For each model component, our working hypotheses during development of the model were: (1) one or more drivers associated with the component were responsible for an adverse change at the time of the POD; and (2) this change resulted in a population-level effect. However, the emphasis of the POD effort has evolved from concern with changes that took place at the time of the POD to understanding drivers and drivers affecting the abundance of POD species, regardless of time frame.

In the following sections, we present a synopsis of how thinking has evolved on each driver within the four major components and the current thinking of the POD-MT about how that topic relates to POD species. The intent of this approach is to provide readers with a perspective on the evolution of scientific knowledge on specific topics and how the POD-MT has utilized historical and emerging knowledge to guide the POD investigations.

Previous Abundance

The relationship between numbers of spawning fish and the numbers of young subsequently recruiting to the adult population is known as a stock-recruitment relationship. Stock-recruitment 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-recruitment 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-recruitment relationship observable in available data.

Unfortunately, none of the POD species were of sufficient interest as commercial or recreational species to warrant development of stock-recruitment models until the 1970s. There was a commercial fishery for striped bass from 1888 until 1935, when it was closed and only recreational fishing was allowed (Dill and Cordone 1997). The sport fishery was subsequently managed through regulations alone with no sampling or population modeling. Regulations became more restrictive as catch per angler indicated that the population was declining (Skinner 1962). Studies initiated in 1959 in connection with the CVP and SWP led to the first estimates of population size. The population was estimated at 2–3 million legal-sized adult fish in the early 1960s (Herbold et al. 1992) with a plateau of an estimated 1.5–1.9 million legal-sized adult fish from 1969–1976 (Herbold et al. 1992, Kohlhorst 1999). The other species were never extensively harvested, though longfin smelt was once part of the "whitebait" catch from San Francisco Bay (Skinner 1963), or records were not kept if they were harvested.

The initiation of fisheries studies in 1959 in association with the planning and operation of the CVP and SWP provided the first opportunity to develop stock-recruitment type models for striped bass, longfin smelt, and delta smelt. We deliberately say "stock-recruitment type models" because classical stock-recruitment models in fisheries management are based on and produce estimates of the actual population size of a species as either numbers or biomass. The IEP monitoring was not designed to produce an actual population estimate (with the exception of Petersen tag estimates for striped bass and sturgeon), but to provide information on trends based on a population index or CPUE (e.g., number per trawl). Efforts are currently under way to develop methods to calculate population sizes of delta smelt and longfin smelt from currently collected data (e.g. Newman 2008).

Early models related the success of spawning and juvenile recruitment of striped bass with Delta outflow using simple regression models (Stevens and Miller 1983, Stevens et al. 1985). These models were not true stock-recruitment models (nor intended as such) because they assumed that the environmental variable flow was the primary control on recruit abundance. In other words, stock is always sufficient to produce high recruitment given good environmental conditions and good environmental conditions are provided by high flow. These early models began to break down in the late 1970s (Stevens et al. 1985) leading to new work on striped bass and eventually on the other POD species.

Kimmerer et al. (2000) found evidence for a density-dependent stock-recruitment relationship in San Francisco Estuary striped bass. However, the adult striped bass stock is currently not particularly low (Figure 9), so stock size is not likely a mechanism contributing to recent very low age-0 striped bass abundance. In other words, there appear to be enough adults in the system to produce sufficient young for the population to recover. Recent analyses have revealed a change in sex ratio for adults on their spawning migration. The proportion of female striped bass in the spawning population appears to have been declining in recent years (Figure 10, T. Sommer, DWR, unpublished data). The causes for this change are unknown (discussed below) as are the consequences of the change for the population biology of the species, but at the very least the effective spawning stock has been limited by the low female numbers in the spawning runs. The decline does not seem to be an artifact of sampling bias because it has been noted in two types of sampling gear (gill nets and fyke traps) in two widely separated locations (the Delta and the Sacramento River near Knights Landing, respectively) (T. Sommer, DWR, unpublished data unpublished data).

There is little evidence for strong stock-recruitment or stage-recruitment relationships for threadfin shad (Feyrer et al. 2009). For longfin smelt, preliminary analyses support a stock-recruitment relationship between adults approaching their second birthday and age-0 fall recruits (The Bay Institute et al. 2007a). A significant stage-recruitment relationship (fall age-0 to fall age-1 abundance) also exists, but survival declined after 1994 (Rosenfield and Baxter 2007) presumably due to continued food limitation, which in turn may have led to a habitat shift (discussed below). However, current populations of longfin smelt and threadfin shad are similar to low populations observed in previous years (Figure 2). Threadfin shad rebounded fully from previous abundance lows in the 1970s and 1980s. Longfin smelt populations rebounded somewhat in the 1990s following previous lows during the 1987–1992 drought. Recovery of these species is only expected if the factors affecting recruitment have not changed substantially. If the factors affecting survival from egg to adult have changed substantially since the beginning of the POD, then recovery might not occur even though recovery from low abundance occurred in the past. The changes in the statistical relationships between outflow and population abundance indices for longfin smelt and age-0 striped bass (Figure 11) indicate that changes in the drivers of recruitment have occurred. These changes are discussed in more detail in subsequent sections.

Population size can potentially affect survival at multiple points over the life cycle of a species. Typical examples include stock relationships, where the number of adults influences the number of offspring, and cohort relationships, where the abundance of one life stage affects survival to the following stage. In any form of a stock-recruitment model, there is a point at which low adult stock will result in low juvenile abundance and subsequent low recruitment to future adult stocks. This can occur even under favorable environmental conditions while the stock “rebuilds” itself. From a stock-recruitment perspective, the present low abundance of delta smelt is of particular concern. The current population is smaller than at any time previously in the record (Figure 2). The delta smelt stock-recruitment relationship appears to be density–independent, particularly since the latter 1970s (Figure 12). The Fall Midwater Trawl (FMWT) index (pre-spawning adults) explains about half of the variation in the TNS index (juveniles) over the period of 1978 to present. Feyrer et al. (2007) found that incorporating fall salinity increased the explanatory power of this stock-recruitment relationship during this period. As noted above, transitions between life stages (i.e. cohort relationships) can also influence survival. The life history transition between the TNS index (juveniles) and the following FMWT index (pre-spawning adults) (Figure 12) has been influenced by density-dependent mechanisms and declining carrying capacity (Bennett 2005). In a plot of this relationship, the most recent POD years (2005–2009) plot well below the relationships based on the entire record (Figure 13). A plot of adult production from the adults in the previous year, represents an interaction of the above relationships and any other factors affecting survival. This plot suggests declining survival of delta smelt throughout the POD period (Figure 14).

The combined effects of stock-recruitment and cohort relationships are somewhat complicated to assess without a proper life cycle model. However, the change in the relationship in summer to fall survival (Figure 13) suggests that the primary factors affecting juvenile survival recently changed and shifted to earlier in the life cycle; however, this would not necessarily affect the stock-recruitment relationship. It would only affect available stock. In other words, an individual adult delta smelt might still produce the same number of young; however, fewer young survive to reproduce as adults. In addition, the fecundity of adult smelt has likely changed. The mean size of adult delta smelt has declined since the early 1990s (Sweetnam 1999), possibly due to changes in the food web (see Bottom up section). There may also be selection for late-spawned larvae as a result of water export schedules related to the Vernalis Adaptive Management Plan (VAMP), which began in 2000 (Bennett et al. 2008). These smaller larvae have less opportunity to grow to large adult size. Smaller adults due to reduced food supplies and younger adults due to selection for late-spawns are not mutually exclusive mechanisms and the combination could easily have a nonlinear impact on overall fecundity.

These observations strongly suggest that recent population trends for delta smelt are outside the historical realm of variability and may be associated with a new state of the system (see Regime Shift Model section). This inference is supported by a recent changepoint analysis, which indicated a decline in abundance in the early 2000s independent from environmental variables that previously explained abundance. Thus, recovery is likely to require changes in the drivers that have produced the current low levels of abundance and perhaps new drivers or previous drivers that have since become more important.

Given the unprecedented low abundance of delta smelt since 2000 (Figure 2), serious consideration should be given to evaluation of Allee effects. Allee effects occur when reproductive output per fish declines at low population levels (Berec et al. 2006). In other words, below a certain threshold the individuals in a population can no longer reproduce rapidly enough to replace themselves and the population, exhibiting inverse density dependence, spirals to extinction. For delta smelt, possible mechanisms for Allee effects include processes directly related to reproduction and genetic fitness such as difficulty finding mates, genetic drift, and inbreeding (Gascoigne et al. 2009). Other mechanisms related to survival such as increased vulnerability to predation (Gascoigne and Lipcius 2004) are also possible and will be briefly discussed in the Top-Down model component section. While theoretical work suggests that Allee effects might be common in nature, empirical evidence for Allee effects in natural populations remains sparse, possibly because they are often masked by measurement errors (Gregory et al. 2010). In addition, the interactive effects of multiple Allee effects may have important implications for species conservation, but have not yet been well explored in ecology (Berec et al. 2006).

Habitat

According to Hudson et al. (1992), “habitat is simply the place where an organism lives.... Physical, chemical and biological variables (the environment) define the place where an organism lives.” Hayes et al. (1996) explain further that “space is the primary component of fish habitat, and other resources and environmental conditions modify the utility of space." The maintenance of usable space (i.e. suitable habitat quality) is essential to the long-term health of aquatic resources (Rose 2000, Peterson 2003). For the habitat component of the model, a key point is that *habitat suitability affects all other components of the model*. This is indicated by the overlap of habitat with all other components in Figure 3. Hence, changes in habitat not only affect pelagic fishes, but also their predators and prey, which, in turn, can also have effects on the habitat they occupy. Although not a focus of this report, we expect that the habitats of the POD species are especially vulnerable to future climate change. Thus, policy and management alternatives regarding habitat should consider expected changes in climate as well as other changes in major system drivers such as altered water management.

Habitat for pelagic fishes: Habitat for pelagic fishes in the estuary 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, estuarine pelagic fish habitat is water with suitable values for a variety of physical-chemical properties (e.g., salinity, turbidity, and temperature), suitably low levels of contaminants, and suitably high levels of prey production to support growth. A key to understanding pelagic fish habitat in the estuary is recognizing that it is not fixed to a specific geographic location. Freshwater and seawater will always meet somewhere in an estuary and this zone will move within the estuary at time scales ranging from annually and seasonally in response to freshwater outflow to hourly in response to tides. However, the geographic locality where the interface between freshwater and saltwater occurs at any particular time may have implications for the effects of other factors (e.g., exposure to a point source of contaminants). Thus, pelagic fish habitat suitability at any specific geographic point in the estuary can be strongly influenced by variation in freshwater flow (Jassby et al. 1995, Bennett and Moyle 1996, Kimmerer 2004).

We know that aquatic habitats in the Delta have changed substantially since the mid-1850s. The Delta has been converted from a complex mix of seasonal wetlands, perennial wetlands and riparian habitats with many dead-end waterways to a geographically simplified system of leveed agricultural islands separated by a network of interconnected channels, which are often deeper and more steep-sided than natural channels and have hardened, rip-rapped levee shorelines. It has been estimated that 95% of wetlands in the Delta have been lost (The Bay Institute 1998). Large pulses of sediment associated with hydraulic mining have now largely moved through the estuary and dam construction has prevented recruitment of new sediments from upstream areas. This has contributed to increasing water clarity in recent years (Wright and Schoellhamer 2004). The effects of many of the early habitat changes are largely unknown. There is speculation that the success of the striped bass introduction in 1879 was partially due to their semibouyant embryos and pelagic larvae that were better adapted than those of native species to the high sediment loads carried in the rivers at that time due to hydraulic mining (Moyle 2002). The changes in channel configuration, water storage behind dams, and operations of the CVP, SWP, and other water management projects have resulted in complex hydrodynamic and water quality patterns (Kimmerer 2004, Monsen et al. 2007, Healey et al. 2008, Kimmerer and Nobriga 2008) that are very different from what existed in the past (e.g., Brown and Bauer 2009). However, only recently have these changes become of major management concern (ROD 2000). This concern has resulted in tightened restrictions on water diversions, passage of California water legislation in the 2009, the development of new flow criteria for the Sacramento-San Joaquin Delta ecosystem by the SWRCB, and the Bay-Delta Conservation Plan (BDCP) planning process. Kimmerer (2004) has summarized much of the existing knowledge on factors affecting open water habitats.

Development of habitat-based ideas related to Delta fish populations basically began with the simple regression models, described in the previous section, which related Delta outflow to recruitment of young pelagic fishes of several species (Stevens and Miller 1982, Stevens et al. 1985). The next step was the development of X2 as an index of the response of the estuarine community to net freshwater flow (Jassby et al. 1995). X2 denotes the distance (in km) along the axis of the estuary from the Golden Gate to the 2 psu isohaline measured near the bottom of the water column. X2 has been linked to the success of various species including POD species. X2 is related to flow but provides a more direct link to fish habitat (Kimmerer 2002a, b) and has thus been used as a habitat indicator and adopted for regulatory purposes. Unfortunately, the X2 relationships for longfin smelt and age-0 striped bass have changed in association with other drivers (e.g., invasive species). Delta smelt has never shown a strong relationship to X2, and the freshwater threadfin shad has no relationship to X2. As a result of the POD, several investigations were started to define appropriate habitat for various POD species so changes in habitat suitability could be better assessed.

Several of the POD fishes use 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 (e.g., Dege and Brown 2004, Feyrer et al. 2007), so at any point in time, salinity is a major factor affecting their geographic distributions. As mentioned earlier, pelagic habitat suitability in the San Francisco Estuary can be characterized by changes in X2. The abundance of numerous taxa increases in years when flows into the estuary are high and the 2 psu isohaline is pushed seaward (Jassby et al. 1995, Kimmerer 2002a, b), implying that the quantity or suitability of estuarine habitat increases when outflows are high. Recent analyses indicated that neither changes in area or volume of low salinity water (habitat) account for this relationship for species showing relationships with X2, except for striped bass and American shad (Kimmerer et al. 2009). This suggests that X2 is indexing other environmental variables or processes rather than simple extent of habitat.

It is also worth noting that the change from net outflow models to more complex habitat models occurred in concert with a change in thinking about Delta hydrodynamics. Through the 1980s the perception was that river-like net flow through Delta channels was the major feature of flow important to the ecosystem even though it was recognized that the Delta was a tidal system. From the 1990s onward there has been increasing recognition that tidal flows combined with the highly altered nature of the Delta channel network combine to create complex hydrodynamic patterns. These patterns can result in sometimes surprising results regarding transport of weakly swimming fishes, other organisms, and water quality constituents (e.g., salt) through the Delta. For example, Lucas et al. (2002) and Lopez et al. (2006) showed that the production and distribution of phytoplankton biomass can be highly variable within and between nearby habitats of the same type in the Delta due to variations in phytoplankton sources, sinks, and transport. Therefore, superficially similar, geographically proximate habitats can function very differently and assessment of the role and functioning of different habitat types needs to include a regional landscape perspective (Lopez et al. 2006, Cloern 2007). This perspective could be essential in predicting the success of habitat restoration efforts (Lopez et al. 2006). Kimmerer and Nobriga (2008) used a particle tracking model to explore the relationships between hydrodynamics and entrainment risk and found release location and hydrology to be important factors. This latter application is especially relevant to entrainment issues discussed in a later section.

Based on a 36-year record of concurrent midwater trawl and water quality sampling, there has been a long-term decline in fall habitat suitability for delta smelt and striped bass, but not for threadfin shad (Feyrer et al. 2007). The long-term habitat suitability declines for delta smelt and striped bass are defined by a lowered probability of occurrence in samples based on changes in specific conductance (a surrogate for salinity) and Secchi depth (a measure of water clarity or, conversely, turbidity). Notably, delta smelt and striped bass habitat suitability declined recently coinciding with the POD. The greatest changes in habitat suitability occurred in Suisun Bay and the San Joaquin River upstream of Three Mile Slough and in the southern Delta (Feyrer et al. 2007). 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-recruitment relationship described above improved the fit of the model, suggesting adult numbers and their habitat conditions exert important influences on recruitment. Subsequently, Feyrer et al. (2010) developed a model for estimating habitat suitability based on X2.

The importance of salinity in this study was not surprising, given the relationships of population abundance indices with X2 for many species. Fall X2 has been high during the POD years despite moderate to high outflow conditions during the previous winter and spring of most years. Contra Costa Water District (2010) recently reviewed and summarized a wide range of historical reports and analyses regarding salinity in the western Delta and Suisun Bay. The basic conclusion was that a variety of human activities including channelization of the Delta, elimination of tidal marsh, construction of deepwater ship channels and diversions of water have contributed to increased salinity in the region. Consistent with fall X2 observations, the report also noted that fall salinity in 21 of the last 25 years has resembled that expected during a drought, even though half the years have been relatively wet. Although the operations of reservoirs and water diversions have been able to ameliorate the effects of salinity on water supply, salinities still exceed pre-1900 levels.

There appeared to be a curious anomaly in the salinity distribution of delta smelt collected during the September 2007 survey of the FMWT. All seven delta smelt collected during this survey were captured at statistically significant higher salinities than what would be expected based upon the relationship generated by Feyrer et al. (2007) ($p=0.0012$, K. Newman, USFWS, personal communication 2007). There could be any number of reasons why this occurred, including a substantial *Microcystis* bloom in the western Delta in 2007, which extended further downstream than previous blooms and may have affected the distribution of biological organisms.

The importance of Secchi depth in the long-term changes in pelagic fish habitat suitability (Feyrer et al. 2007) was more surprising. Unlike salinity, interannual variation in water clarity in the Delta is not primarily a function of flow variation (Jassby et al. 2002). Water clarity in the

Delta has been increasing since routine monitoring began in 1975 (Jassby et al. 2002, Wright and Schoellhamer 2004, Jassby et al. 2005, Jassby 2008). 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) sediment washout from very high inflows during the 1982–1983 El Nino (Jassby et al. 2005); and (3) biological filtering by submerged aquatic vegetation (SAV) (Brown and Michniuk 2007, Hestir 2010).

Results from a recently completed POD-funded study (Hestir 2010) indicate that the three mechanisms likely played sequential roles in the increasing water clarity in the Delta. The initial increase in clarity was likely brought about by reductions in sediment supplies due to the first two mechanisms. The resulting clearer water facilitated the rapid spread of invasive submerged aquatic vegetation which in turn led to further clearing of the water. In lakes, high densities of the Brazilian waterweed *Egeria densa* and similar plants can mechanically filter suspended sediments from the water column (Scheffer 1999). Vegetation has also been shown to facilitate sedimentation in marshes and estuaries (Yang 1998, Braskerud 2001, Pasternack and Brush 2001, Leonard et al. 2002). The most abundant invasive SAV species in the Delta is *E. densa*. *E. densa* invaded the estuary in the 1980s and rapidly expanded its distribution in the 1990s (Service 2007). *E. densa* continued to spread by expansion of existing patches and invasion of new areas during the POD years (Hestir 2010). Areal coverage of *E. densa* increased more than 10% per year from 2004 to 2006; however, *Egeria* may now occupy most of the Delta habitat suited to its establishment and growth and the rate of expansion may have declined substantially over the past few years (E. Hestir, UCD, personal communication). The current growth and spread of SAV in the Delta is likely controlled by water velocities, rather than light availability (Hestir 2010). In clear water, *E. densa* can grow to depths of 6 m (Anderson and Hoshovsky 2000). Salinity likely limits its spread into the seaward areas of the estuary (Hauenstein and Ramirez 1986). According to Hestir (2010), Delta SAV grows best at annual water velocities below 0.49 m/s and suppresses turbidity levels in its vicinity by reducing sediment resuspension. The expansion of invasive SAV in the Delta can explain 21–71% of the total increasing trend in water clarity in the Delta from 1975–2008. Although *E. densa* may have reached the current limits of its distribution in the Delta, it is possible that additional clearing due to further reductions in sediment supplies and water velocities will allow *E. densa* to spread into progressively deeper water and contribute to even more clearing.

The mechanisms causing the negative associations between water clarity and delta smelt and striped bass occurrence are currently under investigation. Based on research in other systems (e.g. Gregory and Levings 1998), Nobriga et al. (2005) hypothesized that higher water clarity increased predation risk for delta smelt, young striped bass, and other fishes typically associated with turbid water. A certain concentration of suspended particles also seems to be necessary for proper feeding by young delta smelt (Baskerville-Bridges et al. 2002, Mager et al. 2004). Turbidity, and to a lesser degree salinity, were also found to be extremely important parameters influencing larval delta smelt survival in laboratory flow-through assays exposing larval delta smelt to water collected at Delta and Suisun Marsh sites (Werner et al. 2010). Increased turbidity associated with the “first flush” after winter storm events may also play a role in the upstream spawning migration of delta smelt in the winter (Grimaldo et al. 2010, Sommer et al. in review). However, it is currently unknown if it acts as a migration cue, an important habitat attribute preventing predation during the upstream migration, or is simply correlated to other relevant variables.

Trends in habitat suitability for delta smelt differ during the summer period compared to the fall. Specific conductance, Secchi depth, and water temperature all significantly predict delta smelt occurrence in summer, suggesting they all interact to affect delta smelt distribution (Nobriga et al. 2008). However, none of the water quality variables were correlated with delta smelt abundance (as indexed by the TNS) at the scale of the entire estuary (Nobriga et al. 2008). Based on these habitat variables, Nobriga et al. (2008) identified three distinct geographic regions that had similar long-term trends in the probability of delta smelt occurrence. The primary habitat region was centered on the confluence of the Sacramento and San Joaquin rivers near Sherman Island; delta smelt relative abundance was typically highest in the confluence region throughout the study period. There were two marginal habitat regions, one centered on Suisun Bay where specific conductance was highest and delta smelt relative abundance varied with specific conductance, with lower abundance at higher conductance. The third region was centered on the San Joaquin River and the southern Delta. The San Joaquin River region had the warmest water temperatures and the highest water clarity. Water clarity increased strongly in this region during 1970–2004. This is also the region most heavily invaded by *E. densa* (Hestir 2010). In the San Joaquin River region, delta smelt relative abundance was correlated with water clarity; catches declined rapidly to zero from 1970–1978 and remained consistently near zero thereafter. Note that in a year of low outflow, the low salinity zone would be at the confluence and summer delta smelt habitat might collapse to a restricted area around the confluence because salinity of the Suisun Bay region might increase to levels unsuitable for delta smelt. These results support the hypothesis that basic water quality parameters are predictors of summer delta smelt relative abundance, but only at regional spatial scales. These regional differences are likely due to variability in habitat rather than differences in delta smelt responses. Water management operations are targeted on keeping the lower Sacramento and San Joaquin rivers fresh for water exports so the range in salinity is probably relatively smaller than the range in turbidity. In the Suisun Bay region, there is a wider range of salinities relative to the other regions, so a response to that variable is possible.

Although Nobriga et al. (2008) recognized water temperature as an important aspect of delta smelt summer habitat, specific conductance and water clarity appeared to have more explanatory value. However, that does not mean that temperature is never important. Bennett et al. (2008) observed patterns in liver glycogen depletion and single cell necrosis in liver tissue of delta smelt collected in 2005 that were consistent with fish being stressed by warm water temperatures (22–23°C). As of yet, there is no strong evidence that delta water temperatures are increasing in response to climate change. Jassby (2008) detected a slight upward trend (0.2°C) in March–June water temperature (1996–2005) in the Delta but not in Suisun Bay. There was not a statistically significant increase in annual water temperatures if a longer time interval was considered (1975–2005), although there were some significant monthly trends at some locations (e.g., near Stockton in the summer months). Flow did not have a strong effect on water temperature. Water temperature in the Delta is mainly driven by air temperature and statistical models have been constructed for monitoring stations with a sufficient period of record. When these models are used to estimate water temperatures under various scenarios of climate change, temperatures stressful or potentially lethal to delta smelt become more common (Wagner et al. submitted).

Contaminants and Disease: In addition to habitat changes associated with changes in the estuarine habitat characteristics discussed above, contaminants can also change habitat suitability and overall ecosystem functions and productivity through numerous pathways. While there has been recent progress on assembling and analyzing data on trends in contaminant concentrations in and loadings to the Delta (Kuivila and Hladik 2008, Johnson 2010), the effects of contaminants on Delta fishes and other organisms are still not well understood. Evaluation of 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) remains an important and active component of the POD investigation. The main indirect contaminant effect under investigation is inhibition of prey production. The current state of knowledge about effects of contaminants on the POD fishes has recently been summarized by Brooks et al. (in review). This work suggests that while acute contaminant toxicity is not a likely cause for the population declines, sublethal stress from metals, nutrient-rich effluents, *M. aeruginosa* blooms, and pesticides are all potential contributors to, but not the sole cause of, past and ongoing declines.

Concern over contaminants in the Delta is not new. There are, for example, long standing concerns related to metals such as mercury and selenium in the watershed, Delta, and Bay (Davis et al. 2003, Linville et al. 2002).

Mercury contamination is mainly a result of historic gold mining. Contamination occurred as a result of mining mercury, primarily in the Coast Ranges, and loss of mercury during gold mining operations in the Sierra Nevada. As a result, mercury is a nearly ubiquitous contaminant throughout the Bay, Delta, and watershed. A TMDL (total maximum daily load) was recently promulgated for the Delta by the CVRWQCB. However, despite the concerns for mercury in general, mercury has not been associated with POD declines.

Selenium (Linville et al. 2002) has had two major sources in the system. Selenium in agricultural drainage water in the San Joaquin River drainage is the most well known source because of the bird deformities documented at Kesterson Reservoir at the terminus of the never completed San Luis Drain (e.g., Ohlendorf 2002). There is no strong evidence that selenium from agricultural sources in the San Joaquin Valley and transported by the San Joaquin River have been a major problem for POD species in the estuary; however, future changes in water management and hydrodynamics could conceivably increase exposure of Delta biota to this source (R. Stewart, USGS, personal communication, 2009). Other sources of selenium were oil refineries along the shoreline of San Francisco Bay, primarily San Pablo Bay and Carquinez Strait. These sources were controlled as part of the Clean Water Act. There is no evidence that these sources of selenium affected POD species; however there were effects on some benthic-foraging species, including white sturgeon, Dungeness crab *Cancer magister* and Sacramento splittail (Stewart et al. 2004).

In the 1960s, municipal and industrial waste disposal was a major issue in the San Francisco Estuary, as it was elsewhere in the nation. Passage of the Clean Water Act in 1972 eventually led to upgraded water treatment and improved water quality conditions in the estuary and recovery of resident biota (e.g., Nichols et al. 1986, Hornberger et al. 2000). However, passage of the Clean Water Act did not lead to removal of all municipal and industrial contaminants, and in some cases, unexpected sources and consequences of contamination and interactions of urban and agricultural contaminants are only now beginning to emerge.

One example of an unexpected consequence of ongoing contamination that is currently receiving much attention is the newly emerging idea that municipal ammonium pollution can lead to suppression of phytoplankton production in the estuary. Ammonium is the ionized form of ammonia gas, which forms when ammonia is dissolved in water according to the following equilibrium: $NH_4^+ \leftrightarrow NH_3 + H^+$. The equilibrium between ammonium and un-ionized ammonia depends primarily on pH (more H^+ available at lower pH), and also on temperature and salinity. Ammonia can cause toxicity to organisms, including fishes. Ammonium is considered a plant nutrient.

In many ecosystems around the world, increasing nutrient loading from agricultural run-off and urban waste disposal has led to eutrophication with often catastrophic consequences for many of the resident biota. In contrast to many other estuaries, the San Francisco Estuary has been considered relatively resilient to nutrient pollution and has not shown many of the common symptoms of eutrophication such as enhanced algal growth (Nichols et al. 1986, Cloern 2001, Kimmerer 2004). From 1975 to 1995, the Delta has actually experienced a long-term decline in phytoplankton production (Jassby et al. 2002). However, this trend has started to reverse since the mid-1990s (Jassby 2008) and potentially harmful algal blooms consisting mostly of floating colonies of the cyanobacteria (blue green algae) *M. aeruginosa* have become a common and widespread occurrence in the Delta in the late summer and fall (Lehman et al. 2008, see also sections below for more details). The long-standing and widely accepted explanation for the overall low levels of water column phytoplankton production and biomass in the estuary has been the suppression of phytoplankton growth by low water clarity, losses due to intense benthic grazing pressure, and transport through the Delta to San Francisco Bay (Cloern 2001, Jassby et al. 2002, Lucas et al. 2009a). The consequences of low phytoplankton production on the Delta food web are presented in more detail in the Bottom-Up section below. New studies suggest that phytoplankton growth may at times also be inhibited by high ammonium concentrations in and upstream of Suisun Bay and that changes in nutrient loadings may have also affected phytoplankton species composition, with repercussions throughout the food web (Wilkerson et al. 2006, Dugdale et al. 2007, Jassby 2008, Glibert 2010, Parker et al. in review, R. Dugdale, CSUSF-RTC, unpublished data). The largest source of ammonium to the system is the Sacramento Regional Wastewater Treatment Plant (SRWTP) (Jassby 2008). The inhibitory effect of ammonium on phytoplankton was unexpected by the agencies regulating wastewater treatment plants and thus was not considered during the development of past permits.

In addition to the unexpected inhibitory effect on phytoplankton, ammonia, the unionized, toxic gas form of the nutrient ammonium, can also have direct toxic effects on fish and their food organisms (EPA 2009). Evaluation of possible direct toxicity effects of dissolved ammonia and ammonium on delta smelt indicated that ambient concentrations in the Sacramento River and Delta were not high enough to be acutely toxic to 55-day old delta smelt (Werner et al. 2009a, 2010b). However, delta smelt appear to be more sensitive to ammonia than many other fishes (Werner et al. 2009b). A new molecular tool called a DNA microarray has recently been developed to evaluate sublethal contaminant effects on delta smelt (Connon et al. 2009), which might help elucidate chronic effects and causal mechanism of ammonia toxicity for delta smelt. Mortality and growth of the amphipod *Hyalella azteca* in Delta water samples collected biweekly over a 4-year period (2006–2010) was significantly and negatively correlated with ammonia and ammonium concentrations at several sites throughout the Delta and Suisun Marsh (Werner et al. 2010a). Some important food organisms of delta smelt such as the copepod *Pseudodiaptomus forbesi* may also be particularly sensitive to ammonia according to preliminary results from ongoing studies (Werner et al. 2010b). Further results and discussions of ammonium and ammonia dynamics and effects in the estuary can be found in Ballard et al. (2009), Foe (2009), Werner et al. (2009a, 2010b) and CVRWQCB (2010).

There is increasing concern regarding endocrine disrupting compounds (EDCs), which are often but not exclusively associated with wastewater discharges. Like ammonium, advanced wastewater treatment can lead to substantial removal of at least some classes of EDCs (Huang and Sedlak 2001). Some pesticides (e.g. synthetic pyrethroids) also have endocrine disrupting properties (Jin et al. 2010). EDC contamination of the environment can lead to disruption of sexual functions and changes in population sex ratios. Ongoing research shows a higher proportion of male Mississippi silversides *Menidia beryllina* at an urban sampling site near the discharge of a waste water treatment plant compared to an agricultural site in Suisun Marsh (S. Brander, UCD, personal com.). This study found estrogenic activity (i.e., feminization) at both sites, but significantly higher androgenic activity (i.e., masculinization) at the urban site. Lavado et al. (2009) conducted a survey of estrogenic activity in 15 agriculturally impacted waterways of the California Central Valley including the Delta and found that overall estrogenic activity was highest in water from their Delta sampling site and in water from a Napa River site. Teh (2007) found evidence of intersex (ovatestis, ovarian tissue within testes) in 9 of 65 male delta smelt (14%) collected from Delta and Suisun Marsh sites, but did not measure endocrine disrupting compounds or their activity in the water. While no firm conclusions about the effects of EDCs on the POD fishes can be drawn from these few lines of evidence, it seems clear that the role of EDCs in the Delta deserves further study.

The effects of pesticides, including herbicides and insecticides, are perhaps the largest unknowns relative to POD. Pesticides can cause acute toxicity (mortality) or chronic, sublethal effects. Agricultural applications of pesticides are well regulated and tracked in detail by the California Department of Pesticide Regulation (http://www.cdpr.ca.gov/docs/pur/purmain.htm). Urban applications are less well documented but county-wide sales information is available. However, there are many different chemicals applied and the relationship between the amount of a pesticide applied and the transport of that pesticide into waterways is not simple. Furthermore, there is no established long-term monitoring program for dissolved or sediment-bound pesticides currently in place in the Bay, Delta, or watershed. The existing evidence is weak, but a recent review of available information collected before and during the POD investigation (Brooks et al. in review) suggests that pesticides and other toxicants may affect POD fishes or other parts of the ecosystem.

Studies conducted before the POD investigations included studies of acute and chronic pesticide toxicity effects on phytoplankton, invertebrates, and fishes in the Delta and watershed. Phytoplankton growth rate may have occasionally been inhibited by high concentrations of herbicides (Edmunds et al. 1999). Toxicity to invertebrates was 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 (long-term) 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. Sublethal effects of contaminants were detected in striped bass larvae even after these regulations were in place (Bennett et al. 1995). Bioassays using caged fish (non-POD species) 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.

We initiated several studies to address the possible role of contaminants and disease in the POD. The largest study centered on biweekly monitoring of ambient water toxicity over 4 years in two phases (2006–2007 and 2008–2009) with standard bioassays using the amphipod *Hyalella azteca* at 15 to 16 sites in the Delta, Suisun Bay, and the Napa River as well as additional monitoring of water toxicity to larval delta smelt during the spring months (Werner et al. 2008, Werner et al. 2010a, Werner et al. 2010b). The study also included laboratory investigations on the comparative sensitivity of important fish and aquatic invertebrate species to chemical contaminants of concern in the Delta, development and application of *in situ* exposure systems, and studies to develop biomarker tools for fish species of special interest.

Significant amphipod mortality was observed in 5.6% of 693 ambient water samples collected in 2006–2007 and in 0.5% of 752 samples collected in 2008–2009. The tests also included addition of the enzyme inhibitor piperonyl butoxide (PBO) which synergizes (increases) pyrethroid pesticide toxicity, but antagonizes (reduces) organophosphate (OP) insecticide toxicity. PBO additions significantly affected survival in 1.1% and 0.9% of all samples collected in 2006–2007 and 2008–2009, respectively. Growth was affected by PBO addition in 10.1% and 13.3 % of ambient samples collected in 2006–2007 and 2008–2009, respectively. Some of the toxic water samples contained measurable amounts of pyrethroids, such as bifenthrin and esfenvalerate, OPs such as chlorpyrifos and diazinon, relatively high levels of ammonium and/or ammonia, and, in two cases, relatively high concentrations of dissolved copper. Numerous samples contained more than one contaminant. Water from sites in the lower Sacramento River had the highest total ammonia and ammonium concentrations. Water from the lower Sacramento River region had the largest number of acutely toxic samples and, a relatively high occurrence of PBO effects on amphipod growth. Werner et al. (2010a) concluded that ammonia and ammonium and/or other contaminants occurring in mixture with these, likely contributed to the observed toxicity to the test invertebrates and that toxicity to invertebrates is most common in the northern Delta.

Laboratory flow-through assays exposing larval delta smelt to ambient water samples were conducted in 2007–2009. Results from these assays indicated that water quality in the Sacramento River at Hood, in the northern Delta near Cache and Lindsey Sloughs, and in the southern Delta in the San Joaquin River near Stockton was at times unfavorable for larval delta smelt. Delta smelt survival was highest in water from Suisun Slough.

It is important to note that delta smelt and *H. azteca* mortality were not necessarily observed in the same water samples. While the *H. azteca* tests are very useful for detecting biologically relevant levels of water column toxicity (especially pyrethroids), interpretation of the *H. azteca* test results with respect to fish should proceed with great caution. In addition, results from controlled bioassays conducted with grab samples under laboratory conditions may not be readily transferrable to variable field conditions.

To address the limitations of laboratory bioassays, Werner et al. (2010b) used a novel *in situ* exposure system for simultaneous tests of multiple fish and invertebrate species at Hood on the Sacramento River and in Stockton on the San Joaquin River. The *in situ* devices renewed the test water continuously, exposing test organisms to the same water quality fluctuations that would be experienced by stationary organisms in the river. Six *in situ* exposure experiments with larval delta smelt, larval fathead minnow (*Pimephales promelas*), and the amphipod *H. azteca* were conducted in spring 2009. No toxicity to *H. azteca* or *P. promelas* was detected. Larval delta smelt survival was low in the treatment and in the control water. Werner et al. (2010b) concluded that larval delta smelt may be too sensitive to stresses of transport, salinity, and temperature to be suitable test organisms for *in situ* tank systems and recommended using surrogate species, such as rainbow trout, in future tests.

To assess the comparability and relevance to Delta species of test results from bioassays conducted with different organisms, Werner et al. (2010b) compared the contaminant sensitivity of standard test organisms, such as larval fathead minnow, the waterflea *Ceriodaphia dubia* and the amphipod *H. azteca*, with important Delta species, such as larval delta smelt and the copepod *Eurytemora affinis*. They exposed these organisms to a series of chemical contaminants previously detected in Delta water samples, including copper, total ammonia, the OP insecticides chlorpyrifos and diazinon, and the pyrethroid insecticides bifenthrin, cyfluthrin, esfenvalerate, and permethrin. Larval delta smelt were 1.8 to >11 times more sensitive than fathead minnow to ammonia, copper, and all insecticides tested with the exception of permethrin. Invertebrates were more sensitive than the two fish species. The zooplankton species *E. affinis* and *C. dubia* were most sensitive to total ammonia, and *C. dubia* was most sensitive to copper. *C. dubia* was the most sensitive, and *E. affinis* the least sensitive to the tested organophosphates insecticides. *H. azteca* was the most sensitive to all tested pyrethroid insecticides.

Pyrethroid insecticides are of particular interest in the POD investigation because use of these insecticides has increased during the most recent decade (Amweg et al. 2005, Oros and Werner 2005) as use of some OP insecticides has declined. Toxicity of sediment-bound pyrethroids to macroinvertebrates has been observed in watersheds upstream of the Delta (Weston et al. 2004, 2005). In recent toxicity tests, urban source waters to the Delta were almost always toxic to *H. azteca* due to pyrethroid pesticides (Weston and Lydy 2010). Agricultural runoff samples were toxic less often. Similar to the findings for ammonium (Jassby 2008), the effluent from the SRWTP was the largest source of pyrethroids to the Delta in this study and *Hyalella azteca* always experienced high mortality rates and swimming impairment when exposed to effluent from this treatment plant (Weston and Lydy 2010). This was not the case with effluent from the Stockton Wastewater Treatment Plant, which utilizes tertiary treatment, suggesting that different treatment methods may remove or retain pyrethroids differently. Prior to this study, urban inputs in general and wastewater treatment plants in particular had not been considered a primary source of insecticides in the Delta. Urban insecticide applications thus represent an unexpected contaminant source. This is of concern because the estuary as a whole as well the southern and western subregions can be classified as stressed by urbanization on the basis of impervious cover due to the rapid growth of the Bay Area, Sacramento, and Stockton metropolitan areas (Stoms 2010).

Brander et al. (2009) showed that mixtures of the two pyrethroid pesticides, permethrin and cyfluthrin, are lethal to *H. azteca* at concentrations found in Delta water samples. Beggel et al. (2010) found that commercial formulations of two commonly used insecticides, bifenthrin and fipronil, were more toxic to fathead minnows than the pure active ingredients. Significant sublethal effects on fish swimming performance or growth were observed at 10–20% of the concentrations required to kill 10% of exposed fish (LC10). These results suggest that increased toxicity due to inert ingredients should be considered in risk assessments and regulation of insecticides (Beggel et al. 2010).

The sublethal effects measurements conducted by Beggel et al. (2010) represent another major aspect of the POD contaminants studies, examining sublethal effects. Werner et al. (2008, 2010b) focused primarily on the development and application of biochemical and molecular biomarkers of sublethal stress responses to contaminants. Geist et al. (2007) investigated the effects of copper and the pyrethroid insecticide esfenvalerate on survival, growth, swimming behavior, and expression of stress response genes in juvenile (81–90 d old) striped bass (*M. saxatilis*). They found that the expression of stress response genes was the most sensitive indicator for copper and esfenvalerate exposures at low concentrations. Expression of stress response genes was also seen in striped bass exposed to Delta water samples (Werner et al. 2008).

Connon et al. (2009, in press, in review) developed a cDNA microarray for delta smelt to study the sublethal effects of chemical exposure. Connon et al. (2009) used the microarray to assess the effects of exposure of larval delta smelt to the pyrethroid esfenvalerate and identified specific patterns of gene expression related to affected physiological functions. Connon et al. (in press) then exposed larval delta smelt to sublethal concentrations of esfenvalerate. The microarray results showed patterns of gene expression indicating neurological impairment, supported by anomalous behavior, and suggesting effects on gonad and brain development. Connon et al. (in review) evaluated the effects of copper on survival, swimming velocity and gene expression in larval and juvenile delta smelt. Swimming velocity declined with increasing copper concentration. The microarray results indicated significant sublethal effects of copper on nerve and muscle function, digestion and immune function at approximately 20% of the LC50 concentration. In ammonia exposure experiments, genes predominantly encoding for membrane bound proteins responded significantly; however, neurological activity and muscular activity were also impaired (Werner et al. 2010).

Biomarkers were also developed and applied in studies with striped bass and fathead minnows (Werner et al. 2010). Juvenile striped bass were exposed to extracts from SPMDs (semi-permeable membrane devices, which collect dissolved lipophilic compounds from water), which were deployed at several sites in the Delta, Tissue samples from the striped bass were analyzed for expression of four stress-responsive genes. Results indicated general stress and immune system responses at Boynton Slough (Suisun Marsh) and Sherman Lake (confluence) sites (Werner et al. 2010). In fathead minnows, observed gene responses suggested stress-related cellular effects in fathead minnow larvae exposed to bifenthrin and fipronil (0.07 and 53 μg/L, respectively) (Beggel et al. 2010, Werner et al. 2010). The concentrations associated with the gene responses corresponded to the concentrations causing abnormal swimming. Patterns of gene response in delta smelt exposed to water from different delta sites show great promise for toxicity monitoring in field surveys (R. Connon, UC Davis, personal communication). Results from these initial studies support the use of microarrays to assess the effects of contaminants on aquatic species in field studies. Further method development and application for delta smelt are in progress.

In addition to the novel methods described above, the POD investigations have included the use of biomarkers and histological techniques used previously to evaluate toxic effects on POD fishes (Bennett et al. 1995, Bennett 2005). The results to date have been mixed for the four POD fish species. Histopathological and viral evaluation of young longfin smelt collected in 2006 and 2007 indicated no histological abnormalities associated with toxic exposure or disease (Foott et al. 2006, Foott and Stone 2008). 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, Foott and Stone 2008). 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 and 2007. Adult delta smelt collected from the Delta during winter 2005 also were considered healthy, showing little histopathological evidence for starvation or disease (Bennett et al. 2008). However, there was some evidence of low frequency endocrine disruption. In 2005, 3 of 47 (6%) of adult delta smelt were intersex, having immature oocytes in their testes (Bennett et al. 2008). This is a lower percentage than reported by Teh et al. (2007) (9 of 65 male delta smelt, 14%). Juvenile delta smelt exhibited a high incidence of glycogen depletion (80% of fish) and liver abnormalities (85% of fish), presumably in response to stressful summer rearing conditions (Bennett et al. 2008).

In contrast, 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 (D. Baxa, UCD, unpublished data). Severe viral infection was found in Mississippi silverside and juvenile delta smelt collected from Suisun Bay during summer 2005 (Baxa et al. in prep.).

Contaminants and disease may severely impair striped bass of all life stages in the estuary (Ostrach et al. 2008a). Contaminants were identified as having significant effects on larval striped bass and juvenile striped bass up to 6–8 months old. Juvenile striped bass were found to be suffering from sublethal contaminant exposure and abnormal disease and parasitism. Adult striped bass are likely adversely affected by the bioaccumulation of contaminants such as polybrominated diphenyl ethers (PBDEs). In addition to these contaminant and disease effects, striped bass may be especially vulnerable to contaminant effects because the long-lived females can bioaccumulate contaminants over several years and then transfer the contaminants to egg yolk. This results in maternal transfer of xenobiotics to eggs resulting in severe adverse effects on larval development and subsequent larval survival that may be contributing to population level effects (Ostrach et al. 2008b). Contaminants are thus likely a significant driver contributing to the decline of young striped bass in the San Francisco Estuary (Ostrach et al. 2008a).

Finally, the POD investigation has also included studies of the potentially toxic cyanobacterium *M. aeruginosa*. Large blooms of *M. aeruginosa* were first noted in the Delta in 1999 and have since become an annually recurring feature of the Delta plankton community (Lehman et al. 2005, 2008). During the low flow conditions of summer 2007, blooms of this cyanobacterium spread downstream to the western Delta and beyond (P. Lehman, DWR, unpublished data). Microcystis is more abumdant in dry years (2007 and 2008) compared to wet years (2004 and 2005) (P. Lehman, DWR, unpublished data). Genetic analysis determined that the *M. aeruginosa* strain in the Delta is unique (Moisander et al. 2009). The *M. aeruginosa* blooms peak in the fresh waters of the central Delta during the summer at warm temperatures (20–25°C; Lehman et al. 2008). Large striped bass and all life stages of threadfin shad occur widely in the central and southern Delta during summer, and thus may be at the highest risk of exposure to toxic blooms. Longfin smelt and delta smelt are generally not present in this region of the Delta during summer (Nobriga et al. 2008, Rosenfield and Baxter 2007) so it is less likely that *M. aeruginosa* toxicity is a factor in their recent decline. However, a recent study by Miller et al. (2010) documented a complex transfer of toxic microcystins from freshwater, through mollusks (which bioaccumulated the microcystins), to sea otters, resulting in mortality of sea otters in coastal Monterey Bay. This study suggests there is some potential that fish residing in brackish and marine parts of the estuary could be affected by toxic *Microcystis* blooms through trophic pathways.

Baxa et al. (2010) developed a genetic technique for quickly identifying *Microcystis* abundance and toxicity and determined that *Microcystis* toxicity is spatially and temporally variable in the Delta. Elevated toxicity was common in the brackish western Delta near Antioch. This was unexpected and may indicate the presence of a salinity tolerant strain in this region. This is the same area where elevated microcystin levels and biomarker scores for juvenile striped bass were found. A recent laboratory study (Deng et al. 2010) showed that dietary *Microcystis* is toxic to Medaka fish (*Oryzias latipes*) and has a more adverse impact on male fish. Results suggest that long-term exposure to microcystins in the Delta may be a health problem for fish.

Microcystins probably do not reach concentrations acutely toxic to Delta fishes (Lehman et al. 2008), but during blooms, the microcystin concentrations may be high enough to impair invertebrates, which could influence prey availability for fishes. Lehman et al. (2010) found that *Microcystis* may indeed contribute to changes in phytoplankton, zooplankton and fish populations in the Delta. Ger et al. (2009) determined toxicity of one form of microcystin (LR) to two species of calanoid copepods, *E. affinis* and *P. forbesi*, which are important as food to POD species. They found that, although the copepods tested were relatively sensitive to microcystin-LR compared to other types of zooplankton, ambient concentrations in the Delta were unlikely to be acutely toxic. However, chronic effects were not determined. Feeding trials indicated that both species of copepods were very sensitive to *Microcytis* (Ger et al. 2010a). Both species experienced significant mortality when *Microcystis* was 10% or more of the diet, whether the *Microcystis* strain produced toxic microcystins or not. This suggests that consumption of *Microcystis* by wild populations of copepods has the potential to affect food resources of POD fishes. *P. forbesi* ingested an order of magnitude less than *E. affinis*, suggesting it is better able to tolerate the presence of *Microcystis* in its diet than *E. affinis* via more efficient selective feeding on alternative food (Ger et al. 2010b). It also appears that selective feeding by *P. forbesi* becomes more pronounced during long-term exposure to different *Microcystis* strains during blooms.

In summary, many different man-made and natural toxins are present in the estuary. The absence of consistent long-term monitoring of contaminant concentrations does not allow for a correlative assessment of contaminant effects on Delta biota over time (Johnson 2010) and prevents contaminants from being included in statistical analyses of the POD declines such as those conducted by MacNally et al. (2010) and Thomson et al. (2010). While four years of biweekly water toxicity tests have provided evidence for sporadic direct, acute toxicity, the majority of contaminant effects are likely sublethal and/or mediated by the food web (Scholz et al. in review, Brooks et al. in review). Unfortunately, conventional methods of testing pesticides on a chemical by chemical basis or conducting bioassays with standard test organisms are unlikely to be useful in assessing the effects of complex mixtures of many chemicals on the ecosystem, especially when many of the effects are nonlethal and chronic (Scholz et al. in review). From a scientific perspective, novel biomarkers such as those developed by Connon et al. (2009) hold great promise for arriving at a more reliable and nuanced understanding of contaminant effects. From a management perspective, these problems might best be addressed by reducing transport of all pesticides to the aquatic environment rather than managing chemicals suspected to be important on a case by case basis (Scholz et al. in review).

Habitat for Planktonic and Benthic Aquatic Organisms: Much of the previous discussion about how physical conditions and water quality affect pelagic fishes is also relevant to other aquatic organisms including plankton and the benthos. The abundance and distribution of pelagic organisms in an estuary, particularly plankton, results from the interaction of production, consumption of the organism, and transport (Lucas et al. 2009b). Factors limiting phytoplankton growth in the estuary have already been discussed above. The distribution and abundance of benthos represents an interaction between conditions during the period when species are recruiting to the bottom and subsequent conditions for survival, growth, and reproduction.

It is important to keep in mind that river flows and exports influence estuarine salinity gradients and water transport times (i.e., how fast water or transported constituents move through the system). These factors affect both habitat suitability for benthos and the transport of pelagic plankton. High delta outflow leads to more rapid transport through the Delta (days), which generally results in lower plankton biomass (Kimmerer 2004), but also lower cumulative entrainment effects in the Delta (Kimmerer and Nobriga 2007). In contrast, longer transport times (a month or more), which result from low delta outflows, may result in higher plankton biomass, depending on consumption rates by grazers (see Lucas et al. 2009a). This can increase food availability for planktivorous fishes; however, much of this production may be lost to filter feeding benthos (e.g., Lucas et al. 2002) or water diversions (Arthur et al. 1996) under low delta outflow conditions. In the San Joaquin River 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 2005). Recent particle tracking modeling results for the Delta show that transport times in the central Delta are highly variable depending on Delta inflow, exports, and particle release location (Kimmerer and Nobriga 2007). Very high inflow leads to rapid transport times. The longest transport 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 more mobile pelagic organisms. 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 and Vayssières 2010). Specifically, the invasion of the clam *C. amurensis* in the late 1980s resulted in a fundamental change in the benthic community; however, the center of distribution of *C. amurensis* and other benthic species shifts geographically with the estuarine salinity gradient, as the salinity gradient responds to outflows. 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. There was nothing unusual about the composition of benthic assemblages during the POD period. As will be discussed below, changes in the benthos can have major effects on food availability to pelagic organisms.

Climate Change Effects on Habitat: While climate change did not cause the POD, there are several reasons we expect climate change will have negative influences on future 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, moving X2 landward, unless sufficient freshwater resources are available to repel the seawater. This will shift fish distributions upstream and possibly further reduce habitat suitability for some species. Based on the results of Feyrer et al. (2007), Feyrer et al. (2010) developed a model to predict delta smelt habitat quality in response to X2. Data from several scenarios of climate change predict declining habitat suitability as climate change proceeds (Feyrer et al. 2010). Sea level rise will also increase the likelihood of levee failures (Mount and Twiss 2005) and perhaps reduce the likelihood of repairing such failures, given economic considerations (e.g., Suddeth et al. 2010). Levee failures and flooding of islands would lead to changes in available aquatic habitat (Lund et al. 2007, 2008). In addition, currently unleveed wetlands and other habitats will be susceptible to inundation (Knowles 2010).

Third, climate change models project warmer air 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 21–24°C (Nobriga et al. 2008) and high mortality of delta smelt is expected above about 25°C based on several lines of evidence. First, the critical thermal maximum of delta smelt acclimated to 17°C is 25°C (Swanson et al. 2000). Second, delta smelt are rarely captured in field surveys when water temperatures reach 25°C (Bennett 2005, Nobriga et al. 2008). Third, following acclimation by gradually increasing temperature to match ambient temperatures and with daily feeding, juvenile delta smelt can survive short term exposure to ambient temperatures up to about 27°C for several days (G. Castillo, USFWS, unpublished data). However, continued exposure to daily peaks in ambient temperatures over 27.0 °C lead to sudden high mortality, even if subsequent water temperature decline (G. Castillo, USFWS, unpublished data). Models developed for water temperature in the delta (Wagner et al. submitted) suggest that warmer air temperatures predicted by climate change will result in summer temperatures in the upper estuary exceeding 25°C on more days. This will likely affect viability of the delta smelt population. Temperatures between 20 and 25°C may lead to sublethal stress of delta smelt and other native species that could reduce growth rates or otherwise affect fish populations (Bennett et al. 2008). On the other hand, some non-native and nuisance species adapted to warmer temperatures such as largemouth bass and *M. aeruginosa* will likely increase in abundance with rising water temperatures (Feyrer and Healey 2003, Paerl and Huisman 2008).

There may be some opportunities to ameliorate or mitigate the effects of increasing water temperatures. Thermal refugia may persist in deeper channels near the bottom. The role of shade from riparian vegetation may also be important. Many levees do or can support riparian trees; however, such vegetation may be removed by the US Army Corp of Engineers to maintain the structural integrity of the levees. Greenberg (UCD, unpublished data) modeled the relative difference in incident solar radiation on channels in the Delta under the current conditions and in a treeless Delta. The model used Lidar data acquired in 2007 to assess the structural conditions and a solar irradiation model to calculate daily irradiation for summer months. The results indicated that as much as a 10% increase in solar radiation could occur in a treeless Delta, which may result in significant increases in water temperature – clearly an undesirable side effect of removing trees. Increasing shade over current levels might help mitigate the temperature increases calculated by Wagner et al. (submitted). Tidally driven daily water exchanges between shallow and deeper water areas can also affect overall water temperatures (C. Enright, DWR, personal communication), and tidal marsh restoration may provide an opportunity for counteracting expected increases in water temperature if tidal marshes can cool water sufficiently.

Top-Down

Predation is a common mechanism by which weakened fish are ultimately killed. Thus, increased predation can be a manifestation of other changes in the ecosystem like decreased habitat suitability, starvation, and disease. However, in the top-down section of our conceptual model, we are referring to elevated mortality of healthy individuals due to predation or removal by water diversions and associated factors. Thus, the top-down effects are predicated on two hypotheses, which are not mutually exclusive. The first is that consumption or removal of healthy fish biomass by piscivores (principally striped bass and largemouth bass *Micropterus salmoides*) increased around 2000. The second is that mortality due to water diversions (SWP/CVP exports; power plant diversions) increased around 2000. This could have occurred if one or more of the following happened: (1) water diversions and exports increased during periods the POD fishes were vulnerable to them; (2) piscivorous fishes became more abundant relative to the POD fishes; (3) pelagic fish distribution shifted to locations with higher predation risk (e.g. habitat changes); or (4) the POD fishes became more vulnerable to predation as a consequence of their extremely low population size (i.e., predation could contribute to the Allee effect hypothesized in the Previous Abundance section) or increases in water clarity.

Predation-driven Allee effects can arise from diminished anti-predator behavior or increased predator swamping of individuals in smaller prey groups (Berec et al. 2006). They are most likely to occur with generalist predators in situations where predation is a major source of mortality, and predation refuges are limited (Gascoigne et al. 2004). In this situation, individuals of depleted populations continue to be consumed even though they are at low density. Specialized predators that tend to focus on only a few species at any one time often switch between abundant prey species and consequently reduce consumption of rare prey species. As will be described below, the combination of a widely distributed pelagic piscivore (striped bass), an efficient littoral piscivore (largemouth bass), cumulative entrainment losses of multiple life stages, and decreased habitat suitability suggest the conditions listed by Gascoigne et al. (2004) could apply in the Delta.

Predation Effects: Predation is a natural process that occurs in almost all ecosystems. However, problems can occur when established predator-prey relationships are disrupted by environmental changes or species introductions. Many examples of ecosystem change due to introduced predators (e.g., Brown and Moyle 1991, Goldschmidt et al. 1993) or changes in established predator-prey relationships (e.g., Carpenter et al. 2001, Frank et al. 2005) have been documented in aquatic systems. This hypothesis suggests that predation effects have increased in all water year types as a result of increased populations of pelagic and inshore piscivores.

Predation processes were almost certainly changed with the introduction of striped bass to the Delta in 1879. As mentioned earlier, the striped bass was very successful and supported a commercial fishery within a decade after the introduction. Moyle (2002) observed that the fast growing, pelagic, schooling striped bass was likely a much more effective predator on pelagic prey than the native predators including the relatively sluggish thicktail chub (*Gila craussicauda*, now extinct) and Sacramento perch (*Archoplites interruptus*, extirpated from Delta; Crain and Moyle, in press), slow growing Sacramento pikeminnow *Ptychocheilus grandis*, and cold water requiring steelhead rainbow trout *Oncorhynchus mykiss*. In fact, at least the juvenile stages of all these species are or were likely consumed by large striped bass. Unfortunately, historical data are not available to determine if changes in predation rates have occurred.

Continued predation pressure from striped bass on Delta pelagic fishes in recent years is likely because of the number of predatory juvenile (Figure 15) and adult striped bass (Figure 9) as well as their spatial and seasonal distribution, food habits (Stevens 1966), and bioenergetics (Loboschefsky et al. submitted). Although age-0 striped bass themselves are a POD species, the resiliency of the species is comparatively high and demonstrated in part by the fact that juvenile age-1 and age-2 striped bass have declined more slowly than age-0 striped bass (compare Figure 9 with Figure 15, CDFG, unpublished data). However, a paucity of properly designed striped bass food habit studies has precluded the direct estimation of the number of delta smelt, longfin smelt, threadfin shad, and juvenile striped bass consumed by striped bass during the POD years.

Largemouth bass abundance has increased in the Delta over the past few decades (Brown and Michniuk 2007). Largemouth bass were introduced to the Central Valley in the mid-1890s (Dill and Cordone 1997) and were present in the Delta soon after that. Although none of the IEP surveys adequately tracks largemouth bass population trends, a comparison of abundance estimates between intermittent surveys conducted in the early 1980s, late 1990s, early 2000s (CDFG, unpublised data) and from 2009 to 2010 (L. Conrad, DWR, unpublished data) shows that largemouth bass and sunfish populations more than doubled during the years of the POD (Figure 16).

Analyses of fish salvage data show an abrupt increase in salvage of young largemouth bass in the early 1990s, before the POD, with salvage remaining at high levels since then (Figure 17). This suggests an increase in largemouth bass abundance in the early 1990s. 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). Although the historic distributions of native species of SAV are not known, it is possible that their coverage may not have been as extensive or persistent as *E. densa* is today. For example, unlike most native aquatic macrophytes, *E. densa* has a bimodal growth pattern, with peaks in late spring and the early fall. The second growth period in late fall may help existing patches persist through the winter and provide a head start on growth the following spring. These characteristics likely contributed to the expansion of the distribution of *E. densa* in the Delta and perhaps help *E. densa* compete with other aquatic macrophytes (Santos et al. 2010). The invasion of *E. densa* has occurred during highly altered environmental conditions compared to historical conditions. Historical conditions, including dynamic flow and salinity regimes, higher turbidity, and seasonal (rather than perennial) inundation of large portions of shallow-water habitat would likely have been less favorable for establishment of *E. densa*. The areal coverage of *E. densa* in the Delta has fluctuated from 2004 to 2008, suggesting that this habitat may no longer be expanding (Hestir 2010).

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). Conceivably, 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). However, ongoing analyses of largemouth bass diet suggest that the largemout bass are chiefly consuming common littoral invertebrate and fish species, such as crayfish and juvenile sunfish (L. Conrad, DWR, unpublished data). To date, over 1400 samples collected from sites located throughout the Delta have been examined and these have contained only 12 threadfin shad and 1 juvenile striped bass (L. Conrad, DWR, unpublished data). Furthermore, no salmonid or osmerid species have been found in largemouth bass stomachs. The zero or low frequencies of the POD species in bass stomachs may be due largely to limited spatial overlap with largemouth bass; however, increased abundance of largemouth bass may still impose an important predation threat in limited instances where they do co-occur.

Predation pressures on the early life stages of POD species are poorly understood but likely have highly significant impacts on recruitment. Historically, questions involving predation of larval fish have been difficult to address due to the quick degradation of fragile larvae in predator guts.

However, such studies have become feasible with the development of a genetic assay to look for the DNA of delta smelt in the guts of predators (M. Baerwald et al., DWR, unpublished data). Initial application of this assay has focused mainly on Mississippi silversides; largely due to their increasing abundance in the Delta and their ability to eat delta smelt larvae in captivity (Bennett, 2005). To date, sampling conducted in portions of the Sacramento deepwater ship channel where larval smelt are relatively abundant, found that of 37 captured silversides, 15 tested positive for delta smelt DNA in their gut contents (B. Schreier, DWR, unpublished data).

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 (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 a stronger influence on the biotic community 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 and fall. Multi-year wet cycles probably increased (and still do) the overall “abiotic-ness” of the estuary, allowing populations of all species to increase. Drought cycles likely increased the estuary’s “biotic-ness” (Livingston et al. 1997), with low reproductive output and increased effect of predation on population abundances. Flow management in the San Francisco Estuary and its watershed has reduced flow variation much of the time and in some locations more than others (Moyle et al. 2010). This has probably affected the magnitudes and durations of abiotic and biotic phases (Nobriga et al. 2005). In other words, reduced variability in environmental conditions of 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.

Entrainment: The water diversions that are of most concern for fishes in the estuary are the SWP and CVP export facilities, Antioch and Pittsburg power plants, and within-Delta agricultural diversions. Of these, the operations of agricultural diversions are the least likely to have had an effect on the POD species because of the small volumes they divert and because it does not appear they have changed operations from the 1990s to 2000s. A detailed study of one of these diversions found evidence that their effects on delta smelt are small (Nobriga et al. 2004). Because agricultural diversions seem an unlikely contributor to the POD declines, we do not address them further. We do not mean to assert that such diversions have no effect on Delta fishes. Addressing that issue would require additional analysis and study.

The Antioch and Pittsburgh power plants divert approximately 3200 cubic feet per second for non-consumptive water use when they are being operated. The power plants can directly entrain pelagic fishes or affect them indirectly through discharge of heated water (Matica and Sommer, DWR, unpublished data). Studies at the power plants in the late 1970s indicated that losses of delta smelt and longfin smelt were on the order of hundreds of thousands of individuals; however, the plants were operated less frequently during the 2000s, suggesting that the power plants played a minor, if any, role in the POD (Cavallo et al. 2009).

Entrainment losses at the SWP and CVP represent the largest sources of observable mortality for many pelagic fishes in the estuary (Brown et al. 1996, Sommer et al. 2007, Kimmerer 2008, Grimaldo et al. 2009). SWP and CVP entrainment losses are indexed by fish captured (salvaged) at the state Skinner Fish Protective Facility (SFF) and the federal Tracy Fish Collection Facility (TFCF). These facilities are located at the intakes to the State and Federal export pumps on Old River in the south-western Delta. While the TFCF is located directly on Old River, the SFF is preceded by the large Clifton Court Forebay (CCF), a reservoir that is connected to Old River via operable radial gates. Subsamples of the fish captured at the fish facilities are identified and counted and all fish are trucked to several locations in the Delta where they are released back into the wild.

It is important to note that fish salvage represents only the fraction of the total number of entrained fish. As many studies have shown, many more fish are entrained, but not salvaged due to pre-screen losses and capture inefficiencies at the fish facilities (Brown et al. 1996, Gingras 1997, Kimmerer 2008, Clark et al. 2009). While capture inefficiencies occur at both facilities, pre-screen losses at the SWP are exacerbated by the CCF. CCF is a shallow reservoir with high numbers of predatory fish, piscivorous birds, and in recent years large beds of SAV requiring removal (Kano 1990, Brown et al. 1996, Clark et al. 2009). Predation rates likely increase with increasing residence time in CCF. Recent hydrodynamic and 3-D particle tracking modeling studies in CCF showed that wind and exports affect residence time in CCF (M. MacWilliams, River Modeling Environmental Consulting, unpublished data). During periods of high winds and low exports, a strong counterclockwise circulation gyre in CCF results in significant mixing and increases the average travel time from the radial gates to the SFF, with a large range of estimated particle residence times. During low wind and high export conditions, residence times are much shorter and most particles are transported roughly in a straight line trajectory from the radial gates to the Banks Pumping Plant.

Results of 11 mark-recapture and telemetry studies conducted in CCF with juvenile hatchery-raised striped bass and salmonids between 1976 and 2007 showed consistently high pre-screen losses ranging from 63% to 99% (Gingras 1997, Clark et al. 2009), likely due to high levels of predation in CCF. In a recent study, thousands of marked juvenile and adult hatchery-raised delta smelt were released into CCF and recaptured in the SFF (G. Castillo, USFWS, unpublished data). The mean percent recovery of adult fish released in CCF varied from 3.01% and 0.41% in February and March, respectively, to 0.03% for juveniles in June. This means that most delta smelt entrained into CCF may never be captured and accounted for at the SFF, with entrainment varying 10 to 100-fold between February and June. As this and previous studies have shown, pre-screen losses are both variable and consistently high. *Salvage is thus not a sensitive index of entrainment*. There has not been any monitoring of actual entrainment and no correction factors for prescreen losses and capture inefficiencies have been developed or applied to estimate entrainment. Therefore, salvage numbers have been and continue to be used as a substitute for entrainment in spite of their well-documented limitations.

During the POD years, summer, fall, and winter exports sharply increased from the 1990s, which led to increased salvage and thus likely increased entrainment of several pelagic fishes in the estuary (Sommer et al. 2007, Kimmerer 2008, Grimaldo et al. 2009). Winter exports increased the most during the POD years, which led to increases in salvage of adult delta smelt, adult longfin smelt, and threadfin shad (Figure 18). Similar increases in the salvage of littoral species, including centrarchids and inland silverside, were observed during the same period (Figure 19). The littoral species are less influenced by flow changes than the POD fishes. The increases in salvage for centrarchids, including largemouth bass, may be at least partially a result of the range expansion of *E. 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 pelagic and littoral fishes suggests a large change in the hydrodynamic influence of the export diversions during recent winters. Note that winter salvage of all the POD species declined during the winters of 2005–2006, 2006–2007 and 2008–2009, possibly due to the drop in their population abundance.

In trying to evaluate the mechanism(s) for increased wintertime salvage, early POD studies produced three key observations (IEP 2005). First, there was an increase in exports during winter as compared to previous years. 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. Finally, there was an increase in the duration of the operation of barriers placed into southern 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 (OMR) (Figure 1B), which integrate changes in inflow, exports, and barrier operations (Arthur et al. 1996, Monsen et al. 2007). Net flow refers to the magnitude and direction (seaward or landward) of the water in OMR with the effects of the semidiurnal tide removed. Grimaldo et al. (2009) found significant relationships between OMR flows and fish salvage for delta smelt, longfin smelt, and striped bass (Figure 20). Not only has net OMR flow been useful to understand entrainment of fishes in the estuary (Kimmerer 2008, Grimaldo et al. 2009), it was adopted as a regulatory tool to manage entrainment risk of delta smelt from the SWP and CVP exports (USFWS 2008).

Although entrainment into water diversions is well recognized as a source of mortality for individual fish, there has been debate about whether entrainment has important population-level effects for the pelagic fishes in the estuary. Kimmerer (2008) estimated that entrainment of delta smelt at the SWP and CVP accounted for high population losses (up to 50%) during POD years, suggesting that exports played a major role in the POD decline. However, the population-level effects of entrainment can also be obscured by interactions between year classes or life stages of a species. For example, Kimmerer (2008) found that exports explained little variability in fall abundance of delta smelt because of a 50-fold variation in their summer to fall survival. Kimmerer concluded, “This is not to dismiss the rather large proportional losses of delta smelt that occur in some years; rather, it suggests that these losses have effects that are episodic and that therefore their effects should be calculated rather than inferred from correlative analyses.” Similarly, Manly and Chotkowki (2006) used log-linear modeling to evaluate environmental factors that may have affected long-term trends in the FMWT abundance index of delta smelt. They found that monthly or semi-monthly measures of exports or OMR flow had a statistically significant effect on delta smelt abundance; however, individually exports and flow explained only 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 long-term trends of delta smelt fall abundance.

Thomson et al. (2010) found that turbidity (discussed as water clarity in that paper) and winter exports were important factors associated with the long-term trend in annual fall abundance of delta smelt (as measured by FMWT) but could not explain the step decline in fish abundance in the early 2000s. For longfin smelt, they found that a long-term population trend was associated with turbidity and spring X2. As for delta smelt, these factors could not account for the POD decline. A long-term trend in age-0 striped bass was associated with turbidity and an autocorrelation with abundance in previous years. Again, the POD decline was unexplained by the variables that accounted for the long-term trend. There was weak evidence for winter and spring exports and calanoid copepod abundance being important for long-term trends in threadfin shad abundance but again the POD decline could not be explained. So, in all cases, exports (a surrogate for entrainment) were not useful in explaining the POD declines (Thomson et al. 2010). In a multiple autoregressive analysis of the same data sets, Mac Nally et al. (2010) found some evidence for export effects on delta smelt and threadfin shad, however, other factors had stronger effects on POD species including X2 and water clarity. These results suggest that exports (i.e., entrainment) did not play a major role in the post-2000 POD, although they may have played an important role in setting up the POD through their longer-term effects and through interactions with other drivers.

However, these results do not mean that direct export effects can be dismissed as contributing causes of the POD. There are two aspects of entrainment that were not addressed by the earlier analyses (Manly and Chotkowski 2006, Thomson et al. 2010, Mac Nally et al. 2010) and are not well understood: (1) larval entrainment, and (2) the cumulative effects of entrainment of multiple life stages. Larval entrainment is unknown because larvae are not sampled effectively at the fish screening facilities. To address this shortcoming, Kimmerer and Nobriga (2008) coupled a particle tracking modeling with survey results to estimate larval entrainment. Kimmerer (2008) 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 inflow 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. A recent attempt to manage diversions to protect fish, the Environmental Water Account, proved effective at increasing water supply reliability, but benefits to fish were not clear (Brown et al. 2009).

Moreover, export effects may be subtle and operate only at specific times or in specific years to disproportionately affect only one life stage of delta smelt. For example, it has been proposed that losses of larger females and their larvae may have a disproportionate effect on the delta smelt population (B. Bennett, UCD, unpublished data). Bennett (unpublished data) proposes that larger females spawn earlier in the season and produce more eggs, which are of better quality and have higher probabilities of survival, as has been noted for Atlantic cod and other commercially harvested species (Marteinsdottir and Steinarsson 1998, Swain et al. 2007). As a consequence, winter exports, which have increased since exports began (Figure 21), 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 predictors.

Some recent studies suggest possible strategies for minimizing the effects of entrainment. There may be alternative ways to operate CCF to reduce prescreen losses (G. Castillo, USFWS, unpublished data). Grimaldo et al. (2009) suggested that salvage of pelagic fishes could be reduced if exports were reduced during periods when specific species were vulnerable to exports. For example, Grimaldo et al. (2009) found that adult delta smelt entrainment increased in the period following the first winter rains (first flush) when turbidity increased. This is the time period when adult delta smelt migrate upstream towards the interior delta to prepare for spawning. Grimaldo et al. (2009) suggested that entrainment risk for adult delta smelt during this time period could be reduced if exports were reduced during and after the first flush. On an intra-annual scale, adult delta smelt entrainment was related to OMR flow but there was also an interaction of OMR flow with X2. This suggests that the position of the population in relation to the salinity field prior to migration is important, but only if OMR flows are negative following first flush events. For age-0 fish, the only model explaining inter-annual differences in delta smelt salvage included zooplankton abundance suggesting a food effect. In contrast, age-0 striped bass salvage was best predicted by year class strength, indicating that salvage is based simply on the number of fish in the system. Within years (intra-annual scale), age-0 delta smelt salvage was best explained by OMR flows, turbidity, and abundance. High turbidity and abundance resulted in increased salvage. Relationships between OMR flows and salvage were not found for any non-POD fishes (Grimaldo et al. 2009).

Bottom-Up

In this portion of the conceptual model, we propose that changes in the quality and availability of food have had important consequences for pelagic fishes. Here, we describe the evidence that there have been long-term and recent changes in food web structure and function. In the first section we discuss the availability of overall phytoplankton biomass and changes in the composition of the phytoplankton community. In the second section we discuss the implications of phytoplankton availability and species composition for primary and secondary consumers. Finally we briefly discuss the issue of food co-occurrence with fish consumers.

Food Availability: 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 phytoplankton biomass and primary productivity in the upper San Francisco Estuary is poor (Cloern and Jassby 2008) and a low fish yield is expected (Figure 22). Understanding food webs is difficult. Conceptual models for estuarine food webs have progressed from simple nutrient-driven models to much more complex models incorporating nutrient cycling, light conditions, hydrodynamics, and grazing to adequately model primary production (Cloern 2001, Jassby 2008). Understanding of the Bay-Delta food web and drivers of the food web have advanced rapidly in the last several years.

Productivity of estuarine ecosystems is broadly believed to be fueled by a detritus-based food web. In the San Francisco Estuary, much of the community metabolism in pelagic waters does result from microbial consumption of organic detritus. However, evidence suggests that metazoan production in pelagic waters is primarily driven by phytoplankton production (Sobczak et al. 2002, 2005, Mueller-Solger et al. 2002, 2006, Kimmerer et al. 2005). Protists (flagellates and ciliates) consume both microbial and phytoplankton prey (Murrell and Hollibaugh 1998, York et al 2010) and are an additional important food source for many copepod species in the estuary (Rollwagen-Bollens and Penry 2003, Bouley and Kimmerer 2006, Gifford et al. 2007, MacManus et al. 2008). However, the conversion of dissolved and particulate organic matter to microbial biomass available to zooplankton is a relatively slow and inefficient process. Thus, shifts in phytoplankton and microbial food resources for zooplankton might favor different zooplankton species. The recognition that phytoplankton production might impose limits on POD species through food availability has led to intense interest in factors affecting phytoplankton production and species composition.

In the 1970s, highest phytoplankton standing stock and primary production generally occurred in the Suisun Bay-Honker Bay region in association with the entrapment zone (Ball and Arthur 1979), which is now generally referred to as the low salinity zone. Since those early studies, there has been a significant long-term decline in phytoplankton biomass (chlorophyll *a*) and primary productivity (estimated from measurements of chlorophyll *a* and of water column light utilization efficiency) to very low levels in the Suisun Bay region and the lower Delta (Jassby et al. 2002). Jassby et al. (2002) detected a 47% decline in June–November chlorophyll *a* and a 36% decline in June–November primary production between the periods 1975–1985 and 1986–1995. This decline was associated with changes in relationships between X2 and various metazoan populations (see below for details), including some pelagic fishes; however, the decline occurred well before the recent POD declines. Jassby (2008) updated the phytoplankton analysis to include the more recent data (1996–2005) from the Delta and Suisun Bay. Jassby (2008) confirmed a long-term decline in chlorophyll *a* from 1975 to 2005 but also found that March–September chlorophyll *a* had an increasing trend in the Delta from 1996 to 2005. Suisun Bay did not exhibit any trend during 1996–2005. A similar pattern was noted for primary production in the Delta. These chlorophyll *a* patterns continued to hold through 2008 according to a more recent study by Winder and Jassby (2010). In summary, phytoplankton biomass and production in the Delta and Suisun Bay seem to have reached a low point by the end of the 1987–1994 drought. While they recovered somewhat in the Delta, chlorophyll *a* stayed consistently low in Suisun Bay through the POD years. Jassby (2008) did not analyze primary production for Suisun Bay because of evidence of inhibition of primary production in Suisun Bay associated with ammonium (see below for details; Dugdale et al. 2007). 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 in the estuary but not for the recent POD declines.

A major reason for the long-term phytoplankton reduction in the upper estuary after 1985 is benthic grazing by the invasive overbite clam (*C. amurensis*) (Alpine and Cloern 1992), 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 invasive Asiatic freshwater clam (*Corbicula fluminea*) (introduced in the 1940s) 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 *C. amurensis* invasion changed this formerly dynamic clam assemblage because *C. amurensis*, which is tolerant of a wide range of salinity, can maintain large, permanent populations in the brackish water regions of the estuary. Petersen and Vayssières (2010) analyzed 27 years of benthic data from Grizzly Bay and three other long-term monitoring stations and documented the establishment and expansion of *C. amurensis* during the 1987–1994 drought. The drought provided low-flow/high-salinity conditions that favored establishment. The population has persisted through subsequent high-flow/low-salinity years. In addition, the grazing influence of *C. amurensis* 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.

Shifts in nutrient concentrations and ratios may also contribute to the phytoplankton reduction and changes in algal species composition in the San Francisco Estuary. Phytoplankton production in the San Francisco Estuary is generally light limited with nutrient concentrations exceeding concentrations limiting primary production. 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. This occurs because diatoms preferentially utilize ammonium in their physiological processes even though it is used less efficiently. Thus, diatom populations must consume available ammonium before nitrate, which supports higher growth rates, can be utilized. Glibert (2010) analyzed long-term data (from 1975 or 1979 to 2006 depending on the variable considered) from the Delta and Suisun Bay and related changing forms and ratios of nutrients, particularly changes in ammonium, to declines in diatoms and increases in flagellates and cyanobacteria. Similar shifts in species composition were noted by Brown (2009). More recently, Parker et al. (in review) found that the suppression of algal blooms extends upstream into the Sacramento River to the SRWTP, the source of the majority of the ammonium in the river (Jassby 2008). Parker et al. (submitted) found that at high ambient ammonium concentrations, river phytoplankton cannot efficiently take up any form of nitrogen including ammonium, leading to often extremely low biomass in the river. A study using multiple stable isotope tracers (C. Kendall, USGS, personal communication) found that the cyanobacteria *M. aeruginosa* utilized ammonium, not nitrate, as the primary source of nitrogen in the central and western Delta. The SRWTP reduced its discharge by 12% starting in May 2009 (S. Dean, Sacramento Regional County Sanitation District, personal communication). This reduction likely contributed to the relatively low ambient Sacramento River ammonium concentrations observed in spring 2010 and may have led to subsequent unusually strong spring diatom blooms in Suisun Bay (R. Dugdale, CSUSF-RTC, personal communication). Only a very muted summer *Microcystis* bloom occurred in 2010 (C. Mioni, UCSC, personal communication) which might have been due to lower summer water temperatures than in previous years, but the causes for this have not yet been fully investigated.

Ammonium concentrations in the Delta and Suisun Bay have significantly increased over the last few decades, due largely to increased loading from the SRWTP (Jassby 2008). Van Nieuwenhuyse (2007) 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. Van Nieuwenhuyse (2007) explored the effects of delta inflow and light but did not address the possible effects of Delta hydrodynamics or grazing on the observed relationships. It is also unclear how the three stations analyzed relate to the Delta as a whole.

Jassby (2008) conducted a more comprehensive assessment of factors affecting primary production and suggested the following comprehensive explanation for his observations. Phytoplankton production in the lower Delta is associated with flow and residence time; however, other factors introduce a substantial degree of interannual variability. Benthic grazing by *C. fluminea* is likely a major factor (Lucas et al. 2002, Lopez et al. 2006) but data are inadequate for a quantitative evaluation of the hypothesis. In Suisun Bay, benthic grazing by *C. amurensis* is a controlling factor that keeps phytoplankton at low levels. Thus, metazoan populations in Suisun Bay are dependent on importation of phytoplankton production from the upstream portions of the Delta. Ammonium concentrations and water clarity have increased; however, these two factors should have opposing effects on phytoplankton production. These factors likely also contribute to variability in the interannual pattern but the relative importance of each is unknown. The interactions among primary production, grazing, and transport time can be complex (Lucas et al. 2002, 2009a,b)

The invasion and establishment of the overbite clam *C. amurensis* during the 1987–1994 drought was also accompanied by a series of major changes in consumers. Many of these changes likely negatively influenced pelagic fish production. Some of these changes may have been directly caused or at least exacerbated by the clam. For example, a major step-decline was observed in the abundance of the copepod *E. affinis* possibly due to predation by the overbite clam (Kimmerer et al. 1994) or indirect effects on copepod food supply. Predation by *C. amurensis* may also have been important for other zooplankton species (Kimmerer 2008). Northern anchovy abandoned the low salinity zone coincident with the *C. amurensis* invasion, presumably because the clam reduced planktonic food abundance to the point that occupation of the low-salinity waters was no longer energetically efficient for this marine fish (Kimmerer 2006). Similarly, longfin smelt shifted its distribution toward higher salinity in the early 1990s, also presumably because of reduced pelagic food in the upper estuary (Fish et al. 2009). There was also a major step-decline in mysid shrimp in 1987–1988, likely due to competition with the overbite clam for phytoplankton (Orsi and Mecum 1996). 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, Bryant and Arnold 2007). As described above, the population responses of longfin smelt and juvenile striped bass to winter–spring outflows changed after the *C. amurensis* invasion. Longfin smelt relative abundance was lower per unit outflow after the overbite clam became established (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).

Zooplankton species composition, abundance, and size in the Delta and Suisun Bay have changed tremendously over the last four decades. Mysid and copepod species present four decades ago have largely been replaced by newly introduced species. While some of these new species have reached high abundance levels, overall zooplankton abundance, biomass, and size have declined markedly and have remained at low levels for the last two decades (Winder and Jassby 2010). Food limitation and predation pressure by the overbite clam and possibly other invasive species are likely explanations for these trends (Winder and Jassby 2010).

P. forbesi, a calanoid copepod that was first observed in the estuary in the late 1980s, has replaced *E. affinis* as the most common delta smelt prey during the summer. It may have a competitive advantage over *E. affinis* due to its more selective feeding ability. Selective feeding may allow *P. forbesi* to utilize the remaining high-quality algae in the system while avoiding increasingly more prevalent low-quality and potentially toxic food items such as *M. aeruginosa* (Mueller-Solger et al. 2006, Ger et al. 2010b). After an initial rapid increase in abundance, *P. forbesi* declined somewhat in abundance from the early 1990s in the Suisun Bay and Suisun Marsh region but maintained its abundance, with some variability, in the central and southern Delta (Winder and Jassby 2010). Although substantial uncertainties about mechanisms remain, the decline in the Suisun region may be related to increasing recruitment failure and mortality in in this region due to competition and predation by *C amurensis*, contaminant exposures, and entrainment of source populations in the Delta (Mueller-Solger et al. 2006, Winder and Jassby 2010, J. Durand, UCD, unpublished data).

The abundance of a more recent invader, the cyclopoid copepod *Limnoithona tetraspina*, significantly increased in the Suisun Bay region beginning in the mid-1990s. It is now the most abundant copepod species in the Suisun Bay and confluence region of the estuary (Bouley and Kimmerer 2006, Winder and Jassby 2010). Gould and Kimmerer (2010) found that it grows slowly and has low fecundity. Based on these findings they concluded that the population success of *L. tetraspina* must be due to low mortality and that this small copepod may be able to avoid visual predation to which larger copepods are more susceptible. 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, Gould and Kimmerer 2010). Nevertheless, this copepod has been found in the guts of delta smelt (S. Slater, CDFG, unpublished data). Recent experimental studies addressing this issue suggest that larval delta smelt will consume and grow on *L. tetraspina*, but growth is less than with *P. forbesi* (L. Sullivan, SFSU-RTC, unpublished data). It remains unclear if consuming this small prey is energetically beneficial for delta smelt at all sizes or if there is a breakpoint above which larger delta smelt receive little benefit from such prey. *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 (Hennessy 2010). Its suitability as food for pelagic fish species remains unclear, but is also being investigated (L. Sullivan, SFSU-RTC, unpublished data).

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 (Bennett et al. 2008). As previously noted, warm water temperatures during the summer period may have exacerbated lack of food by raising metabolic rate of delta smelt. Based on their entire suite of delta smelt data from 2005 (histopathology, date of birth from otoliths, and growth rates from otoliths). Bennett et al. proposed a novel strategy for delta smelt survival in 2005. Natural selection appeared to favor individuals with a specific set of characters, including relatively slow larval development, but faster than average juvenile growth in July: a period with extremely high water temperatures and salinity encroachment. Many of these fish surviving into the pre-adult stage had also hatched earlier in the spawning season (i.e. before May). During 2003 and 2004 striped bass condition factor decreased in a seaward direction from the Delta through Suisun Bay (Gartz and Vu 2006).

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. Our working hypothesis is that the poor fish growth and condition in the upper estuary are due to food limitation. However, data from Bennett et al. (2008), suggest that stressful environmental conditions may be an important contributing factor. Pollutants may be contributing to poor phytoplankton growth (Dugdale et al. 2007) and invertebrate mortality (Werner et al 2010a, b), which could exacerbate food limitation. If fishes are food limited in Suisun Bay and western 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.

Food Quality: Studies on food quality have been relatively few 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.

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 good quality food sources for zooplankton, while the nutritional value of cyanobacteria such as *M. aeruginosa* can be very low (Brett and Müller-Navarra 1997), particularly for toxic varieties (Rohrlack et al. 2005). Several studies have documented shifts in phytoplankton species composition in the upper San Francisco Estuary from dominance by larger cells and diatoms to dominance by smaller cells and flagellates (Lehman 1996, 2000, Brown 2009, Glibert 2010).. 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.

Microcystis is more generally more abundant in dry years compared to wet years with high adundances in 2007 and 2008 (P. Lehman, DWR, unpublished data). During the low flow conditions of summer 2007, blooms of this cyanobacterium spread downstream to the west Delta and beyond (P. Lehman, DWR, unpublished data).The highest cell densities were observed near Antioch, considerably west of the previous center of distribution, and may thus have affected fish in the confluence and Suisun Bay regions of the upper estuary. Although ambient concentrations of microcystins are unlikely to cause acute toxicity to copepods, chronic or episodic effects on populations are possible; however, copepods recover rapidly once the microcystins dissipate (Ger et al. 2009). Consumption of *M. aeruginosa* by copepods can cause mortality, even when a low percentage of the diet (≥10%) and whether or not the strain consumed produced toxic microcystins (Ger 2010a); however *P. forbesi* appeared better able to selectively avoid *M. aeruginosa* when feeding. Therefore, the *M. aeruginosa* bloom may have indirectly affected the food supply for POD species, primarily threadfin shad and delta smelt, and other biota.

Other factors besides *M. aeruginosa* can also affect food quality for zooplankton and potentially affect food quantity and quality for higher trophic levels. 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, 2005); 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. Gifford et al. (2007) reported that larger zooplankton in the estuary are often omnivorous, and that smaller zooplankton, especially ciliates, are an important diet component for mesozooplankton in the estuary. In both studies, *L. tetraspina* clearance rates were highest for ciliates and flagellates, suggesting a greater importance of the detrital carbon pathway for this species. 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 effects on the success of particular zooplankton species. Additional research into the detrital pathway, especially the link to zooplankton through ciliates and other microbes, might be useful in understanding the factors controlling zooplankton populations, which are critical food resources for pelagic fishes in the estuary. Furthermore, the nutritional effects of an increasingly detrital-based food web also need to be explored in more depth.

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/western Delta and Suisun Bay (Lehman 1996, 2000, Brown 2010, Glibert 2010) 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 of Durand (UC Davis, unpublished data) who showed that transport from upstream was essential for maintaining the *P. forbesi* population in Suisun Bay. Finally, as already mentioned above, zooplankton size has significantly decreased in the estuary over the past four decades. This has likely reduced the catchability of zooplankton by visually oriented planktivorous fish with negative energetic consequences for the fish (Winder and Jassby 2010).

Food Co-occurrence: Recently, interest has focused on determining patterns of co-occurrence of fish predators and their zooplankton prey. The assumption is that for successful predation, 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. Kimmerer (2008) showed a positive relationship between delta smelt survival from summer to fall and zooplankton biomass in the low salinity zone (Figure 23). Miller and Mongan (unpublished data) concluded that April and July co-occurrence of delta smelt and copepod prey is a strong predictor of juvenile delta smelt survival. Mueller-Solger (DSP, unpublished data) defined delta smelt habitat based on the habitat suitability results of Nobriga et al. (2008) and defined the prey spectrum more broadly (as all copepods) compared to Miller and Mongan (unpublished data). Using these assumptions, Mueller-Solger 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.

There are two major problems for co-occurrence analyses using available monitoring data. 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 data). However, diet data show that delta smelt will actually feed on a wide variety of prey (Lott 1998, S. Slater, CDFG, unpublished data; Figure 24). 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 used by an individual delta smelt to harvest a similar biomass of *L. tetraspina* compared to the energy used to harvest a larger species could be very different, as suggested by optimal foraging theory (e.g., Stephens and Krebs 1986).

The second major problem 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 biweekly) "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.

Summary: The weight of evidence strongly supports bottom-up food limitation as a driver influencing long-term fish trends in the upper estuary. However, the bottom-up hypothesis is unlikely as a *single* mechanism for the recent POD decline for several reasons. First, phytoplankton and zooplankton declines preceded the POD, with lowest abundance and biomass levels in the 1980s and 1990s (Winder and Jassby 2010). Second, *C. amurensis* levels during the POD are not unprecedented; they are similar to those found during the 1987–1994 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, the hypothesis that the San Francisco Estuary is driven by phytoplankton production rather than through detrital pathways (Sobczak et al. 2002, 2005, 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.

Species-specific Models

The basic conceptual model provides a useful context for the major drivers likely affecting the POD species. However, it has limited value for helping policy makers and managers identify actions or guide research studies for individual POD species because it does not show how the major drivers differ for each species, and how they differ in relative importance during different life history stages or seasons. In response to these shortcomings, we developed initial species-specific models for each of the four POD fishes in 2007 (Baxter et al. 2008) and we update them here. The degree of detail for each model varies substantially based on the available data, so the degree of confidence in each is not consistent. Nonetheless, we believe that these models are an effective way to conceptualize the effects of different drivers and how they interact in time and space, which helps identify research and management priorities. Like the basic conceptual model, the species-specific models will continue to evolve as more information becomes available. We have also attempted to be consistent with the draft DRERIP (Delta Regional Ecosystem Restoration Implementation Plan; http://www.dfg.ca.gov/ERP/DRERIP.asp) conceptual models for delta smelt and longfin smelt, which are still in revision.

As with the basic conceptual model, we relied on a qualitative *weight of evidence* approach (Burkhardt-Holm and Scheurer 2007) in constructing the species-specific models. We identified the most *plausible* linkages between drivers and fish life stages based on our evaluation of all available POD laboratory results, long-term monitoring data, correlations, models, and our understanding of how the estuary functions. Here, we present the outcome of this approach. We do not describe all steps of the process itself or reiterate the description of all factors and results already covered in the basic conceptual model sections in each of the four species-specific model. In these models, we also generally deemphasize individual study results, including simple correlations between fish abundance and individual drivers. As with the basic conceptual model, we expect additional changes to these models as new information is collected. Some drivers that are deemphasized in the current species-specific models may play a more prominent role in future versions of these models.

The graphic representation of each species-specific model consists of four panels, each representing a portion of the species' life history (Figure 4–7) in relation to season and approximate center of distribution in the estuary. The arrows show progression through the life cycle in a clockwise direction. The seasons for each species generally correspond to the traditional definitions of summer (June – August), fall (September – November), winter (December – February), and spring (March – May); however, the exact timing of life history events varies somewhat from year to year, depending on environmental conditions. Within each panel, major drivers are shown in red boxes and proposed mechanisms by which they may affect the fish population are shown in yellow boxes. Below, we provide narrative descriptions of each species-specific model. Each narrative description consists of a general section followed by narratives for each season. The general section briefly summarizes important aspects of the four main basic conceptual model components for each species and explores drivers of particular concern. The narratives for each season highlight drivers particularly relevant to each species in that season and also include spatial considerations.

Delta Smelt

We hypothesize that degradation of habitat is the fundamental cause of delta smelt decline and that it affects the species mainly through effects on growth and subsequent reproductive potential rather than immediate mortality. Both abiotic and biotic aspects of habitat suitability have declined over time. This has led to smaller, less healthy adults, which have lower per capita fecundity. These ecosystem challenges have probably been exacerbated by periodic high entrainment loss. We hypothesize that habitat degradation has reduced carrying capacity. Thus, entrainment losses at historical levels could have increased in importance because the population is smaller. Large-scale water diversion may also influence delta smelt carrying capacity through seasonal effects on Delta outflow. The following conceptual model approaches factors influencing delta smelt season by season (Figure 4).

Delta smelt population dynamics have apparently changed over time with declining estuarine feeding and habitat conditions. In the early years of IEP sampling, no delta smelt stock-recruitment relationship was apparent (Moyle et al. 1992). However as sampling continued and abundance declined, a stock-recruitment relationship has emerged. Over the entire period of IEP sampling, delta smelt now show a fairly strong and linear (i.e., density-independent) stock-recruitment relationship (Figure 12). In contrast, the summer survival of delta smelt appears to have been a density-dependent life stage transition starting early in the record (Bennett 2005). Food availability is a likely limiting factor for this planktivorous fish as Kimmerer (2008) noted a statistically significant relationship between juvenile smelt survival and zooplankton biomass over the long term (Figure 23). Also consistent with the food limitation hypothesis is the decline in the mean size of adult delta smelt following the introduction of the clam *C. amurensis*

(Sweetnam 1999, Bennett 2005), which caused declines in key zooplankton prey. Bennett et al. (2008) noted complex interactions between life history traits and environmental conditions with the summer period being a particularly stressful time for juvenile delta smelt. These observations are consistent with Nobriga et al. (2008), who noted a strong reduction in probability of capture at water temperatures that approached the laboratory-derived acute lethal limit of 25°C (for fish acclimated to 17°C; Swanson et al. 2000).

Statistical analyses of the long-term delta smelt trends confirm that in the early 2000s there was a step decline in the abundance of delta smelt (Manly and Chotkowski 2006, Thompson et al. 2010). We propose that changes in water project operations and low egg supply resulting directly from low adult abundance and small size of surviving adults are contributing causes of this recent decline and a current impediment to rapid recovery. The population is now at such low levels that recovery is unlikely in a single year but will require several consecutive years with positive population growth rates. Thomson et al. (2010) concluded that the POD decline could not be explained by the variables that best explained abundance trends prior to the POD. Increased water project exports during winter resulted in higher losses of adult smelt, particularly early spawning fish (and their offspring) that may be proportionally more important to the population (Bennett et al. 2008). By contrast, reduced exports during spring may have increased survival of later-spawned larvae. Although these larvae may be saved from exports, their small size at the beginning of the stressful summer period likely leads to slow growth, reduced survival, and small size at maturity (i.e., lower fecundity) (Bennett et al. 2008). Reduced spring exports from the Delta since 2000 have been the result of VAMP, a program designed to benefit outmigrating juvenile Chinook salmon from the San Joaquin River system.

It is unclear whether the population has dropped below critical levels where Allee effects inhibit recovery. However, the observation that delta smelt have exhibited a declining trend in production of adults from the population of adults in the previous year (Figure 14) suggests that record low abundance levels may now be below the threshold for Allee effects. These concerns were reinforced again by the 2008 and 2009 FMWT delta smelt abundance indices of 23 and 17, respectively, which represent the lowest indices on record (http://www.delta.dfg.ca.gov/data/mwt).

The delta smelt has been considered semi-anadromous, but in recent years investigations centered on its northern Delta spawning and early rearing areas have detected delta smelt year-round, leading to the idea that these putative “resident” individuals might represent alternate life history contingents (Sommer et al. 2009, Sommer et al. in review). The southern end of the Yolo Bypass, including Liberty Island, Cache Slough, and the Sacramento deepwater ship channel are known to support delta smelt spawning and rearing (see Bennett 2005). During 2003 – 2005 the USFWS collected delta smelt during monthly sampling activities throughout the year, not just during spring time, suggesting that delta smelt were using this relatively shallow, flooded island habitat throughout their entire life cycle (USFWS, unpublished data). Similarly, extensions of the 20-mm Survey, TNS and FMWT surveys into the Sacramento deepwater ship channel caught delta smelt consistently from June through October, the warmest months of the year (CDFG unpublished data). Like the “core” rearing habitat of delta smelt near the Sacramento-San Joaquin River confluence, Liberty Island and adjacent deeper habitats in the Ship Channel and Cache Slough are very turbid and have very little SAV (Nobriga et al. 2005, Lehman et al. 2010, CDFG, unpublished data). However, Liberty Island is somewhat warmer during the summer than the river confluence (Nobriga et al. 2005) and may prove to be a challenging habitat for rearing. The following conceptual model applies only to the traditional view of delta smelt as a semi-anadromous species. We are currently evaluating how to integrate these observations into our conceptual model (T. Sommer, DWR, unpublished data).

Summer: Summer is the season that usually has the highest primary and secondary productivity in a temperate zone estuary. Given its annual life cycle, summer is also the primary growing season for delta smelt. We propose that delta smelt growth rates are potentially limited during summer by high water temperature, low food quality and low food quantity.

Nobriga et al. (2008) found that the catch of delta smelt began decreasing at temperatures above 20° C and became almost zero at 25°C suggesting avoidance of stressful conditions or high mortality. Temperatures near 25°C are likely to be near the lethal end of delta smelt tolerance (Swanson et al. 2000) and would certainly affect growth rates and metabolic activities after prolonged exposure. Jassby (2008) noted a significant temperature increase in the Delta in recent years, but cautioned that it was not the result of a long-term trend. Using data from 2005 field observations and the culture facility, Bennett et al. (2008) created a specific growth curve with respect to water temperature (Figure 25), which reinforces the observations of Nobriga et al. (2008). Bennett et al. (2008) also noted that high July temperatures may have led to poor growth, cell damage and poor liver function of the juveniles examined.

Fishes require substantial food resources to maintain positive growth when they experience temperatures near their upper tolerances. However, the trend in the estuary has been toward lower summertime food quantity and potentially quality. Overbite clam grazing has reduced zooplankton availability (Kimmerer et al. 1994), but nutrient loading and water export may also impact zooplankton production. Copepod population dynamics are strongly affected by grazing pressure from *C. amurensis* (Kimmerer et al. 1994, Winder and Jassby 2010), resulting in fewer high quality calanoid copepods, the most common prey of juvenile delta smelt (Figure 24; Lott 1998). Moreover, in the decade including the early POD years, there has been a further decline in the abundance of calanoid copepods in Suisun Bay and the western Delta (Kimmerer et al. 2008). At the same time, these calanoid copepods are being replaced by the much smaller cyclopoid copepod *L. tetraspina*, which is presumed to be a less suitable prey species (L. Sullivan, CSUSF-RTC, unpublished data). A laboratory feeding study showed that larval delta smelt will consume *L. tetraspina*, and when given the choice between *L. tetraspina*, *P. forbesi*, and *E. affinis*, they will consume each in proportion to its abundance (L. Sullivan, CSUSF-RTC, unpublished data). *L. tetraspina* is also being consumed in the wild (Figure 24). However, Sullivan's research indicates that delta smelt grow more slowly when fed *L. tetraspina* compared to other prey. Thus, the decline in calanoid copepod abundance (and biomass) may not be compensated for by high abundance of *L. tetraspina*, even if biomass remains roughly the same (see Baxter et al. 2008; Figure 21) if growth is slowed by a diet of *L. tetraspina.*

Little has been published about the jellyfish in the upper estuary. They may compete with smelt for food resources (A. Wintzer and P. Moyle, UCD, unpublished data), but it is unlikely they are a direct source of mortality due to their small size and their absence during the delta smelt larval period in spring when smelt vulnerability would be highest. Jellyfish abundance in the upper estuary appears to peak in late summer or early fall and persist for 2–3 months thereafter (CDFG unpublished data).

The long-term reduction in calanoid copepod availability in the upper estuary has likely resulted in slower growth rates of delta smelt, as observed in otolith studies by Bennett et al. (2008) and in part, as a reduction in the mean size of delta smelt in fall (Sweetnam 1999; Bennett 2005). Baxter et al. (2008) previously hypothesized that over the long term, reduced summer growth rates due to reduced food availability during the thermally stressful summer period reduced the summer to fall survival of juvenile delta smelt; however, analysis of available IEP index data do not support this hypothesis for the initial POD period (2001–2004), but do suggest reduced summer to fall survival in 2005 and possibly subsequent years (Figure 13). Thus, increased mortality seems like a periodic or more recent occurrence, and the more substantial effect of reduced growth is smaller adults, which affects fecundity and reproductive potential, and possibly aspects of adult survival. These results suggest that summer food limitation remains a major stressor on delta smelt.

Habitat availability and suitability also may be indirectly influencing food quantity and quality. Specifically, the summer habitat of juvenile smelt has become restricted due to high water temperatures and decreased turbidity in the southern and eastern Delta, and saltwater intrusion in Suisun Bay (Nobriga et al. 2008). This has limited the area available for feeding. By late summer toxic algae blooms and possibly, competition with jellyfish could be affecting delta smelt.

When the toxic blue-green alga *M. aeruginosa* blooms during late summer (generally August and September), it occurs primarily on the San Joaquin River side of the Delta (Lehman et al. 2005) and most delta smelt occur to the north and west of the bloom's epicenter (Nobriga et al. 2008). Typically, the bloom only partially overlaps with delta smelt distribution. At concentrations found in the wild, microcystins have been shown to have only sublethal effects on delta smelt prey species in laboratory experiments (Ger et al. 2009). However, chronic and episodic effects on zooplankton remain possible. For example, Ger et al (2010 a) found negative dietary effects of *M. aeruginosa* cells on copepods. Thus, there may be indirect effects on food resources (see Food Quality section). In addition, it appears that potentially toxic effects of *M. aeruginosa* may propogate well beyond the observed bloom region, and particularly downstream. Lehman et al. (2010) found, for example, that striped bass and Mississippi silversides co-occurring with *M. aeruginosa* exhibited signs of toxic and carcinogenic effects, but so did many from areas apparently outside the bloom range. Similar results were obtained for some food organisms. The mechanism for this phenomenon is unknown. The work of Lehman et al. (2010) indicates a strong likelihood that delta smelt are also exposed to microcystins and the direct effects of *M. aeruginosa*.

Other water quality variables such as contaminants could be important, particularly to early life stages and when fish are already stressed by other factors (see Anderson et al. 2007). For example, larval delta smelt were found to be 3–10 times more sensitive than other fish species to ammonia, copper, and insecticides found in the Delta (Werner 2008). Isolated cases of short-term exposures may not be lethal, but exposure to such contaminants when fish are already stressed by high temperatures, osmotic stress, or other factors could result in mortality or degraded physiological condition (Brooks et al., submitted). Bennett et al. (2008) observed a small number of fish with ovatestis (intersex fish) during the stressful year of 2005.

In summary, there is evidence of bottom-up and habitat suitability effects on delta smelt during the summer over the long term, and these interactions may ultimately affect delta smelt production. The lack of observed salvage during the summer suggests SWP/CVP entrainment effects are minimal during this period. Improved habitat (including water quality) and food conditions during the summer would likely improve growth and survival as well as individual fitness of maturing delta smelt and ultimately their fecundity.

Fall: Fall represents the time period when the delta smelt year class completes its somatic growth and begins gonad development. Some summertime drivers continue to affect delta smelt into early fall before declining (e.g., high water temperature and *Microcystis* toxicity). Other drivers such as current water management practices, which lead to chronic low fall Delta outflow and landward X2 (Figure 26), likely play a key role in reducing delta smelt habitat suitability. Evidence to date indicates that fall habitat is a significant current (and future) issue affecting the abundance of delta smelt (Feyrer et al. 2007, 2010). Delta smelt are strongly associated with low salinity and high turbidity, which have been used to model the availability and suitability of its habitat (Feyrer et al. 2007, 2010). Fall habitat suitability has shown a long-term decline (Feyrer et al. 2007, 2010). Because these habitat suitability indices are derived from delta smelt catch data, they directly reflect population-level effects. In addition, the fall abundance index is the best single predictor of juvenile production the following year (Figure 12). Thus, the accumulation of factors that affect fall abundance (FMWT index) influence the abundance of the next year class.

Reduction of habitat area likely interacts with bottom-up and top-down mortality mechanisms to affect delta smelt survival. There are several potential mechanisms by which habitat area can affect delta smelt as described by Feyrer et al. (2010). In general, increased habitat area provides more space for individuals to safely live and reproduce. More specifically, increased habitat area presumably reduces the probability of density-dependent effects on the delta smelt population (e.g., food limitation, disease, and predation). Moreover, increased habitat area also presumably reduces the probability that stochastic, localized, catastrophic events will affect a sizable portion of the population. The geographic placement of the remaining habitat area likely also plays an important role. A key concern for delta smelt is that as habitat suitability declines to low levels, remaining habitat is centered on the western Delta in closer proximity to anthropogenic sources of mortality such as water diversions and certain contaminant sources such as agricultural runoff. Although, direct entrainment is not a major stressor during the fall, shrinking fall habitat that places delta smelt in closer proximity to the hydrodynamic effects of the export pumps is linked, along with negative OMR flow, to increased winter salvage (Grimaldo et al. 2009).

In summary, there is good evidence for reduction in habitat availability and suitability during the fall and a linkage of these reductions with abundance. Slow growth due to food limitation and physiological stress during summer may affect survival in fall, but the evidence points to poor growth in summer and fall, which likely contributes to the species decline via reduced size and fecundity of maturing fish.

Winter: Winter represents the main period of adult delta smelt upstream migration, sexual maturation, and the beginning of spawning. Delta smelt upstream migrations are associated with winter flow pulses and coincident increases in turbidity (Grimaldo et al. 2009). Conditions triggering migrations generally follow winter storms starting as early as late December and extending into February. By March, delta smelt appear to migrate even in absence of such flow-turbidity events (CDFG unpublished data). This movement is considered an active group behavior that is likely triggered by olfactory cues associated with changes in water quality or turbidity (Sommer et al. submitted). Once cues initiate migration, groups of smelt presumably move quickly and efficiently upstream by swimming with incoming tides until they reach their holding grounds (Sommer et al. submitted).

We hypothesize that winter entrainment of adults (top-down effects) can affect the delta smelt population in some years. Salvage and corresponding population loss estimates of delta smelt increased during the POD years (2000–2005) in comparison to most of the previous decade (Kimmerer 2008, Grimaldo et al. 2009). Specifically, Kimmerer (2008) estimated that cumulative proportional population losses were between 3 and 50% for adult delta smelt during the winter export periods between 2002 and 2006, and concluded that the rather large proportional losses and their effects occurred episodically and therefore should be calculated rather than inferred from correlative analysis (e.g., Manly and Chotkowski 2006; Thomson et al. 2010). The recent relatively high adult proportional entrainment in 2002–2004 identified by Kimmerer (2008) likely negatively affected subsequent recruitment. Moreover, young delta smelt in the same years also suffered relatively high proportional losses. These repeated, paired, cross-generational losses, though small individually, could have had a more substantial cumulative effect on the delta smelt population; they coincide with a sharp decline in delta smelt abundance (Figure 2). Note that high winter exports may not have demonstrable effect on delta smelt salvage during periods of high delta outflow because OMR flows are rarely negative and fewer delta smelt are located within the hydrologic influence of the export facilities during high outflow periods (Sweetnam et al. 1999, Grimaldo et al. 2009). Similarly, during critical dry years when the southern Delta has high water transparency, entrainment risks for delta smelt appear low. There are several possible reasons for this. Under these conditions, most delta smelt likely migrate up to the northern Delta where turbidity is higher (Sommer et al. submitted). Also, delta outflow standards (i.e. Water Rights Decision 1641) and limited water in upstream reservoirs available for release, severely constrain exports so that OMR flows are rarely or only briefly strongly negative.

There is presently no evidence of habitat constriction or food limitation during this period; however, no studies have addressed these questions. Contaminant effects are possible during flow pulses because many agricultural and urban-related contaminants enter waterways with the first rain events (Kuivila and Foe 1995, Kuivila and Hladik 2008).

Spring: Bennett et al. (2008) propose that reduced spring exports resulting from VAMP (mid-April to mid-May) has selectively enhanced the survival of spring-hatched delta smelt larvae as compared to those hatching earlier. Initial otolith studies suggest that these spring-hatched fish dominate subsequent recruitment to adult life stages; by contrast, those delta smelt hatched prior to the VAMP have been poorly-represented in the adult stock in recent years. Bennett et al. (2008) further propose that the differential fate of early- and late-hatched cohorts may affect the sizes of delta smelt in fall because the later cohorts have a shorter period in which to grow. In addition, Bennett et al. (2008) found that fish in the early-spawned cohorts of 2005 were generally smaller at age than late-spawned cohorts. The early-spawned fish appeared to partition their growth during the first few weeks after hatchig. These early-spawned fish developed more slowly during the larval stage, but were able to maintain much higher growth rates during the juvenile phase, and in particular, the first two weeks of July. Because the early-spawned cohort grew slower during spring, they were potentially more vulnerable to predation. Also, because they reared in the Delta longer, they were vulnerable to exports for a longer period of time and were also vulnerable before the VAMP-related flow pulses and export decreases took place. Despite longer exposure times, these slower growing fish actually had higher survival probabilities once they reached summer and fall. Later-spawned fish hatching immediately before or during VAMP were usually comparatively protected from entrainment via reduced exports and more positive flows in southern Delta channels, but because of their high growth rates and correspondingly higher energy needs, they were less well equipped to handle extreme summer conditions in 2005, including low food and high temperatures (Bennett et al. 2008). Thus, current water management favors delta smelt larvae that hatch immediately before or during the mid-April to mid-May period of reduced exports; however, this advantage can be severely curtailed if spring conditions abruptly change to raise water temperatures and food resources simultaneously decline, as they did in 2005.

From the perspective of an individual female, choice of a spawning date is critical to larvae hatching into favorable biotic and abiotic conditions. Until recently, female delta smelt were believed to spawn once or repeatedly over a short period of time (Moyle 2002). Thus, the choice of when to spawn was believed to determine fitness to a large degree. Recently, both the laboratory and field based observations confirm that delta smelt have the potential to produce multiple clutches. Lindberg et al. (UCD, unpublished data) documented cases where 1-year-old wild-origin females produced 3 viable clutches of eggs under ideal (i.e., cold water, unlimited food) conditions over a period of several months. This information was further corroborated by S. Teh (UCD, unpublished data) who found histological evidence of repeat spawning by females collected in the wild. Thus, at least some females can potentially hedge their bets by spawning repeatedly throughout the spawning season. Repeat spawning likely has several prerequisites: (1) healthy adults with energy reserves to develop gonads early in the season and survive spawning; (2) ripe and spent fish are able to locate sufficient food resources to develop additional gametes; and (3) a protracted period of suitable spawning conditions to allow for the development and release of multiple sets of gametes. Egg survival is linked to temperature and temperatures associated with 50% or better survival to hatching range from just below 10°C to about 18°C (Bennett 2005). Bennett (2005) found that the presence of successive cohorts of post-larvae in the 20-mm Survey was linked to the duration of a 15–20°C temperature window and suggested that a similar temperature window for spawning might be the duration of 14–18°C. Thus, protracted spawning and recruitment windows relate to broader success of both individual spawning events and provide time necessary for some individuals to undergo several successful spawnings. Such a spawning strategy would greatly increase the probability of individual females producing at least one clutch of eggs that hatched under conditions favoring survival of young delta smelt and is more consistent with life-history theory for annual fishes (Winemiller and Rose 1992) than the semelparous spawning previously assumed (Moyle 2002).

Until recently, the numbers of larvae entrained in the south Delta export pumps were unknown because fish less than 20 mm long are not identified in salvage (see Brown et al. 1996). Kimmerer (2008) estimated that entrainment of larval smelt was greatest during April based on estimates of abundance from the 20-mm Survey, OMR flows, and risk calculations based on particle tracking models (PTM). During April, larval entrainment is not observable at the salvage facilities because fish less than 20 mm SL are not counted at the facilities. Juvenile delta smelt salvage peaks between May and June of most years (Grimaldo et al. 2009); however, the magnitude of entrainment is dependent on flow (Kimmerer 2008). Kimmerer (2008) estimated that larval and juvenile population losses ranged from 0 to about 25% from 1995 to 2006, with the highest losses occurring in dry years 2001–2004. This period of increased loss overlaps a similar period of relatively high loss for adults (see winter section above); thus, there was a period of sequential, intergenerational loss that may have had a cumulative effect on the delta smelt population. A complicating factor in estimating entrainment are prescreen losses of delta smelt. The magnitude of these losses is currently unknown, but according to a recent study (G. Castillo, USFWS, unpublished data) it is likely high. This is consistent with the results of previous studies of prescreen losses conducted with other species (Clark et al. 2009, Gingras et al. 1997).

Because of natural variability and delta outflow standards (i.e. Water Rights Decision 1641), there have been few significant long-term trends in upper estuary spring salinity (Figure 26, Enright and Culberson 2009). This suggests that it is unlikely that there have been any recent changes in spring abiotic habitat availability or suitability. Habitat effects based on calanoid copepod densities, contaminants or disease may have worsened during spring. The dietary importance of *E. affinis* and calanoid copepods in general suggests that declines in either might affect delta smelt survival and recruitment. Spring densities of *E. affinis* did not decline substantially during the POD years and even spiked upward in 2006 and 2008, and neither *Sinocalanus doerrii* nor *P. forbesi* exhibited consistent low abundance during the POD years (Hennessy 2008, 2010), so there was little evidence of spring food being limited. There has been little evidence of direct toxicity to delta smelt larvae, based on limited numbers of bioassays using water collected during spring from the upper estuary, though a few acute results were detected using samples from the lower Sacramento River at Hood and near Rio Vista (Werner et al. 2008, 2010). Lethal and sublethal effects on the invertebrate *Hyallela azteca* were observed more often and at even more sites (Werner et al. 2008, 2010) suggesting possible sublethal effects on fishes, including delta smelt, through the food web, but this was not supported by calanoid copepod abundances (see Hennessy 2010). Upper estuary habitat does not appear to have declined based on the factors we were able to assess.

Longfin smelt

We hypothesize that winter–spring outflow, adult abundance and food availability most strongly influenced the long-term pattern of longfin smelt recruitment (Figure 5). X2 (or freshwater outflow) during the winter–spring spawning and rearing periods continues to exert a significant positive effect on abundance (year-class strength) (Figure 27; Stevens and Miller 1983, Jassby et al. 1995; Kimmerer 2002b; Sommer et al. 2007, Kimmerer et al. 2009). The historical relationship changed subsequent to the establishment of the overbite clam in 1987. The slope of the relation between X2 and the population remained the same after the introduction, but the intercept changed indicating that the abundance of fish expected at a specific X2 value declined significantly (Kimmerer 2002b). Reduced prey availability due to clam grazing is believed to be the mechanism for the change (Kimmerer 2002b). An additional change in the relationship occurred after 2002, particularly from 2003 through 2005, when abundance did not increase when outflow increased (Figure 27 a–c; Sommer et al. 2007, Baxter et al. 2008). After a large, abundance increase in 2006 in response to substantially higher outflow, the 2007 FMWT annual index declined to a record low of 13 and has remained low in 2008 and 2009 (http://www.delta.dfg.ca.gov/data/mwt). Some decline in 2007 was expected due to low winter–spring outflows, but the 2007 index fell well below the post-clam FMWT outflow abundance relationship (Figure 27a) and represented a statistical outlier (Studentized residual = -2.802; R. Baxter, CDFG, unpublished data). The 2008 and 2009 abundance indices more closely fit the post-clam outflow abundance relationships (Figure 27 a–c). The mechanism(s) underlying the 2003–2005 lack of longfin smelt abundance response to increased outflow remain(s) unknown as does the mechanism for the 2007 abundance response, though shifts in distribution away from habitat sampled by the midwater trawl may have an effect. A similar lack of response was not apparent in the Bay Study otter trawl relationship (Figure 27c) suggesting that a portion of the population continued to respond as it had in the recent past.

Preliminary analyses support a stock-recruitment relationship between adults approaching their second birthday and age-0 fall recruits (The Bay Institute et al. 2007a). Moreover, longfin smelt abundance in the FMWT exhibits a significant autocorrelation based on a 2-year time lag ($r_{\text{lag } 2}$ = 0.486, 36 df, p = 0.002). Since longfin smelt typically spawn at the end of their second year of life (Baxter 1999, Moyle 2002, CDFG 2009a), this 2-year lag can be interpreted as additional evidence of a stock-recruitment relationship. Development of a revised, direct stock-recruitment relationship is in progress. A significant stage-recruitment relationship (fall age-0 to fall age-1 abundance) also exists, but survival declined after 1994 (Rosenfield and Baxter 2007) presumably due to continued food limitation. The distributions of the two age classes differ (Baxter 1999, Rosenfield and Baxter 2007) so discussions of seasonal drivers will include both young of the year (age 0) and age-1 fish when relevant. Age-2 fish are generally only captured in the estuary during the winter spawning season, so they will not be discussed in detail. Declining juvenile recruitment and reduced stage-recruitment survival are important factors in the declining population trends of longfin smelt, and likely limit its positive response to favorable environmental conditions.

Winter: Upstream migration of mature adults and most spawning occurs in winter with spawning probably confined to freshwater portions of the estuary (Moyle 2002; Rosenfield and Baxter 2007). The distribution of longfin smelt has the greatest overlap with the distributions of the other POD fishes during this season. The geographic and water column distributions of adults and larvae in winter lead us to hypothesize that entrainment is having an important effect on the population during this season, particularly during low outflow years when a higher proportion of the population may spawn farther upstream in the Delta. A CDFG conceptual model of longfin smelt migration features adults moving up to and congregating in the low salinity zone (0.5–6 psu) as temperatures decline, starting in late fall (see CDFG 2009a, b). From here, ripe individuals are believed to make generally short-distance, brief spawning runs into freshwater where spawning takes place over a sand substrate. The fish are then believed to return to the low salinity zone if partially spent and farther down estuary when completely spent (CDFG 2009b). Individual fish are believed to be capable of spawning several times during the spawning period. When the low salinity zone (indexed by X2) is upstream in the Delta, increasing numbers of adult longfin smelt probably move into and upstream of the influence of the export pumps on their spawning migration. This hypothesis is supported by: (1) generally higher salvage during low outflow years (Sommer et al. 1997, CDFG 2009b); (2) winter catch density plots showing the population shifting upstream and downstream in concert with shifting X2 (CDFG 2009b); (3) and increasing winter salvage in relation to fall abundance with increasing X2 in winter (CDFG 2009b). Increased winter salvage of mostly adult longfin smelt after 2000 suggests that entrainment levels may have been higher during POD years (Figure 18; IEP 2005). This entrainment occurred when the adult population was at a fairly low level (Figure 2). Recent calculations of longfin smelt adult entrainment and loss showing relatively high adult entrainment and loss during winters of water years 2002–2004 (CDFG 2009b). However, these losses have yet to be placed into a population context, so we cannot provide conclusions regarding their recent effect on abundance. Combined winter exports were generally high from 2000 through 2005 creating a high upstream net flow toward the export pumps in OMR, known as negative OMR flow (CDFG 2009b). Grimaldo et al. (2009) evaluated the effects on salvage of a suite of environmental, hydrologic and biological variables, and winter adult salvage was most parsimoniously attributable to strong negative OMR flows. Thus, X2 and negative OMR flows can be interpreted as distal and proximal factors, respectively, influencing longfin smelt winter salvage.

Entrainment effects on longfin smelt larvae could be higher than those for adults due to their predominant surface orientation (Hieb and Baxter 1993, Bennett et al. 2002) and protracted larval (i.e., weak swimming) period: almost 90 days are required to reach 20 mm FL (fork length) (J. Hobbs, UCD, personal communication 2008). However, larval entrainment remains undocumented because larvae are not identified in salvage until they are ≥20 mm in length (Kimmerer 2008). Similar to adults, entrainment of larvae is presumed highest during periods of low winter–spring outflows when X2 is near or within the Delta because more spawning occurs above and within the influence of the export pumps, larval downstream transport is reduced and exports comprise a substantial fraction of inflow and can draw pelagic larvae into the pumps. CDFG (2009b) assessed loss of larvae to entrainment in south Delta export pumps by temporally and geographically scaling particle tracking model results for surface oriented particles to emulate the timing, distribution and behavior of longfin smelt larvae in the Delta. Annual percent entrainment was then estimated for 3 relatively low outflow years (1992, 2002, 2008), when spawning was assumed to be predominantly within the Delta. They found that with strongly negative OMR flows as occurred in 2002, annual combined SWP/CVP particle entrainment reached almost 15% of the modeled population; under higher outflow conditions and much reduced exports in 2008, combined particle entrainment dropped to 3.7%. These particle tracking results suggest that during some years a substantial fraction of longfin smelt larvae may be entrained, but entrainment of larvae is not likely to exert much of a negative effect on longfin smelt recruitment during years with modest to high outflows.

Otolith studies by Bennett et al. (2008) suggest that winter-spawned delta smelt have recently contributed poorly to the adult population as compared to spring-spawned fish, which benefited from spring export reductions associated with the VAMP. Similarly, early spawning longfin smelt may be losing higher numbers of larvae to higher winter exports in the early to mid-2000s and in general because of less restrictive December and January flow criteria that allow export to inflow (E/I) ratios as high as 65%, whereas E/I ratios for February through June cannot exceed 35% except in critically dry years, and then must remain < 45%. Existing data provide some support for this hypothesis. Accounting for recent high winter and spring longfin smelt salvage (i.e., 2001–2004) and estimated loss of larvae (CDFG 2009b) did in some cases greatly reduce expected recruitment based on post-clam outflow-abundance relationships (Figure 27). However, in 2002, the high winter adult loss, the almost 15% larval loss from estimated particle entrainment, and estimated recent peak in spring–summer juvenile loss (CDFG 2009b) were not sufficient to obviously reduce 2002 juvenile abundance from that expected based on the post-clam outflow abundance relationship (Figure 27 a–c). This suggests that flow-abundance relationships already incorporate entrainment effects among the negative factors limiting recruitment during low outflow years, and that these effects were not substantially higher in 2001 and 2002, but may have been higher in 2003–2005.

Winter habitat for adult and juvenile longfin smelt is broad and non-restrictive, and probably did not change during the POD years except at the upstream boundary with shifting X2. For larvae, habitat varies with winter–spring outflow and X2 (Kimmerer et al. 2009), and was probably reduced compared to the late 1990s because of a general shift in winter X2 location upstream during the POD years (CDFG 2009b). Adult and juvenile longfin smelt occupy the entire range of salinities and temperatures available during winter, though ripe adults are believed to seek freshwater for spawning (Baxter 1999, Moyle 2002, Rosenfield and Baxter 2007). Larvae are rare at salinities >18 ppt and salinities between 0.1 and 18 ppt have been hypothesized to represent nursery habitat (Hieb and Baxter 1993, Kimmerer et al. 2009). Estimated nursery habitat based on salinity varied significantly positively with outflow (negatively with X2), though the slope of the outflow-habitat relationship was much less than that of the outflow-abundance relationship (Hieb and Baxter 1993). Similarly, the comparison of slopes of the X2-habitat and X2-abundance relationships showed a similarly steeper slope for the latter (Kimmerer et al. 2009). These results suggest that other factors besides salinity that are associated with longfin smelt larval survival were positively influenced by outflow. The downstream transport and distribution of larvae within the estuary varies positively with outflow (Baxter 1999, Dege and Brown 2004). Specifically, larvae disperse farther downstream when X2 is farther downstream and young juveniles historically remained in the same regions even as X2 recedes upstream. Thus, in relatively high outflow years, the longfin smelt distribution immediately begins to diverge from those of other POD species; this is not the case in relatively low outflow years when most longfin smelt are initially distributed upstream of Carquinez Strait. Turbidity has recently been linked as a significant component of a longfin smelt larva habitat (Kimmerer et al. 2009). Increased turbidity, associated with outflow events, may provide a competitive feeding advantage to longfin smelt larvae or may reduce predation (Stevens and Miller 1983, Chigbu 2000). Recent histology revealed that longfin smelt larvae and juveniles possess a large, well developed olfactory system (Scott Foott, USFWS, personal communication 2006, Foot and Stone 2008), which can be used for food acquisition in a turbid or dark environment; longfin smelt are known to feed effectively after dark (Dryfoos 1965, Hobbs et al. 2006). We have no evidence of a change in winter turbidity levels during the POD years.

Contaminant effects have not been evaluated for longfin smelt eggs or winter larvae, but such effects seem possible given the general contaminant sensitivity of fish eggs and larvae and the presence of both life stages during winter when both waterborne and sediment borne toxicants can be high (see Anderson et al. 2007). In particular, life stages present during first-flush events may be at greater risk. First flush events carried increased pesticide concentrations in the form of suspended-sediment associated pesticides (Bergamaschi et al. 2001). These authors reported that such sediments settled out and re-suspend, likely increasing residence time in the Delta. The proclivity of longfin smelt for spawning on sand and a 20+ day egg incubation period in winter Delta temperatures (see CDFG 2009a, Tigan and Lindberg, UCD, unpublished data, CDFG unpublished data) could place them in protracted proximity to a suite of pesticides (see Bergamaschi et al. 2001 and reference therein). Only limited evidence has been found of recent winter-time water toxicity to a *H. azteca* (Werner et al. 2008a, b). Nonetheless, longfin smelt eggs and surface oriented early-stage larvae would be particularly vulnerable to pulse-flow transported contaminants. Increasing ammonia/ammonium levels from riverine discharges (see Jassby 2008) represent an emerging issue both in terms of direct toxicity – delta smelt larvae/juveniles have proven sensitive to ammonia but ambient concentrations are below those causing acute mortality (Werner et al. 2008a, b) – and indirectly through changes in phytoplankton community composition (Kimmerer 2005, Lehman et al. 2005). We have no information on ammonia toxicity for any life stage of longfin smelt and toxicity testing requires the ability to culture the species. Laboratory spawning and rearing of longfin smelt commenced during winter 2009 and continued in 2010 (Rettinghouse 2009, 2010).

Food availability for larvae has not been fully evaluated for winter. Limited diet analysis revealed that longfin smelt larvae feed predominantly on calanoid copepods in general and *E. affinis* in particular (S. Slater, CDFG, unpublished data). Trends in winter abundance indices of calanoid copepods do not show declines during the POD years (A. Hennessy, CDFG, personal communication). Recent otolith analysis shows that longfin smelt larvae grow relatively slowly during winter and early spring, attaining 20 mm in length only after almost 90 days of growth post hatch (J. Hobbs, UCD, personal communication). Such slow growth could be adaptive for modest food resources in winter, similar to that observed for delta smelt (cf., Bennett et al. 2008). Age-1 and age-2 longfin smelt most likely feed on mysids when and where available, and rely on copepods and amphipods otherwise (Feyrer et al. 2003, S. Slater, CDFG, unpublished data).

Spring: Like delta smelt, longfin smelt hatched in spring probably benefited from reductions in spring exports associated with VAMP (i.e., reduced top-down effects) since 2000. Based on particle tracking modeling, longfin smelt also likely benefited from additional export restrictions in place in 2008 to protect delta smelt (CDFG 2009b); similar benefits were achieved in 2009 and 2010. Low winter and spring outflows in 2001–2002, and modest outflow combined with strongly negative winter and spring OMR flows in 2003 and 2004 likely kept many young longfin smelt in the Delta resulting in increased juvenile entrainment (CDFG 2009b). Higher winter and spring flow coupled with less negative OMR flows in 2005 and 2006 (CDFG 2009b) likely resulted in the transport of many larvae and juveniles to Suisun Bay and farther downstream (http://www.delta.dfg.ca.gov/data/20mm/CPUE_Map.asp).

In spring, age-1 longfin smelt are broadly dispersed within the estuary (Baxter 1999, Rosenfield and Baxter 2007) and similar to the winter, not restricted by habitat. Immediately after hatching buoyant larvae are dispersed downstream such that their mean location is approximately that of X2 or just upstream (Dege and Brown 2004). Small juveniles then disperse downstream into more saline habitats (Dege and Brown 2004, Kimmerer et al. 2009). Kimmerer et al. (2009) found longfin smelt spring habitat based on 20-mm Survey data (larva and small juveniles) peaked at about 2 ppt and declined rapidly to about 15 ppt, similar to that observed for larvae in winter (see previous section). The importance of low salinity habitat to the apparent survival of larvae was examined by Hobbs et al. (2010) who found that larvae surviving to recruit to older ages (i.e., summer and fall juveniles and fall adults) had primarily reared in low salinity waters (0.4–3 ppt) as compared to fresh (≤ 0.3 ppt) or more saline water (≥ 4.0 ppt). However, some fish recruited from all habitats. As observed for winter habitat, turbidity may also be an important constituent of spring habitat. Kimmerer et al. (2009) found the combination of salinity and Secchi depth substantially improved the model fits as compared to salinity alone or salinity and water depth, suggesting that both salinity and reduced water clarity were important constituents of habitat for young longfin smelt. Kimmerer et al. (2009) also found that longfin smelt habitat size varied inversely with X2 location. However, X2 location was not consistently high during spring in POD years (see CDFG 2009b), so a decrease in habitat did not appear well related to the POD longfin smelt decline.

Age-0 longfin smelt take advantage of seasonally increasing copepod numbers in spring, feeding particularly strongly on *E. affinis* and switching to mysids as soon as they are capable (CDFG 2009b, S. Slater, CDFG, unpublished data). The dietary importance of *E. affinis* and mysids suggests that declines in either might affect longfin smelt survival and recruitment. Spring densities of *E. affinis* have not declined substantially during the POD years, and even spiked upward in 2006 and 2008 (Hennessy 2008, 2010). Conversely, spring mysid densities did decline after 2000 and were substantially lower in odd than even years, culminating in extremely low numbers in 2007 (Hennessy 2008). Although there was a recovery in 2008, spring 2009 mysid numbers were lower than those of 2007 (Hennessy 2010). These mysid declines probably reduced feeding opportunities for age-1 longfin smelt in the upper estuary, but we have not evaluated recent survival. Although no histological evidence of food limitation (or contaminant effects) was found in young longfin smelt collected in spring 2006 (Foott et al. 2006) or 2007 (Foott and Stone 2008), such young affected fish may not survive long enough to be represented in collections. No viruses were detected in either year. There was also a low incidence of parasites, inflammation, or other evidence of cell damage (Foott et al. 2006, Foott and Stone 2008). These data suggest that reduced food in spring may have affected older longfin smelt but not age-0 longfin smelt, and that disease and parasites were not important factors in spring.

Summer: By mid-summer entrainment in south Delta export pumps is no longer an issue for longfin smelt, because like delta smelt, most of the population moves downstream of the zone affected by water exports. Increasing Delta water temperatures (>22ºC) are believed to limit longfin smelt distribution and cue emigration (CDFG 2009a). More highly mobile age-0 longfin smelt disperse farther downstream and their distribution further diverges from other POD fishes, now ranging primarily from eastern Suisun Bay to marine waters of central San Francisco Bay (Baxter 1999). By summer, age-1 longfin smelt have left the Delta and begin a slow migration toward central San Francisco Bay (Baxter 1999).

As age-0 longfin smelt grow through summer their diet rapidly broadens to include amphipods and even more mysids (S. Slater, CDFG, unpublished data). In 2005 and 2006, the transition away from copepods to mysids (and later amphipods) occurred in summer (S. Slater, CDFG, unpublished data, CDFG 2009b) as *E. affinis* seasonally declined and *P. forbesi* increased (Hennessy 2008). Summer mysid abundance declined through the POD years, but remained at >10 m^{-3} until 2007 (Hennessy 2008). Like spring mysid abundance, summer abundance rebounded in 2008 and declined again in 2009 (Hennessy 2010). Since the early 1990s the upper estuary mysid community has been dominated by *H. longirostris*, which is smaller and slimmer than *Neomysis mercedis*, and thus may not provide similar nutrition. This trend is reflected in the long term decline in the mean size of mysid in the estuary (Winder and Jassby 2010). In summers since 1987, *C. amurensis* grazing has reduced calanoid copepod and mysid availability, and has probably affected age-0 longfin smelt survival to fall in a manner similar to that observed for young striped bass (Kimmerer 2002 and reference therein). During the period from 1995 through 2004 (including early POD years) there has been a further decline of calanoid copepods, particularly *P. forbesi*, in Suisun Bay and the western Delta (Baxter et al. 2008), which represents a sizable portion of the longfin smelt summer distribution. Regionally diminishing food resources may also be responsible for reduced fall recruitment in 2003–2005 (Sommer et al. 2007) and for reduced post drought survival of longfin smelt from their first through second falls (Rosenfield and Baxter 2007). Feeding conditions may improve during high outflow years. *E. affinis* numbers increased sharply and mysid numbers remained stable in 2006 (Hennessy 2008), the only recent high outflow year. Age-0 longfin smelt collected from San Pablo and Suisun bays in summer 2006 exhibited 13% (n=107) incidence of hepatocyte vacuoles that contained either fat or glycogen reserves, which is uncommon for rapidly growing fishes (Foott et al. 2006). Longfin smelt abundance increased substantially during fall 2006, though only to the low range of their recent outflow abundance relationship (Figure 27, Sommer et al. 2007). Unfortunately, no data on abundance of longfin smelt food resources are collected in San Pablo or central San Francisco Bay where most longfin smelt appear to rear in recent years.

Changes in food availability may also be responsible for historical and recent changes in longfin smelt distribution as well as abundance. Longfin smelt exhibited a historical shift to higher salinity soon after the introduction of *C. amurensis* (Fish et al. 2009). This shift, similar to that of northern anchovy (Kimmerer 2006), was also likely a response to reduced pelagic feeding opportunities. More recently, while investigating the Bay Study midwater and otter trawl catch relationships, we observed a general shift in where longfin smelt are captured in the water column. The ratio of catch in the water column to catch at the bottom declined sharply during the POD years and has remained low, suggesting a shift in habitat use toward the bottom (Figure 28). Through the entire period of record, summer–fall longfin smelt (mostly age 0) catches in the midwater trawl generally exceeded those in the otter trawl in Suisun Bay and the west Delta, whereas from San Pablo Bay downstream the reverse was true (Figure 29a). During the POD years, coincident with the sharp drop in the midwater to otter trawl catch ratio (Figure 28), relative otter trawl catches by embayment shifted downstream and the greatest proportion occurred in central San Francisco Bay (Figure 29b). Thus both historical and recent downstream shifts in habitat use have occurred, in addition to the recent shift toward the bottom indicated by the trawl ratio decline. These shifts downstream and toward the bottom further suggest that the pelagic feeding environment of the upper estuary has declined and that the longfin smelt response occurred in stages. Also, such shifts undoubtedly affected longfin smelt abundance as indexed by midwater trawls, and probably contributed in part to the declines observed in midwater trawl abundance indices.

No direct link has been made between contaminants and longfin smelt. In 2006, invertebrate toxicity (*H. azteca*) was detected from water samples taken within the range of longfin smelt, in particular in eastern San Pablo Bay (Werner et al. 2008a), however, histopathological examination of longfin smelt collected from the same region before and after the water collection did not reveal evidence of contact with a toxic substance (Foott et al. 2006). Few longfin smelt were collected in summer 2007 to assess possible contaminant or parasite effects (Foott and Stone 2008).

Fall : Age-0 longfin smelt seek deep water and may be geographically limited by high water temperatures (>22°C) and possibly food resources in fall. Presumably, seasonally high water temperatures limit use of habitat in south San Francisco Bay and the shallows of San Pablo Bay (Rosenfield and Baxter 2007). Upper estuary drivers (e.g., entrainment effects) probably have little effect on age-1 fish during fall, because they appear to emigrate to central San Francisco Bay and some leave the estuary and enter the near coastal ocean (Rosenfield and Baxter 2007). Observational data suggests high Delta water temperatures may also limit their distribution in early fall, but both age-0 and age-1 longfin smelt reoccupy the Delta as water temperatures drop in late fall (Baxter 1999, Rosenfield and Baxter 2007). By late fall, age-1 longfin smelt begin to mature and their movement into the Delta represents the start of their spawning migration (Baxter 1999; Rosenfield and Baxter 2007).

The fall distribution of longfin smelt has changed in the long and short terms (see discussion in the Summer section above). Fall copepod and mysid numbers did not exhibit a distinct, consistent decline after 2000, but since 2005 mysid numbers, primarily *H. longirostris* (formerly *Acanthomysis bowmani*), declined sharply and remained low through 2009 (Hennessy 2010). Low fall mysid abundance in the upper estuary undoubtedly had an effect on longfin smelt distribution, if not abundance.

Contaminant effects on fall fish remain unresolved. Hepatocyte vacuoles were observed in 76% (16 of 21) of liver sections from fish collected between September and November 2007, as compared to 25% of 77 longfin smelt collected between July and October of 2006 (Foott and Stone 2008). In 2006, these vacuoles were attributed to storage of lipoproteins in maturing fish; however, the fish collected in 2007 were immature age-0 fish, suggesting that other factors may be at least partially responsible for the vacuoles. Alternately, the vacuoles may have represented a biomarker of contaminant exposure, but additional biomarkers often present after contaminant exposure were not present (Foott and Stone 2008). Hinton and Lauren (1990) discuss factors associated with changes in fat storage in fish hepatocytes, including exposure to toxicants, nutritional state, and vitellogenesis in maturing females. Foott and Stone (2008) conclude that before hepatocyte vacuolation can be used as a biomarker for contaminant exposure it will be necessary to distinguish it from normal developmental processes by examining the seasonal changes in healthy longfin smelt.

Summary: The conclusion of Thomson et al. (2010), that no single or combination of factors stands out as responsible for the POD decline of longfin smelt, seems to be an appropriate summation for this current review. Though these authors detected a step decline in the FMWT abundance of longfin smelt and the other POD fishes, they were not able to attribute it to any of the suit of variables assessed, including winter and spring exports, spring X2 location, spring and summer calanoid copepod biomass, and summer mysid biomass. This was not unexpected given the complex interactions among environmental and biological drivers. In addition to identifying both group and individual species step declines during the POD years, their results further supported water clarity and spring X2 (Mar–May, winter not tested) as important correlates to longfin smelt abundance. The longfin smelt individual species step decline identified by Thomson et al. (2010) occurred in 2004 after the multi-species step decline in 2002 and coincident with the 2004–2005 downward deviation in abundance indices from the outflow abundance regression line (Figure 27a). Currently, longfin smelt abundance trends are best explained by changes in winter–spring outflow (X2 location) and possibly stock-recruitment effects (to be further examined). The abundance declines reflected in the deviations observed in the outflow abundance relationships likely resulted, at least in part, from recent downstream and vertical shifts in distribution. These distribution shifts may be related to changes in food resources; however, these linkages are not yet firmly established and need to be investigated further.

Striped bass

The San Francisco Estuary striped bass population has been monitored and researched for many decades, so some of the drivers influencing its long-term abundance index trend are fairly well-understood (Figure 6). The age-0 striped bass abundance index has declined steadily since the latter 1960s (Figure 2), but adult abundance, as indexed by a long-term Petersen mark-recapture survey (Figure 9) has not. The lack of change in adult abundance is supported by San Francisco Bay and Delta Commercial Passenger Fishing Vessel data (Figure 30). This is partly attributed to active management actions (Kohlhorst 1999). The long-term decline in juvenile abundance was originally attributed largely to entrainment in the SWP and CVP water diversions (Stevens et al. 1985). River flows and south delta exports historically explained much of the variation in striped bass year class strength, although the strongest relationships occurred during the summer (Stevens et al. 1985). Survival from egg to 38 mm larvae in early summer appeared unchanged through the mid-1990s (Kimmerer et al. 2000). However, recent research suggests that there was a step-decline around 1977 due to adult mortality and subsequently reduced egg supply (Kimmerer et al. 2000, 2001). There was another step-change around 1987 coinciding with the *Corbula* invasion that decoupled age-0 production from spring X2 (Sommer et al. 2007). The most recent step decline in the early 2000s remains unexplained (Sommer et al. 2007, Thomson et al. 2010)

Young striped bass have a strong predator-prey association with mysid shrimp (Stevens 1966, Feyrer et al. 2003). The carrying capacity for age-0 through age-3 striped bass has shown a long-term decline that is correlated with declining mysid densities (Kimmerer et al. 2000, Winder and Jassby 2010). Thus, it is likely that the much lower abundance of mysids in the post-*Corbula* period has strongly and negatively affected juvenile striped bass production. The adult striped bass population increased in the 1990s and was at about a 30-year peak in the year 2000. This was likely due to a combination of improved survival resulting from successive wet years in the mid to late 1990s and planting of millions of juvenile striped bass into the estuary through 2000 (Kohlhorst 1999). Restored populations of striped bass on the east coast have caused large reductions in populations of their prey and in high incidence of disease in striped bass (Hartman 2003, Uphoff 2003)

The reasons for the continued decline of the age-0 striped bass abundance index to record lows during the POD years, despite an increase in the adult abundance index and by extension, egg supply, is unknown (Thomson et al. 2010). Striped bass appear to show more signs of contaminant-related health problems than the other POD species (details below), but we do not know whether this reflects a long-term chronic problem or a recent change. Abiotic habitat suitability, calculated as a function of Secchi depth (clarity) and specific conductance, for young striped bass has declined during fall like it has for delta smelt (Feyrer et al. 2007) and the entrainment of striped bass increased during the early POD years (Figure 18). Thus, it is possible that direct (entrainment) and indirect (habitat suitability, particularly salinity) effects of water diversions have exacerbated the longer-term stresses of reduced prey availability and contaminant effects. Data from two different long-term monitoring studies indicate that age-0 striped bass may be shifting in distribution from channel stations to shoal stations, possibly contributing to the discrepancy seen in the age-0 and adult abundance indices. The percent of shoal-caught striped bass is increasing through time relative to channel-caught fish in the San Francisco Bay Study (Figure 31, T. Sommer, DWR, unpublished data). Likewise, catches of age-0 and age-1+ striped bass in Suisun Marsh have increased concurrent with decreased catches in Suisun Bay, which may reflect improved prey availability in the marsh or reduced habitat quality in Suisun Bay (Schroeter 2008). However, the modest shift in striped bass towards shoal habitat does not appear to be sufficient to fully explain the extreme decline in age-0 striped bass abundance (Sommer et al. submitted).

Spring: In spring, adult striped bass migrate into the Sacramento and San Joaquin rivers where they broadcast spawn in currents that will suspend eggs and larvae in the water column. Larvae require roughly 2 weeks of development before they can maintain their position in the water column (Moyle 2002). In both rivers, migrating adults and suspended eggs and larvae are subject to discharges carrying potentially toxic contaminants. Agricultural return water can transport pesticides and other contaminants (Saiki et al. 1992, Bennett et al. 1995, Weston and Lydy 2010). Municipal discharges may carry a variety of contaminants including potentially estrogenic compounds (Huang and Sedlak 2001, Weston and Lydy 2010). Springtime contaminant effects influence egg and larval survival via two pathways: (1) maternally accumulated contaminant(s) passed on to eggs and larvae that negatively affect viability and development; and (2) direct mortality effects of contaminants in the environment on larvae (Ostrach et al. 2008). Maternal transfer of contaminants was assessed by comparing larvae produced by domestic (controls) and wild striped bass spawned in the laboratory in 2006 and 2007. Developmental studies showed that wild larvae grew slower than control larvae. Wild larvae also developed abnormally with some processes accelerated (e.g., development of caudal fin, and notochord) and other processes retarded (e.g., development of brain and liver from 3 to 5 days posthatch) (Ostrach et al. 2008). Chemical analyses of unfertilized eggs from 21 striped bass collected from the Sacramento River found biologically significant lipophilic compounds and known endocrine disruptors such as polychlorinated biphenyls (PCBs), PBDEs, and current-use and legacy pesticides. These analyses, coupled with the morphometric and histopathological results from the brain and liver indicate that contaminants are maternally transferred and likely disrupt early development of river larvae (Ostrach et al. 2008). Striped bass eggs and larvae are likely exposed to the same suite of contaminants as delta smelt (Kuivila and Moon 2004), possibly in higher concentrations because striped bass spawn closer to locations of upper river discharges (e.g., Colusa Basin Drain). During the late 1980s and early 1990s, striped bass larvae captured in the Sacramento River exhibited liver lesions sufficient to cause mortality (Bennett et al. 1995).

Rapid loss of large fecund females from the spawning stock could reduce total fecundity, and in turn cause a decline in juvenile recruitment (Stevens et al. 1985, Kimmerer et al. 2000). Such a decline occurred between 1976 and 1977 (Stevens et al. 1985, Kimmerer et al. 2000). Bennett and Howard (1997, 1999) hypothesized that a decline in striped bass fecundity since the 1970s resulted from warming ocean conditions leading to an improved coastal feeding environment, which in turn resulted in increased fishing mortality along the coast and increased straying to other river systems. This scenario fits data from the late 1970s through late 1990s, but ocean conditions shifted to a cool regime in 1999 and although the adult population size decreased after 2000 it remained at or above early 1990s levels (Figure 9).

A dramatic decrease in the female:male sex ratio of adult striped bass (≥ 3 years old) is apparent in long-term Petersen mark-recapture data from the estuary (Figure 10; CDFG, unpublished data). Skewed sex ratios during spawning can result from a difference in the maturity schedule for male and female striped bass. On average, males mature two years younger than females and, thus appear on spawning grounds in a much higher abundance. This pattern holds true for the delta population (Figure 32) and is characteristic of stocks outside the estuary as well (Trent and Hassler 1968, Hoff et al. 1988). However, the recent change in the ratio indicates that something has changed. There has been a steady decline in the number of older females (Figure 33) which is troubling given that a wide distribution of age classes and a relatively high proportion of older females are generally good indications of a healthy stock. Since the early 1980s, the number of females ≥ 7 collected in adult tagging efforts is often zero or one. The same data indicates that there has been a reduction in apparent growth of males and females, most noticeable in the upper age classes (Figure 34), an increase in natural and total annual mortality, and a decrease in harvest rate (Figure 35). The loss of these older age classes coupled with the reduction in apparent growth can lead to smaller, less fecund females, and consequently lower juvenile production.

Many factors could be responsible for the change in sex ratios. Hypotheses include change in sampling methodology, increased mortality of females, changes in distribution, or physiological effects. Some evidence for each is described below.

A change in location of Sacramento River fyke trap sampling of spawning adults in 1990 may have introduced a gear bias that could account for some, but not all, of the sex ratio change. Bias also seems unlikely because a similar shift was also noted in gill net captures from the Delta. Apparent growth rates of females have declined (T. Sommer, DWR, unpublished data) so females may be increasing the number of years between spawning migrations, reducing their capture rates in the fyke traps or gill netting surveys in the Delta.

Changes in natural or fishing mortality could also affect sex ratios. Anglers may exert selective fishing pressure on females but since the sex ratio of recaptured fish closely approximates the sex ratio of tagged fish, it is unlikely this is a major factor. The female:male ratio of recaptured fish is higher than the female:male ratio of tagged fish in all but four of the 34-year period of record, so an angler effect should not be ruled out entirely. An alternative is that there have been changes in natural mortality. For example, increased predation of female striped bass by pinnipeds could be important. No time series for the delta exists, making this difficult to examine, but it is generally recognized that there has been an increase in pinniped numbers since the passage of the Marine Mammal Protection Act in 1972. It is estimated that the California sea lion and Pacific harbor seal populations have been increasing at an annual rate of 5% (NMFS 1997). For example, NMFS (1997) report summer counts of 4900 harbor seals in San Francisco Bay utilizing 118 different haul out locations.

Another potential mechanism for changes in the sex ratio during the spawning season is that adult striped bass distribution may have shifted. One possibility is that females may leave the estuary for the nearshore ocean and not return to the estuary for annual spawning events. Such departure from the estuary has been observed in the Chesapeake Bay striped bass population, where as much as half the adult population has been observed in the ocean, far from spawning habitats (Secor et al. 2001, Secor 2008). It is unclear if this mechanism would result in skewed sex ratios unless females are more likely to skip spawning. Secor (2008) reports that skipping rates for Chesapeake Bay striped bass were less than 20%, which may not be able to account for the currently extreme low percentages of females detected during migration in the San Francisco Estuary. A related factor is that it is possible that maturation schedules have changed for female striped bass, which in turn could alter their seasonal distribution. If females are maturing more slowly, they may remain in downstream areas for longer periods. Males are already known to migrate upstream at a younger age, so a delay in female maturation would have a strong effect on sex ratios in young adults (e.g. age-3 and age-4).

A fourth explanation for the shift in sex ratios is that there may be environmental effects that reduce the number of females in the population. Temperature has been strongly implicated as a co-factor in sex determination in various members of the family Moronidae (Ospina-Alvarez and Piferrer 2008; Vandeputte et al. 2007), although temperature effects on sex ratios have not been documented for striped bass. Chemical inputs can also be a factor. Female adult fish concentrate lipophilic contaminants in their tissues, many of which can be estrogenic. These chemicals can adversely affect larval development, causing organ deformities, retarded growth, reproductive system abnormalities, and hatching difficulties (Ostrach et al. 2008). Based on research on other species, abnormalities include the increased presence of intersex fish, feminized males, and an increase in female fish. As evidence that this could apply to Pacific striped bass, intersex fish have also been observed in high numbers in striped bass populations in Oregon. However, the high incidence of hermaphroditism may also be a result of insufficient genetic diversity (Waldman et al. 1998).

Striped bass consume primarily copepods and cladocerans at first feeding (Heubach et al. 1963, Foss and Miller 2004), and prey density has been positively correlated with larval growth rate (Heubach et al. 1963, Foss and Miller 2004), which is believed to be inversely related to mortality. Although a long-term reduction in calanoid copepods has occurred (Orsi and Mecum 1986, Kimmerer et al. 1994, Orsi and Mecum 1996, Winder and Jassby 2010), we have not found evidence of a recent decline in spring coincident with the striped bass decline. Also, cladoceran abundance increased steadily during spring of the POD years (Hennessy and Hieb 2007). However, broad annual and seasonal indices of abundance may mask important short term patterns. For example, in the low salinity zone, early first feeding larvae probably rely on *E. affinis*, whereas those hatching later will encounter primarily *P. forbesi*. During the spring-time transition period from *E. affinis* to *P. forbesi* dominance, it is possible that finding sufficient numbers of either species might be problematic.

Summer: Summer is a generally a period of rapid growth for striped bass, but food resources may not be uniformly adequate throughout their range to support this growth. In particular, calanoid copepod numbers have been reduced recently in the western Delta and Suisun Bay (Winder and Jassby 2010). However, striped bass grow rapidly, even with the relatively low copepod densities found in the upper San Francisco Estuary (Foss and Miller 2004). Success from first feeding to 25 mm may have influenced recruitment since 2000, but there was no suggestion of a bottle neck during this period in the past (Kimmerer et al. 2000). By 25 mm in length, age-0 bass exploit larger mysid and amphipod prey, appearing to seek out mysids (Feyrer et al. 2003; Bryant and Arnold 2007). The dominant upper estuary mysid, the introduced *H. longirostris*, has slowly declined in summer since 2000, (Hennessy and Hieb 2007) but densities remain higher than those of the late 1990s, thus are unlikely to have influenced the striped bass decline since 2000. Long-term diet and growth have not changed substantially since 2000. Diet data from a long-term study (1973–2002) of striped bass collected from the pelagic environment during their first summer of life , revealed that the percentage of age-0 striped bass stomachs with food did not decline in the last two years, nor did the mean ration size, except perhaps in 2002 for fish <25 mm (Bryant and Arnold 2007). In a short-term shore-based study, a bioenergetic modeling (BEM) approach was used to evaluate food limitation in age-0 striped bass. The comparison of field collections with the BEM simulations did not provide evidence of food limitation and in fact, field-collected striped bass grew larger relative to their BEM growth predictions (Nobriga 2009). Most recently, feeding incidence calculated from age-0 fish collected from May–September of 2005 and 2006 gave no indication of food limitation. On average, 84% of the stomachs examined had at least one prey item. Amphipods (*Gammarus* spp. and *Corophium* spp.) were detected in large amounts during fall, which could be evidence of a switch to larger demersal prey items, possibly due to low mysid availability (DFG, unpublished data). Examination of apparent growth patterns (growth determined from length-frequency data) for striped bass did not reveal a decline subsequent to 2000 (IEP 2006). However, when fish condition was compared regionally, striped bass collected from western Suisun Bay weighed significantly less at the same length compared to those collected in regions farther east (IEP 2006).

No long-term studies exist of disease or parasites in young striped bass of the San Francisco Estuary. The incidence and intensity of tapeworm larvae (plerocercoid) was examined in fish collected from 1986–1993 (Arnold and Yue 1997). In this study, up to 79% of the larval and juvenile striped bass examined annually contained encapsulated plerocercoids (cestodes) in mesenteries and stomachs, but little immune response was detected. Recent sampling revealed no viral effects in summer 2006. There was a high incidence and intensity of trematode and flagellated/ciliated gill and mouth parasites in 2005–2007, with importance of the various parasites varying from year to year (Ostrach et al. 2009). The direct importance of such infections is unknown but, at a minimum, such infections represent a chronic stress on the immune systems of individual fish.

There is no direct evidence for the importance of contaminants in recent summers. High vitellogenin levels in male fish collected from Suisun Slough and elevated levels in fish from Honker Bay indicated contact with estrogenic compounds (Ostrach et al. 2005, Ostrach et al. 2009). The use of pyrethroid pesticides doubled in the early 2000s as compared to the early 1990s and the main period of application, July through October (Oros and Werner 2005), corresponds to the striped bass growing period.

Striped bass summer distribution appeared to shift after the invasion of the overbite clam in 1987. The San Francisco Bay Study deploys two nets at each sampling location: an otter trawl, towed on the bottom, and a midwater trawl towed obliquely through the water column. The proportion of total age-0 striped bass caught in the midwater trawl has been highly variable, but with a downward trend and lower peaks over time (Figure 31). Similarly, the proportion of age-0 striped bass caught by the otter trawl at shoal stations compared to deeper stations increased and remained consistently high after 1987, and became less variable after the late 1990s (Figure 31). This suggests that age-0 striped bass spent less time in the water column and moved to relatively shallow water sooner in the years after the clam arrived. Current analyses cannot discriminate whether these trends became more extreme in the 2000s. If a similar shift also occurred in the Delta, age-0 striped bass might become more vulnerable to shoreline predators, such as largemouth bass.

Fall: Fall has historically posed a feeding challenge for striped bass, but it is not clear if available food resources changed substantially after 2000. Seasonal and decadal declines in mysids (a highly selected diet item) density led to a broadened feeding niche and an early initiation of piscivory among age-0 striped bass in fall (Stevens 1966, Feyrer et al. 2003). Fall mysid numbers in the upper estuary declined steadily after 2000 with the exception of 2005. However, current mysid abundances are greater than densities in the early 1990s when *N. mercedis* declined to very low densities. The most abundant mysid currently is *H. longirostris* which invaded the estuary in about 1994 (Hennessy and Hieb 2007). Reduced food availability has been linked to observed declines in carrying capacity (Kimmerer et al. 2000) but recent studies (described above) do not indicate that age-0 striped bass are experiencing food limitation during the fall (Nobriga 2009, DFG unpublished data).

Age-0 striped bass environmental quality during the fall can be effectively described by Secchi depth and specific conductance (Feyrer et al. 2007). Physical habitat is important during this time since conditions during their first fall play a role in the density-dependent survival exhibited by striped bass from age-0 to age-3 (Kimmerer et al. 2000). Long-term trends indicate a decline in environmental quality from the late 1960s to present. Fall environmental quality in the 2000s declined from levels in the 1990s, and most of the remaining high quality habitat exists in the lower Sacramento River upstream of the confluence (Feyrer et al. 2007). If the age-0 striped bass population is also shifting toward the Delta and to a smaller habitat area there could be increased intra-specific competition, and predation might increase locally with increased densities and the overlap with additional piscivores, particularly largemouth bass (Nobriga and Feyrer 2007). In addition, the upstream shift may increase vulnerability to entrainment at the south delta water export pumps.

Winter: We hypothesize a potential winter bottleneck where only the largest and healthiest individuals survive. This derives in part from analyses by Kimmerer et al. (2000) who found little relationship between two indices of age-0 abundance and the number of bass entering the fishery at age 3. This contrasts with the results for age-1 fish, which are correlated with the number of age-3 fish. Hence, it appears likely that the problem occurs between age-0 and age-1. We hypothesize that the bottleneck occurs soon after fall, when age-0 abundance is measured. In winter, young striped bass revert back to feeding on invertebrate prey (Stevens 1966). In addition to mysids and amphipods they likely prey upon the recently introduced decapod shrimp, *Exopalaemon modestus*, as they do later in spring (Nobriga and Feyrer 2007). The increased numbers of *E. modestus* (Hieb 2007) likely improved food resources for winter striped bass.

Similar to other species, young striped bass showed increased winter entrainment as evidenced by salvage shortly after 2000 (Figure 18; IEP 2005, Grimaldo et al. 2009). This effect occurs after age-0 trends are assessed by FMWT. Losses indexed by winter salvage from the early 2000s would only begin to be reflected in adult numbers in 2003 and beyond. However, adult striped bass estimates do not show a substantial drop in age-3 or age-4 abundance in 2003 or 2004 (Figure 33).

Threadfin shad

Prior to the POD investigation there was very little information available on the ecology of threadfin shad in the Delta. Thus, one element of the POD investigation was to compile and synthesize the available data from IEP monitoring programs and special studies on threadfin shad. This effort has recently been completed (Feyrer et al. 2009) and forms the basis for the threadfin shad species conceptual model presented below (Figure 7).

Threadfin shad successfully invaded and has persisted in the Delta because of suitable environmental conditions. It is widely distributed but is most commonly encountered and most abundant in the southeastern Delta, especially the San Joaquin River near and just downstream of Stockton, where suitable abiotic habitat coincides with high prey abundance (Feyrer et al. 2009). These regions also have a relatively high density of SAV, which provides important spawning and larval rearing habitat (Grimaldo et al. 2004). Historic studies conducted in 1963–1964 (Turner 1966) and those more recently (Feyrer 2004, Grimaldo et al. 2004) identified a similar distribution for threadfin shad. Turner (1966) also found that threadfin shad was relatively abundant in dead-end sloughs of the northeastern Delta, areas which are not sampled by the current monitoring programs but provide functionally similar habitat.

Threadfin shad appear to grow relatively fast in the Delta and reach 70–90 mm by the onset of their first winter. This is generally consistent with fish lengths reported for Lake Powell, Utah and Arizona, U.S.A. (Blommer and Gustaveson 2002), but substantially larger than that observed in central Arizona reservoirs (Johnson 1970). Apparent growth rates in the Delta during fall declined with increasing abundance (Feyrer et al. 2009). This suggests density-dependent effects may be important and is consistent with previous research indicating that intraspecific competition for food can be a major factor limiting growth of threadfin shad in reservoirs (Johnson 1970).

It is important to note that threadfin shad has a limited distribution in the Delta. Of the 100 sites in the FMWT survey, catches at just seven adjacent southern Delta sites in the San Joaquin River drive the long-term patterns in the FMWT abundance indices (Feyrer et al. 2009). The overall pattern in interannual abundance has been variable with periods of high and low abundance and no apparent long-term trend. The recent period of near-record low indices is not unprecedented but is especially noteworthy because it has persisted. The decline is also apparent in the 20-mm Survey, salvage density in all seasons, and commercially harvested biomass (Feyrer et al. 2009). Finally, the decline is coincident with similar declines for other pelagic fishes (Sommer et al. 2007, Thomson et al. 2010). The persistent low abundance of threadfin shad is also noteworthy because of the documented ability of threadfin shad to rapidly recover from low abundance levels, so called population explosions, in part because of their synchronous spawning behavior (Kimsey et al. 1957, McLean et al. 1982). In addition to lower abundance, threadfin shad have been captured in fewer trawls suggesting that the recent decline in abundance may be driven by the FMWT encountering fewer and smaller-sized schools of threadfin shad. There have been similar periods of smaller-sized catches in the past, especially around the mid-1980s. However, the persistently low fraction of samples with fish present is unprecedented in the time series (Feyrer et al. 2009).

Threadfin shad are influenced by many of the same drivers affecting the other POD fish species; however, several drivers do not seem to be important for threadfin shad. Recent studies suggest that there are no measurable effects of disease on the population (Baxter et al. 2008). There is also no evidence that abiotic habitat of threadfin shad – measured as the combination of water temperature, clarity, and salinity – has declined in recent years (Feyrer et al. 2007). There is little evidence from the data examined for consistent stock-recruitment or stage-recruitment effects on the population (Feyrer et al. 2009). However, there does appear to be a complete disconnect between abundance in summer and fall. There are two drivers that are of particular concern for threadfin shad during this time period, episodes of low dissolved oxygen (DO) and blooms of the toxic algae *M. aeruginosa*, both of which occur in the center of threadfin shad distribution. Other drivers such as predation and low water temperatures are also known to affect threadfin shad populations in other systems (Parsons and Kimsy 1954, Griffith 1978, Blommer and Gustaveson 2002, McLean et al. 2006) and may be important at times in the Delta.

A final important note is that focused studies and sampling of threadfin shad are lacking and limit what can currently be concluded about its ecology in the system. Improved field observations and controlled laboratory studies designed specifically for threadfin shad, which can then inform modeling studies, are desperately needed to better understand the drivers that affect threadfin shad population dynamics in the Delta.

Summer: Based on preliminary analyses, Baxter et al. (2008) reported that prior fish abundance appeared to be important because there was a significant stock-recruitment relationship for threadfin shad. New analyses suggest that, although there is generally some positive response to prior abundance, there is little evidence for large scale stock- or stage-recruitment effects on the population (Feyrer et al. 2009). This is not a surprising result as stock-recruitment relationships are generally poor for opportunistic-type fishes such as threadfin shad (Winemiller 2005). However, there does appear to be a complete disconnect between abundance in summer and fall, suggesting that there are important drivers acting on threadfin shad during the summer-to-fall transition. We hypothesize that two drivers might be particularly important during this period, episodes of low DO and blooms of the toxic algae *M. aeruginosa*. These conditions occur in the center of the threadfin shad distribution in the central and southeastern Delta.

Episodes of low DO concentration commonly occur in the San Joaquin River and have been known to cause die-offs of threadfin shad. Persistent DO sags in the Stockton Deepwater Ship Channel portion of the San Joaquin River are well documented (Jassby and Van Nieuwenhuyse 2005). It is likely that smaller and shorter-term events occur in smaller Delta channels, but such events have not been documented.

In recent years, there have been dense blooms of *M. aeruginosa* geographically centered where threadfin shad are most abundant in the southern Delta (Lehman et al. 2008a). The blooms also occur during the critical late summer/early fall when newly spawned fish are recruiting to the population (Lehman et al. 2008a). The effects of *M. aeruginosa* on threadfin shad could be indirect by affecting food availability or direct by inhibiting feeding and by physiologically impairing threadfin shad.

For a variety of herbivorous crustacean zooplankton, *M. aeruginosa* can be toxic, non-nutritious, or inhibited feeding on co-occurring nutritious food (Fulton and Paerl 1987). Ger et al. (2009) found that ambient concentrations of a *Microcystis* toxin (microcystin LR) in the Delta were unlikely to be acutely toxic to two Delta copepod species, *E. affinis* and *P. forbesi*, but both species were very sensitive to *M. aeruginosa* in their diet (Ger et al. 2010a) and experienced significant mortality when *M. aeruginosa* was 10% or more of the diet, whether the *Microcystis* strain produced toxic microcystins or not.

A recently concluded POD study (Teh et al. 2010) on *Microcystis* effects on threadfin shad found that in laboratory feeding experiments, diets spiked with *M. aeruginosa* collected from the Delta had detrimental effects on the health of threadfin shad, including decreased growth, malnutrition, severe liver lesions, and increased ovarian degeneration (atresia) which may impair reproduction. This study also included health evaluations of 296 sub-adult threadfin shad collected from four Delta sites (Sherman Island, Brannan Island, Mildred Island, and Stockton) in 2007. Threadfin shad from the two San Joaquin River sites (Brannan Island and Stockton) were of poorer health than fish caught at the other two sites, but histopathologic analysis revealed that lesions in fish from the Stockton site were more likely related to effects of anthropogenic contaminants than to *Microcystis* toxicity. In contrast, the severe intestinal epithelial cell necrosis and the localization of microcystins in the liver and *Microcystis* in stomachs and intestines of threadfin shad collected at Brannan Island strongly indicated *Microcystis* toxicity.

In addition to the above drivers, declines in zooplankton abundance in the Delta (Winder and Jassby 2010) may have also affected threadfin shad. Feyrer et al. (2009) found evidence for density-dependent effects in threadfin shad that were consistent with previous research in reservoirs which showed that intraspecific competition for food could limit growth of threadfin shad (Johnson 1970). Other studies found that the condition of young threadfin shad was sensitive to prey abundance (Kashuba and Matthews 1984) and that interactions between food availability and water temperature affected growth rates and cohort survival of young threadfin shad (Betsill and Van Den Avyle 1997). It is possible that other biotic and abiotic habitat attributes are also important for threadfin shad in the Delta, but long-term trends in threadfin shad summer habitat have not yet been systematically and comprehensively examined.

Long-term trends in abiotic habitat during summer have not been examined. However, there is no evidence that abiotic habitat – measured as the combination of water temperature, clarity, and salinity – has declined in recent years in fall (Feyrer et al. 2007). Indirectly, habitat conditions may affect the abundance or survival of young threadfin shad by controlling the density of suitable prey organisms, particularly cladocerans.

Threadfin shad is a major component of piscivorous fish diets (Stevens 1966, Nobriga and Feyrer 2007). However, there is insufficient data to determine if predation mortality significantly affects the population during summer. Threadfin shad is also the most common fish collected at the export facilities (Brown et al. 1996). However, there are no significant results to date for an effect of summer exports on the population.

Fall: As mentioned above, Feyrer et al. (2009) noted a disconnect between threadfin shad abundance in summer and fall which may be related to episodes of low DO, toxic *M. aeruginosa* blooms, and limited food supply in late summer. An analysis of fall abiotic habitat condition for threadfin shad – measured as the combination of water temperature, clarity, and salinity – found no trend in the southeastern part of the Delta where threadfin shad are most commonly found (Feyrer et al. 2007).

Threadfin shad is a major component of piscivorous fish diets (Stevens 1966; Nobriga and Feyrer 2007). Striped bass, one of the primary predators on threadfin shad, move into the Delta from downstream bays and the ocean during the fall. This large influx of predators undoubtedly increases predation pressure on threadfin shad. The other primary predator, largemouth bass, resides in the Delta all year. However, as mentioned, the effects of predation on the population have not been studied. Two additional sources of top-down mortality include water exports and commercial harvest. Seasonal salvage of threadfin shad has been highest and most variable during fall. Two recent modeling efforts provide limited support for some effect of exports (Thomson et al. 2010, Mac Nally et al. 2010). Commercial fishing harvest has also been highest during the fall months (Feyrer et al. 2009). The effects of the loss of these fish from the population have not been studied.

There is no direct correlational evidence that food densities affect threadfin shad abundance. However, apparent growth rates during fall have been negatively related to abundance. As mentioned above, this relationship suggests density-dependent effects may be important.

Winter: The abundance of threadfin shad is not measured during winter, thus it is not possible to determine the potential importance of individual drivers. Long-term trends in habitat conditions (salinity and temperature) during winter are presumed to be generally similar to the fall, which would suggest no major impacts on the population. However, low water temperatures are known to cause massive die offs of threadfin shad and may be important at times in the Delta because winter temperatures occasionally decline below the minimum tolerances of threadfin shad (6–8°C; Turner 1966).

The top-down effects of predation are presumed to be similar to the fall; however, there is insufficient data to determine if predation mortality significantly affects the abundance of threadfin shad during winter. There was an increase in the salvage of threadfin shad during winter prior to the onset of the POD, but it has steadily declined since that time.

Spring: As mentioned above, there is little evidence for large-scale stock-recruitment effects (Feyrer et al. 2009). There are years in which spring abundance appears to respond to fall abundance, but the data are highly variable.

Long-term trends in abiotic habitat conditions during spring have not been studied.
As already mentioned above, indirect evidence suggests that the availability of food resources may have an effect on the survival and abundance of young threadfin shad during spring and summer.

Seasonal salvage of threadfin shad is lowest during spring and exports are not likely to affect the population during this season. As water temperatures increase during spring so does predation pressure from other species. The extent to which this affects the population has not been studied.

The Pelagic Organism Decline: A Historical Perspective

Why a historical perspective?

Since its inception in 2005, the POD investigation has largely focused on drivers that currently affect resources in the San Francisco Estuary. It is, however, important to understand that current conditions represent the outcome of a continuum of major changes to the system. Some of these historical changes are likely as important in understanding the POD as some of the more recent changes. Carpenter and Turner (2000) state this concept as follows: “ecosystem dynamics are history dependent because of the coupling of events across a range of cycling times” (or time scales). Note that we do not present this historical perspective to represent historical conditions as a baseline or target for management; however, it is instructive to compare the functioning of the current ecosystem with earlier periods. Such comparisons provide useful insights into some of the structural and functional ecosystem attributes that have been lost, and insight into the magnitude of changes that might be necessary to recover them.

Ecological resilience is a key concept for understanding how ecosystems respond to natural and human disturbances. Ecological resilience is the capacity of an ecosystem "to absorb disturbance and reorganize while undergoing change so as to retain essentially the same function, structure, identity, and feedbacks" (Folke et al. 2004). In other words a resilient ecosystem will look and function the same, before and after a disturbance, given adequate time to recover. A resilient ecosystem has options to adapt to change – it has "adaptive capacity" (Folke et al 2002). Understanding changes in ecological resilience of the San Francisco Estuary due to long-term historical changes or relatively recent changes is central to the emerging understanding of the POD as an ecological regime shift. An ecological regime shift is an abrupt transition from the previous state (regime) to a fundamentally different state with altered functions, structure, identity, and feedbacks. These concepts are explored in more detail in the following sections.

Change in Ecosystems

Estuaries are highly dynamic ecosystems that constantly undergo change (Healy et al. 2008). Before summarizing the historical changes in the San Francisco Estuary, we will briefly discuss drivers of change in ecosystems, and define some terms used in the remainder of the report.

Ecological change is brought about by interlinked drivers operating across a large range of temporal and spatial scales and often occurs in cycles (Chapin et al. 2009). Adaptive cycles consist of a slow growth and conservation phase which, after a significant disturbance, is followed by rapid collapse and release and eventually by reorganization and renewal. The growth and conservation phases are characterized by increasingly efficient, but also increasingly rigid use of available resources which erodes the resilience of the system to disturbance. Persistent small-scale disturbances (e.g. seasonally variable hydrographs, localized floods, small-scale fires) prevent optimization of resource use, but can help maintain resilience to larger scale disturbances.

Exogenous drivers, such as climate and geology, generally affect large regions and remain relatively constant over long periods of time (centuries). They set the context for drivers operating at the ecosystem scale. At the other extreme are small-scale, rapidly (less than a day to a few years) acting drivers with more localized, but sometimes large and/or lasting effects. They include individual events such as fires, floods, droughts, disease outbreaks, or toxic spills as well as variables exhibiting daily (e.g. tides), seasonal (e.g. seasonal upwelling or oxygen sags), or multi-year (e.g. strong upwelling) variations and cycles. The operational time scale of these fast variables is similar to biological response times (e.g., spawning migration and mating, reproductive cycle, and life span; see Figure 2 in Kimmerer 2004) and human planning horizons. These coinciding temporal scales may be the reason that fast variables have received a disproportionate amount of attention and many of them have come to be regarded as undesirable stressors. From an ecosystem resilience perspective, however, slower ecosystem drivers – usually just a few per ecosystem – that operate at intermediate scales are most important (Carpenter and Turner 2000). These "critical slow variables" (Chapin et al. 2006) include presence and redundancies of particular functional types of organisms, disturbance regimes, hydrological and nutrient regimes, biogeochemical processes, and biotic and abiotic landscape features. These variables change relatively slowly (years to decades). They provide important stabilizing feedbacks that may counteract the effects of more rapid drivers, thus influencing resilience and the likelihood of regime shifts. More than any other drivers, slow variables establish the identity of an ecosystem, including its structure (the biological and physical components) and functions (processes), and longevity as an entity. In spite of their importance, they have received relatively less attention, as have the linkages between drivers interacting across temporal and spatial scales (Groffman et al. 2006).

An ecological regime shift is a large change in the identity of an ecosystem such that there is a transition from one ecological state (regime A) to another (regime B) (Figure 36). When the ecosystem responds more or less linearly to changes in drivers, the regime change happens gradually. When there is a non-linear response to a relatively small change in drivers, change happens more abruptly and is often referred to as a “regime shift” (Scheffer and Carpenter 2003). If the trend in drivers reverses direction, the system may respond with a transition back to regime A that closely mirrors its previous transition to regime B; however, a return to regime A may not occur (Davis et al. 2010). Some change is simply irreversible because key attributes of the original regime have been irretrievably lost. In other cases, the back-transition may require a larger change in drivers than expected based on the original transition. This is particularly common for non-linear changes, where driver thresholds for the back-transition may be different than the thresholds for the original transition. This pattern is called “hysteresis,” or system memory. Hysteresis is the result of regime-specific internal feedbacks most often associated with slow variables. These features of regime shift have many important implications for ecosystem management and restoration such as surprising collapses, slower than expected recovery, or overall unexpected outcomes of recovery efforts. Consequently, adaptive management approaches require flexibility with a strong learning (science) component.

Drivers of ecosystem change include both natural drivers and human activities. In the remainder of this report, we define natural and anthropogenic drivers that produce adverse or undesirable changes in ecosystem structure and functions as stressors. Like many other estuaries around the world, the San Francisco Estuary has been severely altered by humans over the last 150 years (Lotze et al. 2006). Some of the changes were gradual, while others were more rapid (see Atwater et al. 1979, Nichols et al. 1986, Lund et al. 2007, Healey et al. 2008, Moyle et al. 2010).

Environmental History: Four Eras

Here, we provide a brief summary of four major periods in the environmental history of the San Francisco estuary: (1) Pre-European; (2) Gold Rush; (3) Post-Reservoir; and (4) POD. We selected these periods based on our understanding that each transition between these periods involved an extreme change to the ecosystem with major structural and functional alterations. In many cases, the transitions were associated with important slow variables.

Our summary of the Post-Reservoir and POD periods relied mostly on actual data from sampling in the region. By contrast, data are largely lacking for the first two periods. There are some data on salinity regimes and landscape changes (e.g. Byrne et al. 2001, Atwater et al. 1979), but almost no quantitative information about the biota. In the absence of these data, much of the analysis of earlier periods is based on professional judgment and reasonable assumptions about how the ecosystem likely functioned. As a consequence, the description of the Pre-European and Gold Rush periods should be interpreted with caution.

1. Pre-European Period

Before the arrival of Europeans, the San Francisco estuary was characterized by high landscape heterogeneity and hydrological variability with strong oscillations at tidal, seasonal, and decadal scales (Enright and Culberson 2010). Sediment cores indicate that the three millennia prior to European colonization had two extended dry perFiods lasting centuries during which salinities in the Delta were relatively high (Byrne et al. 2001). Except for these dry periods, however, salinity in the Delta was generally very low. At the time of European arrival, the estuary was in an extended wet period that started around 1250 AD and was characterized by high freshwater inflows (Byrne et al 2001). Seasonally, inflows and outflows were highest in the winter and spring and lower in the summer and fall. High San Joaquin River inflows extended longer into the summer than inflows from the Sacramento River due to later snow melt from higher mountain ranges in the southern Sierra Nevada (Moyle et al 2010). Mean Delta salinities during this period were overall very low (Byrne et al 2001) and probably similar to those documented in early technical reports, which placed the boundary between freshwater and saltwater near Carquinez Straits (Means 1928 cited in Contra Costa Water District 2010). This has since been confirmed by paleoecological studies (summarized in Contra Costa Water District 2010). Seasonally, the Delta my have occasionally become somewhat salty in the summer and fall, but would always return to freshwater in the winter and spring.

The pre-European Delta landscape was not untouched by humans – many native American tribes lived in and around the Delta. The Delta they knew was characterized by extensive inland tule marsh, seasonal floodplain, and complex channel geometry including many small distributary channels and dead-end sloughs as well as larger channels with natural levees of varying sizes (Moyle et al. 2010, R. Grossinger and A. Whipple, SFEI, unpublished data). This complexity likely resulted in substantial spatial heterogeneity of various habitat attributes such as water temperature. On the other hand, small-scale (fast) temporal variability may have been lower than later on. For example, the extensive tidal marshes (a slow variable) likely muted tidal effects by dissipating tidal energy, thus reducing short-term variability in salinity and possibly other water quality variables (Moyle et al. 2010, Enright and Culberson 2010). Other pre-European ecosystem attributes are less certain, but may have included higher levels of biological-based turbidity and lower dissolved nutrient concentrations. This represents the baseline period for our review, when productivity of native phytoplankton, zooplankton, fishes, and waterfowl (migratory and resident) were likely at peak levels and invasions by non-native species were rare. In addition to the native resident and migratory pelagic fishes, the pelagic zone was inhabited by relatively large invertebrates including native mysid shrimp and calanoid copepods. Primary producers included the phytoplankton community that likely underwent regular spring bloom cycles and likely featured abundant nutritious species, as well as benthic algae and various types of macrophytes. In addition to autochthonous phytoplankton production, young detritus from adjacent tidal marsh production, easily broken down by microbes, likely subsidized pelagic production in the summer and fall. Allochthonous riverine and floodplain phytoplankton and detritus might have been a particularly important subsidy in the spring.

2. Gold Rush Period

The Gold Rush Period, starting in the mid-1800s, was characterized by perhaps the most extreme and rapid changes to the estuary (Atwater et al. 1979). Many of these changes resulted from human engineering activities such as mining, levee construction, draining of wetlands and dredging of channels. Mercury was mined in the Coast Ranges for use in gold mining in the western Sierras. Both the mercury mining and subsequent loss of portions of the mercury used during gold mining operations contributed to later concerns about bioaccumulation of mercury in biota. Abandoned hardrock mines for copper, gold and other metals began contributing acid mine waste containing a variety of metals to streams in the watershed. Upstream hydraulic gold mining activities resulted in the mobilization of massive quantities of sediment which increased sediment loading to peak levels in the late 1800s (Shvidchenko et al. 2004, Meade 1982). This likely resulted in greatly increased non-biogenic turbidity and mineral sediment deposition in the estuary. It also resulted in filling of river channels with sediments which decreased the capacity of channels to transport high flows. The resulting increased flooding of surrounding areas and filling of navigation channels led to a court decision that abruptly curtailed hydraulic mining activities in 1884. In addition, levees were constructed along channels to support shipping traffic, reduce flood risks, and flush excess sediments. These actions had the intended effects of increasing channel capacity and reduce flooding, but also caused substantial losses of marginal habitat (e.g. tules and riparian areas) and marshes as well as major alterations to channel geometry. In addition, the levees were used to isolate areas for drainage and conversion into farmland. Overall, the formerly complex estuarine landscape was simplified into large, diked polders locally called "islands" intersected by a roughly linear grid of relatively deep, steep-sided channels. Development activities also likely increased inputs of nutrients and some contaminants, but loss of wetlands may have reduced inputs of dissolved and particulate organic carbon. Loss of shading by tules and riparian vegetation in the Delta and upstream in the watershed may have increased average water temperatures to some degree but more likely decreased temperature heterogeneity. The simplified habitat geometry from loss of dead-end sloughs likely resulted in changes in mixing that may also have further decreased temperature heterogeneity.

Salinity in the Delta appears to have remained low until upstream diversions started significantly reducing Delta outflows in the 1920s (Contra Costa Water District 2010). Low salinity until the 1920s was associated with high levels of freshwater diatoms in sediment cores (Byrne et al. 2001). However, phytoplankton productivity probably decreased substantially as a result of light limitation from increased turbidity levels caused by increased suspended sediment. There is little doubt that the huge input of hydraulic mining sediments radically altered the benthic community. Benthic microalgae, once likely a major component of the estuarine primary producer community, were likely subjected to higher rates of deposition of fine materials from upstream mining activities. Similarly benthic invertebrates would have been subject to higher sedimentation rates. This may have favored benthic plants and animals with high tolerances for silt and the ability to avoid smothering, which may have caused changes in species composition, but there is no historical information to evaluate this hypothesis. A drop in primary productivity likely cascaded upward to zooplankton. Zooplankton composition may have been altered by the start of invasions from ballast water, the intentional introduction of sport fishes (and water from their native habitats), and more frequent salinity intrusions after 1920 with especially high salinity levels during the 1928–1934 drought.

Following the Gold Rush, Europeans introduced many fishes intended to provide food or sport. The early introductions included American shad, striped bass, centrarchids (bass and sunfish) catfish and carp (Dill and Cordone 1997). American shad and striped bass did particularly well, thriving in the high turbidity estuary. Native species are thought to have declined substantially during this period because of habitat alteration and competition from introduced species. The once common native thicktail chub started declining in the late 19th century and finally became extinct in the late 1950s. Salmonids, particularly Chinook salmon were heavily fished during this period. Mining activities resulted in sedimention and loss or reduced quality of spawning gravels for salmon and all other riffle spawning species. At the same time access to upstream spawning areas was reduced due to relatively small and sometimes temporary dams and diversions constructed for mining or agricultural purposes. The construction of larger, permanent dams accelerated through this period for municipal and agricultural water supply and flood protection. The area of dam construction reached its peak with the construction of the SWP and CVP.

3. Post-Reservoir Period

The construction of reservoirs and the CVP and SWP started in the first half of the 20th century and led to additional extreme changes to the estuary. The hydrology of the estuary was altered by reservoirs that held spring run-off and then released stored water during summer and fall for municipal and agricultural use (Mount 1995, Moyle et al. 2010). These changes reduced flood flows, which reduced seasonal inundation of floodplains. The absence of flooding, also facilitated by levee construction, allowed development of former floodplains for agricultural and urban uses. The reservoirs also disrupted the sediment transport processes by intercepting and storing sediments transported down from the Sierra Nevada. Sediments immediately below the dams that could be transported by the altered flow regime were eventually depleted and could not be renewed from above the reservoir. The construction of levees, loss of floodplain, and reduction in flooding, decreased sediment recruitment from the floodplains and banks of the low elevation portions of the larger rivers.

Water diversions from the Delta increased with increased urban and agricultural demands due to steady population growth. Year-round water exports from the Delta started in 1968 after the completion of San Luis Reservoir and eventually led to mostly negative (upstream) river flows in the OMR channels of the central and southern Delta. Upstream and in-Delta diversions reduced inflows from the San Joaquin River to a minor proportion of freshwater inflows into the Delta. After removing seasonal and decadal-scale oscillations, the long-term trend in outflow was positive from 1929 until 1960 and followed the long-term positive trend in precipitation. Precipitation continued to increase after 1960, but the long-term trend in outflow turned negative after 1960. There was overall lower outflow for the period from 1968 to 2006 compared to the previous four decades. The greatest outflow reductions occurred during the last two decades (Enright and Culberson 2010). Reservoir and water project operations also had a dampening effect on outflow variability; however, both seasonal and annual outflow variability became overall more, not less, variable in the post-reservoir period due to overall wetter hydrology during this period. To date, the Mediterranean climate of California remains the most powerful driver of long-term variability in outflow at the seasonal and interannual scale (Enright and Culberson 2010). The spatial extent of salinity intrusions peaked early in the 20th century before fresh water was drawn from the Sacramento River across the Delta to the CVP and SWP export facilities. However, while saltwater was kept out of the central Delta by drawing fresh water across the OMR corridor, the western Delta and Suisun Bay became increasingly salty in the summer months (Contra Costa Water District 2010) and, similar to outflow, exhibited more variability in salinity after 1968 than in the previous decades (Enright and Culberson 2010). Several multi-year droughts tested the capacity of the system to satisfy the competing human and environmental needs for water and other ecosystem services. This is in spite of the relatively stable and moderate climate enjoyed by California over the last 150 years (Malamud-Roam et al. 2007) and higher precipitation than in the previous period (Enright and Culberson 2009).

Nutrient inputs increased as a result of inputs of fertilizer in agricultural and urban runoff. The expansion of agricultural and urban land uses in the San Francisco Estuary and watershed also increased the diversity and amounts of contaminants in the system. Organochlorine insecticides, including dichlorodiphenyltrichloroethane (DDT), were already being phased out during this period but were replaced by organophoshate pesticides. Residues of organochlorine compounds can still be found throught the system. A wide array of herbicides was used during this time period. Waste products from industrial processes led to inputs of a wide variety of contaminants. Urban uses of pesticides, fertilizers and other industrial products resulted in contaminant inputs through urban runoff and in treated wastewater. Many such inputs were reduced after their detrimental effects were recognized through implementation of legislation, such as the Clean Water Act, or other regulations. These reductions resulted in real benefits to the environment and organisms; however, low-level, sub-lethal inputs continued. New pesticides and other chemicals continued to be developed, used, and transported into aquatic ecosystems.

Biologically, the post-reservoir period is characterized by an accelerating rate of invasion by alien species, especially at lower trophic levels (Nichols et al. 1986, Cohen and Carlton 1998). There were multiple invasions of mysids, copepods, and jellyfish,with an overall drop in body size of crustacean zooplankton (Winder and Jassby 2010). Some of the most extreme changes occurred in the benthic community, where successive invasions by the bivalves *C. fluminea* and *C. amurensis* led to their dominance of this habitat (Peterson and Vayssieres 2010). These bivalves greatly increased benthic grazing pressure on planktonic phytoplankton and zooplankton (Jassby et al. 2002). The zooplankton community was also almost entirely replaced by non-native species (Winder and Jassby 2010). The dramatic displacement of indigenous pelagic and benthic primary consumers by introduced species during this period was accompanied by changes in primary producers notably: (1) the decline of diatoms; (2) increases in flagellates; and (3) an overall decline in phytoplankton cell size, biomass and productivity (Lehman 2000, Jassby et al. 2002). Finally, two exotic aquatic macrophytes also appeared in the Delta during this period. The floating aquatic macrophyte *Eichhornia crassipes* (water hyacinth) started proliferating in the early 1980s; however a successful control program has reduced the ecological effects of this invasion. *E. densa* was introduced in the 1960s, but did not reach nuisance levels until after the 1987–1992 drought (Jassby and Cloern 2000). In addition to their direct effects on native species via competition and predation, some of the invasive species, especially *E. densa*, also act as powerful “ecosystem engineers” (Jones et al. 1994, Breitburg et al. 2010), adding to the human reengineering of the system during the Gold Rush and Post-Reservoir periods.

Downward trends in several fish species became apparent in the second half of the 20th century, resulting in the eventual listing of seven fish species under the CESA or FESA, including two of the POD species. Declining turbidity was implicated in the long-term declines of delta smelt, longfin smelt, and age-0 striped bass. Increases in water exports, X2, and changes in the food web also contributed to varying degrees to the long-term decline in the POD fish species (Thomson et al 2010, Mac Nally et al. 2010). There were relatively fewer introductions of fishes during the Post-Reservoir Period. Increasing populations of previously introduced littoral fishes, particularly largemouth bass and other centrarchids which benefitted from expanding SAV in shallow water habitat may have affected native species, especially through predation (Dill and Cordone 1997, Brown and Michniuk 2007, Moyle and Bennett 2008). Similarly, Mississippi silverside, a habitat generalist, may affect native species through both competition and predation on egg and larval life stages (Bennett 2005, B. Schreier, CDWR, personal communication).

4. POD Period

The POD Period represents a period of continued decline in turbidity as the last of the mining sediments were transported out of the river and estuarine channels. Careful control of reservoir operations and exports resulted in a stabilized hydrology (Moyle et al. 2010) and a relatively upstream location of X2 especially in the fall irrespective of water year type (Figure 26; Feyrer et al. 2007). Another major change to physical habitat during this period was the rapid expansion of *E. densa*, which likely benefited from the more hydrologically stable conditions and reached peak levels (Brown and Michniuk 2007, Baxter et al. 2008, Hestir 2010). The proportion of San Joaquin River water in the Delta was low relative to Sacramento River contributions. Water temperatures were relatively warm as compared to the previous decade. Ammonium levels reached their highest levels as a result of urban inputs (Jassby 2008), while phosphorus inputs (total phosphorus and soluble reactive phosphorus) declined due to an abrupt 2-fold decrease in urban phosphorus loading in the mid-1990s (Van Nieuwenhuyse 2007). Similarly, pyrethroid pesticides, herbicides and “emerging contaminants” showed increases because of agricultural and urban inputs, but other pesticides, including Ops, declined (Oros and Werner 2005).

Phytoplankton biomass and primary production in the Delta and Suisun Bay declined to the lowest levels ever observed in the mid-1990s and recovered somewhat in the Delta during the POD period; however, there continued to be major changes in phytoplankton species composition (Baxter et al. 2008). Perhaps the most substantial change in phytoplankton was the increase in the frequency, duration, and geographical extent of *M. aeruginosa* blooms (Lehman et al. 2008a). Similarly, there were continued changes in the zooplankton community, notably the virtual disappearance of native mysids and the increase of the cyclopoid copepod *L. tetraspina* (Orsi and Kimmerer 1986, Bouley and Kimmerer 2006, Winder and Jassby 2010). Jellyfish adapted for brackish water increased in the western Delta, Suisun Bay and Suisun Marsh (Schroeter 2008). Pelagic fishes reached historic lows, while invasive species such as largemouth bass, other centrarchids, and inland silversides reached their highest levels (Moyle and Bennett 2008).

Human History – Then and Now

The four ecological eras of the San Francisco Estuary summarized above were closely linked with social and scientific developments in California and the nation. Here we briefly touch on a few of these changes because they pertain to our understanding of the POD in a historical context.

Many of the human-caused environmental changes over the past 150 years were intentional and the outcomes were initially considered highly desirable based on the prevailing social values. Some are still regarded as desirable by some segment of society. Examples include the "reclamation" of seasonal and tidal wetlands to support agricultural production and urban development, intentional introduction of exotic species, prevention of seasonal flooding, diversion of water from rivers to support a growing human population, and the dilution, transformation and export of wastes in waterways. Other changes that have occurred were largely unnoticed because they did not appear to directly affect ecosystem services valued by humans. Examples of these types of changes include changes in water quality that ultimately affect ecosystem productivity but do not exceed legal thresholds, and changes in sedimentation processes that slowly affect clarity of downstream waters. The effects of both types of changes on important slow variables, such as hydrological and landscape heterogeneity, that previously had defined and maintained the unique identity of the system during the pre-European period were largely ignored in favor of more immediate gains through control of adverse (to humans) impacts of fast variables, such as individual flood or drought events and seasonally unreliable freshwater supplies. It has now been recognized that some of these changes have affected other segments of society. For example, decreasing fish populations have affected the economic well being of some recreational and commercial fishing industries. Perceptions of value have also changed with society placing new emphasis on the recreational, aesthetic and ecological functions of natural systems, including the San Francisco Estuary and watershed.

New scientific findings about ecosystems, increasing environmental consciousness, and finally the new environmental laws of the 1960s and 1970s represented an important scientific and social change. In the Delta and Suisun Bay, this resulted, among other things, in the initiation of long-term ecological monitoring and studies by the IEP and others in the 1970s. The latest development in this context was the enactment new water-related legislation by the California legislature in 2009. This comprehensive legislative package included the creation of a new Delta Stewardship Council charged with promoting the: "coequal goals of providing a more reliable water supply for California and protecting, restoring, and enhancing the Delta ecosystem. The coequal goals shall be achieved in a manner that protects and enhances the unique cultural, recreational, natural resource, and agricultural values of the Delta as an evolving place" (California Water Code §85054).

The co-equal goals as well as the creation of the Delta Stewardship Council are in general agreement with a recent change in natural resource management toward "ecosystem-based management" (McLeod et al. 2005) and "resilience-based ecosystem stewardship" of "social-ecological systems" (Chapin et al. 2009), which increases adaptive capacity (Folke et al 2002). The codification of the need to protect the Delta ecosystem as a whole, not just specific ecosystem services or beneficial uses, is particularly consistent with these changes in the approach to resource management. Ideas associated with this new management model are rapidly gaining momentum (e.g., The Johnson Foundation 2010). This represents a fundamental shift from the traditional and still common “steady-state management”, which focuses on preventing change and reducing variability of natural systems, to adaptive management, which incorporates and addresses change (Folke et al. 2002).

In the traditional management model, natural systems are considered largely separate from human systems and are assumed to be relatively stable (unchanging) and infinitely resilient (Folke et al 2004). The traditional management model ignores changes in slow variables (which are simply considered stable) and focuses mostly on rigidly controlling fast variables perceived as undesirable disturbances. The model maximizes a few select ecosystem services (e.g., provisioning of water or food) while discounting others (e.g., nutrient cycling). New management models include change as a fundamental property of social-ecological systems. Instead of suppressing change, management can include variability at various temporal and spatial scales in ways that sustain all ecosystem services (Chapin et al 2009).

Fundamental to the thinking of these new theorists is that ecological resilience cannot be taken for granted (Folke et al. 2004). Reduced resilience is related to changes in slow variables and thereby to recent undesired and unexpected changes in many ecological structures and functions. These unexpected outcomes are opposite to the intent and assumptions of traditional steady-state management, which emphasizes stability and reliable provision of certain ecosystem services (e.g., water supply reliability). Many ecosystems are currently experiencing rates of change much greater than during the past 10,000 years (the Holocene). These high rates of unexpected change lead to catastrophic shifts to less desirable, degraded states (Crutzen 2004, Rockstrom et al. 2009). On a regional scale, reports of major and often rapid changes in ecosystems are increasingly common and include collapses of important natural resources, from fisheries to coral reefs to forest systems (Folke et al. 2004). Many of these changes are so dramatic they have been called regime shifts. We hypothesize that the POD was one such rapid, unexpected collapse.

A Tale of Two Estuaries

Why a new conceptual model?

Here, we introduce the idea of an ecological regime shift in the Delta and Suisun regions of the estuary as a new conceptual model and working hypothesis for the POD. The regime shift conceptual model expands the POD beyond the original focus on pelagic fishes to the ecosystem level and places it in a historical context. This allows integration of the POD with other changes in the system that may not be a clear part of the narrower POD story, but may be essential to understanding and managing the system in its current state. For example, the new conceptual model includes changes in population dynamics and abundance of migratory fish species, such as salmonids and sturgeons, and in littoral and benthic communities. It also includes changes that happened or began long before the POD. In addition to providing a more inclusive narrative outline, the regime shift concept focuses attention on the ideas of system resilience and ecological thresholds, which have implications for choice of management approach. The regime shift approach provides for comparison of the San Francisco Estuary with other systems undergoing regime shifts. Thus, lessons learned in other systems about how to avoid or reverse regime shift can be more directly translated to the Delta (Biggs et al. 2009). Further exploration of the POD in the regime shift context should provide insights into possible future alternative states that may arise as a result of management interventions or other changes in environmental drivers and may usher in a new era of "resilience science" (McLeod and Leslie 2009) in the estuary and watershed. Ultimately, this new conceptual model, the associated extended POD narrative, and the new scientific endeavors that might arise from it are aimed at informing new resilience-based, adaptive ecosystem management and conservation strategies to build or rebuild adaptive capacity of the estuary and watershed. For the purpose of this report, however, the regime shift concept serves to integrate history, drivers, and affected ecosystem attributes in a cohesive narrative with gradual changes in ecosystem resilience, short-term disturbance, and random effects on populations and communities.

Ecological regime shift

As described earlier, ecological regime shifts are rapid, large-scale, lasting changes in ecosystems from one more-or-less stable regime (or state) to another (Scheffer and Carpenter 2003) caused by a non-linear system response to drivers of change. The term regime shift was first introduced in the ecological literature to describe the fluctuating stocks of sardines and anchovies (Lluch-Belda et al. 1989). Regime shifts have since been described worldwide for a wide variety of ecosystems including oceans, lakes, estuaries, and terrestrial systems (reviewed in Folke et al. 2004). A number of studies support the idea of a recent regime shift in the upper San Francisco Estuary associated with the POD (Manly and Chotkowski 2006, Moyle and Bennett 2008, Mac Nally et al. 2010, Thomson et al. 2010, Moyle et al. 2010).

Regime shifts can occur naturally or in response to human actions, and often come as a surprise. A popular analogy (Figure 37) uses an image of a ball to represent a community or ecosystem in a system of valleys, which represent alternative stable states. A regime shift is represented by the ball rolling from one valley across a ridge (an unstable state or threshold) into an adjacent valley (or alternative stable state) (Beisner et al. 2003).

If the initial state is considered desirable by society, the regime shift is regarded as undesirable due to costly consequences to humans and natural resources, and because of difficulties in reverting back to more desirable stable states. The severity of a regime shift and the potential for reversal depends on the resilience of the ecosystem. It is important to note that resilience does not mean that changes do not occur. Rather, the system may absorb disturbance by reorganizing and adapting such that essential "functions, structure, identity, and feedbacks" of the system are maintained (Folke et al. 2004).

In theory, regime shifts happen either because drivers push communities beyond the limits of their resilience and into an alternate stable state within a constant environment (the ball moves from one valley to another), or because environmental drivers change the environment so the stability of one state is reduced while an alternate state becomes more stable (the valley and ridge topography changes) (Beisner et al. 2003). An example of the former mechanism might be a combination of overfishing and species invasions and associated trophic cascades (Daskalov et al. 2007). The latter mechanism can include a slow and often imperceptible reduction of resilience (valley topography) by changes in important slow variables that sustain important internal feedbacks. At some point a threshold is exceeded and there is a rapid and unexpected regime shift. In the context of the ball analogy, changes in slow variables can erode resilience by moving valleys closer together and lowering the height of the ridge around the ball, making a regime shift more likely given current drivers. As mentioned above, such shifts may not be easily reversible. This phenomenon is known as hysteresis. In other words, pushing the ball back uphill is hard and the ball may not actually return to the original valley, which may have irretrievably disappeared.

Finally, random events (i.e., stochasticity) also play an important role in regime shifts. The final push into a different state may come from random variability in populations and communities or the environment. In the ball anology, the ball does not sit perfectly still but changes position in response to random variability in environmental drivers, internal feedbacks of the ecosystem or both. If a random event is strong enough, an unexpected regime shift can occur and can even lead to rapid extinction (Melbourne and Hastings 2008, Hastings and Wysham 2010). Such a regime shift would be unexpected because it could occur even though known drivers remained within the previously observed range of variability. Random effects may also come into play with respect to Allee effects (Allee 1931, Dennis 1989, Courchamp et al. 1999, Berec et al. 2006). This makes forecasting of regime shifts particularly difficult.

POD – a regime shift

As depicted in figure 8, we propose that changes in a suite of mostly abiotic, environmental variables (drivers) led to changes in biological populations and communities in the system that recently became so profound that a regime shift might have taken place that affected not just the four POD fish species, but the entire system. We have started exploring the POD in the context of regime shift and do not yet know if this new regime represents an alternative stable state with stabilizing feedbacks. More work is also needed to establish the slow and fast drivers that led to this regime shift. Most of the environmental drivers in figure 8 have been under investigation by the POD study and have been represented in the habitat and top-down boxes of the basic POD conceptual model. However, the regime shift model explicitly considers operation of these and other drivers over larger geographic scales and longer time scales than previously considered. In addition, the regime shift model includes the effects of the drivers on all species and processes. Importantly, recent analyses have not identified environmental drivers that can explain the POD, but have identified drivers associated with long-term trends in POD fishes (Thomson et al. 2010). Most of these drivers changed gradually before the POD. As a group, the environmental drivers we discuss in this report may represent at least some of the critical slow variables determining the resilience and adaptive capacity of the Delta ecosystem. Additional critical slow variables may emerge as we continue to explore this regime shift.

The environmental, slow drivers we propose for the POD regime shift are (1) outflow, (2) salinity, (3) landscape, (4) temperature, (5) turbidity, (6) nutrients, (7) contaminants, and (8) harvest. These drivers are listed in our hypothesized order of their importance to the resilience of the system and approximate rate of change. This order will likely change as we learn more about the regime shift and associated drivers. The original, pre-regime shift state of the pelagic community has been presented in the description of the Pre-European period provided above. As described in the environmental history section above, the POD shift was preceded by changes in drivers associated with the Gold Rush, changes in land use, and reservoir construction and operation. A better understanding of prior changes will likely lead to a better understanding of the POD shift and the current state of the system. Improved understanding of these changes will also give insights into which drivers might be managed in a way that would improve ecosystem resilience to future threats and perhaps lead to a more desirable state. We hope to explore the POD regime shift and prior changes in drivers and thresholds in more detail in the future.

In the following sections, we will briefly summarize changes in the eight drivers identified above and provide hypotheses abouttheir individual and combined effects on the biota and importance to resilience. We will also briefly mention additional slow abiotic drivers we have not yet explored as part of the POD investigation. Finally, we will describe the resulting new ecosystem regime for the pelagic, benthic, and littoral zones of the Delta and Suisun Bay regions.

1) Outflow – Native species are adapted to the natural flow regime of the estuary which includes natural variability in the frequency, timing, duration, and rate of change of flow events, and the time intervals between major floods and droughts (Moyle et al 2010). Due to its Mediterranean climate and the complex interplay of geomorphology and hydrology, outflow of freshwater from the Delta to San Francisco Bay and the ocean varies greatly on tidal, seasonal, and interannual scales (Enright and Culberson 2010, Moyle et al. 2010, SWRCB 2010). Seasonally, winters are wet and summers are dry. On a decadal scale, multi-year dry and wet periods are common. Major shifts from overall dry to overall wet phases occur at the scale of centuries. Currently, the estuary is in an extended wet period that started around 1250 AD. The decades since the middle of the 20th century have been particularly wet. In spite of some dampening of variability by water project operations, natural climate (precipitation) variability is still the dominant driver of seasonal and interannual outflow variability. Outflow may actually be more variable now than in pre-European times when flows were dampened by large wetland and floodplain areas (Enright and Culberson 2010). Outflow volume, however, is now about 15% lower than before year-round water project operations began in 1968 and the long-term trend in outflow is now decoupled from the long-term trend in precipitation due to flow regulation and water diversions (Enright and Culberson 2010). Recent fall outflows have been uniformly low irrespective of water year type (Feyrer et al. 2007).

We hypothesize that in spite of recent human-caused flow alterations, the remaining strong, climate-driven variability in outflows may presently act as the most important critical slow variable that helps maintain the remaining original resilience of the system. We further hypothesize that outflow volume is another important slow driver of ecological change via its effects on residence time, the estuarine salinity gradient, and other physical processes. Future changes in outflow variability and volume due to climate change will affect the adaptive capacity of the system to respond to other changes.

2) Salinity – The pre-European Delta, Suisun Bay, and Suisun Marsh were predominantly fresh water environments, while much of San Francisco Bay was brackish (Contra Costa Water District 2010). Overall, long-term trends in salinity were closely coupled to long-term trends in climate and hydrology (Enright and Culberson 2010). Starting in 1968, the long-term trend in salinity in Suisun Bay changed from a previously negative association with precipitation to a positive one. In other words, similar to the long-term trends in outflow volume, trends in salinity became decoupled from the previously dominant climate driver (precipitation) (Enright and Culberson 2010). Early water diversions and wetland losses led to increased salinity intrusions deep into the Delta. Reservoir operations and year-round water diversions that necessitated freshwater in the Delta shifted the salinity gradient back toward the west, but Suisun Bay remained brackish. These changes constricted and stabilized the estuarine salinity gradient and shifted the distribution of species adapted to marine, brackish, and freshwater conditions in the estuary from pre-European times. Jassby et al (1995) showed that the location of the 2 psu bottom isohaline along the axis of the estuary (distance from the Golden Gate in km) had simple and significant statistical relationships with annual measures of many estuarine resources including phytoplankton, clams, zooplankton, and fishes. While several of these X2 relationships changed over time (Kimmerer 2002), many have remained intact. The invasion by the clam *Corbula amurensis* and a host of other species as well as the change in some of the X2 relationships coincided with the low flow/high salinity conditions during the extended 1987–1992 drought (Winder and Jassby 2010). The recent decline in fall outflow has led to increased and interannually less variable fall salinity in the western Delta and Suisun Bay since the 1987–1992 drought and especially during the POD years (Figure 26 and Figure 38; Winder and Jassby 2010). The constriction in habitat of suitable salinity (and turbidity) may have contributed to the decline of delta smelt and other pelagic organisms (Feyrer et al. 2010). The more saline conditions in Suisun Bay likely favored invasive species such as *Corbula* and invasive jellyfish, while the uniformly freshwater conditions in the Delta contributed to the widespread colonization by *E. densa*.

We hypothesize that the position, extent, and variability of the estuarine salinity gradient represents another critical slow variable. A westward position of the salinity gradient coupled with sufficient variability, including occasional salinity intrusions into the Delta and freshwater flows reaching San Pablo Bay, favors native species. A more eastward and more constricted and stable salinity gradient favors more non-native and nuisance species. In spite of remaining substantial variability in salinity, the long-term increase in salinity in Suisun Bay, and constriction of the salinity gradient likely contributed significantly to the erosion of the resilience of the original ecological regime. The current situation contributes to the stabilization of the new regime.

3) Landscape – As described above, the pre-European estuarine landscape looked and functioned very differently from today's landscape. By geological standards, the San Francisco Estuary is young – only about 6,000 to 10,000 years old – and its newly evolving landscape likely underwent many substantial transformations. Some of these transformations occurred slowly over centuries, while others occurred much more rapidly, providing for a heterogeneous, variable mix of habitats. The most rapid and dramatic transformation occurred, however, over the last 150 years. Many original landscape features such as the vast wetlands, riparian forests, and floodplain areas were lost, and replaced with new features including a grid of deep, steep-sided channels, dry polders (islands), and large shallow lakes (flooded islands). With the exception of the addition of flooded islands and some small wetland restoration areas,

the current landscape has remained relatively unchanged for nearly half a century. The current landscape is not the landscape in which the native species of this estuary evolved. It likely favors other species better adapted to the altered conditions. The loss of habitat in combination with predation and competition from introduced species is thought to be important in the declines of many native species (Brown and Moyle 2005), including the extinct thicktail chub and Sacramento perch, which has completely disappeared from the Delta.

We hypothesize that the current rigid, simplified landscape configuration is a critical slow driver that stabilizes the POD regime. The dramatic landscape transformation that started 150 years ago was likely the single greatest driver of ecological change in the system and responsible for much of the erosion in its original ecological resilience. Due to the focus on recent changes, the POD investigations have not yet included studies of past landscape transformations and their interactions with other drivers. In addition to better understanding what led to the POD, such studies would be helpful for guiding restoration planning.

4) Temperature – Water temperature in the Delta was once likely as variable as its hydrology due to the Mediterranean climate, variable hydrology, and landscape heterogeneity. Winter and spring flows into the estuary were likely quite cold. Water temperatures during the warmer months were likely heterogeneous because of the variable, complex landscape with dead-end sloughs having little exchange with larger downstream channels. The high degree of connectedness with tidal and non-tidal wetlands likely also played a role. Loss of shading by tules and riparian vegetation in the Delta and upstream in the watershed after the Gold Rush may have increased average water temperatures to some degree but more likely decreased temperature heterogeneity. The simplified habitat geometry from loss of dead-end sloughs likely resulted in changes in mixing that may also have decreased temperature heterogeneity. The role of cool groundwater contributions to tributary rivers is also unknown but may have kept rivers cooler before flowing into the Delta than currently.

We hypothesize that the warmer temperatures and more uniform temperature distributions in the contemporary Delta act as a slow driver that stabilizes the current regime by favoring species adapted to higher temperatures and more stable conditions such as largemouth bass and *M. aeruginosa*, but negatively affects species adapted to cooler and more heterogeneous temperatures such as delta smelt and salmon. Predicted climate change effects on water temperatures pose additional threats to native species.

5) Turbidity – The turbidity regime in the pre-European wetland-dominated Delta was likely very different from what it is now. Wetland-derived organic matter likely played a larger role year-round role. Sediment derived turbidity may have often been higher compared to the present because sediment transport processes would have been fully functional, recruiting fine sediments from the Sierra Nevada, lowland valleys, and wetlands. Seasonal variability in the rivers was likely high; however, wind resuspension of sediments in Suisun Bay and the Delta may have kept turbidity high when river inputs were low. Overall, sediment loading to the Delta increased strongly during the Gold Rush era and has since decreased (Shvidchenko et al. 2004, Wright and Schoellhamer 2004), leading to declining total suspended solid concentrations and associated declining turbidity at most IEP monitoring stations over the last 40 years (Jassby 2008). In addition to being trapped behind dams on tributaries, sediments are also eroded and flushed from areas below the reservoirs during winter storm events, but that source is not renewed from

upstream so it has been diminishing. Wright and Schoellhamer (2004) showed that peak sediment concentrations in Sacramento River water associated with the particularly strong flood events of 1964, 1986 and 1997 have been declining from one strong flood event to the next due to reduced sediment yield from the watershed. In an analysis of total suspended solid data monitoring data from 1975 to 1995, Jassby et al. (2005) showed that concentrations in the north Delta dropped sharply toward the end of the 1982–1983 El Niño-Southern Oscillation (ENSO) event and did not recover afterward, likely due to erosion and flushing of previously stored sediments from the Delta. Suspended solids further decreased from 1996 to 2005, although not as strongly as over the previous decades (Jassby 2008). Jassby (2008) did not report the effect of the 1997–1998 El Niño event on suspended solids, but a more recent analysis (Hestir et al., UCD, unpublished data) showed that it contributed to another decline in suspended solids, flushing sediments from Suisun and San Pablo bays. The narrow, steep-sided, and deep channels and associated levees of the northern Delta and upstream tributaries were originally designed to quickly flush the massive influx of sediments from the hydraulic mining activities of the Gold Rush era, so these effects are not surprising. In addition, the spread of invasive macrophytes, especially *E. densa*, in the Delta was both facilitated by and contributed substantially to losses in suspended sediments over the last two decades (Hestir 2010). Sediment loads to the Delta are now likely at or below pre-European levels. Overall, the increase in sediment loads and associated turbidity levels in the Delta during the Gold Rush era may have benefitted small fish like delta smelt and juvenile salmon by providing refuge from visual predators. It also benefitted alien species adapted to high turbidity such as striped bass. It seems, however, unlikely that such benefits would outweigh the negative effects of the destruction of riverine and wetland habitats during this period. In addition, the influx of sediments during this period likely also had strong negative effects on benthic organisms and primary producers, thus impairing ecosystem production. The gradual and occasionally steep declines in suspended sediments and associated turbidity levels in the post-reservoir and POD eras helped explain long-term declines in three out of four POD fish species (Thomson et al 2010). Turbidity declines were likely detrimental to smaller fish and possibly also larger and more slowly swimming pelagic invertebrates such as the native mysids and calanoid copepods because of increased predation risk. In addition, light availability was clearly the most important limiting factor for phytoplankton production under more turbid conditions, but as the Delta clears other factors are becoming equally or more important. Nutrient effects as well as grazing by littoral and pelagic species will likely become more important, with additional effects on phytoplankton species composition and repercussions throughout the food web.

We hypothesize that the initial rapid increase followed by the slow decline in sediment loads and turbidity represents an important driver that both benefitted and disturbed native species. The most recent sediment-flushing El Niño event of 1997–1998 occurred just before the onset of the POD and may thus have contributed to the POD regime shift. The current much clearer regime benefits non-native fish species and amplifies nutrient and grazing effects on phytoplankton.

6) Nutrients – To our knowledge, the pre-European nutrient regime of the estuary has not been investigated. Early reviews of nitrate and phosphate concentrations in the Delta found that they were “near the highest concentrations reported from other estuaries” (Kohlhorst 1976), perhaps especially during dry years (Siegfried et al. 1978). San Joaquin River water generally had much higher nutrient concentrations than Sacramento River water and nitrate and phosphate

concentrations were lowest during spring phytoplankton blooms. Total nitrogen increased at most IEP monitoring stations over the last 40 years, while total phosphorus decreased (Jassby 2008). The decline in phosphorus was associated with a rapid decrease in loading from the SRWTP in the mid-1990s (Van Nieuwenhuyse 2007). The SRWTP became operational in 1982 and uses secondary treatment. It also contributed to the increase in nitrogen, especially the strong increase in ammonium concentrations in the northern Delta (Jassby 2008). Changes in nutrient loading did not just affect individual nutrient concentrations, but also nutrient ratios. While phytoplankton growth is generally much more limited by light availability than nutrients in this turbid, nutrient rich system, changing nutrient ratios likely affected phytoplankton species composition, possibly with repercussions throughout the food web (Glibert 2010). In addition, ammonium in the northern Delta rose to levels that now appear to be suppressing nitrate uptake (Wilkerson et al. 2006, Dugdale et al. 2007) and perhaps even the uptake of ammonium itself by sensitive algal groups such as diatoms. This suppresses diatom production (Parker et al. in review) and likely also affects microbial processes and community composition. New stable isotope evidence (C. Kendall, USGS, unpublished data) indicates that the toxic *M. aeruginosa* blooms that have been occurring in the Delta over the last decade may largely be fueled by ammonium, not nitrate. The increase in ammonium may thus have contributed to the overall decline in phytoplankton over the last 40 years (Jassby et al. 2002) and long-term shifts in species composition (Lehman 2000). As has been shown elsewhere, elevated levels of ammonium and other nutrients may also benefit invasive rooted and floating aquatic plants in the Delta, such as the water hyacinth (*Eichhornia crassipes*) and the Brazilian waterweed (*Egeria densa*) (Reddy and Tucker 1983, Feijoó et al. 2002). Furthermore, increasing light availability due to declining turbidity levels (see above) may amplify the effects of the recent changes in nutrient concentration in the Delta. In summary, total phosphorus levels declined from the previous to the current regime, while total nitrogen and especially ammonium levels increased.

We hypothesize that in the pre-European period, a high nutrient supply with a low N to P ratio supported high ecological productivity and contributed substantially to the resilience of the original regime. After the Gold Rush, high turbidity levels overwhelmed nutrient effects and suppressed productivity. A long-term (at least since 1970) shift from previously higher to lower phosphorus levels and previously lower to higher total nitrogen and especially ammonium levels contributed to the long-term decline in phytoplankton and estuarine food supplies, substantial species shifts, and the recent establishment of *Microcystis* blooms in the Delta. The previous nutrient regime likely favored diatoms and other nutritious estuarine species, while the current regime favors small flagellates and nuisance species such as *Microcystis,* as well as aquatic weeds such as *Egeria densa* and *Eichhornia crassipes*.

7) Contaminants – While some contaminants decreased after the passage of the Clean Water Act, there has overall been an increase in amount and diversity of chemical contaminants in the system (Johnson et al. 2010, Brooks et al. in review) over the four historical eras. The effects on the biota in the system are difficult to assess due to the paucity of adequate monitoring data, but are likely as diverse as the contaminants themselves, with more severe effects on more sensitive species. Diverse sublethal effects are likely more important than acute toxicity, and interactions among different contaminants and with other variables such as temperature, turbidity, pH, and salinity are likely also important. Sublethal stress effects can also make organism more susceptible to predation and food stress.

We hypothesize that contaminants represent a slow variable that has slowly increased in importance as contaminants have become more abundant and diverse in the environment. They have likely played an increasing role in eroding the resilience of the original regime. The present regime increasingly favors species that are less sensitive to contaminants while presenting an increasingly greater challenge to sensitive organisms such as salmonids, osmerids, and many invertebrate species.

8) Harvest – Harvest represents losses of aquatic organisms. It includes the top-down box in the basic POD conceptual model, which includes effects on fishes from physical (abiotic) entrainment into water diversions as well as biotic variables such as predation and fishing. Fishing has occurred in the Delta even in pre-European times. Unlimited fishing during and after the Gold Rush along with destruction of spawning and migration habitat led to strong declines in salmonids. Recreational fishing has replaced once thriving commercial fishing and is regulated. There is overall less fishing by humans now than before, and most of the fishing is for non-native species, especially largemouth bass and striped bass. Recreational fishing for largemouth bass has dramatically increased in recent years with bass derbies now occurring year-round; however, most of these fish are released. Entrainment, especially by the CVP and SWP, has been high in some recent years with maximum salvage numbers for adult delta and longfin smelt during the POD period in 2003 and 2002, respectively (Grimaldo et al. 2009a). Salvage does not account for entrainment-associated losses that occur before fishes are collected by the fish screens, such as predation in CCF. Predation by introduced predatory fish, specifically largemouth bass, on native species has likely gone up with the more recent proliferation of these predators and increased visibility due to declining turbidity levels. Overall, harvest of native fish species has likely increased over the last 50 years or more, leading to increased top-down control of native fish species.

It is important to note that predation is fundamental to the structure and functioning of ecosystems. The presence or absence of predators influences energy flow in an ecosystem, carbon exchange with the atmosphere and nutrient cycling (Sabo et al. 2010). Predators often help maintain resilience to change, for example by removing weaker prey from the prey population gene pool. Individual predators can change their behavior quickly. In contrast, the number of predators and especially the presence or absence of predators in an ecosystem changes much more slowly (Sabo et al 2010). While predators were likely always an important part of the San Francisco Estuary, the recent more stable hydrology along with the decline in turbidity likely improved conditions for predators in general, but in combination with other habitat changes especially favored invasive predators.

We hypothesize that harvest in the form of human fishing played an important role in decreasing the resilience of the original system early on, while entrainment and predators favored by changing conditions became an important slow variable more recently.

Other drivers – As our focus shifts to understanding regime change, we will likely develop a better understanding and appreciation for the effects of slow variables. There are likely other important slow variables that have not been as thoroughly explored in the POD investigation due to its limited scope. Such variables might include slower or more distant (in time and space) system attributes. Examples may include biogeochemical and geomorphological features, such as carbon cycling or spatial distribution and connections between shallow tidal wetland areas, deeper waterways, and river floodplains. In the Delta and its upstream tributaries, these features underwent massive changes during the Gold Rush and Post-Reservoir periods, including destruction of 95% of the Delta wetlands and associated changes in biogeochemical cycling, and the many changes to the upstream tributaries including levee and dam construction. In the marine-dominated bays of the San Francisco Estuary, biota shift in response to climatic variation associated with the Pacific Decadal Oscillation and North Pacific Gyre Oscillation (Cloern et al. 2010). These biological responses are likely related to fairly rapid climate-driven changes in oceanic winds and coastal currents, upwelling, and surface water temperature which affect the recruitment of marine species into the estuary. Similarly, recent steep declines in Sacramento River fall-run Chinook salmon populations have been linked to rapid changes in ocean conditions superimposed on the slower, more gradual degradation of riverine and estuarine habitat conditions (Lindley et al. 2009).Finally, as already mentioned in the preceding discussion of some of the individual drivers, there are likely many interactions among these environmental drivers that produce additive, synergistic, or compensatory effects and complex feedbacks that cross temporal and spatial scales.

In addition to the mostly abiotic drivers discussed above, the biological communities themselves can also act as slow drivers affecting ecological resilience. The importance of the presence or absence of (top) predators has already been mentioned above (see Harvest). The presence or absence of other functional groups is similarly important. For example, invasive benthic consumers such as the clam *C. amurensis* have been associated with strong declines in phytoplankton biomass and productivity, with substantial bottom-up repercussions throughout the food web and probably stabilizing the current POD regime in Suisun Bay and the Delta (Jassby et al. 2002, Winder and Jassby 2010). In general, functional diversity acts to stabilize a given regime, especially if each functional group consists of several species with different responses to environmental drivers (Folke et al. 2002). Ecological diversity is the biological counterpart to landscape heterogeneity. Both are key components of the adaptive capacity and resilience of ecosystems

The new pelagic regime in the Sacramento-San Joaquin Delta

The new pelagic regime has already been described in detail in previous chapters – it is the POD regime that is the topic of the basic POD conceptual model and the species-specific models. Briefly, it is characterized by lower outflows, a shifted and constricted salinity gradient, a simplified, rigid landscape, warmer temperatures, lower than previous turbidity, higher ammonium concentrations especially in the northern part of the system, lower phosphorus levels, higher contaminant loads and concentrations, and higher harvest including entrainment and predation.

Pelagic biota include an altered phytoplankton community with a smaller proportion of large diatoms and a larger proportion of small and motile species as well as recurring *M. aeruginosa* blooms in the summer and fall. Overall, phytoplankton biomass and production declined through the early 1990s and then remained fairly stable. It may now rebound to some degree, albeit with different species than before. The native zooplankton community has been largely replaced by non-native species. Copepod biomass remained relatively unchanged over the last 40 years, but now includes much greater numbers of small, evasive cyclopoids than before, especially in the western part of the Delta. Rotifers, cladocerans, and especially mysids have all strongly declined and are now at much lower biomass levels than before. Non-native jellyfish started strongly increasing in numbers in the recent decade in the western Delta and Suisun Bay and Suisun Marsh. Some invasive fish species that can use pelagic habitat but are more closely associated with nearshore habitat (e.g., Mississippi silverside) are doing well, while the POD fish species as well as salmon which use estuarine pelagic and littoral habitat during their migrations are doing very poorly.

Reduced turbidity gives visual predators such as adult striped bass and largemouth bass an advantage over small prey species, including introduced species such as threadfish shad or young striped bass, or native species such as delta smelt or longfin smelt or juvenile salmon. Reduced turbidity also benefits primary producers, including native, non-native, and nuisance species. Proliferating beds of the invasive aquatic weed *E. densa* are encroaching on pelagic habitat and are ideal habitat for largemouth bass and many other non-native species. Finally, the area and volume of pelagic habitat has probably been more stable in the Delta since pre-European times than benthic, littoral, and especially tidal and seasonal wetland habitat. However, the suitability (quality) of this habitat for native species has been severely degraded due to the changes in abiotic and biotic drivers described above. In some ways the open water areas of the Delta now resemble those of a eutrophic, shallow lake that is full of aquatic weeds and cyanobacteria such as Clear Lake, California.

The new benthic regime in the Sacramento-San Joaquin Delta

Relatively little is known about the pre-European benthic community of the San Francisco Estuary. Native freshwater mussels were likely an important component of the Delta community, but few persist in the Delta or elsewhere in California (Howard 2010). In contrast, more recent events leading to the regime shift in the benthic community of the upper estuary are well documented. These events began several decades ago with a series of invasive species introductions that would indelibly alter upper estuary benthic community structure (see Peterson and Vayssieres 2010) and produce trophic consequences exhibited at all levels of the food web (e.g., bacteria – Werner and Hollibaugh 1993, Hollibaugh and Wong 1996; phytoplankton – Alpine and Cloern 1992, Jassby et al. 2002; zooplankton – Kimmerer et al. 1994, Kimmerer and Orsi 1996, Orsi and Mecum 1996; fishes – Feyrer et al. 2003, Stewart et al. 2004). Although hundreds of species have invaded the San Francisco Estuary (Cohen and Carlton 1998), perhaps the most consequential among those belonging to the benthic community are the clams *Corbicula fluminea* in freshwater and *C. amurensis* (previously *Potamocorbula amurensis*), which ranges throughout the estuary, but reaches its highest densities in intermediate salinities often found in Suisun or San Pablo bays (Peterson and Vayssieres 2010). *C. fluminea* invaded the system in the mid-1940s so it has inhabited fresh and low salinity regions in the upper estuary since benthic surveys began (see Hazel and Kelly 1966, Painter 1966 and references therein). So, it is not possible to contrast the benthic community before and after its introduction or detect changes in the food web. *C. fluminea* may sequester more pelagic productivity into the benthic portion of the food web than the native freshwater mussels and other freshwater benthic inhabitants, but this is unknown. *C. fluminea* is among the dominant benthic organisms within the Delta and in Suisun Bay after consecutive high outflow years (Peterson and Vayssieres 2010) and is capable of exerting a strong negative effect on pelagic production (Lucas et al. 2002). However, the introduction of *C. amurensis* in 1986 and its rapid establishment (Nichols et al. 1990, Carlton et al, 1990) led to a shift in community structure (Nichols and others 1990) that remains stable to recent years, including the POD years (Peterson and Vayssieres 2010). Since then, high rates of filter feeding by *C. amurensis* have been linked to greatly reduced phytoplankton biomass and the absence of seasonal phytoplankton blooms in the upper estuary (Alpine and Cloern 1992, Jassby et al. 2002, Jassby 2006). Decreases in zooplankton have been linked to these reductions in phytoplankton and also to direct feeding by *C. amurensis* on early life stages of zooplankton (Kimmerer et al. 1994, Kimmerer and Orsi 1996, Orsi and Mecum 1996) and through zooplankton to a reduction in the abundances of fishes (Kimmerer 2002a) or a shift in distribution of others (Kimmerer 2006). By the early 2000s, both introduced clam species were well established and their effects on the upper estuary benthic community and food web had been promulgated for decades. Since Peterson and Vayssieres (2010) did not detect a change in the upper estuary benthic community in the 2000s, the contributions of these introduced clams to the regime shift are those of a major biological driver, acting at intermediate scales by diminishing the upper estuary pelagic food web. The clams themselves are affected by slower acting drivers, especially changes in salinity.

Overall, benthic community structure remains most strongly influenced by salinity, substrate (sediment texture) and current energy (e.g., Nichols 1979, Peterson and Vayssieres 2010). Species diversity peaks in stable marine and freshwater regions of the estuary and declines in the more variable, intermediate salinities. These intermediate salinity regions are often dominated by a few benthic organisms that support the highest benthic biomass (Peterson and Vayssieres 2010). This highlights the productive nature of the estuarine mixing zone and large benefits derived by species tolerant of variable salinity conditions. *C. amurensis* appeared exceptional in regard to tolerance and adaptability. Neither salinity and nor substrate appeared to limit its colonization, but reduced competition with established species as a result of extreme environmental conditions before, during, and after 1986 may have been key to its establishment (Nichols et al. 1990). Within two years of its appearance in 1986, *Corbula* had spread throughout the estuary, inhabiting sub-tidal mud, sand, peat and clay substrates, salinities from <1 to 33 ppt, and reaching densities that exceeded 10,000 m^{-2} at a few locations (Carlton et al. 1990). In the Suisun Bay region, *Corbula* was able to immediately change the benthic community (Nichols et al. 1990, Peterson and Vayssieres 2010). In 1988, when low outflow conditions were expected to favor the clam *Mya arenaria* (indicator species of the intermediate salinity benthic community), *Corbula* remained dominant in Suisun Bay. Nichols et al. (1990) attributed this to alteration of benthic community dynamics by *Corbula.*

The benthic community shifts of most direct relevance to the POD took place in Suisun Bay and the western Delta, so this smaller region will be the focus of a more detailed examination of community changes. As mentioned previously, the only large and significant community changes occurred after the introduction of *Corbula* in 1986 and no additional changes were detected in the early 2000s (Peterson and Vayssieres 2010). Here we describe dominant benthic community members in Suisun Bay and the western Delta, contrasting those present in low and high outflow ("dry" and "wet" years for Peterson and Vayssieres 2010) as well as before and after the introduction of *Corbula*. We summarized the species abundance descriptions of Peterson and Vayssieres (2010). During low outflow years prior to *Corbula* the Suisun Bay community structure, based on Grizzly Bay sampling, strongly resembled that of San Pablo Bay and included the clams *Mya arenaria, Macoma petalum, Musculista senhousia*, and amphipods *Ampelisca abdita*, *Monocorophium acherusicum, Grandidierella japonica,* polychaete *Streblospio benedicti* and several other species. In high outflow years prior to *Corbula* the benthic assemblage was dominated by organisms normally found in the lower Sacramento River, including the amphipods *Americorophium stimpsoni* and *A. spinicorne*, the clam *Corbicula fluminea* and mermithid nematodes. During the years since its invasion *C. amurensis* has been numerically dominant under all outflow types. It is joined in low outflow years by *Nippoleucon hinumensis*, *A. abdita*, *G. japonica*, and a group of polychaete and oligochaete worms. In high outflow years *Corbula* is joined by *Corophium alienense*, *A. stimpsoni*, *Gammarus daiberi*, *C. heteroceratum* and a few polychaete and oligochaete worms. Shifting upstream into the western Delta, the benthic community in the lower Sacramento River was variable over time and suffered a distinct overall decline in organism numbers after *Corbula*. *Corbula* was present in all outflow types, but only ranked among the dominant species during low outflow years (Peterson and Vayssieres 2010). The community was dominated in most pre-*Corbula* years by the amphipods *A. stimpsoni* and *A. spinicorne*, the clam *C. fluminea* and oligochaete worms *Varichaetadrilus angustipenis* and *Limnodrilus hoffmeisteri*. In low outflow years, additional species joined the community: polychaete worms *Boccardiella ligerica* and *Laomome sp.* were abundant with the former numerically dominant and the amphipods *G. japonica, Monocorophium acherusicum* and *Melita nitida* and isopod *Synidotea laevidorsalis* were also abundant. In high outflow years after the *Corbula* invasion the amphipods *A. stimpsoni, A. spinicorne* and *Gammarus daiberi,* polychaetes *Laomome sp.* and *Marenzelleria viridis*, as well as oligochaete and mermithid nematode worms were present. During dry year post-invasion, *C. amurensis* and the polychaete *Boccardiella ligerica* were regularly abundant. The presence of *C. amurensis* after 1986 resulted in 2 snail species and a clam dropping out of Suisun Bay collections and sharp declines in other competing bivalves in both Suisun Bay and the western Delta (Peterson and Vayssieres 2010). Similarly, after 1986 abundance declined for most amphipod species except for *Gammarus daiberi*, which increased in both locations. Five additional recent invaders were consistently associated with *C. amurensis* in the upper estuary and formed a relatively stable assemblage: amphipods *Corophium alienense, Gammarus daiberi,* polychaetes *Marenzelleria viridis,* and *Laomome sp.* and the cumacean *Nippoleucon hinumensis*. The post-*Corbula* benthic community bears little resemblance to the previous community.

Although the presence of *Corbula* strongly affected the pelagic food web as described above and the change in community structure undoubtedly changed feeding opportunities, these changes also created new feeding opportunities for organisms capable of feeding at or near the bottom. *C. amurensis* was rapidly incorporated as a major portion of the diets of several species of diving birds and bottom-feeding fishes (Nichols et al. 1990). White sturgeon and adult splittail utilized *C. amurensis* as a food source, but there were consequences. The inability of *C. amurensis* to efficiently process and excrete selenium led to bioaccumulation in white sturgeon, Dungeness crab, and splittail (Stewart et al. 2004). Stewart et al. (2004) also noted that accumulation levels observed were sufficient to cause reproductive problems and developmental deformities in fishes. Other introduced organisms, particularly amphipods, provided additional links in the food web. With the severe decline of the mysids as a food source, young striped bass rapidly shifted to feeding on amphipods, particularly gammarid amphipods (probably *G. daiberi*) (Bryant and Arnold 2007). Similarly, gammarid and *Corophium* spp. amphipods now provide substantial summer and fall food for longfin smelt (S. Slater, CDFG, unpublished data). Since these organisms are closely associated with bottom during the day (Chapman 1988, Kimmerer et al. 1998), benthic-oriented feeding may partially explain the apparent shift of longfin smelt to the lower portion of the water column (see Longfin smelt section, Figure 28). Thus, to some degree even pelagic fishes have adapted somewhat to the changes in the benthic community.

The new littoral regime in the Sacramento-San Joaquin Delta

The regime shift of the Sacramento-San Joaquin ecosystem manifests in the littoral (shallow, nearshore) zone as a replacement of seasonally inundated tule marshes with perennial beds of SAV. While several species of aquatic macrophytes are native and still present today (coontail *Ceratophyllum demersum*, sago pondweed *Stuckenia pectinata* and *S. filiforms*, American pondweed *Potamogeton nodosus*, and common waterweed *Elodea canadensis*), the SAV community today is dominated by Brazilian waterweed *E. densa.* Other invasive aquatic macrophytes are also present (Eurasion watermilfoil *Myriophyllum spicatum*, Carolina fanwort *Cabomba caroliniana*, and curlyleaf pondweed *Potamogeton crispus)*, but do not comprise nearly the proportion of the biomass as *E. densa* (roughly 85%, L. Conrad, DWR, unpublished data). Indeed, *E. densa* commonly exists in monospecific patches and is often the dominant species when it co-occurs with other macrophytes (Santos et al. 2010). The invasive floating macrophyte water hyacinth *E. crassipes* is also present and has become quite abundant; however, there is currently a very successful control program in place so water hyacinth is not currently having substantial effects in the Delta.

The exact date of the introduction of *E. densa* is unknown but it was established in the Delta by the early 1980s (Brown and Michniuk 2007). The plant was a nuisance to navigation throughout the Delta by the mid-1980s (CDBW 2001) and was well established in all but the northern portion of the Delta by the early 2000s. In June of each year from 2004 to 2008, the Center for Spatial Technology and Remote Sensing at UC Davis (CSTARS) used hyperspectral imagery of the entire Delta to create maps of the SAV distribution for each year. Total SAV coverage was highest in 2005 and 2006, covering approximately 2300 ha, or 7% of the water surface. More recently, this figure has declined, with SAV covering 927 ha (3% of the water surface) in 2008 (E. Hestir, UCD, personal communication). This decrease in coverage is likely a result of an herbicide application program targeting *E. densa* initiated in 2001 by the California Department of Boating and Waterways.

The expansion of *E. densa* is directly important because it alters the characteristics of littoral habitat, but it also acts as an "ecosystem engineer" (Jones et al. 1994, Jones et al. 1997). The species is known for its ability to alter conditions of the physical habitat in other systems (Champion and Tanner 2000). SAV cover is negatively associated with turbidity in the Delta (Hestir 2010), as is *E. densa* specifically (Santos et al. 2010). In fact, the decreasing turbidity trend in the Delta between 1975 and 2008 is highly correlated with the increase in SAV cover. As discussed above, much of the increased water clarity in the Delta may be attributable to a decrease in sediment supply due to dam construction and erosion of sediment deposits from the Gold Rush era (Wright and Schoellhamer 2004). However, even after statistically controlling for reduced sediment inputs, the negative relationship between turbidity and SAV cover is still present and significant, with SAV accounting for an estimated 21–70% of the total trend (Hestir 2010). These results are consistent with work from other systems showing that aquatic macrophytes attenuate water currents, thus increasing sedimentation (Yang 1998, Braskerud 2001). These processes can form into a positive feedback loop in which SAV slows water velocities and increases sedimentation, which provides favorable habitat for more SAV. This positive feedback may be an important factor contributing to the current state of the Delta. The effect of *E. densa* on hydrodynamics is unkown but could be important. Hestir (2010) determined that water velocities in excess of 0.49 m/s limited SAV establishment (Hestir 2010). In some situations *E. densa* can likely completely block channels and in others an equilibrium might be reached with a deep channel with high water velocities between beds of SAV.

Beyond effects on water velocity, turbidity, and sedimentation, SAV can alter DO concentrations and temperature gradients. During summertime, when at its densest and tallest, *E. densa* can cause great swings in DO due to high rates of photosynthesis in beds during the day and high rates of respiration during the night (Wilcox et al. 1999). However, it is not clear to what extent *E. densa* may alter average levels of DO, and at what spatial scale. Water temperatures may be higher in dense beds of SAV because the plants can absorb heat during the day and block heat loss at night, causing vertical stratification of temperature in the water column (Grimaldo and Hymanson 1999, Wilcox et al. 1999). If water exchange between SAV beds and nearby open water areas is limited, increased densities of SAV may also cause horizontal temperature gradients (Stacey 2003).

In addition to altering the physical aspect of the environment, the expansion of *E. densa* also has a profound effect on the littoral zone biological community, at multiple trophic levels. It influences the general aquatic macrophyte community by preventing some species from becoming established and facilitating the persistence of other species (Santos et al. 2010). Its widespread dominance in the Delta is a result of its bimodal growth pattern, with peaks in the late spring and fall. Growth in the fall allows a greater proportion of its biomass to persist through the winter, giving it a competitive advantage over most other macrophytes at the start of the growth season the following year. An exception is the native coontail (*C. demersum)*, which does not root in the substrate and instead relies on external structures (such as other plants) for anchoring. Thus, coontail benefits from ample anchoring structure provided by *E. densa* and the two species commonly co-occur. Co-existence of *E. densa* with other aquatic macrophytes species is relatively uncommon (Santos et al. 2010).

The widespread establishment of *E. densa* led to a dramatic shift in the resident fish community. In particular, largemouth bass and other centrarchid fishes are now prevalent. Historically, the littoral fish community in the Delta was probably a blend of fresh and brackish water fishes whose distributions varied with a dynamic salinity gradient. Freshwater fishes included a suite of cyprinids such as hitch *Lavinia exilicauda*, thicktail chub, Sacramento blackfish *Orthodon microlepidotus*, along with Sacramento sucker *Catostomus occidentalis* and Sacramento pikeminnow. Species with broad salinity tolerances were also present, including splittail, tule perch *Hysterocarpus traski*, prickly sculpin *Cottus asper*, threespine stickleback *Gasterosteus* *aculeatus*, and Sacramento perch, the only native centrarchid (Moyle 2002). Predators included Sacramento pikeminnow, thicktail chub, and Sacramento perch. These species were all strongly associated with littoral vegetated habitats and were likely also found in more open waters away from the littoral zone. By the early 1980s, centrarchids comprised 33% and catfish 17% of the total catch in Delta-wide electrofishing surveys conducted by CDFG, compared to approximately 12% native species (Brown and Michniuk 2007). In 2001–2003, centrarchids dominated CDFG electrofishing catches and contributed 61% of the catch with only 3% native fish (Brown and Michniuk 2007). Recent data from a two-year electrofishing effort conducted at UC Davis between 2008 and 2010 confirmed the centrarchids as unquestionably dominant, comprising approximately 65% of all fish sampled, with native residents accounting for only 2% of the catch. Interestingly, catfish populations have apparently declined, also only comprising 2% of sampled fishes (L. Conrad, DWR, unpublished data).

In 2008–2010, largemouth bass make up approximately 35% of the centrarchids residing in the littoral zone (L. Conrad, DWR, unpublished data). From the perspective of the POD, the rise of largemouth bass is of concern because the species is a voracious predator that has been known to cause dramatic shifts in community composition in other systems (Schindler et al. 1997). Along with other centrarchids, they are positively associated with SAV and likely benefit from clearer waters and warmer temperatures that characterize the present-day littoral ecosystem. However, largemouth bass and other centrarchids may also profit from SAV in an energetic sense. Decreased water velocities, warmer temperatures, and enhanced nutrient cycling allow periphyton to grow on plant stems and leaves, in turn supporting an enriched community of epibenthic prey (e.g., aquatic insects, amphipods, snails) that are consumed by juvenile fishes. Adult largemouth bass can then prey on juvenile fishes residing in the nearshore, though SAV probably offers juveniles a predator refuge.

A recent comparison of stable isotope signatures between pelagic and nearshore fishes support this picture of a self-contained food-web in the littoral zone. While pelagic fish were dependent on a zooplankton-phytoplankton trophic pathway, littoral fishes had carbon isotope ratios consistent with those of SAV and epiphytic macroalgae (Grimaldo et al. 2009b). Analysis of diet samples collected from largemouth bass throughout the Delta are consistent with this result: the most common fish species identified in largemouth bass stomach contents are other centrarchids, including juvenile largemouth bass, followed by prickly sculpin, and shimofuri and yellowfin gobies. In contrast, pelagic fishes are rare in the diet of largemouth bass, with only 12 threadfin shad and 1 striped bass found over 1500 samples analyzed (L. Conrad, DWR, unpublished data). After fish prey, adult largemouth bass appear to rely heavily on the red swamp crayfish, *Procambrus clarkii* (Nobriga and Feyrer 2007). These crayfish are also non-native and appear to be prevalent in beds of *E. densa*, but to date their relative abundance across nearshore habitat types has not been quantified. The nature of feedbacks between *E. densa*, largemouth bass, crayfish, and other residents of the nearshore are not yet fully described for the current littoral ecosystem. Studies of the role of *P. clarkii* in the littoral food web and nutrient cycling are warranted, given that this species has previously been identified as an ecosystem engineer and is associated with catastrophic regime shifts, like *E. densa* (Matsuzaki et al. 2009).

The segregation of littoral and pelagic food webs suggests the separation of whole ecosystem processes between the two habitats. Formation of dense beds of *E. densa* may result in a "biological barrier" for fish and other biota between nearshore open waters and tidal wetlands (Brown 2003) or along migration routes. These barriers may greatly diminish the benefits of natural and restored tidal wetlands (Brown 2003) and upstream spawning areas for native fishes.

2010 POD Program

The POD work for 2010 includes 39 continuing study elements and 32 new elements. Brief descriptions of each element are included in Appendix 1. The coordinated POD study elements address a number of the questions and issues described in the body of this report. The linkages of each study element with the POD conceptual models are listed in Table 1, including information on targeted seasons for each element.

The funding support for the 2010 POD program from DWR, USBR, and SWRCB is approximately $7,547,000 (Table 2). In spite of an increase in allocated funding from these sources of only 1% relative to 2009, the 2010 POD program has 24 more study elements than conducted in 2009, bringing the total number of POD studies to 76 during 2010. The increased number of studies is largely a result of a proposal solicitation (see http://www.water.ca.gov/iep/activities/research.cfm) which resulted in 14 new solicited elements and 15 new directed elements that are broadly distributed across the POD conceptual model topic areas. Several projects funded by research grants from the Delta (previously CALFED) Science Program that are thematically related to the POD efforts are also part of the coordinated POD program and listed and identified in Appendix 1 and Table 2. 2010 funding for these projects is estimated at $3,019,000. In some instances, funding for 2010 work was obligated with 2009 funds, therefore not reflected in the table below.

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Tables

Table 1. Linkages of POD study elements (PEN = POD element number) to the drivers of the basic conceptual model (A=previous abundance, H=habitat, B=bottom up, T=top down), species-specific conceptual models (DS=delta smelt, LFS=longfin smelt, SB=striped bass, TFS=threadfin shad), season when results of the element apply, and contribution to understanding the regime shift conceptual model (B=benthic, P=pelagic, L=littoral).

POD study element	PEN	Basic concep-tual model	Species-specific models	Seasons	Regime shift concep-tual model
2. Ongoing Work					
Development and implementation of IBM of striped bass and longfin smelt	38	All	SB, LFS	All	P
Modeling delta smelt in the S.F. Estuary	41	All	DS	All	P
Estimation of pelagic fish population sizes	43	All	All	All	P
Zooplankton fecundity and population structure	44	B	DS, LFS, SB	All	B, P
Phytoplankton primary production and biomass	45	H, B	All	All	B, P
NCEAS - synthetic analyses of fish and zooplankton	46	All	All	All	All
Evaluate delta smelt otolith microstructure	60	All	DS	All	P
Delta smelt histopathology investigations	61	H, B	DS	All	P
Fish diet and condition	62	B	All	Su	P
Trends in benthic macrofauna abundance and biomass	65	B	All	All	B
Corbula salinity tolerance	76	H, B	All	All	B
Field survey of *Microcystis* bloom biomass and toxicity	79	H, B	All	Su, F	P
Food web support for delta smelt and other estuarine fishes	82	B	DS	All	P, B
Investigation of power plant impacts	87	A, T	DS, LFS	Sp, Su, F	P
SAV abundance and distribution	102	H	All	Sp, Su, F	L
Fish facility history	107	T, A	All	All	P
Delta smelt culture facility	108a/b	A, H	DS	All	
Striped bass bioenergetics	115	T, A	SB	All	P, L
Long-term sources and early warning signals in turbidity	126	H	DS	W	P
Contaminants and biomarkers work	127	H, B	All	Sp, Su	All
Feasibility of using towed imaging systems	130	A	All	Sp, F, W	P
Use of acoustics to measure trawl openings	131	A	All	F	P
Effects of the Cache Slough complex on north Delta habitat	132	H, B	All	All	P
Impacts of largemouth bass on the Delta	133	T	All	All	L, P
Delta smelt genetics	135	A	DS	All	P
Bioenergetics of zooplankton species	136	B	DS	Spring	P
Population genetics and otolith geochemistry of longfin smelt	137	A	LFS	All	P
Effects of waste water management on primary productivity	138	B	All	All	P

Effects of *Microcystis* on threadfin shad	139	B, H	TFS	Su	P
Mark-recapture to estimate delta smelt pre-screen loss and salvage efficiency	140	T	DS	Sp	P
3-D modeling of the Delta	141	H	DS	All	
Contaminant synthesis 2 – impacts of contaminants and discharges	146	H	All	All	All
BREACH III: Evaluating and predicting restoration thresholds	147	H, B	DS, SB, TFS	All	L, P
Spatial and temporal variability of Delta water temperatures	148	H	All	All	P
Plankton dynamics in the Delta: trends and interactions	150	B	All	All	P
Environmental controls on the distribution of harmful algae and their toxins in the San Francisco Bay	152	H, B	All	All	P
Comparison of nutrient sources and phytoplankton growth and species composition	153	H,B	All	All	P
Spatial and temporal quantification of pesticide loadings	154	H	All	All	All
3. New IEP, new CALFED/Delta Science Program or expanded IEP work					
Acute and chronic toxicity of contaminant mixtures and multiple stressors	157	H, B	All		P
Advancing procedures for extracting and recovering chemicals of concern from sediment interstitial water	158	H	All		B
Investigation of pyrethroid pesticides in the American River	159	H, B		W	P, B
Full life-cycle bioassay approach to assess chronic exposure of Pseudodiaptomus forbesi to ammonia	160	H, B	DS	Su, F	P
SRWTP effluent toxicity testing with delta smelt and rainbow trout	161	H	DS	All	P
Potential loss of life history variation and the decline of delta smelt	162	A	DS	All	P
Comparison of 1- and 2-D hydrodynamic and water quality models of the Delta	163	H	All	All	P
Spatial and temporal variability in nutrients in Suisun Bay in relation to spring phytoplankton blooms	164	B	DS, LFS, SB	Sp	P
Ammonia sampling for the Sacramento-San Joaquin Delta and Estuary	165	H	DS	Sp	P
Using PCR to detect sliverside predation on larval delta smelt	166	T	DS	Sp	P, L
Investigation of presence, migration patterns and site fidelity of sub-adult striped bass	167	T	All	All	P, L
Monitoring inter-annual variability of delta smelt population contingents and growth	168	A, T	DS	All	P
Delta smelt feeding and foodweb interactions	169	B	DS	Fall	P
Experimentally determining early life-stage sensitivity to salinity for longfin smelt	170	H	LFS	All	P
Remote sensing mapping and monitoring of Microcystis and turbidity in the upper SFE	171	H	All	Su	P
The role of pyrethroid insecticides in limiting prey availability for delta smelt in the north Delta	172	B, H	DS	W, Sp	P
Distribution, concentrations and fate of ammonium in the Sacramento River and the low salinity zone	173	B, H	DS, SB	Sp, Su, F	P
Influence of elevated ammonium (NH4) on phytoplankton physiology in the SFE during fall	174	B, H	DS	F	P
Effect of seasonal variations in flow on the spatial and temporal variations of nutrients, organic matter and	175	B, H	DS	F	P

phytoplankton					
Influence of water quality and SAV on largemouth bassdistribution, diet composition and predation on delta smelt	176	T, H	DS, SB, TFS	All	L
Metabolic responses to variable salinity environments in field acclimatized Corbula amurensis	177	B, H	DS, SB, LFS	All	B, P
Bivalve effects on the food web supporting delta smelt	178	B	All	All	B, P
Causes of seasonal and spatial variations in NH4 sources, sinks, and contributions to algal productivity using a multi-isotopic approach	179	B, H	All	All	P
Hydrodynamic and particle tracking modeling of delta smelt habitat and prey	180	H, B	All	All	
Longfin smelt bioenergetics	181	A, H	LFS	All	P
Development of an acoustic transmitter suitable for use in delta smelt	182		DS	F, W, Sp	P
Novel molecular and biochemical biomarker work	183	H	DS	All	All
Disease and physiology monitoring in wild delta smelt adults	184	H	DS	Winter	P
Physical processes influencing spawning migrations of delta smelt	187	H	DS	Winter	P
OP and pyrethroid use in the Sacramento River and Delta	188	H	All	Spring, summer	All
Ammonia literature review	189	H, B	All	All	All

Table 2. Costs and funding sources for individual POD study elements.

Element name, program element number (PEN) and estimated budget amounts by funding source for 2010 POD work plan elements (amounts are in $1,000).

1. Expanded Monitoring

	PEN	POD Total	DWR POD	USBR POD	CALFED ERP or Delta Science	SWRCB POD	Other
Fall midwater trawl	3	$22		$22			
Summer townet survey	7	$24		$24			
20-mm survey	33						
Spring Kodiak trawl	88						
Directed field collections	89	$68		$68			
Smelt larvae survey	96	$269		$269			
TOTAL for EXPANDED MONITORING		**$383**		**$383**			

2. Ongoing Work

	PEN	POD Total	DWR POD	USBR POD	CALFED ERP or Delta Science	SWRCB POD	Other
Development and implementation of IBM of striped bass and longfin smelt	38	$125	$125				
Modeling delta smelt in the S.F. Estuary	41						
Estimation of pelagic fish population sizes	43	$188	$94	$94			
Zooplankton fecundity and population structure	44	$41	$41				
Phytoplankton primary production and biomass	45	$35	$35				
NCEAS - synthetic analyses of fish and zooplankton	46	$751	$302	$449			
Evaluate delta smelt otolith microstructure	60	$292			$292		
Delta smelt histopathology investigations	61	$292			$292		
Fish diet and condition	62	$40		$40			
Trends in benthic macrofauna abundance and biomass	65	$40			$40		
Corbula salinity tolerance	76						
Field survey of *Microcystis* bloom biomass and toxicity	79	$144			$144		
Food web support for delta smelt and other estuarine fishes	82	$162			$162		
Investigation of power plant impacts	87	$25	$25				
SAV abundance and distribution	102						
Fish facility history	107	$50					$50
Delta smelt culture facility	108a/b	$2,284	$48	$592			$1,644
Striped bass bioenergetics	115	$30	$30				
Long-term sources and early warning signals in turbidity	126						
Contaminants and biomarkers work	127	$453	$453				
Feasibility of using towed imaging systems	130	$201	$41	$160			
Use of acoustics to measure trawl openings	131	$13		$13			

Effects of the Cache Slough complex on north Delta habitat	132	$334	$116	$218			
2. Ongoing Work (continued)							
	PEN	**POD Total**	**DWR POD**	**USBR POD**	**CALFED ERP or Delta Science**	**SWRCB POD**	**Other**
Impacts of largemouth bass on the Delta	133	$239	$61	$178			
Delta smelt genetics	135						
Feeding and Growth of Delta Smelt	136	$17	$17				
Population genetics and otolith geochemistry of longfin smelt	137	$113		$113			
Effects of waste water management on primary productivity	138	$119				$119	
Effects of *Microcystis* on threadfin shad	139	$178	$178				
Mark-recapture to estimate delta smelt pre-screen loss and salvage efficiency	140	$15			$15		
3-D modeling of the Delta	141						
Contaminant synthesis 2 – impacts of contaminants and discharges	146	$141				$141	
BREACH III: Evaluating and predicting restoration thresholds	147	$1,100			$1,100		
Spatial and temporal variability of Delta water temperatures	148						
Plankton dynamics in the Delta: trends and interactions	150	$83			$83		
Environmental controls on the distribution of harmful algae and their toxins in the San Francisco Bay	152	$82			$82		
Comparison of nutrient sources and phytoplankton growth and species composition	153	$338			$338		
Spatial and temporal quantification of pesticide loadings	154	$395			$395		
Contaminants support	186	$50	$50				
TOTAL for ONGOING WORK		**$8,370**	**$1,616**	**$1,857**	**$2,943**	**$260**	**$1,694**

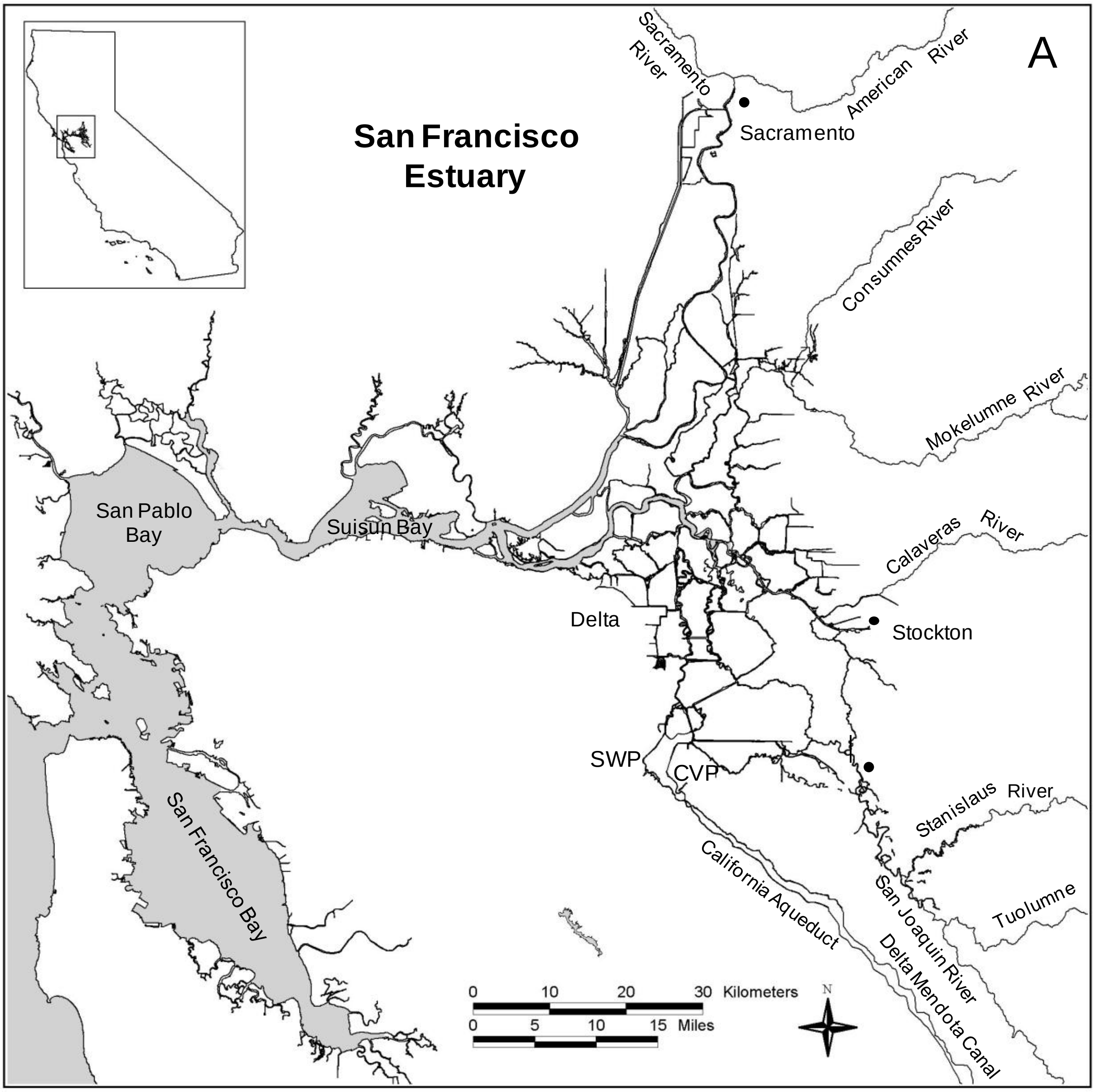
3. New IEP, new CALFED/Delta Science Program or expanded IEP work							
	PEN	**POD Total**	**DWR POD**	**USBR POD**	**CALFED ERP or Delta Science**	**SWRCB POD**	**Other**
Acute and chronic toxicity of contaminant mixtures and multiple stressors	157	$40				$40	
Advancing procedures for extracting and recovering chemicals of concern from sediment interstitial water	158	$40				$40	
Investigation of pyrethroid pesticides in the American River	159	$100				$100	
Full life-cycle bioassay approach to assess chronic exposure of Pseudodiaptomus forbesi to ammonia	160	$77				$77	
SRWTP effluent toxicity testing with delta smelt and rainbow trout	161	$65				$65	
Potential loss of life history variation and the decline of delta smelt	162	$32				$32	
Comparison of 1- and 2-D hydrodynamic and water quality models of the Delta	163	$59				$59	
Spatial and temporal variability in nutrients in Suisun Bay in relation to spring phytoplankton blooms	164	$25				$25	
Ammonia sampling for the Sacramento-San Joaquin Delta and Estuary	165	$68				$68	

3. New IEP, new CALFED/Delta Science Program or expanded IEP work (continued)

	PEN	POD Total	DWR POD	USBR POD	CALFED ERP or Delta Science	SWRCB POD	Other
Using PCR to detect sliverside predation on larval delta smelt	166	$68	$68				
Investigation of presence, migration patterns and site fidelity of sub-adult striped bass	167	$75	$75				
Monitoring inter-annual variability of delta smelt population contingents and growth	168	$98		$98			
Delta smelt feeding and foodweb interactions	169	$400		$400			
Experimentally determining early life-stage sensitivity to salinity for longfin smelt	170	$70		$70			
Remote sensing mapping and monitoring of Microcystis and turbidity in the upper SFE	171	$134		$134			
The role of pyrethroid insecticides in limiting prey availability for delta smelt in the north Delta	172	$158		$158			
Distribution, concentrations and fate of ammonium in the Sacramento River and the low salinity zone	173	$77		$77			
Influence of elevated ammonium (NH4) on phytoplankton physiology in the SFE during fall	174	$114		$114			
Effect of seasonal variations in flow on the spatial and temporal variations of nutrients, organic matter and phytoplankton	175	$42		$42			
Influence of water quality and SAV on LMB distribution, diet composition and predation on delta smelt	176	$173		$173			
Metabolic responses to variable salinity environments in filed acclimatized Corbula amurensis	177	$137		$137			
Bivalve effects on the food web supporting delta smelt	178	$89		$89			
Causes of seasonal and spatial variations in NH4 sources, sinks, and contributions to algal productivity using a multi-isotopic approach	179	$242		$242			
Hydrodynamic and particle tracking modeling of delta smelt habitat and prey	180	$339		$339			
Longfin smelt bioenergetics	181	$128		$128			
Development of an acoustic transmitter suitable for use in delta smelt	182	$178		$178			
Novel molecular and biochemical biomarker work	183	$220		$220			
Disease and physiology monitoring in wild delta smelt adults	184						
Physical processes influencing spawning migrations of delta smelt	187						
OP and pyrethroid use in the Sacramento River and Delta	188	$175				$175	
Ammonia literature review	189	$69				$69	
TOTAL for NEW WORK		**$3,248**	**$143**	**$2,599**		**$750**	

2010 POD TOTAL		**$12,025**	**$1,698**	**$4,839**	**$3,019**	**$1,010**	**$1694**

Figures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San Francisco Estuary
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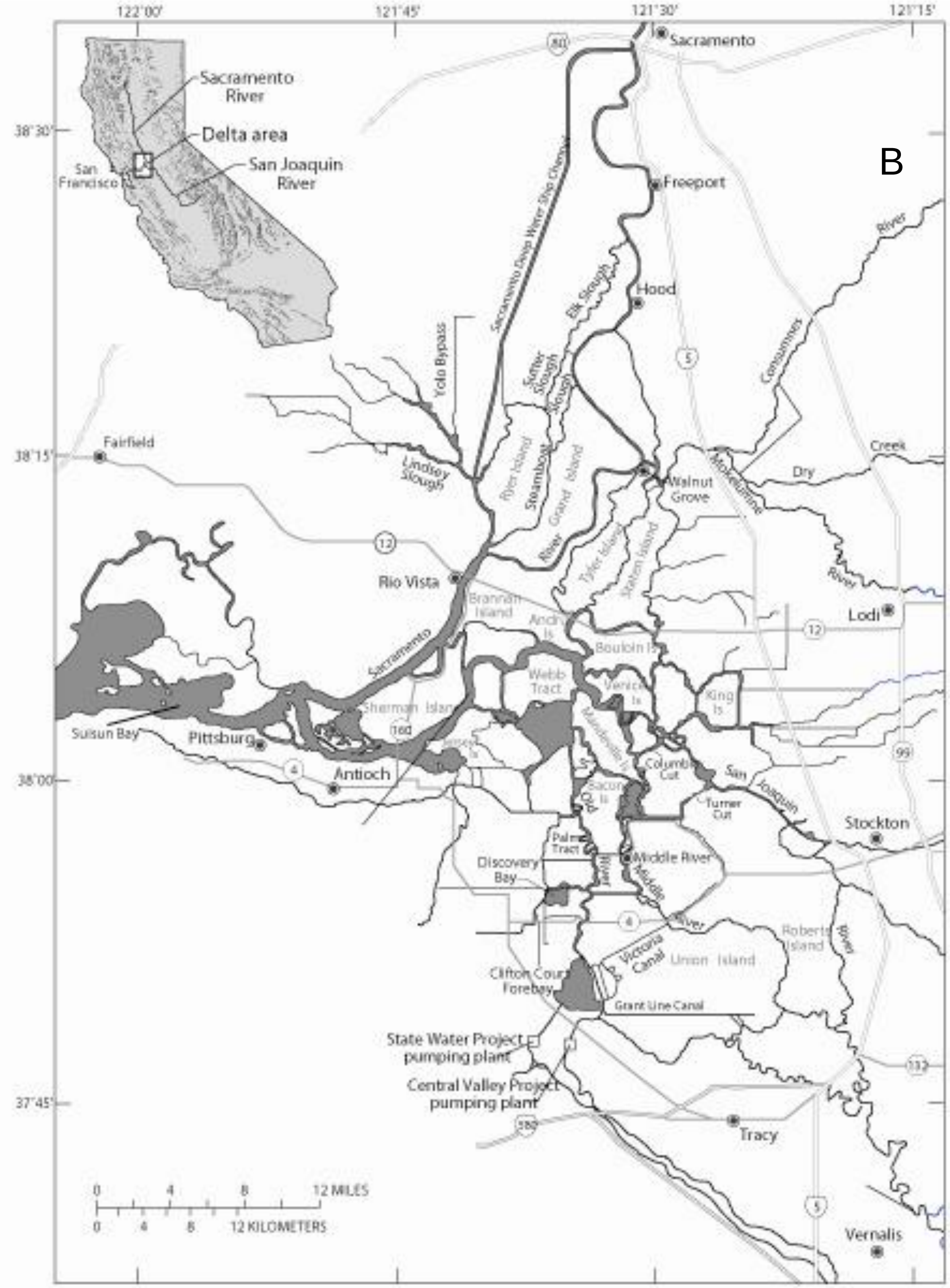
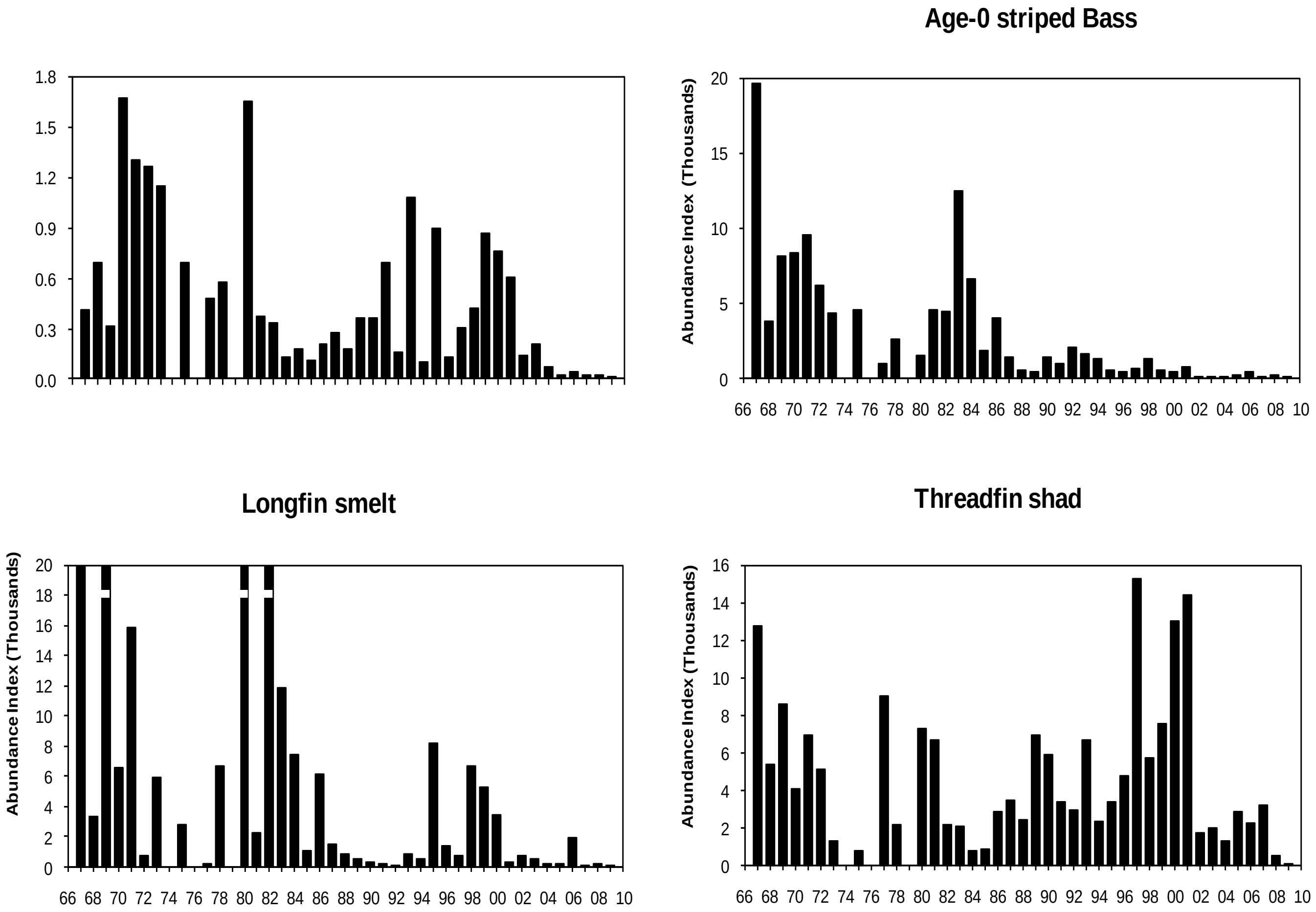


Figure 1. Map of the (A) the entire San Francisco Estuary and (B) the Sacramento-San Joaquin Delta.



2. Trends in abundance indices for four pelagic fishes from 1967 to 2009 based on the Fall Midwater Trawl, a California Department of Fish and Game survey that samples the upper San Francisco Estuary. No sampling occurred in 1974 or 1979 and no index was calculated for 1976. Development of abundance indices from catch data is described by Stevens and Miller (1983). Note that the y-axis for longfin smelt represents only the lower 25% of its abundance range to more clearly portray the lower abundance range.

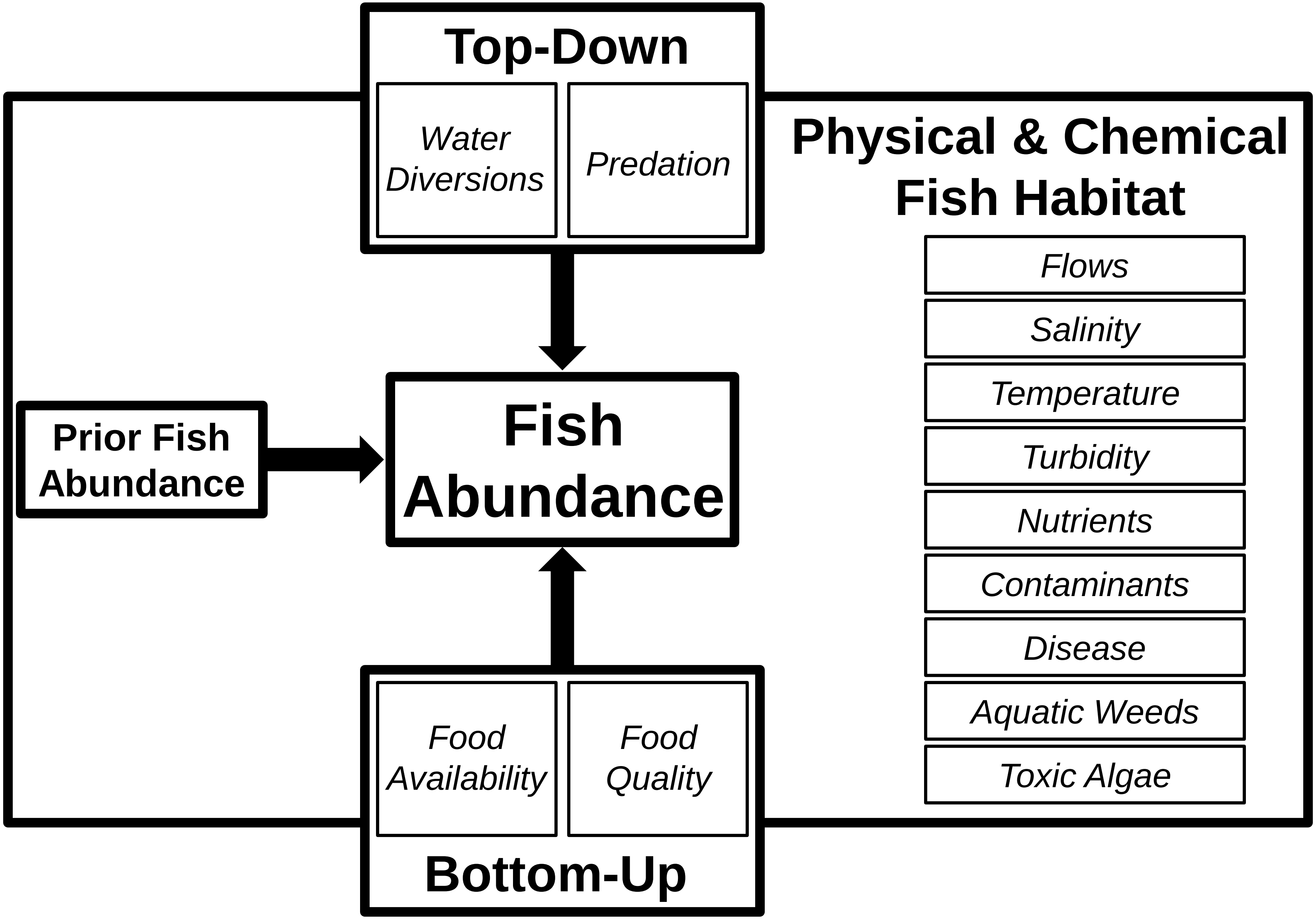
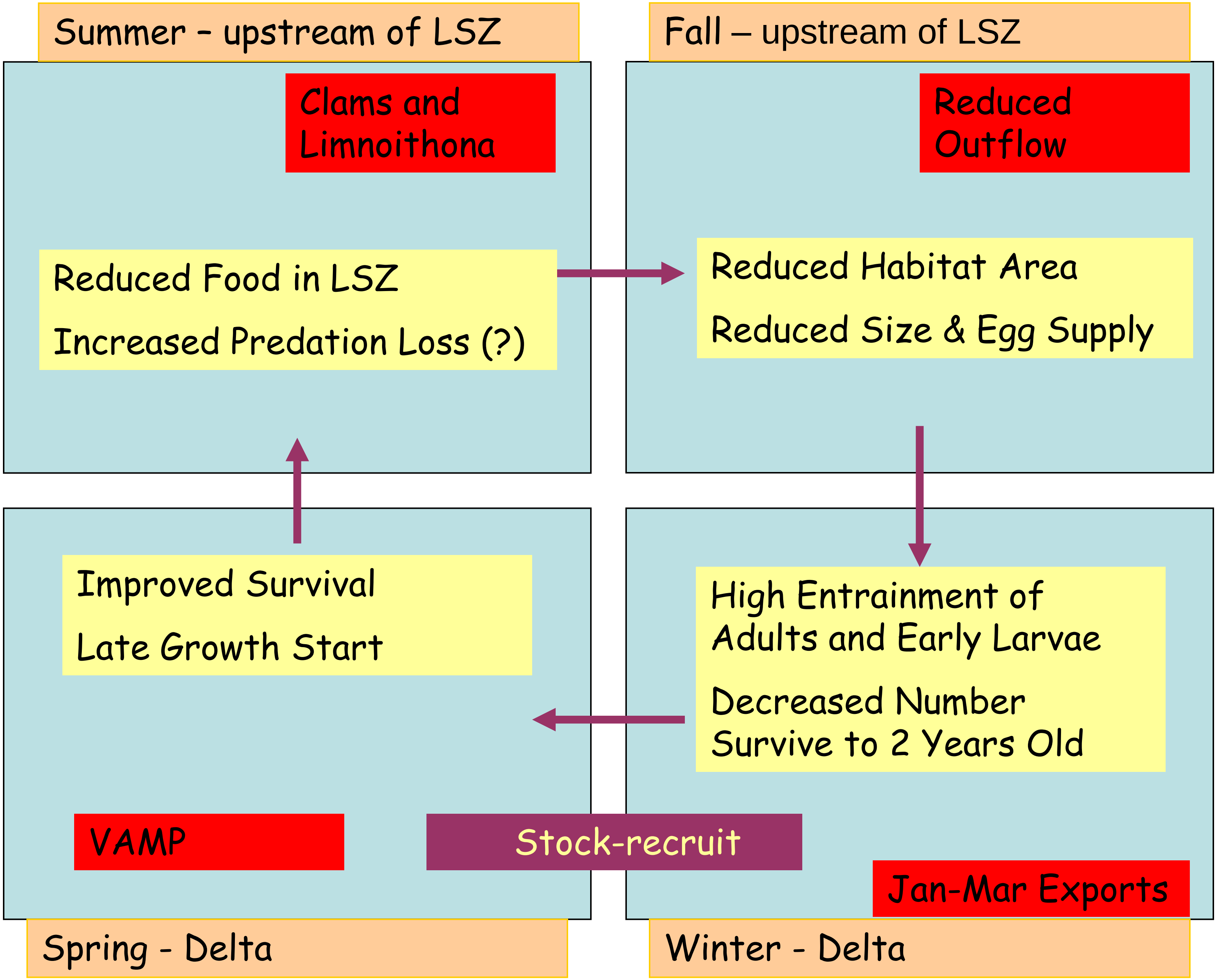


Figure 3. The basic conceptual model for the pelagic organism decline (updated from Sommer et al. 2007).



Summer - upstream of LSZ

Clams and Limnoithona

Reduced Food in LSZ

Increased Predation Loss (?)

Fall – upstream of LSZ

Reduced Outflow

Reduced Habitat Area

Reduced Size & Egg Supply

High Entrainment of Adults and Early Larvae

Decreased Number Survive to 2 Years Old

Jan-Mar Exports

Winter - Delta

Improved Survival

Late Growth Start

VAMP

Stock-recruit

Spring - Delta

Figure 4. Delta smelt species model.

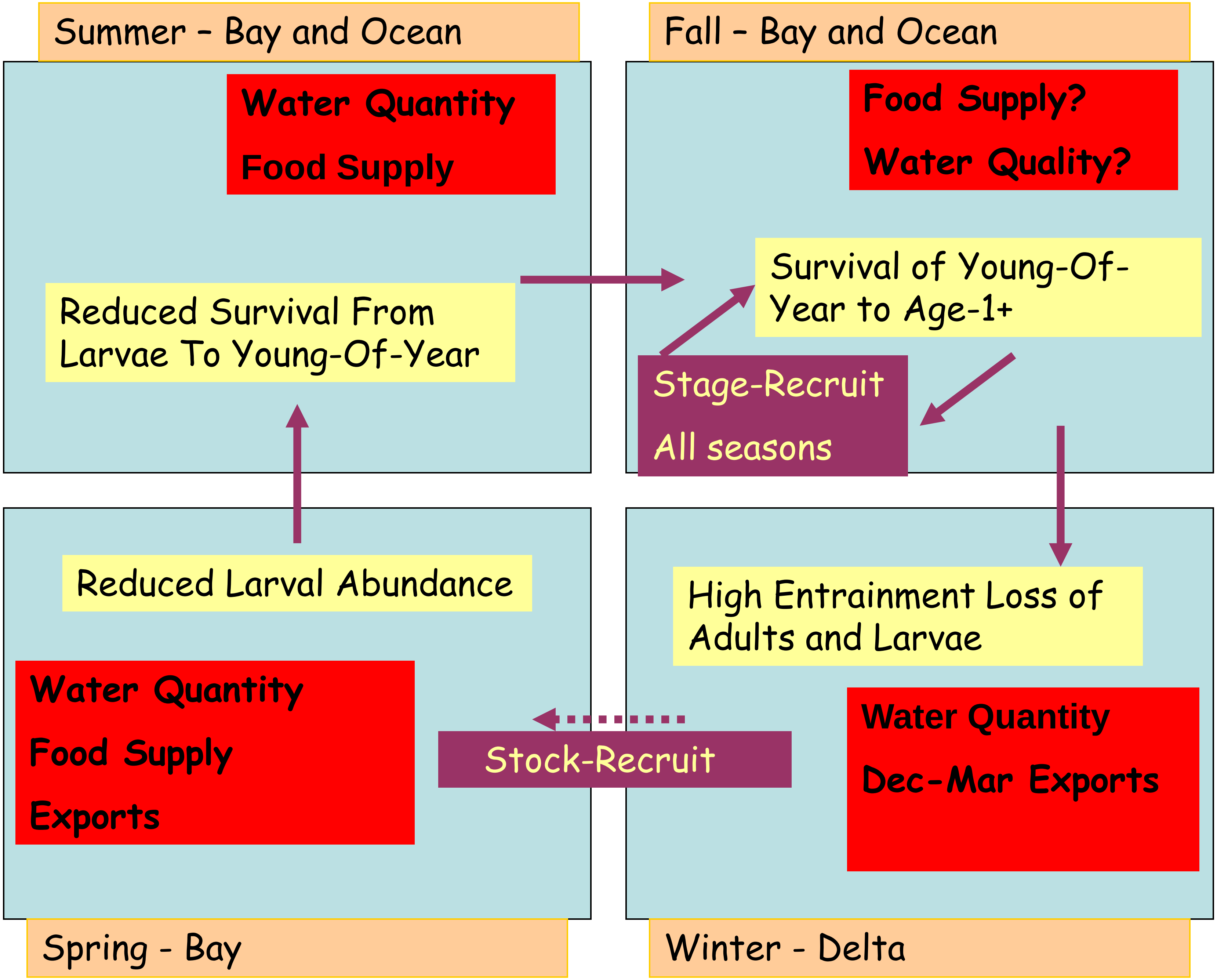


Figure 5. Longfin smelt species model. The dotted line indicates that the importance of a stock recruitment relationship is unclear. The stage recruitment loop illustrates that both survival from age-0 to age-1 and from age-1 to age-2 are important.

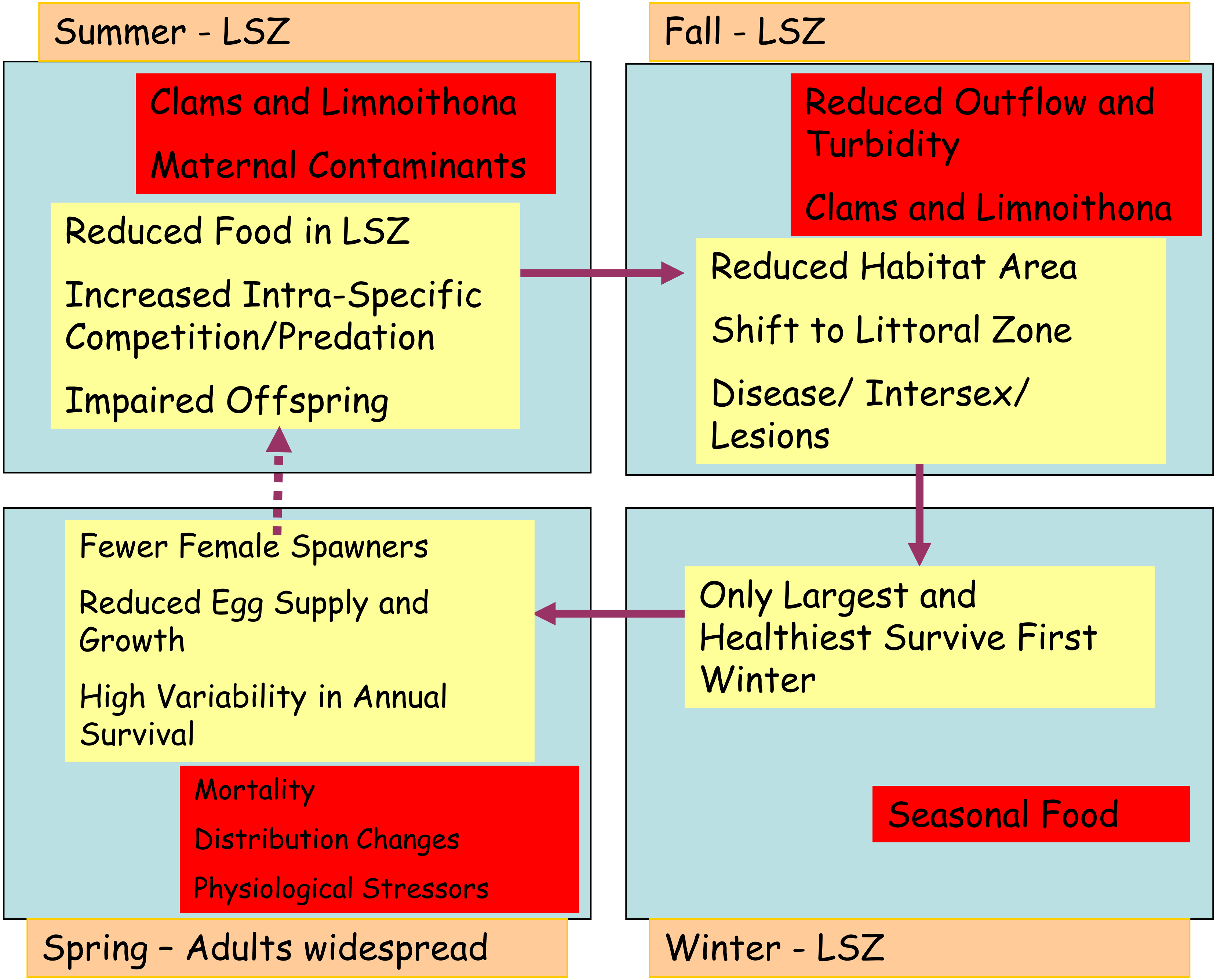
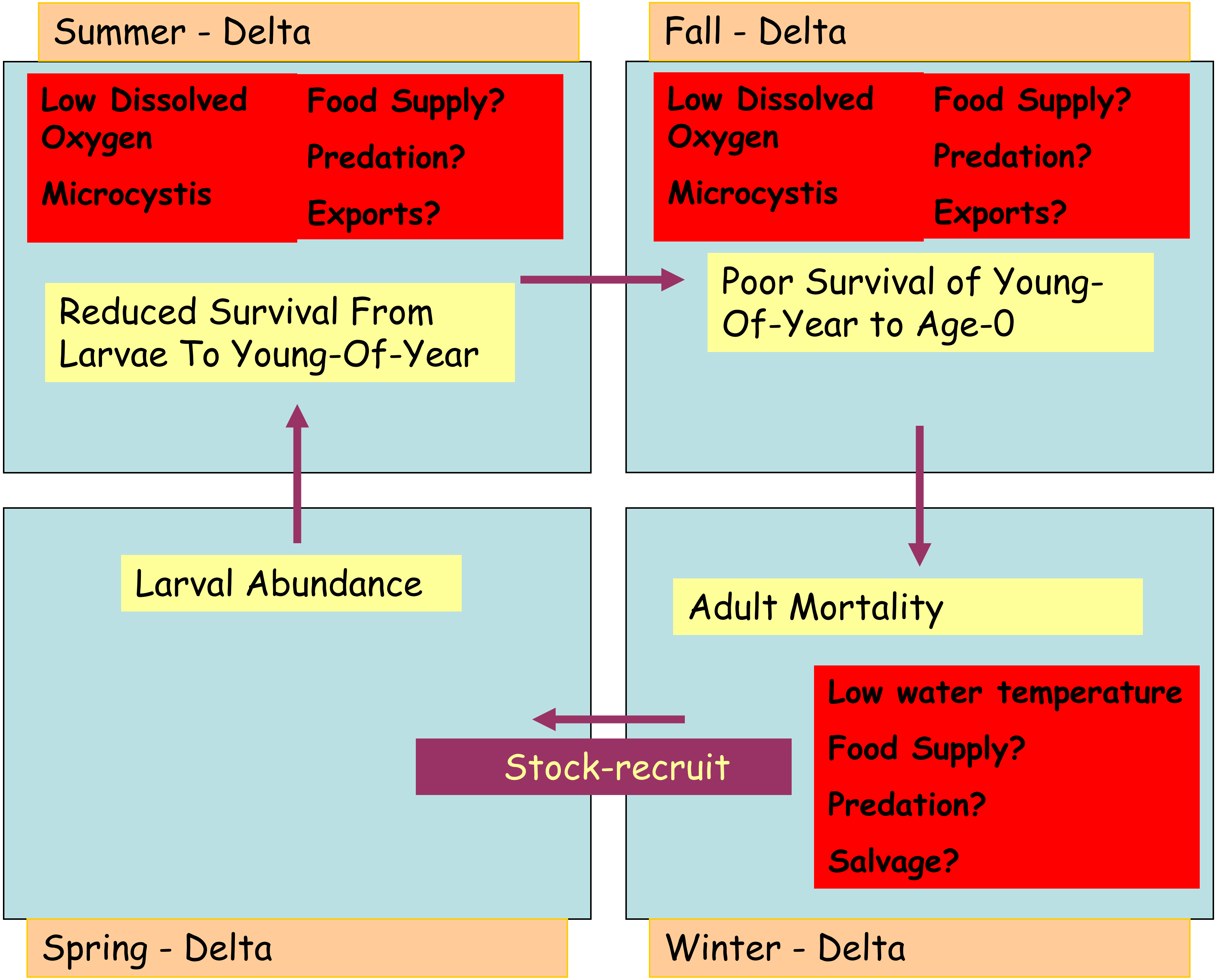


Figure 6. Striped bass species model. The doted line indicates that the form of the stock recruitment relationship has changed and the present stock-recruitment relationship is unclear.



Summer - Delta

Low Dissolved Oxygen

Microcystis

Food Supply?

Predation?

Exports?

Reduced Survival From Larvae To Young-Of-Year

Fall - Delta

Low Dissolved Oxygen

Microcystis

Food Supply?

Predation?

Exports?

Poor Survival of Young-Of-Year to Age-0

Adult Mortality

Low water temperature

Food Supply?

Predation?

Salvage?

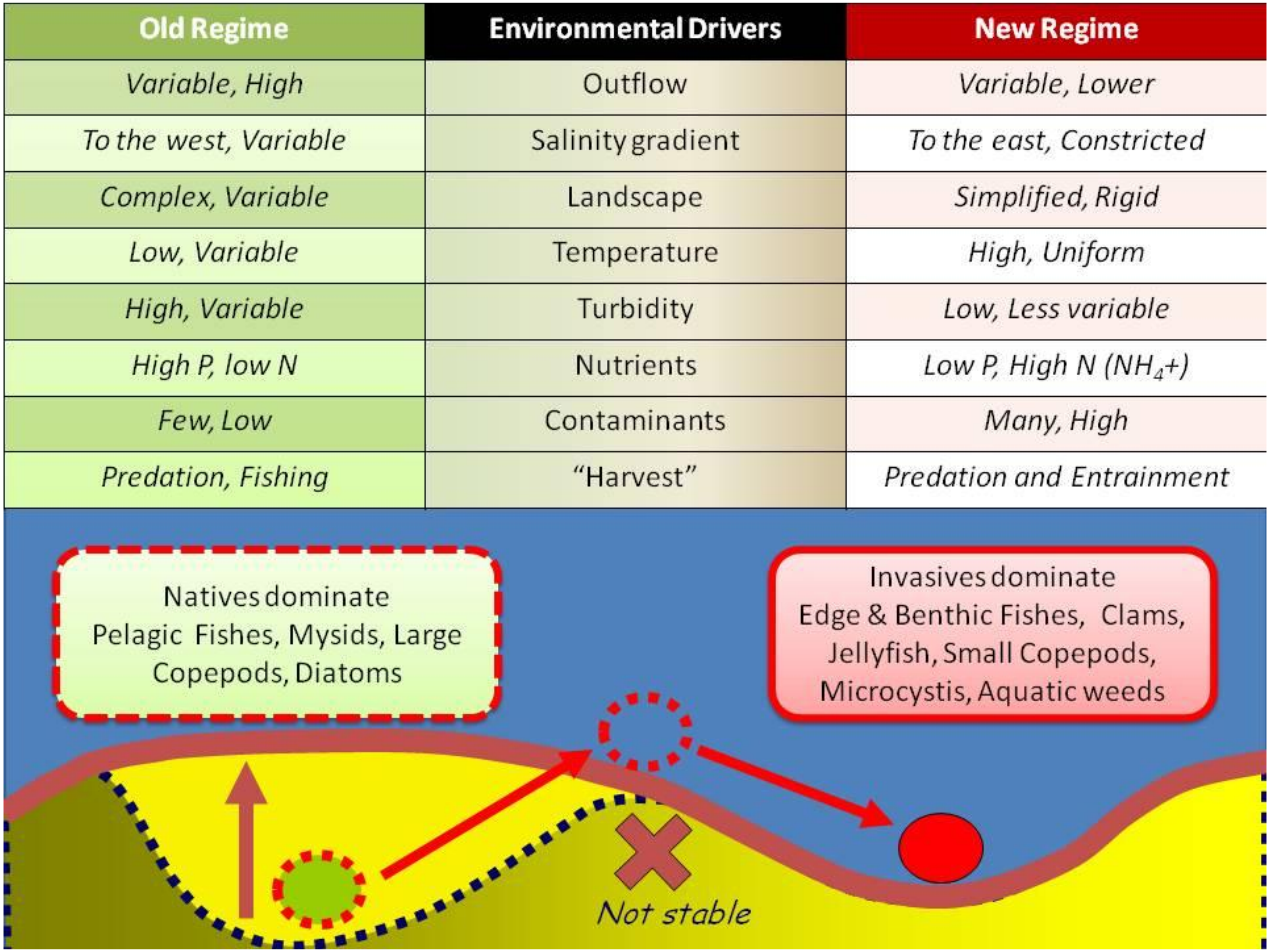
Winter - Delta

Stock-recruit

Larval Abundance

Spring - Delta

Figure 7. Threadfin shad species model. The dotted line indicates that the importance of a stock recruitment relationship is unclear.



Old Regime	Environmental Drivers	New Regime
Variable, High	Outflow	*Variable, Lower*
To the west, Variable	Salinity gradient	*To the east, Constricted*
Complex, Variable	Landscape	*Simplified, Rigid*
Low, Variable	Temperature	*High, Uniform*
High, Variable	Turbidity	*Low, Less variable*
High P, low N	Nutrients	*Low P, High N (NH_4+)*
Few, Low	Contaminants	*Many, High*
Predation, Fishing	"Harvest"	*Predation and Entrainment*

Figure 8. The ecological regime shift in the Delta results from changes in (slow) environmental drivers that lead to profoundly altered biological communities and, as soon as an unstable threshold region is passed, a new relatively stable ecosystem regime.

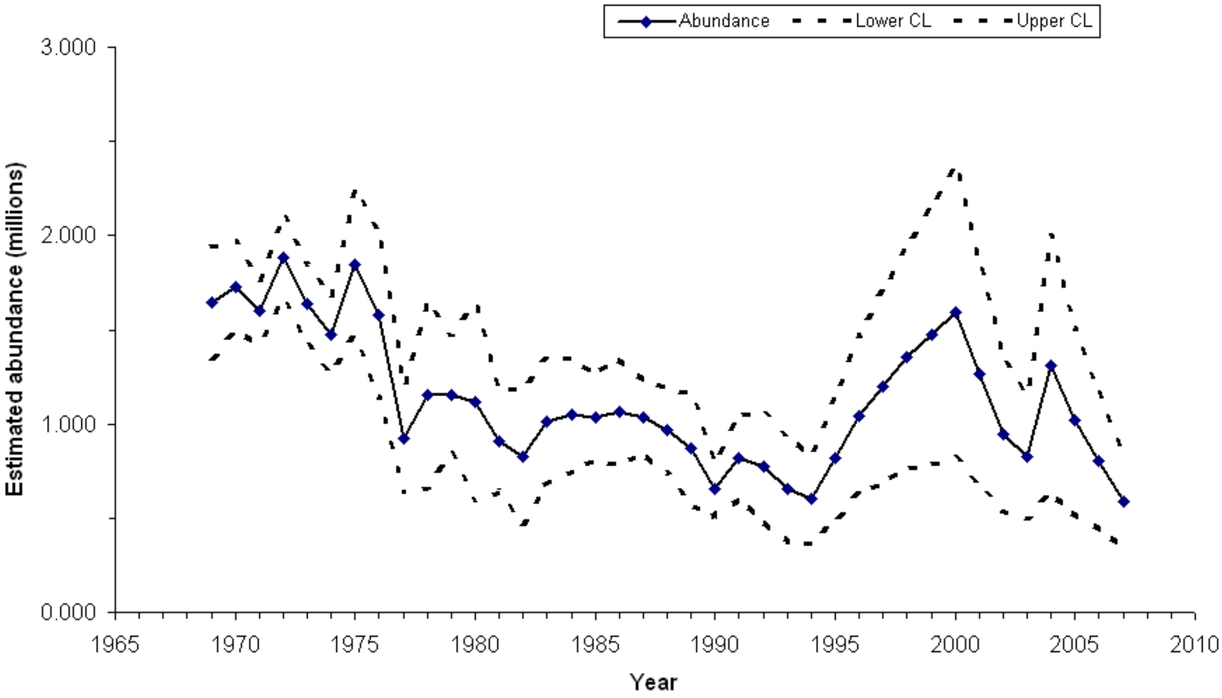


Figure 9. Peterson population estimates of the abundance of adult (3+) striped bass > 460 mm total length from 1969 to 2008, with 95% confidence limits (California Department of Fish and Game, unpublished data). Striped bass were only tagged during even years from 1994 to 2002, so no estimates are available for odd years during that period.

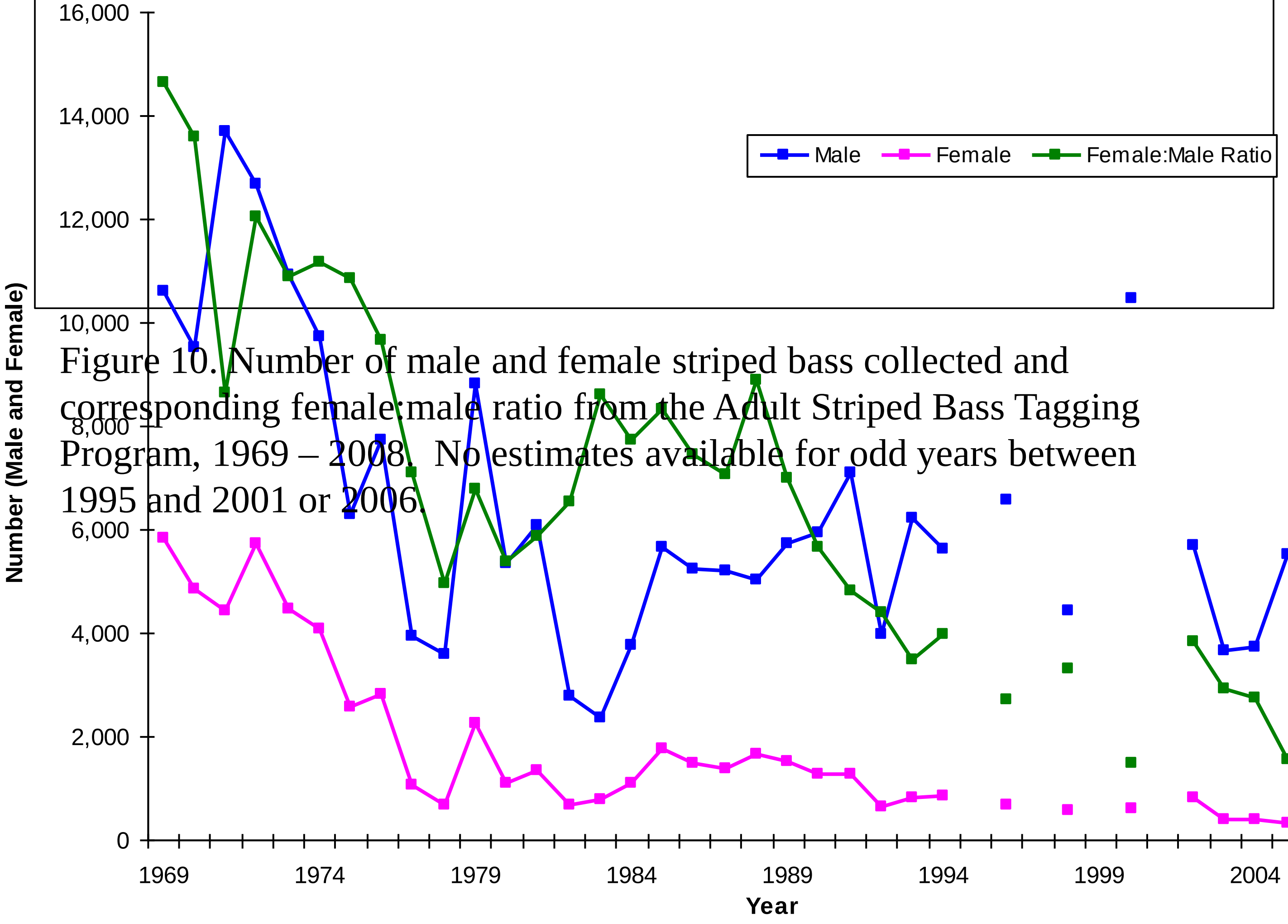


Figure 10. Number of male and female striped bass collected and corresponding female:male ratio from the Adult Striped Bass Tagging Program, 1969 – 2008. No estimates available for odd years between 1995 and 2001 or 2006.

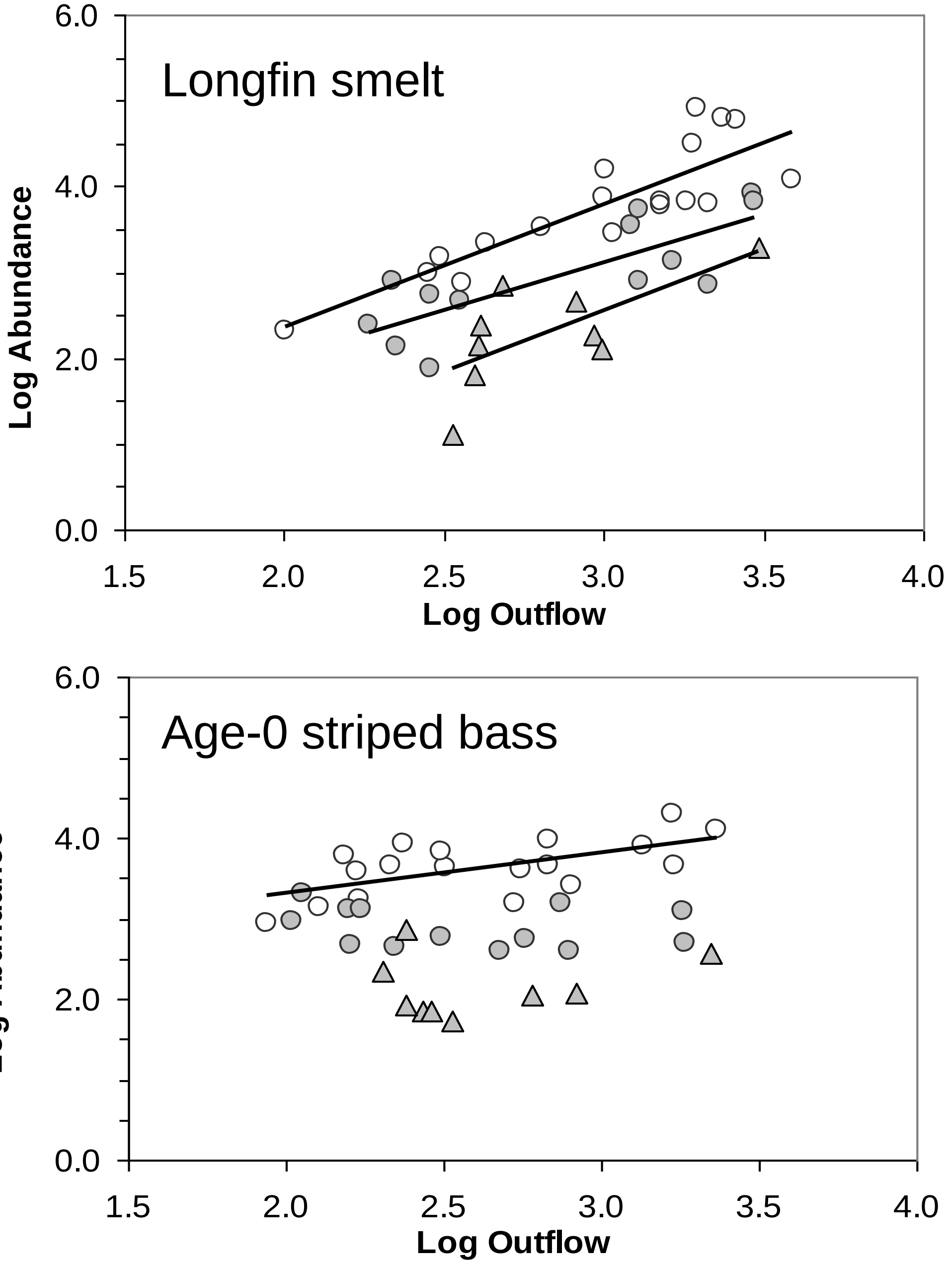
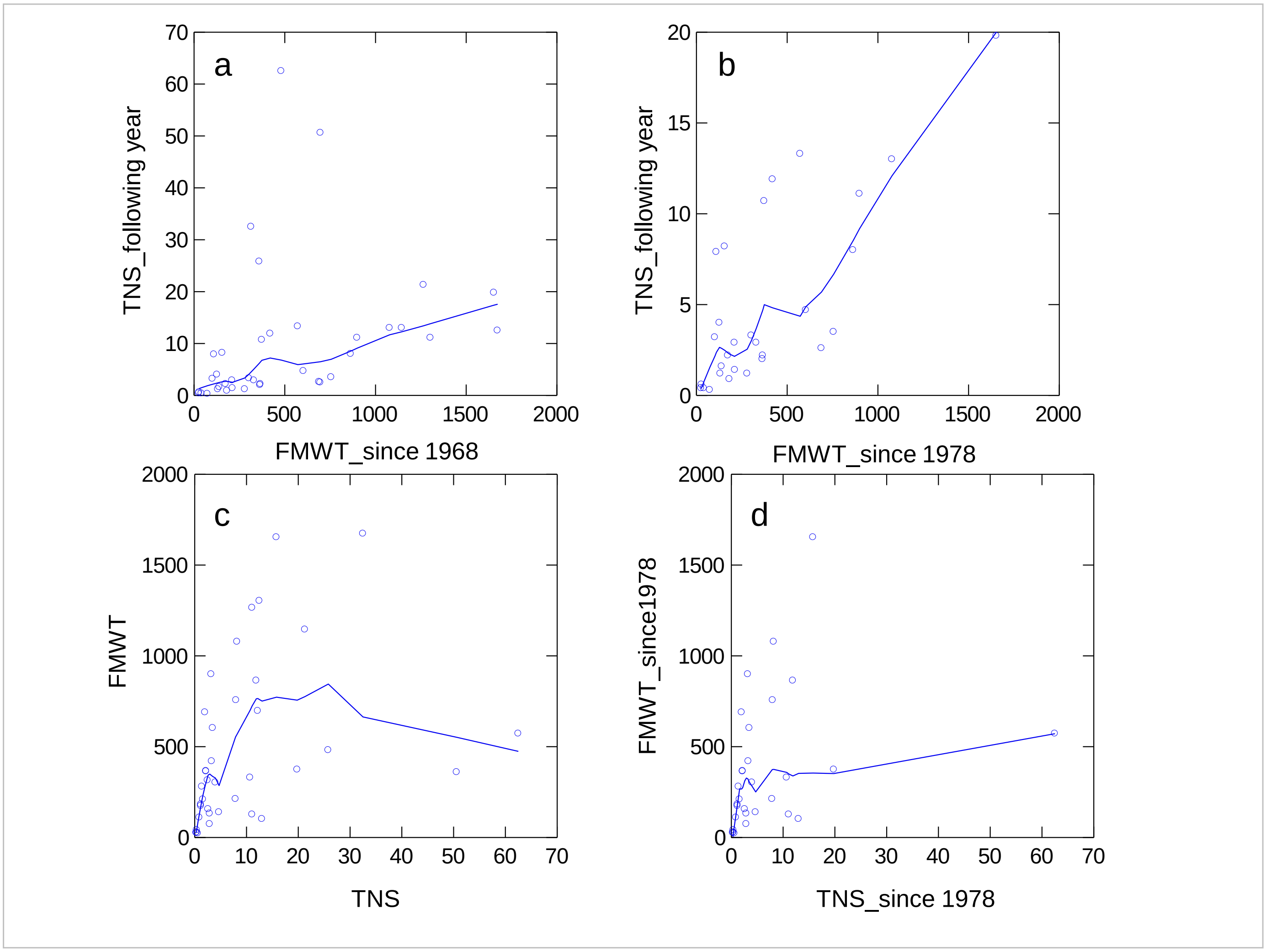


Figure 11. Log-log relationships between Fall Midwater Trawl abundance and delta outflow for longfin smelt (all ages) and age-0 striped bass. Delta outflow (m^3/s) values represent mean levels during January through June for longfin smelt and during April through July for age-0 striped bass . The data are compared for pre-*Corbula* invasion years (1967–1987; white circles), post-*Corbula* invasion (1988–2000; filled circles), and during the POD years (2001–2009 ; triangles). Lines depict significant linear regression relationships ($p<0.05$).



12. Scatterplots and LOWESS splines depicting the relationship between a) the Fall Midwater Trawl index of delta smelt relative abundance (FMWT) versus the following calendar year's Summer Townet Survey index of delta smelt relative abundance (TNS) for FMWT years 1968–2007; b) the FMWT versus the following calendar year's TNS for FMWT years 1978–2007; c) the TNS and the subsequent FMWT for 1969–2008; and d) the TNS and the subsequent FMWT for 1978–2008.

Figure 12

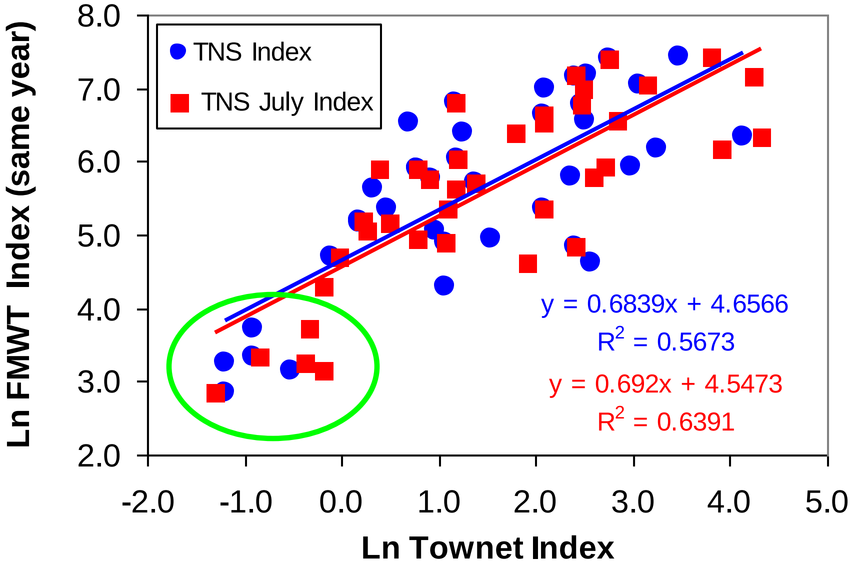


Figure 13. Ln–ln relationships between juvenile and adult lifestages of delta smelt since 1969. The Townet Survey is a measure of summer juvenile abundance. The Fall Midwater Trawl is a measure of fall pre-spawning adult abundance. The blue circles represent the data from the first 2 Townet Surveys which typically begins in June or July and are used to calculate the Townet Survey delta smelt index. The red squares represent data from July only and represent an alternate index. Regression equations and coefficients are given in blue font for the full Townet Survey data and in red font for the July Townet Survey data. Data from 2005 to 2009 are contained in the green ellipse.

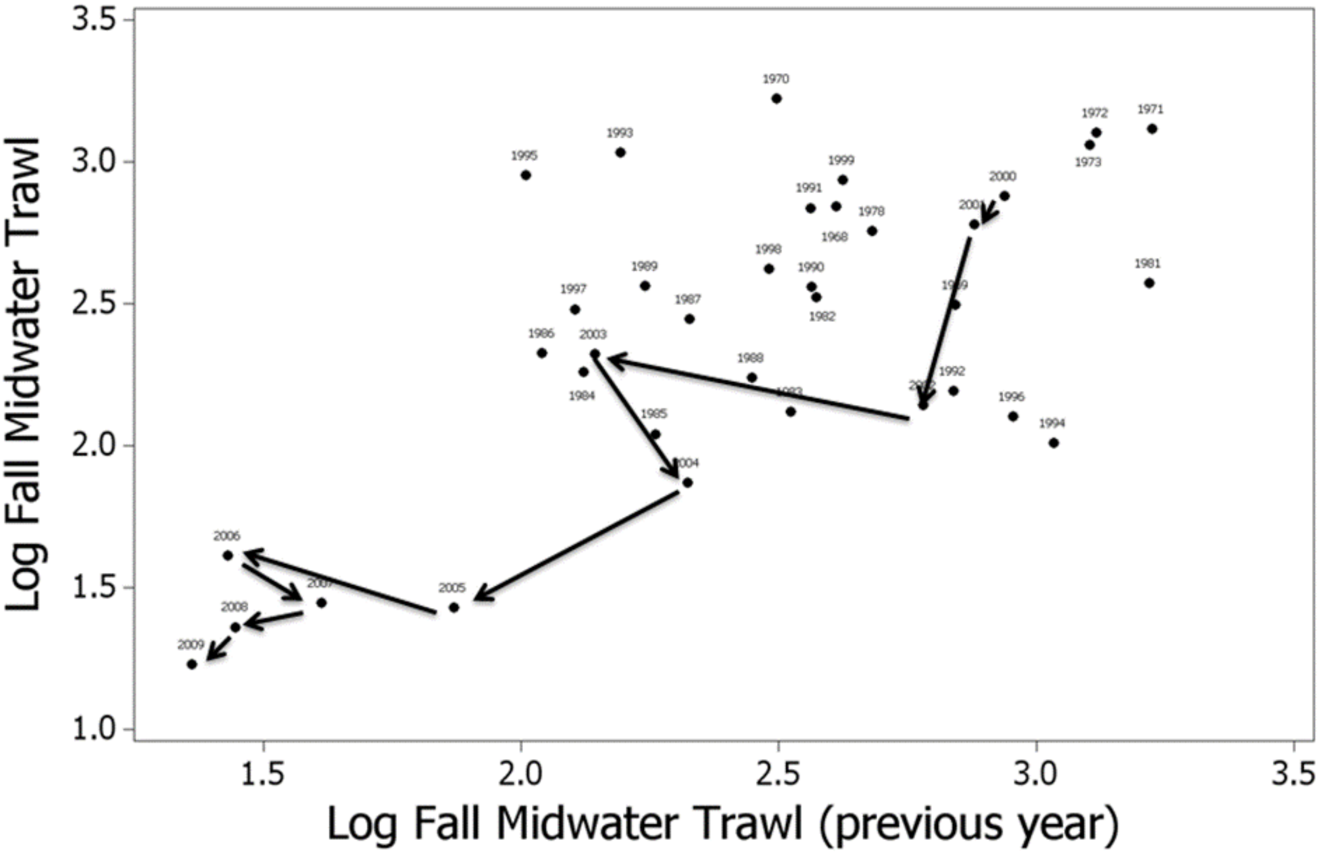
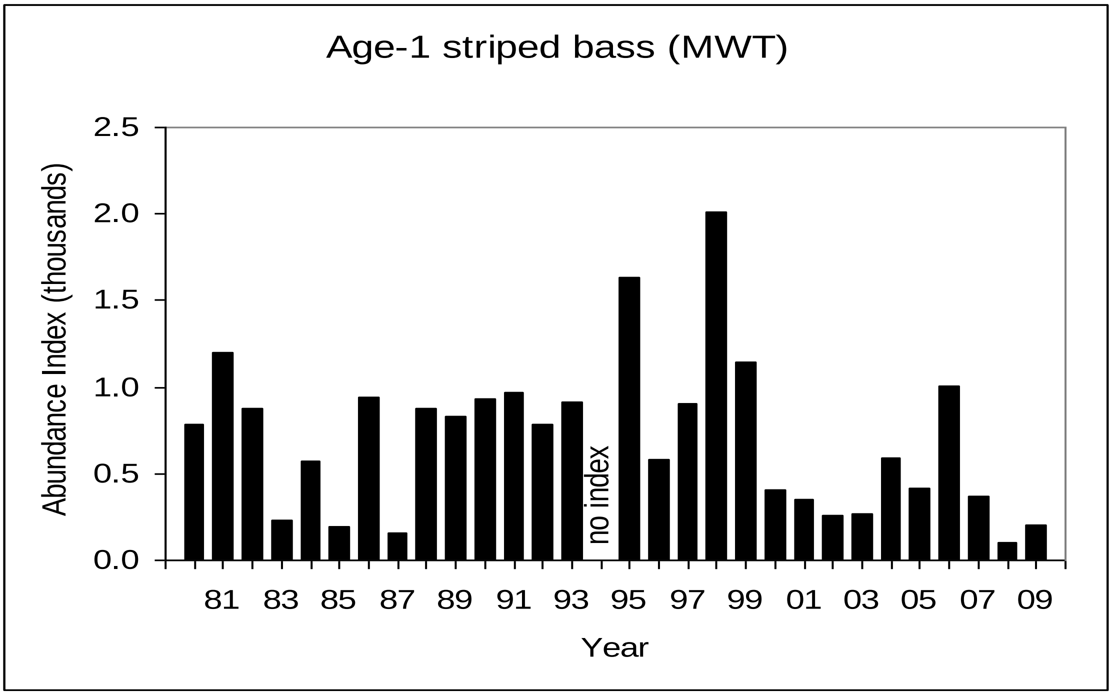
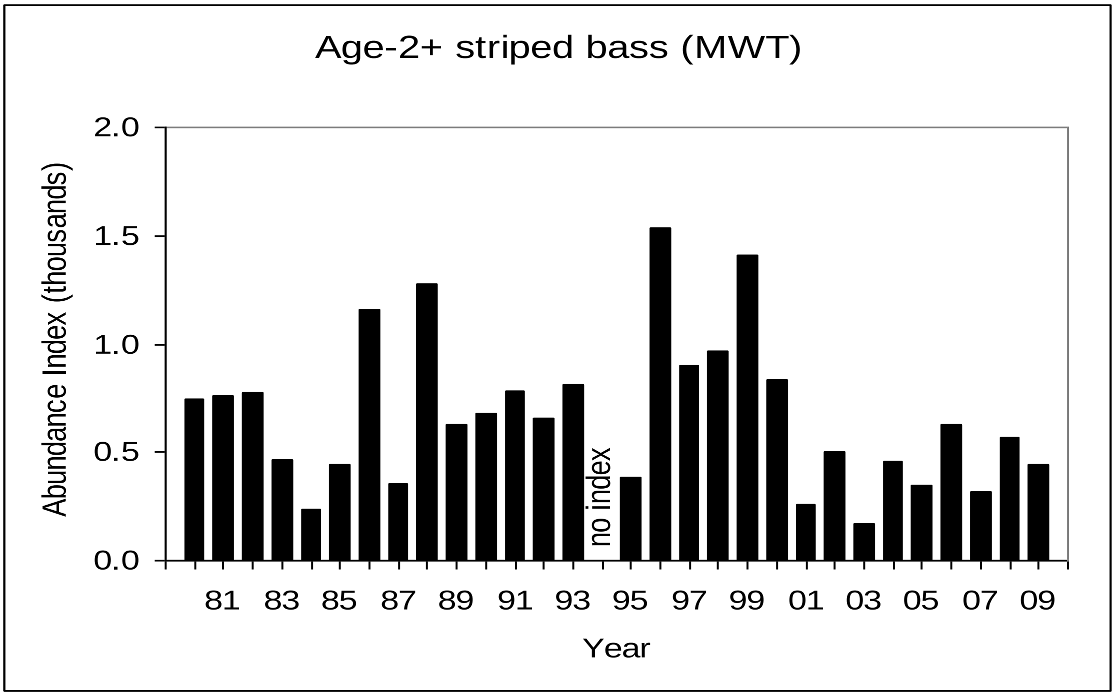
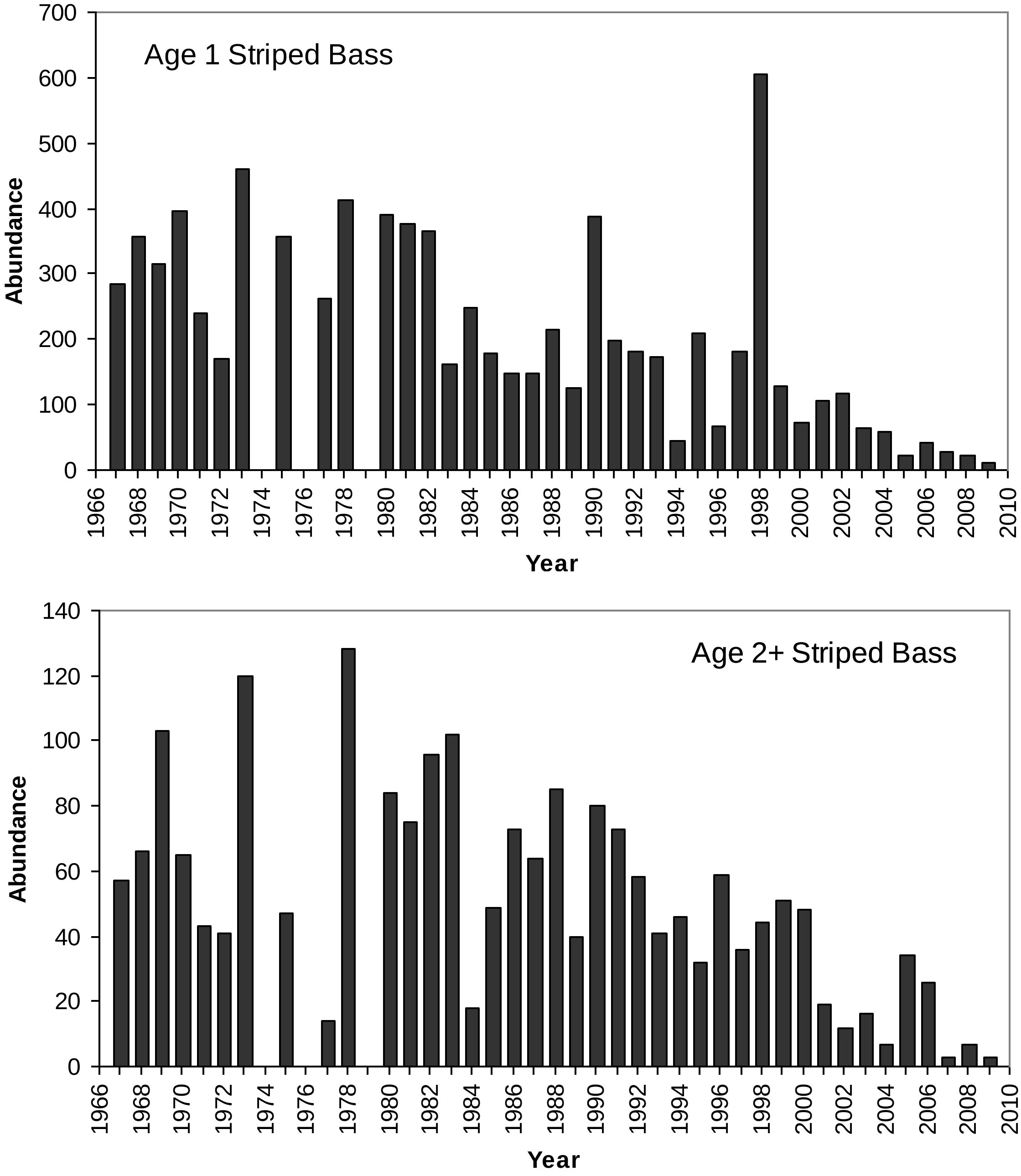


Figure14. Log–log relationships between Fall Midwater Trawl abundance and Fall Midwater Trawl abundance in the previous year. The arrows connect consecutive years from 2000 to 2009.


Age-1 striped bass (MWT)
Abundance Index (thousands)
2.5
2.0
1.5
1.0
0.5
0.0
no index
81
83
85
87
89
91
93
95
97
99
01
03
05
07
09
Year


Age-2+ striped bass (MWT)
Abundance Index (thousands)
2.0
1.5
1.0
0.5
0.0
no index
81
83
85
87
89
91
93
95
97
99
01
03
05
07
09
Year

A



B

Figure 15. Abundance of age-1 and age-2+ striped bass in midwater trawls in A) San Francisco Bay based on the California Department of Fish and Game Bay study (Bay Study) and B) in the Delta from the Fall Midwater Trawl. No Fall Midwater Trawl indices were calculated for years 1974, 1976 and 1979.

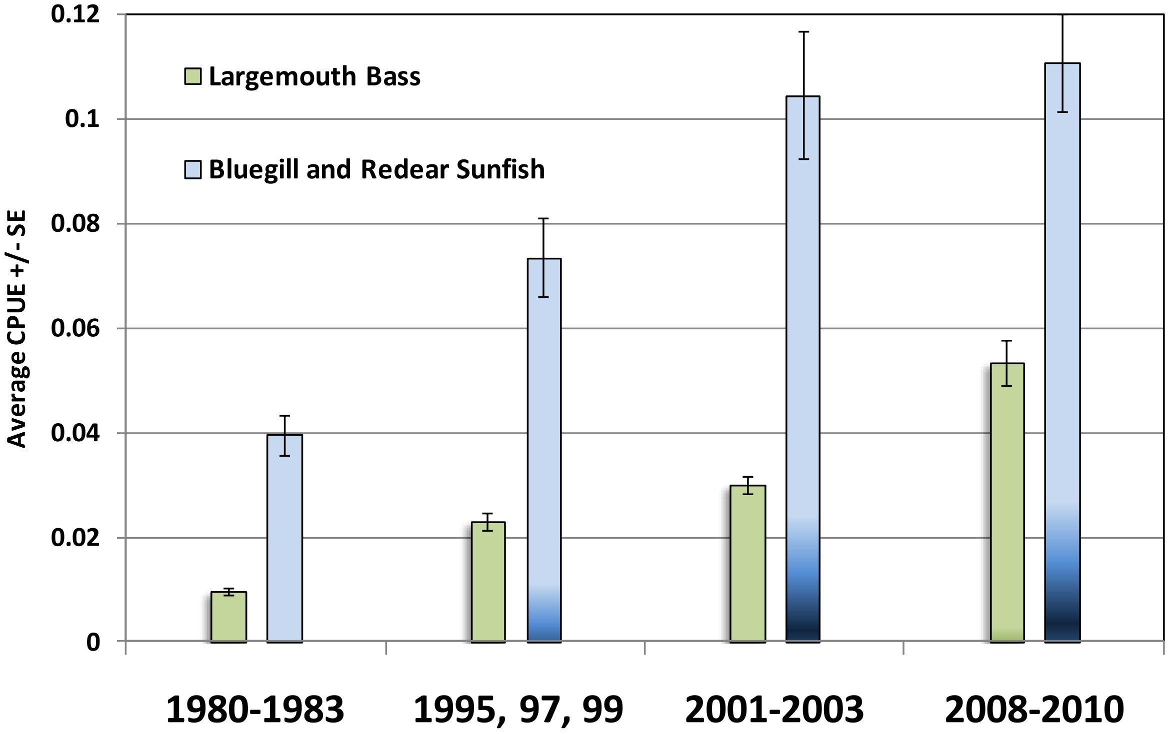


Figure 16. Average catch per unit effort (CPUE) for largemouth bass, bluegill, and redear sunfish from successive electrofishing efforts in the Delta from 1980 to 2010. Data from 1980–2003 is from CDFG (unpublished data) and data from 2008–2010 is from L. Conrad (DWR, unpublished data).

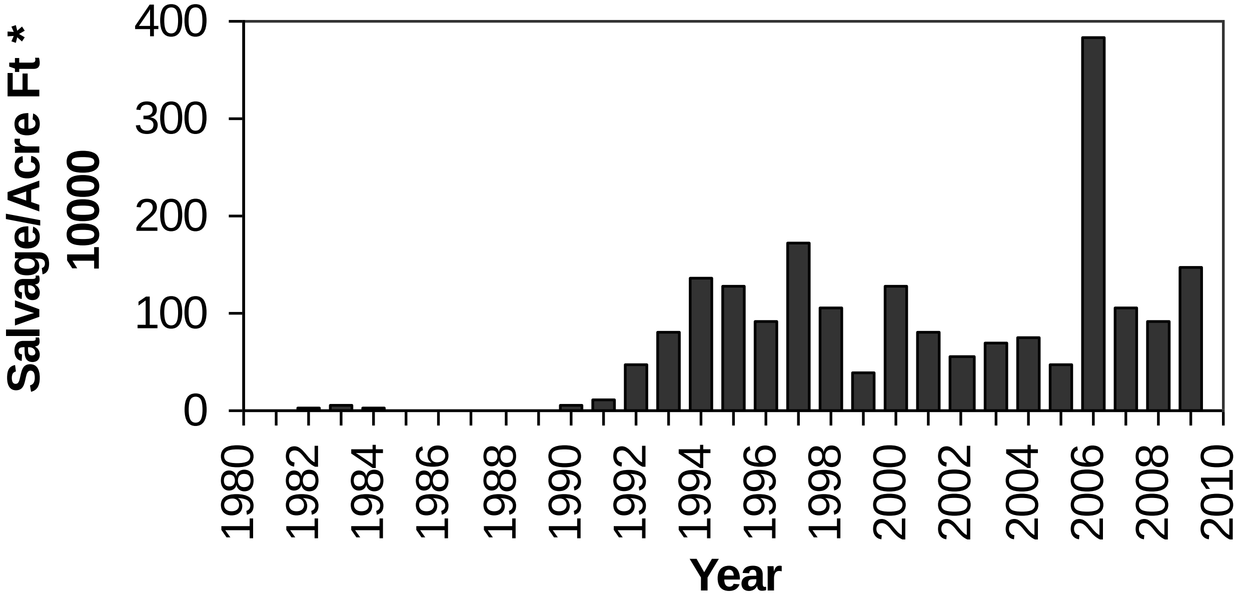


Figure 17. Annual salvage density (fish per 10,000 acre feet) of largemouth bass at the CVP and SWP combined from 1979 to 2009 (California Department of Fish and Game, unpublished data).

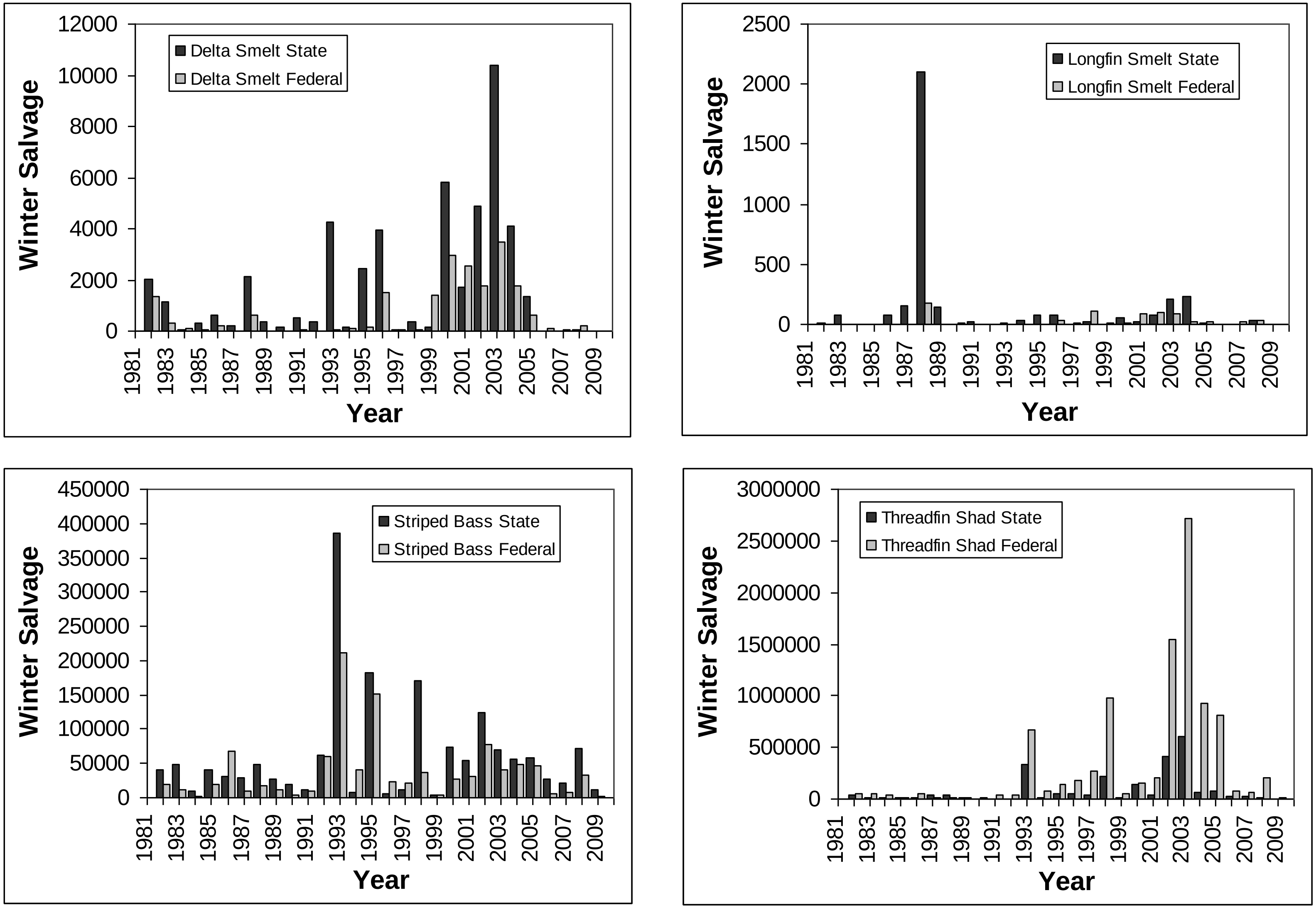
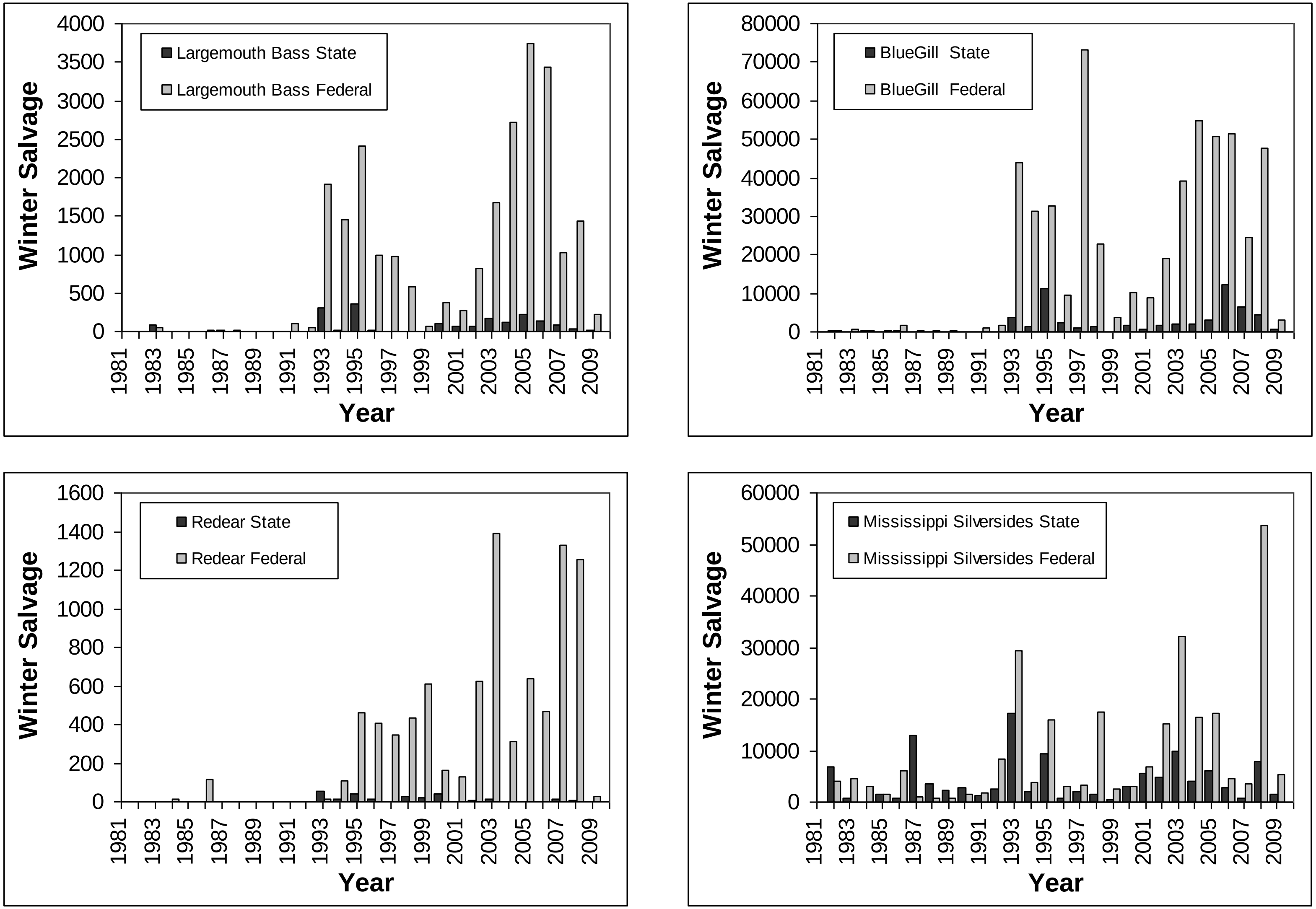


Figure 18. Winter salvage data for striped bass, delta smelt, longfin smelt, and threadfin shad for the federal Central Valley Project (Federal) and State Water Project (State) from 1981 to 2009. Salvage for delta smelt and longfin smelt before 1993 should be interpreted with caution because of variable degrees of training among personnel identifying fishes.



19. Winter salvage for largemouth bass, inland silversides, bluegill, and redear sunfish for the federal Central Valley Project (Federal) and State Water Project (State) from 1981 to 2009.

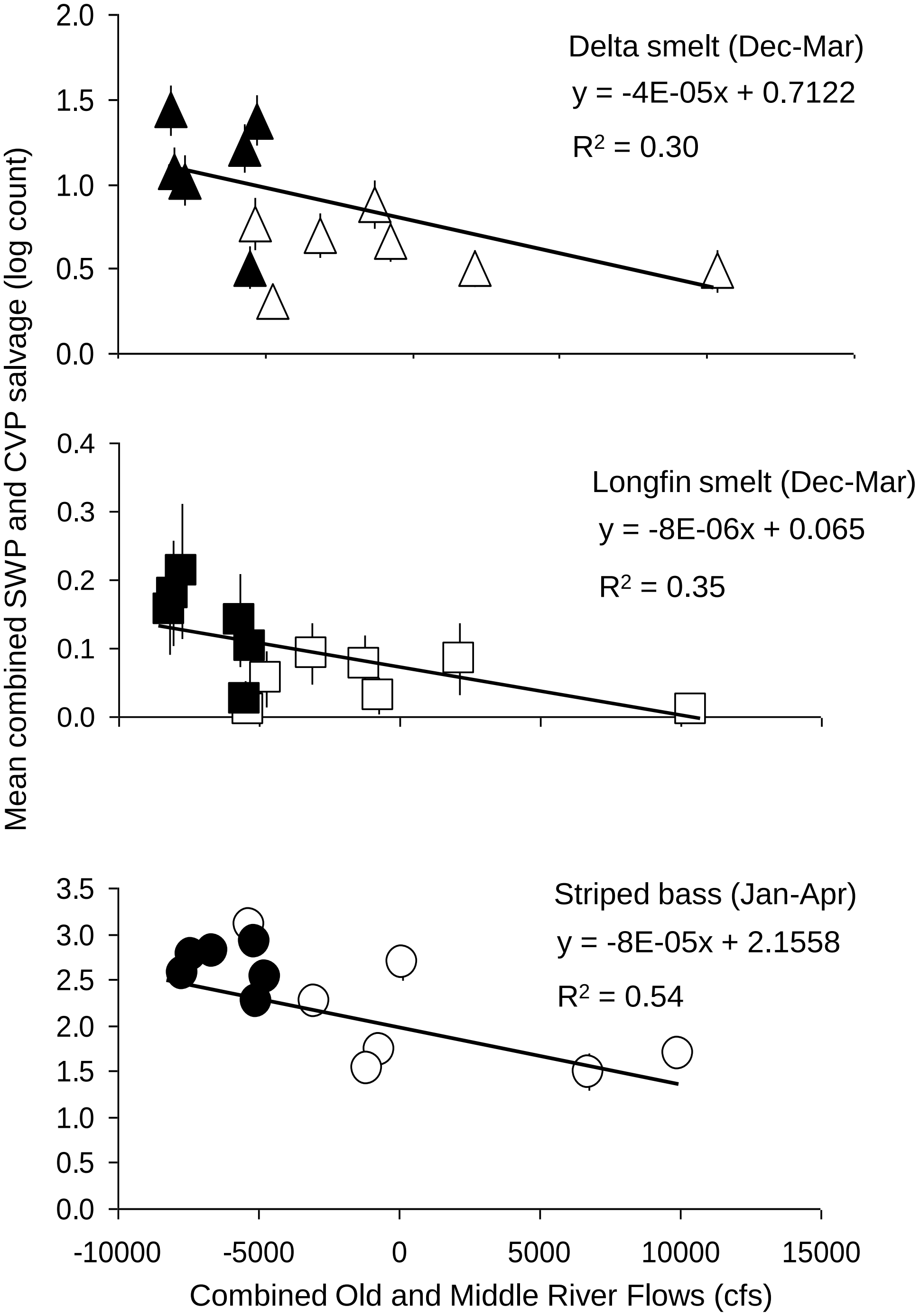


Figure 20. Relationship of mean combined salvage of delta smelt, longfin smelt, and striped bass at the State Water Project (SWP) and Central Valley Project (CVP) to combined Old and Middle rivers flow (cubic feet per second). Open symbols denote pre-POD years (1993–1999) and filled symbols represent post-POD years (2000–2005) (Grimaldo et al. 2009).

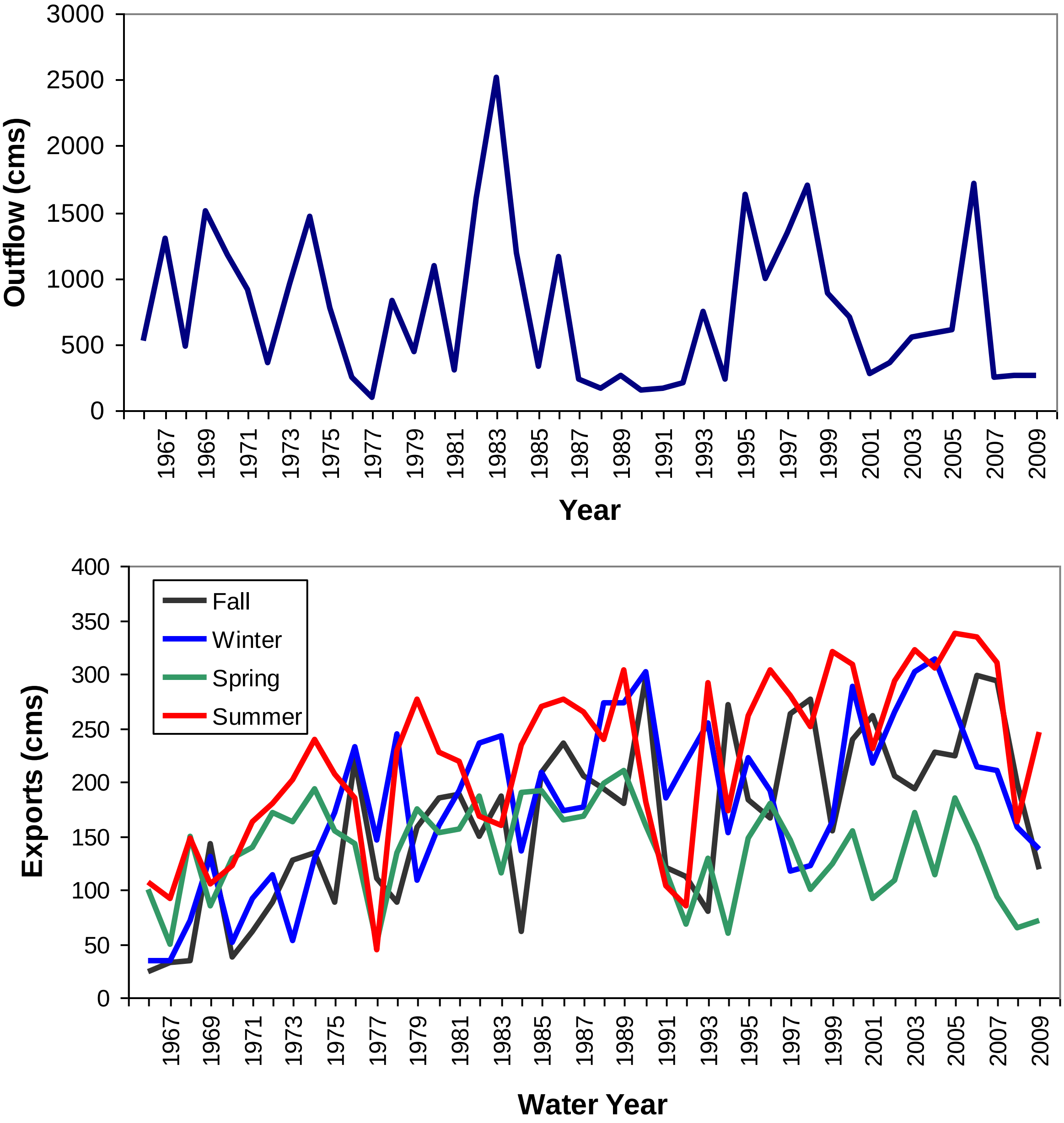


Figure 21. Delta outflow (m^3/s) averaged over water years (top) and export flow (m^3/s) averaged over seasons (bottom). Water years begin on 1 October of the previous calendar year. Seasons are in 3-month increments starting in October. Export flows are the sum of diversions to the federal Central Valley Project and State Water Project pumping plants. The outflow and export data are from California Department of Water Resources (http://iep.water.ca.gov/dayflow).

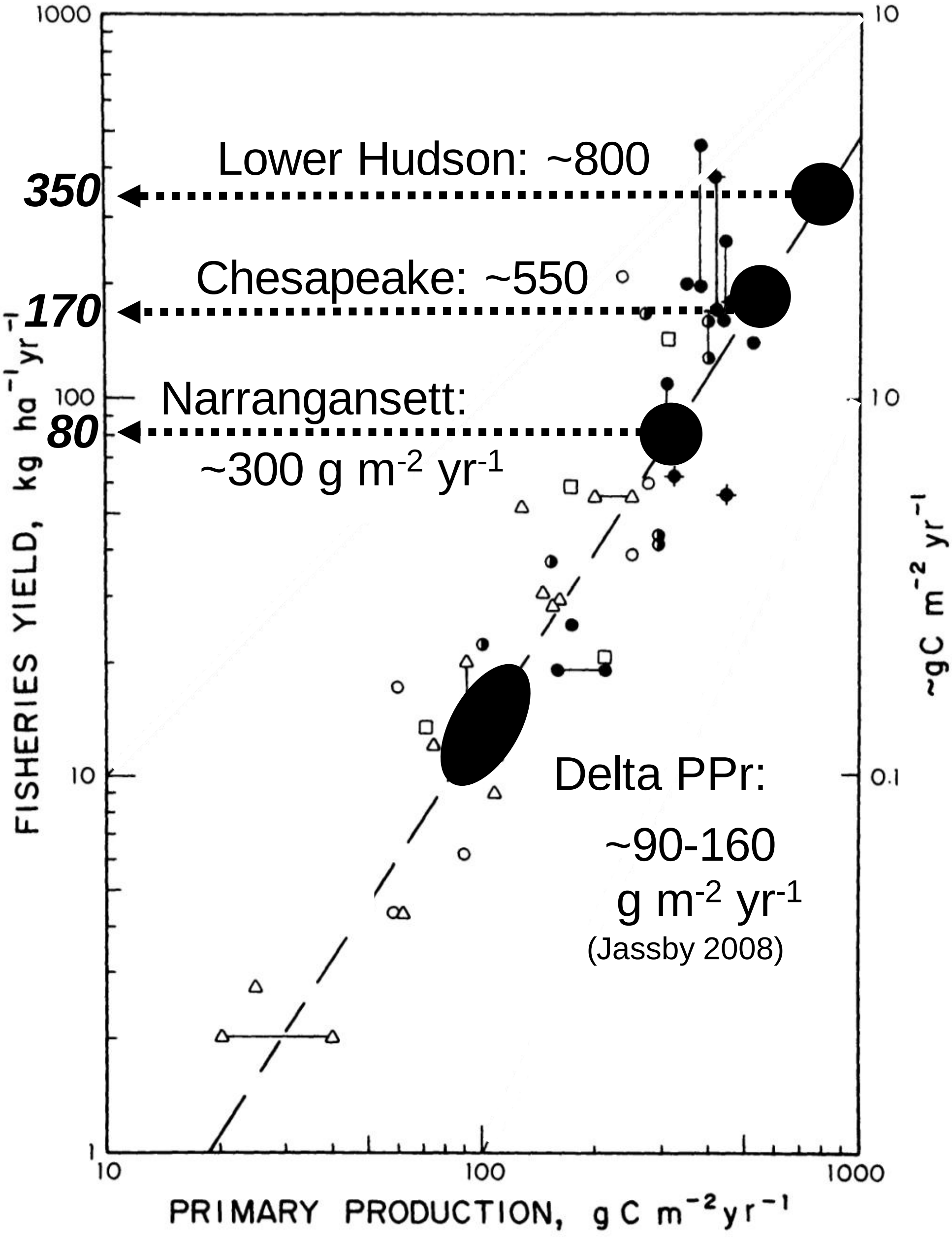


Figure 22. Range in primary production in Suisun Bay and the Delta since 1975 plotted on the relationship of fishery yield to primary production from other estuaries around the world (modified from Nixon 1988, using results in Jassby 2008 and Jassby et al 2002 and data provided by James Cloern, U.S. Geological Survey).

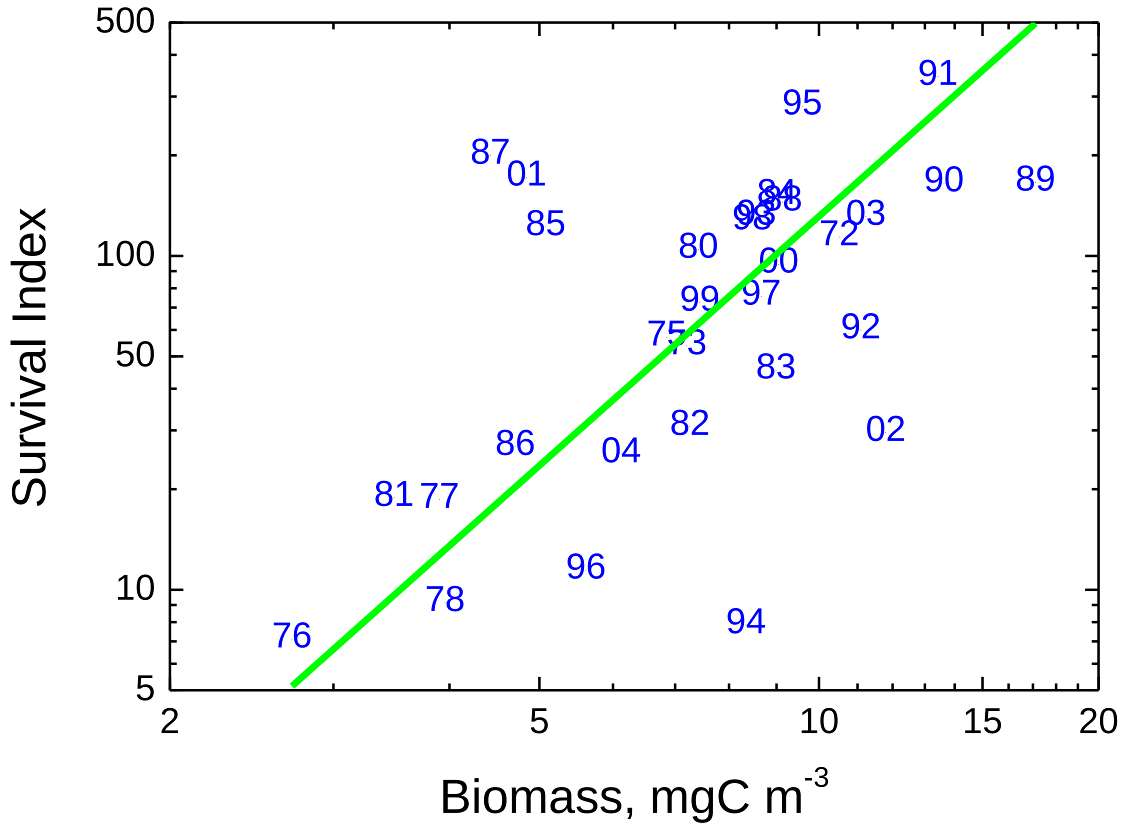
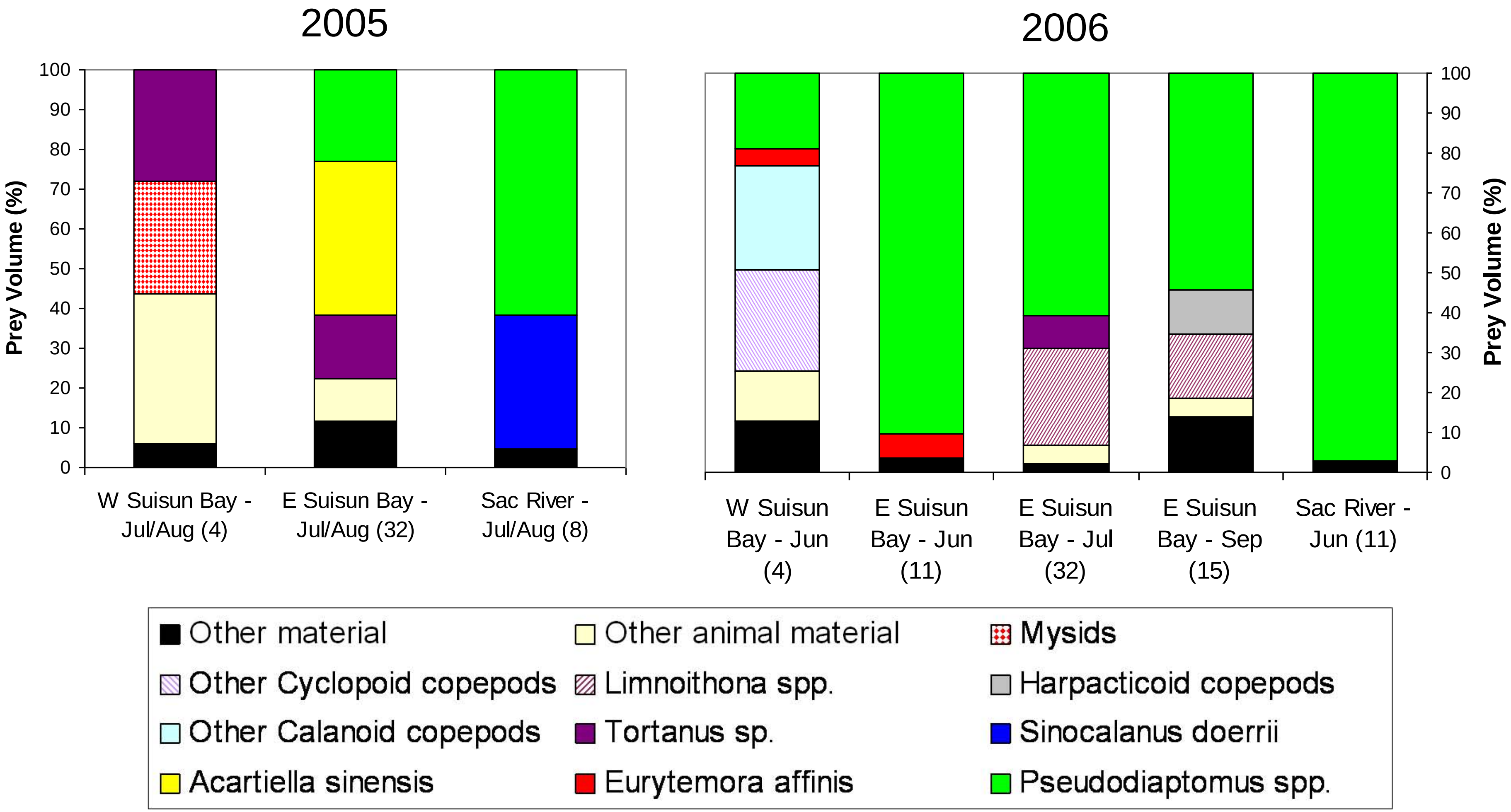


Figure 23. Summer to fall survival index of delta smelt in relation to zooplankton biomass in the low salinity zone (0.15 – 2.09 psu) of the estuary. The survival index is the log ratio of the Fall Midwater Trawl index to the Summer Townet Survey index. The line is the geometric mean regression for log(10)-transformed data, $y = 2.48x - 0.36$. The correlation coefficient for the log-transformed data is 0.58 with a 95% confidence interval of (0.26, 0.78) (Kimmerer, 2008).



24. Prey volume in guts of delta smelt collected during summer 2005 and 2006. Sample size appears in parentheses (S. Slater, California Department of Fish and Game, unpublished data).

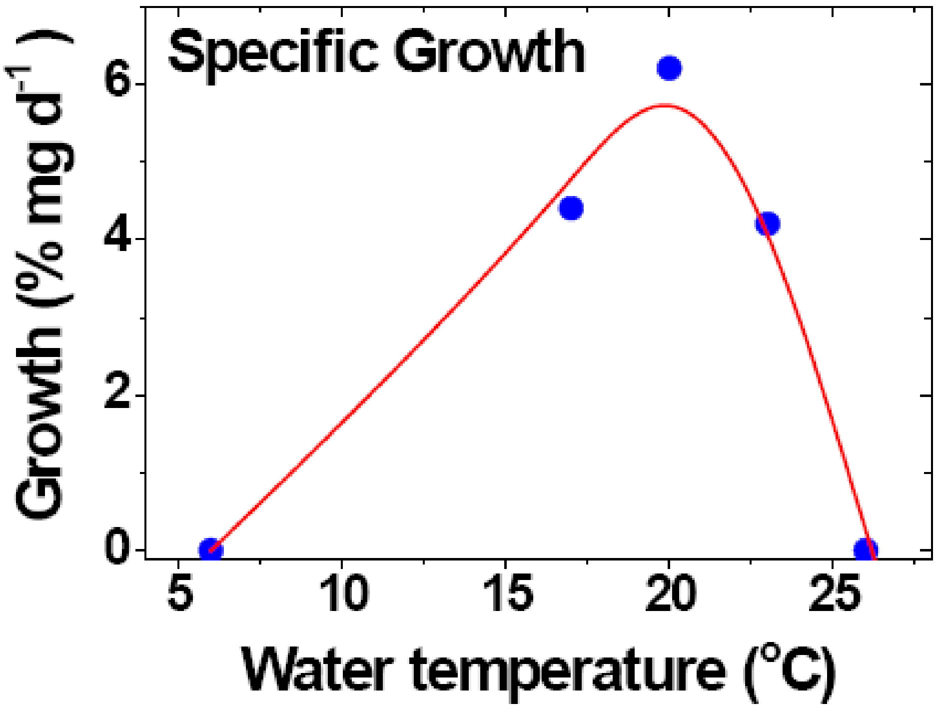


Figure 25. Water temperature influences on growth in the juvenile stage (i.e. specific growth) from studies by Baskerville et al. (2004) during aquaculture. A cubic spline model was fitted to approximate the functional form of specific growth with respect to water temperature (from Bennett et al. 2008).

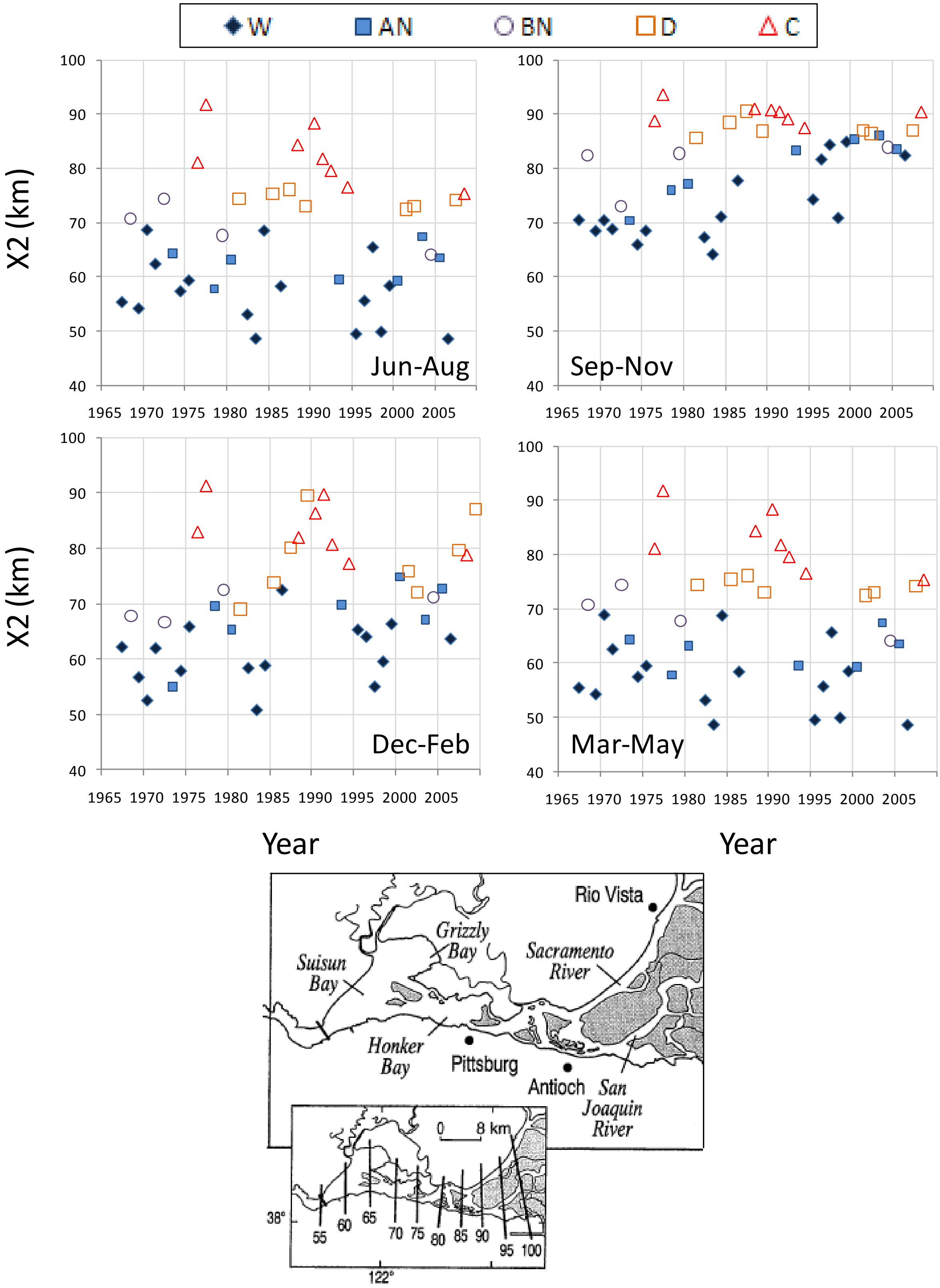


Figure 26. Seasonal means of X2, the location of the 2‰ bottom isohaline along the axis of the estuary (distance from the Golden Gate in km) from 1967–2009. Symbols indicate water year types for the Sacramento Valley (W: Wet, AN: Above Normal, BN: Below Normal, D: Dry, C: Critically Dry). Map (modified from Jassby et al 1995): Suisun Bay and the western Delta. Insert shows lines positioned along nominal distances (in km) from the Golden Gate along the axis of the estuary.

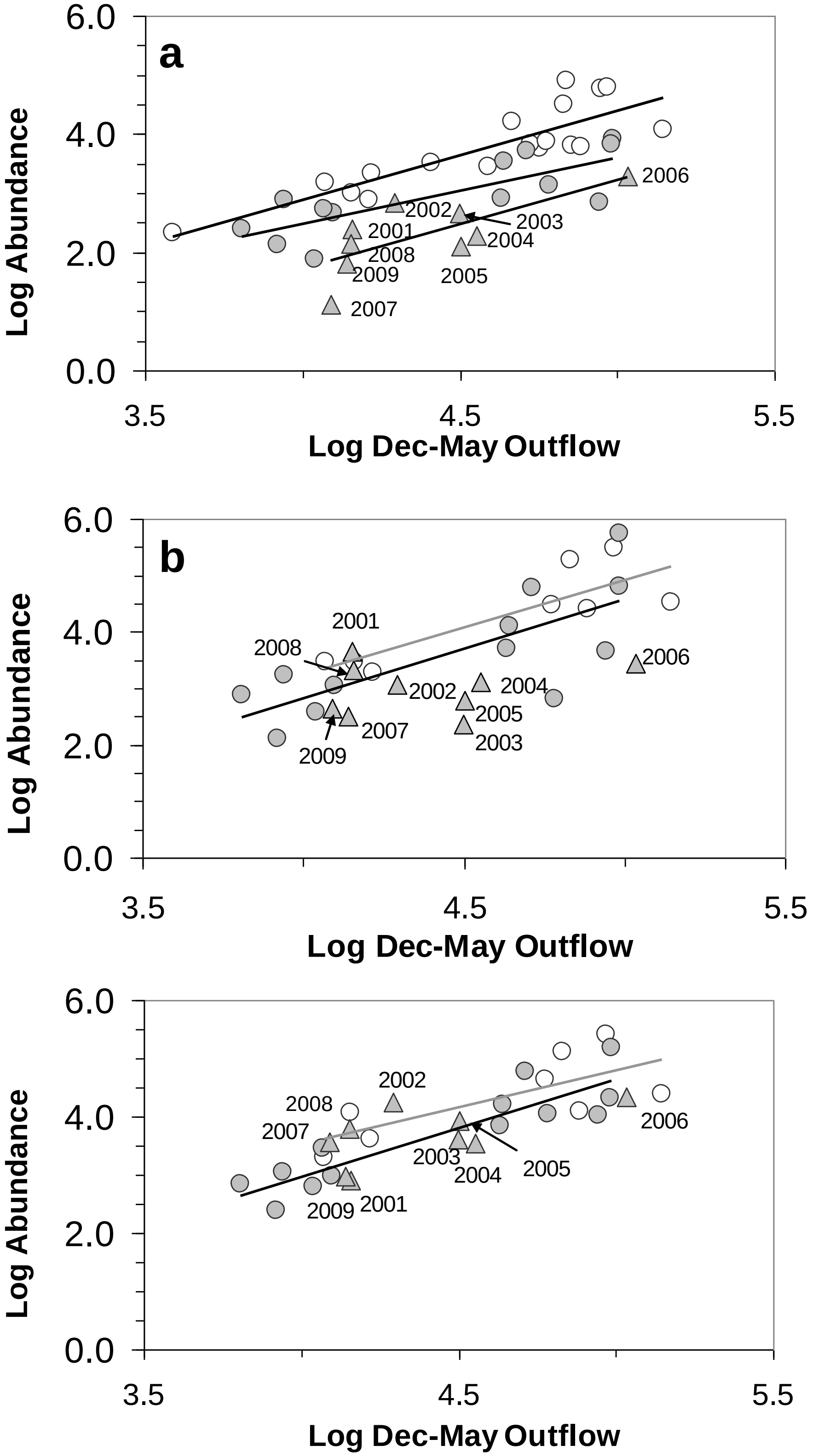


Figure 27. Longfin smelt outflow abundance relationships based on December through May mean outflow (cfs) and (a) Fall Midwater Trawl annual abundance, 1967–2009, all ages, (b) Bay Study Age-0 midwater trawl abundance, 1980–2009, and (c) Bay Study age-0 otter trawl abundance, 1980–2009. Abundance data are compared for pre-*Corbula* invasion years (survey start – 1987, open circles), post-*Corbula* invasion (1988–2000, filled circles) and POD years. Fitted lines indicate linear regression relationships that are significant at the p < 0.05 level.

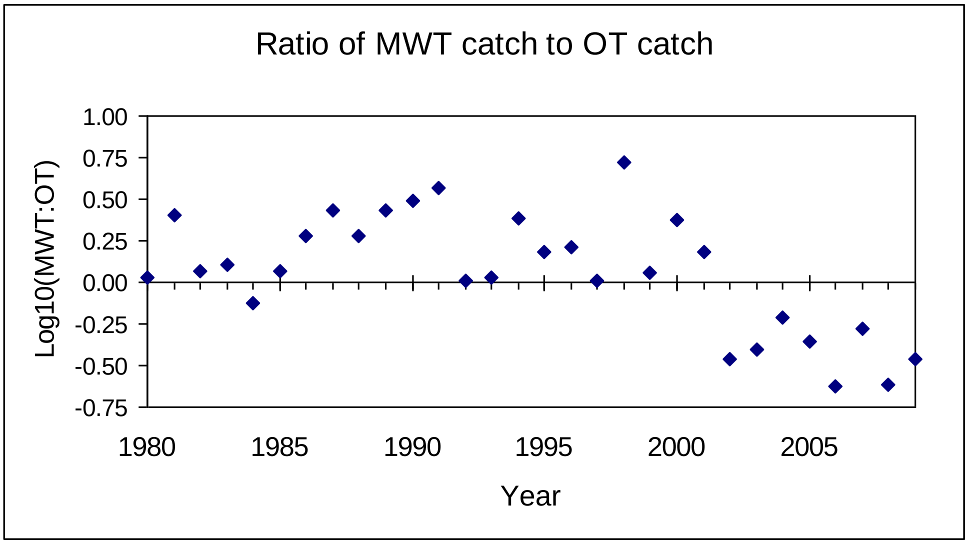


Figure 28. Ratio of annual longfin smelt catch (all ages) in the Bay Study midwater (MWT) and otter (OT) trawls (log 10 transformed), 1980–2009. Catch data are from all months of the year sampled, which varied by year, and all 35 core stations where valid tows were completed for both nets.

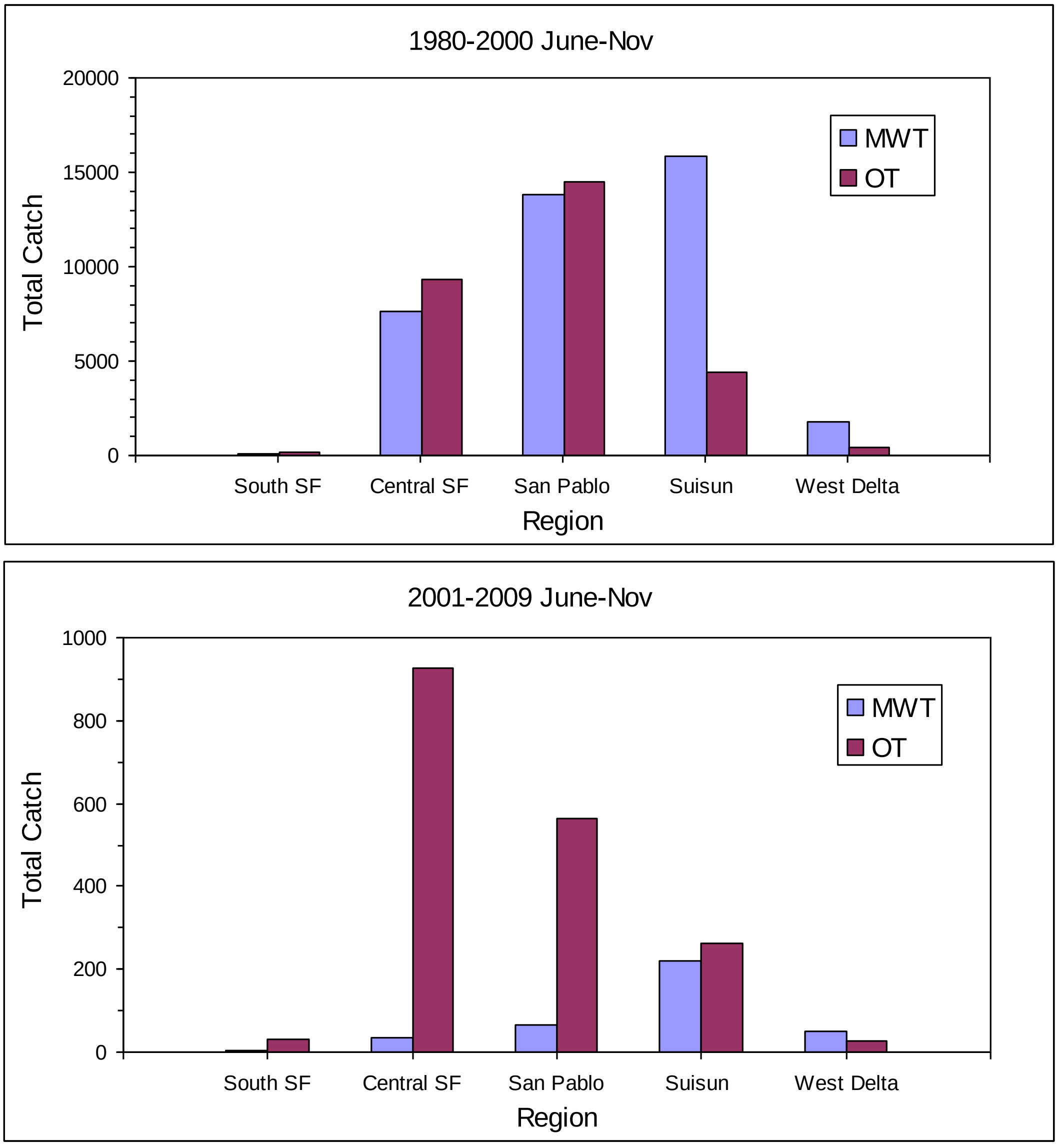


Figure 29. Total June through November longfin smelt catch (all ages) in the Bay Study midwater (MWT) and otter (OT) trawls, 1980–2000 for 35 core stations where valid tows were completed for (a) both the nets, and (b) the same data for POD years 2001–2009.

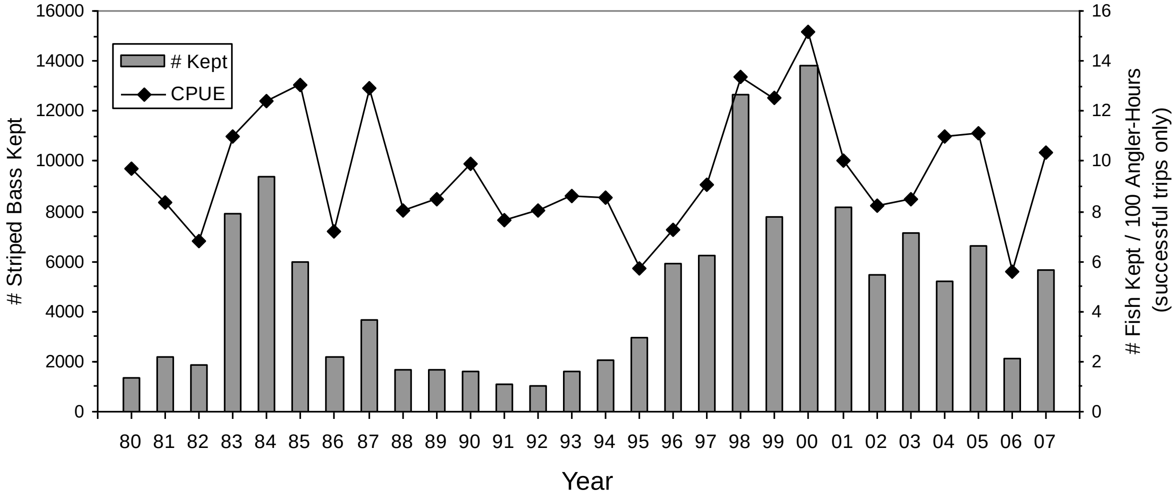


Figure 30. Harvest and CPUE for Striped Bass by Commercial Passenger Fishing Vessels in the San Francisco Bay and Delta, 1980–2009.

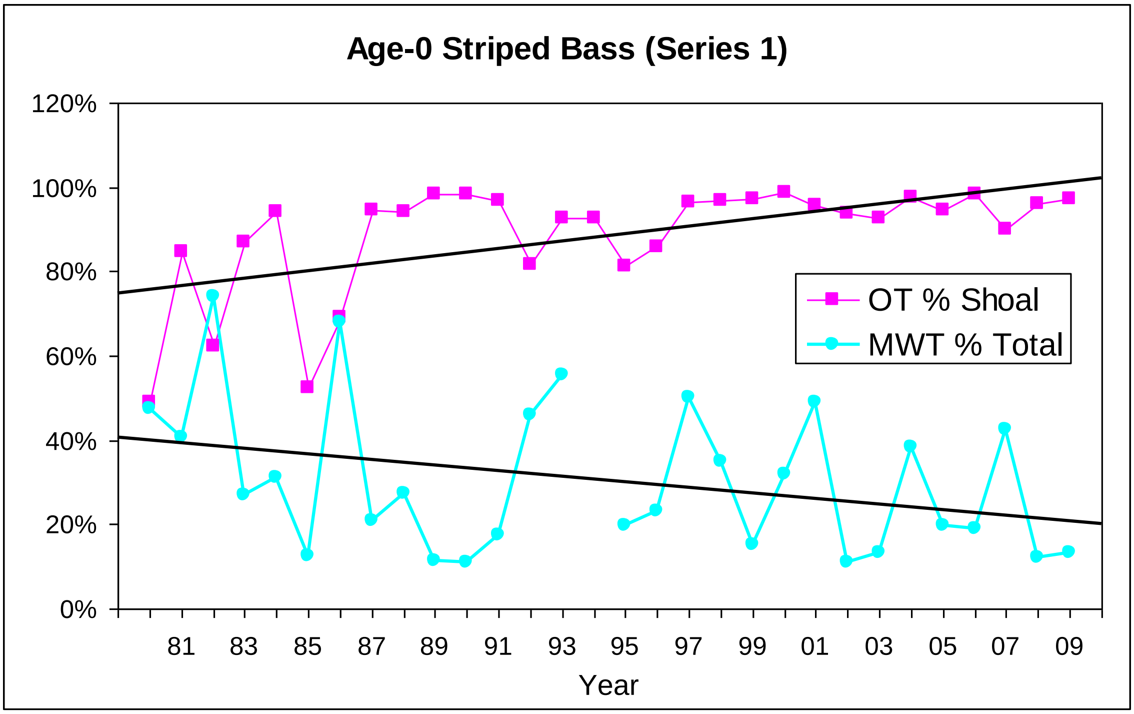


Figure 31. San Francisco Bay Study age-0 striped bass catch May–October. The blue line and circles represent the proportion of the total catch of the combined midwater trawl (MWT) and otter trawl catch (OT) that was taken in the midwater trawl; data for 1994 are incomplete and were not plotted. The pink line and solid squares represent the proportion of the total otter trawl catch taken at shoal stations (<7m deep).

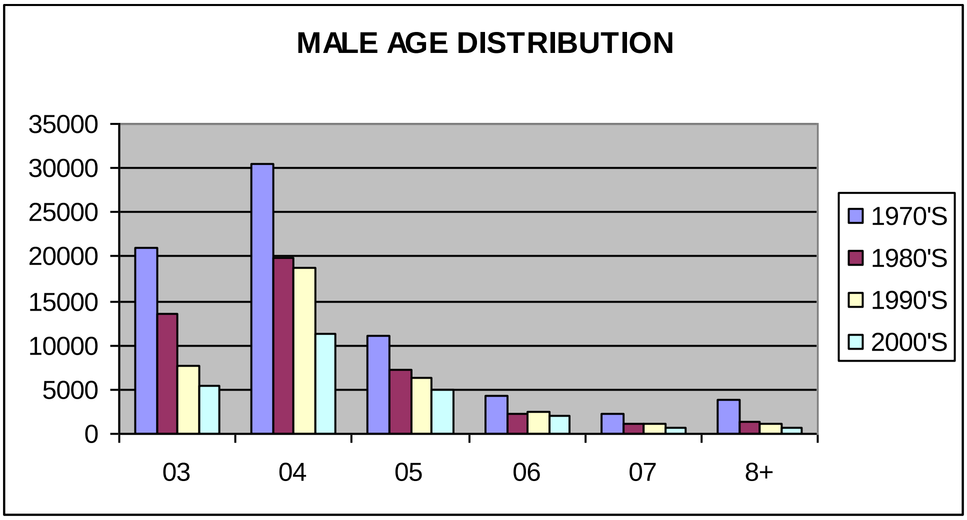
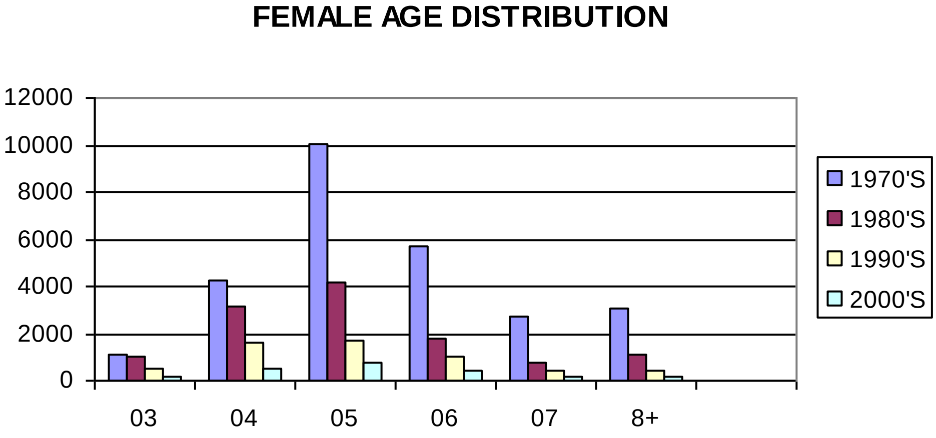


Figure 32. Male and female age distribution by decade for striped bass ages 3 – 8+ in fyke net collections. Note that age distribution is the same for gill-net collected fish (graphic not displayed).



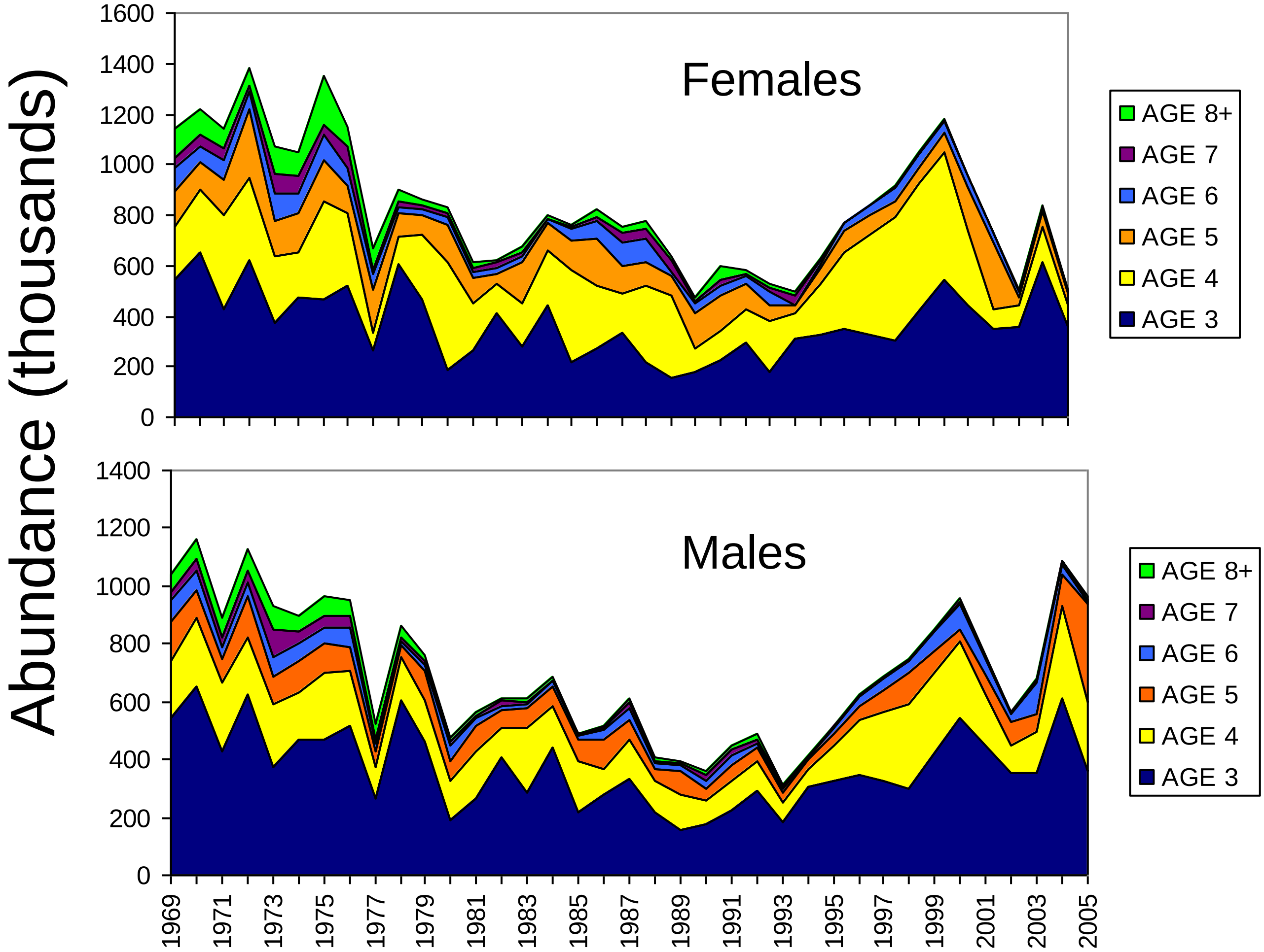


Figure 33. Abundance estimate (in thousands) of male and female striped bass >= 3 – 8+ collected in the Adult Striped Bass Tagging Program, 1969 – 2005.

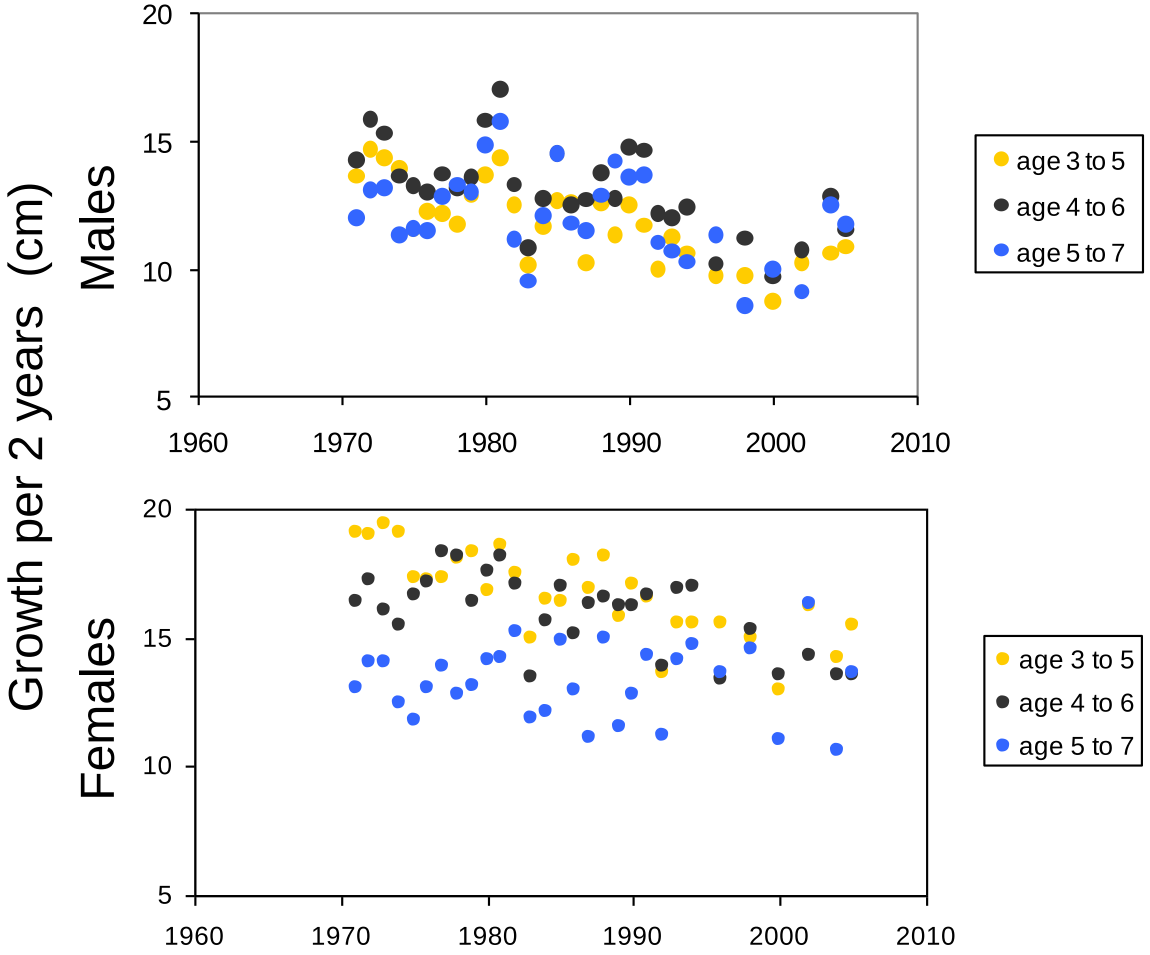
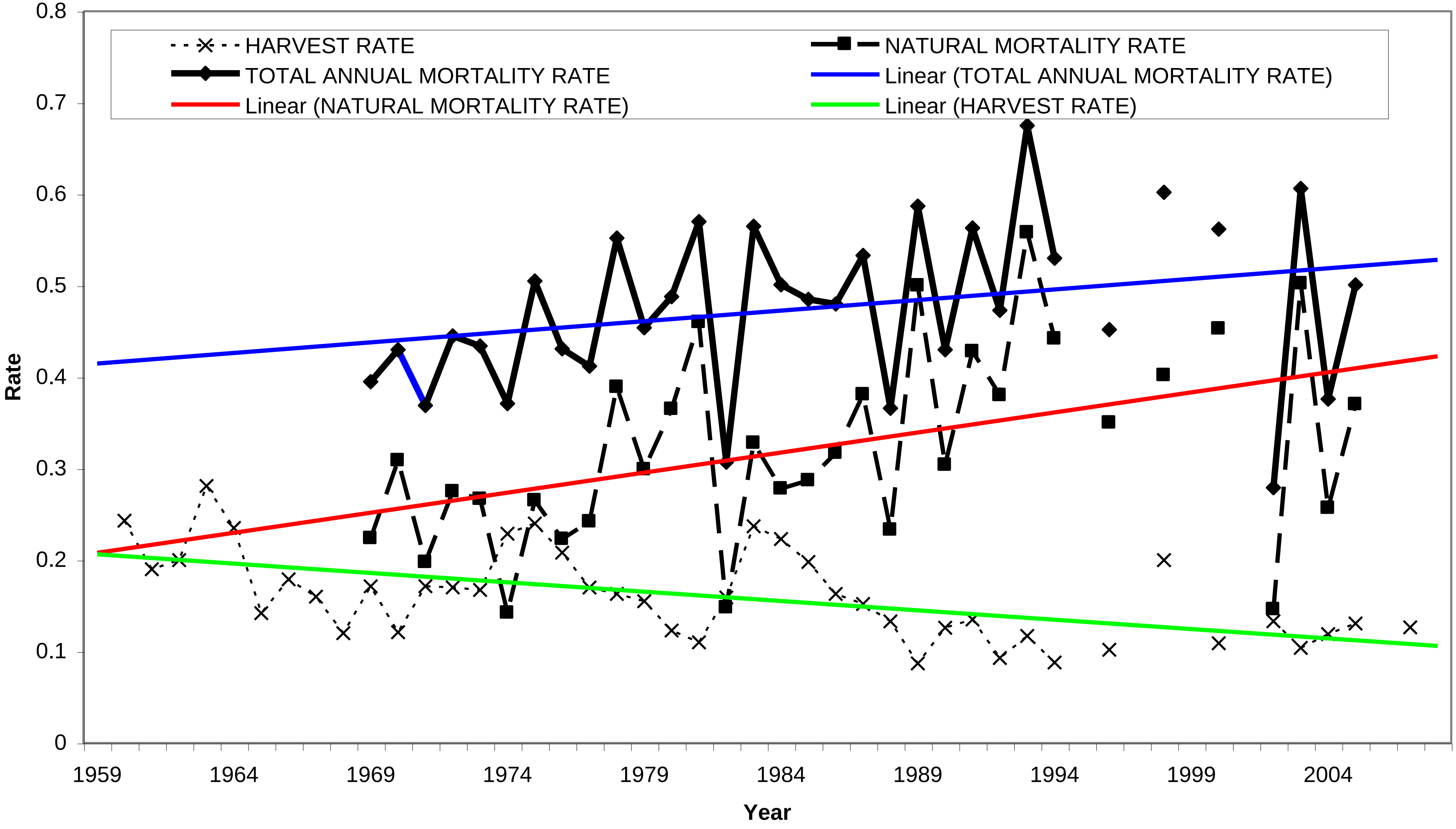
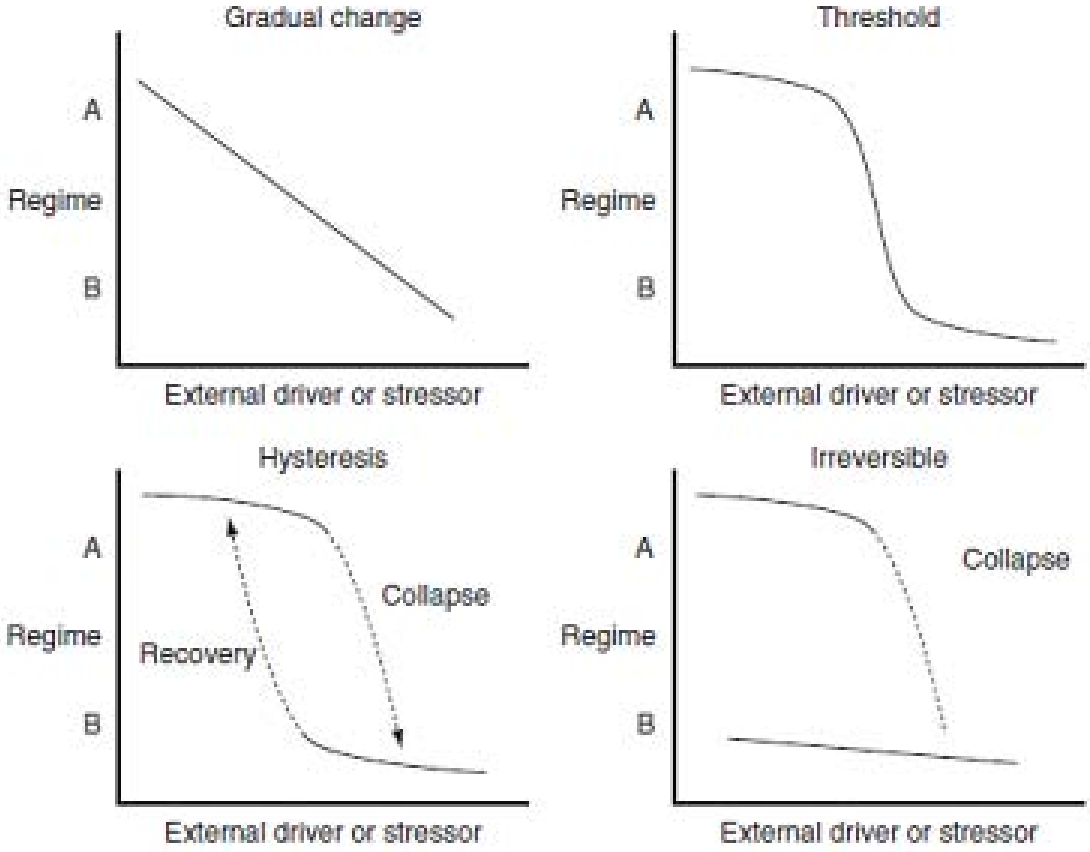


Figure 34. Apparent growth of male and female striped bass ages 3 – 7, calculated from data collected from the Adult Striped Bass Tagging Program, 1970 – 2005.



35. Estimates of harvest rate (1960 – 2007), and natural and total annual mortality rate (1969 – 2007) of legal-sized striped bass ≥ 3 – 8+, Adult Striped Bass Tagging Program.



36. Four models of ecological change. The gradual change model shows a gradual linear change from regime A to regime Bin response to a gradually changing environmental driver. The transition can be reversed by reversing the driver. The threshold model shows a nonlinear abrupt change from regime A to regime B occurring in response to a relatively small change in the environmental driver. Reducing the environmental driver to a value below the threshold results in a change back to the original regime. The hysteresis model describes a nonlinear response to the environmental driver but the threshold for recovery differs from the original threshold causing the collapse. The fourth model describes an irreversible change (adapted from Davis et al. 2010).

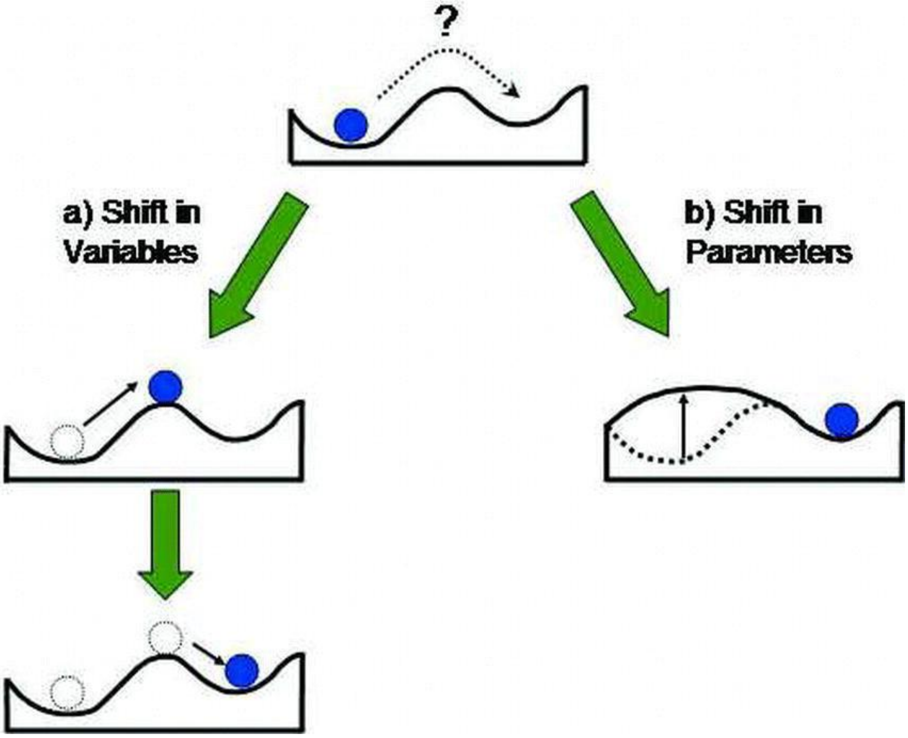
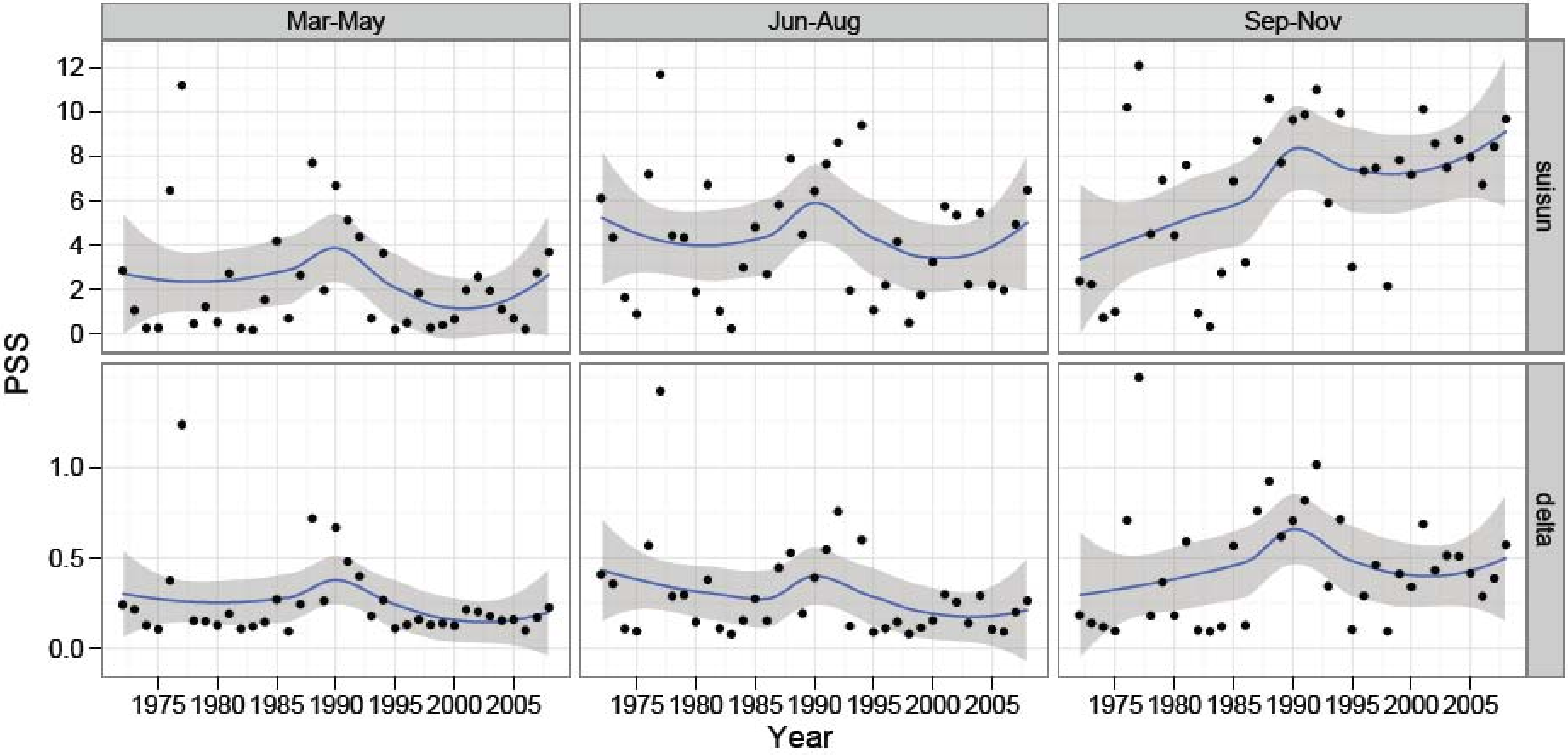


Figure 37. Two-dimensional ball-in-cup diagrams showing (left) the way in which a shift in state variables causes the ball to move, and (right) the way a shift in parameters causes the landscape itself to change, resulting in movement of the ball (from Beisner et al. 2003).



38. Annual average salinity by season (spring, summer, fall) and subregion (see Fig. 1) in the upper San Francisco Estuary between 1972 and 2008. Top panels represent data from stations in the “suisun” subregion, which include Suisun Bay and the western Delta. Bottom panels represent data from stations in the “delta” region, which includes the remaining areas of the Delta. Blue line displays a loess fit standard error (shaded area) (from Winder and Jassby 2010).

APPENDIX 1

2010 Element Descriptions of Ongoing and New Interagency Ecological Program (IEP) Studies for the Pelagic Organism Decline (POD)

6 December, 2010

I. Expanded Monitoring

Fall Midwater Trawl (FMWT)
IEP 2010-03
Point person: Randy Baxter (DFG)
Lead Agency: DFG
Questions: What is the relative abundance (via abundance index) of striped bass, delta smelt and other pelagic fishes of the upper estuary? How are juvenile delta smelt, longfin smelt and striped bass distributed in relation to potential food items?
Description: This survey targets age-0 striped bass and other pelagic species 30-150 mm in length using a midwater trawl towed through the water column for 12 minutes in a stepped oblique manner (Stevens and Miller, 1983). Sampling takes place at 116 stations located from the upstream of San Pablo Bay through the Suisun Marsh and Bay and into the Delta. This survey historically produced annual abundance indices of upper estuary pelagic fishes, which were used to identify the decline in pelagic organisms (Sommer et al., 2007); more recently the survey has provided fish samples for otolith, diet, condition and histopathology studies, and collected zooplankton and mysid samples to investigate food organism presence and diet, and ranked *Microcystis* apparent densities (see below).

During September 2005 and September and October 2006 and 2007, zooplankton tows were made at a subset of stations and mysid samples were collected starting in 2007 (32 sites in 2005, 18 sites in 2007). Beginning in 2005, the heads and bodies of delta smelt and striped bass were preserved separately for otolith and histopathological analyses (Bennett, 2005, section 3a; Teh, 2005, section 3b) or were preserved intact for diet and condition analyses (Gartz and Slater, 2005, section 3c). In 2006-2007, sampling continued as described above and longfin smelt, threadfin shad, and some inland silversides were collected for diet and condition. In 2008, fish preservation remained the same as 2006 and 2007, except longfin smelt heads and bodies were preserved separately for otolith, genetics, diet and sex ratio analyses.

In 2009, only striped bass heads and bodies were preserved separately; longfin smelt and wakasagi were preserved in ethanol, threadfin shad and some American shad were preserved in formalin and all delta smelt and most American shad were immediately frozen in liquid nitrogen. Due to furloughs and sample backlogs, mysid and zooplankton samples were only taken when delta smelt were caught and these samples were supplied to Wim Kimmerer along with the frozen delta smelt. Furthermore, turbidity measurements (Hach Model # 2100P Turbidimeter) were initiated at all stations and 6 supplemental locations in the Sacramento Deepwater Ship Channel (SDWSC) were added to the survey to target delta smelt.

In 2010, sampling will continue to separate heads and bodies of a subset of delta and longfin smelt. Up to 20 striped bass, Mississippi silverside and threadfin shad per station will be preserved in formalin for diet and condition analyses. In addition, the combined mysid and

Clarke-Bumpus (CB) tows will again be conducted at a subset of 10 stations positioned along a transect from the lower Sacramento River through Suisun Bay. These stations overlap the fall distributions of delta smelt and age-0 striped bass. Additionally, we will continue the visual survey technique started in 2007, ranking the density of *Microcystis* observed at each station. The same technique is also used by the Environmental Monitoring Program (EMP).

Time period: Sampling is conducted monthly from September through December and takes 2 weeks to complete.

Resources required:

Cost: The 2010 FMWT budget is $22,000 from POD sources.

Principal Investigator (PI)(s): Randy Baxter, Steven Slater and Dave Contreras (DFG)

Contract needed / in place: Reimbursable contracts with DWR and USBR in place.

Contract manager(s): Rich Breuer (DWR), Erwin Van Nieuwenhuyse (USBR) and Kelly Souza (DFG)

Term of contract: July 1, 2007–December 31, 2010 (DWR) and through December 31, 2011(USBR).

Personnel: The field component of this project requires 1 boat operator, 1 biologist, and 1 scientific aide. The laboratory component requires numerous personnel for preseason preparation, fish identification, data validation, diet and condition procedures, stomach content analysis and zooplankton processing.

Equipment: A boat with davits and hydraulics appropriate to pull a midwater trawl net (such as the *R/V Scrutiny)*, laboratory facilities, warehouse space, formalin, ethanol, and suitable containers for sample collection and preservation.

Deliverables and dates:

- Monthly survey indices will be calculated and checked by the end of each month.
- Annual indices (January 2011).
- Database and flat file of species catch per tow (February 2011).
- Status and trends article for the IEP Newsletter (spring 2011).
- Trends in distribution and abundance of jellyfish will be examined for data collected since 2001.
- Zooplankton and mysid identification has been delayed by lab staff shortages. Once identification is complete, catch per unit effort (CPUE) calculations will be completed and the data will contribute to the fish and food item match–mismatch analysis, which has been temporarily removed from the work plan.

Comments: The FMWT Survey collected delta smelt and striped bass for otolith and histopathology investigations, but did not collect sufficient numbers of either to support all the projects in 2005 - 2007, so additional field collections were necessary. Targeted supplemental sampling for fishes is not planned in 2010 due to smelt collection restrictions. This survey currently reports annual abundance indices for 6 fishes and has collected count data on jellyfish since 2001. The ratio of same-year FMWT to the Summer Townet Survey (TNS) indices for age-0 striped bass is used as an index of summer survival (Stevens et al., 1985).

Summer Townet Survey

IEP 2010-007

Point person: Randy Baxter (DFG)

Lead Agency: DFG
Questions: What is the relative abundance of striped bass and delta smelt? Can these data be used to estimate apparent mortality? How are juvenile striped bass and delta smelt distributed in relation to potential food items? Is the density of food items related to fish condition, growth rate or health indices?
Description: The TNS has collected juvenile fishes in the range of 20 to 50 mm since 1959 (Turner and Chadwick, 1972) and currently provides indices of abundance for age-0 striped bass (38 mm index) and delta smelt. Samples are collected using a conical net with a 1.5 m^2 mouth and 12.7 mm (½ in.) stretched mesh nylon lashed to a hoop frame and mounted on skis. Three, 10-minute oblique tows are made against the current at each of the 32 stations located from eastern San Pablo Bay to Rio Vista on the Sacramento River and Stockton on the San Joaquin River.

This survey was expanded in 2005 to include simultaneous zooplankton sampling at each station, water collections for invertebrate toxicity tests (Werner, 2005, section 3e) at a subset of 10 stations, and a water quality profile at every station. Since 2006, water sample collections for invertebrate toxicity were made by directed sampling, which are not part of this survey. In 2006, we began using a YSI 6600 Sonde that collects temperature, depth, dissolved oxygen, turbidity, chlorophyll *a*, conductivity, salinity, pH, date, and time. The Sonde was very slow to respond and time consuming to keep calibrated, so in 2008 it was replaced with a YSI 30 meter that measured temperature and conductivity. Also in 2006, the heads and bodies of delta smelt and striped bass were preserved separately for otolith and histopathological analyses (Bennett, 2005, section 3a ;Teh, 2005, section 3b) or were preserved for diet and condition analyses (Gartz and Slater, 2005, section 3c).

Beginning in 2007 and continuing through 2008, longfin smelt, inland silverside and threadfin shad were collected for diet and condition; the heads and bodies of delta smelt and striped bass were preserved separately for otolith and histopathology analyses; a visual survey technique ranked the density of *Microcystis* observed at all sampling stations and numeric estimation of jellyfish abundance began.

Starting in 2009, turbidity measurements (Hach Model # 2100P Turbidimeter) were taken at each station. In 2010, only a subset of delta smelt and longfin smelt (5/station) will have heads and bodies preserved separately, and up to 5 additional fish of each species along with up to 20 striped bass, threadfin shad, and Mississippi silversides will be preserved whole in formalin for diet and condition.
Time period: Every other week from June through August.
Resources required:

Cost: The 2010 TNS budget is $24,000 from POD sources.

PI(s): Randy Baxter, Steven Slater and Virginia Afentoulis (DFG)

Contract needed / in place: Reimbursable contracts with DWR and USBR in place or in progress.

Contract manager(s): Rich Breuer (DWR), Erwin Van Nieuwenhuyse (USBR) and Kelly Souza (DFG)

Term of contract: July 2010 – June 2011 (DWR) and through December 31, 2011 (USBR).

Personnel: The field component of this project requires 1 boat operator, 1 biologist, and 1 scientific aide. The laboratory component requires numerous personnel for preseason preparation, larval fish identification, zooplankton identification, data validation, length weight procedures, and stomach content analysis.

Equipment: A boat with an A-frame and hydraulics appropriate to pull a sled-mounted townet (such as the *R/V Scrutiny or Munson)*, laboratory facilities, warehouse space, formalin, ethanol, and suitable containers for sample collection and preservation. A Hach Model # 2100P Turbidimeter is used to measure the turbidity of the water at each station.

Deliverables and dates:

- Survey indices for striped bass (38 mm index) and delta smelt (September 2010).
- Status and trends article for the IEP Newsletter (spring 2011).
- Trends in distribution and abundance of jellyfish will be examined for data collected since 2001.
- 2006 and 2007 zooplankton identification and CPUE calculations (December 2010).
- Fish samples collected in 2010 will be provided to researchers along with associated environmental data (November 2010).

Comments: The TNS collected delta smelt and striped bass for otolith and histopathology investigations, but did not collect sufficient numbers of either to completely support those projects in 2005, so additional field collections were necessary and were added in 2006 and 2007. A similar circumstance is expected for out years. TNS catch data are used to calculate the striped bass 38.1 mm index (Turner and Chadwick, 1972) and an annual abundance index for juvenile delta smelt (Moyle et al., 1992).

20 mm Survey

IEP 2010-033

Point person: Randy Baxter (DFG)

Lead Agency: DFG

Questions: What is the abundance and distribution of POD fish larvae and early juveniles, particularly delta smelt and striped bass? Can catches of larval fishes and zooplankton be used to estimate overlap and possibly recruitment success? What do POD fish larvae eat, and are diet related to availability in the environment? Does turbidity effect larval and juvenile delta smelt feeding success?

Description: This survey targets late-stage larval and early juvenile fishes, particularly delta smelt and has historically focused on providing near real-time information on the distribution of young delta smelt to inform water management decisions. More recently, fish and associated zooplankton data collected have become very important in the investigation of food limitation hypotheses. Starting in March or April and continuing every other week through July, 3 oblique tows are made at each of 47 locations in the upper estuary using a conical, 5.1 m long plankton net composed of 1600 micron mesh with a 1.5 m^2 mouth, mounted on a weighted tow-frame with skids (Dege and Brown, 2004). In addition, zooplankton is collected during the first tow at each location with a CB net composed of 150 micron mesh attached to the top of the 20 mm net frame. General Oceanics flowmeters mounted in the mouth of each net provide estimates of volumes (m^3) filtered. Fish and zooplankton samples are preserved in 10% formalin and identified in the lab.

This survey has sampled annually since 1995 and provides near real-time larval/juvenile delta smelt distribution information via the web (http://www.delta.dfg.ca.gov/data/20mm/) and Data Assessment Team (DAT). Samples from 2005 and 2006 provided young delta smelt and longfin smelt for diet analyses and zooplankton data for comparison to diet data (Slater in prep.).

Length data from 1995-2006 contributed to longfin and delta smelt apparent growth analyses. In March 2008, sampling commenced at 6 new north Delta locations to improve spatial coverage. These new locations are permanent additions to this survey.
Time period: Every other week from early March through early July.
Resources required:

Cost: The budget for the 2010 20 mm Survey is $488,000 from non-POD sources.
PI(s): Bob Fujimura, Julio Adib-Samii (DFG)
Contract needed / in place: In place.
Contract manager(s): Rich Breuer (DWR), Erwin Van Nieuwenhuyse (USBR), Kelly Souza (DFG)
Term of contract: July 2010 – June 2011 (DWR) and through December 31, 2011 (USBR).
Personnel: When the survey starts in late March, it will run 2 boats for the first 3 days and a single boat for the remaining day of survey. Each boat requires 1 boat operator, 1 lead person (biologist, lab assistant or well trained scientific aide) and 1 scientific aide. Numerous lab personnel are needed for preseason preparation, lab processing of samples, and zooplankton and larval fish identification. In 2010, the 20 mm Survey employed 8 fulltime scientific aides to cover laboratory and field personnel needs.
Equipment: This project requires the use of the *R/V Munson* and *R/V Scrutiny* or *RV Beowulf*. Wet lab space is required to process approximately 1,300 larval fish samples and 432 zooplankton samples that are collected throughout the field season. A Hach Model # 2100P Turbidimeter is used to measure the turbidity of water at each station.

Deliverables and dates:

- Larval and juvenile fish distribution data will be posted to the web within 72 hours of field sampling.
- Weekly tabular summaries of smelt catch per 10,000 m^3 will be distributed to the Smelt Working Group (SWG) and DAT.
- Weekly data summaries will be posted in graphic and tabular form to the 20 mm Survey webpage (http://www.delta.dfg.ca.gov/data/20mm/).
- Highlights article for the IEP Newsletter describing the survey outcome, abundance and relevance of the sampling (spring 2011).
- Relational ACCESS database (December 2010).

Comments: Beginning in 2008, the 20 mm Survey went from a 6 day to a 7 day sampling schedule because of the addition of 6 new north Delta stations. This addition, along with the implementation of the state furlough program, and the need to reduce weekend and overtime work, forced several sampling regime changes. Prior to 2008, each bi-weekly survey was conducted by 1 boat over 5 – 6 days. In 2008, each bi-weekly survey was conducted by 2 boats for the first 2 days and 1 boat for the remaining 3 days of survey. In 2009 and 2010, sampling was conducted by 2 boats for the first 3 days and 1 boat for the remaining day of survey. The 2010 sampling schedule will remain in place for the 2011 field season. In 2010, turbidity readings (in Nephelometric Turbidity Units (NTU)) were taken at each sampling station. Turbidity measurements will be permanently added to the 20- mm protocol.

Spring Kodiak Trawl

IEP 2010-088
Point person: Randy Baxter (DFG)

Lead Agency: DFG

Questions: This survey was developed to identify and monitor the distribution and relative abundance of adult delta smelt throughout the upper estuary during winter and spring. Two other main goals of the survey are (1) to determine gender ratios and (2) to determine stages of sexual maturation of the adult delta smelt population and (3) how male and female maturation varies in time and space. In 2010, we began addressing the question, “Does turbidity effect adult delta smelt migration?”

Description: The Spring Kodiak Trawl Survey (SKT) samples monthly beginning in January and continuing into May. Each monthly Delta-wide survey takes 4-5 days and samples 40 stations from the Napa River to Stockton on the San Joaquin River and Walnut Grove on the Sacramento River. Delta-wide surveys are conducted to locate the areas of adult delta smelt concentration. Historically, Delta-wide surveys were followed by a supplemental survey 2 weeks later that sampled areas intensively for high delta smelt concentration to estimate the proportion of male and female delta smelt and their maturity stages. To minimize take of spawning adults, supplemental surveys are now only conducted under the recommendation of the SWG and the approval of managers. A standard Kodiak trawl, with a mouth opening of 25 ft. by 6 ft., overall length of 65 ft., and 1/4 in. cod-end mesh is used to make 10-minute surface tows at each station. The catch is speciated, enumerated, and measured. Each adult delta smelt is examined onboard for sexual maturity, given a unique alpha-numeric identifier, and dissected for preservation. Quality assurance and control (QA/QC) measures are performed on preserved delta smelt in the laboratory for maturity stage.

Resources required:

Cost: The 2010 SKT budget is $282,000 from non-POD sources.

PI(s): Bob Fujimura and Julio Adib-Samii (DFG)

Contract needed / in place: In place.

Contract manager (s): Kelly Souza (DFG), Erwin Van Nieuwenhuyse (USBR) and Rich Breuer (DWR)

Term of contract: July 2010 to June 2011 (DWR) and through December 31, 2011 (USBR).

Personnel: Each 4 or 5 day survey requires 2 boats, 2 boat operators, 1 biologist and 1 scientific aide. The biologist, assisted by permanent and seasonal staff, is responsible for preseason preparation, lab processing of samples, and fish identification and archiving. In 2010, the Smelt Larva Survey shared 5 fulltime scientific aides with the SKT to cover laboratory and field personnel needs.

Equipment: This project requires the use of the *R/V Munson*, *R/V Scrutiny* or *R/V Beowulf,* as well as a suitable “chase boat” similar to 1 of the Kvichaks. Wet lab space is required to process no fewer than 200 fish samples that are collected throughout the field season. A Hach model # 2100P Turbidimeter is used to collect turbidity measurements from each station.

Deliverables and dates:

- Project staff provides partial tabular summaries of delta smelt catch by station for weekly use by the SWG and the DAT.
- Monthly data summaries will be posted in graphic and tabular form to the SKT web page (http://www.delta.dfg.ca.gov/data/skt/).
- A Highlights article for the IEP Newsletter will describe the survey outcome and relevance of the sampling (spring 2011).

- Relational ACCESS database, complete with fish and environmental measurements (December 2010).

Comments: There are no planned departures from 2010 protocol scheduled for the 2011 field season.

Directed Field Collections

IEP 2010-089

Point person: Randy Baxter (DFG)

Lead Agency: DFG and DWR

Questions: There are no questions related to the Directed Fish Collections effort. Questions are listed under the project description that the fish are being collected for elements 2010-040, 2010-060, 2010-061, 2010-062, and 2010-131.

Description: In 2005 and 2006, directed, short-term field collections were used to increase the number of delta smelt and striped bass available for otolith analyses and histopathological studies, collect threadfin shad and longfin smelt for disease and histopathological studies (Foott et al., 2006), provide samples of POD fishes for diet and condition, and collect water samples from 15 locations within the upper estuary for invertebrate and fish toxicity tests. Sampling efforts were made once or twice a month to increase the numbers of target fish collected and to allow time for field examination of larval and young juvenile fishes.

In 2007, delta smelt were removed as a target organism to reduce IEP's overall take of these fish. However, longfin smelt, striped bass, threadfin shad and water for both invertebrate and fish toxicity tests were still collected. In 2009, directed field collection effort was used to provide supplemental sampling of the SDWSC for delta smelt from spring through early winter and support field work for the "Use of Acoustics to Estimate Trawl Openings" (see 2010-131). In 2010, directed collections effort will be used for field work associated with the "Use of Acoustics to Estimate Trawl Openings."

Time period: As needed and when staff and boats are available. For water collections, sampling will take place 4 days per month, targeted fish sampling can be up to 2 days per month and gear evaluation (2010-131) can be 4 – 10 days per year.

Resources required:

Cost: The 2010 IEP budget for Directed Field Collections is $68,000 from POD sources.

PI(s): Dave Contreras, Jennifer Messineo, Steven Slater and Randy Baxter (DFG)

Contract needed / in place: Near execution as of August 16, 2010.

Contract manager(s): Erwin Van Nieuwenhuyse (USBR) and Kelly Souza (DFG)

Term of contract: April 1, 2010 – December 31, 2013 (when executed).

Personnel: The water sampling requires 1 boat operator and 1 crew member from the participating research group, while fish sampling requires 1 boat operator, 1 scientific aide or biologist and 1-3 researchers from the participating research group. In addition, the point person contributes substantial time coordinating logistics for PIs and field crews.

Equipment: a 25-42 ft. vessel (or 2 vessels for Kodiak Trawling) capable of deploying trawl gear for net mouth dimension measurement ("Use of Acoustics to Estimate Trawl Openings").

Deliverables and dates: See specific project descriptions listed above for this information.

Comments: None.

Smelt Larva Survey

IEP 2010-096

Point person*:* Randy Baxter (DFG)

Lead Agency: DFG

Questions: In 2005 and 2006, we addressed the question, "Can the distribution of larval delta smelt be effectively determined using surface-oriented plankton nets when compared to catches from traditional ichthyoplankton gear and methods?" In 2007, we addressed the question, "What is the vertical distribution of newly hatched larval delta smelt over a 24 hour time period?" The data collected to answer this question has not yet been analyzed. In 2009 and 2010, we addressed the question, "What is the distribution and relative abundance of larval longfin smelt in the upper San Francisco Bay and Delta?" An upper estuary-wide survey that provides near real-time distribution data for longfin smelt larvae in the Delta, Suisun Bay and Suisun Marsh was initiated. These data are used by agency managers to assess vulnerability of longfin smelt larvae to entrainment in south Delta export pumps. We also began collecting turbidity measurements to better understand the role that turbidity or water clarity might have on larval smelt feeding success.

Description: In 2005 and 2006, this survey, under the name Delta Smelt Larva Survey (DSLS), investigated whether surface-oriented, fine-mesh nets could be towed along with traditional 20 mm Survey gear (IEP,1987; Rockriver, 2004; Dege and Brown, 2004) and improve detection of small larval delta smelt since they can pass through the mesh of the 20 mm Survey net. Two field seasons of data collection (2005-2006) were conducted as the basis for evaluating the surface oriented nets with those towed obliquely. However, the January through mid-March sampling period did not overlap with the delta smelt hatching period (only 4 were collected in both years).

A third season in 2007 focused briefly (2 days) on 2 locations where delta smelt were believed to have spawned and when larvae were believed to be present. Based on 2007 sampling, surface-oriented larva tows seemed reasonably efficient, but the relatively small volume sampled only improved detection of larvae for 1 of 7 surveys when compared to standard 20 mm Survey methods. The alternatives, conducting two oblique tows in succession or 2 separate surveys for larva and 20 mm fish, were not feasible with current staff and boats. In 2005 and 2006, sampling began in January and early February to facilitate the capture of larval longfin smelt, and included concurrent collection of zooplankton samples at the 41 20 mm Survey stations plus 3 additional locations in the main channel of central and eastern San Pablo Bay. In 2007, sampling was limited to 2 days (April 16-17) when 10 tows during daylight and 10 tows after dark were made at each of the 2 locations. Sampling was not conducted in 2008.

In 2009, sampling was reinitiated under the name Smelt Larva Survey (SLS) and began in the first 2 weeks in January and repeated every other week through the second week in March targeting longfin smelt larvae. Each 4-day survey consists of a single 10-minute oblique tow conducted at each of the 35 locations using an egg and larva net. The 505 micron mesh net is hung on a rigid, U-shaped frame attached to skis to prevent it from digging into the bottom when deployed. The net mouth area measures 0.37 m^2. Immediately after each tow, juvenile fishes are removed, identified, measured and returned to the water and the remaining larvae are preserved in 10% formalin for identification. No changes in the 2009 protocol occurred in 2010 except sampling was extended into April. This survey will be ongoing in its current form.

Time period: Every other week from early January through early July (2005-2006), 2 days in April (2007), every other week from early January through mid-March (2009), and every other week from early January through April (2010).

Resources required:

Cost: The 2010 SLS budget is $269,000 from POD sources and $201,000 from non-POD sources.

PI(s): Bob Fujimura and Julio Adib-Samii (DFG)

Contract needed / in place: In place.

Contract manager(s): Kelly Souza (DFG), Erwin Van Nieuwenhuyse (USBR) and Rich Breuer (DWR)

Term of contract: July 2010 –June 2011(DWR) and through December 31, 2011 (USBR).

Personnel: Each 2-day survey requires 2 boats, 2 boat operators, 1 lead biologist and 1 scientific aide per day. Numerous lab personnel are needed for preseason preparation, lab processing of samples, and larval fish identification. In 2010, the SLS employed 5 fulltime scientific aides to cover laboratory and field personnel needs.

Equipment: This project requires the use of the *R/V Munson* and *R/V Scrutiny* or *R/V Beowulf*. Wet lab space is required to process approximately 250 larval fish samples that are collected throughout the field season. A Hach model # 2100P Turbidimeter is used to collect turbidity measurements from each station.

Deliverables and dates:

- Distribution data, particularly larval longfin smelt, will be posted to the web within 72 hours of field sampling.
- Weekly tabular summaries of smelt catch and catch per 1,000 m^3 will be distributed to the SWG and the DAT..
- Weekly data summaries will be posted in graphic and tabular form to the SLS webpage (http://www.delta.dfg.ca.gov/data/sls/).
- A Highlights article for the IEP Newsletter describing the survey outcome and relevance of the sampling (spring 2011).
- A relational ACCESS database complete with fish and environmental measurements (December 2010).

Comments: The 2005 and 2006 Delta Smelt Larva Survey replaced the North Bay Aqueduct monitoring on a pilot basis as required by the USFWS 2005 Operations Criteria and Plan (OCAP) Biological Opinion for delta smelt. The SWG designed this survey as a 2-year trial. Protocol and methods developed in 2005 were used in 2006. Surface tows proved ineffective for larval delta smelt (unpublished DFG data), so the USFWS asked the SWG to modify the sampling design for 2007, wherein oblique tows using standard larval sampling gear (plankton net composed of a 500 micron mesh possessing a mouth 0.37 m^2 attached to a skid mounted frame) were compared with traditional 20 mm sampling. The sampling for delta smelt larva in 2007 was guided by catches of ripe and spent adult delta smelt that were caught in the SKT. SLS sampling was not conducted in 2008. Sampling was reinitiated in 2009 specifically to provide information on the distribution of larval longfin smelt and their potential vulnerability to entrainment in south Delta exports as part of the minimization measures during the state candidacy period as a threatened species. The 2010 SLS was mandated by the CA DFG State Water Project (SWP) longfin smelt incidental take permit (ITP) (2081). There is no planned departure from 2010 protocol for the 2011 season.

II. On-going Studies

Development and Implementation of Life-cycle Models of Striped Bass and Longfin Smelt in the Bay-Delta Watershed

IEP 2010-038

Point person: Ted Sommer (DWR)

Lead Agency: UCD

Description: Recent declines in the abundances of several pelagic fish species in the Bay-Delta have increased the need for data-supported quantification of the relationships between dynamics of the striped bass and longfin smelt populations and the ecosystem components that affect striped bass and longfin smelt. To better explore these dynamics, a striped bass individual-based life-cycle model (IBM) was developed. More recently, the striped bass population life-cycle model has been extended and modified to be applicable to longfin smelt in the Bay-Delta. Both models are at points where different scenarios could be run through them. An example of potential scenarios include effects of temperature, food web shifts, diversions/operations, modified habitat preferences, contaminant accumulation, mortality rates, peripheral canal, and changes in slot limits of the adult fishery. The original IBM contract ended in February 2009 and a 2 year amendment began in March 2009. The remaining duration of the amendment includes the following tasks:

- Task 1: Longfin smelt abundance measures and rate expressions for specific life-stage processes (e.g., growth, mortality, and fecundity) have been obtained from all permissible and existing data sources. Bioenergetics rate parameters are currently based upon Lantry and Stewart's (1993) work with rainbow smelt in the Great lakes, however a separately funded study will be providing bioenergetics rate parameters specific to longfin smelt in the Bay-Delta. This longfin smelt IBM will be applied to explore the relative significance of specific factors influencing population numbers of longfin smelt and in the prioritization of future data collection.
- Task 2: In February 2010, a series of scenarios was developed to be run in the striped bass IBM. The cumulative goal of these scenarios is to explore the cause of the apparent disconnect between the FMWT index and the adult striped bass abundance index. To fully explore this disconnect, the IBM is being applied under a variety of scenarios, which include evaluating the effect of changes in sex ratios, changes in various life-stage specific mortality rates and changes in spawning patterns.

Time period: The completion date of this project is June 2011.

Resources required:

Cost: $125,000 (DWR → UCD)

PI(s): Frank Loge (UCD)

Contract needed / in place: In process.

Contract manager(s): Erwin Van Nieuwenhuyse (USBR) and Rich Breuer (DWR)

Term of contract: TBD

Personnel: Tim Ginn, Kenneth Rose, Arash Massoudieh, and Kai Eder

Equipment: This is a data mining exercise.

Deliverables and dates:

- Progress report, Delta Science conference presentation (September 2010).
- Progress report, IEP newsletter article and presentation (March 2011).
- Submission of 3 manuscripts, computer codes for each model, supporting documentation explaining use, inputs and outputs (June 2011).

Modeling the Delta Smelt Population in the San Francisco Estuary

IEP-related 2010-041
Point person: Anke Mueller-Solger (DSC)
Lead Agency: SFSU-RTC, LSU, Stanford and UCD
Questions: What are the best management strategies for conserving this species?
Description: This element was designed to develop and test 3 different modeling approaches for looking at delta smelt population dynamics. The modeling approaches can be generally characterized as particle tracking, matrix projection and individual-based. The purpose of these models is to evaluate how environmental conditions influence population vital rates, which then determine how the modeled population responds.
Time period: 2006-2010
Resources required:

Cost: This contract was not reinstatned from the 2008 bond freeze. No funding is allocated to it in 2010.
PI(s): Karen Edwards and Wim Kimmerer (SFSU), Bill Bennett (UCD), Kenny Rose (LSU), Stephen Monismith (Stanford)
Contract needed / in place: Cancelled (see comment below).
Contract manager(s): Shem Ayalew (DSP)
Term of contract: 3 years, beginning in 2006 and expiring on March 31, 2009.
Personnel: Karen Edwards (SFSU)
Equipment: None, this is a modeling exercise.

Deliverables and dates: Originally listed: papers on the individual-based model, matrix modeling and particle tracking. Due dates no longer relevant (see below).
Comments: The bond freeze in late 2008 ran through the end of the contract and DWR elected not to reinstate the contract. We are currently closing out the project even though it is incomplete. We still intend to produce the papers originally promised, but there is no funding to do so. Hence, we must do so on our own time and it will have lower priority than funded projects.

Estimation of Pelagic Fish Population Sizes

IEP 2010-043
Point person: Pete Hrodey (USFWS)
Lead Agency: DFG, DWR, USBR, consultants and contractors
Questions: What are the most efficient regions (strata) for each target species sampled by the TNS, FMWT and Kodiak surveys? Do fixed sampling stations in a highly tidal system approximate random distributions? What are the population sizes for each of the target pelagic species? Should strata variance be calculated based upon a normal distribution? How can long-term monitoring data be used to provide better information to managers regarding trends in biological resources? Additional questions will be developed over time.
Description: Except for adult striped bass, the status of pelagic fish populations has primarily been assessed using relative abundance indices. IEP has been reluctant to translate these data into population estimates since gear efficiencies are unknown for each of the sampling programs, fish distribution tends to be patchy, and surveys do not have random site selection, likely adding substantial variability. Other approaches for pelagic fish population estimation are unreasonable (e.g., direct counts, mark-recapture, and change in ratio). However, the POD effort would benefit

greatly from at least crude population estimates, allowing calculation of mortality rates and population modeling. The development of mean-density expansion estimators based upon stratified random trawl sampling represents the most practicable alternative. As initial steps to estimate population size, Bennett (2005) has used the TNS and FMWT data and Miller (2005) has analyzed the Kodiak trawl data. This element will:

- Build upon earlier efforts to develop population estimates for as many of the target pelagic species as possible, beginning with delta smelt. Refinements of these efforts may include the use of known salinity and temperature effects on target species distributions, updated bathymetry and the particle tracking models to: (a) post-stratify survey data (i.e., set more efficient region boundaries); (b) improve habitat volume estimates represented by fixed stations and regions for each of the surveys; and (c) test the assumption of randomness in the data.
- Study designs for gear evaluation including development of mesh retention probabilities, gear avoidance measures and information on vertical and lateral distributions.
- IEP/POD statistical and analytical support – time to assist agency researchers with study design and analysis questions.
- NCEAS participation and modeling that incorporate delta smelt life history information, information from past and future special studies examining horizontal and vertical distribution behavior and multiple long-term monitoring data sets into a single population model.

Time period: 2008-2010
Resources required:
    Cost: $188,000 in 2010 from POD sources.
    PI(s): Ken Newman (USFWS)
        Contract needed / in place: Reimbursable contracts are in place for 2010.
        Contract manager(s): Erwin Van Nieuwenhuyse (USBR) and Rich Breuer (DWR) and John Netto (USFWS)
        Term of contract: 5-year reimbursable with annual modifications.
    Personnel: Wim Kimmerer (SFSU), Bill Bennett (UCD), Fred Feyrer (USBR), Jim Thompson and Ralph MacNally (Monash University), Wendy Meiring (UCSB)
    Equipment: None
Deliverables and dates: Life history model for some of the fish populations, beginning with delta smelt.
Comments: Although there are substantial obstacles to measurement of population sizes, the recent efforts of Bennett (2005) and Miller (2005) provide a reasonable foundation for future work. Newman's involvement with IEP/POD is anticipated to be long-term, during which time tasks will evolve. For 2010, substantial new tasks will be reviewed by the POD management team (MT) and when approved forwarded to Newman through Kim Webb with an indication of relative priority.

Zooplankton Fecundity and Population Structure

IEP 2010-044
Point person: Anke Mueller-Solger (DSC)
Lead Agency: SFSU-RTC
Questions: Has there been a downward shift in egg production and/or nauplius survival that resulted in lowered ratios of copepodites to adults? Has there been a change in copepodite

survival? What is the biomass of individual zooplankton species, and how has the zooplankton community biomass changed over time?

Description: This work plan element consists of 2 parts:

- The continuation of an analysis of *Pseudodiaptomus forbesi* and *Eurytemora affinis* life stage structure and fecundity from archived zooplankton samples (1996-2005) and associated water temperature data. The goals are to determine whether the recent increase in *Corbula* abundance was associated with an increase in mortality of sub-adult (i.e., copepodite stage) *P. forbesi* and *E. affinis*, and/or a reduction in adult *P. forbesi* and *E. affinis* fecundity.
- The determination of the biomass of zooplankton species and their life stages using laboratory analysis of dry weight and carbon content of freshly collected specimens from the San Francisco Estuary. The goal is to provide species-specific biomass conversion factors that will then allow for more appropriate and realistic analysis of biomass, production, and consumption trends and comparisons with other estuaries.

Time period: 2006-2010

Resources required:

Cost: $41,000 in 2010 from POD sources.

PI(s): Wim Kimmerer (SFSU)

Contract needed / in place: In place.

Contract manager(s): Ted Sommer

Term of contract: Through December 30, 2010.

Personnel: SFSU

Equipment: None

Deliverables and dates:

- Year 1 progress report will be provided as 1or more IEP Newsletter articles or manuscripts, depending on the results to date (October 2010).
- Present preliminary results at Delta Science Conference (October 2010).
- Final reports, which will comprise draft manuscripts for submission to journals or the IEP Newsletter (October 2010).

Comments: We have completed analysis of a selected set of zooplankton samples; once QC measures on the data are complete, we will begin analysis of mortality patterns. Biomass analyses are about half complete, but have been delayed several times by instrument problems and staffing issues.

Phytoplankton Primary Production and Biomass in the Delta

IEP 2010-045

Point person: Anke Mueller-Solger (DSC)

Lead Agency: UCD, DWR-DES

Questions: Is there a signal of ammonium discharge from the Sacramento Regional Wastewater Treatment Plant (SRWTP) that can be discerned in the annualized fish indices? Is there a signal of ammonium concentration in estuary waters that can be discerned in these same indices?

Description: It has been suggested that total ammonium and/or free ammonia affect biota in the Delta through inhibition of physiological processes of plankton and higher organisms. This hypothesis has been forwarded on the basis of experimental evidence and general knowledge of ammonia and ammonium toxicity. As there are so many processes at work in the Delta, it is also necessary to show that this specific process

manifests in the long-term variability of Delta population abundances. Otherwise, the hypothesis may be true, but the ecological implications will be insignificant. This study will (1) review existing studies underlying the ammonium hypothesis, particularly those based on long-term data from the Delta; (2) search for an ammonium wastewater discharge and river concentration signal in the annualized fish indices and related data such as fish length; and (3) add an algorithm to Jassby's wq software package to calculate the free ammonia (toxic) fraction based on pH (and pH scale), salinity, depth, and temperature, which will be more appropriate for estuarine analyses than ones in common use.
Time period: Ongoing through 2011.
Resources required:
Cost: $35,000 in 2010.
PI(s): Alan Jassby (UCD)
Contract needed / in place: In place.
Contract manager(s): Ted Sommer (DWR)
Term of contract: Through June 30, 2011.
Personnel: Alan Jassby (UCD)
Equipment: None
Deliverables and dates:

- Technical report describing results of the above research (July 2011).
- IEP newsletter article describing results of the above research (July 2011).
- Additional journal publication (letter, comment, note or article) is optional, depending on results.
- A journal article (Winder and Jassby, 2010, in revision) for Estuaries and Coasts and a conference presentation (American Society of Limnology and Oceanography 2010, Santa Fe) have already been completed based on research conducted during July 1, 2009 - June 30, 2010.

Comments: This work is a natural accompaniment to Jassby's current participation in a summary analysis of the long-term water quality data set collected by the USGS for over 30 years in the San Francisco Bay.

Synthetic Analysis of POD data (Workgroups convened by UC Santa Barbara, formerly NCEAS)

IEP 2010-046
Point person: Larry Brown (USGS)
Lead Agency: USFWS, USGS, DFG, DWR
Questions: Erica Fleishman at the Bren School of Environmental Science & Management at UC Santa Barbara (formerly with NCEAS, which also is part of UCSB) assembled working groups to address 3 general questions. What is the role of contaminants in the POD? What are the direct and indirect drivers of system dynamics in the Delta ecosystem? Does the nearshore ocean and San Francisco Bay affect abundance of POD species, and do atmospheric factors affect abundance of invertebrates and fishes in the Bay? More specific questions are being developed by subgroups within each working group. A new group will consider if the changes in the Bay-Delta constitute a regime shift, what alternative future system states might be possible, and what inputs might be required to achieve those states. The existing groups will finish ongoing work after which they will disband or address new questions.

Description: The overall goal for the UCSB-convened working groups is to conduct or guide the integration, analysis, and synthesis of POD and other relevant data and information in a more efficient, sophisticated, unbiased, and synergistic manner than would be possible with local resources alone. The UCSB-convened working groups on system dynamics, contaminants, and ocean-estuary interactions were formed after consultation with the POD MT and the steering committee for the project indicated that these were areas where the working group process could be most helpful to the IEP because of the lack of IEP expertise. Similarly, the topic of regime shift was identified as a new area deserving attention and will likely provide a useful framework for synthesizing the entire POD effort. The effort will tie together and analyze field data, environmental data, operations information and contaminants/bioassay from POD research components and other sources. These efforts will feed directly into POD synthesis/summary reports through Larry Brown and other POD MT members participating in the UCSB-convened workgroups and steering committee.
Time period: Continuation agreement will extend work into 2012.
Resources required:
Cost: $751,000 for 2010 from POD sources.
PI(s): Larry Brown (USGS), Ken Newman and Gonzalo Castillo (USFWS), Fred Feyrer (USBR) and other agency personnel.
Contract needed / in place: Continuation agreement required.
Contract manager(s): Paul Cadrett (USFWS) will manage the UCSB-CESU contract. Other investigators are funded through annual reimbursable contracts with USBR and DWR.
Term of contract: Scientifically sophisticated approaches and defensible conclusions require substantial time. It is possible the IEP/POD-UCSB interaction could continue beyond the term of this contract (2012) if additional issues are identified.
Personnel: Other key staff members include Bruce Herbold (EPA), Anke Mueller-Solger (DSC) and Ted Sommer (DWR)
Equipment: None, these are data-mining efforts.
Deliverables and dates:

- Peer-reviewed journal articles and presentations geared at scientific and lay audiences that are authored by individual POD members of working groups convened by UCSB.
- Final Synthesis Report, lead by Larry Brown, will include material from POD sponsored studies and working groups convened by UCSB.

Comments: Existing staff members from the IEP agencies are redirected, as needed, to work closely with UCSB and the working groups to participate in the synthesis of IEP data as it relates to the POD. All such assignments are cleared through supervisory channels.

Evaluation of Delta Smelt Otolith Microstructure and Microchemistry
IEP 2010-060 and 2010-061
Point person: Randy Baxter (DFG)
Lead Agency: UCD
Questions: Do growth rates of delta smelt vary seasonally or geographically? When and where in the estuary is delta smelt produced?
Description: Analysis of delta smelt otoliths can determine daily growth rate and area of origin. In addition, analysis of otoliths that includes microchemical work can provide detailed

information on fish origin and growth that can be related to histopathology analyses and potentially to ambient water toxicity for 2005 and 2006. This work has been done successfully on delta smelt (Bennett submitted).

Otolith age and incremental growth measures for young fish will be derived through the use of imaging software. Furthermore, otolith weighing and morphometric methodologies will be developed and evaluated for reliability in determining age of adult fish (>300 days post hatch). Chemical composition of otoliths at their core will be measured to provide a micro-chemical “signature” of natal habitat and compared via trace elements and isotopic rations to water samples collected at various locations in the lower rivers and Delta to determine likely region of natal origin. Fish samples for this element will be collected by the SKT, TNS, and FMWT, with supplemental sampling based on availability of boats and crews. In 2010, delta smelt will again be preserved, so otolith microstructure can be examined, but these samples are expected to contribute to a subsequent study.

Time period: Extended through June 30, 2011.

Resources required:

Cost: Estimate is $292,000 from the Ecological Restoration Program (ERP) to process approximately 500-600 samples per year for aging.

PI(s): Bill Bennett, Swee Teh and James Hobbs (UCD)

Contract needed / in place: In place.

Contract manager(s): Mitsuko Grube (DFG)

Term of contract: Through June 30, 2011.

Personnel: Above named investigators and other UCD staff.

Equipment: Equipment for this project has already been purchased.

Deliverables and dates:

Semi-annual reports for 2009 are overdue. The last semi-annual report covered the time period from July 1, 2008 – December 31, 2008.

Comments: This work will be an extension of the delta smelt work (Bennett submitted) and striped bass work carried out by Bennett et al. (1995). This work is part of a larger contract including a histopathological element (2010-061) and a food availability and feeding element (not listed), but similar to the diet and condition work (2010-062), which together provide a comprehensive view and timeline of the relative condition of the fish that we could compare to timing of potential stressors.

Quantitative Analysis of Stomach Contents and Body Weight for Pelagic Fishes

IEP 2010-062

Point person: Randy Baxter (DFG)

Lead Agency: DFG

Questions: What is the feeding ecology of pelagic fishes in the estuary? Is there evidence of reduced feeding success during specific times of the year or in certain parts of the estuary? If so, are these changes associated with changes in growth rate, relative weight or condition?

Description: This study was initiated in 2005 to investigate temporal and spatial differences in the diet composition and feeding success of age-0 delta smelt, striped bass, and threadfin shad that might help explain the pelagic species decline. This list of target fishes has since been expanded to include longfin smelt, Mississippi silversides and American shad. Food habit studies have been done on many of the fish and zooplankton found in the estuary (IEP, 1987; Orsi, 1995; Lott, 1998; Nobriga, 2002; Feyrer et al., 2003). However, many of these studies were done more than 10 years ago and the feeding habits of the local Mississippi silverside and threadfin shad populations have only been studied in a limited geographical range (Grimaldo, 2004).

As evidence that feeding success may be an important issue for survival, initial studies by BJ Miller suggest that delta smelt survival in different parts of the estuary was linked to whether there was co-occurrence of prey. In 2003, IEP started a study of fish length-weight relationships needed to estimate species biomass and to develop a program to monitor trends in relative weight. Collection of length and weight data was expanded beginning in 2005 to include calculation and analysis of fish condition for those fish processed for gut contents. When observations indicated that fish lengths and weight changed over time in preservative, a study was conducted in 2006 and 2007 to evaluate changes and their effect on several measures of fish condition. Work on diet and condition continued in 2006 and 2007, and was expanded to include larval fish collected by the 20 mm Survey and longfin smelt from salvage. In 2010, specimens will be collected through December and will be archived for future investigations or increased sample size when staff time permits. However, work in 2010 will focus on completing lab work, analysis and initial publication. Fish collected from 2010 will be archived for future processing and analysis.

Time period: 2006 - 2010

Resources required:

Cost: $40,000 from POD sources.

PI(s): Randy Baxter and Steve Slater (DFG)

Contract needed / in place: Close to execution as of August 16, 2010.

Contract manager(s): Erwin Van Nieuwenhuyse (USBR) and Kelly Souza (DFG)

Term of contract: April 1, 2010 – December 31, 2012

Personnel: Field collection is conducted by all long-term fish monitoring surveys. Fish are retained after reaching quotas for otolith and histopathology samples; all POD fishes are retained by the San Francisco Bay Study (SFBS) for condition and diet analyses. Laboratory personnel (3 scientific aides and a part time senior lab assistant) are directed in sample processing by a biologist.

Equipment: Current long-term monitoring vessels and gear will be employed; some gear modification may occur for directed sampling. Laboratory equipment is currently available at DFG Stockton.

Deliverables and dates:

- Annual IEP Workshop poster presentation (March 2010).
- Manuscript describing the effects of formalin preservation on the determination of fish condition. Target journal is the North American Journal of Fisheries and Management (NAJFM) (August 2010).
- Draft delta smelt diet and condition manuscript. Target journal is the San Francisco Estuary and Watershed Science (SFEWS) (September 2010).
- IEP Newsletter article about longfin smelt, striped bass and threadfin shad diet composition (December 2010).

Comments: In 2006, examination of parasite load was transferred to researchers conducting histopathological investigations (2006-061, 2006-042). DFG staff will collect samples and process diet information. The IEP has extensive experience with these techniques, but lost leading staff for this work. Lab work was delayed substantially by the loss of a biologist and long delays in hiring scientific aides and senior lab assistants.

Trends in Benthic Macrofauna Biomass

IEP 2010-065

Point person: Karen Gehrts (DWR)

Lead Agency: DWR

Questions: What are the long-term trends in biomass, production and grazing rates of benthic species? How are these changes related to physical-chemical gradients? How do changes in benthic functions, such as production and grazing, affect the pelagic food web?

Description: Over the past 3 decades, the IEP EMP has collected benthos community composition and abundance information at 22 sites, including 4 long-term monitoring stations. Unfortunately, the EMP monitoring did not include measurements of benthic macrofauna biomass. Biomass data are crucial in determining the role of benthic organisms in the ecosystem, especially the feeding potential of various functional groups, potential availability and transmission of contaminants bioaccumulated in benthos, and trends in production as well as the ecological significance of changes in benthic community composition and abundance. The EMP has developed a comprehensive plan to analyze archived benthos samples dating back to 1975, which can be used for biomass estimation using a simple wet-weight method.

The objective of this project is to measure and examine the biomass of benthic organisms collected from the EMP benthic monitoring stations. Currently, staff collects an additional benthic sample and obtains ash-free dry mass for *Corbula amurensis* and *Corbicula fluminea*. This will allow the project team to create site specific biomass conversion factors for historic length data. To accomplish the goal of obtaining and examining complete biomass time series at 2 long-term stations, the Benthic Biomass project has received a grant from DSP to obtain length measurements for stations D4 and D28A from 1976 to the present. Data analysis is conducted in part as part of work plan element IEP 2010-078 and other ongoing EMP data analyses. The USGS will help to characterize long-term trends in biomass at the 2 EMP sites.

Time period: Data for site-specific biomass conversions will be collected on an ongoing basis. Data for the long-term analysis of stations D4 and D28 will continue through 2010.

Resources required:

Cost: Redirected staff from the EMP will be used to accomplish this work. Funding for the analysis of D4 and D28A is from a DSP grant, $40,000.

PI(s): Karen Gehrts (DWR), Wayne Fields (Hydrobiology) and Janet Thompson (USGS)

Contract needed / in place: In place early 2010 (DSP –>DWR).

Contract manager(s): Karen Gehrts (DWR)

Term of contract: Calendar year (CY) 2010

Personnel: Dan Riordan and Tiffany Brown (DWR)

Equipment: Staff will use existing oven, furnace, scale, microscope and computer to determine ash-free dry mass, length to weight conversions and historical shell length data.

Deliverables and dates:

- Final report to DSP (December 2010).
- Delta Science Conference presentation (October 2010).

Comments: Analysis of D4 and D28A invasive bivalve biomass does not depend on the availability of new field data. However, for the determination of site-specific biomass estimates, an additional grab sample needs to be taken during the monthly EMP benthic survey.

Corbula salinity tolerance, distribution and grazing rates

IEP 2010-076

Point person: Ted Sommer (DWR)
Lead Agency: DWR, USGS and SFSU
Questions: What is the salinity tolerance of C*orbula amurensis?* How well do salinity tolerances explain the distribution of *Corbula*? What are regional trends in benthos and grazing rates?
Description: Initial analyses of benthic abundance trends suggest that *Corbula* distribution shifted upstream around 2001, perhaps in response to recent salinity increases during autumn. To better evaluate this hypothesis, we need to develop salinity tolerance information for the clam. This will be performed in a controlled laboratory setting, likely at SFSU Romberg Tiburon Center.
Time period: Mid-2006 - 2010
Resources required:

- Cost: No funds required for 2010.
- PI(s): Jonathan Stillman and Wim Kimmerer (SFSU)
  - Contract needed / in place: Expired
  - Contract manager(s): Ted Sommer (DWR)
  - Term of contract: October 1, 2006 – September 30, 2008
- Personnel: Jonathon Stillman, Adam Paganini, Nathan Miller, and additional student researchers (SFSU).
- Equipment: Several items of equipment used for physiological assays, including a microplate spectrophotometer used in enzyme assays and feeding rate determination, have been purchased.

Deliverables and dates:

- Manuscript representing final report of this work was submitted to Marine Ecology Progress Series (April 2010).
- Revised manuscript will be sent to Aquatic Biology (September 2010). This manuscript, once published, can be summarized as an IEP Newsletter article, if desired.
- Research presented at numerous conferences, including the annual IEP Workshop, Estuarine Ecology Team (EET) meetings, California Estuarine Research Society Conference (CAERS), American Physiological Society Conference (APS), and Bay-Delta Science Conference, from spring 2009 to fall 2010.

Comments: This work explores a range of physiological responses of *Corbula* to environmental salinity and temperature, including thermal tolerance, salinity tolerance, cardio-respiratory and metabolic responses to salinity and temperature, energetics and feeding rates at different salinities, enzyme activities at different salinities, and osmoregulatory physiology. Our research led to a number of interesting findings, including the fact that *Corbula* always hyporegulate their osmotic content, but do so to a greater extent at high salinity, suggesting greater metabolic demands and food intake at high salinity may be related to osmoregulatory costs.

Field Survey of Microcystis Aeruginosa Bloom Biomass and Toxicity

IEP-related 2010-079
Point person: Rich Breuer (DWR)
Lead Agency: DWR-DES, DFG
Questions: Is *Microcystis* biomass or toxicity increasing over time in the Delta? Does *Microcystis* bloom biomass or microcystins toxicity occur in areas important to pelagic fish species in the Delta? What are the long term trends in Microcystis and potential controlling

factors? What are the origins of the *Microcystis* blooms? What environmental factors affect bloom development?
Description: In 2010, phytoplankton sample analysis and data analyses will be conducted to evaluate density, biomass and toxicity data collected during *Microcystis aeruginosa* blooms in the Delta between 2007 and 2008.
Time period: Summer and fall 2007-2011.
Resources required:
Cost: $144,000 in 2010 from Delta Science grant.
PI(s): Peggy Lehman (DWR)
Contract needed / in place: In place.
Contract manager(s): Ted Sommer (DWR)
Term of contract: Through December 31, 2011.
Personnel: This work would be conducted by DWR personnel.
Equipment: None
Deliverables and dates:

- Semi-annual reports submitted by June and December 2009 and 2010.
- Oral progress reports to IEP project work teams by September 2009 and September 2010.
- Oral or poster presentations at the 2009 and 2010 IEP Workshop.
- Post study report to peer reviewed journal and/or published in the summer 2010 IEP Newsletter.
- Protocol for laboratory culture of threadfin shad (August 2010).

Comments: Toxicity analysis will be done by G. Boyer of the State University of New York, an expert on cyanobacterial toxicity. His group has extensive experience in the determination of cyanobacterial toxins and routinely analyzes samples for NOAA, Center for Disease Control (CDC, and other departments of health and conservation for several states. They also participated in the previous surveys. Future analyses may be possible at DFG's Water Pollution Control Laboratory.

Food-web Support for Delta Smelt and Estuarine Fishes in Suisun Bay and Upper Estuary
IEP 2010-082
Point person: Anke Mueller-Solger (DSC)
Lead Agency: SFSU-RTC
Questions: Within the low salinity zone (LSZ) of the northern estuary:
How do benthic grazing, available solar irradiance, and the concentrations and composition of nitrogenous nutrients interact to influence the species composition and production of phytoplankton? How does bacterial production respond to changes in particulate and dissolved organic carbon (POC & DOC) delivered primarily through river flow? What is the role of the microbial food-web in supporting higher trophic levels?
To what extent is copepod production dependent on these alternative energetic pathways (phytoplankton and bacterial production)?
Description: This is a DSP-funded study focused on 2 related topics:

- Topic 1: The threatened delta smelt (*Hypomesus transpacificus*) is now the principal species of concern for management of freshwater flow and diversions in the Delta, and the principal target for restoration in the upper San Francisco Estuary. The abundance of this federally-listed threatened species has been low since the early 1980s and it has not recovered to the point where it can be considered for delisting; indeed, the 2004 abundance index was the lowest on record. Potential reasons for its low abundance are many, but evidence points to the direct and indirect effects of export pumping of freshwater in the south Delta, toxic substances, and low food supply as likely contributing factors. We believe that the feeding environment of delta smelt may be implicated in the continued low abundance of this species. Delta smelt feed for their entire lives on zooplankton, principally copepods, mainly in the brackish waters of the western Delta and Suisun Bay. As outlined in the submitted proposal, copepod abundance is depressed in this region.

- Topic 2: Previous work on the responses of the estuarine ecosystem to inter-annual variation in freshwater flow has demonstrated a decoupling between the abundance of lower trophic levels and that of fish and shrimp (Kimmerer 2002; Kimmerer 2004). This decoupling may imply that variability in food-web support is unimportant to variability of higher trophic levels, but there are some important pieces missing from the puzzle. Chief among these is the fact that the supply of labile organic matter from freshwater to the LSZ varies with freshwater flow and this flux has not been accounted for in analyses of the estuarine food-web.

The funded proposal includes efforts aimed at understanding and possibly improving the food-web supporting delta smelt and other estuarine species.

Time period: 2006-2010
Resources required:
Cost: $162,000 per year from a DSP PSP-funded grant.
PI(s): Wim Kimmerer (SFSU)
Contract needed / in place: In place.
Contract manager(s): Shem Ayalew (DSP)
Term of contract: 3 years
Personnel: Richard Dugdale, Frances Wilkerson, Edward Carpenter, Alex Parker (SFSU); Risa Cohen (Georgia Southern University); Janet Thompson, Francis Parchaso (USGS); George McManus (University of Connecticut)
Equipment: The bulk of the laboratory work will be conducted at Romberg Tiburon Lab.

Deliverables and dates: There are 5 tasks within this element: phytoplankton (task 1), benthic grazing (task 2), bacteria (task 3), microbial foodweb (task 4), and copepods (task 5).

- Tasks 1, 2, 3, and 5 will all produce at least 1 peer-reviewed journal article, at least 1 presentation at the Delta Science Conference, and presentations at the Estuarine Ecology Team and other venues.
- Tasks 3 and 4 will produce a joint paper together.
- All tasks will produce a synthesis article. The target milestone for paper submission is December 2010.

Comments: This project was delayed by the bond freeze. The delay did more than push the project back and caused a serious disruption that has made it difficult to advance to the synthesis stage. Many presentations have been made as a result of this project. At least 5 manuscripts are now in preparation and data are ready for 2 more.

Power Plant Operations

IEP 2010-087
Point person: Ted Sommer (DWR)
Lead Agency: DWR

Questions: What are the characteristics of the cooling water diversions associated with the Contra Costa and Pittsburg power plants, and what effects might they have on pelagic fishes? Have there been recent increases in pelagic fish entrainment?
Description: This study was previously a component of the 2005 work element, "Analysis/summary of recent changes in Delta water operations". Based on the initial data review, we believed that the issue warranted a focused study. The purpose of this element is to closely examine power plant operations to identify whether there were effects strong enough to contribute to the long-term and recent apparent step-change in pelagic fish abundances.
Time period: Ongoing through April 2011.
Resources required:
    Cost: $25,000 from DWR POD sources.
    PI(s): Carol Raifsnider (Tenera Environmental)
        Contract needed / in place: In place.
        Contract manager(s): Steve Bauman (Mirant) manages the contract with Tenera. Funding for Brian Schreier (DWR) is from DWR POD sources.
        Term of contract: Current through 2011.
    Personnel: Brian Schreier (DWR)
    Equipment: None
Deliverables and dates:

- Monthly progress reports detailing entrainment and impingement results, submitted to IEP agency biologists.
- Annual summary report submitted 4 months after laboratory sampling has been completed.

Comments: Entrainment and/or impingement surveys were coordinated to occur during the same time as the FMWT, SKT, TNS and the 20-mm Survey, when the surveys were conducted in the vicinity of the power plants. Monitoring was conducted at a minimum of once a month from November 2007 through October 2009. Two annual reports summarizing results of entrainment and impingement monitoring were submitted. The study plan was amended (Amendment 2) and approved in March 2010. Amendment 2 Entrainment and Impingement Monitoring Program is conducted only during times when the power plants generate electricity and is no longer conducted parallel to IEP sampling.

SAV Abundance and Distribution

IEP 2010-102
Point person: Ted Sommer (DWR)
Lead Agency: USGS and UCD
Questions: Has submerged aquatic vegetation (SAV) increased in the Delta? Has SAV altered the habitat to effect fish populations? Has SAV increased retention of suspended solids to create a less turbid environment, which is less hospitable to delta smelt?
Description: Using hyperspectral imagery, this project will provide annual acreage calculations of SAV and quantify regional distribution trends in the Delta for 2003-2006. Three tasks have been identified: (1) classify SAV in the Delta using Hy Map hyperspectral imagery, (2) create SAV distribution maps in concert with SAV acreage calculations to quantify distribution trends in the Delta, and (3) investigate methodology that will detect and monitor turbidity trends in the Delta using surface and aircraft hyperspectral remote sensing instruments and satellite remote sensing data.

Time period: 2006-2010
Resources required:
Cost: This program has billed remaining funds.
PI(s): Susan Ustin (UCD)
Contract needed / in place: In place.
Contract manager(s): Ted Sommer (DWR)
Term of contract: Through June 30, 2010.
Personnel: Erin Hestir (UCD)
Equipment: Equipment provided by UCD.
Deliverables and dates:

- Oral presentation at CALFED Science Conference, October 22, 2008 (tasks 1 and 2).
- Oral presentation at IEP Workshop, February 28, 2009 (tasks 1, 2 and 3).
- Progress report to DWR, February 28, 2009 (tasks 1, 2 and 3).
- IEP Newsletter article and at least 1 written manuscript for peer-reviewed journal, June 30, 2009 (tasks 1, 2 and 3).
- Poster presentation at State of the Estuary, October 2009 (task 3).
- Oral presentation at IEP Workshop, February 28, 2009 (task 3).
- IEP Newsletter article summarizing results of each task, June 30, 2008.
- Manuscript detailing the method used to create the spatially explicit geographic information system (GIS) layer of SAV, June 30, 2010.

Comments: None

Fish Facility History

IEP 2010-107
Point person: Marty Gingras (DFG)
Lead Agencies: DFG, USBR
Questions: What changes have occurred at the state and federal fish facilities that would change the reported number of salvaged fish?
Description:
This project will identify changes that have occurred at the state and federal fish facilities from 1956 to 2010 that may have impacted the reported number of salvaged fish. However, this investigation will not report on the survival of fish once counted (debris loads in holding tanks and impacts on released fish).
Time period: Through December 31, 2010.
Resources required:
Cost: $50,000 from USBR Operations (non-POD).
PI(s): Jerry Morinaka (DFG) and Brent Bridges (USBR)
Contract needed / in place: N/A
Contract manager(s): Erwin Van Nieuwenhuyse and Ron Silva (USBR)
Term of contract: N/A
Personnel: Above named investigators.
Equipment: No equipment is required for this analysis.
Deliverables and dates:

- IEP technical report describing changes that have occurred at the state facilities (December 2010).

- The federal portion of this element will begin in August 2010 and the target deadline is winter 2011.

Comments: None

Delta Smelt Culture Facility

IEP 2010-108(a)
Point person: Rich Breuer (DWR)
Lead Agency: UCD
Questions: Reliable supplies of all life stages of delta smelt are valuable to management and scientific communities for a number of reasons. Cultured delta smelt provide specimens with known rearing history (required for toxicological experiments), aids research and design of fish screen efficiency and pre-screen losses, allows investigations into basic biology with application to wild populations, and enables the development of a delta smelt refugial population.
Description: This program will collect sub-adult broodfish via purse seine from the wild and spawn, and rear all life stages of delta smelt in the following year in accordance to the Delta Smelt Culture Manual (Baskerville-Bridges et al., 2005). Delta smelt will be housed and reared at the newly expanded Fish Conservation and Culture Laboratory (FCCL).
Time period: Ongoing
Resources required:

Cost: $48,000 available from DWR contract and $881,000 from USBR contract.
PI(s): Drs. Raul Piedrahita, Joan Lindberg and Brad Baskerville-Bridges (UCD)

Contract needed / in place: In place.
Contract manager(s): Rich Breuer (DWR), Erwin Van Nieuwenhuyse (USBR), Joan Lindberg (UCD)
Term of contract: July 1, 2007 to June 30, 2010 (DWR); January 1, 2010 to December 31, 2014 (USBR).

Personnel: UCD personnel.
Equipment: Equipment to rewire the collection, handling, transport and release (CHTR) building, and the purchase of additional chillers will be needed.

Deliverables and dates:

- 5,000 adult delta smelt (>50 mm).
- 10,000 juvenile delta smelt (20-50 mm).
- Annual Production Report (December 2010).

Comments: In 2010, SKT personnel will experiment with artificial gamete stripping of wild-caught delta smelt and cold storage of gametes. If cold-stored gametes prove viable, this will provide a means to introduce additional genetic diversity into cultured delta smelt. These same fish will be sampled for delta smelt genetic testing (2010-135) and be preserved for otolith (2010-060) and histopathology (2010-061).

Quantifying Effects of Naturally Occurring Physical Stimuli on Delta Smelt Behavior

IEP 2010-108(b)
Point Person: Pete Hrodey (USFWS)
Lead Agency**:** UCD
Questions**:** Do juvenile and adult delta smelt discriminate levels (and types) of turbid and saline environments, make behavioral choices based on this information? Does delta smelt show differences in feeding, survival and swimming behavior at several levels and/or types of

turbidity? Does salinity or temperature affect feeding, survival and swimming behavior under optimal turbidity conditions?

Descriptions**:** The study includes the following tasks:

- **Task I: Effect of salinity and turbidity on juvenile and adult delta smelt behaviors:** In the first task, we aim to test whether juvenile and adult delta smelt discriminate levels (and types) of turbid and saline environments and make behavioral choices based on this information. We will develop test equipment (similar to our successful raceway design used in testing larval delta smelt) to try to document residence time (or volitional movements) under conditions where the animals can choose between turbid and clear water, and between saline and fresh water. Identifying volitional responses of the late juvenile and sub-adult life stages to salinity and turbidity and to various types of turbidity will yield practical information regarding the smelt's responses to changes in environmental elements and inform management decisions. We will test delta smelt juveniles and adults in "Y-maze" raceways, with physical variables randomized between arms of the mazes. An additional test apparatus may be explored where fish are tested in a large oval or circular tank in which water velocity could be manipulated to simulate tidal movements (flood, slack, ebb).
- **Task 2: Effects of turbidity, salinity, and temperature on feeding, survival, and behavior of delta smelt:** Building on experiments performed at the FCCL (Baskerville-Bridges et al., 2004), delta smelt at juvenile and early adult stages will be exposed to different levels (NTU) and types of turbidity (phytoplankton, humic acids, suspended sediments/silt) for 1-7 days in a flow-through system. Swimming behavior, feeding and survival will be monitored to assess optimal conditions. Experiments will be performed at different water temperatures or salinities to determine potential interactive effects. Current test protocols will follow those developed at UCD-Aquatic Toxicology Laboratory (ATL) and described in detail by Werner et al. (Final Report to IEP-POD, 2009) for testing with delta smelt larvae at different stages of development. A flow-through system will be used for testing. Upon arrival at UCD-ATL, the transport containers with fish will be placed into a temperature-regulated water bath maintained at 16º C. Glass beakers are used to gently transfer fish from transport containers to replicate exposure tanks. Six fish will be placed into each of the test tanks containing 7 L of filtered hatchery water adjusted to (1) a range of turbidity (0-25 NTU) using phytoplankton, humic acids or silt, and (2) optimal turbidity determined in experiment 1at different salinities/conductivities (150-200 uS/cm, 1.5-2 ppt, 5-8 ppt). Fish will be acclimated to different salinities/conductivities for 2 weeks before the test, and hatchery water and electric conductivity (EC) adjusted hatchery water will be used as control water. During acclimation and testing, fish will be fed 3 times a day with *Artemia*. Water quality parameters (EC, pH, temperature, dissolve oxygen (DO), turbidity and ammonia concentration) will be measured, and dead fish will be recorded and removed daily. At test termination, mortality will be recorded. Half of the fish will be then be fed and gut contents examined subsequently. The other half will be subject to swimming trials.

Time Period**:** June 2010 – June 2011

Resources required**:**

For Task 1:

1. Facilities at the FCCL of UCD, located near Byron, CA.
2. Cultured delta smelt: 2,000-3,000 fish of each life stage, juveniles and adults as follows:

20 delta smelt per behavior test x 2 tests x 30 replicate experimental runs = 1,200 juveniles and 1,200 adults. Estimate double the number of fish for developing techniques, mortalities, and unforeseen complications.

For Task 2:

1. Facilities at the UCD - ATL.
2. Cultured delta smelt: 1,000 juveniles-subadults (140-150 dph); 2 tests, 12 treatments with 4 replicates per test, 6 fish/replicate; 400 fish for developing techniques and unforeseen complications which necessitate repeat testing.

<u>Cost</u>**:** $100,000
<u>PI(s)</u>: Joan Lindberg and Inge Werner (UCD)
<u>Contract needed / in place</u>**:** In place.
<u>Contract manager(s)</u>: Erwin Van Nieuwenhuyse (USBR) and Joan Lindberg (UCD)
<u>Term of contract</u>: January 2010 – December 2014
<u>Personnel</u>: Above named investigators and other UCD staff.
<u>Equipment</u>: No new equipment at this time.

<u>Deliverables and dates</u>**:**

Task 1

- Results will be presented at the Delta Science Conference or annual IEP Workshop.
- Report at termination of project.

Task 2

- Results will be presented at the Delta Science Conference or annual IEP Workshop.
- Report at termination of project.

<u>Comments:</u> This study will complement earlier studies conducted at the FCCL on larval movement and feeding behavior in response to turbidity and incident light. In addition, it follows up on observations made during larval testing at UCD-ATL, indicating that different types of turbidity may influence feeding and swimming activity of delta smelt. If the juvenile and adult smelt show increased residence times and better feeding behavior in turbid and slightly-saline environments, then this would have management implications for habitat protection and hydraulic manipulations of the low-salinity and higher turbidity zone in the Delta.

Striped Bass Bioenergetics Evaluation

IEP 2010-115
<u>Point person</u>: Ted Sommer (DWR)
<u>Lead Agencies:</u> DWR and DFG

<u>Questions:</u> What are the trends in estimated population consumption demand of age-1 and older striped bass? Has age-1 and older striped bass consumption demand decreased more slowly than prey relative abundance/relative biomass?

<u>Description:</u> This element will couple bioenergetics analyses to data provided by element 2010-116 (adult striped bass population dynamics) to estimate the long and short-term (i.e., POD years) trends in consumption demand of striped bass.

<u>Time period</u>: 2010; assuming the population demographic data are available in early 2010.

<u>Resources required:</u>
<u>Cost:</u> $30,000 in 2010 from POD sources.
<u>PI(s)</u>: Marty Gingras (DFG), Gina Bengino (DWR)
<u>Contract needed / in place</u>: Not needed, work will be covered by agency staff.

Contract manager(s): N/A
Term of contract: N/A
Personnel: Jason DuBois (DFG)
Equipment: None required – this is a data mining/data analyses effort.
Deliverables and dates: Draft manuscript for publication (December 2010).
Comments: None

Long-term Sources and Early Warning Signals in Turbidity Monitoring Data
IEP 2010-126
Point person: Ted Sommer (DWR)
Lead Agency: USGS
Questions: (1) Do smelt move towards the water diversions because they are following specific turbidity pulses, or because their habitat has shifted towards the pumps? (2) Where are the sources of turbidity for water exported by the SWP and Central Valley Project (CVP)?
Description: This study will determine the origin, movement, and extent of turbidity pulses that affect delta smelt behavior and salvage at the pumps. Recent analyses by DWR and Metropolitan Water District show that delta smelt salvage counts increase at the CVP and SWP during periods (i.e., days) immediately following the first significant storm event in the basin. Though the mechanism is unclear, water turbidity is a good measure of the storm event and the data indicate that salvage typically begins when turbidities increase over 12 NTU. As a result of a recent court ruling, this finding was incorporated into water project operations as a tool to help reduce fish losses. However, the sources of turbidity are not well understood. A more comprehensive source of long-term turbidity data could help elucidate the question as to whether fish are following a turbidity gradient to the salvage facilities or whether they are migrating in response to a flow pulse. Data sources will focus on USGS continuous suspended-sediment concentration time series at Rio Vista, Jersey Point, Threemile Slough, and Stockton from 1998-2005.
Time period: 12 months.
Resources required:
Cost: Funding for this element was obligated with previous year funds.
PI(s): David Schoelhamer and Scott Wright (USGS)
Contract needed / in place: In place.
Contract manager(s): Erwin Van Nieuwenhuyse (USBR) and Darcy Austin (USGS).
Term of contract: 12 months, expiring 9/30/2011.
Personnel: Tara Morgan (USGS) in collaboration with Lenny Grimaldo (USBR).
Equipment: None
Deliverables and dates:

- Process 2003-2005 suspended sediment (SSC) data.
- Develop relations between turbidity and SSC from the Bay Delta and Tributaries (BDAT) database for specific sites and seasons relevant for delta smelt.
- Develop statistical models of turbidity at USGS sites for 1993-1997.
- Define origin, movement, and extent of key turbidity pulses identified by Lenny Grimaldo (USBR) from 1993-2005.
- Collaborate with Lenny Grimaldo (USBR) on peer reviewed manuscript.

Comments: Processing of 2003-2005 SSC data and development of turbidity and SSC relations is proceeding.

Contaminants and Biomarkers Work

IEP 2010-127

Point person: Rich Breuer (DWR)

Lead Agency: UCD

Questions: Is water in ecologically sensitive areas of the Delta toxic to delta smelt and other pelagic fish and their prey? What are the causes and sources of water column toxicity in areas of the Delta and how do they affect fish species of concern? How sensitive are Delta species to contaminants in comparison to surrogate species commonly used in toxicity testing? Is it meaningful to use surrogate species for toxicity monitoring in the Delta? Are contaminants associated with wastewater treatment effluents affecting fish species of concern? Is there a relationship between toxicity results and other POD study components, such as histopathological examination of fish and Microcystis blooms?

Description: The overall goal of this study is to assess the potential for contaminated water to contribute to the observed declines of pelagic species in the Delta. The study is designed to build from the results of the 2006 and 2007 Delta-wide monitoring project, which investigated toxicity of Delta water samples to invertebrates and early life stages of fish species of concern.

The 2009 – 2010 study will intensify toxicity testing in the Cache Slough, lower Sacramento, Suisun Marsh and Suisun Bay areas. Like the 2006 and 2007 study years, if toxicity is detected, toxicity identification evaluations (TIEs) and chemical analysis will be used to identify toxicant(s). *In situ* tests with delta smelt, fathead minnow or inland silversides, and *Hyalella azteca* will be conducted at Hood on the Sacramento River, and Rough and Ready Island on the San Joaquin River. This study will generate sensitivity data (in the form of 96-h LC50, EC50, no observed effect level (NOEC), and lowest observed effect level (LOEC)) and compare sensitivity of Delta species with that of standard toxicity test species for *Pseudodiaptomus forbesi*, *Eurytemora affinis*, *Ceriodaphnia dubia*, *Hyalella azteca*, delta smelt, and fathead minnow or inland silverside for select chemicals. Lastly, molecular biomarkers developed for striped bass in 2006-2007 will be used to detect and quantify stress responses in field-collected specimens from 2005-2009 to detect sublethal toxic effects and help identify the causative chemical(s) or other stressors. Biomarker development for delta smelt will continue with the immediate aim of selecting appropriate biomarkers for use in field and *in situ* studies, as well as in laboratory studies to determine cause and effect.

Time period: This study will be completed in 2010.

Resources required:

- Cost: $453,000 from POD sources in 2010.
- PI(s): Drs. Inge Werner and Swee Teh (UCD)
    - Contract needed / in place: In place.
    - Contract manager(s): Ted Sommer (DWR)
    - Term of contract: Through June 30, 2010.
- Personnel: UD Davis staff, Kevin Reece (DWR)
- Equipment: Equipment will be provided by UCD.

Deliverables and dates:

- Semi-annual progress reports will be submitted to the DWR contract manager and will include the number of samples processed, number of samples analyzed, results and a timeline for the completion of the analyses.
- Oral progress reports will be given to the IEP project work teams (September 2009 and 2010).
- Annual IEP workshop presentation (February 2009 and May 2010).
- A post-field progress report that describes the study and outcome to a peer-reviewed journal and/or published in the IEP Newsletter (summer 2009).

Comments: This project is dependent on the ability to obtain 5,000 – 6,000 delta smelt larvae aged 30 – 90 days each year for the toxicity testing and sensitivity studies, and 1,000 40 – 45 day old larvae for tests with ammonia and wastewater treatment effluent from Sacramento River water.

Feasibility of Using Towed Imaging Systems

IEP 2010-130

Point person: Ted Sommer (DWR)

Lead Agency: USBR

Questions: Are towed video imaging systems a feasible technique for measuring the abundance and distribution of pelagic fishes in the Delta and San Francisco Estuary? If so, what species, life stages, and regions would be most suitable for this technique?

Description: Trawls presently form the foundation of IEP fish monitoring. Although these gear types have proved exceptionally useful, they are much less effective with patchy or rare species such as delta smelt. Moreover, the recent decline in delta smelt population has led to concern over lethal "take" by trawling methods. Recent progress in towed video imaging systems may provide a supplemental method that could be used to examine pelagic fish distribution and abundance. The potential use of underwater video cameras retrofitted to trawl surveys as a new non-lethal tool to measure the abundance and distribution of pelagic fishes has gained recent interest. An underwater housing has been designed, fabricated, and tested to attach to the cod-end of a towed-net and perform under strict buoyancy, pitch, yaw, and roll specifications. The device has been tested in flows up to 0.9 m/sec (3 ft/sec) in turbid water. The aluminum hull contains a video imaging system, using a black and white, right-angled Gig-E high-speed camera to capture image data and send to boat-side computer system over Ethernet. The electrical system includes lighting, light driving, sensor sampling, cameras, camera power, lightning protection, and smaller subsystems. Sensors have been included that interface with the computer and provide information pertaining to the global positioning system (GPS) location, pressure for depth (inner and outer), humidity, temperature (air inside hull), water flow rate (from pressure differential), and tilt angle (and rate) from accelerometers.

The computer system processes images in real-time using a combination of NVIDIA compute unified device architecture (CUDA) parallel computing platform, LabVIEW, and the image processing toolkit from National Instruments. Vision system improvements include the programming of algorithms software to determine fish profile outline and estimate approximate pose, develop and train software to recognize objects as fish from a library database and statistical models, and classify objects automatically, as fish or non-fish and give probability of each object of being a delta smelt. An adaptive software reduction of turbidity through known fish position and gamma correction is an ongoing process and will be further designed.

The software system is composed of 2 parts: (1) a user interface that includes data visualization, sensor acquisition, alarming conditions, camera inputs, and data recording, and (2) a vision algorithm that is actively detecting fish-sized objects using CUDA (CUDA is the computing engine in NVIDIA graphics processing units). Other feature trackers and algorithms have been implemented to detect and describe local features that will help in tracking objects and deciding whether or not it is a fish, debris, or bubbles. A more rigorous testing phase will occur in the fall, winter, and spring 2010–2011, including more laboratory and field analysis of the underwater camera fish recognition system.

Time period: Through 2011 and possibly beyond, depending on how long it takes to build an object image library.

Resources required:

Cost: $201,000 from POD sources.

PI(s): Don Portz (USBR) and Darren Odom (SureWorks, LLc.)

Contract needed / in place: In place.

Contract manager(s): Erwin Van Nieuwenhuyse (USBR) and Ted Sommer (DWR)

Term of contract: Annual

Personnel: USBR, DFG and DWR staff

Equipment: Aluminum underwater submersible, Dalsa high-speed camera, laptop computer, LED lighting, camera cabling, flumes, and use of trawls.

Deliverables and dates:

- Progress report (September 2010).
- IEP Newsletter article draft (December 2010).

Comments: The software system that the Bureau of Reclamation and SureWorks, LLc. is designing requires more work on the vision algorithm, some flume testing, and field trials for the fall, winter, and spring 2010–2011.

Use of Acoustics to Estimate Trawl Openings

IEP 2010-131

Point person: Randy Baxter (DFG)

Lead Agency: DFG

Questions: What are the mouth dimensions of a standard midwater trawl? Do these dimensions vary based on differences in trawling depth or current direction? Are trawl mouth dimensions affected by variation in rigging among the vessel being used (i.e., does the block height and width among vessels affect mouth dimensions)? The information should improve the accuracy of abundance indices and will be directly applicable for the development of mean-density expansion estimators (see 2010-043 above) used to estimate the population size of delta smelt and other fishes susceptible to the trawling. Results may suggest appropriate alternative rigging configurations to improve consistent deployment of trawls.

Description: This study will employ a commercially-available transmitter/transponder/computer system to calculate dimensions of a midwater trawl mouth while the net is being towed during special deployments to emulate a variety of different depth, current, vessel speed, and vessel configuration circumstances. The midwater trawl will be towed by all currently operational DFG vessels used for the FMWT and SFBS . If time permits, the gear will be used to measure mouth dimensions of the SKT, SFBS otter trawl, and the USFWS Chipps Island midwater and Kodiak trawls.

Time period: January – December 2010

Resources required:

Cost: $13,000 from POD sources.

PI(s): Randy Baxter, Steve Slater, Dave Contreras and Jennifer Messineo (DFG)

Contract needed / in place: Not needed.

Contract manager(s): N/A

Term of contract: N/A

Personnel: 2 -3 biologists, 1 mate, and 1 scientific aide would be temporarily directed.

Equipment: Software and hardware have been purchased and successfully used to complete part of the list of net measurements. The equipment malfunctioned and has been returned to the vendor for repair, which must be successful to complete this study.

Deliverables and dates:

- Not less than 5 memo-reports and companion Excel summary files, each submitted within a month following any deployment of the equipment.
- IEP newsletter article describing initial field work (fall 2010).
- Draft a manuscript describing inter-vessel effects on trawl mouth dimensions including a discussion on how rigging affected trawl dimensions (December 2011).

Comments: Equipment malfunctions may limit work possible in 2010.

The Effects of the Cache Slough Complex on North Delta Pelagic Habitat: Regional Transport of Turbidity, Phytoplankton, and Zooplankton

IEP 2010-132

Point person: Ted Sommer (DWR)

Lead Agencies: DWR and USGS

Questions: This study will examine the hydrodynamic "footprint" of Liberty Island in the north Delta, one of the key habitats of delta smelt. Two of the alternative hypotheses to be tested include:

Alternative 1: Liberty Island has a dominant effect on the hydrodynamics of Cache Slough Complex channels and perhaps other parts of the north Delta. Hence, we expect to see pulses of turbidity, chlorophyll *a*, and zooplankton coincident with tidal export from Liberty Island. Specifically, we should see these pulses on an ebb tide in lower Cache Slough (and perhaps Rio Vista) and on a flood tide in the Deep Water Ship Channel.

Alternative 2: Transport of particulates in the Cache Slough complex is determined largely by localized production (phytoplankton, zooplankton) or resuspension (sediment). For turbidity, the hypothesis is that sediments are deposited in Cache Slough Complex channels during flood events. Hence, high turbidity during other times of the year would occur in the Deep Water Ship Channel and lower Cache Slough during (1) peak ebb and flood tides; (2) high wind periods; or (3) both conditions. Chlorophyll *a* in lower Cache Slough and the Deep Water Ship Channel would show diel and seasonal variation, but no tidal effects. Zooplankton would show seasonal effects and perhaps diel effects.

Description: The POD has created substantial interest in characterizing the habitat of pelagic fishes. This includes analyses of short term (e.g., tidal) and long-term (e.g., seasons, years) changes. Recent studies have revealed several important observations: (1) the Cache Slough Complex represents key habitat for delta smelt; (2) turbidity is an especially important component of habitat for the Delta pelagic fishes; (3) much of the sediment and organic carbon flux in the estuary passes through the Cache Slough Complex; and (4) the Cache Slough

Complex appears to be a important "food bank" for the Delta. Hence, understanding the patterns of hydrodynamics, turbidity, chlorophyll *a*, and zooplankton is important to describe the habitat of pelagic fishes including delta smelt. The proposed study will examine the hydrodynamic "footprint" of Liberty Island, the major body of water in the Cache Slough Complex. Flux of phytoplankton out of Liberty Island will be studied by Peggy Lehman as part of the Breach III study, providing a good opportunity to examine the fate of the exported material. We suspect that transport of biological and physical constituents from Liberty Island has a dominant effect on the channels of the Cache Slough Complex and perhaps a large area of the north Delta. The study approach includes both continuous monitoring and 24-hour flux studies. Ongoing work in 2010 will include 2 additional 24-hour sampling events to capture "wet" winter conditions, and more focused continuous monitoring in the upper Cache Slough and Liberty Island areas.

Continuous Monitoring:
    Wind: Rio Vista, Hastings (existing stations)
    Flow: Cache Slough at Ryer Island, Upper Cache Slough, Deep Water Ship Channel, Miner Slough, and Lindsay Slough.
    Turbidity: Cache Slough at Ryer Island, Upper Cache Slough, Ulatis, Deep Water Ship Channel, Miner Slough, and Lindsay Slough.
24-Hour Intensive Studies (once every 3 months):
    Phytoplankton and zooplankton: Liberty Island, Cache Slough, Deep Water Ship Channel.
    Chlorophyll *a*: Liberty Island, Cache Slough at Ryer Island, Upper Cache Slough, Deep Water Ship Channel, Shag Slough, Lindsay Slough.
Time period: 2008 to 2010
Resources required:
    Cost: $334,170
        DWR biological sampling $89,270
        DWR hydrodynamic sampling $27,000
        USGS turbidity sampling $217,900
    PI(s): Gina Benigno, Shawn Mayr and Ted Sommer (DWR); Tara Morgan and Dave Schoellhamer (USGS).
        Contract needed / in place: In process.
        Contract manager(s): Rich Breuer (DWR), Erwin Van Nieuwenhuyse (USBR) and Roger Fujii (USGS)
        Term of contract: To be determined.
    Personnel: Identified PIs plus additional IEP staff during the 24 hour flux studies.
    Equipment: An Acoustic Doppler Current Profiler (ADCP) for some of the locations, turbidity sensors for all the sites, and the use of 3 small boats during the four 24-hour flux studies.
Deliverables and dates:

- Delta Science Conference presentations (October 2010).
- Peer reviewed manuscript for publication (December 2010).

Comments: None

Impacts of Largemouth Bass on the Delta Ecosystem

IEP 2010-133

Point person: Ted Sommer (DWR)
Lead Agency: UCD
Questions: How much time do centrarchids spend foraging in pelagic habitat? What is the relationship between increasing biomass of *Egeria* and centrarchids density, as well as other species in the littoral zone? What are "ballpark" estimates of centrarchid population sizes and prey requirements?
Description: Although "top-down" effects are a key part of the POD conceptual model, predation from inshore piscivores represents a relatively poorly understood source of mortality. There is good evidence that centrarchid populations have thrived as a result of the expansion of *Egeria* beds; however, it is unclear whether this may have contributed to the POD. Specifically, we need estimates of inshore predator abundance and information about their effects on pelagic habitat. Four tasks comprise this element: (1) field surveys of largemouth bass and other fish, (2) feasibility study of acoustic tracking methods for largemouth bass in the Delta, (3) mesocosm studies on largemouth bass diets, and (4) statistical models of largemouth bass abundance and impacts.
Time period: 2009-2010
Resources required:

- Cost: $239,000 in 2010 from POD sources.
- PI(s): Drs. Andy Sih, Peter Moyle and Peter Klimley (UCD)
  - Contract needed / in place: This work is included in the DWR-UCD umbrella contract that expired June 30, 2010 and will be continued through a USBR-UCD contract.
  - Contract manager(s): Ted Sommer (DWR)
  - Term of contract: Through June 30, 2010 (DWR).
- Personnel: Louise Conrad (DWR) and Anna Stephensen (UCD)
- Equipment: This work requires the use of an electrofishing boat, likely borrowed from DFG.

Deliverables and dates:

- Progress report for task 1 to IEP MT (fall 2010).
- IEP Newsletter submissions for task 1 (fall 2010).
- Oral presentation at Delta Science Conference for tasks 1, 2 and 4 (October 2010).
- Poster presentation for task 1 at State of the Estuary Conference (October 2009).
- Oral presentation for task 3 at the IEP Annual Workshop (May 2010).
- 1 or more peer-reviewed journal articles for task 1, 2, 3 and 4 (fall 2010).

Comments: None

Delta Smelt Genetics

IEP 2010-135
Point person: Randy Baxter (DFG)
Lead Agency: USFWS
Questions: What is the current and historic population structure of the delta smelt population? What is the mating strategy of delta smelt? What is the extent of hybridization between delta smelt and wakasagi smelt or longfin smelt? What type of genetic breeding plan would be effective to maintain genetic variability in a captive refugial population? Is genetic variability being maintained in the captive refugial population?

Description: The delta smelt abundance has declined recently to record low levels (Sommer et al., 2007), prompting petitions to "uplist" it from the current threatened status to endangered under both the California and Federal Endangered Species Acts (The Bay Institute et al., 2006 and 2007). Low abundance levels also lead to unprecedented restrictions in biological sampling in 2007, promulgated under IEP delta smelt "take" and DFG collection permit authority. Other efforts to manage delta smelt include investigations into reproductive biology and culture conducted at the UCD FCCL, located near the Skinner Fish Facility in Byron. The facility has been acquiring wild brood stock annually to produce young for experimental purposes, but these collections were restricted in 2007. As a result of the declining abundance and reduced access to wild brood stock, a refugial population has been developed. However, to effectively establish and maintain a refugial population, the genetic structure and dynamics of the population must first be determined. This study proposes to increase understanding of wild delta smelt population structure, hybridization, population dynamics, and spawning strategies through several years of study. Based on these findings, a breeding plan will be developed that will maintain "natural" genetic variation and population structure in the captive population. In addition, wild population genetic studies will help guide conservation management of delta smelt and permit genetic monitoring of the wild population.

Four tasks comprise this element:

- **Task 1:** Microsatellite marker development (begun in July 2007 and completed in April 2008).
  - Develop and optimize delta smelt specific primers to characterize microsatellite loci.
  - Test cross-species microsatellites (Saint-Laurent et al., 2003; McLean and Taylor, 2001; Kaukinen et al., 2004).
- **Task 2:** Determine the population structure of delta smelt throughout the Delta using microsatellite markers. Genotype all individuals by polymerase chain reaction (PCR) amplification using highly polymorphic loci lacking null alleles from already collected samples in collections held by R. Baxter and W. Bennett in addition to any wild individuals caught during project. Estimate allele frequencies, observed (H_o) and expected (H_e) heterozygosities, and inbreeding coefficients (F_{IS}) for all populations.
  - Determine the existence of genetically distinct populations of delta smelt in the Delta.
- **Task 3**: Assess the extent of hybridization between delta smelt and longfin (*Spirinchus thaleichthys*) or wakasagi smelt (*H. nipponensis*) to evaluate the role of hybridization in population abundance of delta smelt. Genotype longfin and wakasagi smelt by PCR amplification using polymorphic loci used for delta smelt.
  - Compare delta smelt genotypes to detect levels of hybridization and any introgression.
  - Evaluate level and percentage of hybridization with delta smelt.
  - Examine mitochondrial DNA of hybrids to determine if hybridization is species-directional.
  - Assess degree of downstream movement of wakasagi smelt from their original introduction in reservoirs.
- **Task 4:** Determine spawning strategies using breeding experiments and microsatellite markers to understand delta smelt population dynamics.
  - Conduct breeding experiments of delta smelt in a controlled environment.

  - Examine progeny from tanks containing multiple individuals with different ratios of males to females.
  - Use highly polymorphic microsatellite markers and computer algorithms to assign parentage to progeny.
  - Assess timing and frequency of female egg release and male contribution to progeny to determine mating system (polygamous, polyandrous, or both) and spawning strategies.
  - Determine effective population size from clarification of spawning strategies.
- **Task 5:** Develop a breeding plan to maintain natural genetic variation and population structure in captive populations using information obtained on population structure, dynamics, and spawning strategies of delta smelt.
  - Characterize the wild founding fish population structure and implications for management of potential breeding population.
  - Design breeding plan using information obtained from Tasks 2 and 4 to maintain natural variation in refugial population.
  - Determine number of refugial populations according to wild delta smelt population structure.
  - Assess natural breeding sex ratios and timing to facilitate desired crosses.
  - Develop a monitoring program to assess maintenance of genetic variation in wild and captive populations.

Time period: 2007 - 2012, with possible extensions and additional work funded through additional sources (see comments for contract extension).

Resources required:

Cost: $53,000 from non-POD sources for 2010. This element is underfunded and projects needing an additional $250,000 to complete all tasks by 2012.

PI(s): Bernie May and Katie Fisch (UCD)

Contract needed / in place: In place.

Contract manager(s): Paul Cadrett (USFWS) and Bernie May (UCD)

Term of contract: September 2007– September 2012

Personnel:

Equipment: Work for this element will take place at the Genomic Variation Laboratory (GVL) at UCD. Additional genetic work may be considered between the GVL, W. Bennett and S. Cohen, or between GVL and the FCCL.

Deliverables and dates:

General:

- Progress reports to agency funders as required in contracts.
- Year end final contract reports.
- Refereed publications.
- IEP Annual Workshop presentation (May 2010).
- Delta Science Conference presentation (October 2010).
- Scientific meeting presentations (e.g., Evolution and/or American Fisheries Society (AFS) annual and regional meetings).

Task 1

- Microsatellite markers for use in subsequent genetic analyses.
- Peer reviewed journal article (Published in Molecular Ecology Resources Issue 9, 2009).

Task 2

- Population structure.
- Peer reviewed journal article (2010).

Task 3

- Hybridization
- IEP Newsletter or peer reviewed journal article (2010).

Task 4

- Spawning strategy of delta smelt.
- Peer reviewed journal article (2011).

Task 5

- Genetic management plan and monitoring.
- Peer reviewed journal article (2012).

Work on this element will be completed by September 2012 if fully funded.
Comments: A new contract is being developed with USBR to fund genetic component of yearly maintenance of captive delta smelt refugial population through 2015.

Feeding and Growth of Delta Smelt
IEP 2010-136
Point person: Ted Sommer (DWR)
Lead Agency: SFSU
Questions: Year 1 questions: Do larval and juvenile striped bass and delta smelt exhibit selection for different zooplankton species? How does prey selection differ among larvae and juveniles? How do light and turbidity influence prey selection? What are the underlying mechanisms that determine prey selection?

Year 2 questions: What are the growth rates of larval delta smelt that are fed different prey species? What are the assimilation efficiencies of larval delta smelt feeding on different prey species? How do growth rates and assimilation efficiencies of larval delta smelt differ among diets comprised of different prey species?

Description: Video-graphic techniques will be used to record observations of predator-prey interactions and specific patterns of prey selection will be used to develop quantitative models of prey selection. Growth rates of larval delta smelt fed field-collected zooplankton will be measured in laboratory experiments. Length and weight measurements of larval fish, combined with biomass estimates of copepods will allow for calculations of assimilation and growth efficiency of larval fish feeding on different copepods. Data on respiration, ingestion, growth and excretion will be used to create an energy budget for larval delta smelt, allowing for the possibility of more accurate models of population dynamic.

Time period: 2009 - 2010
Resources required:
    Cost: $17,000 in 2010 from DWR POD.
    PI(s): Lindsay Sullivan (SFSU)
        Contract needed / in place: Requires modification of existing SFSU contract.
        Contract manager(s): Ted Sommer (DWR) and Wim Kimmerer (SFSU).
        Term of contract: Requires modification of existing contract with SFSU.
    Personnel: Wim Kimmerer (SFSU)
    Equipment: No new equipment is needed at this time.

Deliverables and dates:

- Presentation of results to date at Delta Science Conference (October 2010).

- Progress report to IEP MT (winter 2010).
- Scientific paper prepared for peer-reviewed journal (winter 2009 and 2010).
- Presentation of results at the State of the Estuary Conference (fall 2009).

Comments: This study is dependent on obtaining 5,000 newly hatched larvae for use in laboratory experiments. Prey selection and growth experiments have been completed. The data are currently being analyzed and publications are in preparation on both. Preliminary results were reported at the 2009 IEP Food Webs and Invasive Species Workshop, 2009 State of the Estuary Conference and 2009 Coastal and Estuarine Research Federation Conference. An abstract has been submitted to the 2010 Delta Science Conference.

Population Genetics and Otolith Geochemistry of Longfin smelt

IEP 2010-137
Point person: Ted Sommer (DWR)
Lead Agency: UCD

Questions: What is the genetic population structure of longfin smelt? Is there evidence of a recent change in life-history variability based on otolith chemistry and growth? Have there been changes in the demographics of longfin smelt?

Description: Longfin smelt recently has been proposed for listing as an endangered species. Although there is substantial concern about the status of this pelagic fish, there has been relatively little research on this species compared to delta smelt or striped bass. Hence, the basic population structure, demographics, and life history variability are unknown. The present study seeks to address some of these data gaps using 3 major tasks:

- Task 1-**Compare life-history variability from pre-POD to POD era (PI: Hobbs):** Using fish collected in the 1999-2001 FMWT Survey and the 2003 Bay Study, as well as the more recent collections from these sampling programs, the life-history of these longfin smelt samples will be reconstructed through examination of the strontium isotope 87Sr:86Sr ratios to reflect salinity history. In addition, we plan to expand on this tool by including the carbon isotope history 12C:13C since this tool has recently discovered high resolution relationships with salinity. Strontium isotopes samples are collected with the ablation multi-collector, inductively coupled plasma mass spectroscopy (ICP-MS) and the carbon isotopes are collected by micro-milling samples from the otolith and are analyzed with gas chromatography combustion isotope ratio mass spectrometry (GC-CIRMS).
- Task 2-**Genetic population structure of longfin smelt (PI: Israel, May)**: This task will identify population structuring among tissue collections from the Bay-Delta, Klamath River, and west coast. Additional collection sites are currently being considered from museum collections at the California Academy of Science and Burke Museum at the University of Washington. In 2009, 17 microsatellite markers were optimized from the Bay-Delta and Washington State longfin smelt collections, and subsequently published for studying genetic variation in longfin smelt (Israel and May, 2010). These microsatellite markers appear to characterize 2 distinct populations of longfin smelt between the Bay-Delta and Washington State collections. They are now being used to evaluate genetic structuring based on clustering of genotypes among annual groups of collections at local, state, and regional scales. Traditional population differentiation analyses will be utilized for evaluating genetic structuring among tissue sample collections.

- Task 3-**Contemporary demographics of longfin smelt (PI: Israel, May):** This task will evaluate multiple annual collections of longfin smelt collected pre-POD and post-POD decline to compare genetic variation in the population during these periods. This information can be insightful into demographics, effective population size, and assessing bottlenecks within a population.

Time period: 2009 - 2010
Resources required:
    Cost: $113,000
    PI(s): Bernie May and James Hobbs (UCD), Josh Israel (USBR).
        Contract needed / in place: This work is being included in the DWR-UCD umbrella contract, currently in process.
        Contract manager(s): Ted Sommer (DWR) and Bernie May (UCD).
        Term of contract: Through June 30, 2010.
    Personnel: Emily Ringelman (UCD)
    Equipment:
Deliverables and dates:

- Manuscript accepted to Conservation Genetics (spring 2010).
- Oral presentation at the annual IEP Workshop (May 2010).
- Oral presentation at the Delta Science Conference (October 2010).
- Final report, which will comprise draft manuscripts for submission to journals or the IEP Newsletter (spring 2011).
- Databases, as appropriate (July 2011).

Comments: The project is intended to complement “data-mining” studies (e.g., Feyrer, Baxter) that will examine changes in longfin smelt habitat, abundance, and distribution.

Effects of Wastewater Management on Primary Productivity in the Delta

IEP 2010-138
Point person: Anke Mueller-Solger (DSC)
Lead Agency: SFSU, RTC & Water Boards
Questions: Do ambient ammonia levels in the Sacramento River affect phytoplankton primary production and community composition in the Delta?
Description: Primary production rates and standing chlorophyll levels in the Delta are among the lowest of all major estuaries in the world and may be declining further. The reason(s) for this are unclear, but decreasing primary production rates are cited as a possible cause of the pelagic organism decline (IEP, 2007). Recent work by Dugdale et al. (2007) and Wilkerson et al. (2006) has shown that elevated ammonia concentrations reduce phytoplankton production rates in San Francisco and Suisun bays by inhibiting nitrate uptake. Should phytoplankton production in the freshwater Delta be suppressed in the same way, this may contribute to the long-term declines in pelagic productivity and thus constitute an important "bottom-up" factor in the POD conceptual model. The primary sources of ammonia to the Delta are sewage treatment plants, principally the SRWTP.
Description: This work plan element focuses on the SRWTP discharge to the lower Sacramento River. SRWTP employs secondary treatment and the main form of nitrogen in its effluent is ammonium. Field studies will include transect surveys of nutrients and phytoplankton as well as phytoplankton "grow-out" enclosures experiments (Dugdale et al, 2007) upstream and

downstream of the SRWTP discharge location. Controlled laboratory experiments with added effluent, ammonium, and nitrate will complement the field study.
Time period: 2008 – 2010
Resources required:
Cost: $119,000
PI(s): Richard Dugdale, Alex Parker and Francis Wilkerson (SFSU)
Contract needed / in place: SWRCB contract in place.
Contract manager(s): Mark Gowdy (SWRCB) and Chris Foe (CVRWQCB)
Term of contract: January 2008 – March 2010
Personnel: Above named investigators and 2 technicians.
Equipment: None
Deliverables and dates:

- Annual reports to the SWRCB, Delta Science Program and POD MT.
- IEP Newsletter articles, presentations as appropriate and a manuscript.

Comments: This element was completed as of March 31, 2010.

Effects of Microcystis aeruginosa on Threadfin Shad (Dorosoma petenense)
IEP 2010-139
Point person: Ted Sommer (DWR)
Lead Agency: UCD
Questions: What are the lethal and sublethal effects of microsystins (MCs) on growth and survival of threadfin shad (TFS)? How does the accumulation and fate of MCs affect TFS? The hypotheses to be tested are:

H1: Microcystis can cause lethal and sublethal toxicity to embryo, larval, and juvenile TFS.
H2: Single-celled form of MC is more lethal than colonial form of MC in filter feeder such as TFS.
H3: Microcystis affect the quality and quantity of *E. affinis*, and *P. forbesi* and thus lead to poor survival and growth of TFS.
H4: Microcystis affects the growth and reproduction of TFS.

Description: TFS are small fresh water plankton feeders which inhabit open waters of reservoirs, lakes, and shallow water habitat in the upper San Francisco Estuary (SFE). The purpose of this study is to examine the potential effects of the toxic alga *Microcystis,* which creates blooms that overlap substantially with the range of TFS. The working hypothesis is that TFS can be exposed to these toxins either during feeding (especially for filter feeder such as TFS) or passively when the toxins pass through gills during breathing. Work to date has successfully established culture of: (1) copepods (*Eurytemora affinis* and *Pseudodiaptomus forbesi*), (2) positive (microcystin-LR+) and negative (microcystin-LR-) strains of single-celled forms of *Microcystis aeruginosa*, and (3) a re-circulating temperature of controlled fish culture system in our laboratory.

The study is divided into 4 tasks. Task 1 will establish laboratory culture of TFS. Task 2 will perform lethal *Microcystis* studies on TFS. The work will provide information on the sensitivity of TFS to *Microcystis*. Data will be compared to microcystis studies in other fish species and copepods. The elements of this task will evaluate: (1) acute toxicity (lethal concentration that kills 50% of the TFS) of MCs on larval and juvenile TFS; (2) water exposure of larval and juvenile TFS to environmentally-relevant concentrations of MCs; and (3) dietary exposure of larval and juvenile TFS to single-celled and colonial form of *Microcystis.* Task 3

will focus on sublethal *Microcystis* studies on TFS including growth, histopathological, and reproductive effects of MCs. Finally, task 4 will determine bioaccumulation and fate of MCs in TFS.
Time period: Ongoing through 2010.
Resources required:
Cost: $178,000 for 2010 from POD sources.
PI(s): Swee Teh (UCD) and Peggy Lehman (DWR)
Contract needed / in place: Requires modification of existing contract.
Contract manager(s): Rich Breuer (DWR) and Swee Teh (UCD)
Term of contract: Through June 30, 2010.
Personnel: UCD staff; Kevin Reece and Ted Sommer (DWR)
Equipment: UCD laboratory facilities, as well as some IEP boat time to help collect threadfin shad for laboratory cultures.
Deliverables and dates:

- Progress report, presentation and protocol for laboratory culture of threadfin shad (February 2010).
- Progress reports, presentations and publications for tasks 1, 2, 3 and 4 (December 2010).

Comments: None

Mark-Recapture Study to Estimate Delta Smelt Pre-screen Loss and Salvage Efficiency
IEP-related 2010-140 (2006 CALFED PSP)
Point person: Anke Mueller-Solger (DSC)
Lead Agency: USFWS
Questions: What is the relation between salvage and total entrainment losses for juvenile and adult delta smelt at the SWP?
Description: The purpose of this project is to evaluate the efficacy of mark-recapture tests to ensure a feasible approach to quantifying the extent of entrainment losses of juvenile and adult delta smelt in the south Delta. Delta smelt was historically one of the most common open-water species of fish in the Delta. Delta smelt declined significantly between the late 1970s and early 1980s and is now listed as a threatened species by the California and Federal Endangered Species Acts. Record low abundance indices for delta smelt and other pelagic fishes in the Delta have been observed since the early-mid 2000's. Leading factors potentially implicated in this pelagic organism decline are water project operations, introduced species and contaminants. Despite the lack of information to quantify absolute entrainment losses of delta smelt to water exports and diversions, such losses have long been assumed to be a factor contributing to the decline of delta smelt and other species, particularly in the south Delta where the SWP and CVP water export facilities are located. The tasks for the project are listed as follows:

- Task 1 - Project management.
- Task 2 - Culture delta smelt for mark-recapture experiments.
- Task 3 - Mark delta smelt for mark-recapture experiments.
- Task 4 - Mark-recapture experiments for juvenile delta smelt.
- Task 5 - Mark-recapture experiments for adult delta smelt.
- Task 6 - Analyze and interpret results of mark-recapture experiments.

Time period: August 2007 –July 2010
Resources required:
Cost: $15,000 in 2010. This work is co-funded with USBR bridge funds and DSP.

PI(s): Gonzalo Castillo (USFWS), Robert Fujimura (DFG), Joan Lindberg (UCD), Jerry Morinaka (DFG), Victoria Poage (USFWS)

Contract needed / in place: CESU agreement with UCD is completed. The cooperative agreement with DFG is in place until December 11, 2010 (delayed due to unforeseen logistical issues).

Contract manager(s): Kim Webb (USFWS) and Gina Ford (DSP)

Term of contract: August 2007 – July 2010

Personnel: Above named investigators and Jason Dubois (DFG), Luke Ellison and Galen Tigan (UCD), and scientific aides.

Equipment:

Deliverables and dates:

- Progress report 1 and IEP Workshop presentation (March 2009).
- Progress report 2 (September 2009).
- Progress report 3 and IEP Workshop presentation (March 2010).
- Final report (September 2010).
- Submission of 1 manuscript to a scientific journal (October 2010).
- Delta Science Conference presentation (October 2010).

Comments: Field work was completed in 2009. Data analyses and manuscript preparation are in progress. A second methods manuscript about marking is anticipated in 2011.

3-D Modeling of the Delta

IEP 2010-141 (Expansion of existing element)

Point person: Fred Feyrer (USBR)

Lead Agency: DWR

Questions: What are the predicted pathways of particle movement through the Delta and what is the likelihood of entrainment in the pumps for different release locations and Delta conditions? How do wind-driven velocities influence the vertical migration behavior of fish in Clifton Court Forebay (CCF) and other regions?

Description: The focus of the present scope is to further refine the particle tracking simulation approach and simulate additional periods and scenarios. The scope is divided into 5 major tasks. Under the first task, the particle tracking approach will be refined to take into account additional biological variability (e.g., hatching rates and periods). Under the second task, the refined approach will be applied to periods of low abundance of delta smelt, such as 2007, 2008 or 2009. These particle tracking applications will focus largely on comparisons of model predictions with observed salvage to evaluate the ability of the modeling approach to predict entrainment during recent years, which are characterized by low delta smelt abundance. Under the third task, the model will be applied to stimulate adult delta smelt distribution and entrainment for a hypothesized “tidal surfing” behavior. Under the fourth task, the model will be applied to simulate a period of field observations in CCF. The fifth task includes meetings, presentations, and documentation of the work completed under this scope of work.

Time period: June 2009 – June 2010

Resources required:

Cost: Obligated with previous year funding.

PI(s): Edward Gross (Bay Modeling)

Contract needed / in place: In place.

Contract manager(s): Erwin Van Nieuwenhuyse (USBR)

Term of contract: June 2009 – September 2010
Personnel: Edward Gross (Bay Modeling) and Michael MacWilliams (River Modeling)
Equipment: None

Deliverables and dates:

- IEP Presentation (February 2010).
- Final Technical Report (May 2010).
- Manuscript submitted to journal (September 2010).

Review and Synthesis of Existing Discharger and Ambient Surface Water Toxicity and Chemical Contaminant Monitoring in the Delta

IEP 2009-146 (Expansion of existing element)
Point person: Stephanie Fong (CVRWQCB)
Lead Agency: CVRWQCB
Questions: Is there evidence that the magnitude, duration and frequency of toxicity, and/or chemical concentrations presently being measured in the Delta might impair its aquatic beneficial uses? Is there evidence that water column toxicity is contributing, at least in part, to the POD? How might ongoing surface water monitoring be improved to more definitively answer the above 2 questions?
Description: The purpose of this work plan element is to develop and synthesize contaminant and toxicity information needed to support development of a comprehensive regional monitoring program for the Delta and review chemical, toxicity, and histological data from monitoring programs to investigate impacts of contaminants while assessing the impact of discharges from irrigated lands on beneficial uses in the Delta, specifically on emerging concerns related to the POD. Specific tasks are as follows:

- Prepare a synthesis report of the monitoring programs conducting ambient monitoring in the Delta and 30 miles upstream on the Sacramento and San Joaquin rivers, and include monitoring conducted under all Regional and State Water programs (e.g., storm water and wastewater NPDES permits, Irrigated Lands Regulatory Program, Surface Water Ambient Monitoring Program (SWAMP), etc.), the IEP and USGS.
    - The report will summarize the programmatic objectives for the monitoring, parameters and locations being monitored, the frequency of monitoring, and the anticipated term of future monitoring.
    - The report will include an estimate of the cost of the ambient monitoring summarized in the synthesis report. The cost estimate shall be broken down by funding entity, sampling costs, and analysis costs.
- Prepare recommendations for a framework to coordinate monitoring summarized in the synthesis report under above named task. The framework should build upon the ongoing efforts to coordinate monitoring in the San Joaquin and Sacramento River basins as well as the Delta Science Program's proposal to develop a monitoring strategy for the Delta.

Time period: 2008 - 2010
Resources required:
Cost: $141,000 in 2010.
PI(s): Michael Johnson (UCD)
Contract needed / in place: In place.
Contract manager(s): Mark Gowdy (SWRCB)
Term of contract: 2008 - 2010

Personnel: Above named investigator and additional technicians.
Equipment: None

Deliverables and dates:

- Synthesis Report written jointly by the contractor and expert panel (spring 2010).
- Final oral report to the Contaminants Project Work Team.

Comments: None

BREACH III: Evaluating and Predicting 'Restoration Thresholds' in Evolving Freshwater-Tidal Marshes

IEP-related, 2010-147 (Ecosystem Restoration Program)
Point person: Pete Hrodey (USFWS)
Lead Agency: USFWS

Description: The purpose of this project is to provide a predictive level of understanding about (1) how abiotic and biotic factors influence a restoring (levee breach) wetland, Liberty Island and Little Holland Tract, control vegetation colonization and expansion and subsequent responses by native fish and wildlife, and (2) how restoration processes influence local flooding and levee erosion over the course of the restoration. A quantitative approach to predicting the ecological responses to change in habitat structure will be developed as a restoring system passes through the vegetation recolonization threshold and continues to expand into a predominantly vegetated wetland landscape. The models used will also be valuable for interpreting or, with modification, even predicting alternative flood conveyance scenarios as the Island evolves. Specific tasks are as follows:

- **Informing Flood and Erosion Hazard Management Decisions**
  This task will address the knowledge gap concerning the risks of flooding and levee erosion associated with the projected geomorphic evolution of Liberty Island from flooded island to tule marsh and mudflat. The modeling results will inform resource management and planning processes related to the Lower Yolo Bypass.
- **Channel/Tidal Flat Morphology and Wave Climate**
  This task will measure channel and mudflat dimensions to provide time series data on landscape features and processes, and investigate the geomorphic and ecological processes that define channel evolution across Liberty Island.
- **Landscape Structure and Change**
  This task will describe vegetation and geomorphology changes of Liberty Island from 1997 to 2008. Geomorphology, topography and data from other tasks in this agreement will be used to develop rules that govern the expansion and development of emergent vegetation after initial vegetation colonization. Qualitative and quantitative predictions of restoration landscapes and tidal channel development, both at Liberty Island and other Bay-Delta tidal freshwater restoration sites, will be produced.
- **Elevation Change**
  This task will quantify above-ground vegetative processes, below-ground biomass accumulation, and sediment deposition responses to plant colonization on open mudflats as factors in elevation change of marsh substrate. Field studies will be structured to identify differences in soil building processes (i.e., rates, and the relative role of mineral sediment vs. organic accumulation) in newly colonizing vegetated areas.
- **Plant Colonization Dynamics**

This task will study physiological tolerances and biotic interactions of key emergent wetland plant species under 2 sets of dispersal conditions in order to discover the opportunities and constraints for the establishment of key plant species. The experimental results will be used to produce an assessment of the range of suitable habitats for desirable species.

- **Macroinvertebrate Response**
  This task will identify macroinvertebrate assemblages associated with spatial and temporal development of the restoring tidal freshwater wetland. These assemblages will be monitored, in the vicinity of restoring wetlands, for changes during the course of vegetation colonization. Emphasis will be placed on monitoring the assemblages known to be the prominent prey of key fish species.
- **Nekton Response**
  This task will evaluate fish use of incipient vegetation colonization habitat structure and early expanding habitats by studying the use of restoring wetlands by specific life stages of delta smelt, longfin smelt, Chinook salmon, striped bass, threadfin shad and Sacramento splittail.
- **Food Web Sources and Pathways**
  This task will conduct monitoring for food web sources and pathways at Liberty Island to determine whether Liberty Island is a source or sink of organic carbon, phytoplankton and zooplankton biomass, nutrients and suspended solids. Local, exported and imported productivity will be characterized at various scales.
- **Hydrodynamic and Morphological Modeling**
  This task will develop and apply a detailed numerical model to improve understanding of the physical processes (e.g., sediment supply, delivery, resuspension and redistribution) that control morphologic evolution of Liberty Island and to assess the validity of using models as predictive tools. Recommendations on how management and restoration activities can be applied to leveed sites within Liberty Island for a variety of desired endpoints will be prepared.
- **Development of Ecological Modeling Tools**
  This task will develop the Liberty Island Basin Model from process-based algorithms using existing models, modules, and other rules and inputs. Model parameters will be collected and developed sufficiently to enable resource managers and restoration planners to assess restoration and management activity for long-term trajectories associated with levee breach restoration and other landscape alterations.
- **Development and Use of Predictive Modeling Tools Using a Synthesis Process**
  The models, modules, data, and other rules and inputs developed in previous tasks will be integrated to produce a system of linked hydrodynamic-ecological numerical models (model system). The model system will convert resource management and ecosystem restoration parameter inputs into ecosystem outcomes for a specified location and range of variables.

Time period: March 2008 – March 2011

Resources required:

Cost: $2,440,000 over 3 years (CALFED ERP → DFG → USFWS → subcontractors) with approximately $1,100,000 allocated for 2010.

PI(s): Pete Hrodey (USFWS), Charles Simenstad (UW), Philip Williams (PWA), Nadav Nur (PRBO), Denise Reed (UNO), Mark Hester (ULL), Enrique Reyes (ECU), Stephen Bollens (WSUV), and Peggy Lehman (DWR)

Contract needed / in place: Sub-contracts not in place and affected by the December 2008 'stop-work' order.

Contract manager(s): Pete Hrodey (USFWS), Steven Rodriguez (DFG) and Leann Androvich (GCAP Services)

Term of contract: March 2008 – March 2011

Personnel: Above named investigators and additional technicians.

Equipment: A variety of equipment will be purchased by the various subcontractors and agencies associated with this work.

Deliverables and dates:

Year 1:

- Quarterly progress reports.
- Breach III internet website.
- Flood and Erosion Hazard Analysis Report.
- Restoration Practitioners and Resource Managers Modeling workshop.

Year 2:

- Quarterly progress reports.
- Restoration Practitioners and Resource Managers Modeling workshop.

Year 3:

- Quarterly progress reports.
- Restoration Practitioners and Resource Managers Modeling workshop.
- Final task reports.
- Final Hydrodynamic and Morphological Model Development.
- Liberty Island Basin Model Development.
- Final report.
- Several peer-reviewed journal articles to follow.

Comments: None

Spatial and Temporal Variability of Delta Water Temperatures: Long-term Trends and the Dynamics of Refugia

IEP 2010-148

Point person: Larry Brown (USGS)

Lead Agency: UCB

Questions: How do Delta water temperatures vary temporally and spatially? What are the historical trends in water temperature? Are there trends at the decadal and longer timescales that may be explanatory of the observed population declines? Spatially, how representative are point measurements of temperature in determining the thermal habitat of fish and other pelagic organisms? As an extension to this question, what is the spatial extent and persistence of thermal refugia? How do water temperature dynamics differ between Delta sloughs and the primary river channels? What is the spatial scale of interaction between these habitats?

Description: As global climate trends increase, Delta water temperatures are expected to increase, making delta smelt and other temperature-sensitive species more vulnerable. Previous work through the Computational Assessments of Scenarios of Change for the Delta Ecosystem (CASCaDE) project has developed statistical models of water temperature that can effectively forecast over a 100-year time horizon for a number of different climate change scenarios. The statistical model employed uses air temperature, solar radiation and water temperature from the previous day. The resulting model is more than just a correlation of water temperature with atmospheric drivers, but also has an auto-regressive component. This approach successfully projects what water temperature would be measured at the instrumentation site but it is unclear how representative those temperature measurements are of local or regional water temperatures. Because all of the long-term stations are located along the channels of the Sacramento or San Joaquin rivers, the question of how representative the observed water temperatures are of conditions in other sloughs and channels in the Delta still needs to be investigated. Specific tasks are as follows:

- Task 1- **Historical analysis of Delta water temperatures**: The statistical model will be applied to the last century to examine how water temperatures have evolved in the last 50 – 100 years. The first step will be to collect and analyze historical atmospheric data (air temperature) which provides the dominate forcing of the statistical model. Once the forcing data is identified and processed, the model will be explored in back-casting mode, where calculations are run backwards in time. Analyses of backcast temperatures will be pursued as motivated by discussion with the POD managers during presentations of results and other meetings.
- Task 2- **Evaluating spatial variability of Delta water temperatures:** This task will be accomplished by performing shorter timescale observations of spatial variability focused on the local variation of temperature in the Cache Slough complex, which serves as both a representative Delta habitat and has its own distinct ecological interest. Within Cache Slough, using direct observations of flows, temperature and conductivity, we will analyze the spatial and temporal variability of transport and refugia at a range of scales. Spatially, we will examine dispersion from the scale of the Cache Slough-Liberty Island complex to the mixing of differentially heated waters within a channel to the detailed exchange between shallow habitats and the deeper sloughs. Temporally, we will examine tidal and seasonal variations. Information from this task will help in understanding the dynamics of water temperature and thermal refugia in dendritic channel systems that include shallow water habitats.
- Task 3-**Analysis and modeling:** The primary modeling goal will be to develop descriptions of the spatial and temporal structure of water temperature locally and regionally surrounding historical measurements sites. Additionally, the investigators aim to develop a fundamental understanding of how temperature refugia may be developed and maintained.

Time period: June 2009 – June 2011

Resources required:

Cost: Funding was obligated with previous year funds.

PI(s): Mark Stacey (UCB), Erwin Van Nieuwenhuyse (USBR)

Contract needed / in place: In place via CESU.

Contract manager(s): Mark Stacey (UCB) and Erwin Van Nieuwenhuyse (USBR).

Term of contract: June 2009 – May 2011, considering an extension.

Personnel: Graduate student at UCB.

Equipment: None.

Deliverables and dates:

- Annual report including a summary of data collected and analysis pursued (December 2010).
- Two peer-reviewed publications and a PhD thesis will result from this research.

Plankton Dynamics in the Sacramento-San Joaquin Delta: Long-term Trends and Trophic Interactions

IEP-related 2010-150 (2009 CALFED Science Fellow)
Point person: Anke Mueller-Solger (DSC)
Lead Agency: UCD
Questions: What are the long-term trends of the Delta's zooplankton community and can distinct sub-regions be identified that show similar patterns? What are the long-term patterns in zooplankton species and functional groups? How does phytoplankton and environmental variability affect zooplankton production on a Delta-wide scale and appropriate sub-regions? Are seasonal patterns between primary producers and zooplankton consistent throughout the sampling record? How do changes in plankton community composition relate to biotic and environmental variation?
Description: This project seeks to identify: (1) long-term spatial and temporal patterns in zooplankton; (2) long-term interactions between primary producers and zooplankton; and (3) biotic interactions in the plankton community. Analyses of historical data, trends, seasonal variability, and foodwebs will be conducted using a variety of techniques appropriate to each analysis area.
Time period: September 2008—September 2010
Resources required:
    Cost: $83,000 in 2010.
    PI(s): Monika Winder and Geoffrey Schladow (UCD)
        Contract needed / in place: In place.
        Contract manager(s): Rebecca Fris (DSP)
        Term of contract: September 2008 – September 2010
    Personnel: Above named investigators.
    Equipment: None
Deliverables and dates:
Year 1:

- Annual progress report.
- Presentations at local (Delta Science Conference) and national or international professional meetings.
- Draft of first manuscript.

Year 2:

- Annual progress report and final research report summarizing results and accomplishments.
- Presentations at local (Delta Science Conference) and national or international professional meetings.
- Peer-reviewed scientific publications (at least 2 are anticipated).

Comments: None

Environmental Controls on the Distribution of Harmful Algae and Their Toxins in San Francisco Bay

IEP-related 2010-152 (2009 CALFED Science Fellow)
Point person: Anke Mueller-Solger (DSC)
Lead Agency: DSP
Questions: What predicted environmental changes favor dinoflagellates and cynobacterial growth in the South Bay and Delta, respectively? What predicted environmental changes will result in increased frequency in blooms of these species? Does alleviating light limitations increase the influence of nutrient availability and relative concentrations, and does that result in enhanced toxicity of the harmful algae? Can spatial and temporal mapping of harmful algae and their toxins help explain the triggers for the algal blooms, and provide a baseline for measuring future trends and forecasting?
Description: This project will determine the distribution of harmful algae and their toxins in San Francisco Bay and characterize the environmental parameters that control toxin production by harmful algae in the Bay. It will combine monitoring and mapping of biological, chemical, and physical components throughout the Bay and Delta along with controlled manipulations to examine specific parameters likely to control growth and toxicity in the natural population of these species.
Time period: September 2008—August 2010
Resources required:
    Cost: $82,000 in 2010.
    PI(s): Cecile Mioni and Adina Paytan (UCSC)
        Contract needed / in place: In place.
        Contract manager(s): Rebecca Fris (DSP)
        Term of contract: September 2008 – September 2010
    Personnel: Above named investigators.
    Equipment:
Deliverables and dates:

- Monthly monitoring and data collection of harmful algae and toxins in the San Francisco Bay and Delta.
- *In-situ* incubation experiments conducted seasonally.
- Publications describing the results of the research.
- Presentations describing the results of the research.
- Monthly report cards describing the health of the Bay, published on the website.
- Monthly reports of elevated levels of toxins or toxic algal in the “Harmful Algal Blooms” section of the website.

Comments: None

Comparison of Nutrient Sources and Phytoplankton Growth and Species Composition in the Sacramento and San Joaquin Rivers: Their Roles in Determining Productivity and Food Web Conditions in Suisun Bay and the Delta

IEP-related 2009-153 (2008 CALFED Science supplemental grant)
Point person: Anke Mueller-Solger (DSC)
Lead Agency: SFSU-RTC & DSP
Questions: How do differences in nutrient and phytoplankton community composition between the San Joaquin (SJ) and Sacramento (Sac) rivers influence conditions downstream in the Delta and Suisun Bay? How do phytoplankton growth rates and community structure respond to the

differences in nutrient concentrations in the SJ River vs. the Sac River, resulting from differences in wastewater treatment?

Description: Low primary production rates and changes in phytoplankton community composition may play an important role in the pelagic organism decline. Recent work by Dugdale et al. (2007) and Wilkerson et al. (2006) has shown that elevated ammonium concentrations reduce phytoplankton production rates in San Francisco and Suisun bays by inhibiting nitrate uptake. The primary sources of ammonium to the Delta are wastewater treatment plants (WWTPs). It is not yet known whether ammonium at concentrations measured in the Delta, inhibits freshwater diatom production rates (similar to the inhibition observed in San Francisco and Suisun bays) and thus could be a contributing cause to the low primary production rates in the Delta.

This work plan element is closely linked to an ongoing DSP project (PIs: Dugdale and Wilkerson; April 2007- February 2010, Agreement #1039) focusing on phytoplankton production in Suisun Bay and extends these investigations into the Delta. It focuses on the effects of the 2 main WWTPs in the Delta: the SRWTP and the Stockton WWTP ("Stockton"). The SRWTP is the largest sewage treatment plant in the Delta. Its effluent is discharged into the Sacramento River at Freeport. It employs secondary treatment and the main form of nitrogen in its effluent is ammonium. The Stockton WWTP is the largest WWTP in the southern part of the Delta. It completed an upgrade to tertiary treatment in 2008 and now discharges primarily nitrate into the lower San Joaquin River in Stockton. These treatment differences, along with differences in river nutrient loadings, offer a great opportunity for a comparative investigation of the effects of regional differences in river and WWTP nutrient loadings on Delta phytoplankton. Field studies will include transect surveys of nutrients and phytoplankton along the Sacramento and San Joaquin rivers and as well as phytoplankton "grow-out" enclosures experiments (. Dugdale et al., 2007).

Field sampling will consist of under-way measurements of temperature, salinity, turbidity, fluorescence, as well as continuous sampling using flow cytometry and the FluoroProbe. Discrete sampling at river and Delta stations will include vertical profiles of temperature and salinity, and light penetration using a conductivity, temperature and depth (CTD) instrument fitted with a photosynthetically active radiation (PAR) sensor as well as a Secchi disk. Water will be sampled at the surface and near the bottom for determination of inorganic nutrients (NO_3^-, NO_2^-, NH_4^+, PO_4, Si(OH)4), dissolved inorganic carbon (DIC), and size fractionated chlorophyll. Primary production and phytoplankton
NO_3^- and NH_4^+ uptake will be assessed under saturating light (50% of PAR) and light limited (10% of PAR) conditions using 15N/13C tracer methods in light attenuated, flow-through incubators. Comparison of NH_4^+ gradients along the river with 15 NH_4^+ uptake rates will provide an indication of nitrification. Samples will be collected for phytoplankton identification by microscopy, flow cytometry high-performance liquid chromatography (HPLC) technique, and the FluoroProbe at each of the 24 discrete stations. Grow-out experiments will be conducted at locations downstream of the Sacramento and Stockton WWTPs. If NH_4^+ depletion rates in grow-outs are greater than the measured 15 NH_4^+ uptake rates, then this will suggest the presence of nitrification.

Time period: 2008 – 2010

Resources required:

Cost: $338,377 through a DSP (previously CALFED) supplemental grant.

PI(s): Richard Dugdale, Alex Parker and Frances Wilkerson (SFSU) and Anke Mueller-Solger (DSC)

Contract needed / in place: In place.

Contract manager(s): Shem Ayalew (DSP)

Term of contract: January 2008 – April 15, 2010

Personnel: Above named investigators and 2 technicians.

Equipment: None

Deliverables and dates:

- Data and technical reports, presentations at IEP meetings, EET workshops and the Delta Science Conference.
- Publications in peer-reviewed journals.

Spatial and Temporal Quantification of Pesticide Loadings to the Sacramento River, San Joaquin River, and Bay-Delta to Guide Risk Assessment for Sensitive Species

IEP-related 2009-154 (DSP-funded)

Point person: Rich Breuer (DWR)

Lead Agency: DWR

Questions: What is the fate and transport of agricultural chemicals in the Sacramento and San Joaquin rivers? When and where should we be looking for potential toxicity based on modeling results?

Description: A weight-of-evidence analysis is being conducted to identify major sources of pesticide loadings to the Sacramento River, San Joaquin River, and Bay-Delta estuary. The objective of this study is to improve decision making and optimize resource spending across a number of federal, state, and regional water quality programs. Objectives are being addressed through a combination of tools, including GIS analysis, simulation modeling, and an evaluation of existing in-stream monitoring. Results are being used to: (1) provide further knowledge of the fate and transport of agricultural chemicals (e.g., copper, organophosphates) and emerging pesticides (e.g., pyrethroids), (2) match results to the location of sensitive species critical habitats, (3) identify and rank pesticide source areas, (4) evaluate implications of future pesticide use trends and changes in climatic conditions, (5) aid in developing plans to improve ecosystem quality and water quality by strategic placement of best management practices and hydrologic operations, (6) support future monitoring programs (strategic locations, sampling frequency), (7) link results to life cycle models currently under development for striped bass and delta smelt, as well as existing models for salmonids, and (8) provide a data-link to support other water quality models and population models.

Time period: 2008 – 2010

Resources required:

Cost: $395,000

PI(s): Minghua Zhang(UCD) and W. Martin Williams (Waterborne Environmental, Inc.)

Contract needed / in place: DSP receivable and subcontracts to UCD and Waterborne Inc. in place.

Contract manager(s): Brianne Noble (DWR)

Term of contract: July 2008 – June 2010

Personnel: Above named investigators and Technical Advisory Group (TAG) that provides technical direction on the project to ensure that cross-agency goals are met. The

TAG consists of 15 members representing federal and state agencies, universities and private industries. Their involvement will begin at the initiation of the project to coordinate data collection and avoid duplication of efforts with other activities that either have occurred or are in progress. Interaction with the TAG will be continuous and iterative.

Equipment: None

Deliverables and dates: The TAG will receive progress reports and other interim communication and redirect efforts as necessary to maximize the success of this study.

2010 New IEP POD Elements

Acute and Chronic Toxicity of Contaminant Mixtures and Multiple Stressors

IEP 2010-157

Point person: Stephanie Fong (CVRWQCB)

Lead Agency: CVRWQCB

Questions: How do various contaminant mixtures affect their toxicity to *Hyalella azteca*?

Description: This study will address the mixture toxicity of several contaminants of concern in the Delta in the presence and absence of other environmental stressors (temperature, food deprivation). A sensitive resident invertebrate species, the amphipod *Hyalella azteca,* will be used as test organism, and toxicity will be quantified by means of acute (10 day survival) and chronic (growth, swimming ability) endpoints.

Time period: March 2010-June 2011

Resources required:

Cost: $40,000 contract and CVRWQCB staff time.

PI(s): Inge Werner

Contract needed / in place: In place May 2010.

Contract manager(s): Stephanie Fong (CVRWQCB) and Inge Werner (UCD ATL)

Term of contract: N/A

Personnel: Inge Werner and graduate student (UCD)

Equipment: No new equipment is needed; these are typical laboratory tests.

Deliverables and dates:

- Peer-reviewed study plan (July 2010).
- Progress reports and/or participation in the POD Contaminants Work Team (CWT), quarterly throughout the study.
- Final report (June 2011).

Comments: None

Advancing Procedures for Extracting and Recovering Chemicals of Concern from Sediment Interstitial Water

IEP 2010-158

Point person: Stephanie Fong (CVRWQCB)

Lead Agency: CVRWQCB

Questions: How do sediment-bound toxicants react to TIE manipulations when extracted from the interstitial water?

Description: This study will address a critical need to develop better techniques to extract and recover organic chemicals in sediment interstitial water, as part of the TIE Phase II toxicant identification process. The study will implement a set of tests to evaluate better extraction and elution techniques, and is designed to complement other ongoing efforts.
Time period: February 2010 – June 2011
Resources required:
Cost: $40,000 contract and CVRWQCB staff time.
PI(s): Ron Tjeerdema and John Hunt (UCD)
Contract needed / in place: In place February 2, 2010.
Contract manager(s): Stephanie Fong (CVRWQCB)
Term of contract: N/A
Personnel: John Hunt, Bryn Phillips, and laboratory staff (UCD) and Stephanie Fong (CVRWQCB)
Equipment: No new equipment is needed; these are typical laboratory tests.
Deliverables and dates:

- Peer-reviewed study plan (July 2010).
- Progress reports and/or participation in the POD CWT, quarterly throughout the study.
- Final report (June 2011).

Comments: This will augment ongoing efforts by San Francisco Estuary Institute (SFEI) .

Investigation of Pyrethroid Pesticides in the American River

IEP 2010-159
Point person: Stephanie Fong (CVRWQCB)
Lead Agency: CVRWQCB
Questions: Is storm water runoff to the American River toxic to *H. azteca*?
Description: Samples will be collected during 3 separate rain events at a minimum of 4 sites on the American River below Folsom Dam. Each river site will be sampled between 2 and 4 times during each rain event. Samples will be collected at up to 5 of the largest discharges of runoff to the American River below Folsom Dam. Each discharge site shall be sampled 2 times during 3 separate rain events, yielding up to 30 samples. All samples will undergo chemical analysis for pyrethroids. River samples (not discharge samples) will be tested with *H. azteca*, and toxic samples will undergo toxicity identification evaluations and follow-up sampling.
Time period: December 1, 2009 – May 30, 2011
Resources required:
Cost: $100,000
PI(s): Don Weston (UCB)
Contract needed / in place: In place May 26, 2010.
Contract manager(s): Stephanie Fong (CVRWQCB) and Don Weston (UCB)
Term of contract:
Personnel: Don Weston and laboratory staff (UCD)
Equipment: No new equipment is needed; these are typical laboratory tests.
Deliverables and dates:

- Quality Assurance Project Plan (QAPP) and monitoring plan (July 2010).
- Sample collection (March 2010).
- Submission of electronic data (May 2010).
- Progress reports and/or participation in the POD CWT, quarterly throughout the study.

- Final report (May 2011).
- Journal article, if accepted (June 2011).

Comments: This study is following up on toxic results from monitoring performed in early 2009.

Full Life-Cycle Bioassay Approach to Assess Chronic Exposure of Pseudodiaptomus forbesi to Ammonia

IEP 2010-160

Point person: Mark Gowdy (SWRCB)

Lead Agency: SWRCB

Questions: What are effects of chronic exposure to ammonia for the copepod *Pseudodiaptomus forbesi*?

Description: The study will use full life-cycle tests to assess the effects of chronic exposure to ammonia for the estuarine copepod *Pseudodiaptomus forbesi.* This copepod is the dominant zooplankton during summer and fall months and is important food for pelagic fishes in the upper San Francisco Estuary. *P. forbesi* has 3 distinguishable life stages (i.e., naupliar, copepodite (juvenile), and sexually mature adult stages). By performing a 30 day bioassay at 25°C, eggs will hatch and grow up to all life stages, therefore facilitating counting at test termination. Copepods have an easily distinguishable sexual morphology and their egg sacs are external, making clutch sizes easy to count. Such characteristics will allow for the assessment of life table parameters and sublethal ammonia effects on the reproduction of this copepod in a period of 30 days.

Time period: January 2010 – April 2010

Resources required:

Cost: $77,000

PI(s): Swee the (UCD)

Contract needed / in place: In place December 2009

Contract manager(s): Mark Gowdy (SWRCB)

Term of contract: January 2010 – April 2010

Personnel: Swee Teh and ATL staff

Equipment: No new equipment is needed; these are typical laboratory tests.

Deliverables and dates:

- Draft final report (March 2010).
- Presentation of results at the POD-CWT Conference (date TBD).
- Final summary report (April 2010).

Comments: None

Acute Toxicity of Ammonia/SRWTP Effluent on Delta Smelt and Surrogate Species

IEP 2010-161

Point person: Mark Gowdy (SWRCB)

Lead Agency: SWRCB

Questions: What is the range of NOEC and low LOEC effect ranges of SRWTP effluent mixed into Sacramento River water from Garcia Bend for delta smelt? Can larval rainbow trout be used as a surrogate species for toxicity testing and toxicity identification evaluations?

Description: The goal of toxicity testing (including reference toxicants) with delta smelt is to determine the range of SRWTP effluent toxicity. In previous toxicity tests with delta smelt, ammonia/um in effluent was shown to be more toxic (7-day LC50: 5.4 mg/L) than ammonia/um

alone (7-day LC50: 7.5 mg/L). In addition, larval rainbow trout will be used in concurrent toxicity tests (including reference toxicants) to evaluate if they could be used as a surrogate species for delta smelt in toxicity testing and enable the application of toxicity identification evaluations when needed.
Time period: January 2010 – December 2010
Resources required:
  Cost: $65,000
  PI(s): Inge Werner (UCD)
    Contract needed / in place: In place.
    Contract manager(s): Mark Gowdy (SWRCB) and Inge Werner (UCD ATL)
    Term of contract: January 2010 – December 2010
  Personnel: Inge Werner and ATL staff
  Equipment: No new equipment is needed; these are typical laboratory tests.
Deliverables and dates:

- Final draft report (October 2010).
- Peer review of draft report and submission of final report (December 2010).

Comments: None.

Potential Loss of Life History Variation and the Decline of Delta Smelt

IEP 2010-162
Point person: Mark Gowdy (SWRCB)
Lead Agency: SWRCB
Questions: Has selective entrainment of early-spawned larvae been of sufficient magnitude and duration to cause undesirable evolutionary change in delta smelt? If such changes have occurred, how can management reverse the process and contribute to restoration of the species?
Description: This project will investigate the so-called, Big Mama hypothesis (term coined by Kenny Rose, LSU), for the decline of delta smelt. Larger, more robust, delta smelt (i.e., big mamas) tend to reproduce earlier in spring, spawning larger numbers of better provisioned larvae that are more likely to survive and reproduce than those hatching from smaller parents later in the spawning season. Early-spawned larvae, however, comprise the majority of annual entrainment losses in the SWP and CVP export facilities. This imposes a form of artificial selection on the population that may oppose natural selection. Moreover, the very short generation time (only 1 year) of delta smelt implies that any potentially undesirable evolutionary changes would manifest rather quickly (e.g., < 10 years). Given the seriousness of the delta smelt problem, verifying the accuracy and scope of the Big Mama hypothesis is critical for understanding restoration options for this imperiled species. The primary product of this work will be a completed manuscript for submission to a peer-reviewed scientific journal.
Time period: October 2009 – July 2010
Resources required:
  Cost: $32,000
  PI(s): Bill Bennett (UCD)
    Contract needed / in place: In place
    Contract manager(s): Mark Gowdy (SWRCB)
    Term of contract: October 2009 – July 2010
  Personnel: Bill Bennett (UCD)
  Equipment: Software upgrade.

Deliverables and dates:

- Manuscript evaluating the Big Mama hypothesis (July 2010).

Comments: None

Comparison of Flow and Transport Models for the Sacramento-San Joaquin Delta

IEP 2010-163

Point person: Mark Gowdy (SWRCB)

Lead Agency: SWRCB

Questions: How do the 1- and 2-D model simulations of flow and contaminant transport in the delta compare relative to one another and against measured conditions?

Description: The purpose of this study is to compare the performance of diverse modeling approaches in 1- and 2-D to simulate the flow and transport in the Sacramento-San Joaquin Delta, to identify model improvement needs, and Delta locations with poorer flow representation. The project will define 7 flow scenarios *(*4 corresponding to low and high flows for which field data are available) to compare model performance, for a common set of boundary conditions. Two more scenarios will correspond to events of low and high pumping, to be defined. All models will be run with the same boundary conditions, the same domain and with the same flow forcing mechanisms. An additional scenario of sea level rise will be included in the analysis. Models to be compared will include: RMA 1- and 2-D models, RMA-TAM (tidally averaged model), and DSM2.

Time period: March 2009 – June 2010

Resources required:

Cost: $59,000

PI(s): Fabian Bombardelli (UCD)

Contract needed / in place: January 2009

Contract manager(s): Mark Gowdy (SWRCB)

Term of contract: March 2009 – June 2010

Personnel: Fabian Bombardelli (UCD) and PhD student

Equipment: Required computer equipment and software is already available.

Deliverables and dates:

- Final report of results (June 2010).
- Presentation of results to the California Water Environmental Modeling Forum (CWEMF) and DSM2 users’ group meetings (dates to be determined).

Comments: None

Spatial and Temporal Variability in Nutrients in Suisun Bay in Relation to Spring Phytoplankton Blooms

IEP 2010-164

Point person: Karen Taberski (SFBRWQCB)

Lead Agency: SFBRWQCB

Questions: How do nutrients vary in Suisun Bay temporally and spatially and how does this relate to spring phytoplankton blooms? What are the major sources of ammonium in Suisun Bay?

Description: This study would be an extension of earlier work on the effect of ammonia on phytoplankton blooms in the estuary. The purpose of this project is to better understand the

variability of nutrients in Suisun Bay, their relation to spring phytoplankton blooms, and sources of ammonium.
Time period: Sampling will be conducted weekly from March to June 2010. Analysis should be completed by August 31, 2010.
Resources required:
    Cost: $25,000 contract from SWAMP to Dick Dugdale SFSU-RTC for nutrient analysis.
    PI(s): Dick Dugdale (SFSU)
        Contract needed / in place: In place February 1, 2010.
        Contract manager(s): Russell Fairey/ Karen Taberski (SFBRWQCB)
        Term of contract: February 1, 2010 – December 30, 2010
    Personnel: Water Board SWAMP staff and SFSU Romberg Tiburon staff
    Equipment: No new equipment is needed; these are typical laboratory tests.
Deliverables and dates:

- Data delivered to SWAMP Data MT at Moss Landing Marine Labs in SWAMP format on August 31, 2010.
- We intend to contract for a report next fall.

How is this activity related to HSG? The results of this analysis will contribute to the understanding of toxicant effects in the Delta.
Comments: None

Ammonia Sampling Program for the Sacramento-San Joaquin Delta Estuary
IEP 2010-165
Point person: Chris Foe (CVRWQCB)
Lead Agency: CVRWQCB
Questions: What are the concentrations and distribution of chlorophyll, ammonia, and various nutrients, primarily in the lower Sacramento River and northern Delta? Are total and unionized ammonia concentrations in these areas potentially toxic to sensitive resident aquatic organisms? Provide data to support development of an ammonia fate and transport model.
Description: The purpose of this study is to collect water quality data, including total and unionized ammonia, primarily in the lower Sacramento River and northern Delta to determine whether ambient concentrations are potentially toxic to sensitive resident aquatic organisms and to support development of an ammonia fate and transport model. A spatial emphasis is placed on the lower Sacramento River and northern Delta as the biological risk from elevated ammonia is likely to be greatest here. However, other areas of the estuary are also proposed for monitoring as it is likely that the SRWTP is not the only source of ammonia. Temporally, the sampling emphasizes the months of March through June as delta smelt spawn in the northern Delta around Lindsey and Cache Sloughs and juvenile salmon are migrating down the Sacramento River and out into the estuary during these months. Samples are being collected by CVRWQCB staff and analyzed by Randy Dahlgren's lab at UCD.
Time period: March 2009 – July 2010
Resources required:
    Cost: $68,000 (analytical services only)
    PI(s): Chris Foe (CVRWQCB) and Randy Dahlgren (UCD)
        Contract needed / in place: (analysis contract) March 2009
        Contract manager(s): Mark Gowdy (SWRCB)
        Term of contract: March 2009 – March 2010 (analytical contract)

Personnel: Chris Foe and CVRWQCB staff and Randy Dahlgren's lab staff
Equipment: Nothing new; typical sampling and laboratory equipment.

Deliverables and dates:

- Regional Board staff draft interpretive report (May 2010).
- Final report 30-days after receiving comments from POD-CWT.

Comments: None

Using Genetic Techniques to Detect Mississippi Silverside (Menidia audens) Predation on Larval Delta Smelt (Hypomesus transpacificus)

IEP 2010-166
Point person: Ted Sommer (DWR)
Lead Agency: DWR

Questions: Can PCR be used to detect delta smelt DNA in silverside guts? How sensitive is the PCR method to detecting delta smelt DNA in gut contents? Do wild silverside predate larval delta smelt and at what frequency? Are there any patterns between larval delta smelt predation and environmental variables (flow, turbidity, salinity, temperature) or other constituents in the gut?

Description: This project addresses top-down trophic effects on delta smelt populations by developing a new set of genetic tools for detecting predation of delta smelt larvae (though the technique will be equally applicable to juvenile and adult delta smelt). These genetic tools (PCR assays) are being developed for use on Mississippi silversides, which are theorized to predate larval delta smelt. Testing and characterization of the assays will use captive silversides and delta smelt, and will include experiments to model the degradation of smelt DNA in the guts of silversides and determine the sensitivity of the assay using dilution experiments. Cross-reactivity will also be tested using genetic samples from multiple fish species from around the Delta. The refined assay will then be used on wild silversides sampled from areas where larval delta smelt are known to occur for the purposes of detecting predation events.

Time period: June 2010 – June 2011

Resources required:
Cost: $68,389
PI(s): Brian Schreier (DWR), Bernie May and Melinda Baerwald (UCD)
Contract needed / in place: In process.
Contract manager(s): Rich Breuer (DWR) and Bernie May (UCD)
Term of contract: TBD
Personnel: Brian Schreier and Nick Van Ark (DWR)
Equipment: Molecular reagents, lab supplies, fish aquaculture supplies, dissection and preservation supplies.

Deliverables and dates:

- Poster presentation at IEP Annual Workshop (2011).
- Results and assay details presented at Delta Science Conference and published in an appropriate peer-reviewed journal (October 2010).
- Results and assay details published in an appropriate peer-reviewed journal.
- Development and characterization of a successful assay will be reported in the IEP Newsletter.

Comments: This pilot study aims to develop tools that will be applicable for detecting predation on delta smelt by multiple different predators. These predators will be expanded in future studies to include multiple species of non-native centrarchids and striped bass. Additionally, utilization of the assay to detect predation on longfin smelt will be relatively straight forward and may also be a future direction this research could take.

Investigating the Presence, Migration Patterns and Site Fidelity of Sub-Adult Striped Bass

2010-167

Point person: Ted Sommer (DWR)

Lead IEP Agency: DWR

Questions: What geographical areas are sub-adult bass using and when? How do the patterns of presence and movements vary seasonally, annually and between age classes?

Description: Striped bass (*Morone saxatilis*) are the major pelagic predator in the San Francisco Estuary. "Top down" effects from striped bass and other species are being evaluated as part of ongoing POD studies (Sommer et al., 2007). Of particular interest is whether striped bass have substantial effects on the threatened delta smelt Since striped bass are a relatively well-monitored species, there has been good progress in understanding some of the major factors that affect striped bass populations (Kimmerer et al., 2001). However, there are important data gaps in our knowledge of this species. For example, current monitoring programs do not effectively measure the population and distribution of sub-adult (1-3 year old) striped bass, however this group is likely to be the most abundant group of pelagic predators in the estuary. Hence, there is a need to understand basic information about the distribution and movements of sub-adult fish in the estuary.

Using the existing 456 km telemetry array located between Colusa on the Sacramento River out to the Golden Gate on the San Francisco Bay, 100 sub-adult striped bass (290-350 mm) total will be tagged with V9-2L coded ultrasonic tag with an inter pulse burst interval of about 90 seconds and a life of 417 days. Equal numbers of fish will be caught and tagged between 3 general geographic areas: Sacramento River, Delta and San Francisco Bay.

Time period: June 2010 – July 201

Resources required:

Cost: $75,000

PI(s): Cynthia LeDoux-Bloom and Ted Sommer (DWR), Bernie May and Melinda Baerwald (UCD)

Contract needed / in place: Not needed.

Contract manager(s): N/A

Term of contract: N/A

Personnel: Brian Schreier and Cynthia LeDoux-Bloom (DWR)

Equipment: 100 Vemco tags, existing receiver array, small boat during tagging.

Deliverables and dates:

- Poster or oral presentation at the IEP Annual Workshop (2011).
- Presentation at 2011 Delta Council.
- IEP Newsletter article.
- Journal articles, if appropriate.

Comments: Top-down effects from striped bass and other species are being evaluated as part of ongoing POD studies (Sommer et al., 2007). The impact of striped bass on the POD is thought to be significant, although little data exists showing their migration and movement patterns due to lack of data. Knowledge of striped movement patterns will provide valuable information regarding timing of habitat usage and suitability, and may have the potential ability for future integrated analyses of multiple data sets.

Monitoring inter-annual variability of delta smelt population contingents and growth

IEP 2010-168
Point person: Randy Baxter (DFG)
Lead Agency: UCD
Questions: Can life-history and growth of fish salvaged at CVP and SWP be compared to fish that survive the TNS to determine the effects of entrainment and salvage? What are the habitat effects on delta smelt population dynamics? Do life-history contingents vary inter-annually, in association with growth, freshwater outflow, water temperature, abundance? Does growth rate increase with increased fall outflow?
Description: The primary goal of this research is to gain a better understanding of the mechanisms (e.g. climate variability, hydrology) responsible for different life history contingents and how salvage at CVP and SWP could alter life history diversity. Archived samples from 1999 – 2008, already prepared for otolith microstructure and microchemistry studies, will be assayed with a laser line from the ore to the edge to reconstruct the entire life history. Sub-adult and adult sampled collected by the IEP in 2010 will be examined for microchemistry and growth rates will be quantified by otolith microstructure analysis.
Time period: June 2010 – June 2011
Resources required:
    Cost: $98,000
    PI(s): Jim Hobbs (UCD)
        Contract needed / in place: In place.
        Contract manager(s): Erwin Van Nieuwenhuyse (USBR)
        Term of contract: 1 year.
    Personnel: Above named investigator
    Equipment: Needed equipment is already housed at the Interdisciplinary Center for Inductively Coupled Plasma Mass Spectrometry at UCD.
Deliverables and dates:

- Oral presentations will be provided to the IEP Management Team as requested.
- IEP Annual Workshop presentation, as requested.
- A manuscript will be submitted to a high-impact journal.

Delta Smelt Feeding and Food Web Interactions

IEP 2010-169
Point person: Larry Brown (USGS)
Lead Agency: SFSU
Questions: To what extent is individual delta smelt limited by the food supply in the LSZ, and how is food limitation affected by flow variability? What are the food availability and quality for delta smelt in the LSZ, and how are they affected by flow variability? What are the effects of gelatinous plankton in the LSZ on delta smelt and the food web, and how are they affected by flow variability?
Description: The proposed project investigates the food supply for delta smelt, how it is affected by predators and competitors, and how these interactions are affected by interannual variability in freshwater flow. This work comprises 3 tasks: (1) food limitation and functional response of

larval to early juvenile delta smelt; (2) population dynamics and production of the zooplankton prey of delta smelt; and (3) the role of jellyfish in the delta smelt food web.

In Task I, we will examine how the feeding of the early life history stages of delta smelt depends on concentration of copepod prey (=functional response). We will also measure the metabolism of early stage delta smelt, which will be used to estimate the energetic impact of the functional response, and investigate behavioral changes in feeding related to predator avoidance and turbidity. In Task II, we will employ a combination of field, laboratory, and modeling approaches to examine the population dynamics of the copepod *Pseudodiaptomus forbesi*, the principal prey of delta smelt in the LSZ and the freshwater Delta during fall. In Task III, we will measure the abundance and distribution of gelatinous predators throughout the LSZ during fall and quantify feeding rates of the gelatinous competitors of delta smelt using gut content analysis.

Time period: June 2010 – June 2011

Resources required:

Cost: $399,840

PI(s): Wim Kimmerer and Lindsay Sullivan (RTC-SFSU); Jan Thompson (USGS)

Contract needed / in place: In process.

Contract manager(s): Erwin Van Nieuwenhuyse (USBR) and Wim Kimmerer (SFSU)

Term of contract: TBD

Personnel: Toni Ignoffo and Anne Slaughter (RTC-SFSU)

Equipment: Stereomicroscope with image analysis capabilities.

Deliverables and dates:

- Poster or oral presentation at the IEP Annual Workshop or EET (February 2011).
- IEP Newsletter article (early 2011).
- Final 2010-11 report (July 2011).

How is this activity related to HSG? This proposed project addresses the "bottom-up" or food supply topic of the Pelagic POD conceptual model (Sommer et al., 2007; Baxter et al., 2008). As applied to delta smelt, this topic has 2 components or subsidiary questions: (1) To what extent is growth or survival of delta smelt food limited; and (2) What limits the availability of food for delta smelt? In particular, this project focuses on the food supply of delta smelt in the LSZ during late summer to fall. The principal reason for this focus is that salinity during this period has been persistently high since around 1999, roughly coincident with the POD, and several possible causal links between fall flow/salinity and smelt abundance have been identified (USFWS, 2008). This project addresses numerous potential mechanisms by which flow variability may affect the abundance of food for delta smelt. Broadly these include hydrodynamic effects, food effects, and predatory losses: (1) Changes in the physical shape or size of the low-salinity habitat cause a reduction in abundance of delta smelt or their food when X2 is high (landward); (2) Low flow results in reduced transport of phytoplankton and zooplankton from the freshwater Delta into the LSZ, reducing biomass in the LSZ; (3) Landward X2 exposes foodweb organisms to pumping losses, reducing abundance in freshwater and therefore transport to the LSZ; (4) Low flow results in a higher concentration of ammonium entering the LSZ, suppressing phytoplankton growth; (5) A landward X2 value (LSZ position) results in landward settlement of the clam *Corbula amurensis* and, in turn, reduction in biomass of phytoplankton, bacteria, microzooplankton, and mesozooplankton in the LSZ due to clam grazing; (6) A stable X2 value (particularly during clam recruitment periods) allows for a high abundance of clams to overlap with the LSZ over a period of months, maximizing consumption of copepods by clams, whereas

movement of the LSZ in either direction reduces this overlap; (7) Overlap between the copepods *Pseudodiaptomus forbesi* and *Limnoithona tetraspina* increases with a landward X2, intensifying competition for food between these copepods; (8) Overlap between *P. forbesi* and the predatory copepod *Acartiella sinensis* increases with a landward X2, intensifying predation on early stages of *P. forbesi*; and (9) Recruitment of gelatinous plankton to the LSZ is higher when X2 is landward, increasing predation on zooplankton and possibly also delta smelt.
Comments: This project will build on our experience and knowledge gained in the CALFED-funded Food web Study (CALFED Project SCI-05-C107, 2006-2010) and delta smelt feeding studies (CA Bay-Delta Authority, Sea Grant Authorization, U-04-SC-005, 2007-2009). Additionally, we will use IEP zooplankton and water-quality monitoring data to provide a long-term context for the proposed study. It will further be linked to the following funded and proposed projects: (1) Copepod feeding study (funded, National Science Foundation), (2) Hydrodynamic modeling (Kimmerer, Gross, MacWilliams, IEP), (3) Clam grazing study (Thompson, Gehrts, IEP), (4) Clam physiology study (Stillman, IEP) and (5) Ammonium investigation (Dugdale, Wilkerson, Parker, IEP).

How Will Longfin Smelt Respond to Fall X2 Manipulations? Experimentally Determining Early Life Stage Sensitivity to Salinity

IEP 2010-170
Point Person(s): Randy Baxter (DFG)
Lead IEP Agency: UCD
Questions: What is the optimal salinity range for longfin smelt embryo hatching, and larval rearing success? Does otolith core chemistry reflect maternal or environmental influence? How does the fall X2 position affect spawning and larval rearing habitat for longfin smelt recruitment?
Description:

- **Develop culture techniques and examine salinity tolerance for longfin smelt eggs and larvae:** We will develop fish culture techniques to provide specimens for research and information on egg-incubation-time necessary for assessing the duration of embryo vulnerability to disturbance (e.g., dredging or changing salinity). The fish-culture protocols developed for delta smelt (Baskerville-Bridges et al., 2005) will be modified to accommodate the more euryhaline longfin smelt. We will capture longfin smelt directly or receive live adults from on-going field monitoring studies. Adults will be held close to the salinity and temperature of field-capture locations. Fish are monitored for ripe ova and sperm at transfer to culture tanks and either spawned immediately (through manual expression of gametes) or monitored closely at field-caught salinities until ready to spawn. Fertilization of ova is conducted in fresh water or 2 ppt salt water. Fertilized eggs are totaled (volumetrically estimated) and transferred to egg-incubators (ca. 2-3000/incubator, 10-12 °C). Incubation duration will be documented. At hatch, larvae will be transferred to a larval tank system (70l L black tanks with a re-circulating system at 12 ºC) for rearing at 2 or 4 ppt saltwater. Water will be greened (Nanochloropsis spp; 10 NTU) daily. Two cultures of live prey (rotifers and *Artemia* nauplii) will be reared and fed to longfin smelt larvae at 2-hour intervals daily. Subsets of larvae will be monitored for growth and development, and preserved to create a developmental series and for subsequent otolith analysis. Salinity tolerance of eggs and larvae will be examined in order to shed light on, whether fall X2 location influences longfin smelt spawning locations, egg incubation and larval rearing locations, and potential vulnerability of adults and larvae to south delta entrainment. The total number of treatments and replications depends on the number of broodfish collected, subject to our permit limits. Test salinities for 2011 may deviate slightly from what is described below based on recent findings (January - February 2010).

- **Maternal and environmental influence on otoliths core chemistry**: Previous POD funded research examining salinity histories of longfin smelt revealed that many individuals exhibit otolith strontium isotope ratios indicative of (1) high salinities at the core, followed by (2) low salinities shortly outside the core (post-larval to juvenile stages (3) and then a return to high salinity into maturity. This pattern may reflect a maternal transfer of marine-derived strontium to developing offspring (i.e., otolith core) or, could reflect salinities at which eggs were incubated and hatched. We will test the environmental influence mechanism by exposing embryos to different salinity levels and rearing larvae at fresh, 2 ppt and 5 ppt for about 30 days. Experiments will be conducted in conjunction with culture experiment from task 1 (above). Maternal influence will be examined by reconstructing maternal life history of brood fish with otolith strontium isotope ratios prior to first clutch release, and holding adults for a period of time in freshwater prior to a release of a second clutch. Results from these experiments will provide us a powerful tool (validated otolith chemistry) for examining how freshwater management may influence the life-history and recruitment of longfin smelt.

Time Period: October 2010 – November 2011

Resources required:

Cost: $70,000

PI(s): Joan Lindberg and James Hobbs (UCD)

Contract needed / in place: In place.

Contract manager(s): Erwin Van Nieuwenhuyse (USBR) and Joan Lindberg (UCD)

Term of contract: Through December 2014.

Personnel: Above named investigators and other UCD personnel.

Equipment: None at this time.

Deliverables and dates:

Task 1

- Development of cultured animals for research, preserved developmental series of larvae reared in 2 and 4 ppt salt water, and report on development of longfin smelt culture methodologies.
- Culture of larvae and juveniles reared in saline conditions to evaluate reliability of otolith core tracing developmental salinity exposure of developing longfin.
- Results presented at the at the Delta Science Conference or IEP workshop following termination of this 12-month study.
- Report at termination of project.

Task 2

- 100 otoliths (50 from embryo exposures and 50 for larval salinity tests (April 2011).
- 4 broodstock fish (4) from the salinity trials in Task I (b) (April 2011).
- 100 TNS samples from 2010 (November 2010).
- 100 TNS samples from 2011 (November 2011).
- 100 samples from the FMWT and Bay Study (April 2011).
- Delta Science conference presentation (October 2011).

- Report (November 2011).

<u>How is this activity related to the POD investigations and what is its relevance to understanding the effects of fall flow variations on delta smelt?</u> The study will evaluate the salinity tolerance of longfin smelt embryos, larvae, and refine culture techniques for the longfin smelt, a key POD species. The experiments will provide otolith age and microchemistry validation for interpreting data for the current IEP funded POD project (May et al., 2008). The effect of salinity on longfin smelt spawning/rearing habitat has direct implications for the manipulation of fall flow variation and will provide evidence for a mechanistic relationship between fall X2 and longfin smelt recruitment.

<u>Comments:</u> With this study, we hope to develop many of the specific methods for successful longfin culture, thereby elucidating physical parameters that enable or improve holding and rearing success. Comparisons can be drawn between the several life stages of delta smelt and longfin smelt and relative survival and/or growth for fish reared under 1 or more salinity conditions, as follows: holding of adult wild fish, fecundity (or egg-clutch) estimates, spawning and fertilization of eggs, and the rearing of larvae and juveniles. Species segregation, of the 2 smelts in question, and location in the natural habitat appears to depend on salinity, at least for several life stages, and manipulation of the position of X2 in the fall could affect these life stages significantly. This study will provide validation for otolith strontium isotope-salinity relationship developed in May, Israel and Hobbs (2008), as well as provide information for studies regarding the influence of fall X2 and variable delta salinity management strategies.

Remote Sensing Mapping and Monitoring of Microcystis and Turbidity in the Upper San Francisco Estuary

IEP 2010-171

<u>Point Person</u>: Anke Mueller-Solger (DSC)

<u>Lead Agency</u>: UCD

<u>Questions:</u> What are the reflectance properties of the water in the San Francisco Estuary across gradients of suspended solids and toxic algae (*Microcystis*) abundance? How do chlorophyll *a* concentration, total and volatile suspended solids, total and dissolved organic carbon and *Microcystis* abundance vary across the Delta over seasons? What are the distributions of total suspended matter and *Microcystis* blooms and how do these change with time?

<u>Description:</u> We will investigate and develop a procedure to map the spatial distribution of suspended sediments, colored dissolved organic matter and *Microcystis* blooms using NASA Landsat satellite imagery. The Landsat Thematic Mapper (TM) satellite images, which have a 30 x 30 meter pixel resolution, are free and have a weekly return interval over the San Francisco Estuary. Our procedure will have the potential to be used to create spatially contiguous weekly maps that will characterize both the spatial and temporal variation in suspended solids and *Microcystis*.

Our research approach begins with 6 field sampling excursions over July, August and September 2010 concurrent with Landsat TM overpasses to obtain training data for the mapping procedure. We will collect GPS locations and discrete water samples to derive relevant optical properties, along with surface and subsurface water reflectance data. These data will be complemented by monthly discrete monitoring data which will be used to implement and validate the mapping procedure. Using the field data we will investigate 2 approaches to mapping total suspended solids and *Microcystis* (Task 3). The first approach correlates field measurements with reflectance measurements to create a statistical model that can be used to predict water quality at each pixel of the Landsat image from the reflectance information contained in that pixel. The second approach uses a radiative transfer model (Hydrolight), which models the physical interaction between light and water, also retrieving a map of water quality at each pixel of the Landsat imagery. This model can also estimate in-water light fields which are useful inputs into primary productivity models for the estuary. We will provide a procedural manual for remote sensing mapping of total suspended solids and *Microcystis* and other water quality constituents to the IEP.

Time Period: June 2010 - June 2011

Resources Required**:**

Cost: $134,000

PI(s): Susan Ustin and Erin Hestir (UCD), Peggy Lehman (DWR) and Bryan Downing (USGS)

Contract needed/in place: In process.

Contract manager(s): Erwin Van Nieuwenhuyse (USBR) and Susan Ustin (UCD).

Term of contract: TBD

Personnel: Above named investigators and Jonathan Greenberg, George Scheer, Richard McIlvaine (UCD).

Equipment: None

Deliverables and Dates:

- Excel file containing water quality and *Microcystis* abundance data with GPS location information for model parameterization and calibration (Task 2A).
- Excel file containing water quality and *Microcystis* abundance data with GPS locations for model implementation and calibration (Task 2B).
- Digital maps (raster image or shapefiles) of all water quality variables successfully modeled and mapped with accuracy estimates for each one. Maps will be uploaded to CaSIL hosted on Cal Atlas (http://www.atlas.ca.gov).
- Quarterly progress reports (September 2010, January 2011, April 2011).
- 1 draft manuscript for submission to a peer review journal describing the spatial and temporal variation of Microcystis in relation to turbidity (July 2011).
- 1 procedural manual written in the form of a how-to training guide for mapping procedures developed during the investigation (July 2011).

How is this activity related to the HSG? Remote sensing maps of turbidity and Microcystis can improve existing habitat quality monitoring by providing synoptic (wall-to-wall) measurements of habitat quantity and quality. This information can be used to understand the spatial distribution of delta smelt habitat, and identify discontinuities or changes in habitat availability, as well as identify the spatial distribution of *Microcystis* blooms. We anticipate developing maps of total suspended solids, *Microcystis,* and the in-water light field for Landsat dates in July, August, and September, allowing investigation into the relationship between fall habitat conditions and those occurring earlier in the year as well as the overall trophic conditions of the estuary. Furthermore, our mapping procedures manual will provide the information needed to continue monitoring throughout the entire year. Measuring habitat quality in space and in time is critical to understanding not only how much potential habitat is available to delta smelt in the fall, but how their fall habitat varies spatially and temporally in relation to spring and summer habitat conditions and hydrologic variability.

Comments: None

The Role of Pyrethroid Insecticides in Limiting Prey Availability for Delta Smelt in the North Delta

IEP 2010-172
Point person: Stephanie Fong (CVRWQCB)
Lead IEP Agency: CVRWQCB

Questions: Data emerging over the past few years have shown that pyrethroid insecticides are entering the northwest Delta waters of Cache Slough and nearby areas. These waters are critical habitat for delta smelt, as it is an important spawning area, and particularly so during dry years. This study is designed to determine if pyrethroid pesticides in the Cache Slough region could be reducing populations of copepod prey upon which spawning adult smelt and larval fish depend.

Description: Sampling will be conducted in Cache Slough and surrounding areas during February through June, as the adults gather to spawn and as the larvae/post-larvae remain in the area. Sampling will include water samples for pyrethroid analysis and toxicity testing. Plankton samples will be collected both to quantify availability of copepod prey, and determine if copepod toxicity, as seen in the pyrethroid analytical data and laboratory toxicity tests, is reflected in a concurrent decline in resident populations.

Toxicity testing will be done with the amphipod *Hyalella azteca* for all samples, and with the copepods, *Eurytemora affinis* and *Pseudodiaptomus forbesi*, for selected samples. Should toxicity be found, the pyrethroid chemical analysis will help establish if they are the causative agents, and this linkage further established by TIE tools. Piperonyl butoxide can be used to increase toxicity, if initially caused by pyrethroids, and enzymes engineered to hydrolyze pyrethroids can be used to decrease toxicity due to these compounds.

Time period: December 1, 2010 – November 30, 2011

Resources required:

Cost: $158,000

PI(s): Donald Weston (UCB), Swee Teh (UCD), Michael Lydy (Southern Illinois University) and Fred Feyrer (USBR)

Contract needed/in place: In process.
Contract manager(s): Erwin Van Nieuwenhuyse (USBR)
Term of contract: 12 months, once executed.

Personnel: The PIs listed above, assisted by students and staff in their labs.
Equipment: None

Deliverables and dates:

- Quarterly progress reports.
- Draft final report (October 2011).
- Final report (November 2011).
- IEP newsletter article (November 2011).
- Two oral presentations during term of contract.

Comments: IEP-NCEAS has convened a working group, chaired by Dan Schlenk, on pyrethroids in urban runoff and their potential impact on POD species. The Cache Slough area is of specific interest to this group, and a modeling exercise is now in progress to estimate pyrethroid inputs to those waters, and compare this estimate to thresholds of toxicity for aquatic life. The planned study will provide a great deal of data from the Cache Slough area that will be extremely valuable in confirming model predictions and validating the modeling approach as a tool for risk assessment.

Distribution, Concentrations and Fate of Ammonium in the Sacramento River and the Low Salinity Zone: Determination of Phytoplankton Uptake and Bacterial Nitrification Rates

IEP 2010-173

Point person: Larry Brown (USGS)

Lead Agency: SFSU

Questions: Can pelagic nitrification rates be measured (and validated to a degree) in the San Francisco Bay using ^{15}N labeling, the NH_4^+ micro-diffusion technique and mass spectrometry? What are the rates of (a) bacterial/archaeal nitrification and (b) phytoplankton NH_4^+ uptake downstream from Sacramento to Suisun Bay in spring, summer and fall? Does the fate of NH_4^+ (i.e., uptake and nitrification) change with season, salinity and flow?

Description: This research will emphasize quantifying 2 key biological processes influencing river NH_4^+ distribution, bacterial nitrification (= NH_4^+ oxidation) and phytoplankton uptake, and in future years will investigate the degree of river flow-dependence on these processes. This funding will focus on working collaboratively with C. Kendall (USGS, Menlo Park), to develop a protocol for measuring water column nitrification using ^{15}N-labeled NH_4^+ as a tracer. In addition, we will work with estuarine scientists to investigate other tracer –based nitrification methods and determine the most efficient means for determining rates. Towards the end of year 1 it is expected that the protocol will start to be applied to archived river samples that will be incubated and collected in spring and summer 2010 (as part of the CALFED-funded “Two Rivers” project, Dugdale and Mueller-Solger, Lead-PIs) and the Fall 2010 IEP Foodweb (Parker, et al., 2010). C. Kendall will also be involved by collecting samples for natural abundance stable isotope work, for independent estimates of nitrification and phytoplankton N uptake.

Time period: June 2010- May 2011

Resources required:

Cost: $77,000

PI(s): Dick Dugdale, Alex Parker and Francis Wilkerson (SFSU)

Contract needed / in place: In process.

Contract manager(s): Erwin Van Nieuwenhuyse (USBR)

Term of contract: N/A

Personnel: Above named investigators, Al Marchi (Research Technician) and a graduate student yet to be determined.

Equipment: Temperature controlled large shaker table / freeze dryer.

Deliverables and dates:

- Presentation at an IEP forum such as EET or the CWT (May 2011).
- If methodology is successful and applied to samples, then preliminary results will be written up as an IEP newsletter article (May 2011).
- With continued support to analyze more samples, it is expected that a peer reviewed journal article will be prepared and the data presented at a national meeting such as Coastal Environmental Rights Foundation (CERF).

How is this activity related to the POD investigations and what is its relevance to understanding the effects of fall flow variations on delta smelt? The primary productivity of the river ecosystem is reduced by the change from a NO_3^- based phytoplankton system to an NH_4^+ based phytoplankton and bacterial system, forced by the input of NH_4^+ from the SRWTP. Recovery of the system to NO_3^- based phytoplankton productivity and recovered primary production requires the reduction of ambient NH_4^+ concentrations to ~4 µM· to initiate blooms, and to 1 µM to substantially relieve NH_4^+ inhibition of

NO_3^- uptake. Consequently, the conversion of NH_4^+ to NO_3^- (not available to the phytoplankton) represents a potential loss of primary productivity to the section of the river with elevated NH_4^+ concentrations. The most desirable form of inorganic nitrogen, NO_3^-, is exported downstream and out of the area of concern for the POD. The rate of nitrification determines the point in the river at which NH_4^+ concentration is reduced to the critical point for bloom formation (4 µM) and then to 1 µM for access to the now elevated pool of NO_3^-

Comments: Synergies with past and present research programs:

- Parker/ Dugdale: State Water Contractors (SWC) Project - ^{15}N uptake by phytoplankton and NH_4^+ distributions available.
- Dugdale/A. Mueller-Solger CALFED "Two Rivers" CALFED Project.
- Kendall: SWC Project and IEP Project, parallel measurements of stable isotopic $\delta^{15}N$ (natural abundance).
- Patin: Masters thesis research, SFSU, "Abundance of Ammonia oxidizing Archaea in SF Bay" (Ashby, Advisor).
- Melloy: Masters thesis research, SFSU, "Use of bacterial inhibitors to evaluate the role of nitrifying Archaea" (de la Torre, Advisor).

The influence of elevated ammonium (NH_4) on phytoplankton physiology in the San Francisco Estuary Delta during fall: exploring differences in nutrients and phytoplankton in the Sacramento and San Joaquin Rivers and how variation in irradiance via changing river flow, modulates NH_4 effects.

IEP 2010-174

Point person: Anke Mueller-Solger (DSC)

Lead Agency: SFSU

Questions: What are the rates of primary production and phytoplankton NO_3 and NH_4 uptake in the Sacramento and San Joaquin rivers during the fall period? What role does DIN composition and concentration play in modulating the above phytoplankton rates and phytoplankton species composition? How does river flow affect nutrient distribution and phytoplankton rates? Does the conceptual model of NH_4 suppression of phytoplankton NO_3 uptake and primary production hold under low-light conditions?

Description: Emerging evidence suggests that shifts in nutrient composition from NO_3 to NH_4 as a result of the Clean Water Act and population increases (Jassby 2008) likely play a role in the long-term phytoplankton decline that has been observed in the northern SFE (Dugdale et al. 2007). NH_4 likely affects SFE phytoplankton species composition and also appears to influence primary production rates by modulating phytoplankton physiology, particularly that of fast growing and nutritious diatoms (Dugdale et al. 2007). Elevated NH_4 concentrations (>4 $\mu mol\ L^{-1}$) appear to inhibit phytoplankton NO_3 uptake. Only during brief periods NH_4 is reduced to low concentrations and phytoplankton NO_3 uptake increases rapidly (termed "shift-up", Dugdale et al. 1990) resulting in increased phytoplankton growth. The major source of dissolved inorganic nitrogen (DIN, i.e. NH_4 and NO_3) in the northern SFE is from agriculture and municipal wastewater treatment plants (Hager and Schemel, 1996; Jassby 2008) with DIN in the Sacramento River coming primarily in the form of NH_4. In contrast, due to differences in municipal wastewater processing, discharge in the San Joaquin River is largely in the form of NO_3. The contrast between the Sacramento River (NH_4-dominated) and the San Joaquin River (NO_3-dominated) provides a natural experiment to test primary production and phytoplankton community composition responses as a result of NH_4 and NO_3 loading.

One outstanding question is whether the NH_4 inhibition effect or the NO_3 shift-up that follows NH_4 exhaustion occurs at low irradiances characteristic of the natural system. Research in marine settings has demonstrated an irradiance response for phytoplankton DIN uptake, including a differential response for phytoplankton NH_4 and NO_3 uptake (McCarthy et al. 1996; Kudela et al. 1997; Parker et al. in review). Phytoplankton DIN versus irradiance relationships are not clear for the SFE or estuarine environments, generally.

Time period: July 2010 - July 2011

Resources required:

Cost: $114,000

PI(s): Alex Parker, Francis Wilkerson and Richard Dugdale (SFSU).

Contract needed / in place: In place.

Contract manager(s): Erwin Van Nieuwenhuyse (USBR) and Richard Dugdale (SFSU).

Term of contract: 1 year.

Personnel: Al Marchi and Erica Kress (SFSU) and above named investigators.

Equipment: None

Deliverables and dates:

- IEP final report (July 2011).
- Poster or presentation at the 2011 IEP annual workshop.
- IEP Newsletter article (spring 2011).
- Manuscript draft for submission to a peer-reviewed journal (July 2011).

How is this activity related to the POD investigations and what is its relevance to understanding the effects of fall flow variations on delta smelt? This project aims to better constrain the role that NH_4 plays in modulating primary production and ultimately, the bottom-up controls on the food web of POD species. Historically nutrients have not been considered important in regulating primary production as the SFE was identified as a light-limited estuary. Recently, there has been considerable renewed interest in the role of nutrients (particularly NH_4, but also PO_4) in shaping the phytoplankton community composition and primary production rates in the Central Delta. Long-term shifts in phytoplankton taxa (including the proliferation of harmful algal bloom species such as *Microcystsis*) in the northern San Francisco Bay as well as the decades long decline in primary production rates are likely a function of multiple ecosystem drivers. Changes in wastewater treatment practices may be a potentially beneficial management strategy in support of improved conditions for POD species.

Comments:

- We will work with Kimmerer et al. (funded) for cruise planning / preparation and in synthesis of results.
- Under this budget we will collect, incubate and archive all ^{15}N nitrification rate measurements in fall 2010 for analysis under the Dugdale et al nitrification project (funded).
- This dataset will provide greater temporal coverage (by completing transects in fall) for the “Two Rivers” project underway by Dugdale and Anke Mueller-Solger (DSC).
- These projects will extend the dataset currently being collected by C. Foe (CVRWQCB) on delta-wide DIN distribution.
- We will extend the dataset collected during the SWC transects, including data collection during the fall and in the San Joaquin River complimenting the existing Dugdale and Parker State Water Contractors Project.

Evaluation of the Effect of Seasonal Variations in Flow on the Spatial and Temporal Variations of Nutrients, Organic Matter and Phytoplankton in the Sacramento River and Northern San Francisco Bay

IEP 2010-175
Point person: Anke Mueller-Solger (DSC)
Lead Agency: USGS

Questions: How does the location of X2, especially in the fall, affect constituents important to the base of the smelt and other foodwebs in the northern San Francisco Bay, Delta, and lower Sacramento River? What areas in the Delta act as nutrient sources and sinks, and what processes are involved? Does the Yolo/Cache/Liberty area act as a sink or a source for ammonia and other nutrients? Under what conditions do nutrient sources from the Yolo/Cache/Liberty area support the food web in the LSZ? Are there regional, river reach-dependent, and temporal variations in nitrification rate or other rates of nutrient degradation? If so, what is the dominant cause? Does algal growth rate appear to depend on the relative proportions of ammonia and nitrate? What are the dominant processes affecting the downstream location (denoted in river miles or RM) where NH_4^+ concentrations approach levels where NH_4^+ no longer appears to inhibit NO_3^- uptake?

Description: The purpose of this data synthesis project is to investigate how seasonal and spatial changes in freshwater flow and the relative amounts of water from different sources (e.g., the Sacramento River, the San Joaquin River, the Yolo Complex, SRWTP, et – as estimated using DSM2 and RMA) affect the temporal and spatial variations in the sources, transport, and sinks of NH_4^+, NO_3^-, chlorophyll, and organic matter in the Sacramento River and lower Delta. In specific, we propose to take advantage of several large sets of existing chemical and isotopic data to ask questions about how the location of the 2% salt front (X2), especially in the fall, relates to constituents important to the base of the smelt and other foodwebs in the northern San Francisco Bay, Delta, and lower Sacramento River.

A main focus of this project will be the calculation of nitrification rates for different river reaches and seasons, and identifying how seasonal changes in flow, effluent levels and composition, proportions of water from different sources, temperature, etc. affect nitrification rates. Available chemistry from the recent Foe and Dugdale transects – and our nitrate isotope data – show that nitrification is the dominant N cycling process in the Sacramento River below SRWTP and is considerably more important for reducing NH_4^+ levels to below the inhibition threshold than algal uptake.

Time period: July 2010 - July 2011
Resources required:
Cost: $42,000
PI(s): Carol Kendall (USGS)
Contract needed / in place: In progress.
Contract manager(s): Erwin Van Nieuwenhuyse (USBR) and Roger Fujii (USGS).
Term of contract: To be determined.
Personnel: Megan Young, Steve Silva, and Tamara Kraus (USGS); Marianne Guerin (RMA); Chris Foe (CVRWQCB); Alex Parker, Dick Dugdale, and Frances Wilkerson (SFSU)
Equipment: None
Deliverables and dates:

- Quarterly progress reports with invoices.
- An update presentation at an IEP forum (such as EET or the POD CWT), and a talk or poster at a CALFED, American Geophysical Union (AGU), or other national meeting during the first year.
- At the completion of the project, we will provide an electronic copy of our entire database, and 1 or more USGS-approved and journal-intended articles.

How is this activity related to the POD investigations and what is its relevance to understanding the effects of fall flow variations on delta smelt? This project addresses 2 of the priority research topics: habitat effects and food web effects on delta smelt population dynamics. By "habitat effects", we mean the quantification of abiotic variables such as net flow and residence time within the study area or in sub-regions of that area, and the effect of these variables on nutrient sources and concentrations within the LSZ and elsewhere within the study area. The project focus on "food web effects" is at the level of nutrients and primary productivity. This proposed project also supports 3 of the 4 key research priorities from the 12 framework-panel-identified topics listed as part of the "CALFED Science Program Issue Summary" on the role of ammonium (http://science.calwater.ca.gov/pdf/publications/Ammonium_one-pager_070109.pdf):

- Use models to explore the transport of ammonia/ammonium within the Delta and effects on the amount of, type of, and growth of algae, the base of the Delta food web.
- Determine the main sources of ammonia/ammonium (and phosphorus) and trace the fate of these substances within the Delta.
- Explore possible links between specific types of algae and aquatic plants and the amount of ammonium in the water.

Comments:

Determination of Influences of Water Quality and Submerged Aquatic Vegetation on Largemouth Bass Distribution, Abundance, Diet Composition and Predation on Delta smelt in the Sacramento-San Joaquin Delta

IEP 2010-176

Point person: Ted Sommer (DWR)

Lead Agency: UCD

Questions: How do abiotic and biotic factors influence largemouth bass distribution and abundance in the Delta, and their impacts on delta smelt and other pelagic species? What are the abundance and the diet composition of largemouth bass and other potential predators in areas where delta smelt are known to be present? What is the relationship between biomass density and species composition of submerged vegetation beds and the invertebrate community assemblage and biomass? Does variation in the invertebrate community within the submerged vegetation explain variability in the abundance and/or diet composition of juvenile largemouth bass captured at the same locations?

Description: This project builds on an IEP-supported study (currently underway) that is investigating abiotic and biotic influences on the spatial distribution, abundance, size distribution, movements, and diet of largemouth bass (LMB). The proposed project will allow the current sampling program to carry out 3 more months of the current study's sampling protocol to complete 2 full years of field surveys at 33 sites spread throughout the Delta. This field effort will complete 2 full years of bimonthly data collection, leaving approximately 6 months for data compilation, analyses, and preparation of manuscripts. We will produce a spatially explicit dataset that integrates aquatic macrophytes, abundance of each fish species, diet composition of LMB, and water quality parameters. Analyses will address how seasonal and inter-annual variation in environmental conditions, including salinity, fall X2, and SAV influence LMB distribution, density, and diet, as well as the general fish assemblage in the littoral zone. In addition to extending the sampling program already underway, this project will also examine the abundance and diet composition of LMB and other predators in specific locations where delta smelt are known to occur. A second new goal is to examine how the increased biomass of SAV– largely due to the proliferation of the invasive Brazilian waterweed– may contribute to the success of the largely non-native littoral fish assemblage, particularly LMB, by boosting secondary (invertebrate) production that in turn provides a prey base for juvenile fish.

Time period: July 2010 – June 2011

Resources required:

Cost: $173,000

PI(s): Andrew Sih, and Peter Moyle (UCD); Louise Conrad (DWR)

Contract needed / in place: In process.

Contract manager(s): Erwin Van Nieuwenhuyse (USBR)

Term of contract: To be determined.

Personnel: In addition to PIs, other UCD staff include Patrick Crain, Matthew Young, Kelly Smith, a second junior specialist and an, undergraduate student researcher.

Equipment: No new equipment needed at this time.

Deliverables and dates:

Task 1: Influence of biotic and abiotic factors on LMB abundance, distribution, and diet

- Final report to IEP (June 2011).
- 2 manuscripts for publication in peer-reviewed journals (June 2011).

Task 2: Abundance and diet composition of largemouth bass and other predators co-occurring with delta smelt

- Final report to IEP (June 2011).
- IEP newsletter and/or presentation at relevant IEP conference or workshop, as requested (spring 2011).

Task 3: Influence of the SAV species and biomass on invertebrate community composition and biomass

- 1 manuscript for publication (June 2011).

How is this activity related to the POD investigations and what is its relevance to understanding the effects of fall flow variations on delta smelt? LMB are voracious piscivores that have been recognized as keystone species because of their far-reaching impacts on the resident food web in systems where they have been introduced. LMB are introduced in the Delta and have demonstrated a dramatic population increase in recent decades. Thus, they may be important predators of native fishes, including species that are part of the POD. Major goals of our proposed work are thus to quantify potential impacts of LMB on delta smelt, threadfin shad, and juvenile striped bass and to elucidate factors that explain the recent success of LMB in the Delta. Specifically, we will complete a 2-year field effort to examine how biotic factors (e.g., aquatic macrophytes) and abiotic variables (e.g., temperature, salinity, and fall flow variation) influence the distribution and abundance of LMB throughout the Delta. The spatial distribution of LMB with respect to environmental factors such as annual variation in Delta outflow will aid in predicting the degree to which delta smelt are likely to overlap with LMB. However, while

spatial overlap between these 2 species suggests the possibility of LMB predation of delta smelt, LMB foraging behavior may limit this possibility. Thus, we will also examine diet contents of LMB in areas where the presence of delta smelt has been established by recent native fish surveys conducted by DFG or other resource agencies to better assess the impact of LMB on delta smelt.
<u>Comments</u>: This project builds on IEP-funded research that is currently underway, under the POD work team's 2008-2010 contract with UCD, entitled, "Impacts of Largemouth Bass on the Delta Ecosystem."

Metabolic Responses to Variable Salinity Environments in Field-Acclimatized Corbula amurensis

IEP 2010-177
<u>Point person:</u> Larry Brown (USGS)
<u>Lead Agency</u>: SFSU
<u>Questions:</u> How much metabolic variation do we see in *Corbula* acclimatized to different salinities across sites and seasons? How are *Corbula* partitioning energy? How does variation in water chemistry and planktonic assemblage alter the metabolic physiology of *Corbula*?
<u>Description</u>: We propose to continue our studies on *Corbula amurensis (Corbula)* metabolic physiology in field-acclimatized specimens collected at monthly intervals from sites representing extremes in salinity variability over the distribution range of *Corbula* in the northern San Francisco Estuary. We will collect clams at 3 sites representing nearly fresh, medium and high salinity fluctuation to address the above questions. For question 1, we will measure metabolic rates and feeding rates of clams within 12 hours of collection. For question 2, we will freeze clams upon collection and characterize tissues and/or biochemical activities associated with growth, reproduction, osmoregulation, metabolism, and energy stores. For question 3, we will measure salinity, temperature, pH and turbidity and will characterize the energetic content of large and small size class plankton assemblages.

In sum, these measurements will tell us at what rate and for what purposes the clams are using energy in the natural habitat across gradients in salinity and temperature exposure, and what the energy reserves of the clams are like depending on when they settle. Clams that have lower energy reserves or that are using greater amounts of energy per unit time will likely have a stronger impact on food-webs as they must graze more to obtain their energy. Thus this information will result in improved food web modeling of clam impacts on pelagic organisms' food supply.
<u>Time period</u>**:** August 2010 to December 2011, with a hiatus from December 2010 to February 2011, when sampling of *Corbula amurensis* is not feasible.
<u>Resources required</u>**:**
<u>Cost</u>: $137,000
<u>PI(s):</u> Jonathon Stillman (SFSU)
<u>Contract needed / in place</u>: In process.
<u>Contract manager(s)</u>: Erwin Van Nieuwenhuyse (USBR)
<u>Term of contract</u>: To be determined.
<u>Personnel</u>: Nathan Miller (SFSU), Postdoctoral Fellow
<u>Equipment</u>: No new equipment needed at this time.
<u>Deliverables and dates:</u>

- Written IEP reports at end of project (January 2012).

- Manuscripts for publication in peer reviewed journals (e.g., Marine Ecology Progress Series (MEPS), Estuaries and Coasts) at end of project (January 2012).
- Poster and/or oral presentations at CERF in Nov 2011, CAERS in spring 2011, IEP/EET in spring 2011 and the Society for Integrative and Comparative Biology (SICB) in January 2012.

How is this activity related to the POD investigations and what is its relevance to understanding the effects of fall flow variations on delta smelt? The invasive clam *Corbula amurensis* is thought to exert a strong bottom-up influence on the pelagic food web by its filtration of phyto- and zooplankton to supply its metabolic demands. This project seeks to characterize the metabolic physiology of *Corbula amurensis* in locations representing the extremes of their salinity distribution ranges in the northern San Francisco Estuary. Understanding the rate at which clams require and use energy is a critical component of their relative interaction strengths in food-web models of the area. Assessment of the variation in metabolic physiology across seasonal variation in freshwater input and at sites that vary across degree of tidally-influenced salinity fluctuations is important in order to parameterize how these clams are likely to respond to natural and anthropogenic variation in salinity.

Comments: This project produce results that should be integrated with results from proposed projects by Thompson & Gehrts, Kimmerer & Sullivan, Gross, MacWilliams & Kimmerer, and Dugdale, Wilkerson & Parker.

Bivalve Effects on the Food Web Supporting Delta Smelt

2010-178

Point person: Larry Brown (USGS)

Lead Agency: USGS

Questions: How do *Corbula amurensis and Corbicula fluminea* affect the food web supporting delta smelt, and how are they affected by flow variability? How do the grazing rates of *Corbicula fluminea* and *Corbula amurensis* vary with longitudinal location in the Delta and the LSZ? How do the grazing rates of *Corbicula fluminea* and *Corbula amurensis* vary with water depth in the Delta and the LSZ? How do the population dynamics of *Corbicula fluminea* and *Corbula amurensis* (recruitment, growth, and mortality) vary as a function of X2 position in fall? How do antecedent fall salinity conditions in the LSZ affect bivalve population biomass and grazing rates in the following spring?

Description: Our task is to establish the distribution, population dynamics, and grazing rate of *Corbula* and *Corbicula* within the LSZ and within the tidal excursion of the LSZ. We will augment current field and laboratory procedures to avoid duplication of current programs, and use DWR EMP monitoring data and USGS benthic bivalve data to provide a long-term context to the study. DWR currently does a spatially intensive benthic Generalized Random Tessellation Stratified (GRTS) sampling study in the spring and fall that will be augmented with a few stations in the region of the strongest gradients in bivalve grazing (within a tidal excursion of the LSZ) and in some shallow water areas to insure that we can adequately model benthic grazing in these areas with some accuracy. Previously collected samples from the fall 1999 “experiment” and the spring of 1999 will be processed in addition to samples collected in 2010. The tasks are listed as follows:

- Task 1: Collect 22 additional stations during the GRTS spring and fall 2010 sampling (USGS and DWR).

- Task 2: Sort 22 additional samples for fall 1999 (we took part in the fall 1999 "experiment"), spring and fall 2010 (USGS).
- Task 3: Measure bivalves from 1999 GRTS samples and from 2010 GRTS samples (USGS).
- Task 4: Convert bivalve measurements to biomass and grazing rate (USGS and DWR).
- Task 5: Report biomass and grazing rate numbers as they become available to IEP and fellow PIs in fall study (USGS and DWR). Work with numerical modelers to establish grazing rates within grids (USGS).

Time period: July 2010 – July 2011

Resources required:

Cost: $89,000

PI(s): Janet Thompson (USGS and Karen Gehrts (DWR)

Contract needed / in place: In process,

Contract manager(s): Erwin Van Nieuwenhuyse (USBR) and Janet Thompson (USGS)

Term of contract: To be determined.

Personnel: Above named investigators.

Equipment: None at this time.

Deliverables and dates:

- Grazing rates available for 1999 (January 2011).
- Grazing rates available for spring 2010 (March 2011).
- Written IEP reports and fall 2010 grazing rates available at end of project (August 2011).
- Presentation at IEP Annual Workshop (2011 and 2012).
- Manuscripts for publication in peer reviewed journal (July 2012).

How is this activity related to the POD investigations and what is its relevance to understanding the effects of fall flow variations on delta smelt? The conceptual model of the delta smelt foodweb shows (1) confirmed links between clams and phytoplankton, larval copepods, bacteria and ciliates (current work by V. Greene with Kimmerer); and (2) potential links with a broader range of zooplankton larvae and ciliates and other forms of POC and DOC. Phytoplankton production is severely light limited in this system and thus positive net production is confined to shallow areas where accelerated vertical mixing rates expose phytoplankton cells to more light than in the channel. However, the phytoplankton cells, while being more rapidly vertically mixed in the shallow water, are also being exposed to more clam grazing. We have 2 species of clams in this system that overlap in the salinity range of 0-10: adult *Corbicula* can live in salinities of 10 and we have observed adult *Corbula* in the tidal river in areas where bottom salinities are at or near zero for large portions of each day. Juveniles of both species can withstand salinities of 2. The species have different pumping rates and our knowledge of their ability to filter zooplankton and ciliates differs. Therefore the distribution and biomass of these clams will determine the loss rate of phytoplankton and other portions of the lower foodweb due to benthic grazing.

Why Fall?: Because *Corbicula* and *Corbula* distributions are a function of salinity, and their larval recruitment periods occur in spring and fall, their effect on the foodweb is a function of the salinity distribution in spring and fall. Once larvae settle, they are more able to withstand a broader range of salinity. A salinity incursion into the Delta in fall followed by a dry or below normal outflow winter may allow *Corbula* to not only settle within the X2 area but also to survive at that location into the following spring and fall even if the salinity declines. Therefore,

we need to determine the distribution and grazing rate of *Corbula* and *Corbicula* in fall and in the following spring.
Comments: This project produce results that should be integrated with results from proposed projects by Stillman, Kimmerer & Sullivan, Gross, MacWilliams & Kimmerer, and Dugdale, Wilkerson & Parker.

Determination of the Causes of Seasonal and Spatial Variation in NH_4^+ *Sources, Sinks and Contributions to Algal Productivity in the Sacramento River, Delta and northern San Francisco Bay Using a Multi-isotope Approach*

IEP 2010-179
Point person: Anke Mueller-Solger (DSC)
Lead Agency: USGS
Questions: Can we quantify the seasonal contributions of NH_4^+ from SRWTP, tributaries, and other sources to critical habitats? Does the phytoplankton species composition in the downstream of SRWTP vary with the concentration of NH_4^+ or any other constituent in the effluent or tributaries identified by isotope analysis? How do nitrification rates (the main biogeochemical process responsible for lowering NH_4^+ levels) vary seasonally and in different reaches of the Sacramento River and upper estuary? Which areas act as nutrient sources and sinks? Can we quantify the $NH_4^+$from WWTPs versus agricultural drains to different sites and seasons? How do NH_4^+, NO_3^- , and organic matter concentrations vary under different hydrologic conditions?
Description: This project will quantify temporal and spatial variations in the sources, transport, and sinks of NH_4^+ , NO_3^-, and organic matter at 21 sites in the Sacramento River, San Joaquin River, and Delta sampled as part of the 1-year NH_4^+ Monitoring Program established and conducted by Chris Foe. We have coordinated with Foe's monitoring program to obtain and archive splits of samples for isotopic and algal speciation analyses. An ongoing SWC-funded pilot study has shown that nutrients and organic matter from different sources, or affected by different biogeochemical processes, have distinctive isotopic compositions that are diagnostic of the different sources and processes.

This project consists of 3 tasks, the first 2 aimed at analyzing the archived samples, and the third to integrate the new data and prepare reports. Task 1 will analyze these samples for δ15N of NH_4^+ , δ15N and δ18O of NO_3^- , δ13C of DOC, δ18O and δ2H of water, and δ13C, δ15N, δ34S, and C:N of seston. Task 2 (funded presumably by the DWR to Peggy Lehman) will analyze archived lugol-preserved samples for algal speciation. Task 3 (as yet unfunded, for year 2 is to (A) combine the chemical, isotope, algal, and hydrological data to quantify temporal and spatial changes in (1) the relative contributions from different sources of NH_4^+ , (2) the nitrification rate, (3) the uptake of NH_4^+ and NO_3^- by different algal species (and bacteria), and (4) how these critical sources and biogeochemical processes are affected by hydrology and management-driven changes in net flow and water source percentages at different sites and dates; and (B) prepare presentations and reports.
Time period: July 2010 to July 2011 (for tasks 1 and 2; task 3 (currently unfunded) will take about an additional 6 months).
Resources required:
Cost: $242,000 (task 1 only)
PI(s): Carol Kendall (USGS)
Contract needed / in place: In process.

Contract manager(s): Erwin Van Nieuwenhuyse (USBR) and Roger Fujii (USGS).

Term of contract: To be determined.

Personnel: Megan Young, Steve Silva, and Tamara Kraus (USGS); Marianne Guerin (RMA); Peggy Lehman (DWR); Chris Foe (CVRWQCB)

Equipment: None planned, unless something critical breaks.

Deliverables and dates:

- Quarterly progress reports for task 1 with invoices. Excel data files at project completion.
- Presentations of preliminary data and findings at EET, IEP, CWT, and other meetings during the first year; memo (to the POD CWT?) describing policy implications of project findings, and recommendations for future monitoring efforts at the end of the first year.
- Excel data files containing the phytoplankton data and a report containing the result of the statistical analyses during the first year (task 2).
- Quarterly progress reports for task 3 with invoices during the second year (funding permitting).
- 1 or more USGS-approved journal paper(s) during the second year (funding permitting) for task 3.

How is this activity related to the POD investigations and what is its relevance to understanding the effects of fall flow variations on delta smelt? This project addresses 2 of the priority research topics: habitat effects and food web effects on delta smelt population dynamics. By "habitat effects", we mean the quantification of abiotic variables such as net flow and residence time within the study area or in sub-regions of that area, and the effect of these variables on nutrient sources and concentrations within the LSZ and elsewhere within the study area (Research Question 1C). The project focus on "food web effects" is at the level of nutrients and primary productivity (Research Question 2C). This proposed project also supports 3 of the 4 key research priorities from the 12 framework-panel-identified topics listed as part of the "CALFED Science Program Issue Summary" on the role of ammonium (http://science.calwater.ca.gov/pdf/publications/Ammonium_one-pager_070109.pdf):

- Use models to explore the transport of ammonia/ammonium within the Delta and effects on the amount of, type of, and growth of algae, the base of the Delta food web.
- Determine the main sources of ammonia/ammonium (and phosphorus) and trace the fate of these substances within the Delta.
- Explore possible links between specific types of algae and aquatic plants and the amount of ammonium in the water.

Hydrodynamic and Particle Tracking Modeling of Delta Smelt Habitat and Prey

2010-180

Point person: John Netto (USFWS)

Lead Agency: USFWS

Questions: How does the habitat area and volume for delta smelt and other fishes vary with freshwater flow? What patterns of vertical swimming by planktonic organisms in the LSZ result in tidal patterns of vertical distribution similar to those observed? How does the observed tidal vertical migration of planktonic organisms influence their retention and transport in and near the LSZ? How does this retention and transport vary with flow conditions?

Description: This project will use existing modeling tools and existing data to accomplish 2 tasks. The first task is to model the variability of physical habitat with X2 for key fish species including delta smelt. We will build on our previous efforts, improving the scope and resolution of habitat modeling by using the Unstructured Tidal, Residual, Intertidal and Mudflat (UnTRIM) San Francisco Bay-Delta Model to describe how physical habitat determined from fish distributions varies with freshwater flow.

In the second task, we will investigate the population dynamics of calanoid copepods, the most important food for delta smelt in summer to fall. Specifically, we will use the UnTRIM Bay-Delta model and the Flexible Integration of Staggered-grid Hydrodynamics (FISH) particle tracking model (PTM) to investigate retention processes that affect abundance of planktonic organisms, focusing on the calanoid copepod *Pseudodiaptomus forbesi*. The modeling will be designed to investigate the consequences of tidal vertical migration of copepods in the LSZ for retention of the copepods within that zone. Data from the intensive Entrapment Zone Studies of 1994-1996 will be used to define the range of migratory patterns, and retention under alternative migratory patterns and freshwater flows will be investigated.

Time period: July 2010 – June 2011

Resources Required:

Cost: $339,000 in 2010.

PI(s): Wim Kimmerer (SFSU)

Co-PI(s): Edward Gross (Bay Modeling) and Michael MacWilliams (River Modeling)

Contract needed / in place: In progress.

Contract manager(s): Erwin Van Nieuwenhuyse (USBR)

Term of contract: To be determined.

Personnel: Rusty Holleman and Sandy Chang (SFSU)

Equipment: None

Deliverables and dates:

- EET presentations (fall 2010 and spring 2011).
- CWEMF presentation on model calibration (February 2011).
- Paper on model calibration (February 2011).
- Paper on habitat analysis (June 2011).
- Paper on copepod retention (June 2011).

What is the relation to POD investigations and effects of fall flow variations on delta smelt?

This project addresses 2 aspects of the POD conceptual model: physical habitat and food supply. Changes in the physical shape or size of the low-salinity habitat have been hypothesized to cause a reduction in abundance of delta smelt or their food when X2 is high or landward (USFWS HSG, 2009). Task 1 of this project will determine how physical habitat of delta smelt, as determined by salinity, responds to changes in flow/X2. This information can be determined only through modeling, and it requires a detailed, state-of-the-art hydrodynamic model.

In Task 2, we will address a particular question on the food supply of delta smelt. A related project will investigate the population processes of the principal food organism, the copepod *Pseudodiaptomus forbesi* and ultimately how they relate to flow conditions. Population dynamics results from reproduction, growth, and development, and mortality. Losses from the population due to transport in the water contribute to total mortality. However, this is complicated by the fact that the copepods are capable of migrating vertically in synchrony with the tides, thereby potentially eliminating the tendency for transport away from the population center. Assessing the effects of this migration on retention is therefore essential for estimating overall mortality, and therefore understanding how population dynamics varies with flow

conditions. This also requires an accurate 3-dimensional hydrodynamic model and a 3-dimensional particle tracking model.
Comments: Task 1 will build on our previous work developing habitat models based on distributions of fish and using the TRIM 3-D model. Task 2 will build on earlier work (Kimmerer, Bennett, and Burau) investigating tidal migrations in the LSZ.

Longfin Smelt Bioenergetics

IEP 2010-181
Point Person: Randy Baxter (DFG)
Lead Agency: UCD
Questions: What are the food and oxygen consumption rates for juvenile and sub-adult longfin smelt? How do these metrics affect longfin smelt growth as assessed by a bioenergetics model? What is the importance of growth in the longfin smelt IBM as related to population dynamics?
Description: In fish bioenergetics studies, the most common parameters investigated in laboratory experiments are those related to consumption and metabolism. To date, no such laboratory experiments have been carried out for longfin smelt, making it difficult to apply bioenergetics data to the longfin smelt IBM. We will measure maximum food consumption, and active and resting oxygen consumption rates at 4 temperatures on hatchery-raised longfin smelt juveniles and sub-adults. These data will be incorporated into a bioenergetics model to determine growth rates over a range of different temperatures.

IBM has been previously developed for longfin smelt to describe the spatial and temporal heterogeneity of parameters affecting fecundity and mortality at all life stages. This IBM is useful for exploring the relative significance of specific factors influencing population numbers of longfin smelt in the Bay-Delta. Specific processes relevant to the IBM include bioenergetics (growth), habitat preference, environmental tolerance, feeding habits, and the age or life-stage dependence of these factors. We will incorporate bioenergetics parameters derived from this study into the IBM to fill in existing key data gaps.

Time Period: May 2010 - April 2011
Resources Required:
Cost: $128,422
PI(s): Frank Loge, Joseph J. Cech Jr., Nann Fangue and Joan Lindberg (UCD)
Contract needed/in place: In progress.
Contract manager(s): Erwin Van Nieuwenhuyse (USBR) and Frank Loge (UCD).
Term of contract: To be determined.
Personnel: Kai Eder, Erik Loboschefsky, Cincin Young and Dennis Cocherell (UCD)
Equipment: Loligo Respirometer and attendant data acquisition software.
Deliverables and Dates:

- Determine longfin smelt bioenergetic parameters of maximum food consumption and resting and active oxygen consumption rates (November 2010).
- Construct longfin smelt bioenergetics model (February 2011).
- Implement longfin smelt bioenergetics model into the IBM (March 2011).
- Final report (April 2011).

How is this activity related to the POD investigations and what is its relevance to understanding the effects of fall flow variations on delta smelt? Temperature changes brought about by variations in flow influence the food and oxygen consumption rates of Delta fish species. Growth of longfin smelt, assessed by the bioenergetics model, may thus be affected by variations

in fall flows. Because growth is a major component of the IBM, flow variation is likely to affect longfin smelt population dynamics. These findings will advance the understanding of flow variation effects on Delta fish populations, including delta smelt.
Comments: This work will require cultured longfin smelt obtained from the FCCL located in Byron, California. Development of the IBM for longfin smelt is funded under a separate IEP funded study.

Delta Smelt Acoustic Tag Development

IEP 2010-182
Point person: Ted Sommer (DWR)
Lead Agency: UCD
Questions: What are the overall physical constraints for a Juvenile Salmon Acoustic Telemetry system (JSATs)-compatible acoustic tag suitable for use in delta smelt?
Description: The overall long-term goal of this project is to work towards developing an acoustic telemetry system for delta smelt and to use this system to monitor their location and behavior within the San Francisco Bay-Delta system. For this specific study, we will determine acoustic transmitter constraints of size, shape, and mass needed for successful surgical implantation into delta smelt. The physical dimensions of a tag should neither interfere nor obstruct proper functioning of internal organs and tissues, while minimizing the likelihood of tag expulsion. Additionally, normal swimming behavior and buoyancy control are behaviors that must be preserved through understanding of tag size constraints within the context of sex and life stage of delta smelt. To this end, we will inject smelt internal body cavities with moldable latex to determine the maximum size of a potential tag within a given smelt size class. We will then construct inoperable "dummy" tags comprising 3 size ranges of measured body cavities (upper, middle, and lower ranges) while keeping the tags within accepted tag body burden limits. The tags will be surgically implanted (or injected if small enough) into various smelt at different stages of maturity and their survival will be assessed over 30 days. Short-term tagging effects such as swimming and moving will be assessed during the first 24 hours, while all fish (30-day mortalities as well as survivors) will be examined by a histopathologist for tag-related tissue and organ damage, and assessments of incision and suture will be performed. Based on outcomes from these various analyses an optimal size, shape, and mass of acoustic transmitter will be determined for delta smelt.
Time period: October 2010 - June 2011
Resources required:
- Cost: $177,544
- PI(s): Frank Loge and Raul Piedrahita (UCD)
  - Contract needed / in place: In progress.
  - Contract manager(s): Erwin Van Nieuwenhuyse (USBR) and Raul Piedrahita (UCD).
  - Term of contract: To be determined.
- Personnel: Kai Eder, Donald Thompson, Joseph Groff and graduate student research assistant (UCD).
- Equipment: A 2HP heat pump for a recirculating water system.

Deliverables and dates:
- Measurement of smelt internal body cavity (January 2011).
- Construction of "dummy" tags used for implantation (March 2011).

- Tag implantation and evaluation of biological effects (June 2011).
- Final report (June 2011).

How is this activity related to the POD investigations and what is its relevance to understanding the effects of fall flow variations on delta smelt? Many, if not all, of the ecological questions surrounding the recovery of delta smelt require knowledge of where these animals are located seasonally, where they spawn, and corridors of movement. To date, little is known on the spatial and temporal distribution of these animals. Through development and subsequent application of miniaturized acoustic tags to delta smelt, fish movement and behavior can be studied.

Comments: None

Refinement and Application of Novel Molecular and Biochemical Biomarkers to Determine Sublethal Contaminant Exposure and Effects in Archived Delta Smelt Samples.

IEP 2010-183

Point person: Anke Mueller-Solger (DSC)

Lead Agency: UCD

Questions: Can novel biomarker tools be used to monitor and assess sublethal impairment of important life history parameters of delta smelt exposed to ambient Delta water and specific contaminants? Can these tools be utilized for toxicant identification?

What is the temporal and spatial distribution of sublethal impairments and contaminant exposure of delta smelt in the Delta? How do results obtained with novel biomarkers compare to acute toxicity patterns found for delta smelt in the Delta?

Description**:** The proposed study builds on investigations performed in 2006-2009 to evaluate chemical-related aquatic toxicity of Delta water to early life stages of delta smelt. Results from these studies identified specific areas of concern in the Delta, particularly the Sacramento River at Hood, Cache Slough near Lindsey Slough, and the San Joaquin River at Rough and Ready Island. Current-use pesticides along with contaminants associated with municipal wastewater treatment effluents were labeled as potential toxicants. However, no toxicity identification tools are currently available for this species. Genomic biomarkers measure the functional response of organisms to contaminant exposures. Different chemicals will elicit a different response that is dependent on their mechanisms of action. To date, we have been successful in identifying the mechanisms of action of contaminants of concern through the application of molecular biomarkers and links have been established between gene expression and responses at higher levels of organization.

The effects of environmental contaminants as a factor in the observed decline of delta smelt will be investigated through a single experimental task: refining and applying novel biomarker tools to determine sublethal contaminant exposure and effects in archived delta smelt samples. These goals will be accomplished in 3 interlinked steps: (*a) assessment of gene expression*, focusing on the molecular responses in delta smelt exposed to environmental water samples collected throughout the Delta; (*b) toxicant identification*, based on the functional classification of these gene responses and response profiles generated under a previous IEP POD project, and (*c) site-specific response classification*, based on the generation of genomic profiles constructed by utilizing genomic data obtained for each specific site. Microarrays will provide information on responding genes and allow distinction between expression patterns elicited by different chemicals (expression signatures) or chemical mixtures. Quantitative PCR of select specific biomarker genes and resulting heatmaps will be applied to investigate exposure effects on muscular, neurological, endocrine, digestive, immune, respiration, membrane disruption and ion exchange alterations in the delta smelt.

Time period**:** July 2010 - June 2011

Resources required**:**

Cost: $220,000 in 2010

PI(s): Inge Werner and Richard Connon (UCD)

Contract needed / in place: In progress.

Contract manager(s)**:** Erwin Van Nieuwenhuyse (USBR) and Inge Werner (UCD).

Term of contract: To be determined.

Personnel**:** Above named investigators, graduate students and research assistants.

Equipment**:** No new equipment required.

Deliverables and dates**:** (assuming a start date of July 1, 2010)

- Study plan, peer-reviewed by the POD CWT (July 2010).
- Quarterly progress preports to the POD CWT (September and December 2010 and March 2011).
- Final report (June 2011).
- 1 or more IEP Newsletter articles (June 2011).
- 1 or more peer-reviewed journal publication(s) (June 2011).

How is this activity related to the POD investigations and what is its relevance to understanding the effects of fall flow variations on delta smelt? This study directly addresses the *IEP Priority Research Topic 1: Habitat Effects on Delta Smelt Population Dynamics.* A gene microarray and novel biomarkers for delta smelt (developed as part of previous IEP POD funded work) will be refined and used to determine exposure to and measure effects of contaminants responsible for causing toxicity to the endangered delta smelt. This study builds on successful previous work funded by IEP POD investigating the effects of environmental contaminants as a factor in the observed decline of delta smelt. This project will provide a sensitive tool to assess the effects of environmental stressors on delta smelt, and to develop site-specific genetic fingerprints for evaluating the effects of seasonal variations in environmental conditions, including flows.

Comments**:** This study builds on successful previous work funded by IEP POD including toxicity tests with larval delta smelt, determination of toxic thresholds of delta smelt for a number of relevant chemicals, development of a delta smelt specific cDNA microarray, and development of a suite of delta smelt-specific molecular biomarkers for assessing the effects of environmental stressors. Archived delta smelt samples from laboratory tests performed in 2008 and 2009 as part of previous IEP POD funded work will be used for this study.

Disease and Physiology Monitoring in Wild Delta Smelt Adults

IEP 2010-184

Point person: Randy Baxter (DFG)

Lead Agency: USFWS

Questions: What is the influence of pathogens, contaminants, and adverse water quality on delta smelt survival?

Description: The projects objective is to survey subadult and adult delta smelt populations collected in the lower Sacramento River for fish pathogens, tissue abnormalities (histology), energy reserves (muscle triglycerides) and osmoregulatory status (gill Na-K-ATPase). The

minimum target sample is 100 smelt collected by DFG's SKT Survey. A maximum of 20 fish will be collected at any given station.
Time period: Field samples will be collected from January – May 2010.
Resources required:
    Cost: This work is not being funded by IEP sources.
    PI(s): Scott Foott (USFWS)
        Contract needed / in place: N/A
        Contract manager(s): N/A
        Term of contract: N/A
    Personnel: DFG will supply field personnel during the SKT Survey.
    Equipment: No new equipment needs to be purchased.
Deliverables and dates:

- Results from laboratory analysis of samples and production of a technical report (August 2010).

Physical Processes Influencing Spawning Migrations of Delta Smelt

IEP 2010-187
Point person: Larry Brown (USGS)
Lead Agency: USGS
Questions: The primary goal of the proposed experiment is to evaluate whether the annual spawning migration of delta smelt is triggered by a sudden decrease in water transparency, i.e. high turbidity.
Description: This study was designed as an outgrowth the hypothesis that that adult delta smelt initiate an upstream spawning migration when the first major storm causes a turbidity pulse above some threshold. The purpose of this element is to test the hypothesis and also determine how delta smelt move upstream, specifically do they take advantage of tidal flows (i.e., tidal surfing). Additional secondary goals/questions will also be addressed to the extent possible. The questions will be addressed using intensive Kodiak trawling before and after the first major storm of the year in coordination with collection of continuous tidal velocity and turbidity data.
Time period: This study is expected to be implemented in the Fall/Winter of 2010. It is unclear if the study will be repeated in additional years. Additional years will likely depend on costs and results obtained in year 1.
Resources required:
    Cost: Cost undetermined at this point. Funding expected from DOI through USBR.
    PI(s): Jon Burau (USGS) and Bill Bennett (UCD).
        Contract needed / in place: Contact/agreement needed
        Contract manager: Presumably Erwin Van Nieuwenhuyse (USBR)
        Term of contract: Unknown. Anticipate year by year funding.
    Personnel: Jon Burau (USGS), Bill Bennett (UC Davis), field help expected from USGS (Sacramento and Columbia River Lab) and possibly IEP (boat operators and crew). Logistics still being worked out.
    Equipment: Boats likely to be borrowed from USGS Columbia Lab. Some equipment may need to be purchased (e.g., nets)
Deliverables and dates:

- Progress report and/or presentation to the Fish Migration PWT, after field work completed and as initial analysis 2011.

- IEP Asilomar presentation (February 2012).
- Final report or journal article, if appropriate (December 2011).

How is this activity related to POD or HSG: The results of this analysis will contribute to understanding how turbidity and possibly other factors influence spawning movements of adult delta smelt.

Comments:

OP and Pesticide use in the Sacramento River and Delta

IEP 2010-188

Point person: Stephanie Fong (CVRWQCB)

Lead Agency: CVRWQCB

Questions: Are past organophosphate (OP) hotspots still exhibiting toxicity in traditional EPA 3-species toxicity tests or to *Hyalella azteca*? Have the OPs been replaced by other pesticides, and are they causing toxicity?

Description: This study will use traditional EPA 3-species testing in addition to *H. azteca* testing and new, sub-lethal endpoints to assess locations in the Sacramento River and Delta that had a history of OP-caused toxicity.

Time period: March 2010-June 2011

Resources required:

- Cost: $175,000 contract and CVRWQCB staff time.
- PI(s): Inge Werner (UCD)
    - Contract needed / in place: In place.
    - Contract manager(s): Stephanie Fong (CVRWQCB) and Inge Werner (UCD).
    - Term of contract: May 2010 to May 2011.
- Personnel: Inge Werner and graduate student (UCD), Stephanie Fong (CVRWQCB)
- Equipment: No new equipment is needed; these are typical laboratory tests.

Deliverables and dates:

- Peer-reviewed study plan (July 2010).
- Progress reports and/or participation in the POD CWT, quarterly throughout the study.
- Final report (June 2011).

How is this activity related to HSG? The results of this analysis will contribute to the abiotic habitat driver section of the fall X2 and delta smelt conceptual model.

Comments: This contract was combined with the acute and chronic toxicity of contaminant mixtures study for ease of contracting.

Ammonia Literature Review and Synthesis

IEP 2010-189

Point person: Mark Gowdy (SWRCB)

Lead Agency: SWRCB

Questions: What do existing data, studies and literature have to say about the effects of ammonia on aquatic species, and are there any data gaps concerning ammonia concentrations and species in the Delta?

Description: Review existing data, studies, and the literature on the effects of ammonia on aquatic species. Prepare a synthesis report on these studies and determine if there are any data gaps, specifically with respect to ammonia concentrations and species residing in the Delta.

Time period: December 2008 – June 2010

Resources required:

Cost: $69,000

PI(s): Mike Johnson (UCD)

Contract needed / in place: In place.

Contract manager(s): Mark Gowdy (SWRCB)

Term of contract: December 2008 – June 2010

Personnel: Mike Johnson), Ling Chu, Jennifer Nickell and Zephyr Papin (UCD)

Equipment: No new equipment is needed.

Deliverables and dates:

- Synthesis report on effects of ammonia on species in the Delta.

Comments: None