Title

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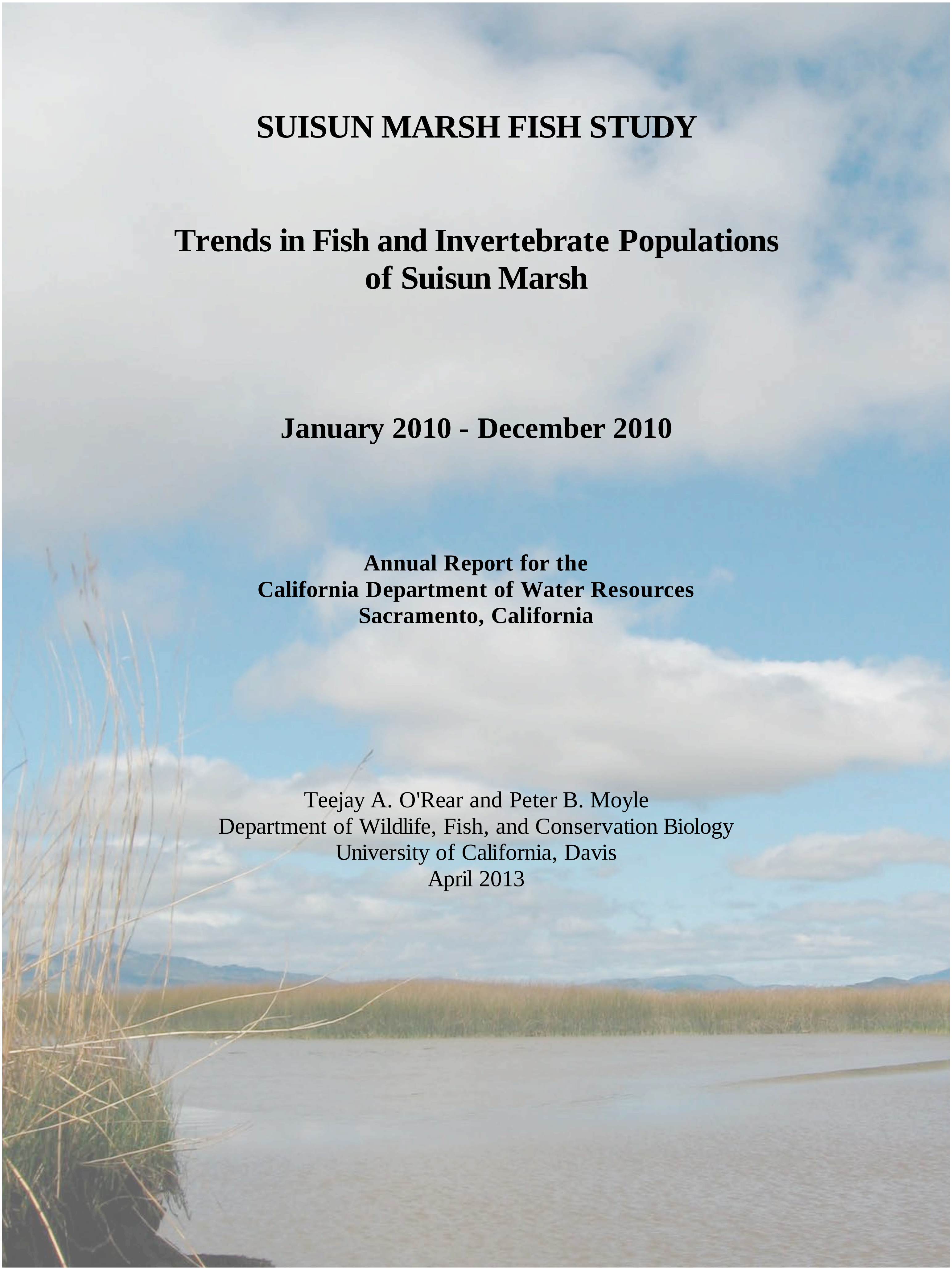
Publication Date
2013



SUISUN MARSH FISH STUDY

Trends in Fish and Invertebrate Populations of Suisun Marsh

January 2010 - December 2010

Annual Report for the
California Department of Water Resources
Sacramento, California

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April 2013

SUMMARY

Suisun Marsh, at the geographic center of the San Francisco Estuary, is important habitat for introduced and native fishes. The University of California, Davis, Suisun Marsh Fish Study has systematically monitored the marsh's fish populations since 1980. The purpose of the study has been to determine the environmental factors affecting fish abundance and distribution within the context of water management.

In 2010, 287 otter trawls and 72 beach seines were performed. In comparison to 2009, when 256 otter trawls and 75 beach seines were conducted, all four common plankton-feeding macroinvertebrates - Black Sea jellyfish (*Maeotias marginata*), overbite clam (*Corbula amurensis*), California bay shrimp (*Crangon franciscorum*), and Siberian prawn (*Exopalaemon modestus*) - increased in otter trawls, implying that pelagic food sources were more abundant. However, the large decline in otter trawl catches of mysids, young-of-year striped bass (*Morone saxatilis*), and shimofuri gobies (*Tridentiger bifasciatus*), coupled with a less pronounced decrease in the beach seine catch of young-of-year striped bass, suggests that pelagic food sources became limiting in late summer and early fall. Higher and more variable flows likely increased recruitment of fishes spawned downstream [yellowfin goby (*Acanthogobius flavimanus*)], upstream [splittail (*Pogonichthys macrolepidotus*)], and within [threadfin shad (*Dorosoma petenense*] the marsh while decreasing recruitment of other species [e.g., white catfish (*Ameiurus catus*)]. Draining of duck ponds appeared to have a very strong positive effect on a few species that substantially influenced the annual fish-per-trawl and fish-per-seine values. Cooler-than-average temperatures affected reproduction of Black Sea jellyfish (*Maeotias marginata*) and, especially, Mississippi silversides (*Menidia audens*). Thus, hydrology, both within and outside the marsh, acting in concert with pelagic food supplies and unseasonably cool temperatures, were largely responsible for our catches in 2010.

More frequent sampling during early autumn in smaller sloughs subject to water manipulations by duck clubs revealed different patterns in fish assemblages through time. In one slough where abiotic conditions did not exceed tolerances of marsh fishes, fish abundance and diversity were relatively high and stable. Conversely, another slough affected by steadily declining dissolved oxygen concentrations had a concomitantly smooth decrease in (1) total fish abundance and (2) the proportion of the assemblage comprised of hypoxia-intolerant fishes. In a third slough, where water temperature and dissolved oxygen levels were more erratic and occasionally at harmful levels, fishes disappeared and were slow to recover. However, the effect of low levels of dissolved oxygen on fishes was partially confounded by other abiotic variables, which could be clarified by use of stations continually monitoring all data of interest.

INTRODUCTION

Suisun Marsh is a brackish-water marsh bordering the northern edge of Suisun, Grizzly, and Honker bays in the San Francisco Estuary (Figure 1); it is the largest, uninterrupted expanse of estuarine marsh remaining on the western coast of the contiguous United States (Moyle et al. 1986). Most of the marsh area is diked wetlands managed for waterfowl, with the rest of the acreage consisting of tidal sloughs (California Department of Water Resources 2001). The marsh's central location in the San Francisco Estuary makes it an important nursery for euryhaline freshwater, estuarine, and marine fishes.

The University of California, Davis, Suisun Marsh Fish Study was begun in 1979 to monitor and to understand the abundance and distribution of fishes in relation to each other, to abiotic and biotic variables, and to water management activities (e.g., water exports). The study has used two primary methods for sampling fishes: beach seines and otter trawls. Juveniles and adults of all species have been surveyed systematically since 1980; between 1994 and 1999, larval fishes were also surveyed to better understand their ecology in the marsh (Matern and Meng 2001). Other objectives have included (1) evaluating the effects on fishes of the Suisun Marsh Salinity Control Gates (Matern et al. 2002), which began operating in 1988 (California Department of Water Resources 2001); (2) examining long-term changes in the Suisun Marsh ecosystem in relation to other changes in the San Francisco Estuary; and (3) enhancing understanding of the life history and ecology of key species in the marsh. Secondary objectives have included supporting research by other investigators through special collections; providing background information for in-depth studies of other aspects of the Suisun Marsh aquatic ecosystem (e.g., studies of jellyfish biology); contributing to the general understanding of estuarine systems through publication of peer-reviewed papers; training undergraduate and graduate students in estuarine studies and fish sampling; and providing a venue for managers and biologists interested in the marsh to experience it firsthand. In 2010, 19 undergraduate students, nine graduate students, 12 environmental management workers, eight state agency employees, one principal investigator, and six others from various backgrounds assisted in trawling and seining for fishes. The project also collected fishes for studies on (1) predation of Delta smelt (*Hypomesus transpacificus*) by marsh fishes using DNA techniques, (2) American shad (*Alosa sapidissima*) life history and distribution, (3) sexual behavior of tule perch (*Hysterocarpus traski*), and (4) longfin smelt (*Spirinchus thaleichthys*) ecology. Additionally, the long-term dataset is currently being used to (1) model Delta and longfin smelt population dynamics, (2) study trends in near-shore fish assemblages along the San Francisco Estuary's longitudinal axis, (3) inform wetland restoration in the western marsh, and (4) to compare the biomass of marsh fishes to those in the bays.

Moyle et al. (1986) evaluated the first five years of data collected by the study and found three groups of species that exhibited seasonal trends in abundance, primarily due to recruitment. The structure of the fish community was relatively constant through time; however, total fish abundance declined over the five years. The decline was partly due to strong year-classes early in the study period, which was followed by both extremely high river flows and drought that resulted in poor recruitment. The authors also found that native fishes tended to be more prevalent in small, shallow sloughs, while introduced species were more prominent in large sloughs.

Meng et al. (1994) incorporated eight more years into their study, which revealed that the fish assemblage structure was less constant over the longer time period than the earlier study indicated. Additionally, introduced fishes had become more common in small, shallow sloughs, possibly as a result of drought and high exports allowing increased salinities in the marsh and depressing reproductive success of native fishes. Like Moyle et al. (1986), Meng et al. (1994) found a general decline in total fish abundance (particularly in the native fishes) through time. Matern et al. (2002) found results similar to Meng et al. (1994): fish diversity was highest in small sloughs, and native fish abundances continued to decrease.

In recent years, O'Rear and Moyle (2010, 2009, 2008) have bolstered the findings of previous studies and documented changes that appear to be happening in other parts of the estuary. For instance, the timing, variability, and magnitude of Delta outflow continues to be an important factor affecting the abundance of fishes recruiting into the marsh from upstream or downstream areas [e.g., striped bass (*Morone saxatilis*), yellowfin goby (*Acanthogobius flavimanus*)]. Additionally, Delta ouflow, through its influence on marsh salinities, has also affected fishes produced in the marsh [e.g., white catfish (*Ameiurus catus*) and black crappie (*Pomoxis nigromaculatus*)]. Perhaps most notably, there appears to be a limitation of pelagic food supplies sometime in summer that results in an inshore movement of fishes. Finally, the marsh still provides vital habitat for at-risk native species (e.g., splittail, longfin smelt) that is largely and increasingly absent from the Delta. Consequently, the Suisun Marsh Fish Study remains instrumental in documenting and understanding changes in the biology of the estuary, especially within the context of climate change.

The purpose of this report is to (1) update the results of the previous Suisun Marsh Fish Study report (O'Rear and Moyle 2010), which explored the composition of fish assemblages in inshore and channel habitats, macroinvertebrate ecology in channels, and patterns in catch of life-history stages of important fishes and (2) discuss the findings of a pilot study undertaken to more finely resolve the effects of low DO and other abiotic factors on fishes during early autumn.

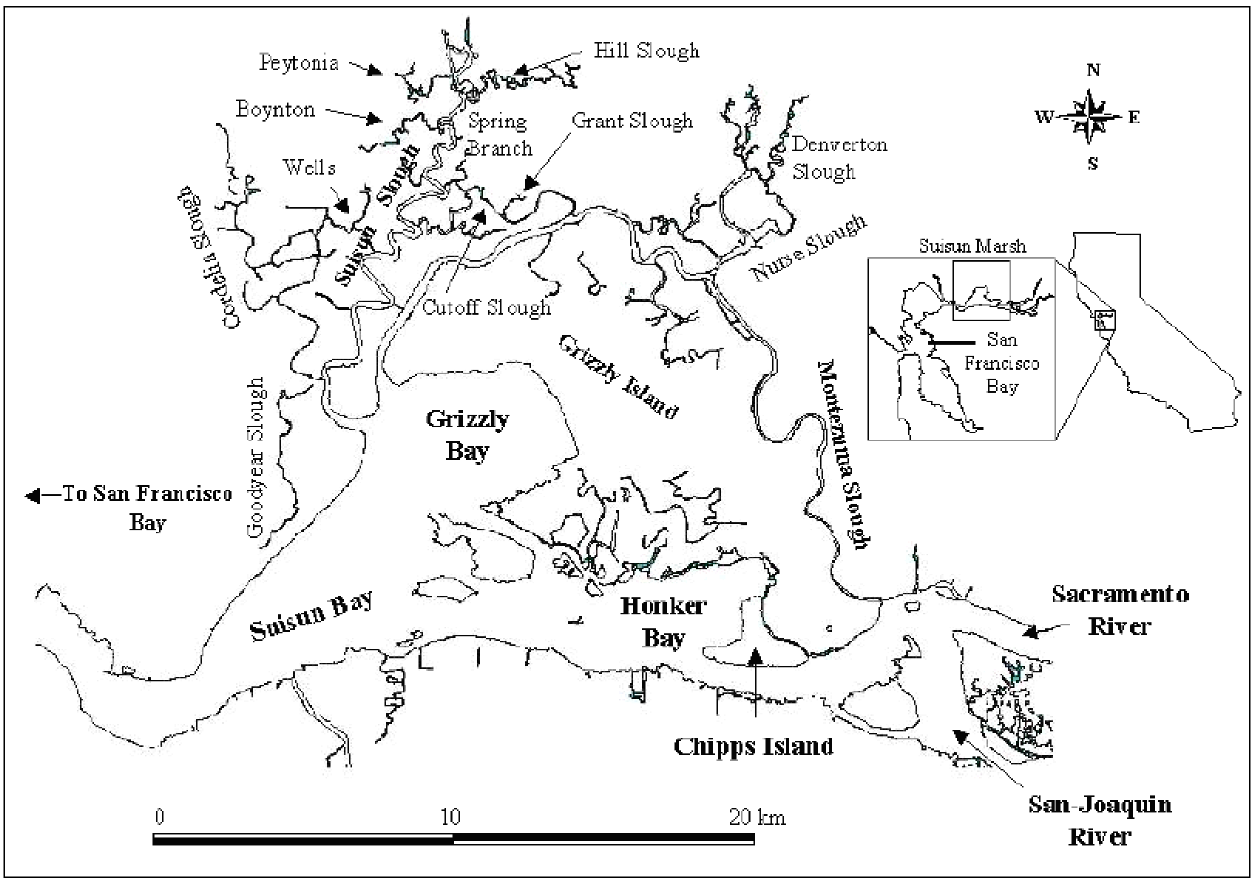

Figure 1. Suisun Marsh and Bay (from Schroeter et al. 2006).

METHODS

Study Area

Suisun Marsh is a tidal brackish-water marsh covering about 34,000 hectares (California Department of Water Resources 2001). Roughly two-thirds of the marsh area is diked wetlands managed for waterfowl; the remainder consists of sloughs that separate and deliver water to the wetland areas (California Department of Water Resources 2001). The marsh is contiguous with the northern boundary of Suisun, Grizzly, and Honker bays and is central to the San Francisco Estuary (Figure 1). There are two major tidal channels in the marsh: Montezuma and Suisun sloughs (Figure 1). Montezuma Slough generally arcs northwest from the confluence of the Sacramento and San Joaquin rivers, then curves southwest and terminates at Grizzly Bay (the major embayment of Suisun Bay). Major tributary sloughs to Montezuma are Denverton and Nurse; Cutoff Slough and Hunters Cut connect Suisun and Montezuma sloughs (Figure 1). Suisun Slough begins near Suisun City and meanders south until emptying into Grizzly Bay southwest of the mouth of Montezuma Slough. Major tributaries to Suisun Slough, from north to south, are Peytonia, Boynton, Cutoff, Wells, Cordelia, and Goodyear sloughs (Figure 1). First and Second Mallard sloughs are tributary to Cutoff Slough and are part of Solano Land Trust's Rush Ranch Open Space preserve; Rush Ranch is part of the San Francisco Bay National Estuarine Research Reserve (http://www.nerrs.noaa.gov/SanFrancisco/welcome.html).

Suisun and Montezuma sloughs are generally 100-150 meters (m) wide, 3-7 m deep, and partially riprapped (Meng et al. 1994). Tributary sloughs are usually 10-20 m wide, 2-4 m deep, and fringed with common reed (*Phragmites communis*) and tules (*Schoenoplectus* spp.). Substrates in all sloughs are generally fine organics, although a few sloughs also have bottoms partially comprised of coarser materials (e.g., Denverton Slough), and the larger, deeper sloughs (e.g., Montezuma Slough) can have sandy channel beds.

The amount of fresh water flowing into Suisun Marsh is the major determinant of its salinity. Fresh water enters the marsh primarily from the Sacramento River through Montezuma Slough, although small creeks, particularly on the northwest and west sides of the marsh, also contribute fresh water. As a result, salinities are generally lower in the eastern and northwestern portions of the marsh. Freshwater inflows are highest in winter and spring due to rainfall runoff and snowmelt in the Sacramento and San Joaquin hydrologic regions; consequently, marsh salinities are often lowest in these seasons. Salt water enters the marsh through lower Suisun and Montezuma sloughs from Grizzly Bay via tidal action, although the effect of the tides is primarily on water surface elevation and not salinity throughout much of the year (Matern et al. 2002). During extreme tides, water depths can change as much as 1 m over a tidal cycle, often dewatering more than 50% of the smaller sloughs at low tide and overtopping dikes at high tide.

A number of water management facilities influence the hydrology and water quality of the marsh. State Water Project and Central Valley Project water export facilities in the southern Delta affect the timing and magnitude of freshwater inflow into Suisun Marsh. The Suisun Marsh Salinity Control Gates, located in Montezuma Slough just downstream of the confluence of the Sacramento and San Joaquin rivers, are operated to inhibit saltwater intrusion into the marsh during flood tides, which provides fresher water for diked wetlands (California Department of Water Resources 2001; Figure 1). Numerous water control structures, most of which are unscreened for fish, are located throughout the marsh; they are most commonly opened in early autumn for flooding wetlands to attract wintering waterfowl and in spring to leach salts from wetland soils. Wetlands are usually drained in late spring, with drainage water being discharged directly into numerous sloughs within the marsh, and remain dry throughout summer. Goodyear Slough is now connected to Suisun Bay by a channel that was built to depress salinities in the slough for water diverters in the western portion of the marsh.

Sampling

Since 1980, monthly juvenile and adult fish sampling has been conducted at standard sites within Suisun Marsh. Prior to 1994, a total of 12 sloughs and 27 sites were sampled. Several of these historic sites were sampled only in 1980 and 1981, with 17 sites being sampled consistently until 1994 (see O'Rear and Moyle 2008). From 1994 to the present, 21 sites in nine sloughs have been regularly sampled (Figure 2). In 2010, we trawled Peytonia, Denverton, and Goodyear sloughs at approximately 10-day intervals from late September to early November to assess if a more frequent sampling schedule could better resolve the response of fish assemblages to low-DO events associated with flood-up of managed wetlands (O'Rear and Moyle 2010, Schroeter and Moyle 2004) and other abiotic factors; the weeks when these additional trawls were performed are given in Table 1. These three sloughs were chosen because they are a subset of smaller sloughs in the marsh and vary in the density of duck-pond water control structures: Goodyear Slough has 3.1 structures per river-kilometer (wcs/rkm), Peytonia Slough has 1.9 wcs/rkm, and Denverton Slough has 1.2 wcs/rkm (Matern et al. 2002). We also trawled two sites in Montezuma Slough immediately downstream of the confluence of Montezuma and Nurse sloughs to give students more experience in fish-sampling methods. Latitude and longitude coordinates for current, regularly sampled sites were obtained (± 100 m) using a Global Positioning System receiver and are found in Schroeter et al. (2006).

Table 1. Timing of trawls during more frequent sampling in early autumn. "X" denotes that the trawl was part of the regular monthly sampling schedule; "A" indicates an additional trawl not part of the standard monthly sampling. A box without a letter denotes that no sampling took place in that slough for the given week.

Slough	Week						
	19-Sep	26-Sep	3-Oct	10-Oct	17-Oct	24-Oct	31-Oct
Denverton	X		X	A		A	X
Goodyear	X		X	A	A	A	X
Peytonia	X		X	A		A	X

Trawling was conducted using a four-seam otter trawl with a 1.5 m X 4.3 m opening, a length of 5.3 m, and mesh sizes of 35 mm stretch in the body and 6 mm stretch in the cod end. The otter trawl was towed at 4 km/hr for 5 minutes in small sloughs and 10 minutes in large sloughs to compensate for small catches. In upper Suisun and Denverton sloughs, inshore fishes were sampled with a 10 m beach seine having a stretched mesh size of 6 mm. For each site, temperature (degrees Celsius, °C), salinity (parts per thousand, ppt), and specific conductance (microsiemens, μS) were recorded with either a Yellow Springs Instruments (YSI) 85 or 95 meter. Dissolved oxygen parameters (milligrams per liter, mg/l, and % saturation), first sampled in 2000, were also measured with the YSI 85. Water transparency (Secchi depth, cm), tidal stage (ebb, flood, high, low), and water depths (m) were also recorded.

Contents of each trawl or seine were placed into large containers of water. Fishes were identified, measured to the nearest millimeter standard length (mm SL), and returned to the water. Sensitive native species were processed first and immediately released. Numbers of

Siberian prawn (*Exopalaemon modestus*), Black Sea jellyfish (*Maeotias marginata),* Oriental shrimp (*Palaemon macrodactylus*), California bay shrimp (*Crangon franciscorum*), overbite clam (*Corbula amurensis*), and Asian clam (*Corbicula fluminea*) were also recorded. Siberian prawn were first positively identified in February 2002, although they were probably present in 2001. Siberian prawn likely comprised a large percentage of the 2001 and early 2002 shrimp catch that was recorded as Oriental shrimp; abundances of Siberian prawn are herein reported separately. Crustaceans from the order Mysida were pooled into one category, "mysids," and given an abundance ranking: 1 = 1-3 mysids, 2 = 4-50 mysids, 3 = 51-100 mysids, 4 = 101-500 mysids, and 5 = >500 mysids. The index was necessary because most mysids pass through the trawl, and those that remain in the net are difficult to accurately count.

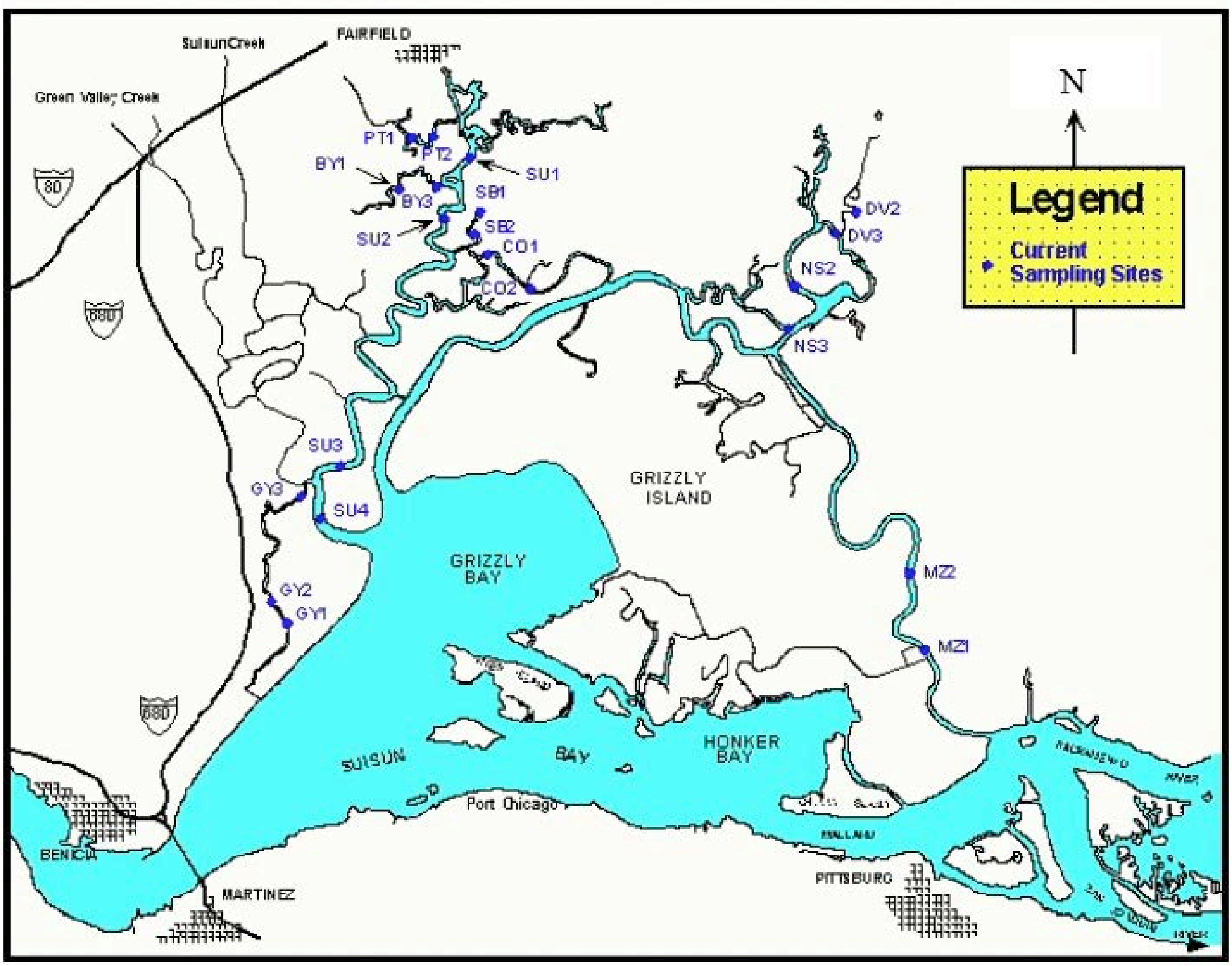

Figure 2. Map of current Suisun Marsh standard sampling sites (from Schroeter et al. 2006).

Data analysis

For this report, catch-per-unit-effort (CPUE) values were calculated differently depending on the type of comparison. For comparisons made among calendar years, CPUE for beach seines and otter trawls was calculated as

$$CPUE = \frac{annual\ number\ of\ \ fish}{annual\ number\ of\ \ trawls}$$

to remain consistent with previous reports (e.g., Schroeter et al. 2006); CPUE values for invertebrates were also calculated likewise, with the annual number of individuals for the invertebrate of interest substituting for "annual number of fish." For monthly comparisons, in order to account for unequal effort among sloughs, CPUE values for otter trawls were calculated as

$$CPUE_j = \frac{\sum_{i=1}^{n} \frac{number\ of\ \ fish_{ij}}{number\ of\ \ trawls_{ij}}}{n}$$

where *i* = slough, *j* =month, and *n* is the number of sloughs; once again, CPUE values for invertebrates were calculated likewise. The Montezuma Slough sites downstream of Nurse Slough were not included in the monthly comparisons because it was not sampled every month of the year; however, catches from those sites were included in annual CPUE values to remain consistent with previous reports and because inclusion of those sites resulted in negligible changes in the annual values. Monthly water quality averages for 2010 were calculated as for CPUE values, with the sum of the measurements of the water quality parameter of interest (e.g., Secchi depth, water temperature) substituting for "number of fish." Monthly beach seine comparisons for 2010 used only catch values (i.e., number of fish) since effort was equal between Denverton and upper Suisun sloughs for each month. X2, the distance in kilometers from the Golden Gate Bridge along the thalweg to the near-bed water with salinity of 2 ppt, was calculated following Jassby (1995). Delta outflow was obtained from the California Department of Water Resource's Dayflow website (2011*a*). Results were then graphed and compared.

Principal components analysis (PCA) in JMP 8.0 was used to further explore the relationship among juvenile striped bass, California bay shrimp, mysids, and abiotic variables. Variables were not transformed because data screening revealed that all relationships were approximately linear. For the more frequent autumn sampling, the nonparametric correlation statistics Spearman's ρ and Kendall's τ were calculated to better resolve the magnitude of the associations among abiotic variables and fish CPUE; these analyses were also carried out in JMP 8.0. Nonparametric methods were chosen because of the nonlinearity, multicollinearity, and small sample size of the data set.

Age-classes for fishes except splittail and striped bass were determined by observing peaks in length-frequency graphs. Splittail age-classes were determined following Matern and Sommer (unpublished data). Striped bass young-of-year were classified as those fish belonging to the length-frequency-graph peak corresponding to the smallest size-classes after April, adults were considered fish larger than 423 mm SL, and all others were classified as "juveniles."

Catch for all fishes and by each method from 1979 to 2010 are found in Appendix A; annual catch for each slough and trawl effort for each slough for 2010 are found in appendices B and C.

RESULTS AND DISCUSSION

Abiotic Conditions

Delta Outflow

The Net Delta Outflow Index (hereafter "Delta outflow"), a proxy for water exiting the Sacramento-San Joaquin Delta, is calculated by summing river flows entering the Delta, channel depletions, in-Delta diversions, and State Water Project, Central Valley Project, and Contra Costa Water District exports. Delta outflow substantially affects myriad physical, chemical, and biological aspects of Suisun Marsh (Enright and Culberson 2009, Matern et al. 2002, Meng and Matern 2001, Meng et al. 1994, Moyle et al. 1986)

The general pattern of outflow in 2010 was fairly typical, with high flows during winter and spring, minimum flows in summer, and the return of higher flows in late autumn. Unlike 2009, storms were generally more frequent and thus kept Delta outflow higher than 10,000 cfs from mid-January to mid-June. An exception to this was a drop in mid- to late March between two sets of fairly moderate storms (Figure 3). Delta outflow slowly and steadily declined until a cold front poured precipitation at the end of the third week in October, causing a spike in outflow. A few storms in November also increased Delta outflow, albeit mildly; however, high runoff and flood-control releases from reservoirs due to one of the wettest Decembers on record raised outflow substantially to close out the year (Figure 3).

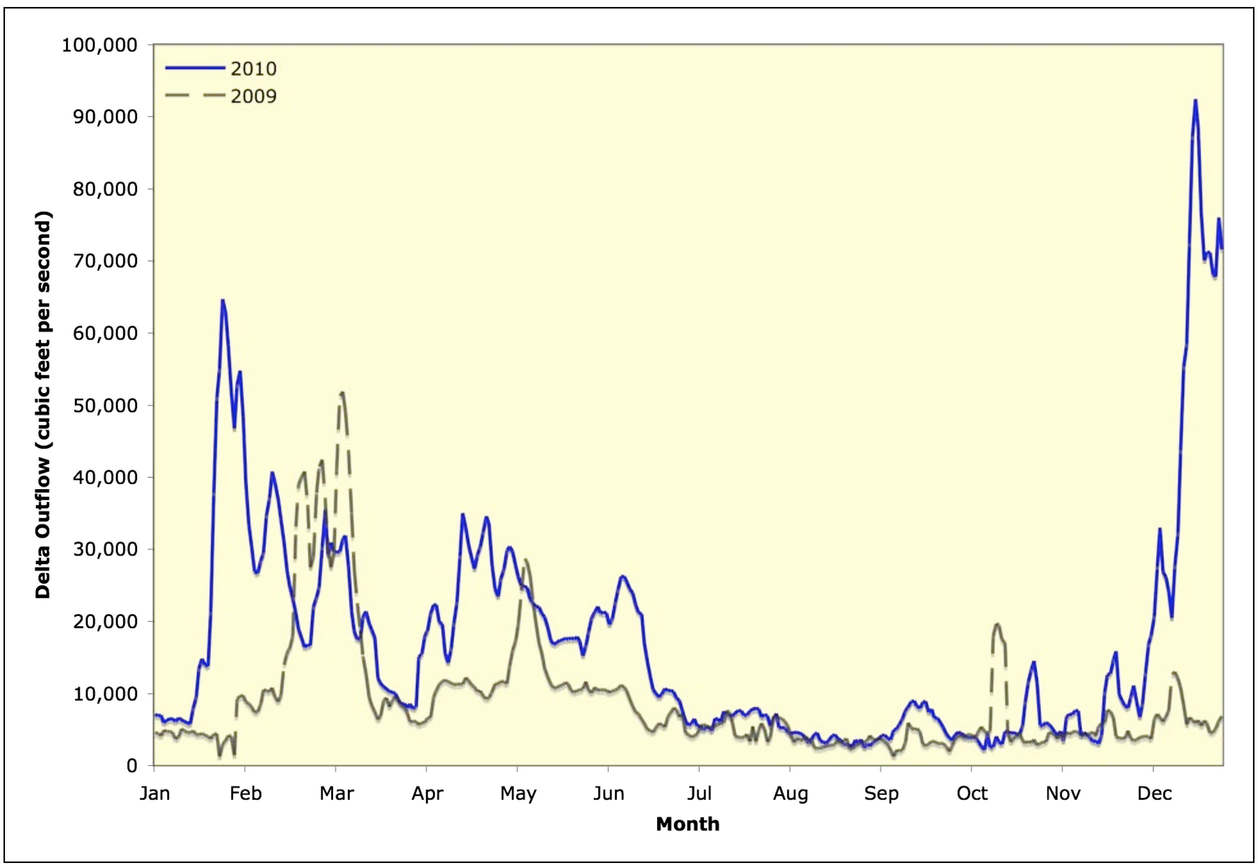

Figure 3. Daily Delta outflow for 2009 and 2010.

Three disparities between 2009 and 2010 worth noting are that (1) peak flows in the first half of both years occurred at different times (late February in 2009 and late January in 2010), (2) higher outflows extended further into 2010 than in 2009, and (3) December 2010 was very wet while December 2009 was comparatively dry. These differences in hydrology likely affected, both directly and indirectly, our catches of fish and invertebrates.

Salinity

Salinities in Suisun Marsh are strongly inversely correlated with Delta outflow (O'Rear and Moyle 2008) and thus are usually lowest in late winter and highest in early autumn (Figure 4). Reflecting the relatively average outflow, mean monthly salinities in 2010 were generally close to the average for all years (1980-2010) except in January and June (Figure 4). January's high values were because we sampled before the first strong storms of the year affected Delta outflow, while June's low mean and low standard deviation was due to low salinities in upper Goodyear Slough.

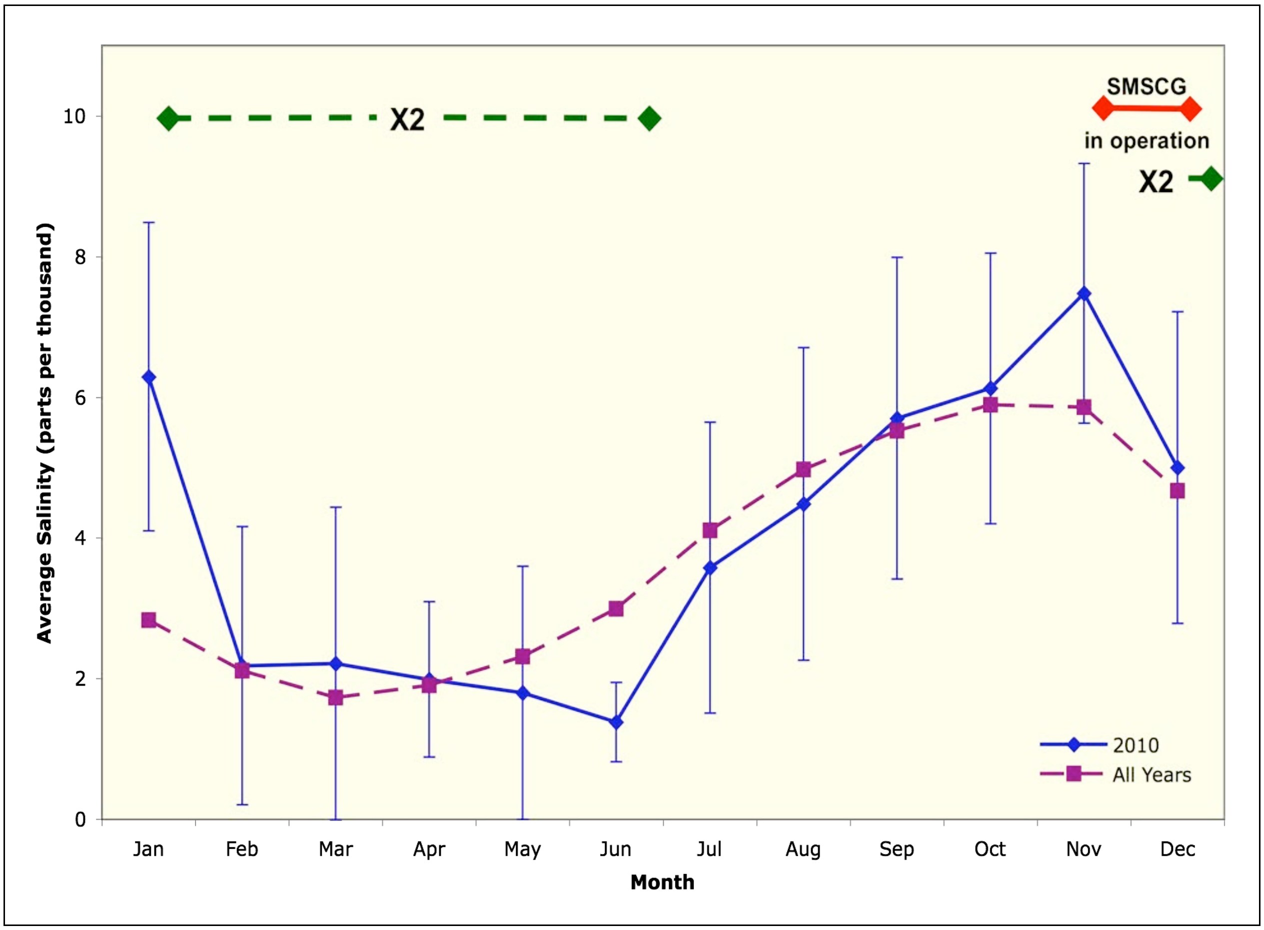

Figure 4. Average monthly salinities for 2010 and from 1980 to 2010 ("all years"); error bars are standard deviations for 2010. Green dashed bars surrounding X2 denote when X2 was within Suisun Marsh; red bar denotes when the Suisun Marsh Salinity Control Gates ("SMSCG") were in operation.

A distinct geographical salinity gradient generally sets up in late spring as Delta outflow subsides, with salinities highest in the southwest part of the marsh and lowest in the eastern and northern portions. With the exception of June, however, this gradient was present throughout 2010. For the most part, the disparity in salinities was driven by very high values in upper Goodyear Slough; during March, for example, the salinity of the two upper Goodyear sites averaged 8.3 ppt, while the next two highest salinities recorded were 2.3 ppt and 3.2 ppt in Denverton and lower Goodyear sloughs, respectively. Circulation in upper Goodyear Slough is often poor (Culberson et al. 2004), which probably contributed to the omnipresent gradient observed in 2010.

The location of X2 is associated with the historically productive entrapment zone and high abundances of phytoplankton, macroinvertebrates, and several fishes (Jassby et al. 1995). Consequently, when X2 is located in Suisun Bay, the abundance of fishes in Suisun Marsh is often relatively high. It also follows that the longer X2 is within Suisun Bay, the abundance of fishes in Suisun Marsh should be greater over a longer time span.

X2 was located in Suisun Marsh for all days of the months February through June (Figure 4). The young of many fishes are spawned in or migrate to the marsh during spring; X2 presence in the marsh during spring coincided when many of these fishes began to recruit. Consequently, high catches of some fishes in the marsh during the first part of the year (e.g., striped bass) could have been at least partially attributed to X2 position (Kimmerer 2001).

Dissolved Oxygen

Dissolved oxygen (DO) concentrations in the marsh are affected by respiration, photosynthesis, temperature, salinity, flow magnitudes, and diverting and draining of duck ponds. Because oxygen solubility decreases with higher salinities and temperatures, oxygen concentrations are frequently lower in summer and autumn than in winter. Hypoxic water is discharged into sloughs from some duck ponds during autumn, further lowering oxygen concentrations (Siegel et al. 2011, Schroeter and Moyle 2004), particularly in some small dead-end sloughs that have limited tidal exchange. Likewise, draining ponds in spring by discharging to the sloughs also depresses marsh oxygen concentrations (Siegel et al. 2011). Consequently, marsh oxygen concentrations are usually high in winter, lower in spring and summer, and lowest in autumn.

The monthly pattern for DO in 2010 generally followed the pattern for all years, with concentrations highest in early winter (i.e., January), lower in late spring and summer, and at a minimum in autumn (Figure 5). A notable disparity is the especially low mean in February, to which relatively low DO in sloughs of the northwest marsh - upper Suisun, Boynton, and Peytonia - contributed substantially. However, DO was lower than normal for all sloughs of the marsh in February. Additionally, a healthy adult striped bass and several tule perch were captured in upper Boynton Slough, where we measured the lowest DO concentration (3.81 mg/L) for the month. Adult striped bass generally avoid hypoxic waters (i.e., DO< 4 mg/L; Costantini et al. 2008, Tupper and Able 2000), and tule perch require well-oxygenated water (Cech et al. 1990). Consequently, our low February measurements may have been biased low due to measurement error.

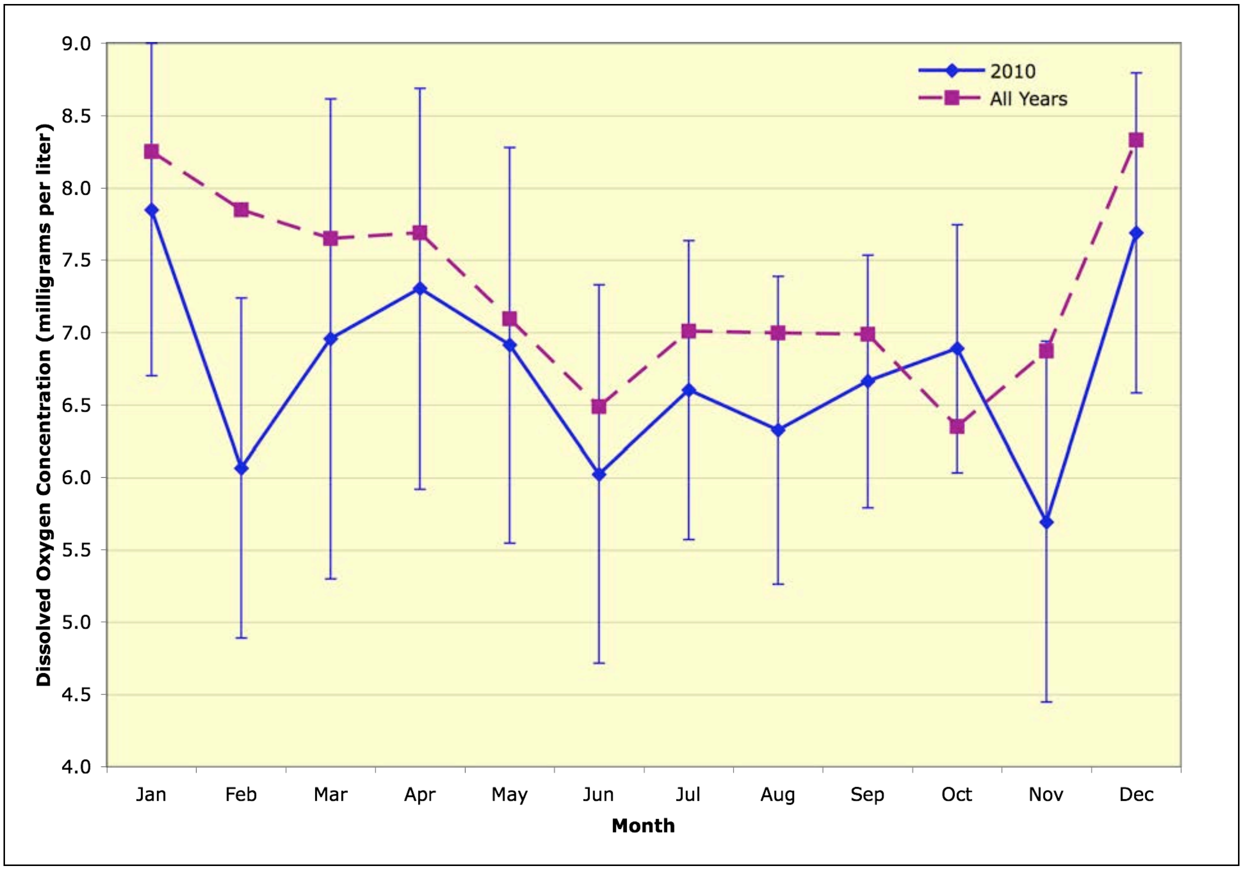

Figure 5. Monthly average DO concentrations for 2010 and from 2000 to 2010 ("all years"); error bars are standard deviations for 2010.

Water Temperature and Transparency

Water Temperature

Water temperatures in Suisun Marsh are primarily a function of solar radiation, local atmospheric conditions (e.g., marine layers) and, to a lesser extent, water volume. Generally, average monthly temperatures follow a pattern typical of temperate regions in the Northern Hemisphere: coldest temperatures occur in winter (December and January) and warmest temperatures occur in summer (July and August). Monthly water temperatures in 2010 followed the usual pattern (Figure 6). However, a number of differences between the monthly averages for all years of the study and for 2010 are worth pointing out. First, April and May in 2010 were unusually cool, resulting in marsh water temperatures almost 2°C below normal (Figure 6). Second, strong onshore flow and a thick marine layer kept much of July and August colder than usual. Third, our sampling in October and November coincided with dry high-pressure systems and thus our higher-than-average temperature readings for those months.

Water Transparency

The magnitude of freshwater inflow (mainly from the Sacramento River) is the primary determinant of water transparency in Suisun Marsh (O'Rear and Moyle 2008). Transparencies in the marsh are usually lowest in spring when river flows are highest; conversely, transparency generally reaches a maximum in October when river flows are at their annual minimum. As a result, the trends in transparency often mirror those for salinity. The pattern during 2010 was no exception (Figures 4 and 6), although transparencies were higher than average for all months except June.

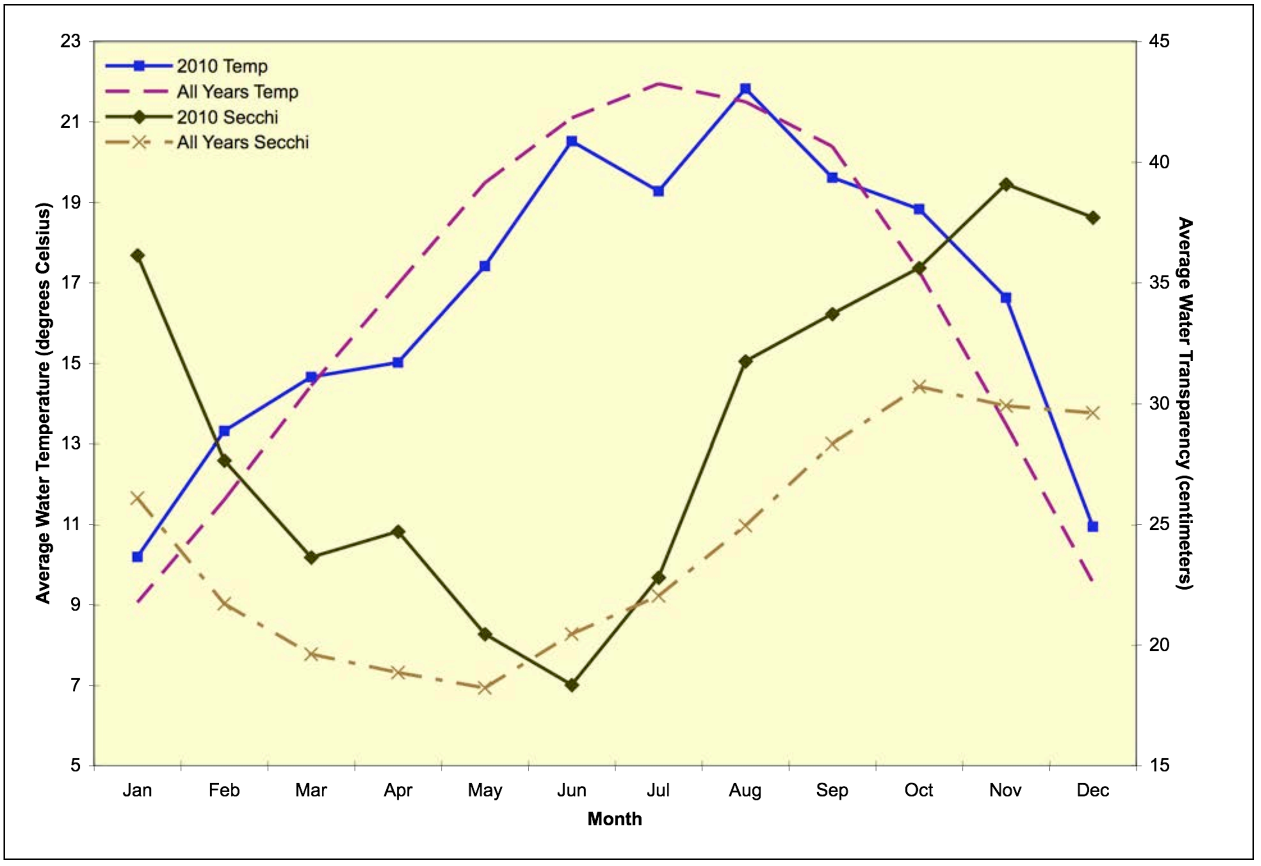

Figure 6. Monthly average temperatures and transparencies for 2010 and from 1980 to 2010 ("all years").

Trends in Invertebrate Abundance and Distribution

Four plankton-feeding macroinvertebrates are commonly captured by otter trawl in Suisun Marsh: California bay shrimp, Siberian prawn, Black Sea jellyfish, and overbite clam, of which only California bay shrimp is native. These invertebrates are important components of the food web, either as competitors [e.g., Black Sea jellyfish (Wintzer et al. 2011), overbite clam (Feyrer et al. 2003)] or as food sources [e.g., California bay shrimp and Siberian prawn (Nobriga and Feyrer 2008)] for fishes of the marsh. Annual catch of California bay shrimp has been highly variable, although decreasing trends in abundance were evident in the early 1980s and early 2000s (Figure 7). While catch of Siberian prawn, first captured in the marsh during 2002 (Schroeter et al. 2006), has also been variable, it has mirrored the catch for California bay shrimp from 2004 to 2010 (Figure 7). Black Sea jellyfish were first captured in 1981 and have been present in trawls during most years of the study's history, while overbite clam was not recorded until 1990 (Figure

7). Both the clams and the jellyfish exhibited increasing trends in the early 2000s and are now commonly captured relative to the 1980s and 1990s (Figure 7).

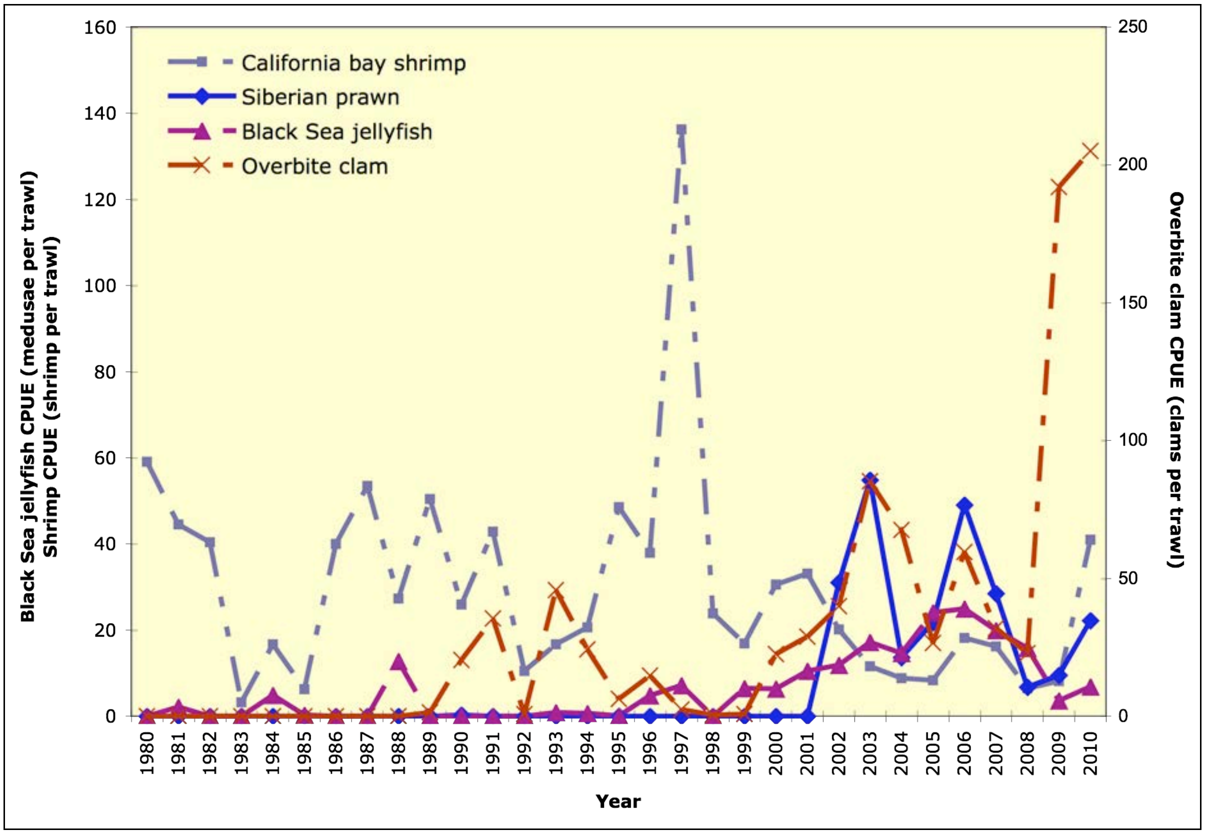

Figure 7. Annual otter trawl CPUE for four common invertebrates in Suisun Marsh from 1980 to 2010.

The abundances of all four macroinvertebrates increased from 2009 to 2010 (Figure 7). The annual CPUE increases for Black Sea jellyfish and overbite clam were relatively mild (107% and 188%, respectively); however, changes were more dramatic for the shrimps, with Siberian prawn more than doubling and California bay shrimp increasing five-fold (Figure 7).

California Bay Shrimp

The monthly pattern in the catch of California bay shrimp was fairly typical, with low catches in autumn and winter (Figure 8). Additionally, a very large proportion (54%) of the annual catch came from the southwest marsh (i.e., Goodyear and lower Suisun sloughs), which is consistent with recruitment of California bay shrimp into the marsh from downstream bays (i.e., Grizzly and San Pablo bays). However, the timing of peak catches in 2010 occurred later than in 2009 (O'Rear and Moyle 2010), which corresponds to differences in the timing of rapidly changing salinities in the marsh between the two years. California bay shrimp are generally more abundant in years of high Delta outflow (Hatfield 1985), and how far upstream they penetrate into the estuary seems dependent on the degree of salinity intrusion and hence Delta outflow. Consequently, the higher catch of California bay shrimp in 2010 appears largely due to higher outflows extending later into the year relative to 2009.

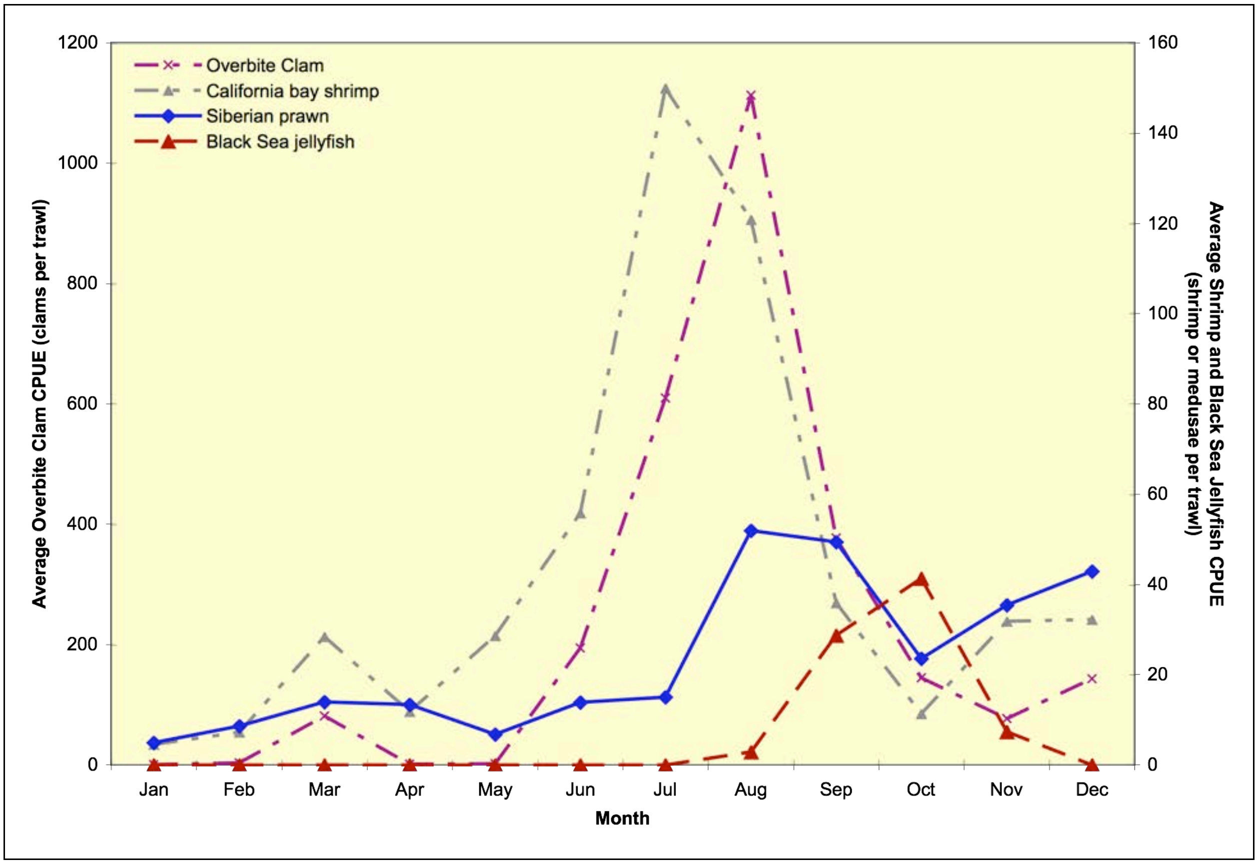

Figure 8. Average monthly otter trawl CPUE during 2010 for four common invertebrates in Suisun Marsh.

<u>Siberian Prawn</u>

The highest monthly catches for Siberian prawn in 2010 occurred during late summer and early fall (Figure 8), which has been seen in previous years (O'Rear and Moyle 2010). This is likely due to recruitment of juveniles to the otter trawl since the height of spawning appears to be summer (Oh et al. 2002). In contrast to the distribution of California bay shrimp, Siberian prawn were generally most abundant in fresher sloughs of the marsh interior, with 50% of the catch coming from the northwest marsh (i.e., Peytonia, Boynton, and upper Suisun sloughs). This corresponds with the preference of Siberian prawn for lower salinities (Emmett et al. 2002).

<u>Overbite Clam</u>

As in 2009, overbite clam were very abundant in 2010. Although the peak catch of overbite clam in 2010 occurred during summer, which is usual, it was a month later than in 2009 (Figure 8). This corresponds to both the spawning period of overbite clam and the delay of intrusion of higher-salinity water into the marsh (Schroeter 2010). While the majority of overbite clam were captured in the southwest marsh (i.e., lower Suisun and lower Goodyear sloughs), the proportion of the total catch from that region was much less than in 2009 (99% in 2009 and 68% in 2010). Virtually all the rest of the catch came from upper Suisun Slough;

additionally, relatively large catches were made in each season in upper Suisun Slough, indicating that overbite clam might be gaining a foothold in the interior of the marsh.

Black Sea Jellyfish

The appearance of Black Sea jellyfish medusae is contingent upon both salinity and temperature, with the medusae most abundant in moderately brackish, warm water (e.g., salinity = 3-7 ppt, water temperature > 19°C; Schroeter 2008). These conditions usually occur in late summer; however, the highest catch of medusae in 2010 did not occur until October (Figure 8). This delayed appearance was probably because of the unseasonably cool summer temperatures since salinities were well within the range for release of medusae in July and August (Figure 4). While medusae were captured in all sloughs of the marsh, they were never abundant in the southwest (lower Suisun and lower Goodyear sloughs), northeast (Denverton Slough), or east (upper Montezuma Slough) marsh.

Trends in Fish Abundance and Distribution

Otter Trawls

Annual otter trawl CPUE generally declined in the first 15 years of the study (1980-1995); from then until 2006, it vacillated around a relatively stable mean (Figure 9; O'Rear and Moyle 2009). From 2006 to 2008, however, catch declined substantially, concurrent with lower Delta outflows and higher marsh salinities. 2009 and 2010 saw a mild increase in catch. The decrease in the annual CPUE for native fishes has been more precipitous and less variable than that for introduced fishes (Figure 9). CPUE for introduced fishes has been highly variable over the study's history (Figure 9).

Annual otter trawl CPUE rose from 16.5 fish per trawl in 2009 to 20.6 fish per trawl in 2010. Unlike the change in catch from 2008 to 2009, which was driven primarily by introduced fishes (O'Rear and Moyle 2010), the difference between 2009 and 2010 was strongly influenced by native fishes. In particular, three native species were substantially more abundant in 2010 relative to 2009: splittail, prickly sculpin (*Cottus asper*), and threespine stickleback (*Gasterosteus aculeatus*; Table 2). The increase in splittail numbers was mostly due to a large catch of young-of-year fish (Table 2), although yearling fish were also more prevalent in 2010 than in 2009 (Figure 20). Splittail require inundated floodplains such as Yolo Bypass for spawning and rearing (Moyle et al. 2004, Sommer et al. 1997); in 2010, some flooding of Yolo Bypass by west-side tributaries (e.g., Cache Creek) did co-occur with the spawning period of splittail (i.e., spring). Consequently, our higher splittail catch in 2010 probably reflected greater reproductive success.

Table 2. Percent change in annual otter trawl CPUE (fish per trawl) for three native fishes caught in Suisun Marsh (% increases are equivalent to percentage points, such that a 100% increase indicates that the value has doubled).

Species	Prickly Sculpin	Splittail	Threespine Stickleback
2009 CPUE	0.22	2.04	0.40
2010 CPUE	0.99	3.28	1.17
%Change	351%	61%	191%

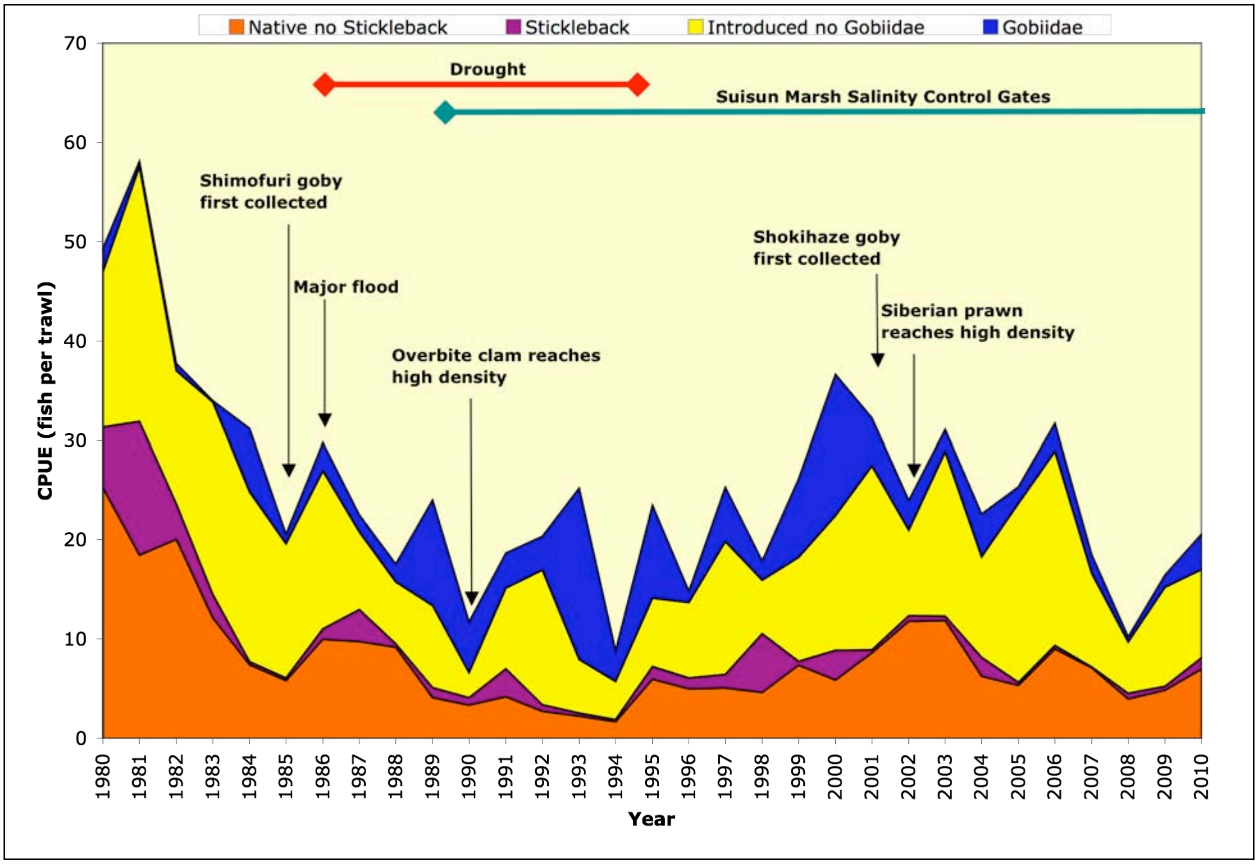

Figure 9. Annual otter trawl CPUE from 1980 to 2010 for four categories of fishes, with timing of important events noted ("drought" and the associated line refer to the drought period spanning the late 1980s and early 1990s; "Suisun Marsh Salinity Control Gates" and associated line refer to the period in which the gates have existed).

While the higher catch of splittail seems easily explained by natural phenomena, the increase in the catch for prickly sculpin and threespine stickleback appears more a function of in-marsh water operations. A large percentage of the annual catch for both species (39% for prickly sculpin and 52% for threespine stickleback) was made during May and June in upper Goodyear Slough, of which all prickly sculpin were young-of-year. Threespine stickleback and prickly sculpin are the two most abundant fishes entrained in duck ponds during spring leaching cycles (California Department of Fish and Game 1996, California Department of Fish and Game 1997, California Department of Fish and Game 1998). These entrained fish are then discharged back into sloughs during draining of the ponds where they are often eaten by adult striped bass aggregating at pond outfalls (O'Rear, unpublished data). The majority of prey in these striped bass stomachs is threespine stickleback and prickly sculpin (O'Rear, unpublished data, Moyle 2002). Our upper Goodyear Slough sampling sites encompass several water control structures; additionally, circulation is often poor in upper Goodyear Slough. Consequently, large numbers of prickly sculpin and threespine stickleback were probably introduced into upper Goodyear Slough by pond discharge water and not dispersed to other areas, hence our large catches, a pattern that has been observed previously (Matern et al. 2002, Moyle 2002).

CPUE for introduced species basically stayed the same from 2009 to 2010 (Figure 9); however, there were a few notable changes. First, white catfish CPUE increased (Table 3), although this was mainly due to additional sampling of Denverton Slough, where white catfish are especially abundant, from the end of September through early November. Yellowfin goby CPUE also rose substantially (Table 3); this was due to high recruitment of young-of-year fish into the marsh in May and June. As in previous years, it appears that most of the yellowfin gobies in Suisun Marsh are produced in downstream bays (Fish et al. 2010, O'Rear and Moyle 2010, Workman and Merz 2007, Meng and Matern 2001, Wang 1986): high catches in 2010 were made first in lower Suisun Slough, after which yellowfin gobies became more evenly distributed throughout the marsh. Unlike in previous years, this increase in the otter trawl catch in yellowfin goby was not accompanied by a decrease in the beach seine catch, which basically stayed the same (4.08 and 4.03 fish per seine haul for 2009 and 2010, respectively). Thus, moderate and varying outflows during late spring likely promoted high recruitment of yellowfin gobies into the marsh. High numbers of young-of-year shimofuri gobies were also captured in the marsh, with 72% of the total catch made in July and August. However, it seems that survival of young-of-year was poor since the catch dropped by 88% from August to September and remained low for the rest of the year.

Table 3. Percent change in annual otter trawl CPUE (fish per trawl) for three introduced fishes caught in Suisun Marsh (% increases are equivalent to percentage points, such that a 100% increase indicates that the value has doubled).

Species	Shimofuri Goby	White Catfish	Yellowfin Goby
2009 CPUE	0.80	1.08	0.36
2010 CPUE	1.63	1.92	1.65
% Change	105%	78%	365%

Beach Seines

Unlike the trend for annual otter trawl CPUE, annual beach seine CPUE has generally increased since the study's inception (Figure 10); however, since reaching a high point in 2006, beach seine catches have basically been decreasing. Similar to otter trawl catches, variability in native fish CPUE among years has been much less than that for introduced fishes (Figure 10). With the exception of a few early years (e.g., 1980 and 1983), catch of native fishes has been consistently low and contributed very little to the total catch. Introduced fishes, particularly Mississippi silverside (*Menidia audens*), have dominated the beach seine hauls.

As in previous years, Mississippi silversides drove the change in the annual CPUE from 2009 to 2010. The catch of silversides in 2010 was only 44% of that for 2009; this appears mainly due to (1) poor survival of mature fish from winter to spring, (2) a delay in the first spawning peak from late spring to early summer, and (3) the lack of a second spawning peak in late summer (see below in "White Catfish and Mississippi Silversides" for further discussion). The low numbers of Mississippi silversides in 2010 is likely the result of higher mortality due to below-normal temperatures: egg mortality increases as water temperature decreases below 20°C (Hubbs et al. 1971), and adults feed little at water temperatures less than 15°C (Stoeckel and Heidinger 1988).

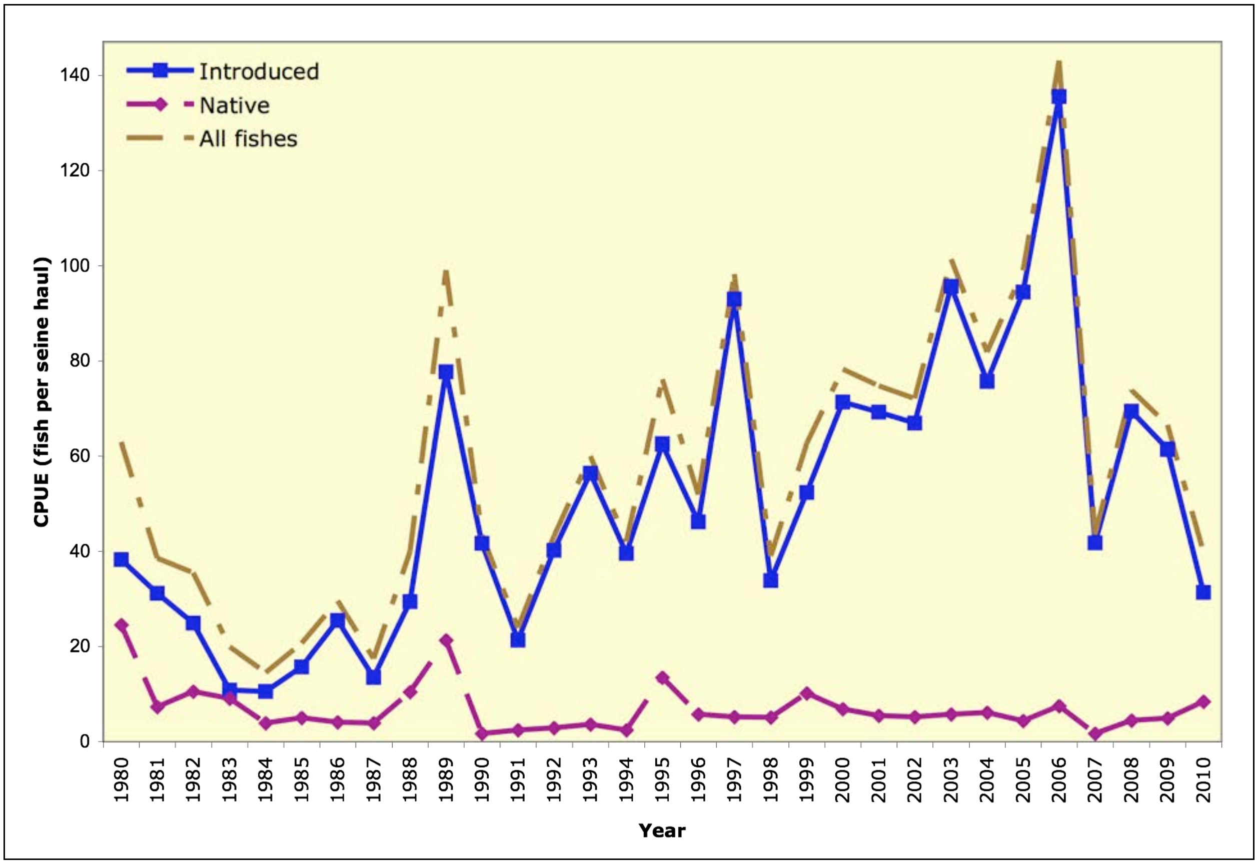

Figure 10. Annual beach seine CPUE from 1980 to 2010 for introduced, native, and all fishes.

Several other species had large changes in catch between 2009 and 2010. Beach seine CPUE of shimofuri goby in 2010 was only 44% of 2009's value (Table 4). Shimofuri goby larvae are pelagic, settling down onto inshore benthic areas after transformation (Matern 1999). Consequently, our high otter trawl catch of shimofuri gobies coupled with a low beach seine catch intimates very high mortality of either transforming larvae or recently settled juveniles. Threadfin shad (*Dorosoma petenense*) CPUE increased nearly three-fold from 2009 to 2010 (Table 4), which corresponds to lower salinities necessary for successful reproduction (Feyrer et al. 2009, Moyle 2002) lasting longer in 2010. Staghorn sculpin (*Leptocottus armatus*) dropped considerably (Table 4), which appears to be due to differences in outflow between the two years. While staghorn sculpin were prominent in beach seine catches in February, March, and April of 2009, they were nearly absent in February 2010 though present in the following two months. Staghorn sculpin spawn in saltier water found in bays downstream of the marsh (Fish et al. 2010, Moyle 2002) during late winter and early spring; consequently, high Delta outflow in January and February of 2010 may have been large enough to prevent newly spawned fish from riding upstream currents into the marsh until outflows subsided in March (Figure 3). The beach seine catch for threespine stickleback jumped by more than 200%; however, like the otter trawl catch, this spike in the beach seine catch was likely more a function of water operations since 89% of the fish were caught on one day in Denverton Slough during April. These fish were likely coming from duck ponds because (1) large volumes of water were being discharged from the land tract between Denverton and Luco sloughs; (2) wading birds [mainly Snowy Egrets (*Egretta thula*)] densely lined the banks near the outfalls, picking off fishes; and (3) we captured several adult striped bass that were in the plume of the discharged water and had stomachs full of threespine stickleback.

Table 4. Percent change in annual beach seine CPUE (fish per seine haul) for four fishes commonly caught in Suisun Marsh (% increases are equivalent to percentage points, such that a 100% increase indicates that the value has doubled).

Species	Shimofuri Goby	Staghorn Sculpin	Threadfin Shad	Threespine Stickleback
2009 CPUE	3.35	1.48	0.28	1.69
2010 CPUE	1.47	0.85	1.08	5.53
% Change	-56%	-43%	287%	226%

Fish Species of Interest

Fishes of the Pelagic Organism Decline

THREADFIN SHAD

Otter trawl catches of threadfin shad were relatively high in the first five years of the study, declined to very low levels during the dry late 1980s and early 1990s, and generally increased from 1996 to 2006 (Figure 11). For the most part, this pattern has been paralleled by the beach seine catch. From 2006 to 2008, both otter trawl and beach seine catches declined precipitously concomitant with higher marsh salinities and lower Delta outflow. From 2008 to 2010, annual CPUE for otter trawls increased mildly, while, as previously mentioned, beach seine catch increased considerably from 2009 to 2010.

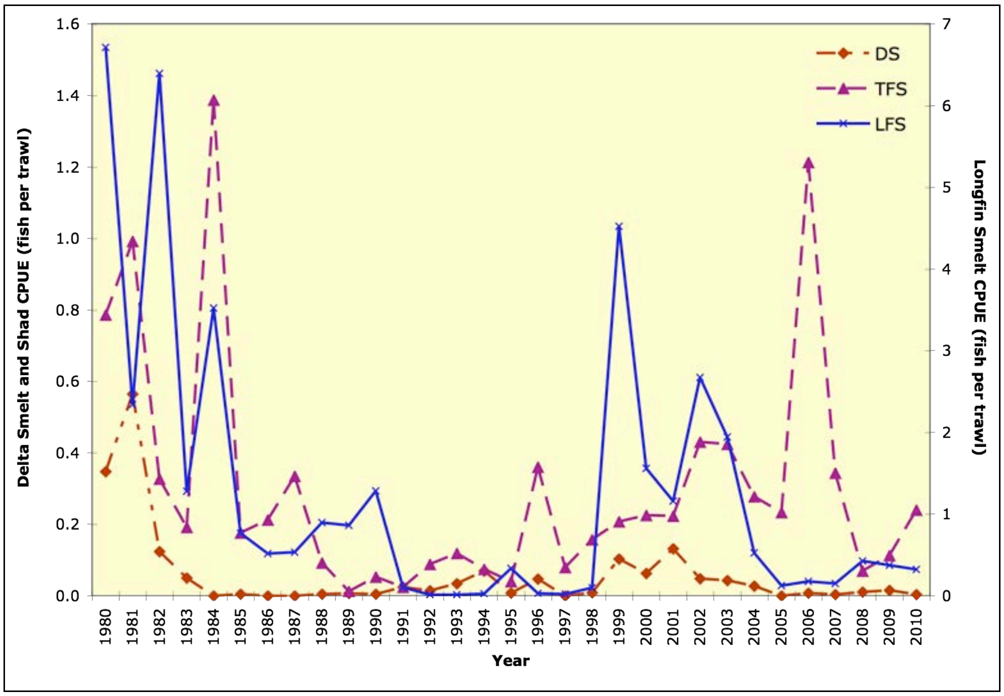

Figure 11. Annual otter trawl CPUE for threadfin shad (TFS), Delta smelt (DS), and longfin smelt (LFS) from 1980 to 2010.

That both the annual otter trawl and beach seine CPUE values increased from 2009 to 2010 reflects greater recruitment, which was probably due to lower salinities coinciding with the spawning period of threadfin shad. For instance, salinity in Denverton Slough (where 87% of the beach seine catch was made) was 3.1 pt in June 2009, while it was 1.8 ppt in June 2010. Threadfin shad probably spawned in June since young-of-year first appeared in July (Figure 12). As the season progressed, the beach seine catch declined while the otter trawl catch increased, reflecting a general offshore movement as the fish became larger (O'Rear and Moyle 2010). This pattern has been commonly observed in years past (O'Rear and Moyle 2009, O'Rear and Moyle 2008, Matern et al. 2002, Moyle et al. 1986).

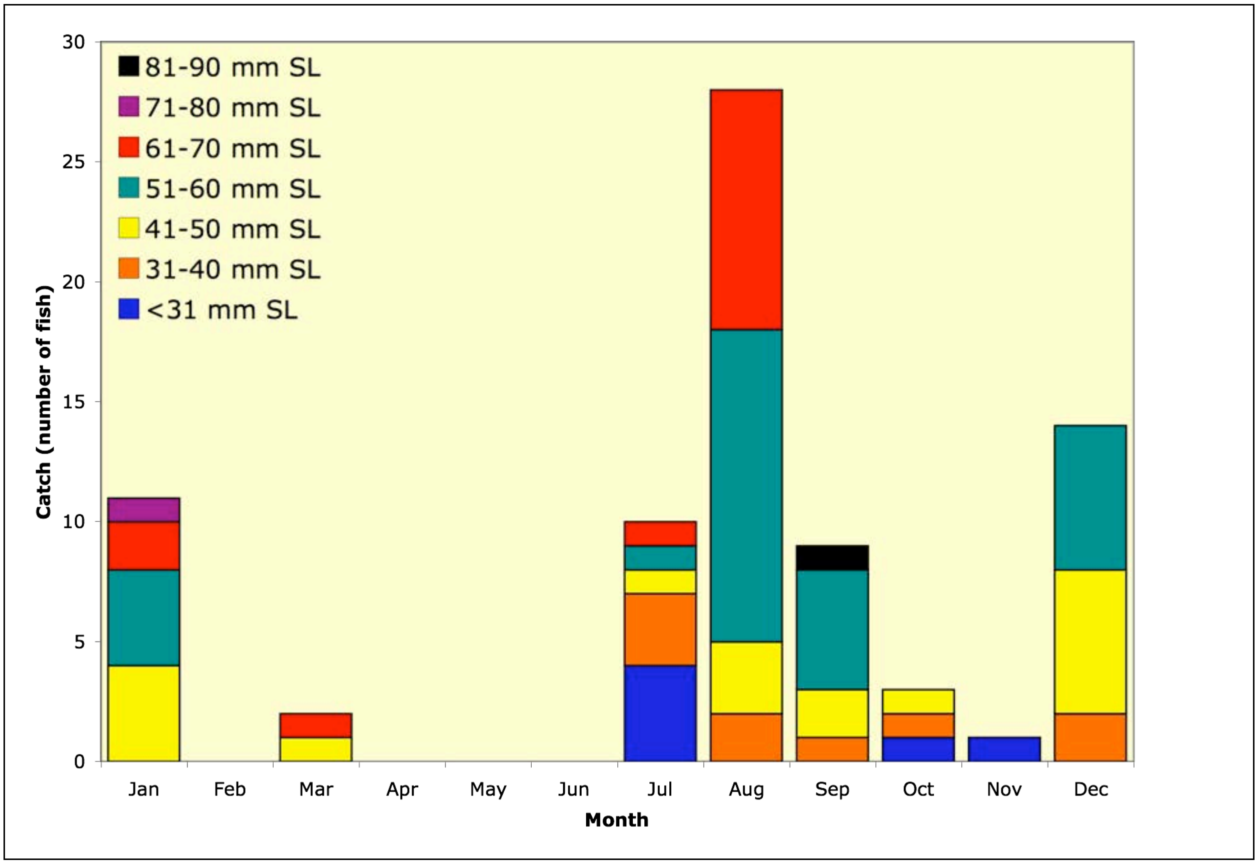

Figure 12. Monthly seine catch during 2010 for size-classes of threadfin shad.

DELTA SMELT

Since 1984, otter trawl catch of Delta smelt has been routinely low (less than 7 fish per year), tracking the estuary-wide decline in smelt numbers (Figure 11; California Department of Water Resources and Department of Fish and Game 2007, Bennett 2005, Moyle 2002). Although we have conducted just 66 midwater trawls over the study's history, it is still somewhat surprising that we have only captured four Delta smelt from the water column of the large sloughs.

In 2010, we caught two Delta smelt, both of which were taken in January (Table 5). The fish caught in upper Suisun Slough was taken in a beach seine, while the Goodyear Slough fish was captured in an otter trawl. The lengths of both fish were visually estimated while they were being immediately returned to the water after capture. In general, the water quality at the time of capture for both fish was good; notably, however, salinities were vastly different between the two sites (Table 5). The sizes indicate that these were adult fish (Moyle 2002).

The most abundant fish caught with Delta smelt was Mississippi silverside, which occurred in the seine at the upper Suisun Slough site (Figure 13). Other types of fish included pelagic species (threadfin shad), benthic species (staghorn sculpin, splittail, shimofuri goby), and a littoral fish (threespine stickleback; Figure 13). All of these fishes were small and less than a year old (O'Rear, unpublished data). The Delta smelt caught in Goodyear Slough was the only fish taken in that trawl.

Table 5. Size, sampling timing, and environmental data for Delta smelt captured in 2010.

Slough	Standard Length (mm)	Date	Time	Water Temperature (°C)	Salinity (ppt)	Oxygen Concentration (mg/L)	Secchi Depth	Tide
Goodyear	50	14-Jan	10:30	9.9	9.5	9.40	33	flood
Upper Suisun	60	24-Jan	17:00	8.7	0.8	6.97	22	low

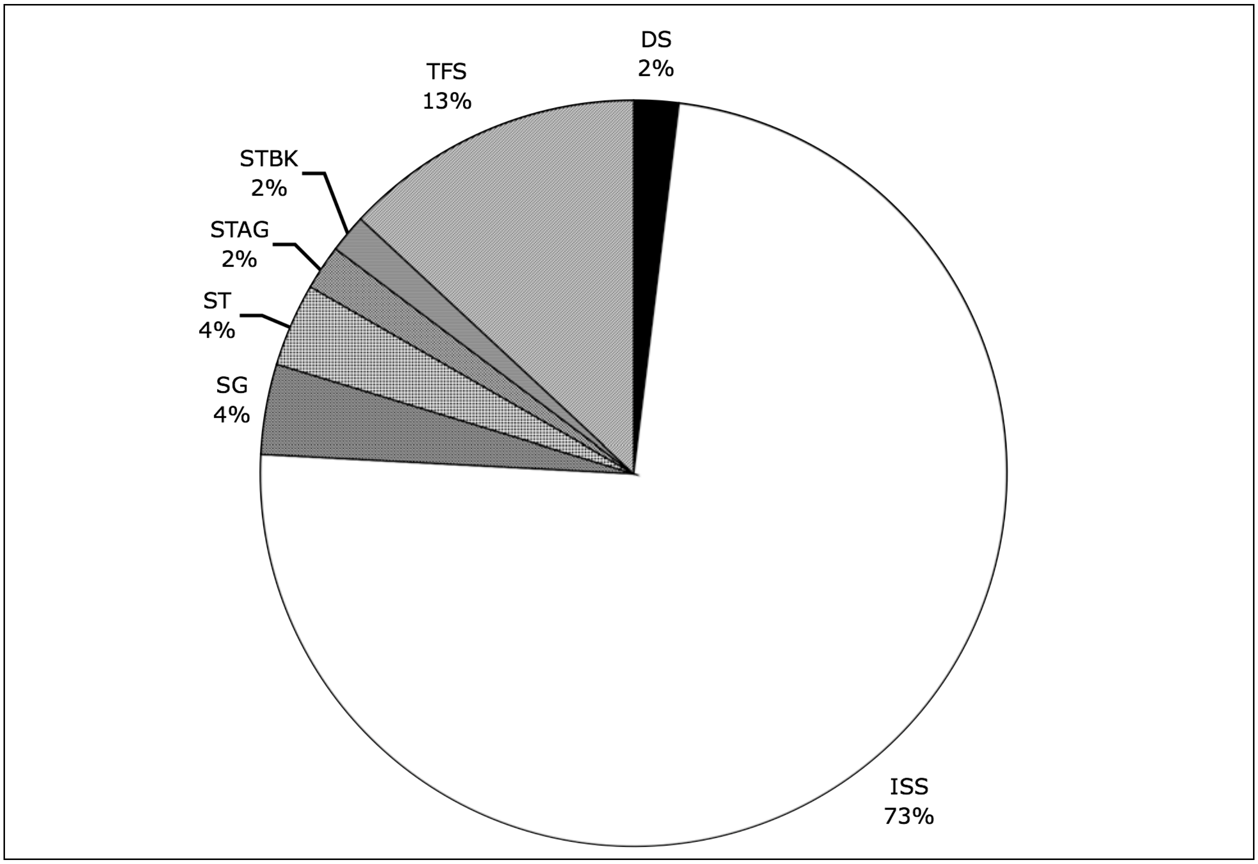

Figure 13. Fish assemblage composition for the beach seine pulled in upper Suisun Slough on 24 January 2010 at 17:00 (DS = Delta smelt, ISS = Mississippi silverside, SG = shimofuri goby, ST = splittail, STAG = staghorn sculpin, STBK = threespine stickleback, and TFS = threadfin shad).

In summary, catch of Delta smelt in Suisun Marsh during 2010 continued the very low numbers seen since 2002 (Figure 11). The 2010 fish did not appear until water temperatures reached their annual minima and water quality was good. Delta smelt were captured only in the western marsh and were accompanied by different types of fishes, although Mississippi silversides - which are possible competitors and predators of Delta smelt (Bennett and Moyle 1996) - were prominent. This suggests that while the marsh provides suitable abiotic conditions for Delta smelt during winter (Feyrer et al. 2007, Moyle et al. 1986), they could be negatively affected by high abundances of Mississippi silversides.

LONGFIN SMELT

The annual otter trawl CPUE for longfin smelt in Suisun Marsh parallels that seen in other parts of the estuary (e.g., the Delta): catches were high in the early eighties, were low throughout the dry years of the late 1980s and early 1990s, increased somewhat in the wetter years of the late 1990s and early 2000s, and declined to low levels again beginning in 2005 (Figure 11). Our catch pattern has been influenced by Delta outflow (Rosenfield and Baxter 2007) which, when large, transports larvae to more productive regions of the estuary (e.g., Suisun Bay; Bay Institute et al. 2007, Moyle 2002) and reduces entrainment mortality (Bay Institute et al. 2007).

The monthly catch pattern of young-of-year longfin smelt in 2010 was very similar to that of previous years (O'Rear and Moyle 2010, O'Rear ad Moyle 2009), with fish most abundant in the marsh in early spring following a decrease in Delta outflow and a concomitant increase in the salinity of lower Suisun Slough (Figure 14). Sixty-nine percent of young-of-year fish were captured in lower Suisun Slough, with the bulk of that catch occurring in April and May (Figure 14). Consequently, it appears that young-of-year longfin smelt were once again transported into the marsh with saltier water from Grizzly and San Pablo bays.

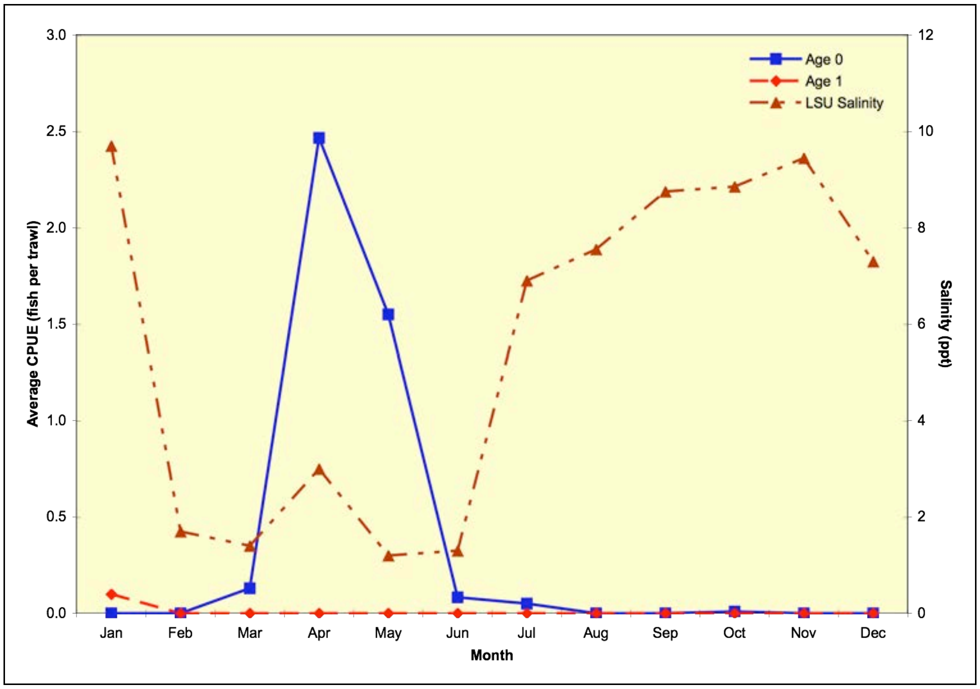

Figure 14. Monthly average otter trawl CPUE for age-classes of longfin smelt and monthly average salinity of lower Suisun Slough during 2010.

Unlike in previous years, we caught no pre-spawn adult longfin smelt migrating through the marsh in autumn, only one fish measuring 60 mm SL that was most likely young-of-year. This continues a declining trend over the last 3 years of fish captured in autumn (23 fish in 2008, 8 fish in 2009, and 1 fish in 2010).

STRIPED BASS

Striped bass are consistently one of the most abundant fishes in trawl catches. Although somewhat variable, annual otter trawl CPUE of striped bass decreased significantly from 1980 to 1990 (Figure 15). From 1991 to 2010, CPUE had no significant increasing or decreasing trends (Figure 15). While the drought period that began in the mid-1980s likely influenced the decline in catch seen in the first 10 years of the study period, this alone cannot fully explain the pattern because large catches have been made in dry years (e.g., 1991, 2001). A plethora of other factors, such as increased water exports, altered food webs, and lower egg production also have no doubt contributed to the pattern of the otter trawl catch (Kimmerer et al. 2009, California Department of Water Resources and Department of Fish and Game 2007, Moyle 2002).

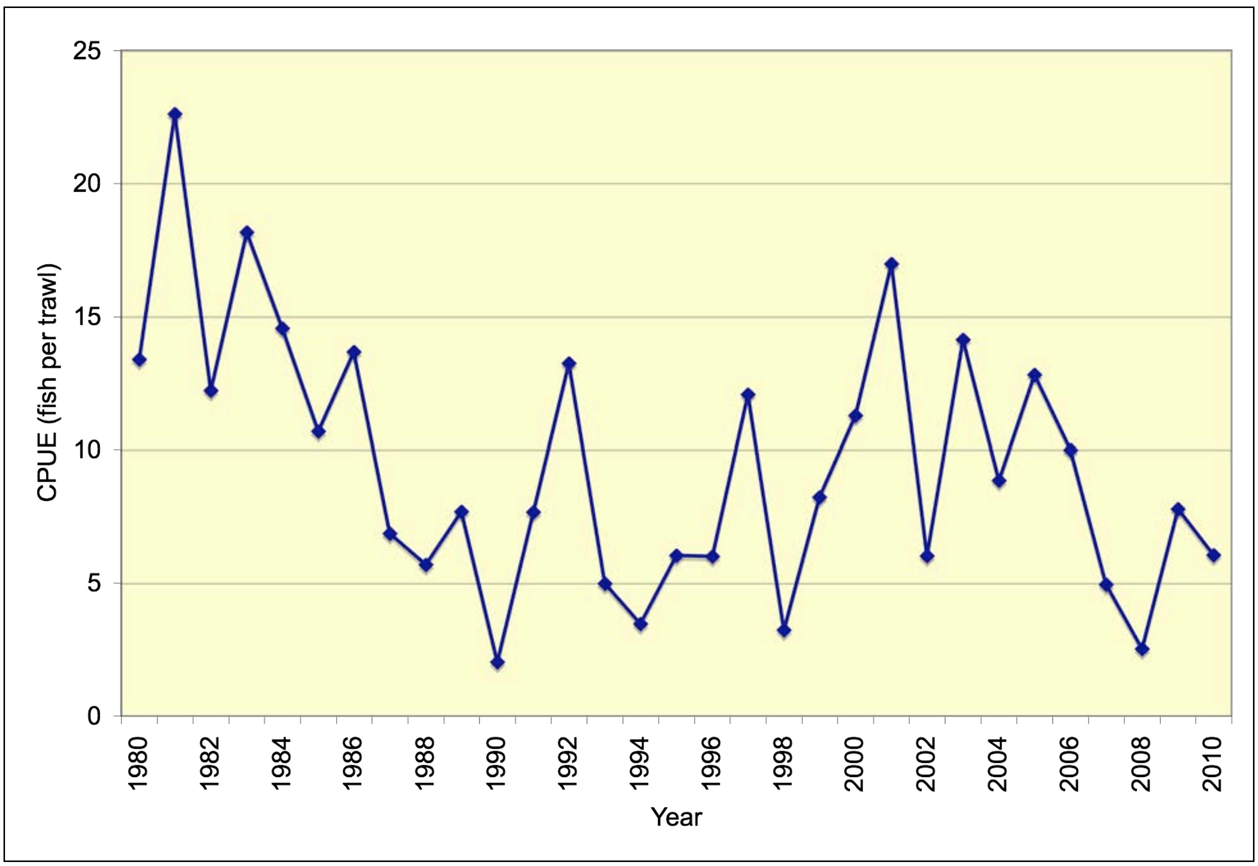

Figure 15. Annual otter trawl CPUE from 1980 to 2010 for striped bass.

The monthly pattern in catch for young-of-year and adult striped bass in the marsh was typical: young-of-year first appeared in high numbers during late spring, after which they declined precipitously concomitant with mysid rank; and adults were present during fall and winter prior to their upstream spawning migration in spring (Figure 16). Young-of-year fish also first appeared in numbers in beach seines during June (Figure 17); however, the decline in catch thereafter was not as severe as that for the otter trawl, implying that food may have been more abundant in near-shore areas than in pelagic waters (O'Rear and Moyle 2010, O'Rear and Moyle 2009).

The monthly trend in otter trawl catch of juvenile fish generally mirrors that for temperature and California bay shrimp: catches were low in winter, increased through spring, reached a maximum in summer, and then declined through autumn (Figure 16). The beach seine catch also followed this pattern, but only for the first half of the year - no striped bass other than young-of-year fish were caught in a seine from July through December (Figure 17). The absence of juvenile striped bass from seines in July occurred concurrent to California bay shrimp becoming extremely abundant (Figures 8 and 17), although the increasing size of juvenile fish through the latter part of the year may have made them invulnerable to beach seines.

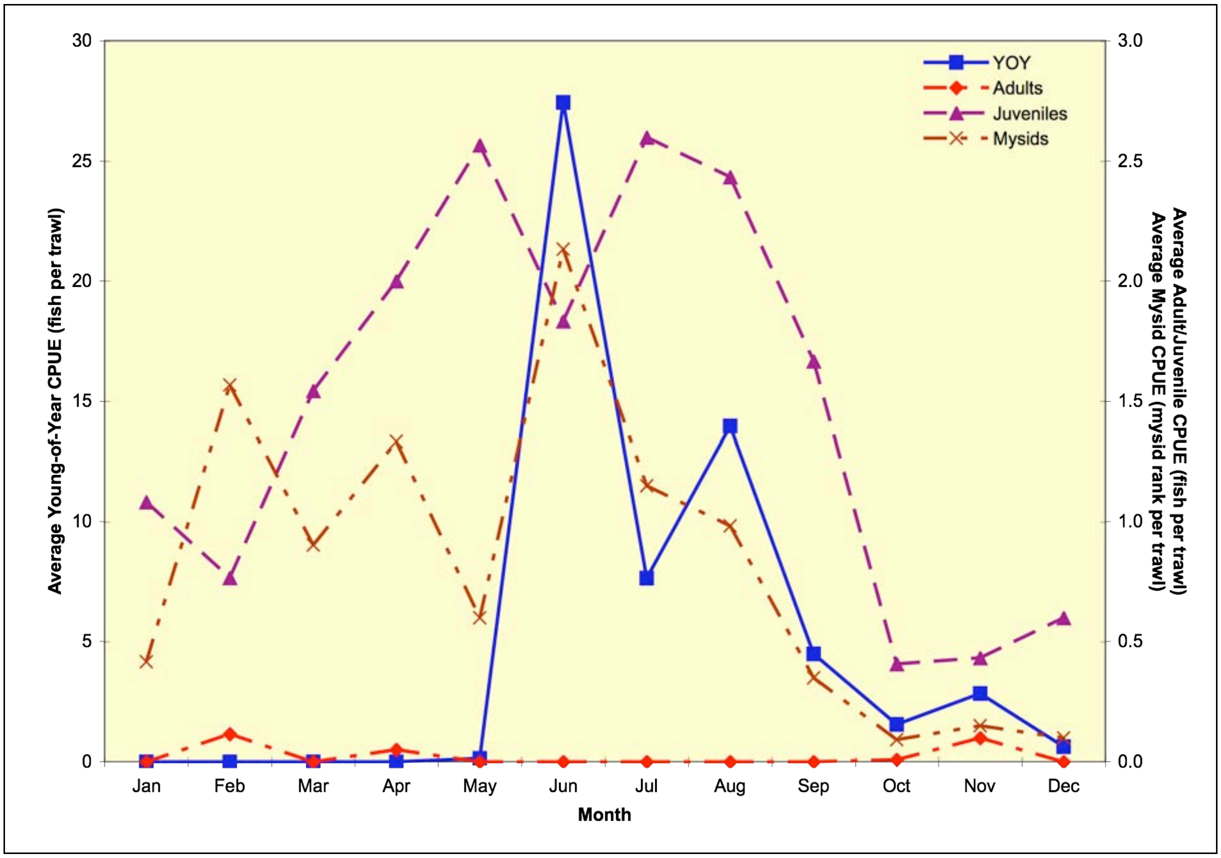

Figure 16. Average monthly otter trawl CPUE for mysids and for age-classes of striped bass during 2010.

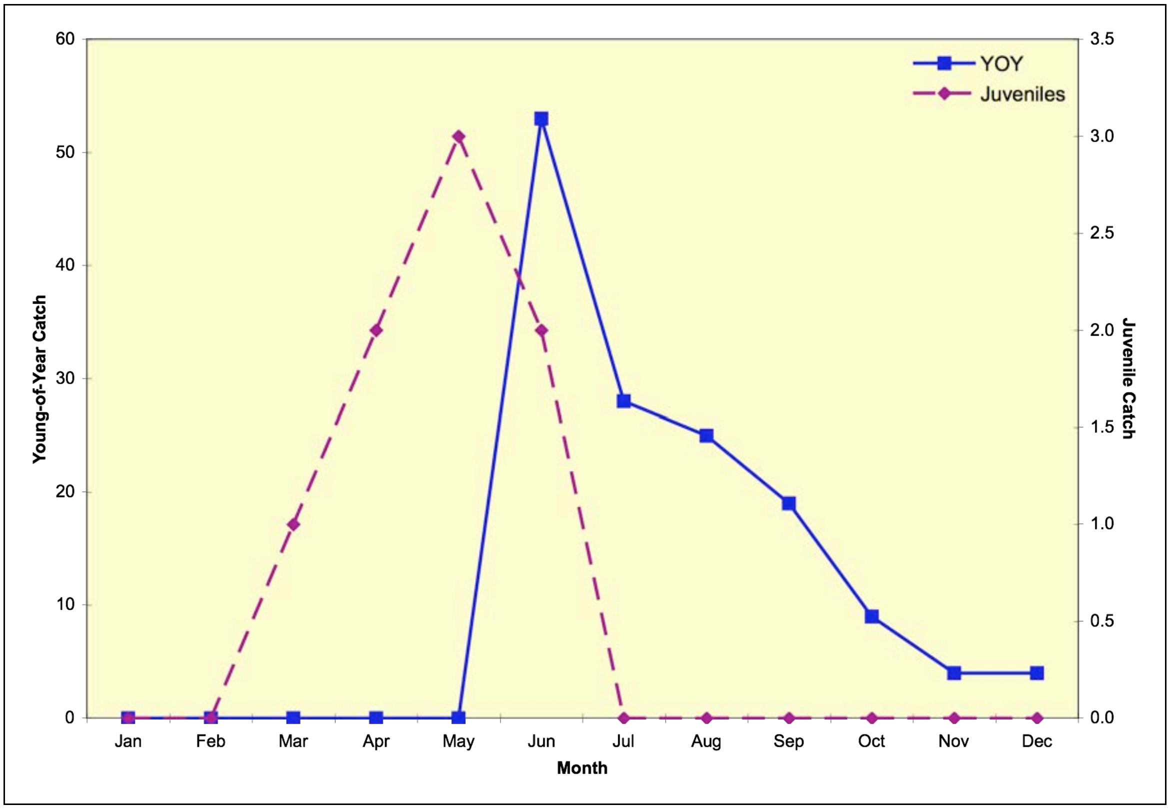

Figure 17. Beach seine catch of age-classes of striped bass during 2010.

That the monthly CPUE for juvenile striped bass followed that of California bay shrimp implies that either (1) both species are responding to similar factors (e.g., salinity or a shared food item), or (2) juvenile striped bass are feeding on and therefore tracking California bay shrimp. Juvenile striped bass and California bay shrimp have both been shown to feed on mysid crustaceans (Feyrer et al. 2003, Siegfried 1982, Stevens 1966). However, striped bass have also fed on decapod shrimp such as Siberian prawn and California bay shrimp (Nobriga and Feyrer 2008, Moyle 2002, O'Rear, unpublished data). Thus, to better characterize the relationships among California bay shrimp, juvenile striped bass, and mysids, a PCA was performed that also included abiotic factors deemed important to the species: salinity, water temperature, and Secchi depth. The PCA (Figure 18) showed that California bay shrimp and juvenile striped bass loaded very similarly and strongly to the second principal component, while water temperature was a less strongly correlated variable. Mysids, water clarity, and salinity loaded heavily along the first axis, with mysids negatively correlated with water clarity and salinity. This supports the notion that juvenile striped bass follow and eat California bay shrimp, hence the common trends in catch throughout 2010; however, diet studies of juvenile striped bass would be needed to confirm this speculation.

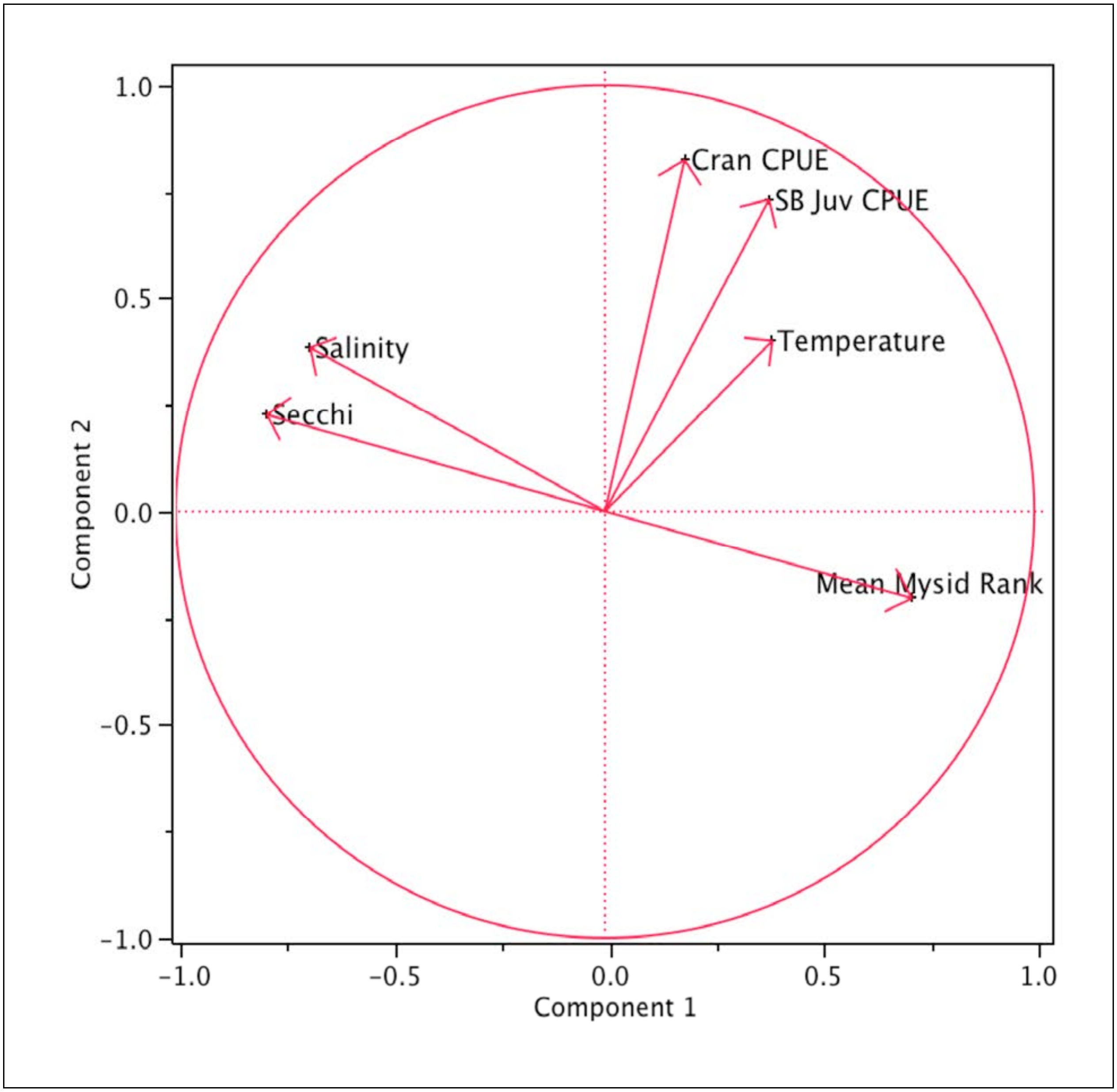

Figure 18. Loading plot of PCA results on juvenile striped bass, California bay shrimp, mysids, and abiotic data from 2010 (n = 120).

As in previous years, lower Suisun and First Mallard sloughs had the highest CPUE values for striped bass (Figure 19), which Schroeter et al. (2006) attributed to shallow depths that provide high food concentrations. This distribution was primarily due to young-of-year fish, which were much more abundant than older age-classes. Juvenile striped bass had a similar distribution in that they were most abundant in lower Suisun Slough, but they were generally more evenly spread throughout the marsh than young-of-year (Figure 19).

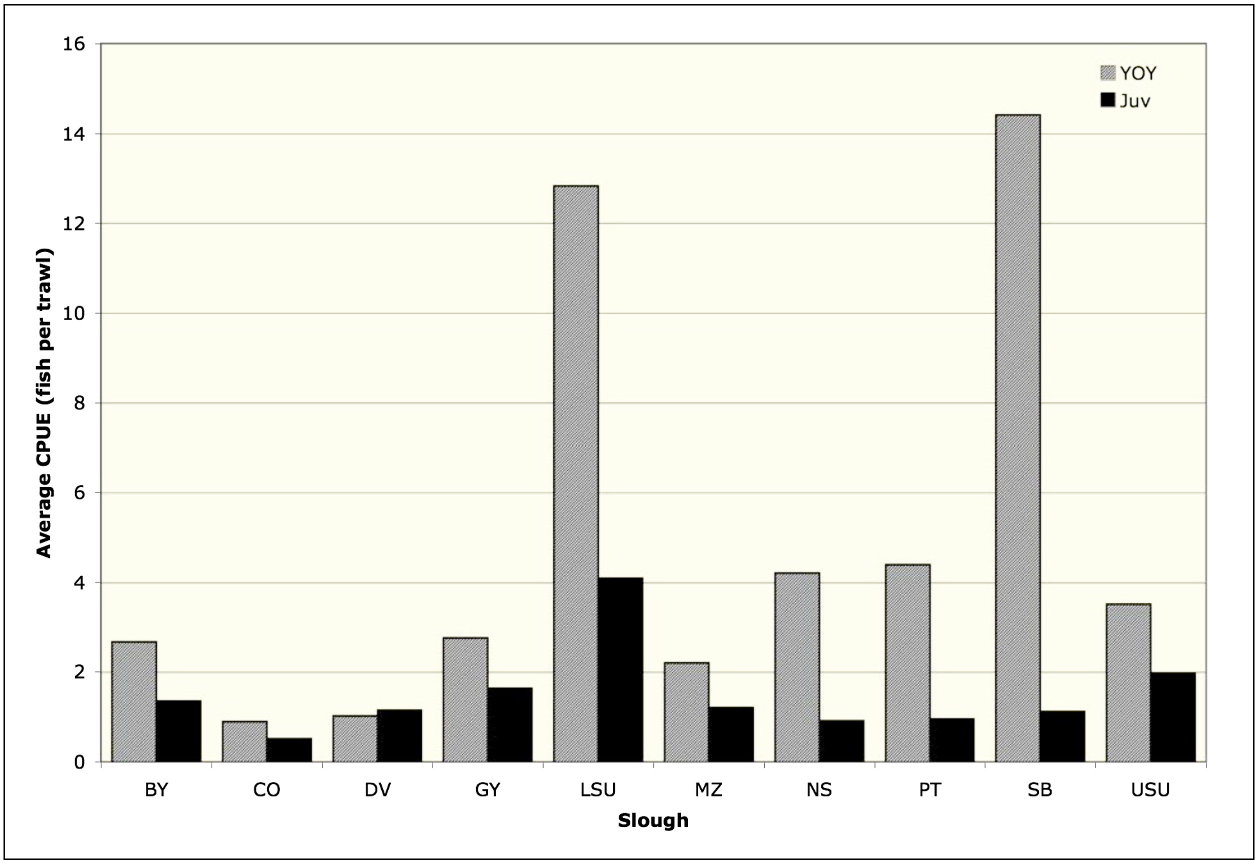

Figure 19. Average otter trawl CPUE for young-of-year and juvenile striped bass in sloughs of Suisun Marsh ("BY" = Boynton Slough, "CO" = Cutoff Slough, "DV" = Denverton Slough, "GY" = Goodyear Slough, "LSU" = lower Suisun Slough, "MZ" = Montezuma Slough, "NS" = Nurse Slough, "PT" = Peytonia Slough, "SB" = First Mallard Slough, and "USU" = upper Suisun Slough).

Splittail

Splittail have been the most commonly captured native fish in Suisun Marsh throughout the study's history. Not including 1986 and 1987, splittail annual otter trawl CPUE declined considerably from 1980 to 1994; this was mirrored fairly well by the beach seine CPUE, which was more variable over that period (Figures 20 and 21). From 1995 to 2006, otter trawl CPUE generally increased and was accompanied by large beach seine catches in years of high springtime Delta outflow (e.g., 1995, 2006). Otter trawl catches once again declined from 2006 to 2009; however, catch increased in 2010 (Figure 20). The otter trawl and beach seine CPUE patterns are likely influenced by the amount of floodplain available for spawning and rearing during the spring (Moyle et al. 2004, Sommer et al. 1997), hence our higher catches during and just following years of high flows.

Both the beach seine catch and the otter trawl catch increased substantially from 2009 to 2010: the otter trawl CPUE rose from 2.25 to 3.36 fish per trawl, while the beach seine catch went from 0.41 to 0.92 fish per haul (Figures 20 and 21). The higher 2010 catches were primarily due to greater numbers of young-of-year fish, which comprised 77% of the 2010 beach seine catch and for which the otter trawl CPUE rose from 0.54 to 1.20 fish per trawl from 2009 to 2010. However, the otter trawl CPUE for age-1 fish also increased considerably from 2009 to

2010 (Figure 20). As previously mentioned, the higher catch of young-of-year is probably due to large areas of inundated floodplain coinciding with the spawning period of splittail; the higher catch of age-1 fish suggests low mortality of this cohort.

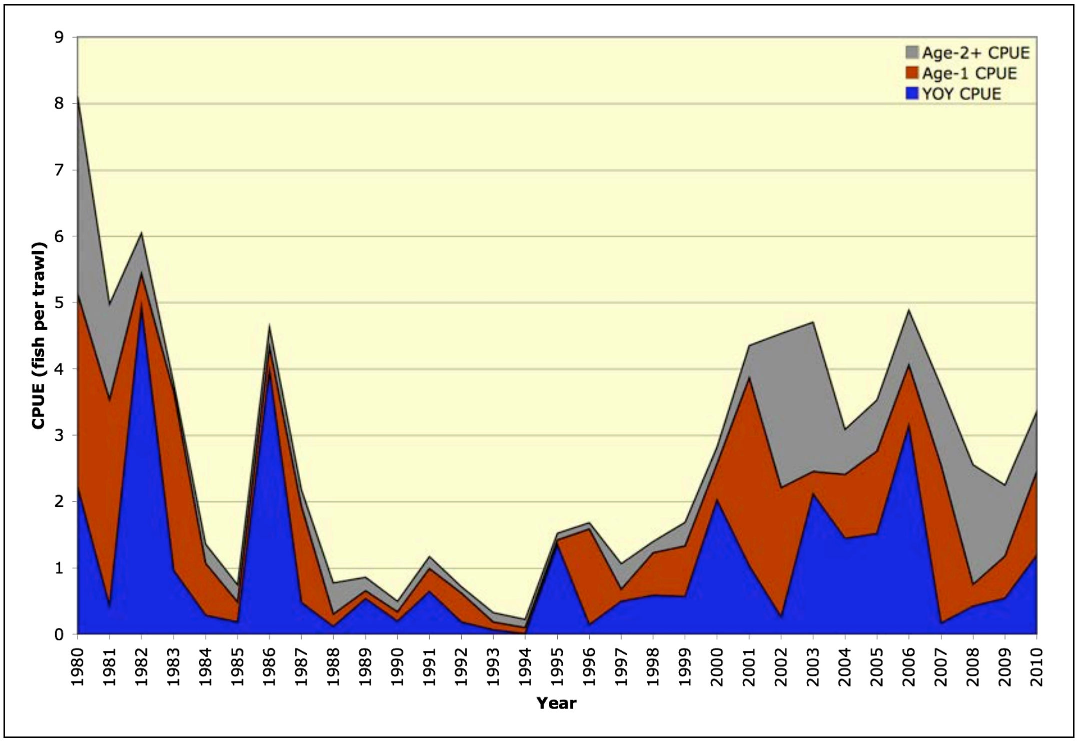

Figure 20. Annual otter trawl CPUE from 1980 to 2010 for age-classes of splittail.

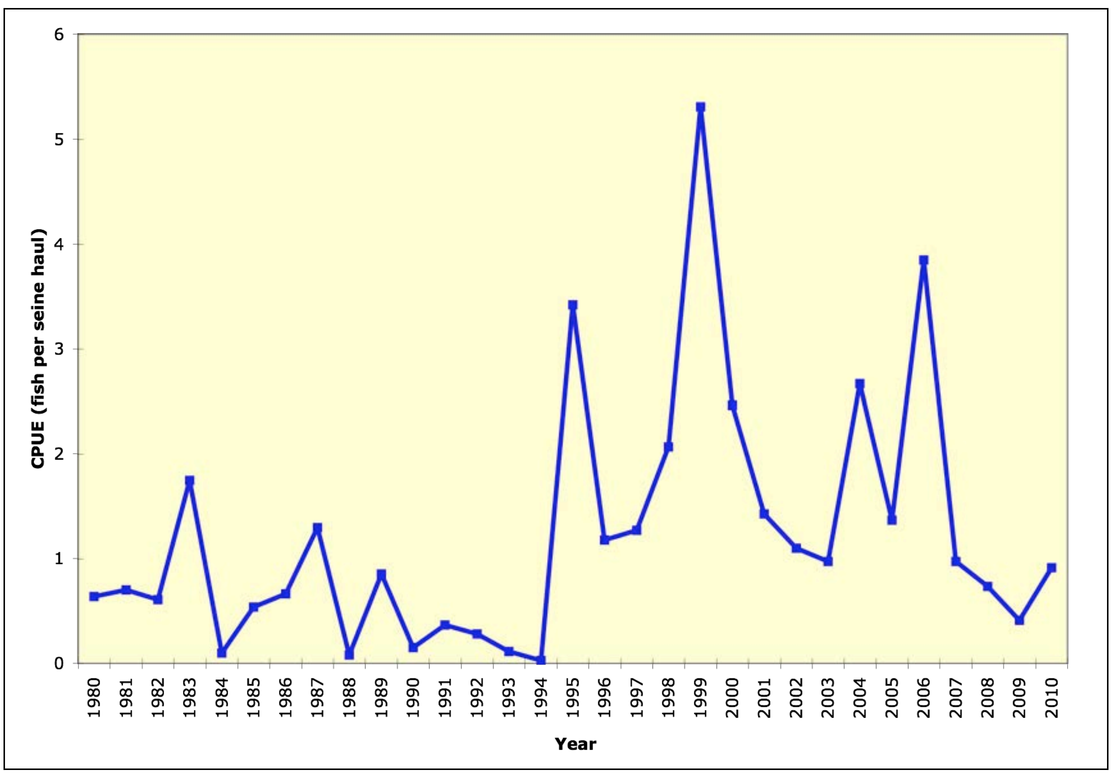

Figure 21. Annual beach seine CPUE from 1980 to 2010 for splittail.

The trend in the monthly otter trawl catch in 2010 followed that seen in previous years. Catch of adult fish (i.e., most of the age-2+ fish) declined in early spring, reflecting movement of these fish either upstream or inshore to spawn (Figure 22). Adult catches increased thereafter concomitant with recruitment of young-of-year fish. Young-of-year reached their peak abundance in otter trawls during July and August (Figure 22) and in beach seines during June and July (O'Rear, unpublished data), implying movement of fish from inshore areas to thalweg habitats (O'Rear and Moyle 2010, Sommer et al. 2008, Sommer et al. 1997). The total otter trawl catch reached its minimum in September, increasing thereafter to close out the year (Figure 22).

While splittail were again very abundant in lower Suisun Slough (4.33 fish per trawl), they were also prevalent in Nurse and upper Suisun sloughs (5.67 and 5.46 fish per trawl, respectively; Figure 23). All three of these sloughs are bordered by large, extensive shoals, which may provide plentiful food. However, age-2+ fish were relatively rare in lower Suisun Slough, age-1 and age-2+ fish comprised the bulk of the catch in Nurse Slough, and all age-classes were abundant in upper Suisun Slough, implying that lower Suisun and Nurse sloughs were not equally attractive to all age-classes. Though the CPUE for all age-classes of splittail in First Mallard Slough was rather average compared to the value for the whole marsh (3.42 and 3.36 fish per trawl, respectively), it still likely serves as an important nursery for splittail since it had the second-highest young-of-year CPUE (2.04 fish per trawl) among all sloughs in the marsh (Figure 23).

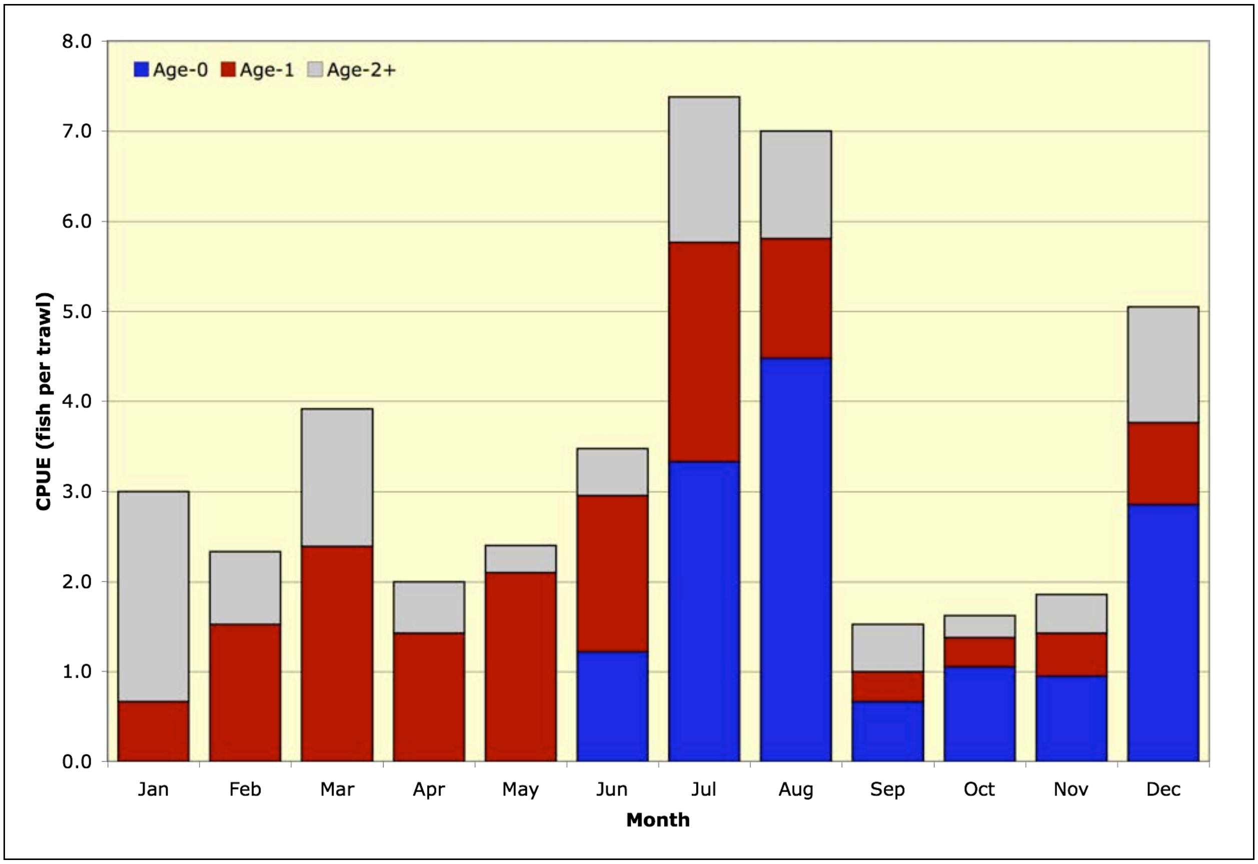

Figure 22. Monthly otter trawl CPUE during 2010 for age-classes of splittail.

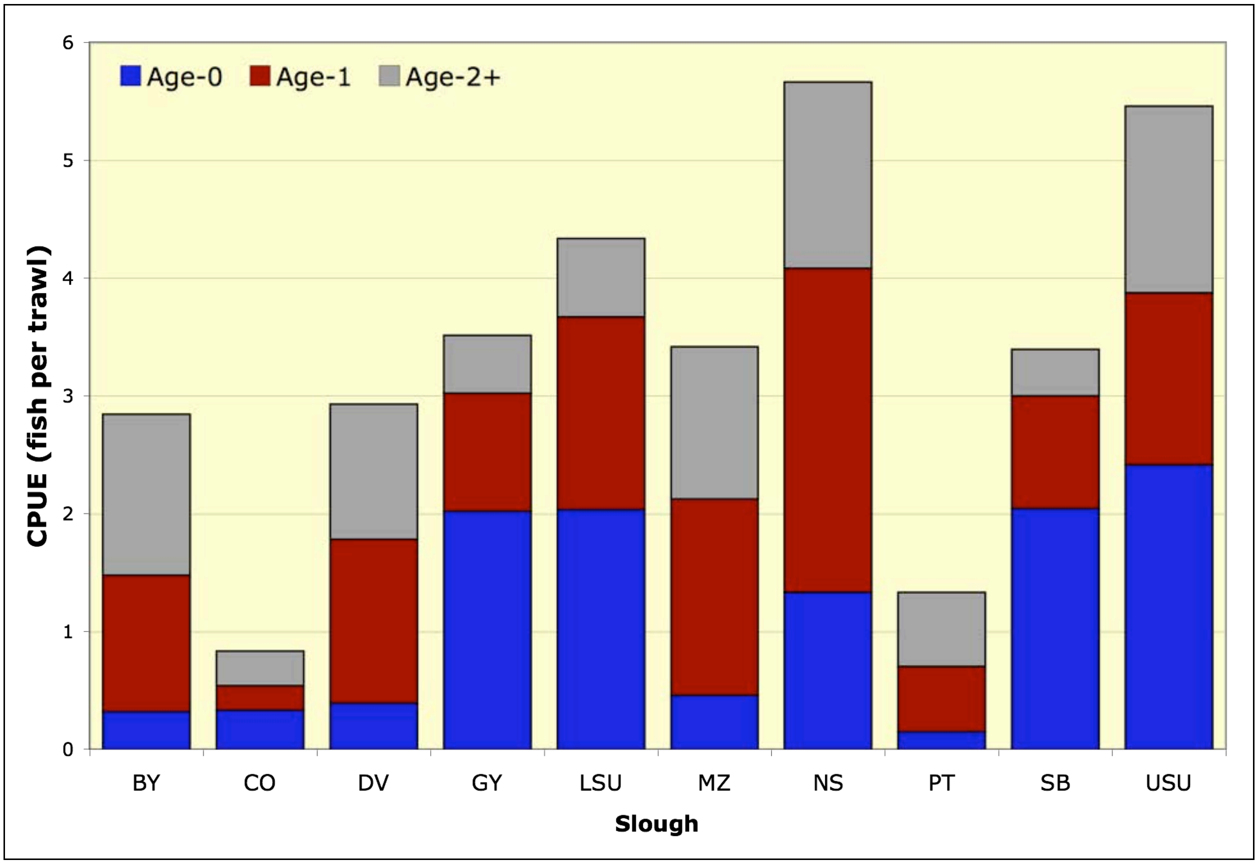

Figure 23. Annual otter trawl CPUE of age-classes of splittail in sloughs of Suisun Marsh (codes as in Figure 19).

White Catfish and Mississippi Silverside

Of all the introduced fish species in the marsh, only two have exhibited long-term increasing trends: white catfish and Mississippi silverside. With the exception of one strong cohort from 1983, white catfish were present only in low numbers during the 1980s and early 1990s (Figure 24). From 1995 to 2010, however, white catfish have become increasingly abundant, which appears to be tied to lower salinities spanning the late-spring/early-summer spawning period during wetter years (see O'Rear and Moyle 2009). Beach seine catch of Mississippi silversides was relatively constant from 1980 to 1988; however, from 1989 to 1997, catch began to vary more around a higher mean (Figure 24). From 1998 to 2006, Mississippi silversides became increasingly more abundant, but numbers have been lower from 2007 to 2010 (Figure 24).

The otter trawl CPUE for white catfish in 2010 was higher than in 2009 (Table 3), although that was due in part to the additional trawls in Peytonia and Denverton sloughs during autumn 2010; both sloughs generally contain high numbers of white catfish (O'Rear and Moyle 2008). Notably, no young-of-year white catfish were captured in 2010. Consistent with years past, Denverton and Peytonia sloughs had the highest CPUE values in the marsh, while no white catfish were caught in the more saline southwestern sloughs. Catches were lowest in winter and late autumn, and, though variable, were generally high from March through November. All of these patterns reflect the affinity of white catfish for low salinities and warm water temperatures.

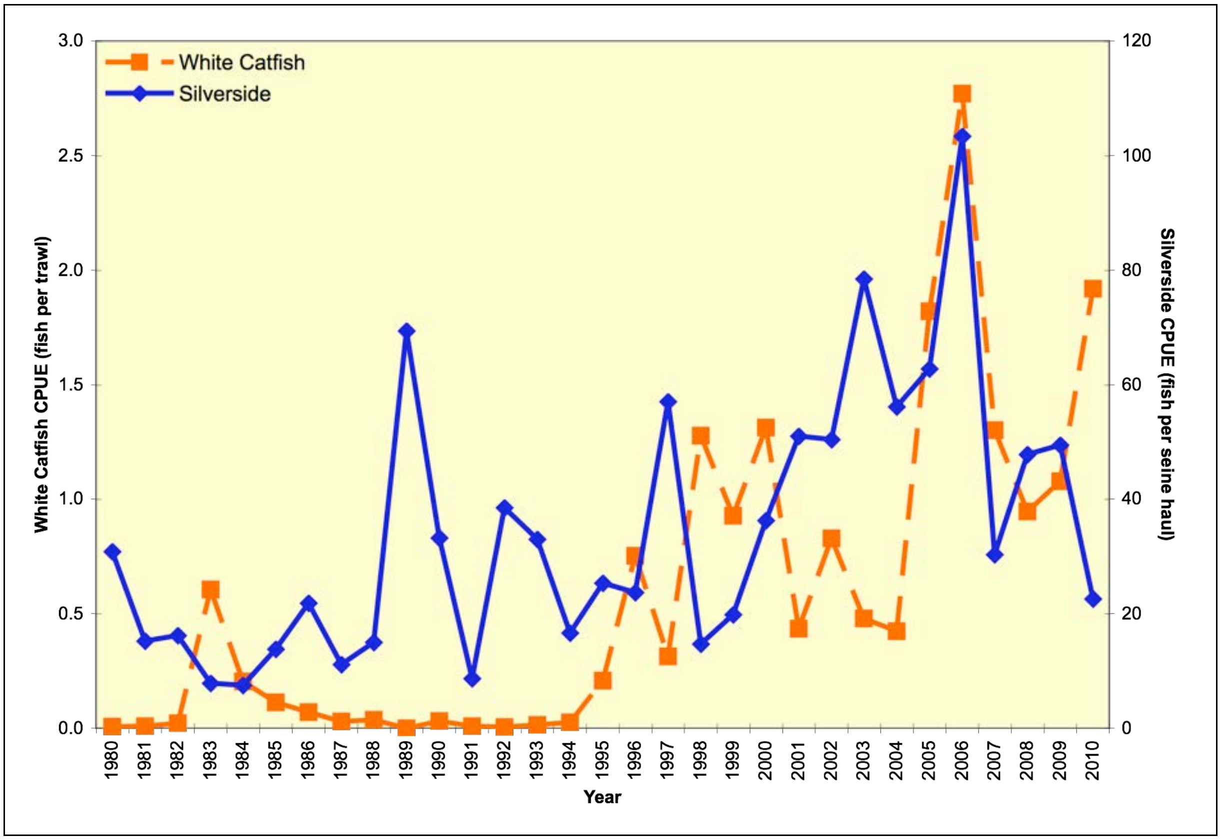

Figure 24. Annual CPUE for white catfish and Mississippi silverside from 1980 to 2010.

Previous studies in other waterways have revealed that silversides frequently have two spawning peaks per year (Moyle 2002, Middaugh and Hemmer 1992), with fish produced the previous year spawning in spring and the resultant young-of-year spawning in late summer. The pattern in beach seine catches suggests that there are also generally two major spawning peaks in the marsh (O'Rear and Moyle 2010, O'Rear and Moyle 2009). However, 2010 did not follow this trend. Appreciable numbers of young-of-year fish were not evident until July and, in the case of upper Suisun Slough, August (Figure 25), while young-of-year in most years are common by June (O'Rear and Moyle 2010). Additionally, the late-summer cohort, which usually enters the beach seine catches in autumn (O'Rear and Moyle 2010), was completely absent (Figure 25). Cooler springtime temperatures appeared to be the major factor affecting our catches. The activity level and feeding of Mississippi silversides are reduced when water temperatures dip below 15°C (Stoeckel and Heidinger 1988). Expected effects of this include slower growth, hence greater mortality and/or slowed reproductive development (Cech and Moyle 2004). Both of these scenarios are consistent with our beach seine catches: catches crashed in spring and the appearance of young-of-year was later than in previous years. Given that the first young-of-year cohort (i.e., the cohort that is spawned and spring and first appears in seines in early summer) spawns the second (i.e., the cohort that is spawned in late summer and first appears in seines in autumn), and that age at maturity is partially a function of size (Middaugh and Hemmer 1992, Hubbs 1982), then the first cohort may not have had enough time to grow large enough to become mature. Consequently, no second cohort would be produced, which is what our data show (Figure 25).

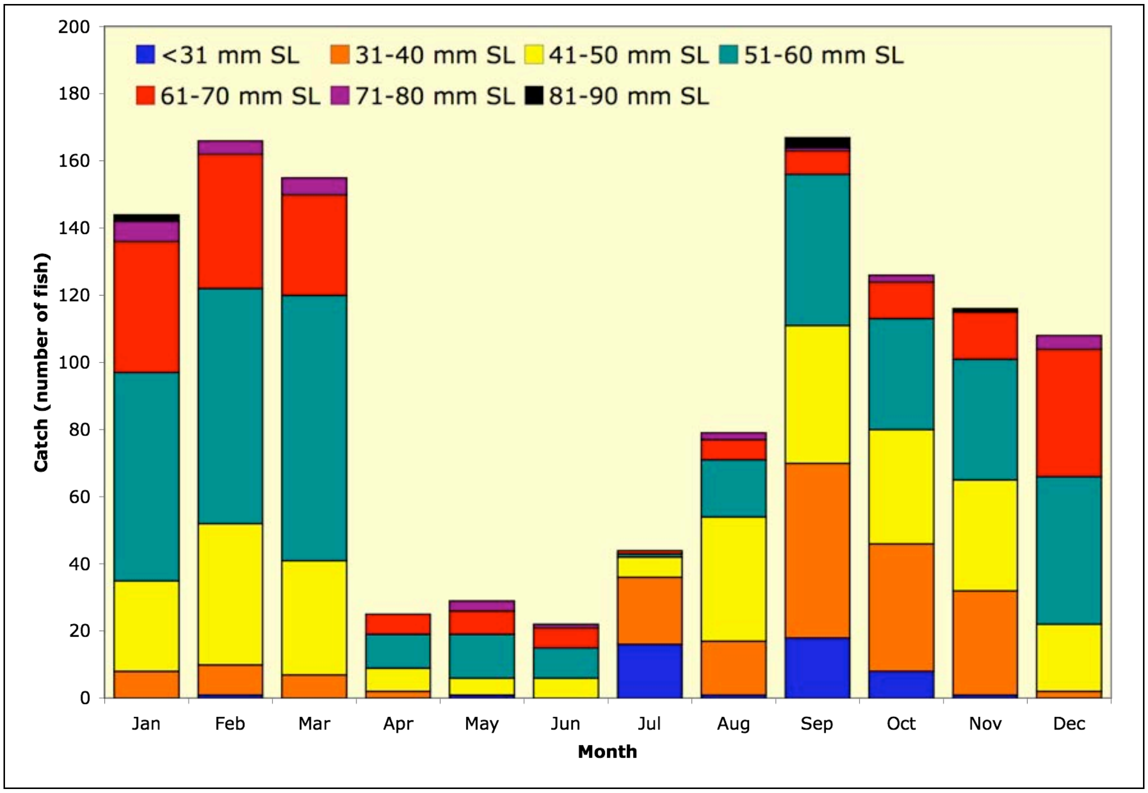

Figure 25. Monthly beach seine catch of size-classes of Mississippi silversides during 2010.

Weekly Sampling in Early Autumn

Water quality conditions among Denverton, Peytonia, and Goodyear sloughs differed substantially, although the trends in temperature and salinity were similar. [For the purposes of this section, Goodyear Slough was split into upper and lower sections, with the upper containing the GY1 and GY2 sites and the lower the GY3 site (Figure 2), because they are geographically far apart and differ in abiotic conditions (O'Rear et al. 2010, Schroeter and Moyle 2004)]. Salinity in Goodyear Slough was higher than in Peytonia and Denverton sloughs, although it increased steadily in both Denverton and Goodyear sloughs from late September through early November (Figure 26). Salinity in Peytonia also rose steadily concomitant with the other two sloughs for the first three weeks but then dropped substantially; this was likely due to runoff from Ledgewood Creek freshening the slough since the first large storm of the season occurred during the end of the week of October 17. Temperature trends were similar among the three sloughs (Figure 27); the higher values in Peytonia from late September through the second week of October, and the higher value in Denverton during the week of October 10, were because those sloughs were sampled during the afternoon while Goodyear Slough was sampled in the morning. Dissolved oxygen concentrations varied considerably among the sloughs. Oxygen in Denverton Slough was stable throughout the period and never dropped below 6 mg/L (Figure 28). In contrast, DO dropped sharply in Peytonia between late September and early October and reached a minimum during the week of October 24. Dissolved oxygen concentrations in lower Goodyear Slough were satisfactory until declining below 5 mg/L during the week of October 31 (Figure 28). Conversely, DO concentrations in upper Goodyear Slough dropped sharply between the weeks of October 10 and October 17 and the weeks of October 24 and October 31 (Figure 28).

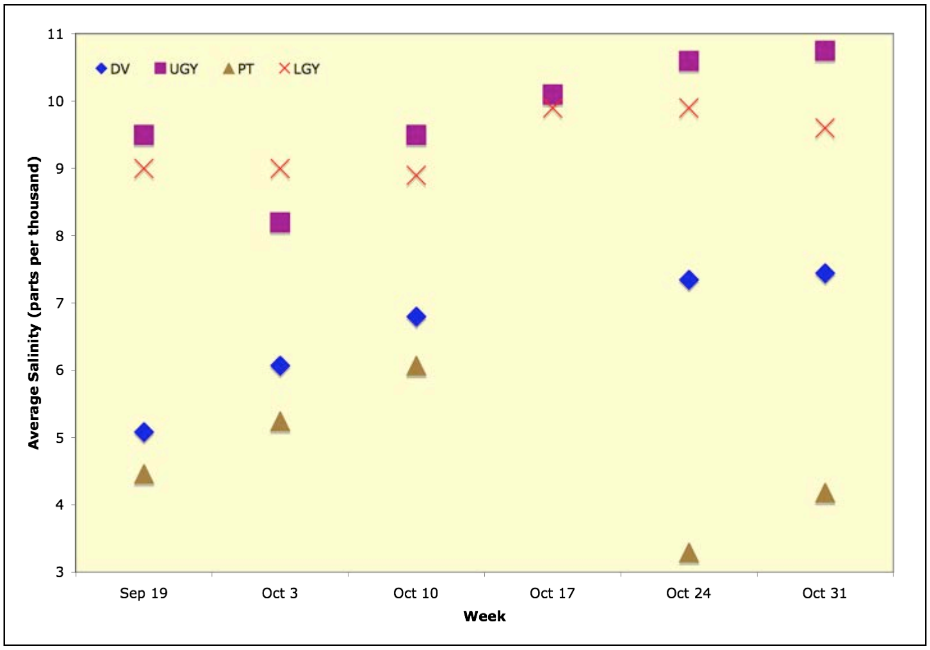

Figure 26. Average salinities for Denverton, Peytonia, upper Goodyear, and lower Goodyear sloughs during early autumn sampling ("UGY" = upper Goodyear Slough, "LGY" = lower Goodyear Slough; other abbreviations as in Figure 19).

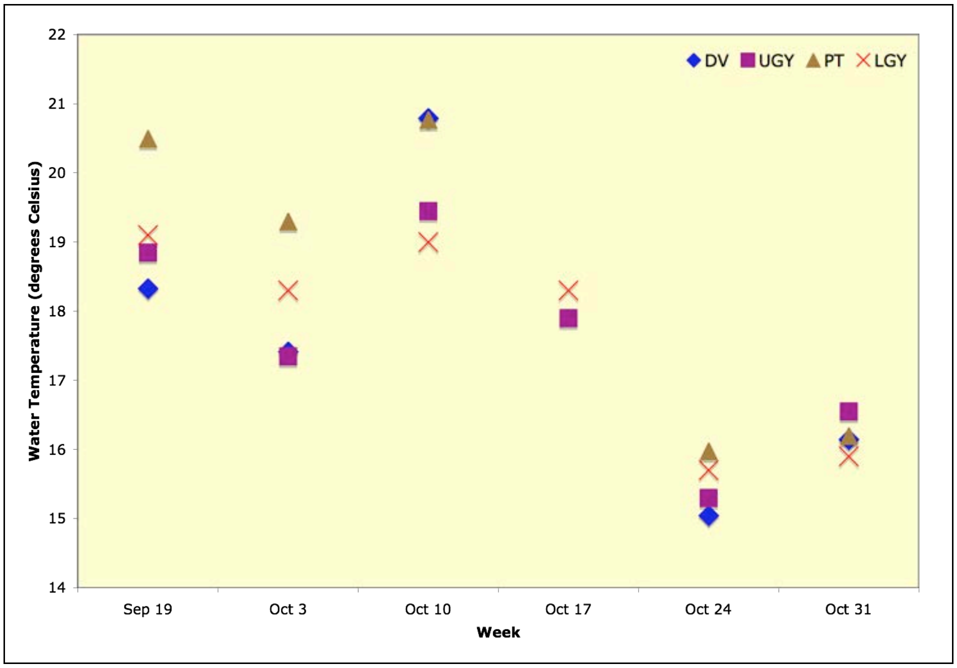

Figure 27. Average water temperatures for Denverton, Peytonia, upper Goodyear, and lower Goodyear sloughs during early autumn sampling (abbreviations as in Figure 26).

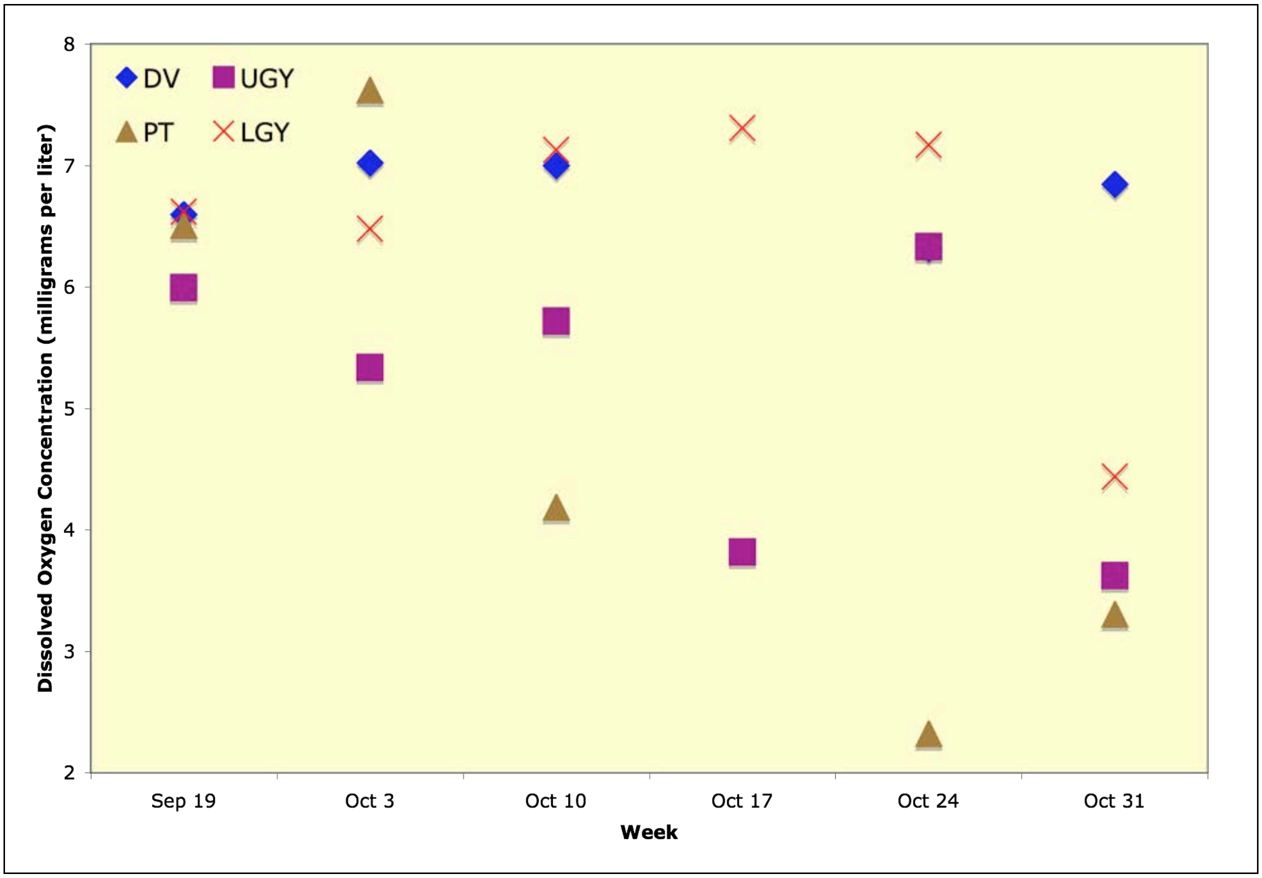

Figure 28. Average DO concentrations for Denverton, Peytonia, upper Goodyear, and lower Goodyear sloughs during early autumn sampling (abbreviations as in Figure 26).

The changes in the abundance of fishes and in the composition of the fish assemblages were markedly different among the three sloughs. Catch and diversity of fishes in Denverton Slough were generally consistent and high (Figure 29). The one notable disparity was the decline in catch during the week of October 24, which was driven almost solely by a drop in white catfish. This was likely due to lower activity levels, and hence lower capture efficiency, of white catfish in the colder water. The abundance and diversity of fishes in Peytonia Slough, however, displayed a smooth decline in catch, mostly due to a decreasing abundance of striped bass, that paralleled DO concentrations (Figure 30). Additionally, when DO in Peytonia Slough reached its minimum, the only species present were benthic species. In upper Goodyear Slough, catches were relatively high until declining to zero during the week of October 17 (Figure 31). Thereafter, catches increased again somewhat, but striped bass and splittail were only present in low numbers. Catches in lower Goodyear Slough were very low throughout the study period except for an anomalously high catch on the week of October 10 (Figure 32). As for Peytonia Slough, striped bass were primarily responsible for the catch pattern in Goodyear Slough, although splittail were important as well.

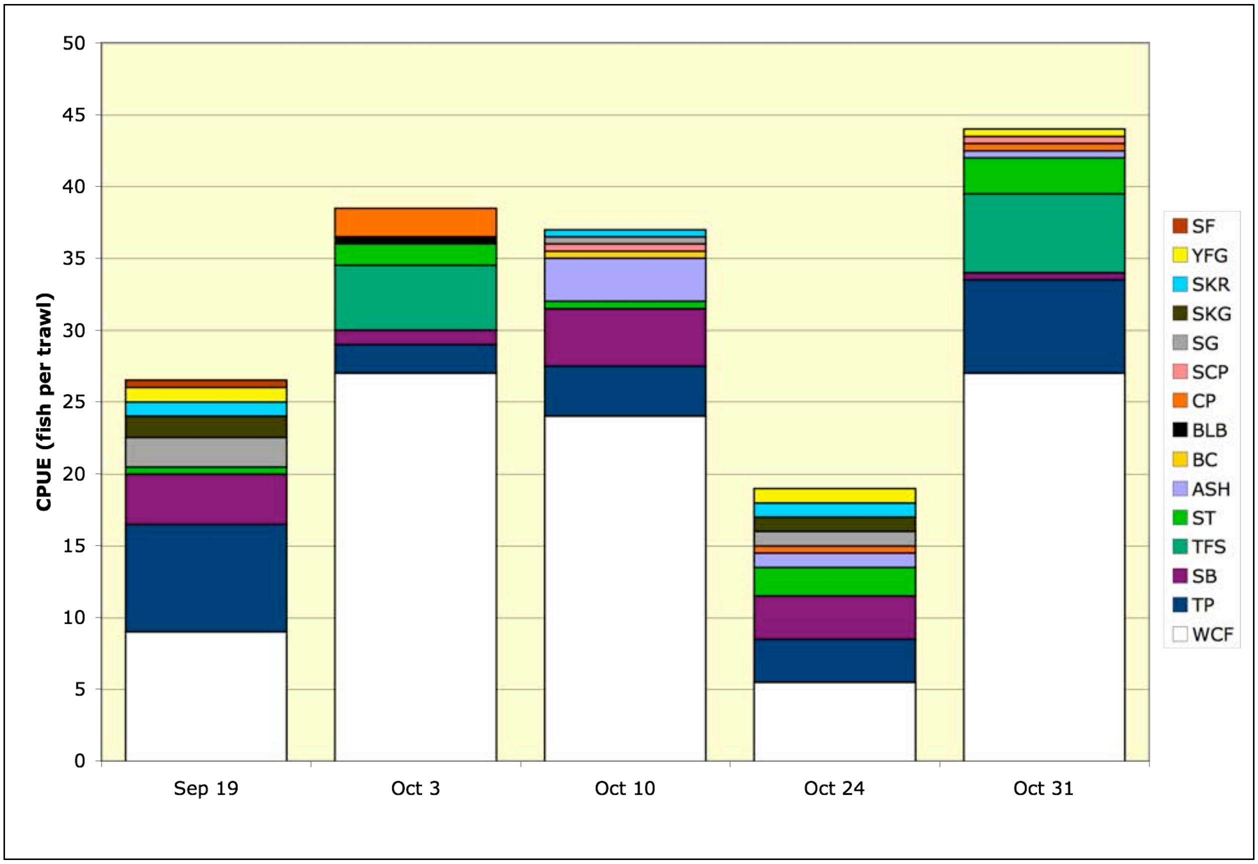

Figure 29. Otter trawl CPUE for fish species captured in Denverton Slough during early autumn [SF = starry flounder (*Platichthys stellatus*), YFG = yellowfin goby, SKR = Sacramento sucker (*Catostomus occidentalis*), SKG = shokihaze goby (*Tridentiger barbatus*), SG = shimofuri goby, SCP = prickly sculpin, CP = common carp, BLB = black bullhead (*Ameiurus melas*), BC = black crappie, ASH = American shad, ST = splittail, TFS = threadfin shad, SB = striped bass, TP = tule perch, and WCF = white catfish].

The pattern in catch and species composition in Peytonia Slough during early autumn appears due in part to DO levels. Three lines of evidence support this conclusion. First, total fish abundance tracked very well the trend in DO concentrations (Figures 28 and 30). It is unlikely that water temperature or salinity had as strong as an effect as DO levels since (1) the trends in these two parameters did not follow the catch as closely as DO; (2) the salinities and water temperatures were well within the tolerance ranges for the fishes present (Moyle 2002); and (3) DO was the variable most strongly correlated with fish CPUE (Table 6). Second, the decline in catch was mostly driven by striped bass, which are known to be intolerant of low DO (Costantini et al. 2008, Tupper and Able 2000, Coutant 1985). Third, when DO concentrations were at their minimum during the week of October 24, three of the four species present - white catfish, common carp (*Cyprinus carpio*), and yellowfin goby - are known to be tolerant of low DO conditions (Moyle 2002). Additionally, the one species present considered to be less tolerant of low DO levels - prickly sculpin - is a benthic species that is much less mobile than striped bass or splittail and thus less able to move out of areas when conditions become harmful. We neither observed nor captured dead fishes in Peytonia Slough during this period; thus the changes we observed in the slough were probably due to movements of more mobile species out of the slough as DO levels declined.

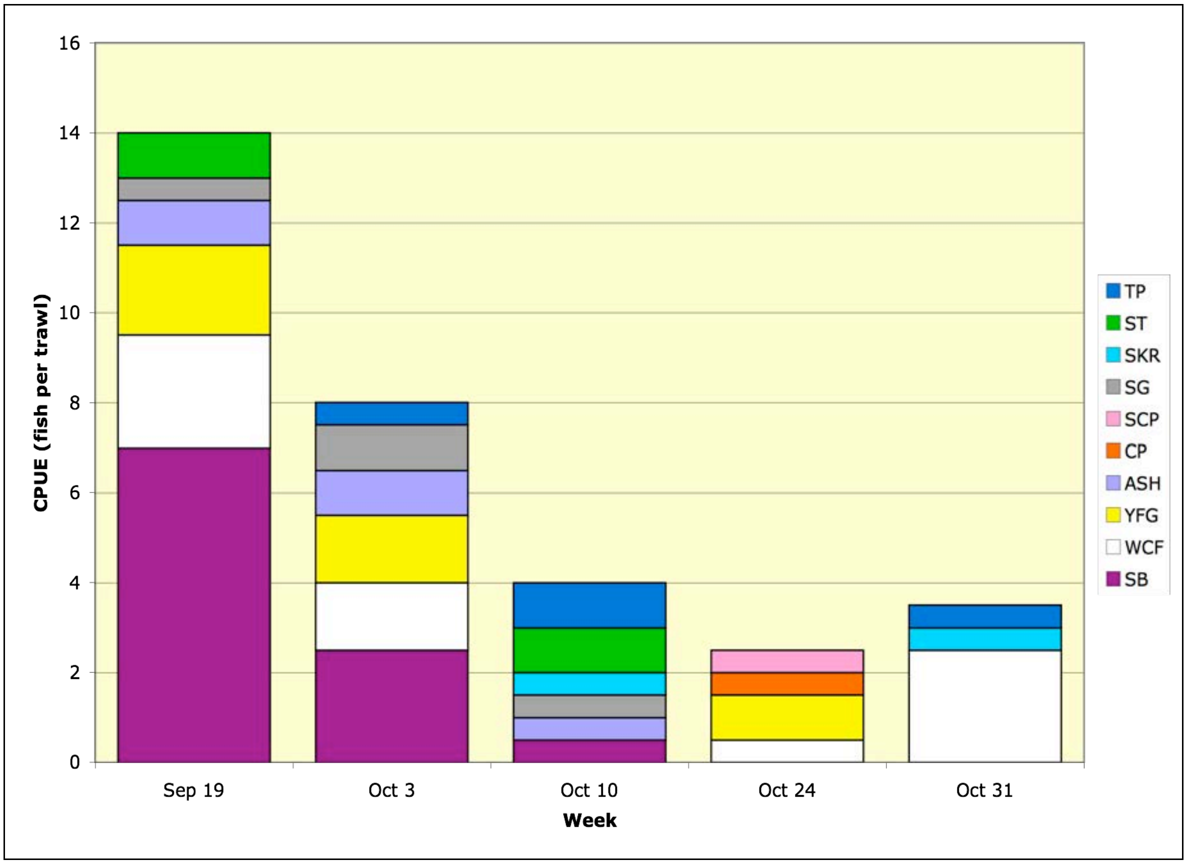

Figure 30. Otter trawl CPUE for fish species captured in Peytonia Slough during early autumn (codes as in Figure 29).

Table 6. Correlations between fish CPUE and three abiotic variables in Denverton, lower Goodyear, Peytonia, and upper Goodyear sloughs during early autumn (n = 22).

Variable	Spearman's ρ	ρ *p*-value	Kendall's τ	τ *p*-value
Salinity	-0.38	0.08	-0.25	0.11
Temperature	0.31	0.16	0.24	0.13
DO	0.41	0.06	0.33	0.03

The major factors affecting fish abundance and assemblage composition in upper Goodyear Slough at first glance are more ambiguous than for Peytonia Slough. The catch of several species of fish, including striped bass, in upper Goodyear Slough during the week of October 10 was followed by a catch of no fish species in upper Goodyear Slough during the following week (Figure 31), suggesting some change in conditions occurred between those sampling events that strongly affected the fish assemblage. This change in catch corresponded to a drop in DO (Figure 28). The fact that, like for Peytonia Slough, striped bass were a primary driver in the catch further suggests low DO as an important factor. However, the DO levels we recorded in upper Goodyear Slough during this time, while probably low enough to affect striped bass, were well within the tolerance range of species that were present before the week of October 17: splittail and yellowfin goby (Moyle et al. 2004, Williams et al. 1998). Additionally, though our temperature data showed only a mild decrease in temperatures, a continuously recording monitoring station just downstream of our GY2 site showed a sharp decline in water temperature between October 15 and 17 (Figure 33). Thus, given the available data, it appears that declines in water temperature and DO were both associated with our catches in upper Goodyear Slough.

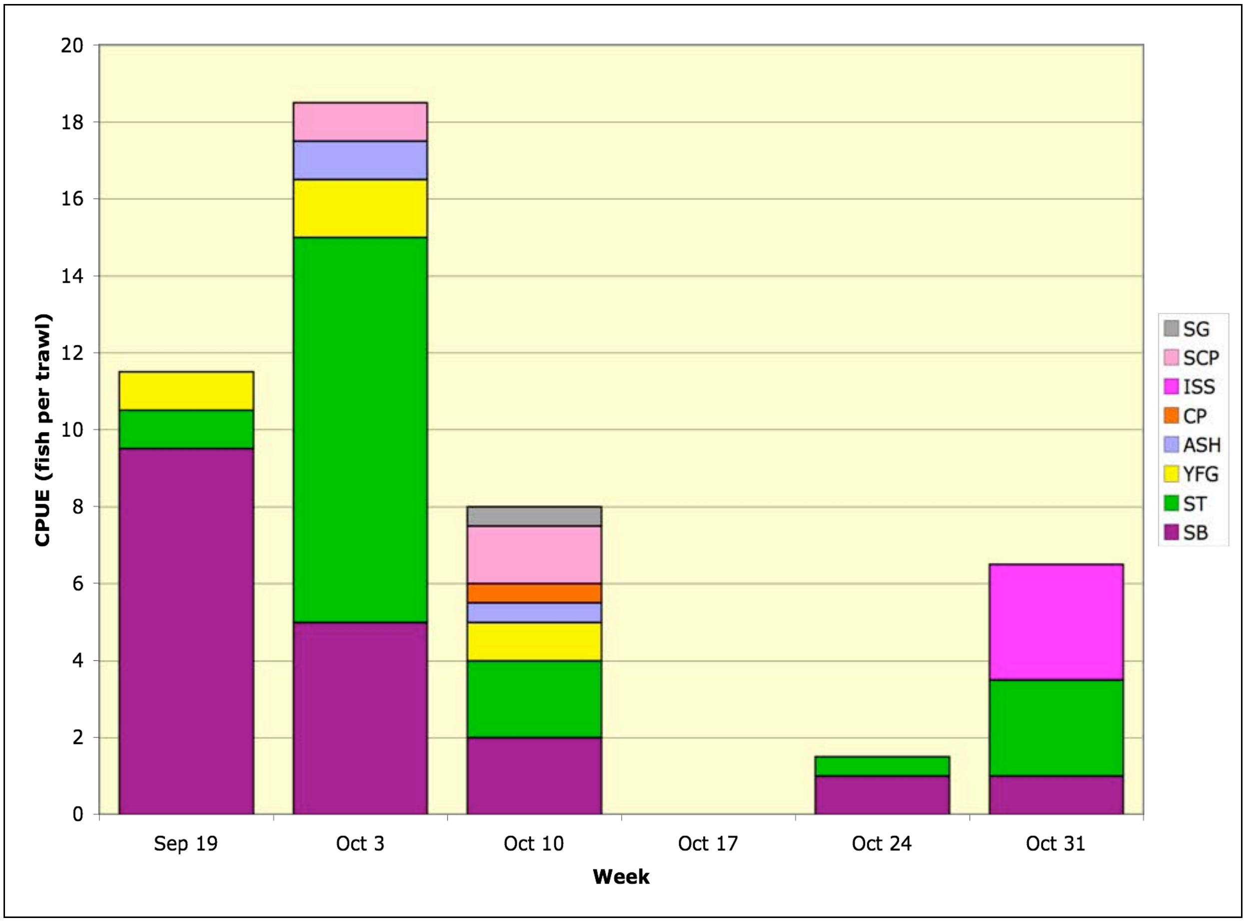

Figure 31. Otter trawl CPUE for fish species captured in upper Goodyear Slough during early autumn (note that no fish were captured during the week of October 17; ISS = Mississippi silversides; all other codes as in Figure 29).

Nevertheless, there are a few other patterns in catch in upper Goodyear Slough during this period that suggest low DO may have been not only the stronger driver in our catches but also may have reached anoxic levels. Trawls conducted during fish kills and concomitant anoxia have captured either no fish or just a few dead fishes (O'Rear et al. 2009, Schroeter and Moyle 2004), similar to our trawls in upper Goodyear Slough during the week of October 17 when no fishes were captured (Figure 31). In upper Goodyear Slough, unlike in Peytonia Slough, yellowfin goby - a species tolerant of low DO but not of anoxia (Schroeter and Moyle 2004, Williams et al. 1998) - was not one of the species remaining after DO dropped during the week of October 17 despite being consistently caught in previous weeks (Figure 31). Although temperature changed rapidly in upper Goodyear Slough coincident with a drop in the striped bass catch, the same was not observed in Denverton Slough (Figure 30), which presumably also experienced a concurrent sharp decline in temperature (Matern et al. 2002). Finally, DO has been observed to increase notably just a few days after an anoxia event (Siegel et al. 2011) and concomitant fish kill (Schroeter and Moyle 2004).

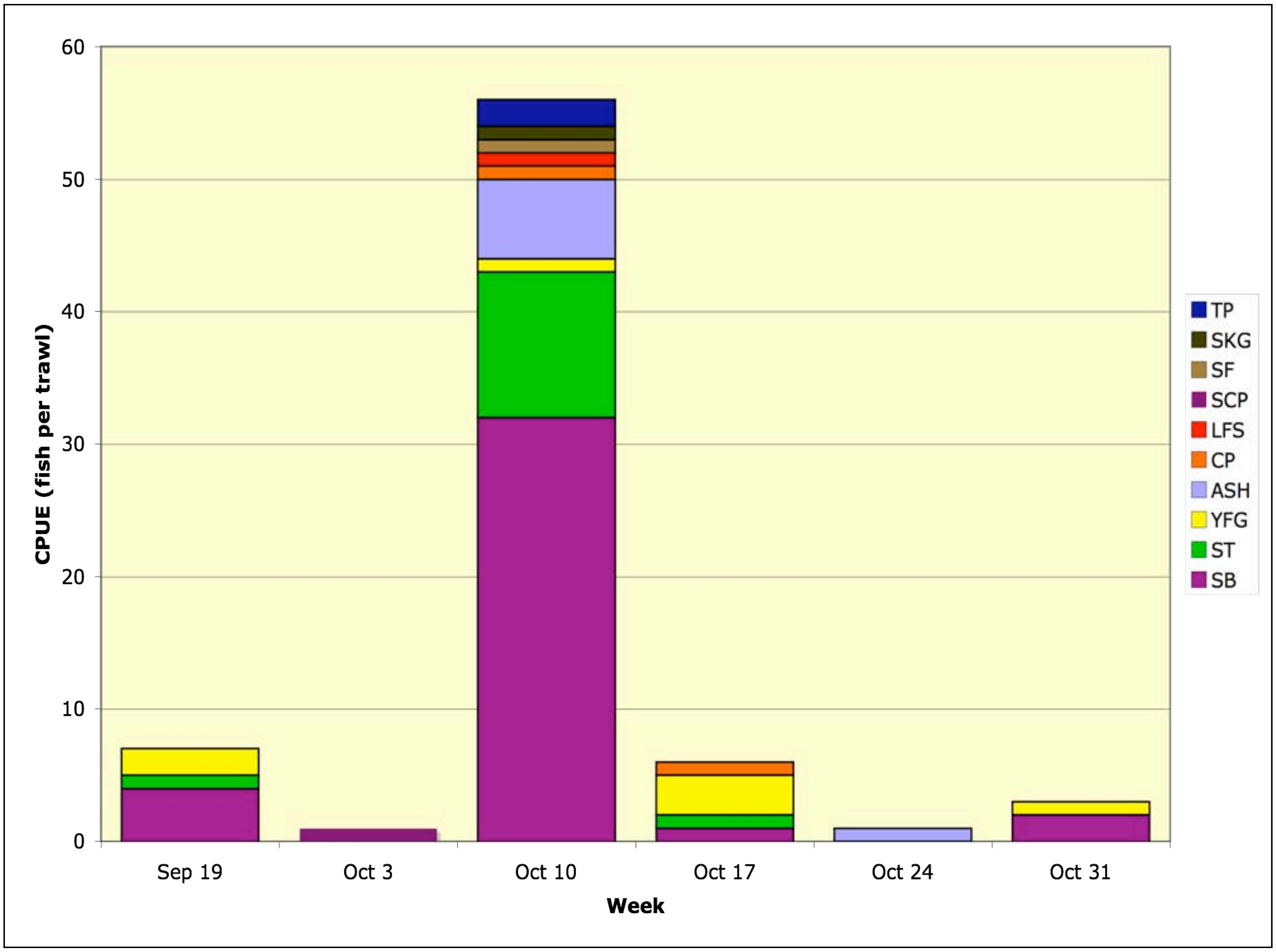

Figure 32. Otter trawl CPUE for fish species captured in lower Goodyear Slough during early autumn (LFS = longfin smelt; all other codes as in Figure 29).

The relationship between fishes and DO levels, and, as a result, in-marsh water operations, appears, not surprisingly, very complex when other factors (e.g., water temperature) are considered. Therefore, while our more frequent sampling in early autumn delineated clear patterns in fish abundance and assemblage structure, it could not clearly identify the magnitude of the effects of abiotic parameters based on our water-quality point data. Continuous monitoring stations that include DO in various regions of the marsh would greatly enhance the understanding of the major drivers of fish ecology in the marsh during not only early autumn but also other times of the year.

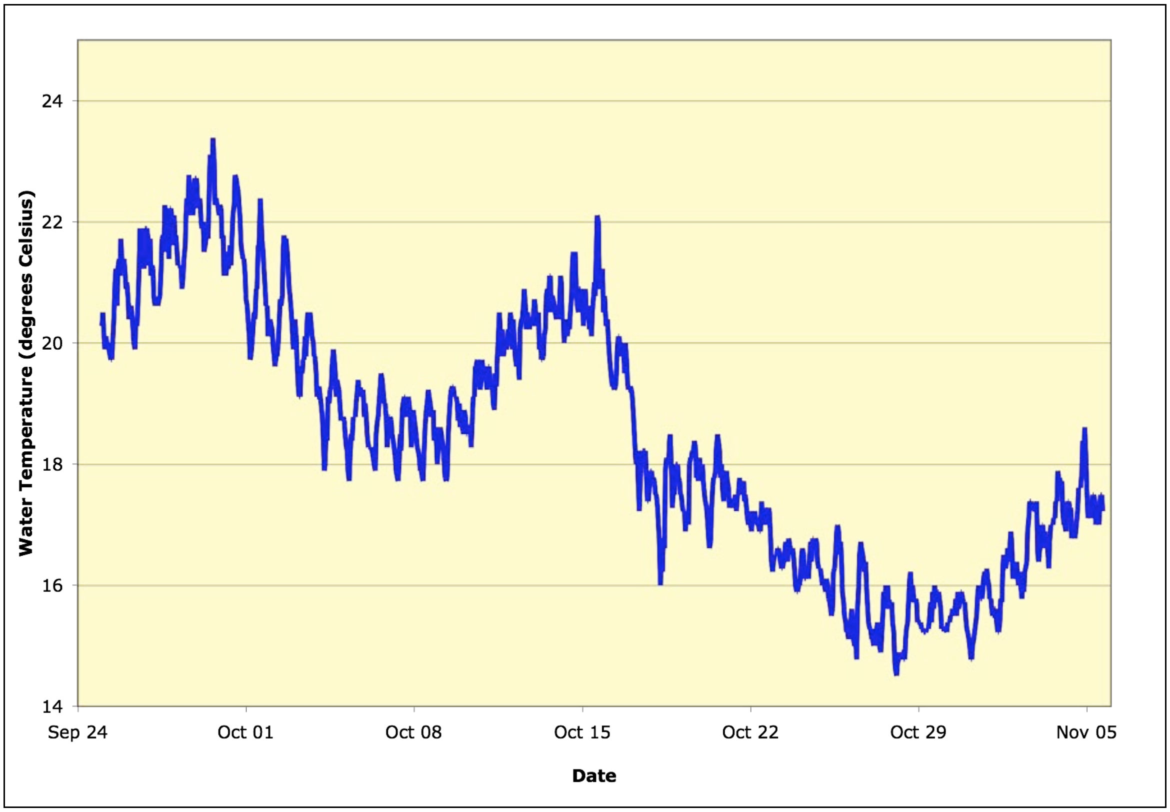

Figure 33. Hourly water temperatures for Goodyear Slough just downstream of the GY2 site (see Figure 2) from 25 September 2010 to 5 November 2010 (California Department of Water Resources 2011*b*).

CONCLUSIONS

In sum, the patterns observed in 2010 both continue to add weight to previous findings and reveal new relationships. Once again, Delta outflow appeared to strongly influence our catches, namely by promoting recruitment of yellowfin goby, threadfin shad, California bay shrimp, and splittail and by repressing recruitment of white catfish and staghorn sculpin. Cooler-than-average water temperatures were associated with delayed reproduction of Black Sea jellyfish and Mississippi silversides, with, in the case of silversides, effects on population dynamics and our total beach seine catch. The increase in the abundance of all four commonly captured plankton-feeding macroinvertebrates from 2009 to 2010 intimates that pelagic food supplies were also more abundant in 2010; however, the patterns in mysids and young-of-year striped bass and shimofuri gobies once again point to pelagic food limitation late in the year. The influence of in-marsh water operations on marsh fishes - both negative and positive - suggests that more attention needs to be given to managed wetlands to better understand the aquatic biology of Suisun Marsh. Continuation of more frequent sampling in autumn, coupled with continuous monitors placed in strategic regions of the marsh, could be a first step to addressing this deficiency in our knowledge. Additionally, a sampling program for waters on the landward side of the marsh's dikes would yield additional insight.

ACKNOWLEDGEMENTS

Sampling in Suisun Marsh has been the responsibility of many graduate students and others over the years, including Donald Baltz, Robert Daniels, Bruce Herbold, Lesa Meng, Scott Matern, Robert Schroeter, Patrick Crain, John Durand, Alpa Wintzer, and Sabra Purdy. They have been assisted by literally hundreds of volunteers and student assistants. We appreciate the continued support of the sampling program over the years by the California Department of Water Resources. Randall Brown of California Department of Water Resources kept the program going during its early uncertain years. The views expressed in this report are those of the authors and do not reflect the official policy or position of DWR.

REFERENCES

The Bay Institute, Center for Biological Diversity, and Natural Resources Defense Council. 2007. Petition to the state of California Fish and Game Commision and supporting information for listing the longfin smelt (*Spirinchus thaleichthys*) as an endangered species under the California Endangered Species Act.

Bennett, W. A. 2005. Critical assessment of the Delta smelt population in the San Francisco Estuary, California. San Francisco Estuary and Watershed Science 3.

Bennett, W.A., and P. B. Moyle. 1996. Where have all the fishes gone: interactive factors producing fish declines in the Sacramento-San Joaquin estuary. Pages 519-542 *in* J. T. Hollibaugh, ed. *San Francisco Bay: the Ecosystem.* San Francisco: AAAS, Pacific Division.

California Department of Fish and Game. 1996. Fishery monitoring program a component of the Suisun Marsh Diversion Screening Program. California, University of California, Davis.

California Department of Fish and Game. 1997. Spring of 1997 diversion monitoring program a component of the Suisun Marsh Diversion Screening Program. California, University of California, Davis.

California Department of Fish and Game. 1998. 1997-1998 sampling report for the diversion monitoring program a component of the Suisun Marsh Diversion Screening Program. California, University of California, Davis.

California Department of Water Resources. 2011*a*. Interagency ecological program. Available: www.iep.water.ca.gov (January 2011).

California Department of Water Resources. 2011*b*. California Data Exchange Center. Available: http://cdec.water.ca.gov/cgi-progs/stationInfo?station_id=GYS (March 2011).

California Department of Water Resources. 2001. Comprehensive Review Suisun Marsh Monitoring Data 1985-1995. California, California Department of Water Resources.

California Department of Water Resources and California Department of Fish and Game. 2007. Pelagic Fish Action Plan. California, California Department of Water Resources.

Cech, J. J., Jr., S. J. Mitchell, D. T. Castleberry, and M. McEnroe. 1990. Distribution of California stream fishes: influence of environmental temperature and hypoxia. Environmental Biology of Fishes 29: 95-105.

Cech, J. J., Jr., and P. B. Moyle. 2004. Fishes: an introduction to ichthyology. New Jersey, Prentice-Hall.
Costantini, M, S. A. Ludsin, D. M. Mason, X. Zhang, W. C. Boicourt, and S. B. Brandt. 2008. Effect of hypoxia on habitat quality of striped bass (*Morone saxatilis*) in Chesapeake Bay. Canadian Journal of Fisheries and Aquatic Sciences 65: 989-1002.
Coutant, C. C. 1985. Striped bass, temperature, and dissolved oxygen: a speculative hypothesis for environmental risk. Transactions of the American Fisheries Society 114: 31-61.
Culberson, S. D., C. B. Harrison, C. Enright, and M. L. Nobriga. 2004. Sensitivity of larval fish transport to location, timing, and behavior using a particle tracking model in Suisun Marsh, Califorrnia. American Fisheries Society Symposium 39: 257-267.
Emmett, R. L., S. A. Hinton, D. J. Logan, and G. T. McCabe, Jr. 2002. Introduction of a Siberian freshwater shrimp to western North America. Biological Invasions 4: 447-450.
Enright, C., & S. Culberson. 2009. Salinity trends, variability, and control in the northern reach of the San Francisco Estuary. San Francisco Estuary and Watershed Science, 7(2).
Feyrer, F., B. Herbold, S. A. Matern, and P. B. Moyle. 2003. Dietary shifts in a stressed fish assemblage: consequences of a bivalve invasion in the San Francisco Estuary. Environmental Biology of Fishes 67: 277-288.
Feyrer, F., M. L. Nobriga, and T. R. Sommer. 2007. Multidecadal trends for three declining fish species: habitat patterns and mechanisms in the San Francisco Estuary, California, USA. Canadian Journal of Fisheries and Aquatic Sciences 64: 723-734.
Feyrer F., T. Sommer, and S.B. Slater. 2009. Old school vs. new school: status of threadfin shad (*Dorosoma petenense*) five decades after its introduction to the Sacramento-San Joaquin Delta. San Francisco Estuary and Watershed Science 7(1): Article 3.
Fish, M., D. Contreras, V. Afentoulis, J. Messineo, and K. Hieb. 2009. 2008 fishes annual status and trends report for the San Francisco Estuary. Interagency Ecological Program Newsletter 22: 17-35.
Hatfield, S. 1985. Seasonal and interannual variation in distribution and population abundance of the shrimp *Crangon franciscorum* in San Francisco Bay. Hydrobiologia 129: 199-210.
Hubbs, C. 1982. Life history dynamics of *Menidia beryllina* from Lake Texoma. American Midland Naturalist 107(1): 1-12.
Hubbs, C., H. Sharp, and J. F. Schneider. 1971. Developmental rates of *Menidia audens* with notes on salinity tolerance. Transactions of the American Fisheries Society 100: 603-610.
Jassby, A. D., W. J. Kimmerer, S. G. Monismith, C. Armor, J. E. Cloern, T. M. Powell, J. R. Schubel, and T. J. Vendlinksi. 1995. Isohaline position as a habitat indicator for estuarine populations. Ecological Applications 5: 272-289.
Kimmerer, W. J., J. H. Cowan, Jr., L. W. Miller, and K. A. Rose. 2001. Analysis of an estuarine striped bass population: effects of environmental conditions during early life. Estuaries 24(4): 557-575.
Kimmerer, W., E. S. Gross, and M. L. MacWilliams. 2009. Is the response of estuarine nekton to freshwater flow in the San Francisco Estuary explained by variation in habitat volume? Estuaries and Coasts 32: 375-389.
Matern, S. A. 1999. Invasion of the shimofuri goby (*Tridentiger bifasciatus*) into California: establishment, potential for spread, and likely effects. Doctoral dissertation. University of California, Davis.

Matern, S. A., P. B. Moyle, and L. C. Pierce. 2002. Native and alien fishes in a California estuarine marsh: twenty-one years of changing assemblages. Transactions of the American Fisheries Society 131: 797-816.

Meng, L., and S. A. Matern. 2001. Native and alien larval fishes of Suisun Marsh, California: the effects of freshwater flow. Transactions of the American Fisheries Society 130: 750-765.

Meng, L., P. B. Moyle, and B. Herbold. 1994. Changes in abundance and distribution of native and alien fishes of Suisun Marsh. Transactions of the American Fisheries Society 123: 498-507.

Middaugh, D. P., and M. J. Hemmer. 1992. Reproductive ecology of the inland silverside, *Menidia beryllina*, (Pisces: Atherinidae) from Blackwater Bay, Florida. Copeia 1:53-61.

Moyle, P. B. 2002. Inland Fishes of California. California, University of California Press.

Moyle, P. B., R. D. Baxter, T. Sommer, T. C. Foin, and S. A. Matern. 2004. Biology and population dynamics of Sacramento splittail (*Pogonichthys macrolepidotus*) in the San Francisco Estuary: a review. San Francisco Estuary and Watershed Science 2(2): Article 3.

Moyle, P. B., R. A. Daniels, B. Herbold, and D. M. Baltz. 1986. Patterns in distribution and abundance of a noncoevolved assemblage of estuarine fishes in California. U. S. National Marine Fisheries Service Fishery Bulletin 84(1): 105-117.

Nobriga, M. L., and F. Feyrer. 2008. Diet composition in San Francisco Estuary striped bass: does trophic adaptability have its limits? Environmental Biology of Fish 83: 495-503.

Oh, C., H. Suh, K. Park, C. Ma, and H. Lim. 2002. Growth and reproductive biology of the freshwater shrimp *Exopalaemon modestus* in a lake of Korea. Journal of Crustacean Biology 22: 357-366.

O'Rear, T. A., and P. B. Moyle. 2010. Long term and recent trends of fishes and invertebrates in Suisun Marsh. Interagency Ecological Program Newsletter 23(2): 26-48.

O'Rear, T.A., N. G. Buckmaster, E. Cheatham, A. Clause, and P. B. Moyle. 2009. A fish kill in a slough of Suisun Marsh. California, University of California, Davis.

O'Rear, T. A., and P. B. Moyle. 2009. Trends in Fish Populations of Suisun Marsh January 2008 - December 2008. California, California Department of Water Resources.

O'Rear, T. A., and P. B. Moyle. 2008. Trends in Fish Populations of Suisun Marsh January 2006 - December 2007. California Department of Water Resources.

Rosenfield, J. A., and R. D. Baxter. 2007. Population dynamics and distribution patterns of longfin smelt in the San Francisco Estuary. Transactions of the American Fisheries Society 136: 1577-1592.

Schroeter, R. E. 2010. The temporal and spatial trends, biological constraints, and impacts of an invasive clam, *Corbula amurensis*, in Suisun Marsh, San Francisco Estuary. California, University of California.

Schroeter, R. E. 2008. Biology and long-term trends of alien hydromedusae and striped bass in a brackish tidal marsh in the San Francisco Estuary. Doctoral dissertation. University of California, Davis.

Schroeter, R. E., and P. B. Moyle. 2004. Dissolved oxygen sags in Suisun Marsh, 2004. California, University of California, Davis.

Schroeter, R., A. Stover, and P. B. Moyle. 2006. Trends in Fish Populations of Suisun Marsh January 2005 - December 2005. California Department of Water Resources.

Siegel, S., P Bachand, D. Gillenwater, S. Chappel, B. Wickland, O. Rocha, M. Stephenson, W. Heim, C. Enright, P. Moyle, P. Crain, B. Downing, and B. Bergamaschi. 2011. Final evaluation memorandum, strategies for reducing low dissolved oxygen and methylmercury events in northern Suisun Marsh. Prepared for the State Water Resources Control Board, Sacramento, California. SWRCB Project Number 06-283-552-0.

Siegfried, C. A. 1982. Trophic relations of *Crangon franciscorum* Stimson and *Palaemon macrodactylus* Rathbun: predation on the opposum shrimp, *Neomysis mercedis* Holmes. Hydrobiologia 89: 129-139.

Sommer, T., R. Baxter, and B. Herbold. 1997. Resilience of splittail in the Sacramento-San Joaquin Estuary. Transactions of the American Fisheries Society 126: 961-976.

Sommer, T. R., W. C. Harrell, Z. Matica, and F. Feyrer. 2008. Habitat associations and behavior of adult and juvenile splittail (Cyprinidae: *Pogonichthys macrolepidotus*) in a managed seasonal floodplain wetland. San Francisco Estuary and Watershed Science 6(2): Article 3.

Stevens, D. E. 1966. Food habits of striped bass (*Roccus saxatilis*)in the Sacramento-San Joaquin Delta. *In* Turner, J.L., and D. W. Kelley (eds) Ecological studies of the Sacramento-San Joaquin Estuary, part 2: fishes of the Delta. California Department of Fish and Game Fish Bulletin 136: 68-96.

Stoeckel, J. N., and R. C. Heidinger. 1988. Overwintering of the inland silverside in southern Illinois. North American Journal of Fisheries Management 8: 127-131.

Tupper, M., and K. W. Able. 2000. Movements and food habits of striped bass (*Morone saxatilis*) in Delaware Bay (USA) salt marshes: comparison of a restored and a reference marsh. Marine Biology 137: 1049-1058.

Wang, J. C. 1986. Fishes of the Sacramento-San Joaquin estuary and adjacent waters, California: a guide to early life histories. Interagency Ecological Program Technical Report 9. 800 pp.

Williams, G. D., J. S. Desomn, and J. B. Zedler. 1998. Extention of 2 nonindigenous fishes, *Acanthogobius flavimanus* and *Poecilia latipinna*, into San Diego Bay marsh habitats. California Fish and Game 84: 1-17.

Wintzer, A. P., M. H. Meek, and P. B. Moyle. 2011. Trophic ecology of two non-native hydrozoan medusae in the upper San Francisco Estuary. Marine and Freshwater Research 62: 952-961.

Workman, M. L, and J. E. Merz. 2007. Introduced yellowfin goby, *Acanthogobius flavimanus*: diet and habitat use in the lower Mokelumne River, California. San Francisco Estuary and Watershed Science 5(1): Article 1.

APPENDIX A

Total number of fishes caught in Suisun Marsh by otter trawl, beach seine, midwater trawl, and all methods from 1979 to 2010.

Common Name	Scientific Name	Otter Trawl	Beach Seine	Midwater Trawl	All Gear Types
American shad	*Alosa sapidissima*	1051	190	0	1241
bay pipefish	*Sygnathus leptorhynchus*	2	0	0	2
bigscale logperch	*Percina macrolepida*	17	2	0	19
black bullhead	*Ameiurus melas*	860	3	0	863
black crappie	*Pomoxis nigromaculatus*	1789	81	1	1871
bluegill	*Lepomis macrochirus*	19	18	0	37
brown bullhead	*Ameiurus nebulosus*	28	0	0	28
California halibut	*Paralichthys californicus*	5	0	0	5
channel catfish	*Ictalurus punctatus*	167	6	0	173
Chinook salmon	*Oncorhynchus tshawytscha*	72	386	1	459
common carp	*Cyprinus carpio*	4754	414	1	5169
Delta smelt	*Hypomesus transpacificus*	626	136	4	766
fathead minnow	*Pimephales promelas*	33	36	0	69
golden shiner	*Notemigonus crysoleucas*	5	3	0	8
goldfish	*Carassius auratus*	293	42	0	335
green sturgeon	*Acipenser medirostris*	3	0	0	3
green sunfish	*Lepomis cyanellus*	5	3	0	8
hardhead	*Mylopharadon conocephalus*	1	0	0	1
hitch	*Lavinia exilicauda*	114	16	0	130
largemouth bass	*Micropterus salmoides*	0	1	0	1
longfin smelt	*Spirinchus thaleichthys*	11359	41	5	11405
longjaw mudsucker	*Gillichthys mirabilis*	1	0	0	1
Mississippi silverside	*Menidia audens*	643	73387	0	74030
mosquitofish	*Gambusia affinis*	18	274	0	292
northern anchovy	*Engraulis mordax*	257	0	37	294
Pacific herring	*Clupea harengeus*	465	116	0	581
Pacific lamprey	*Lampetra tridentata*	43	0	0	43
Pacific sanddab	*Citharichthys sordidas*	2	2	0	4
plainfin midshipman	*Porichthys notatus*	11	0	0	11
prickly sculpin	*Cottus asper*	9783	895	1	10679
rainbow trout	*Oncorhynchus mykiss*	7	4	0	11
rainwater killifish	*Lucania parva*	30	91	0	121
redear sunfish	*Lepomis microlophus*	2	0	0	2
Sacramento blackfish	*Orthodon macrolepidotus*	24	116	0	140
Sacramento pikeminnow	*Ptychocheilus grandis*	135	216	0	351
Sacramento sucker	*Catostomus occidentalis*	3125	98	5	3228
shimofuri goby	*Tridentiger bifasciatus*	9574	2142	1	11717
shiner perch	*Cymatogaster aggregata*	17	0	0	17
shokihaze goby	*Tridentiger barbatus*	564	2	6	572
speckled sanddab	*Citharichthys stigmaeus*	3	0	0	3
splittail	*Pogonichthys macrolepidotus*	22730	2824	14	25568
staghorn sculpin	*Leptocottus armatus*	2335	3204	0	5539
starry flounder	*Platichthys stellatus*	1905	259	4	2168

Common Name	Scientific Name	Otter Trawl	Beach Seine	Midwater Trawl	All Gear Types
striped bass	*Morone saxatilis*	79444	12055	30	91529
surf smelt	*Hypomesus pretiosus*	5	0	0	5
threadfin shad	*Dorosoma petenense*	2594	4993	1	7588
threespine stickleback	*Gasterosteus aculeatus*	16809	4709	6	21524
tule perch	*Hysterocarpus traski*	17963	1898	6	19867
wakasagi	*Hypomesus nipponensis*	10	6	0	16
warmouth	*Lepomis gulosus*	1	0	0	1
white catfish	*Ameiurus catus*	4573	108	13	4694
white crappie	*Pomoxis annularis*	112	0	0	112
white croaker	*Genyonemus lineatus*	1	0	0	1
white sturgeon	*Acipenser transmontanus*	105	0	2	107
yellowfin goby	*Acanthogobius flavimanus*	19077	15599	0	34676
Total		213571	124376	138	338085

APPENDIX B

Total 2010 otter trawl catch of each fish species in each slough of Suisun Marsh (BY = Boynton Slough, CO = Cutoff Slough, DV = Denverton Slough, GY = Goodyear Slough, LSU = lower Suisun Slough, MZ = Montezuma Slough, MZN = Montezuma Slough just downstream of the Montezuma-Nurse confluence, NS = Nurse Slough, PT = Peytonia Slough, SB = First Mallard Slough, and USU = upper Suisun Slough).

Species	Slough											Total
	BY	CO	DV	GY	LSU	MZ	MZN	NS	PT	SB	USU	
American shad	3	2	9	12	16	2		3	8	6	4	65
black bullhead	1		1						4			6
black crappie	1		3					1	1			6
channel catfish			2	1								3
common carp	14	3	23	6	5	7		4	13	4	1	80
Delta smelt				1								1
fathead minnow	5											5
goldfish	3								1			4
longfin smelt	4	2		9	64			1	4	6	3	93
Mississippi silverside				6						10		16
Pacific herring					2					5	1	8
prickly sculpin	24	17	11	160	9	4	1	2	24	15	16	283
rainwater killifish				3								3
Sacramento pikeminnow							1		1			2
Sacramento sucker	26	5	6	3	1	5		2	15	8	2	73
shimofuri goby	127	24	166	6	5	2	3	48	28	22	38	469
shokihaze goby			7	1	2	5	9	42			12	78
splittail	83	20	82	158	117	82	3	136	45	78	137	941
staghorn sculpin	2	3		7	15	1	1	2		1	5	37
starry flounder	1	3	4	2	5	6		10		2	9	42
striped bass	117	40	64	198	423	82	9	124	175	372	137	1741
threadfin shad	1	2	21	2	6	2		12	13	10		69
threespine stickleback	17	1	16	220	38	14	4	4	5	5	12	336
tule perch	59	29	75	7	127	83	1	63	56	10	24	534
white catfish	53	10	311			31	6	29	69	9	32	550
yellowfin goby	71	14	10	45	131	22	1	21	31	15	113	474
Total	612	175	811	847	966	348	39	504	493	578	546	5919

Total 2010 beach seine catch for each fish species in Denverton and upper Suisun sloughs.

Species	Denverton Slough	Upper Suisun Slough	Total
American shad	2		2
Chinook salmon	3		3
common carp	6	2	8
Delta smelt		1	1
fathead minnow		2	2
Mississippi silverside	894	732	1626
Pacific herring	1		1
prickly sculpin	12	35	47
Sacramento pikeminnow	3		3
Sacramento sucker	2		2
shimofuri goby	83	23	106
splittail	42	24	66
staghorn sculpin	3	58	61
striped bass	98	52	150
threadfin shad	67	11	78

Species	Denverton Slough	Upper Suisun Slough	Total
threespine stickleback	367	31	398
tule perch	7	20	27
western mosquitofish	2	2	4
yellowfin goby	29	261	290
Total	1621	1254	2875

APPENDIX C

Number of otter trawls for each slough and each month in 2010.

Slough	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Boynton	2	2	3	2	2	3	2	2	2	2	2	2	26
Cutoff	2	2	1	2	2	3	2	2	2	2	2	2	24
Denverton	2	2	2	2	2	2	2	2	2	6	2	2	28
First Mallard	2	2	2	2	1	2	2	2	2	2	2	2	23
Goodyear	3	3	3	3	3	3	3	3	3	12	3	3	45
Lower Suisun	2	2	5	2	2	2	2	2	2	2	2	2	27
Montezuma	2	2	2	2	2	2	2	2	2	2	2	2	24
Montezuma @ Nurse	2	2	2			2							8
Nurse	2	2	2	2	2	2	2	2	2	2	2	2	24
Peytonia	2	2	3	2	2	3	2	3	2	6	2	2	31
Upper Suisun	3	3	2	2	2	2	2	2	2	2	2	3	27
Total	24	24	27	21	20	26	21	22	21	38	21	22	287