Interagency Ecological Program for the San Francisco Estuary

# IEP NEWSLETTER

VOLUME 28, NUMBER 3, 2015

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# Of Interest to Managers

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This issue of the IEP newsletter contains management highlights from a White Sturgeon study conducted by the U.S. Fish and Wildlife Service (USFWS) researchers as part of the Anadromous Fish Restoration Program, updates regarding three of the California Department of Fish and Wildlife's (DFW) long-term monitoring studies, conducted in 2014, and three contributed papers from the Center for Watershed Sciences at the University of California, Davis (UCD).

First, **Laura Heironimus** and **Zachary Jackson** (USFWS) summarize the first five years of an ongoing study aimed at detecting White Sturgeon (*Acipenser transmontanus*) spawning in the San Joaquin River. Egg mats were deployed each spring along the San Joaquin River, beginning in 2011. The authors describe the conditions under which eggs were detected and provide some insights into how White Sturgeon utilize the San Joaquin River for reproduction.

**Lauren Damon** (DFW) provides updates on three long term monitoring surveys, each examining a different life stage of pelagic fishes in the upper San Francisco Estuary. The Smelt Larva Survey (SLS), initiated in 2009, provides near real-time monitoring of the distribution and relative abundance of larval Longfin Smelt (*Spirinchus thaleichthys*), as well as the larvae of other fish species. Spring Kodiak Trawl (SKT) operates from January to early May to monitor adult Delta Smelt (*Hypomesus transpacificus*) throughout their spawning season. Gonadal maturation is also reported, providing a more detailed picture of the Delta Smelt spawning. Spawning success is monitored by the 20-mm survey, which operates from March to July and targets larval and juvenile Delta Smelt. The results of these surveys, presented in the three articles below, outline the distribution and relative abundance of two life stages of Delta Smelt and larval Longfin Smelt, and provide some interesting insights into other species that were caught incidentally.

Researchers from the Center for Watershed Sciences at the University of California, Davis, contributed the final three papers. **Jacob Montgomery** (UCD) and co-authors present 2 years of zooplankton and chlorophyll-*a* data collected at shallow aquatic habitats in eastern Suisun Marsh and in the Cache Slough region of the North Delta. Chlorophyll-*a* density and variability in phytoplankton blooms were linked to abiotic factors, such as residence time and salinity, as well as zooplankton density, to provide insight into the lower trophic food web. **Matthew J. Young** (UCD) and co-authors reported on habitat and fish assemblages in the Cache Slough region of the North Delta. They determined that the observed differences between the fish assemblages of Cache and Lindsey sloughs could be attributed to habitat differences such as turbidity, density of submerged aquatic vegetation and primary productivity. The differences in habitat and fish assemblage between these two connected waterways are used to tease out characteristics that appear to benefit native fish. Finally, **Brian Williamson** (UCD) and co-authors contrast fish assemblages in a recently restored tidal wetland, a managed pond and adjacent subtidal sloughs. They present a summary of trawl and beach seine data collected in 2014 at five locations within the Nurse-Denverton Slough Complex in eastern Suisun Marsh. Comparisons were made using three indices for species diversity, Catch per Unit Effort, and proportion of native species present in each of the areas sampled. These three articles highlight ongoing efforts by UCD researchers examining the ecology of the north Delta and Suisun Marsh.

# Management Highlights: Five Year Summary of Efforts to Detect White Sturgeon Reproduction in the San Joaquin River

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## Introduction

The purpose of these investigations was to provide scientific information that will assist in developing restoration recommendations to help meet program objectives and achieve the anadromous fish doubling goal. The focus of this study was to determine White Sturgeon (*Acipenser transmontanus*) habitat use, reproductive potential, and recruitment success within the San Joaquin River, California. There has been speculation about White Sturgeon spawning in the San Joaquin River during years of high streamflow (Radtke 1966; Stevens and Miller 1970; Beamesderfer et al. 2004), but no direct evidence prior to 2011 (Gruber et al. 2012). The objective of this report is to briefly summarize the results of the 2011 – 2015 efforts to detect successful White Sturgeon reproduction by means of collecting eggs or larvae within the study area.

## Methods

**Egg Mats** — Each spring since 2011, we have conducted annual sampling in the San Joaquin River in an effort to detect White Sturgeon spawning and understand the conditions under which it occurs (Gruber et al. 2012; Jackson and Van Eenennaam 2013; Faukner and Jackson 2014; Faukner et al. 2015). We constructed artificial substrate samplers (i.e., egg mats), as described in Poytress et al. (2009), to capture eggs. We deployed egg mats in pairs at four to eight sites along the San Joaquin River, from river kilometer (rkm) 115 (measuring from its confluence with the Sacramento River upstream to a point just downstream of the confluence of the Stanislaus River, near Manteca, CA) to rkm 152 (upstream from Laird Park near Grayson, California) (Gruber et al. 2012; Jackson and Van Eenennaam 2013; Faukner and Jackson 2014; Faukner et al. 2015). During the abbreviated sampling season of 2011 (April 18 – May 16), egg mats were deployed in areas bordering the deepest portion of pools where sturgeon spawning was suspected (Gruber et al. 2012). In the subsequent seasons, we generally sampled March – May and selected sites based on previously documented spawning areas with complex or accelerating velocities or gravel substrates (Jackson and Van Eenennaam 2013; Faukner and Jackson 2014; Faukner et al. 2015).

**Larval** — Larval sampling was conducted in March and April of 2013 and May of 2015 to increase the probability of detecting sturgeon reproduction (Faukner and Jackson 2014; Giannetta et al. 2016). In 2013, we deployed benthic D-nets, as described in Poytress et al. (2009), at rkm 119, 143, and 156 to sample for drifting larval sturgeon in the San Joaquin River. In 2015, we deployed two benthic D-nets and a large custom-made drift net at rkm 104 in the San Joaquin River.

## Results

**Egg Mats** — Effort was measured in wetted mat days (wmd), which is one mat set for 24 hours. Total fishing effort across all sampling locations amounted to 183.2 wmd in 2011, 670.9 wmd in 2012, 763.5 wmd in 2013, 306.0 wmd in 2014, and 642.8 wmd in 2015. In 2011, 23 White Sturgeon eggs were collected downstream of Grayson, California, 19 of which were fertilized and developing (i.e., viable). An additional 65 White Sturgeon eggs were collected throughout the study area in 2012, 46 of which were viable. In 2011 and 2012, we back-calculated spawning time by comparing the development stage of the embryo and river temperature, which indicated spawning occurred between late-March and mid-May. Most of the eggs collected during 2011 and 2012 were covered by sand and silt particles (Figure 1). In 2011 and 2012, water temperature ranged between 18 and 20° C on many of the days viable eggs were collected. Wang et al. (1985) documented a decreased hatching rate at these temperatures and an increase in developing embryo mortalities above 20° C. It is unknown whether any eggs from the cohort we collected would have survived to hatching. Despite sampling efforts in 2013-2015, no additional sturgeon eggs were collected.

Sampling during 2011 was not initiated until flood flows had already begun to recede and eggs were collected within the first week of sampling (Jackson et al., in press).

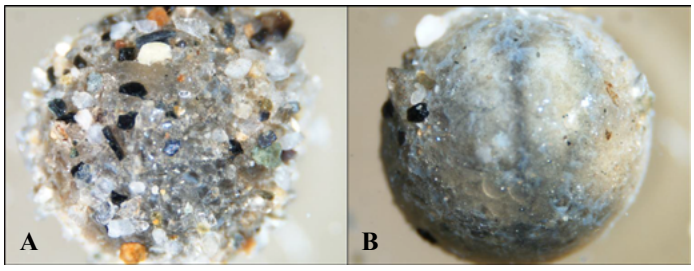


**Figure 1 A viable White Sturgeon egg, collected in the San Joaquin River on March 22, 2012, is shown covered in sand particles (panel A). After careful cleaning under a dissection scope, the neural tube of the embryo is evident (panel B). Photo courtesy of University of California, Davis. Taken with an Olympus dissecting microscope and a Nikon DS-U1 digital camera.**

In contrast, egg collections during 2012 only occurred in close proximity to short-duration increases in streamflow (Jackson et al., in press). Increases in streamflow during the 2013 through 2015 spawning seasons were of lower magnitude than those observed during 2012 (Figure 2).

**Larval** — Total fishing effort across all sampling locations amounted to 156.4 hours in 2013 and 822.8 hours in 2015. No larval sturgeon have been detected in the San Joaquin River since the initiation of this study.

## Conclusion

We have learned in the last five years that not only do White Sturgeon spawn in the San Joaquin River during flood conditions (2011), but also during dry water years (2012). Further, we have captured at least one gravid female in the study area as part of a telemetry study during the years spawning was not detected (2013 – 2015; Faukner and Jackson 2014; Jackson and Faukner 2014; Heironimus et al. 2015). While we do not expect that our spawning surveys are rigorous enough to detect all spawning occurring in the study area, we suspect that environmental conditions, especially temperature, often result in aborted spawning. In fact, we detected evidence of atresia, the degeneration of ovarian follicles, during 2015 telemetry sampling. Efforts to detect White Sturgeon reproduction are planned to continue in order to further identify suitable spawning and rearing habitat within the San Joaquin River, and inform water management and restoration decisions into the future. Understanding how changes in streamflow influence spawning and recruitment will remain an active area of research.

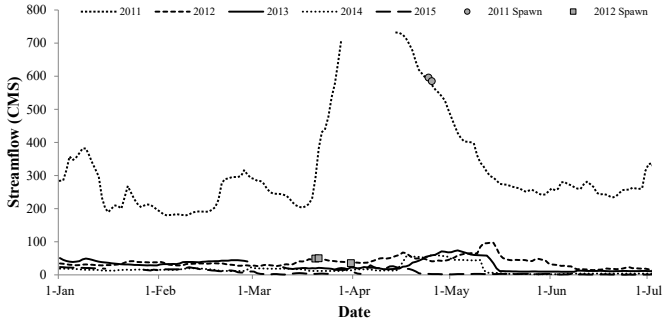


**Figure 2 Comparison of mean daily streamflow on the San Joaquin River during Jan 1st to July 2nd, 2011 – 2015. Circle and square points represent the estimated dates of spawning in 2011 and 2012, respectively, back-calculated from the stage of development of collected eggs. Streamflow data were obtained from the gaging station near Maze Road Bridge (California Data Exchange Center, MRB).**

## Acknowledgements

This project was funded by the Anadromous Fish Restoration Program under the authority of the Central Valley Project Improvement Act (Public Law 102-575). This project would not have been a success without the dedication and determination of the many State and federal staff that assisted with field sampling. The findings and conclusions in this article are those of the authors and do not necessarily represent the views of the U.S. Fish and Wildlife Service.

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## 2014 Smelt Larva Survey

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The California Department of Fish and Wildlife (CDFW) completed the 2014 field season of the Smelt Larva Survey (SLS) in late March. Initiated in 2009, the SLS monitors and reports the distribution and relative abundance of larval Longfin Smelt (*Spirinchus thaleichthys*) in near real-time. This allows resource managers to assess the risk of entrainment for Longfin Smelt at export facilities, while also collecting data on other larval species in the upper San Francisco Estuary.

From January 6 until March 21, 2014, CDFW conducted six bi-weekly surveys. Each survey consisted of 44 stations, including nine stations that were added in the Napa River from Vallejo to the city of Napa (Figure 1). At each of the 44 stations, a single 10-minute stepped oblique tow with a rigid-framed plankton style net was taken along with environmental data (Adib-Samii 2012). The Napa River stations were added as part of a litigation agreement with the State Water Contractors, the Department of Water Resources, and CDFW to increase the understanding of Longfin Smelt's use of the Napa River for spawning.

Near-real time catch data for all species was reported on the SLS project webpage (below) as catch per unit effort (CPUE) and displayed graphically as a bubble plot and listed as a table. Effort was defined as the volume of water sampled during a tow and standardized to 1,000 cubic meters for this survey. To calculate the station's CPUE for a species, divide the number of fish caught (F) by the volume of water sampled by the net (see equation below). Volume was calculated by multiplying the distance traveled in meters (D; measured using counts from a General Oceanics flowmeter), a conversion factor (K; meters/count), and the mouth area of the SLS net ($A = 0.37m^2$).

$$CPUE = \left(\frac{F}{A * K * D}\right) 1000m^3$$

A total of 229,697 fish representing 21 taxa (Table 1; all stations) were collected. Pacific Herring (*Clupea pallasi*) was the most abundant species captured, making up 77% of the total catch. The majority of the remaining catch was comprised of Yellowfin Goby (*Acanthogobius flavimanus*), Prickly Sculpin (*Cottus asper*), and Longfin Smelt, with all other species caught making up less than 1% of the total catch.

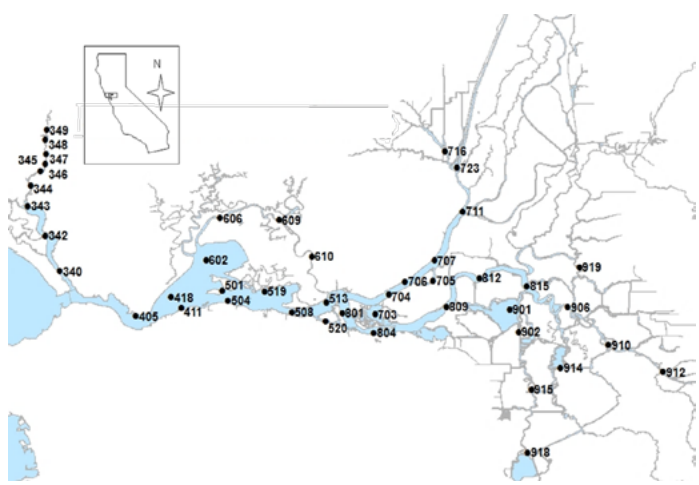


**Figure 1 Station locations sampled by the Department of Fish and Wildlife's Smelt Larva Survey.**

Longfin Smelt showed broad distributions throughout each survey, and were collected in 62.1 percent (n = 164) of the samples (Figure 2). The highest densities of Longfin Smelt generally occurred around the Sacramento-San Joaquin rivers confluence (Confluence), but were present throughout the estuary. Longfin Smelt mean length increased with each consecutive survey, showing growth over time. Mean length by region was consistent until late February, when the oldest (i.e., largest) larvae were found in the Napa River and the South and Central Delta (Figure 3). This was a change from previous years, when it is typical for older larvae to be transported downstream (Adib-Samii 2012). This is likely a function of low river flows in 2014, resulting from low amounts of precipitation and minimal upstream reservoir releases.

The SLS is a resource management tool used by the Smelt Working Group (SWG) to determine the risk of entrainment for Longfin Smelt as outlined in the State Water Project's California Endangered Species Act Incidental Take Permit No. 2081-2009-001-03 (SWP-ITP), and is also described by Adib-Samii (2012). In 2014, none of the triggers that warrant Old and Middle rivers flow-changing advice were met, although exports were limited throughout the season based on other water standards, thus no water management actions in the Southern Delta were taken based on SLS survey results. Despite this, the SWP-ITP indicates that advice is warranted for Barker Slough operations between January 15 and March 31 in dry or critically-dry water-years if Longfin Smelt larvae are detected in Cache Slough (station 716). In January, 2014, those conditions were met, and the SWG recommended Barker Slough limit exports to 50 cubic feet per second (cfs). This advice was lifted at the end of the concern period on March 31 (SWG, 2014).

Newly-hatched (prolarvae) Delta Smelt were caught in Smelt Larva Survey 5 (March 3 – 5), which indicates that was the start of the spawning season. Prolarvae were mostly distributed in the North Delta (n = 7, 5- to 6-mm total length [TL]), but were also present at the Confluence (n = 1, 5-mm TL) and in the Napa River, where slightly older postlarvae were also captured (n = 2, 7-mm TL). In survey 6 (March 17 – 21), Delta Smelt of the same size range as survey 5 were present at the Confluence, the lower Sacramento River, the lower San Joaquin River, and the North Delta (Figure 4). Smelt Larva Survey 6 ran concurrently with another CDFW larval monitoring survey, the 20-mm Survey, which also captured newly-hatched and postlarval Delta Smelt from March 17 to March 21, 2014.

**Table 1 Total species catch for the 2014 Department of Fish and Wildlife's Smelt Larva Survey.**

| *Common Name* | *n* | *% of Catch* |
|---|---|---|
| Pacific Herring | 177,434 | 77.25% |
| Yellowfin Goby | 29,457 | 12.82% |
| Prickly Sculpin | 16,105 | 7.01% |
| Longfin Smelt | 5,631 | 2.45% |
| Arrow Goby | 522 | 0.23% |
| Jacksmelt | 172 | 0.07% |
| Northern Anchovy | 160 | 0.07% |
| Pacific Staghorn Sculpin | 123 | 0.05% |
| Longjaw Mudsucker | 27 | 0.01% |
| Delta Smelt | 24 | 0.01% |
| Bigscale Logperch | 13 | <0.01% |
| Three Spine Stickleback | 13 | <0.01% |
| White Croaker | 4 | <0.01% |
| Cyprinids | 3 | <0.01% |
| Chinook Salmon | 2 | <0.01% |
| Striped Bass | 2 | <0.01% |
| Centrarchids | 1 | <0.01% |
| Cheekspot Goby | 1 | <0.01% |
| Shokihaze Goby | 1 | <0.01% |
| Tridentiger spp. | 1 | <0.01% |
| White Catfish | 1 | <0.01% |

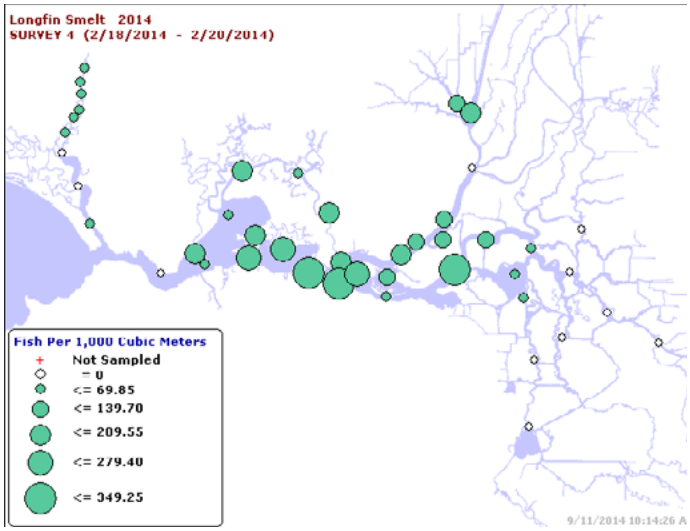


**Figure 2 Geographical distribution and catch per unit effort of Longfin Smelt during survey 4 of the 2014 Department of Fish and Wildlife's Smelt Larva Survey. See "Notes" for URL.**

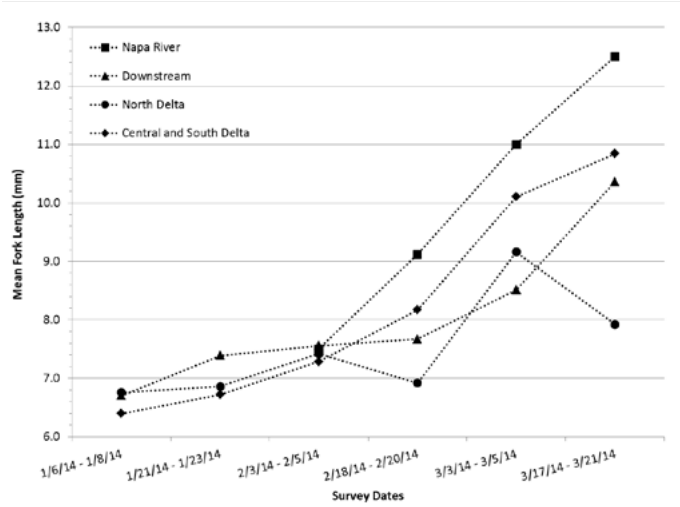


**Figure 3 Mean fork lengths of Longfin Smelt collected in the 2014 Department of Fish and Wildlife's Smelt Larva Survey. Fork lengths are grouped by survey number for 4 distinct geographic regions. "Napa River" refers to all stations at or north of Mare Island on the Napa River. "Downstream" refers to fish collected west of Sherman Island on the Sacramento River and west of Jersey Point on the San Joaquin River. "Central and South Delta" refers to stations within the Central and South Delta. "North" Delta refers to stations upstream of Sherman Island on the Sacramento River.**

Pacific Herring were caught in record abundances and wide-ranging distributions in 2014. Young-of-the-year Pacific Herring are normally captured in SLS throughout the estuary, but typically not upstream of the Confluence and only rarely reach the lower portions of the San Joaquin and Sacramento rivers. However, in February of 2014, Pacific Herring were present as far upstream as Cache Slough to the north and as far south as Old River at Victoria Island (Figure 5). This was likely due to the on-going drought conditions that resulted in low freshwater outflow and salt-water intrusion into the Delta. The location of the 2 parts per thousand salinity contour (isohaline), one meter off the bottom of the estuary, as measured in kilometers upstream from the Golden Gate Bridge (X2), measured over 81 km for 75% of the SLS season (http://cdec.water.ca.gov). The largest season total catch of Pacific Herring (n = 96,656) occurred in 2014 (the Napa River stations omitted), and the highest single station catch of Pacific Herring (n = 37,897) for the entire history of SLS also occurred in February in Carquinez Strait near the Benicia army docks. In 2014, 10,613 Pacific Herring were caught in the Sacramento River (at or above Sherman Island). This was two orders

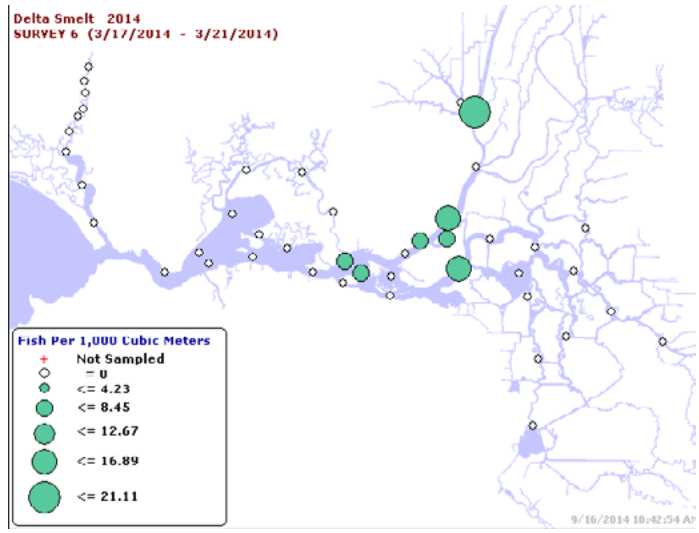


**Figure 4 Geographical distribution and catch per unit effort of Delta Smelt during survey 6 of the 2014 Department of Fish and Wildlife's Smelt Larva Survey. See "Notes" for URL.**

of magnitude greater than previous abundances in that region, the next highest occurred in 2012 (n = 216; Figure 6).

The 2015 SLS is scheduled to begin in early January and conclude in March or April. Existing SLS data are available through our FTP site (ftp://ftp.dfg.ca.gov/Delta%20Smelt/), and fish distribution maps (bubble plots) are available on our project webpage (http://www.dfg.ca.gov/delta/projects.asp?ProjectID=SLS).

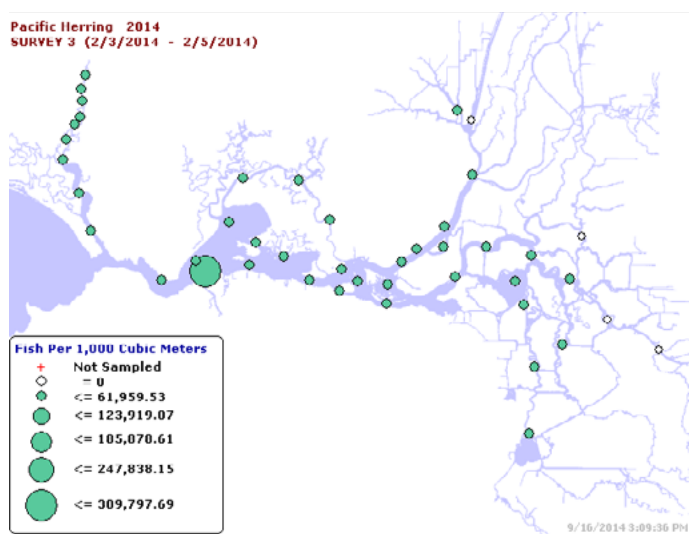


**Figure 5 Geographical distribution and catch per unit effort of Pacific Herring during survey 3 of the 2014 Department of Fish and Wildlife's Smelt Larva Survey. See "Notes" for URL.**

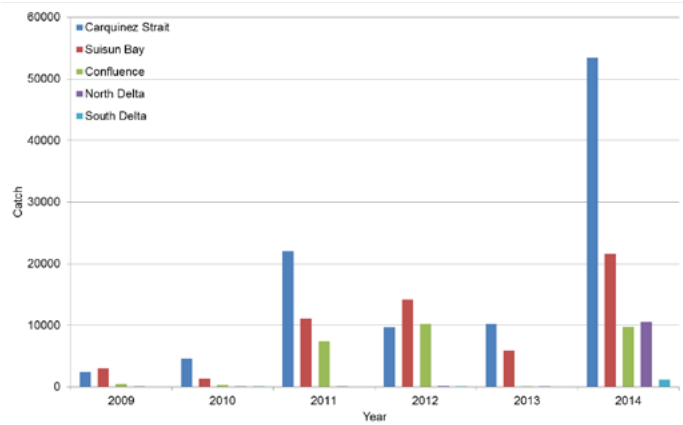


**Figure 6 Pacific Herring catch for the California Department of Fish and Wildlife's Smelt Larva Survey by region for all years during the period of record (2009-2014), excluding Napa River catches, as it was sampled only in 2014.**

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## 2014 Spring Kodiak Trawl Survey


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The 2014 Spring Kodiak Trawl Survey (SKT), conducted by the California Department of Fish and Wildlife (CDFW), ran from January 13 to May 8, 2014, and successfully completed five monthly surveys. The objectives of SKT are to determine the distribution and relative abundance of adult Delta Smelt (*Hypomesus transpacificus*) in the upper San Francisco Estuary and to monitor their gonadal maturation on a monthly basis for use by resource managers as an indicator for when and where spawning is likely to occur or is occurring. The SKT is a 10-minute surface trawl towed between two boats. Each survey runs for 4 days and samples 40 stations, including the lower Napa River through Suisun Bay, the confluence region, and into the North, South, and Central Deltas (Figure 1). All Delta Smelt collected are measured (millimeter [mm] fork-length), sexed, and gonadal-staged in real-time while in the field. For more information on gear descriptions, objectives, methods, and gonadal-stage classifications, see the previous IEP Newsletter articles by Souza (2002) and Adib-Samii (2010).

The 2014 Delta Smelt catch (n = 355) was slightly higher than 2013 (n = 341), but the 5th lowest catch for the history of this survey (2002 – 2014). In January and February (surveys 1 and 2), Delta Smelt were primarily caught at or downstream of the confluence, with large catches in Montezuma Slough, making up over 70% of the total catch (Figure 2). In March (survey 3), distribution began shifting upstream, with 25% of the catch from below the confluence, 15% of catch from the lower Sacramento River or Cache Slough, and over 50% of the catch from the Sacramento Deep Water Ship Channel (SDWC). In April and May (surveys 4 and 5), over 75% and 85% of the Delta Smelt caught were in the SDWC, respectively.

Females made up about 66% of the total catch, but sex ratio fluctuated throughout the spawning season following a typical pattern (Figure 3). Generally in SKT, catches are about 1:1 female/male in January and February, then this ratio increases monthly until females outnumber males about 4:1. This pattern can possibly be attributed to male die-off as spawning takes place through the spawning season, or to males moving from pelagic habitats for feeding to benthic or littoral habitats for spawning.

Mature females (based on gonadal-stage) were present beginning in March (survey 3), with 46% of the females caught already having spawned (i.e., stage 6, as shown in

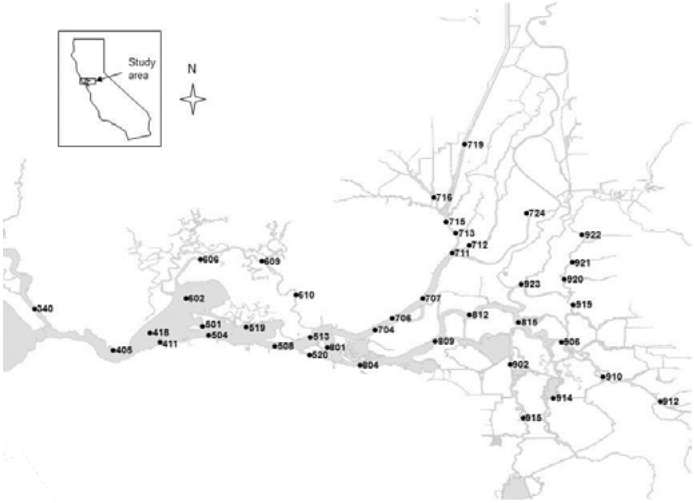
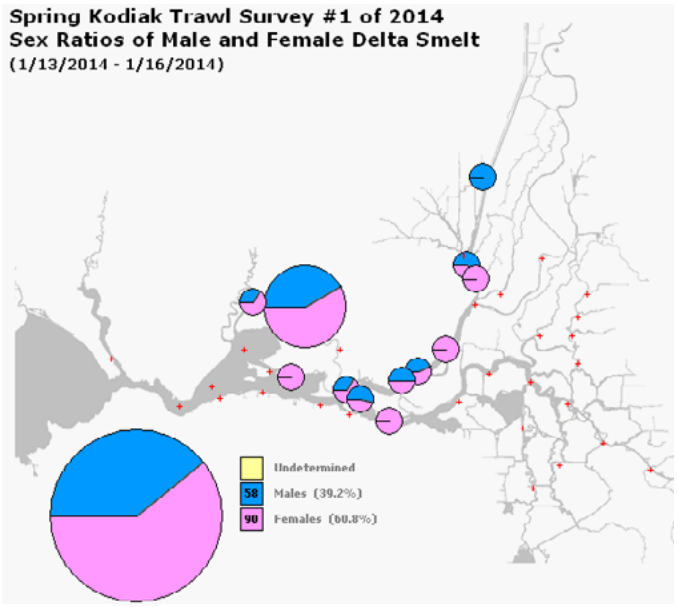
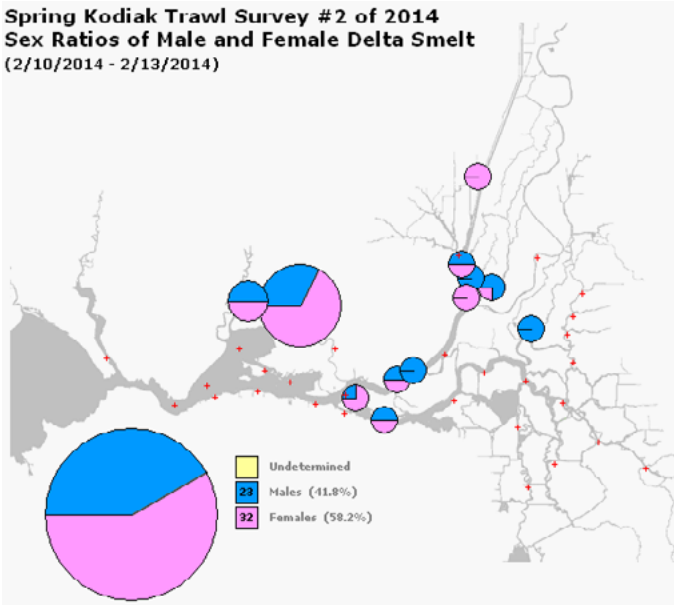


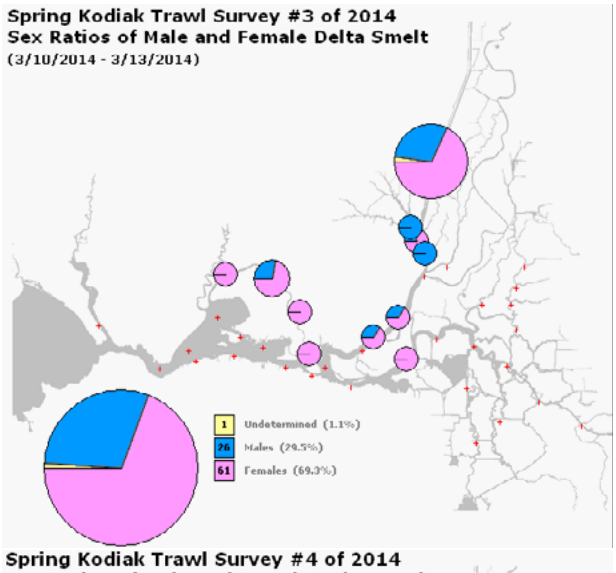

**Figure 1 Current station locations sampled during the CDFW Spring Kodiak Trawl Survey in the upper San Francisco Estuary.**

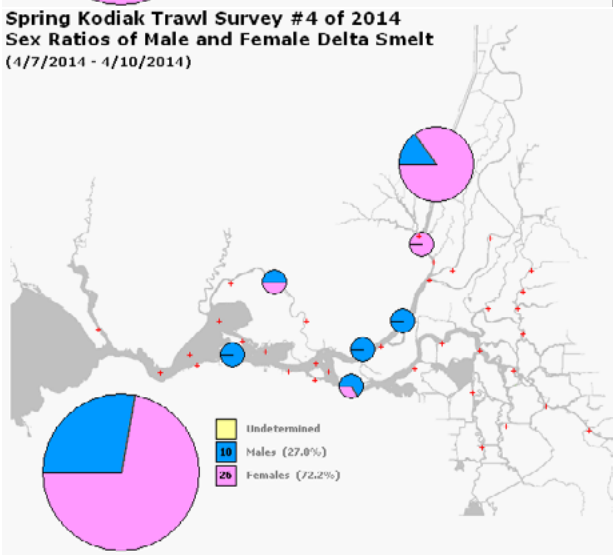
Figure 4). The proportion of post-spawn females increased in April (survey 4), and by May all of the females caught had already spawned (Figure 4). Mature females were present in water temperatures with a mean of 16.3 °C and a range of 13.8 °C to 19.2 °C. Mature males were present earlier in the season (February) than females, and thus occupied a broader temperature range of 11.8 °C to 19.2 °C, with a mean of 15.0 °C. Most of the mature fish, both males and females, were present at conductivities averaging about 800 microSiemens per centimeter (µS/cm), although the range of conductivity was broad (211 µS/cm to 10,730 µS/cm).

In 2012, the SKT staff developed an annual index of



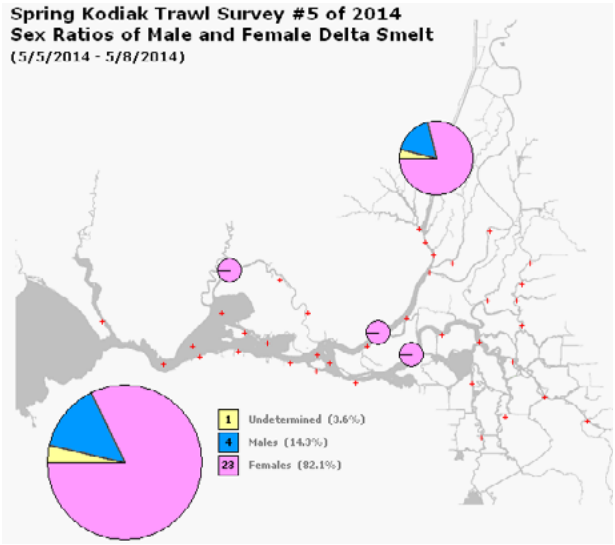




**Figure 2 Geographical distribution of Delta Smelt by catch and by sex ratio for each 2014 SKT survey, from the CDFW Spring Kodiak Trawl Survey webpage.**

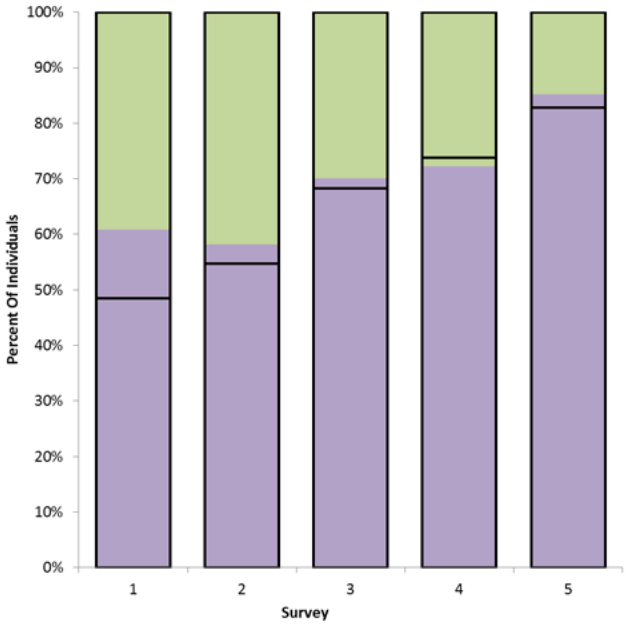



**Figure 3 Overall Delta Smelt sex ratio by survey for all catches combined during CDFW 2014 Spring Kodiak Trawl Survey. Females are purple, males are green, and all other fish of undetermined sex are omitted. Dark lines represent the mean sex ratio for all years combined for the entire period of record (2002-2014).**

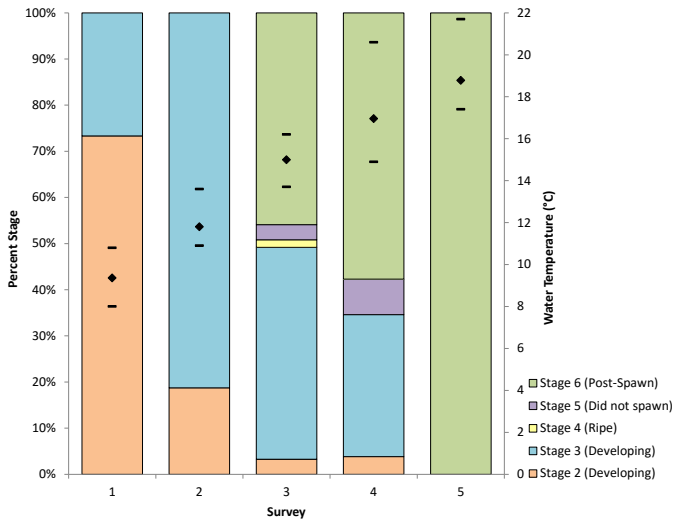



**Figure 4 Gonadal-stage of female Delta Smelt (percent distribution) during each 2014 survey of CDFW Spring Kodiak Trawl Survey. Gonadal-stage classifications are from Adib-Samii (2010). Mean (solid diamond) and range (upper and lower lines) of water temperature by survey for 2014.**

Delta Smelt relative abundance. This index is reported annually via interdepartmental memorandum on the FTP website. A summary memo of the index methods and calculation is also available on the FTP site (Adib-Samii, 2013). The 2014 SKT Delta Smelt Annual Index of Abundance was 30.1 (Figure 5), which was higher than the 2013 index (21.0), but substantially lower than the record high index in 2012 (147.3). Delta Smelt overall catch in 2014 (n = 355) was only slightly higher than in 2013 (n = 341), but the downstream distribution of Delta Smelt in early 2014 drove the index slightly higher. The total catch to index ratio is strongly influenced by catch at station 719, a non-index station that recently has produced large proportions of the total catch. In 2013, nearly 50% of Delta Smelt catch was at station 719, a non-index station, compared with only 30% in 2014.

The 2015 Spring Kodiak Trawl is scheduled to begin in January and run through May. Data, metadata, and protocols are available on the FTP site: ftp://ftp.dfg.ca.gov/Delta%20Smelt/. Geographic distribution maps of Delta Smelt are available for viewing on our web page at https://www.wildlife.ca.gov/Conservation/Delta/Spring-Kodiak-Trawl.

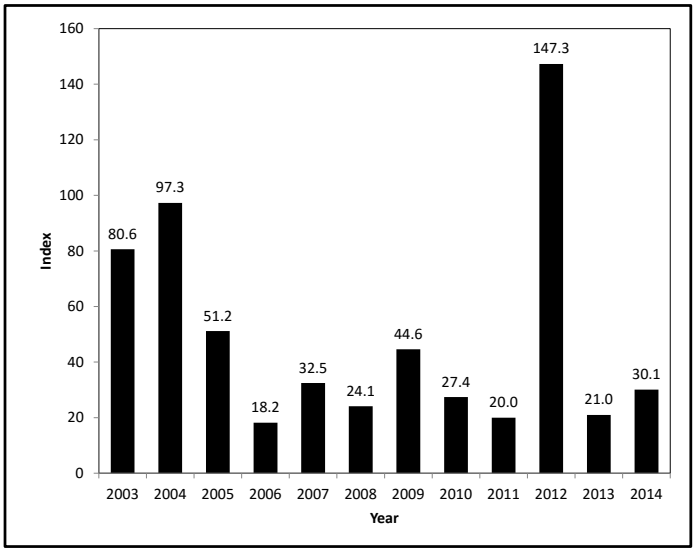



**Figure 5 CDFW Spring Kodiak Trawl Survey adult Delta Smelt annual abundance index (2003-2014).**

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## 2014 20-mm Survey Fish Catch Summary

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California Department of Fish and Wildlife (CDFW) conducts the 20-mm Survey annually to monitor the distribution and relative abundance of larval and juvenile Delta Smelt (*Hypomesus transpacificus*) in the upper San Francisco Bay Estuary. The survey began in 1995 and supplies near real-time catch data to water and fisheries managers as part of an adaptive management strategy to limit the risk of Delta Smelt entrainment during water exports.

From March 17 to July 10, 2014, nine bi-weekly surveys were completed. The 20-mm Survey conducts multiple tows at 47 stations (Figure 1) to measure larval fish and zooplankton densities. Six stations in the Napa River and one station in San Pablo Bay were omitted from survey 1 due to logistical issues, but the Napa River was sampled in the same week by the CDFW Smelt Larva Survey (for more information, see the Smelt Larva Survey article in this issue). The 20-mm survey used a conical net with 1600-micron mesh for collecting young of the year (YOY) fish. The net was 5.1 meters long with a mouth area of 1.51 square meters, and was attached to a rigid steel D-ring frame mounted on skis. At each station, the entire water column was sampled using three stepped-oblique tows and a single zooplankton tow. All samples were preserved in 10% buffered formalin dyed with Rose Bengal for later identification and enumeration in the laboratory. Fish were measured to the nearest millimeter fork length, if the tail was forked, or nearest total length if the tail was not forked. Zooplankton data is available on our webpage (see link below), but is not reported on in this article.

The 20-mm Survey in 2014 caught a total of 47,270 fish representing 45 taxonomic groups (Table 1). Tridentiger spp. (gobies) was by far the most abundant group, making up about 57% of the total catch. Pacific Herring (*Clupea pallasii*), Threadfin Shad (*Dorosoma petenense*), and Northern Anchovy (*Engraulis mordax*) were the next three most-abundant species, making up about 25% of the total catch. Delta Smelt was the 10th-most abundant species, making up less than 0.01% of the total catch. The 257 Delta Smelt caught represent the second-lowest total catch in the history of this survey (1995 – 2014). Larval and juvenile Delta Smelt catches were extremely low in March and early April (survey 1 and 2; n = 3 and n = 1, respectively). Catch increased through April and peaked in mid-May (survey 5) with 112 Delta Smelt caught (20.9-mm mean length). Delta Smelt catch decreased through June, and only three fish were caught in the final survey in July (survey 9). Overall, this is a normal seasonal catch pattern because the 20-mm net's limited efficiency at retaining small larvae and large juveniles (Figure 2).

The first Delta Smelt larvae were caught in the first survey (3/17 – 3/21) and ranged in size from 6 – 12 mm, the larger sizes indicating that spawning began in February when water temperatures reached 12 °C. The last newly-hatched larvae (ca. 6 mm) were caught in late April, indicating the final hatch of the spawning season occurred earlier that month. Delta Smelt grew an average of 4.4 mm between each survey, and reached a mean length of 48 mm by the last survey in July (survey 9). This was the largest mean length reached by Delta Smelt at the end of season for the history of this survey (Figure 3).

Young of the year Delta Smelt were concentrated in the Sacramento Deep Water Ship Channel (SDWC) and

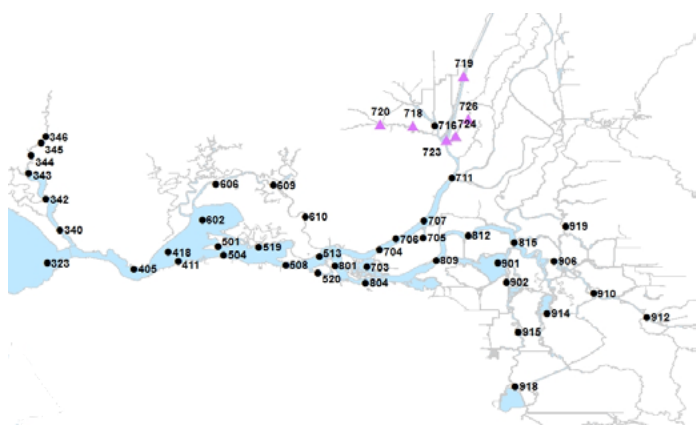


**Figure 1 The CDFW 20-mm Survey stations, showing current sampling locations in the upper Sacramento-San Joaquin Estuary. Stations marked with a black dot are core stations used in index calculations. Stations marked with a purple triangle are non-core stations used for distribution information, but not index calculation.**

North Sacramento-San Joaquin River Delta (Delta) for most of the season, with some catches near the confluence of the Sacramento and San Joaquin rivers (Confluence) and in the lower Sacramento and San Joaquin rivers (Figure 4). Catch during the 20-mm Survey season was sporadic and patchy. Delta Smelt larvae were only present in the South and Central Delta in March and April, when they were caught in Little Potato Slough near Terminous (station 919). They were also caught in Montezuma Slough in three non-consecutive surveys. Only one fish was detected in Honker Bay in late June, indicating a minimal larval presence downstream of the Confluence. This is likely a function of low Delta outflow resulting from minimal precipitation and reservoir releases causing high salinities throughout Suisun Bay and reaching into the Delta. The X2 was located upstream of the Confluence in every survey during the 20-mm season (United States Fish and Wildlife Service Smelt Working Group 2014). Delta Smelt were caught in conductivities ranging from 224 µS/cm to 14,240 µS/cm. The upper end of this conductivity range was relatively high compared to the mean conductivity (about 1,600 µS/cm) of stations where Delta Smelt were caught for all years (1995-2014).

The low abundance and limited distribution of YOY Delta Smelt in 2014 was likely attributable to the drought conditions experienced that year. The Water Year Type for 2014 was critically dry for both the Sacramento and San

**Table 1 Species composition from the 2014 CDFW 20-mm Survey.**

| *Common name* | *n* | *% Catch* |
|---|---|---|
| Tridentiger spp. | 27,119 | 57.37% |
| Pacific Herring | 4,287 | 9.07% |
| Threadfin Shad | 4,223 | 8.93% |
| Northern Anchovy | 3,236 | 6.85% |
| Striped Bass | 2,665 | 5.64% |
| Longfin Smelt | 1,938 | 4.10% |
| Yellowfin Goby | 1,716 | 3.63% |
| Prickly Sculpin | 395 | <0.01% |
| Jacksmelt | 326 | <0.01% |
| Delta Smelt | 257 | <0.01% |
| Three Spine Stickleback | 212 | <0.01% |
| Arrow Goby | 206 | <0.01% |
| American Shad | 169 | <0.01% |
| Bay Goby | 116 | <0.01% |
| Centrarchids | 91 | <0.01% |
| Bay Pipefish | 78 | <0.01% |
| Bigscale Logperch | 35 | <0.01% |
| Inland Silverside | 29 | <0.01% |
| Chinook Salmon | 25 | <0.01% |
| Topsmelt | 25 | <0.01% |
| Cheekspot Goby | 22 | <0.01% |
| Cyprinidae | 13 | <0.01% |
| Rainwater Killifish | 12 | <0.01% |
| Shimofuri Goby | 11 | <0.01% |
| White Catfish | 10 | <0.01% |
| Longjaw Mudsucker | 9 | <0.01% |
| Pacific Staghorn Sculpin | 7 | <0.01% |
| Splittail | 6 | <0.01% |
| Sacramento Sucker | 5 | <0.01% |
| Carp | 5 | <0.01% |
| Mosquitofish | 3 | <0.01% |
| Atherinopsidae | 3 | <0.01% |
| Shokihaze Goby | 2 | <0.01% |
| Channel Catfish | 2 | <0.01% |
| Starry Flounder | 2 | <0.01% |
| Speckled Sanddab | 1 | <0.01% |
| White Sturgeon | 1 | <0.01% |
| Plainfin Midshipman | 1 | <0.01% |
| California Tonguefish | 1 | <0.01% |
| Bluegill Sunfish | 1 | <0.01% |
| Black Crappie | 1 | <0.01% |
| Largemouth Bass | 1 | <0.01% |
| Tule Perch | 1 | <0.01% |
| Wakasagi | 1 | <0.01% |
| English Sole | 1 | <0.01% |

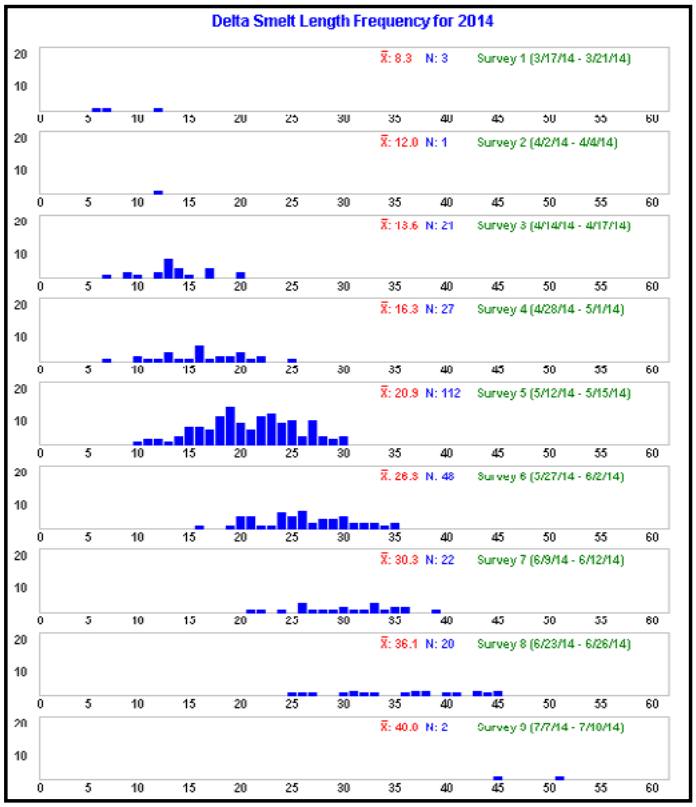


**Figure 2 Delta Smelt length frequency distributions by survey from CDFW 2014 20-mm Survey (http://dfg.ca.gov/delta/data/20mm/Length_frequency.asp). Length in millimeters is on the X-axis and number of individuals is on the Y-axis.**

Joaquin valleys (California Data Exchange Center 2016). As noted above, conductivity in parts of Delta Smelt rearing habitat were high, as were water temperatures in other locations. Delta Smelt tend to spawn and rear upstream in drier water years (Wang 2007), but water temperatures upstream surpassed 23 °C in early June and exceeded 24 °C by July, making those habitats unsuitable for Delta Smelt (Gleason et al. 2007; Nobriga et al. 2008; Sommer and Mejia 2013).

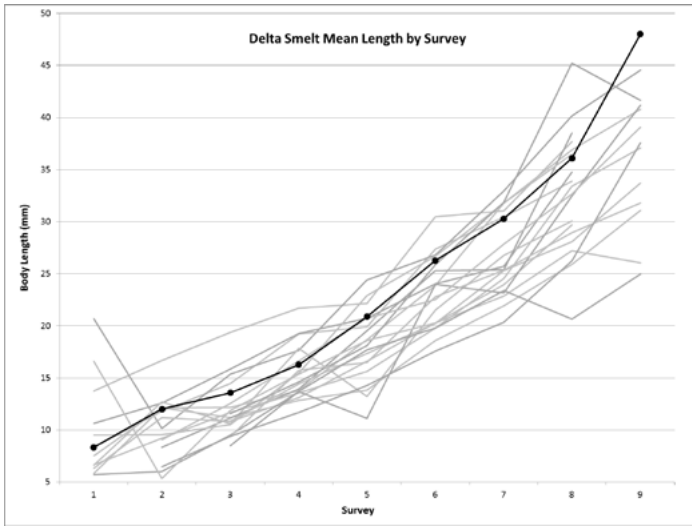


**Figure 3 Mean lengths by survey and year of Delta Smelt caught by CDFW 20-mm Survey (1995–2014). 2014 is the black line with black-filled circles, all other years are grey.**

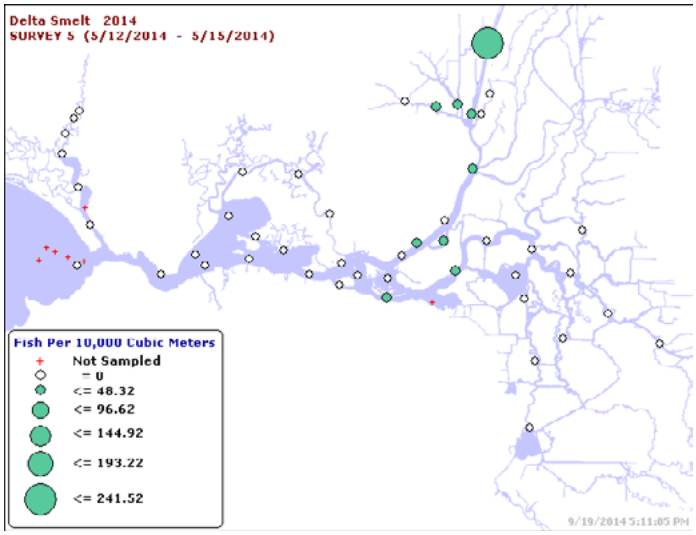


**Figure 4 Delta Smelt distribution from CDFW 20-mm Survey 5 (taken from http://dfg.ca.gov/delta/projects.asp?ProjectID=20mm). Green bubbles represent the relative abundance of YOY Delta Smelt at each site. White bubbles are sampled stations with no YOY Delta Smelt caught. Red crosses indicate the station was not sampled.**

An index of Delta Smelt abundance for the 20-mm Survey was calculated by CDFW using data from the four surveys around which the mean length of the YOY Delta Smelt was 20 mm. The index was calculated using only the 41 stations ("core" stations, Figure 1) which have been sampled consistently since the survey's inception in 1995. The 2014 index was 1.1 (Figure 5) and was calculated using Surveys 3 (April) through 6 (May). The 2014 index represented a large decrease from 2013, and the second lowest index on record after the 2007 index of one.).

Current and past data graphically depicted are available on the 20-mm Survey webpage http://dfg.ca.gov/delta/projects.asp?ProjectID=20mm. Data, metadata, and protocols are available through our FTP site ftp://ftp.dfg.ca.gov/Delta%20Smelt/.

| Year | Index |
|---|---|
| 1995 | 4.4 |
| 1996 | 33.9 |
| 1997 | 19.2 |
| 1998 | 7.7 |
| 1999 | 39.4 |
| 2000 | 23.7 |
| 2001 | 10.9 |
| 2002 | 7.7 |
| 2003 | 13.0 |
| 2004 | 8.2 |
| 2005 | 15.4 |
| 2006 | 9.8 |
| 2007 | 1.0 |
| 2008 | 2.9 |
| 2009 | 2.3 |
| 2010 | 3.8 |
| 2011 | 8.0 |
| 2012 | 11.1 |
| 2013 | 7.8 |
| 2014 | 1.1 |

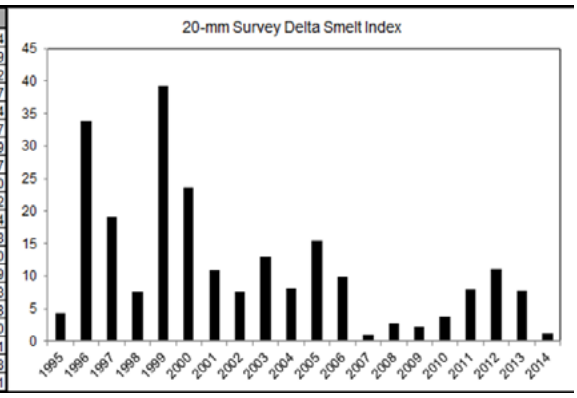


**Figure 5 CDFW 20-mm Delta Smelt Index of Relative Abundance (1995-2014) by year.**

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# Zooplankton biomass and chlorophyll-*a* trends in the North Delta Arc: two consecutive drought years

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## Introduction

Lower trophic level ecosystem dynamics are poorly understood in the upper San Francisco Estuary (SFE) (Durand 2015; Kratina & Winder 2015). Monitoring programs targeting pelagic habitats along the main channels of the San Francisco Bay and Sacramento-San Joaquin River Delta (Delta) have consistently found low abundance of phytoplankton and zooplankton (California Department of Fish and Wildlife 2015, California Department of Water Resources 2015). After 1987 and again after 2000, planktonic organisms displayed steep declines in abundance (Bennett 2006; Sommer et al. 2007; Mac Nally et al. 2009), probably due to the colonization of alien species (such as the grazing clam *Potamocorbula amurensis*) (Carlton et al. 1990; Kimmerer et al. 1994) and changes in water outflow and quality (Glibert et al. 2011; Dugdale et al. 2012). Pelagic plankton-feeding fishes, such as Delta Smelt (*Hypomesus transpacificus*), Longfin Smelt (*Spirinchus thaleichthys*), and Northern Anchovy (*Engraulis mordax*) were affected by low food availability, resulting in near extinction for the Delta Smelt (Matern et al. 2002; Sommer et al. 2007; Moyle et al. 2016). Other species have declined in the upper SFE as well, in part because of low food availability for juvenile fish recruits (Bennett & Hinton 1995; Feyrer et al. 2003; Hammock et al. 2015; Merz et al. 2016), habitat alterations (Nichols et al. 1986; Grimaldo, Stewart, et al. 2009; Whipple et al. 2012), and disruption of Delta hydrodynamics (Jassby & Powell 1994; Feyrer & Healey 2003; Grimaldo, Sommer, et al. 2009).

The North Delta Arc is a series of longitudinally connected habitats that may provide the best remaining opportunities for restoration in the Delta region (Moyle et al. 2012; Hanak et al. 2013), partly because of the greater number and proportion of native fishes observed in the region (Williamson et al. and Young et al., this issue). The North Delta Arc ranges from Suisun Marsh upstream along the Sacramento River to the Yolo Bypass, including the confluence of the Sacramento and San Joaquin rivers, the Cache Slough Complex, Liberty Island, Little Holland Tract, the Toe Drain, and the Deepwater Shipping Channel (DSC).

The UC Davis North Delta Arc Project (Arc) monitors major and minor sloughs and shallow peripheral aquatic habitats in eastern Suisun Marsh (Nurse-Denverton Slough Complex) and the Cache Slough Complex. The goal of the Arc Project is to document the fish assemblages and habitat quality in these areas as a conservation tool, including assessing baseline conditions, occurrences of listed and uncommon native fishes, and post-restoration project succession. Both theory (Kneib 1997; Lucas et al. 1999; Lopez et al. 2006) and empirical evidence (Jassby & Cloern 2000; Durand 2010) suggest that plankton abundance, under some conditions, can be higher in shallow water embayments or terminal sloughs,

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with sufficiently high residence time. Although monitoring indices generally show declines in zooplankton abundance throughout the San Francisco Estuary (Winder & Jassby 2010), we hypothesized that certain locations in the SFE still periodically support high densities of zooplankton, some of which may be available to the broader regional food web. Here we present an analysis of zooplankton and chlorophyll-*a* (chl-*a*) data from select sites from 2013-2014 monthly monitoring cruises.

At the start of 2013, most of California was experiencing "abnormally dry" conditions (United States Drought Monitor [USDM]). By the end of 2013, this had progressed to "severe drought" conditions. By the end of 2014, nearly 95% of California had developed "severe drought" conditions, with up to 58% having experienced "exceptional drought," the most severe category of the USDM scale. Our project was not intentionally designed as a drought-focused study, but results must be interpreted in the context of this drought.

## Methods

Samples were collected and analyzed from two transects in the upper San Francisco Estuary (Figure 1). The eastern Suisun Marsh transect extended from the Salinity Control Gates in Montezuma Slough to the confluence with Nurse Slough, and continued upstream to the terminus of Denverton Slough. The Cache Slough Complex transect extended from the confluence of Cache Slough and the DSC to the terminus of Cache Slough. Transects were run monthly from November 2012 – February 2015 by driving a boat against the tidal flow at a relative velocity of 5 mph. Each transect took about four hours to complete. The Suisun Marsh and Cache Slough transects were collected on two separate days no more than four days apart to minimize differences resulting from changes in tidal cycle and ambient environmental conditions.

Continuous chl-*a* fluorescence measurements were taken along the transects using a HACH Hydrolab Datasonde5 flow-through system in conjunction with TerraSync geographic position software. Other water quality data were collected as well, including temperature, turbidity, specific conductivity, and dissolved oxygen (DO). Continuous chl-*a* fluorescence data were validated and corrected by collecting 5 – 13 in situ 300 mL subsamples which were analyzed using standard laboratory chl-*a* extraction and fluorometry techniques (Clesceri et al. 1989). Chl-*a* extraction values were then regressed against fluorescence values from the Datasonde5 transect cruises from the same place, day, and time to calibrate and correct the range of values recorded by the Datasonde5 chl-*a* fluorescence probe. All chl-*a* values reported in this paper and in analyses were corrected. GPS and corrected chl-*a* data were later linked and displayed on background maps using Esri ArcMap software.

Discrete zooplankton samples were collected using a SEA-GEAR conical 50 cm x 200 cm plankton net with 50 µm mesh and a General Oceanics flowmeter suspended in the center of the opening. The net was suspended 1 meter below the surface of the water between a buoy and a 2 oz spherical lead weight and hand towed 20 meters against the direction of tidal flow. One zooplankton tow was collected at each site every month. Samples were stored in 500 ml wide-mouth mason jars, stained with 1% Rose Bengal, and preserved in 5% formaldehyde.

Zooplankton analysis focused on four sites representing the range of habitats monitored by the Arc Project transects: CA1 (fresh, shallow, upper slough), CA3 (fresh, deep, lower slough), DV1 (brackish, shallow, upper slough), MZ1 (brackish, deep, lower slough). For more information, see Table 1. CA1 and DV1 samples were analyzed for the months Jan – Oct 2013 and Feb – Jul 2014. CA3 and MZ1 samples were analyzed for the months Mar – Oct 2013 and Feb – Jul 2014. The CA3 Aug 2013 sample is missing due to irreparable damage to the zooplankton net during the sampling cruise that month. Spring and summer zooplankton samples were prioritized for analysis to

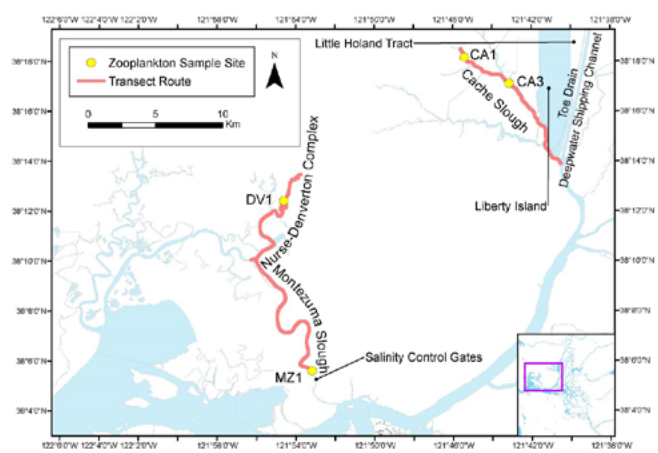


**Figure 1 Arc study area map. Red lines represent transect routes in Suisun Marsh and Cache Slough. Yellow dots represent zooplankton sample locations. Landscape features relevant to the North Delta Arc are labeled as such.**

match the period of recruitment for native and introduced fishes (Meng & Matern 2001; Matern et al. 2002), when zooplankton abundance is a major factor of quality fish habitat. Zooplankton were identified to the lowest taxonomic group (genus or species) and counted under a Leica Apo Z16 Dissecting Microscope. Abundance estimates were calculated from subsamples of known volume and extrapolated to the volume sampled during the initial subsurface tow, as indicated by the flowmeter. Zooplankton biomass was estimated by applying dry-weight conversions to abundance estimates. Dry-weight conversions were taken from the literature (Dumont et al. 1975; Hooff & Bollens 2004) and in-house estimates provided by the Kimmerer laboratory at San Francisco State's Romberg Tiburon Center.

## Results

### *Chlorophyll-a Trends*

Along both transects, the value and variance of chl-*a* concentrations increased exponentially toward the terminal ends of sloughs (Figures 3, 4). This was true across the time series. Lower slough sites reported low (< 10 µg/L) chl-*a* concentrations throughout the entire time series with the exception of three months (April and July 2013, and February 2014) at CA3 and one month (April 2013) at MZ1 with high (> 10µg/L) chl-*a* concentrations. Upper slough sites showed greater variability and higher frequency of high chl-*a* concentrations. CA1 had five months (January and December 2013, and January, August, and October 2014) with low chl-*a* concentrations, and DV1 had three months (April and December 2013, and May 2014) with low chl-*a* concentrations. Over the time series, CA1 showed the greatest average chl-*a* (27 µg/L) followed by DV1 (15 µg/L), CA3 (5 µg/L) and MZ1 (2.5 µg/L). Table 2 shows average chlorophyll-*a* concentration and zooplankton biomass values by site each year.

**Table 1 Site description summary of Arc Project sites selected for zooplankton analysis from 2013 – 2014. CA1 is upper Cache Slough, CA3 is lower Cache Slough, DV1 is upper Denverton Slough, and MZ1 is Montezuma Slough near the Salinity Control Gates. DO is dissolved oxygen.**

| *Site* | *Mean Depth (m)* | *Temp Range (C)* | *Mean Secci (cm)* | *DO Range (mg/L)* | *Mean Salinity (ppt)* |
|---|---|---|---|---|---|
| CA1 | 1.39 | [4.2, 27.7] | 35 | [2.0, 14.0] | 0.3 |
| CA3 | 3.12 | [5.3, 26.5] | 72 | [5.1, 11.7] | 0.2 |
| DV1 | 2.00 | [3.4, 24.0] | 28 | [4.8, 12.4] | 6.1 |
| MZ1 | 7.70 | [6.6, 21.9] | 43 | [6.3, 12.4] | 4.3 |

### *Zooplankton Biomass Trends*

Sites near the slough terminus (upper slough sites CA1 and DV1) generally had greater variability in zooplankton abundance throughout the time series, but achieved much greater zooplankton abundance and biomass during peak zooplankton conditions than did sites near the slough mouth (lower slough sites CA3 and MZ1; Figures 2, 3, 4). Mean zooplankton biomass over both years was highest at the CA1 site (130,000 µgC/m$^3$), followed by the DV1 site (63,000 µgC/m$^3$), the CA3 site (34,000 µgC/m$^3$) and the MZ1 site (9,700 µgC/m$^3$). For more information, see Table 2.

Upper slough sites showed multiple peaks (total biomass > 50,000 µg C/m$^3$) of zooplankton biomass in both 2013 and 2014. In 2013, the peaks occurred in April, May, and July, whereas in 2014 the peaks occurred in February and April. The CA1 site showed a third peak in June, 2014. The 2013 peak zooplankton biomass was

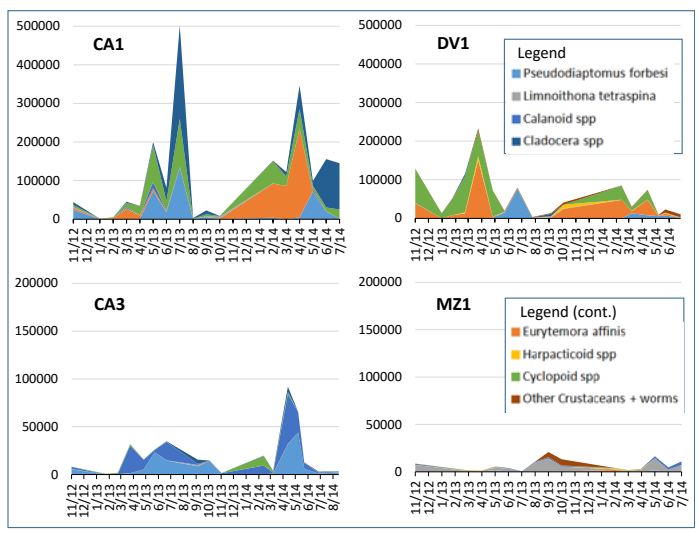


**Figure 2 Zooplankton biomass trends from 2013 – 2014. Upper slough sites are CA1 and DV1, lower slough sites are CA3 and MZ1. X-axis units are µgC/m$^3$ of zooplankton; note the difference in x-axis magnitude between the upper and lower slough sites. Y-axis units represent month/year when samples were collected. Upper slough sites show multiple peaks (> 50,000 µgC/m$^3$) of zooplankton biomass and greater average zooplankton biomass than lower slough sites.**

**Table 2 Results summary of zooplankton biomass and chl-*a* concentration from upper Cache Slough (CA1), lower Cache Slough (CA3), upper Denverton Slough (DV1), and Montezuma Slough (MZ1) from 2013 – 2014.**

| | | *Zooplankton Biomass (µgC/m³)* | | | | *Chlorophyll-a (µg/L)* | | | |
|---|---|---|---|---|---|---|---|---|---|
| | ***Site*** | ***Min*** | ***Max*** | ***Mean*** | ***Confidence Interval*** | ***Min*** | ***Max*** | ***Mean*** | ***Confidence Interval*** |
| | CA1 | 1,600 (Jan) | 523,120 (July) | 100,146 | [-1,200, 200,000] | 6.95 (Dec) | 103.02 (May) | 26.16 | [9.7, 42] |
| ***2013*** | CA3 | 1,003 (Feb) | 63,329 (Apr) | 26,050 | [10,000, 41,000] | 1.52 (Aug) | 28.07 (Apr) | 5.71 | [1.1, 10] |
| | DV1 | 9,877 (Aug) | 268,591 (Apr) | 74,977 | [27,000, 120,000] | 3.35 (Dec) | 38.50 (Mar) | 15.41 | [9.2, 21] |
| | MZ1 | 777 (July) | 24,999 (Sept) | 9,040 | [3,000, 15,000] | 0.97 (Nov) | 10.12 (Apr) | 3.06 | [1.3, 4.8] |
| | CA1 | 108,142 (May) | 374,582 (Apr) | 182,050 | [100,000, 260,000] | 6.35 (Jan) | 77.16 (July) | 27.90 | [14, 41] |
| ***2014*** | CA3 | 5,245 (Mar) | 146,119 (Apr) | 44,404 | [4,100, 84,000] | 1.89 (Oct) | 10.93 (Feb) | 4.43 | [2.9, 5.9] |
| | DV1 | 15, 614 (July) | 87,483 (Feb) | 45,354 | [21,000, 69,000] | 5.51 (May) | 23.79 (Nov) | 14.57 | [11, 17] |
| | MZ1 | 1,827 (Mar) | 25,595 (May) | 10,617 | [3,300, 17,000] | 0.60 (Jan) | 3.60 (Mar) | 2.05 | [1.5, 2.5] |
| | CA1 | 1,600 | 523,120 | 130,860 | [60,000, 200,000] | 1.30 | 103.02 | 27.03 | [16, 37] |
| ***2013 – 2014*** | CA3 | 1,003 | 146,119 | 34,080 | [14,000, 53,000] | 1.52 | 28.07 | 5.07 | [2.3, 7.4] |
| | DV1 | 9,877 | 268,591 | 63,869 | [32,000, 95,000] | 3.35 | 38.50 | 15.01 | [3.4, 26] |
| | MZ1 | 777 | 25,595 | 9,716 | [5,200, 14,000] | 0.60 | 10.12 | 2.55 | [1.6, 3.4] |

greater than the 2014 peak. Maximum biomass achieved at CA1 was about 523,000 µgC/m$^3$ in 2013 and only 374,000 µgC/m$^3$ in 2014. The pattern at DV1 is similar, with maximum biomass being approximately 268,000 µgC/m$^3$ in 2013 and only 87,000 µgC/m$^3$ in 2014 (Table 2, Figure 2).

Lower slough sites showed only a single zooplankton biomass peak at CA3 in April/May 2014. Zooplankton biomass was low (< 50,000 µgC/m$^3$) at CA3 for the remainder of the 2013 – 2014 time series. Zooplankton biomass was very low (< 25,000 µgC/m$^3$) at MZ1 for the entire 2013 – 2014 time series (Table 2, Figure 2)

## *Zooplankton Community Trends*

The zooplankton communities at these four sites were driven primarily by two calanoid and two cyclopoid copepod species: *Eurytemora affinis*, *Pseudodiaptomus forbesi*, *Acanthocyclops vernalis* (primary component of "Other Cyclopoid spp." category), and *Limnoithona tetraspina* (Figure 2). Cladocerans (primarily *Daphnia magna*, *D. pulex*, and *Moina sp*.) also contributed up to 75% of the zooplankton biomass at CA1 in summer months. Other calanoid copepods (e.g., *Tortanus dextrilobatus*, *Sinocalanus doerrii*, and *Acartiella sinensis*) made up a larger portion of the total zooplankton assemblage in the lower slough sites than at the upper slough sites. Other organisms, such as barnacle nauplii, Harris mud crab (*Rhithropanopeus harrisii*) zoea, and polychaete worms (all included in "Other" category) also contributed to the MZ1 zooplankton community. Overall, upper slough sites were dominated by *E. affinis*, *P. forbesi*, *A. vernalis*, and *Cladocera*, while the lower slough sites contained mostly *P. forbesi*, other calanoid copepod species, and *L. tetraspina* (Figure 2).

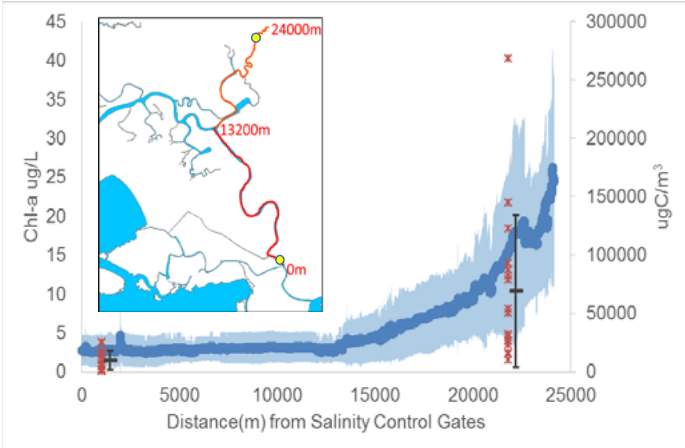


**Figure 3 Summary of eastern Suisun Marsh chl-*a* transect and zooplankton biomass estimates. The red line on the inset map shows the transect; yellow circles are where the zooplankton samples were collected. The x-axis corresponds to distance along the transect. The dark blue line and surrounding light blue cloud correspond to the primary y-axis, chlorophyll-*a* concentration (µg/L). The dark blue line represents the mean chl-*a* value collected at the corresponding location along the transect from all 2013 – 2014 transect cruises (n = 24). The light blue cloud represents ± one standard deviation at each mean calculation. Red Xs and black lines correspond to the secondary y-axis, zooplankton biomass (ugC/m³). Red Xs represent all total zooplankton biomass estimates (n = 17) from the given location included in the current analysis. The black lines represent the mean and ± one standard deviation of all biomass estimates from the given location.**

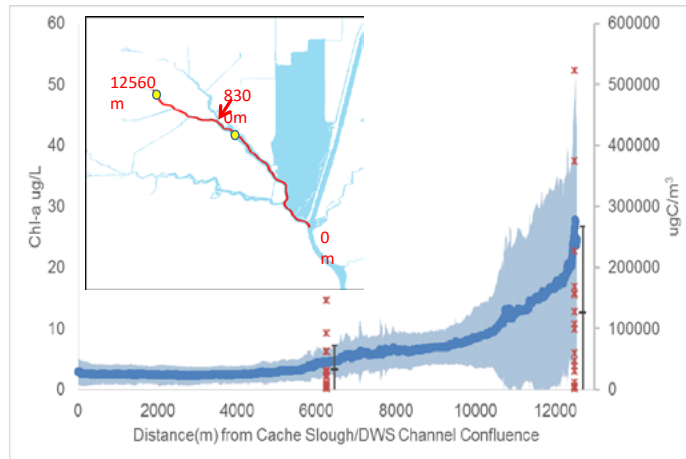


**Figure 4 Summary of Cache Slough chl-*a* transect and zooplankton biomass estimates. The red line on the inset map shows the transect; yellow circles are where the zooplankton samples were collected. The x-axis corresponds to distance along the transect. The dark blue line and surrounding light blue cloud correspond to the primary y-axis, chlorophyll-*a* concentration (µg/L). The dark blue line represents the mean chl-*a* value collected at the corresponding location along the transect from all 2013 – 2014 transect cruises (n = 24). The light blue cloud represents ± one standard deviation at each mean calculation. Red Xs and black lines correspond to the secondary y-axis, zooplankton biomass (µgC/m³). Red Xs represent all total zooplankton biomass estimates (n = 17) from the given location included in the current analysis. The black lines represent the mean and ± one standard deviation of all biomass estimates from the given location.**

## Discussion

### *Slough Geomorphology Comparison*

Although species assemblages differ, zooplankton biomass and chl-*a* concentration trends were consistent for the terminal sloughs (Denverton and Cache) in 2013 – 2014. Upper slough sites contain higher concentrations of zooplankton biomass and chl-*a* relative to lower slough sites (Figures 3, 4). High concentrations of chl-*a* and zooplankton biomass like those achieved at the CA1 and DV1 sites are rarely observed in the SFE. Notably, these regions are especially productive for Pelagic Organism Decline (POD) species and other native fishes (Williamson et al. and Young et al., this issue).

These exceptionally productive sloughs are intriguing from a management perspective. There are two critical questions regarding high concentrations of plankton at these upper slough sites. (1) Can fish access these resources? (2) Are these resources available to the broader regional food web (i.e., exported)? While these two questions are related, the answers for each are fundamentally different. The former requires that fish will actively migrate to upper slough sites and subsequently benefit from the abundance of zooplankton. The latter requires that hydrodynamic forces will redistribute zooplankton from regions of abundance (i.e., upper slough sites) to regions of relative scarcity (i.e., lower slough sites).

The potential for fish to access the abundant food resources at the upper slough sites likely depends on the ability of fish to cope with ambient environmental conditions. While zooplankton can be plentiful, upper slough sites are also characterized by a wider range of environmental conditions (Table 1) which may prohibit fishes from benefiting from available food resources (i.e., high or low temperatures, low DO). High concentrations of food resources at upper slough sites, however, may afford fish greater bioenergetic flexibility in withstanding unfavorable environmental conditions. Nevertheless,

extreme situations may still keep fish from benefiting from abundant zooplankton at upper slough sites.

For mobile fishes, such as the POD species, the location of zooplankton may offer a series of trade-offs. When plankton are abundant at lower slough sites, there may be a higher risk of predation (lower turbidity and greater encounter rate with potential predators), but more stable environmental conditions (i.e., narrower range of temperature and DO) (Moyle et al. 2016). When plankton are abundant at upper slough sites there may be more shelter from predators (higher turbidity and hydrodynamic isolation), but a more variable environment including potentially harmful temperature and DO swings (Table 1).

The capacity for any of the plankton concentrated at upper slough sites to become redistributed regionally depends on the extent of hydrodynamic isolation of these backwaters. Upper slough sites may provide a subsidy of plankton and small fish to less productive regions nearby, increasing local persistence of threatened fishes; however, the magnitude and extent of flux from upper slough sites to lower slough sites remains unknown. Additionally, the patterns of plankton abundance and the hydrodynamic capacity to redistribute plankton from upper slough sites to lower slough sites may be considerably different in wet years.

### *Interannual Comparison*

There are two notable differences in zooplankton biomass between 2013 and 2014. Peak zooplankton abundance in 2013 occurred later in the year and achieved greater biomass than did peak conditions in 2014 (Figure 2). Factors that may have contributed to this difference include temperature, Delta outflow, and/or other environmental stressors associated with an additional consecutive drought year.

Temperature in January of 2014 was uncharacteristically high (National Oceanic and Atmospheric Administration 2015). This exceptional month of warmer temperatures likely increased the speed of metabolic processes and production for all ectothermic organisms (Mullin & Brooks 1970; Huntley & Lopez 1992; Bunker & Hirst 2004). This may have contributed to a phenological shift of plankton blooms and predator responses occurring earlier in the year for 2014. January of 2013 logged relatively normal or above-normal high temperatures during the day, but almost exclusively below normal low temperatures at night. This may indicate the timing of peak zooplankton abundance in 2013 was relatively normal or even late.

Delta outflow in January of 2014 was likewise uncharacteristically low (California Department of Water Resources 2013). The lack of any notable precipitation until the beginning of February, 2014, created relatively stable aquatic conditions, particularly at upper slough sites, where higher water residence time occurs. High residence time (i.e., low exchange) in combination with warm temperatures may have created prime conditions for earlier plankton blooms in 2014. But low Delta outflow conditions may have limited allochthonous nutrient inputs, resulting in shortened bloom duration compared to 2013.

Differences in zooplankton abundance between these two years likely effected POD species and other fishes of concern differently, with respect to food abundance and timing. From the perspective of food availability, 2013 generated more total zooplankton biomass and, as a result, had a greater potential to support successful recruitment for fishes than did 2014. From a timing perspective, if larval fish emerged during periods of abundant zooplankton, recruitment was potentially more successful in both years (Hjort 1926; Cushing 1990). If larval fish emergence did not coincide with zooplankton abundance, recruitment was likely unsuccessful.

## Chlorophyll-*a* and Zooplankton Biomass

Ideally, chl-*a* fluorescence (a surrogate for algal biomass) could be used as a predictor of zooplankton biomass; however, paired observations of chl-*a* and zooplankton biomass from Arc monthly sampling show that their correlation is weak (Figure 5). Paired observations suggest that zooplankton biomass can be relatively high (up to 250,000 µgC/m$^3$) with low chl-*a* values (< 10 µg/L). Likewise, zooplankton biomass can be low (as little as 10,000 ugC/m$^3$) even with chl-*a* values up to 25 µg/L. Discrepancy between rates of phytoplankton production and zooplankton consumption and the time lag between phytoplankton bloom formation and zooplankton community response likely accounts for this weak correlation. Other in situ factors and trophic pathways also influence the production of phytoplankton and zooplankton, such as anomalous temperatures, bottom-up limitations (e.g., nutrient limitation), and/or top-down interactions (e.g., grazing by clams or planktivorous fishes).

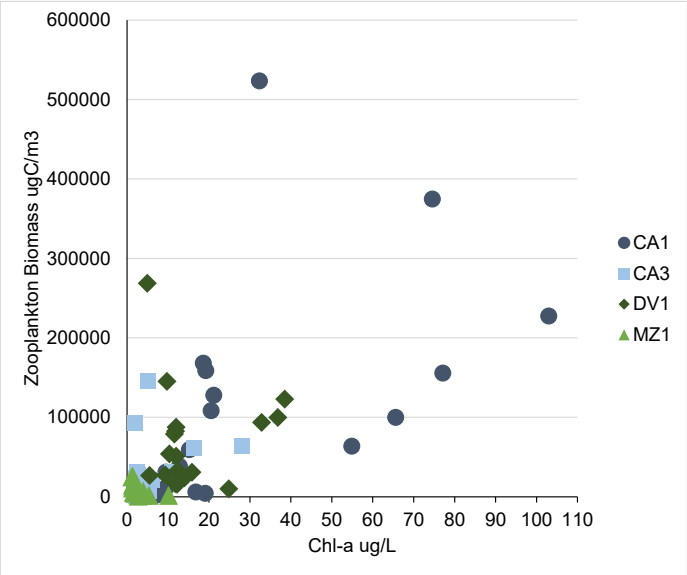


**Figure 5 Scatterplot of chl-*a* concentration and corresponding zooplankton biomass estimates for all zooplankton samples collected in 2013 – 2014 included in the current analysis. CA1 is upper Cache Slough, CA3 is lower Cache Slough, DV1 is upper Denverton Slough, and MZ1 is Montezuma Slough near the Salinity Control Gates. Upper slough sites have high (> 10 µg/L) chlorophyll-*a* concentration and high (> 50,000 µgC/m$^3$) zooplankton biomass more frequently than lower slough sites do. The lack of correlation between variables may be due to trophic cascade, time lags, and/or mismatches between phytoplankton production rates and zooplankton consumption rates.**

The coincidence of high zooplankton biomass with low chl-*a* may be due to high grazing rates. When the rate of phytoplankton production is less than or equal to the grazing rate of the zooplankton community, zooplankton biomass can continue to grow while measurements of chl-*a* remain steady, or even decline (MacIntyre et al. 1996). Lower trophic level production is consumed as quickly as it is produced and is not allowed to accumulate to large concentrations. A high phytoplankton production rate may not be observed by measuring chl-*a* fluorescence, yet it is still able to support an abundant zooplankton community.

Seasonal abundance of planktivorous fishes may induce a trophic cascade that results in low zooplankton biomass and high chl-*a* concentrations (Carpenter et al. 2001). Non-native American Shad (*Alosa sapidissima*), Threadfin Shad (*Dorosoma petenense*), and Mississippi Silverside (*Menidia audens*) populations all generate large cohorts of juveniles that feed almost exclusively on zooplankton. Such a large influx of zooplankton predators could result in depressed zooplankton populations, which releases pressure on phytoplankton, producing high concentrations of chl-*a*. These conditions can generate unexpectedly low zooplankton biomass, particularly in late summer when the non-native planktivores are abundant (see Williamson et al. and Young et al., this issue). Native planktivores, such as Delta Smelt and Longfin Smelt, presumably once had a trophic cascade effect on zooplankton and phytoplankton abundance, but at present, populations of non-native fishes are much larger, and as a result generate a larger magnitude effect.

Additionally, monthly sampling cruises may not be sufficient to detect a meaningful relationship between chl-*a* and zooplankton biomass. A mismatch between sampling interval and plankton bloom development times leads to ambiguity in the data, whereas more frequent sampling might improve detection of zooplankton/phytoplankton trophic dynamics.

Monitoring during winter precipitation events will be crucial for determining deviations from observed patterns in drought years. Immediately following a major precipitation event, much of the zooplankton and chl-*a* concentrated in upper ends of sloughs may be redistributed to surrounding aquatic habitats. If there is enough precipitation to flood the Yolo Bypass, the North Delta Arc is likely to be influenced by the effects of production and drainage of the bypass (Sommer et al. 2001). The magnitude and range of such redistribution events and what patterns emerge after continued precipitation events remain unknown.

## Conclusion

The data support that zooplankton are abundant more frequently at upper slough sites than at lower slough sites in the terminal sloughs, Cache and Denverton. This phenomenon may be altered or completely reversed during periods of higher outflow than were observed during 2013 – 2014. The trade-offs and foraging strategies used by fishes will likely change in such reversed conditions.

The occurrence of such high-density chl-*a* and zooplankton biomass is a promising result for SFE restoration. Not only is this further evidence that Suisun Marsh and Cache Slough are functionally productive regions of the SFE ecosystem, but also the geomorphic

similarities between the two most productive sites (i.e., CA1 and DV1) suggests this may be a critical feature of functionally productive SFE aquatic habitats in general.

Restoration projects may function as productive aquatic habitats if they incorporate geomorphic features, such as terminal sloughs. However, without understanding the suite of drivers of productive "hot spots," simple geomorphic imitation may not be sufficient to create functional aquatic habitats via restoration. For example, quarterly zooplankton sampling at upper and lower sites in New York Slough on Brown's Island throughout water years 2004 (drought year comparable to 2013 [USDM]) and 2005 (wet year [USDM]) consistently observed an order of magnitude lower zooplankton abundance than Arc Project upper slough sites CA1 and DV1 did during the 2013 – 2014 drought (Bollens et al. 2014). Despite its aesthetics (dendritic terminal and flow-through sloughs surrounded by intact intertidal marsh), something is keeping New York Slough from functioning as a productive aquatic habitat in the way that Denverton and Cache Sloughs do. In future restorations, managers should employ monitoring and adaptive management to ensure designed ecosystems function desirably.

Further monitoring of Arc Project sites should continue in conjunction with efforts to locate other productive hotspots in the SFE, and the environmental characteristics that influence them. Hydrodynamic modeling and flux studies will be useful to elicit the role of water circulation patterns in determining the location of productive hot spots and the extent to which hot spots influence their respective surrounding regions. There are likely other environmental features that influence the occurrence of productive areas, such as proximity to a source of nutrients (both natural and anthropogenic) or proximity to other productive areas. Understanding the nature of these high productivity areas in Cache and Denverton sloughs may contribute to the conservation of fishes of concern in the entire SFE by providing an example of functional aquatic ecosystems as a target for restoration.

## Acknowledgements

The Arc Project would like to thank its funding sources: California Department of Water Resources, California Department of Fish and Wildlife Ecosystem Restoration Program, and State and Federal Contractors Water Agency. Collaborations with the Dixon Boat Club and Romberg Tiburon Center were critical in the collection and analysis of data. We are thankful for institutional support from the University of California, Davis, John Muir Institute for the Environment, and Center for Watershed Sciences. Finally, thank you to Arc Project personnel: Matt Young, Teejay O'Rear, Denise DeCarion, Amy Chandos, Kousei Martin Perales, Kathleen Berridge, Brian Williamson, Chris Jasper, James Hobbs, Thomas Handley, Amber Manfree, Felipe La Luz, Cathryn Lawrence, Randy Dahlgren, and William Fleenor. Special thanks to Gena Lasko at CDFW ERP. This research was supported by Ecosystem Restoration Program agreement E1183013, State and Federal Contractors Water Agency grant 15-19, and California Department of Water Resources grant to support the Suisun Marsh Fisheries Survey.

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# Fish Distribution in the Cache Slough Complex of the Sacramento-San Joaquin Delta during Drought

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## Introduction

The Sacramento-San Joaquin Delta (Delta) is a highly altered environment, with native fish populations in sharp decline and increasing numbers of many non-native species (Sommer et al., 2007, Brown & Michniuk 2007). Certain native fish species have been extirpated (Sacramento Perch, *Archoplites interruptus*) or have gone extinct (Thicktail Chub, *Gila crassicauda*), while several others are currently listed under the State and/or federal endangered species acts (e.g., Longfin Smelt, *Spirinchus thaleichthys*; Delta Smelt, *Hypomesus transpacificus*; Winter-run Chinook Salmon, *Oncorhynchus tshawytscha*; Central Valley Steelhead, *Oncorhynchus mykiss*; and Southern Green Sturgeon, *Acipenser medirostris*). In addition, population declines of long-established non-native pelagic species have been observed (Sommer et al. 2007), particularly Striped Bass (*Morone saxatilis*) and Threadfin Shad (*Dorosoma petenense*). These long-term declines have focused both management emphasis and

dollars on improving fish community health in the Delta. A commonly proposed solution is to restore large tracts of the Delta to tidal marsh to benefit at-risk fish populations. However, these benefits are poorly defined and difficult to forecast (Brown 2003, Herbold 2014).

Because regions of the Delta are dominated by different environmental conditions and thus support different fish assemblages, restoration projects in these regions are likely to have differing impacts (Moyle et al. 2012). Restoration projects intend to increase tidal marsh and subtidal habitat, but little is known about how resident fish assemblages use existing tidal marsh and subtidal habitat within the Delta. Delta regions heavily influenced by Sacramento River flow (i.e., the west and north Delta) typically support more robust native fish populations than other regions (i.e., the east and south Delta) (Brown & Michniuk 2007). For this reason, many current and proposed restoration projects are located within sloughs to the northwest of the Sacramento River, upstream of Rio Vista. This region, the Cache Slough Complex (CSC), is a network of dead-end sloughs surrounding flooded Liberty Island (Figure 1). Agency monitoring programs have sampled relatively large numbers of at-risk native fishes in the CSC over the last 15 years (USFWS Juvenile Fish Sampling data), and other studies have reported a local fish assemblage distinct from other parts of the Delta (De Carion 2012).

These discoveries prompted fisheries researchers at the University of California, Davis to begin detailed sampling in the region to establish pre-restoration baselines, and to identify the physical and biological mechanisms explaining why the CSC supports native fishes. In this article, we summarize our findings on local fish assemblages for the first two years of the study, during a period of extreme drought.

## Study Site

During 2013 and 2014, fish sampling was conducted monthly in two channel networks within the CSC, the Cache Slough network and the Lindsey Slough network (Figure 1). The Cache network is comprised of three sloughs: Cache Slough, Haas Slough, and Ulatis Creek. These sloughs are typified by high pelagic primary productivity, high turbidity, and sparse submersed aquatic vegetation (SAV) on slough margins. The Lindsey network is comprised of Barker Slough, Calhoun Cut, and Lindsey Slough. These sloughs typically exhibit low pelagic primary productivity and low turbidity (Figure 2), and have dense SAV along slough margins. Important contrasts between the two slough networks include local water inputs and diversions. Ulatis Creek in the Cache Slough network receives water from the hills north of Vacaville, from Solano County agricultural runoff, and from Elmira Wastewater Treatment Plant effluent before entering Cache Slough. In the Lindsey Slough network, the North Bay Aqueduct pumping station is located at the head of Barker Slough and supplies water to Napa and Solano counties.

In general, the CSC is located at the downstream extremity of the Yolo Bypass, and it is likely that flooding in the Yolo Bypass has a large influence on the CSC during wet years, although our sampling occurred during a period of extended drought, with Delta outflow well below average (Figure 2). These conditions provide important context for the survey because we expect the distribution and abundance of fishes to differ between periods of high and low flow.

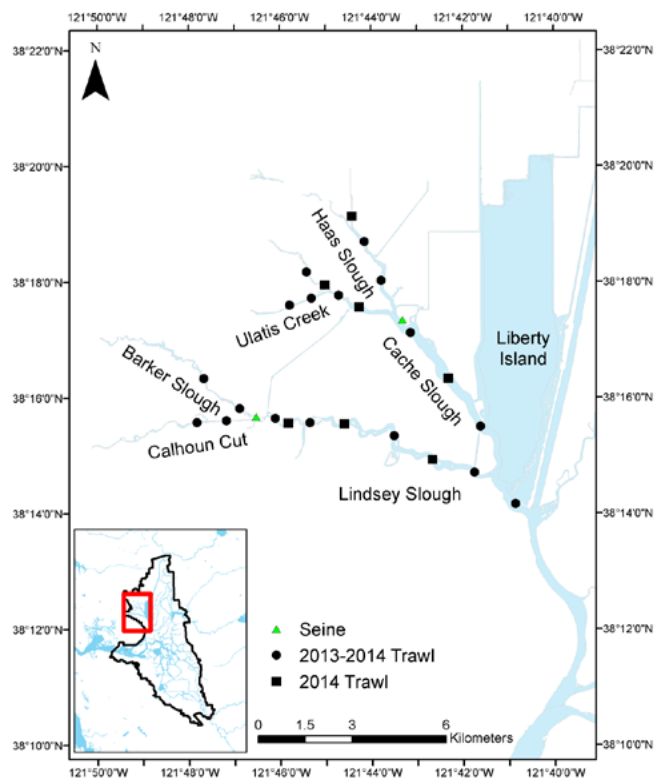


**Figure 1 Map of Arc Study Sites. Inset contains an outline of the legally defined Delta with the Cache Slough Complex highlighted. The Cache Slough Complex is a network of dead-end sloughs surrounding Liberty Island. Sloughs which contain sampling locations for this study are labeled.**

## Methods

The data discussed here represent monthly sampling from January 2013 through December 2014. In 2013 and 2014, we trawled 16 and 23 sites, respectively; two beach seine sites were sampled in both years, one in Cache Slough and one in Barker Slough (Figure 1). All samples were collected using the same methods as the 35-year-long UC Davis Suisun Marsh Fish Study (O'Rear and Moyle 2014). 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 woven mesh in the cod end. The otter trawl was towed at approximately 4 km/hr for 5 minutes along the bottom of the sloughs. Seines were 10 m long with a woven mesh size of 6 mm. At each sampling site we recorded tidal stage (low, flood, high, ebb), salinity (practical salinity units, [psu]), specific conductivity (microsiemens, [µs]), temperature (degrees Celsius), dissolved oxygen (mg/L and percent saturation), Secchi depth (centimeters), and chlorophyll-*a* (µg/L). In addition, we sampled zooplankton concurrently with fish (see Montgomery et al., this issue).

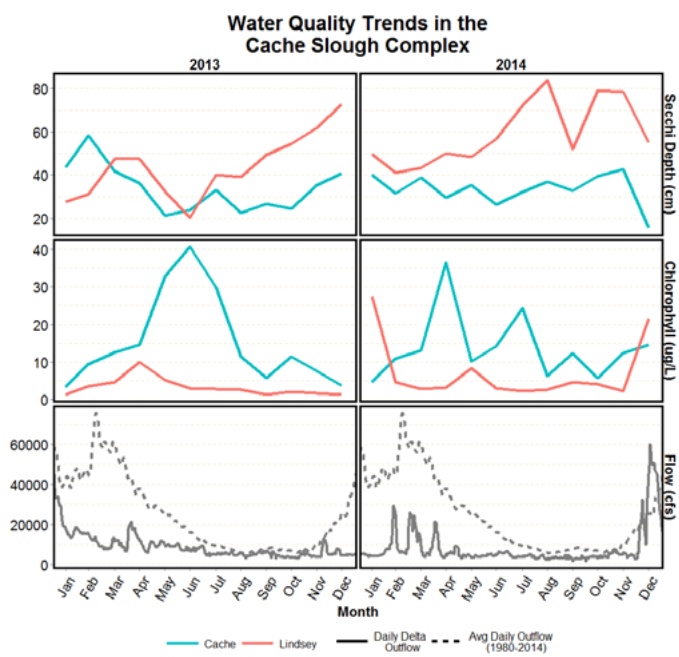


**Figure 2 North Delta Water Quality. Values for Cache & Lindsey slough networks are averaged data for that month from fish sampling locations. Delta flow data is from DayFlow (http://www.water.ca.gov/dayflow/).**

Contents of the trawl or seine were placed in an aerated tub or bucket. All fish were then identified, enumerated, measured, and released after recovery. Decapod crustaceans and other invertebrates (e.g., clams, jellyfish) were counted and released. Smaller invertebrates (e.g., mysid shrimp, amphipods, aquatic insects) were assigned a rank based on their abundance in the sample. Additionally, we quantified the volume of solid organic and inorganic material captured by each trawl. Major categories included SAV, emergent vegetation root mass, organic detritus, and inorganic sediments. All trawl catches were standardized by trawl minute, resulting in a catch-per-unit-effort value defined as a number of individuals per minute. Seine catches were standardized as the number of individual fish per seine haul.

## Results

In total, we pulled 472 otter trawls and 93 beach seines. We collected 13,057 individual fish representing 32 species during this period; 7,673 were caught in trawls, and 5,384 were caught in seines (Table 1). Trawl catches were dominated by pelagic fishes. Threadfin Shad and Striped Bass together made up nearly 60% of total catch (Table 2). Black Crappie (*Pomoxis nigromaculatus*), Tule Perch (*Hysterocarpus traskii*), and White Catfish (*Ameiurus catus*) were the next most abundant fishes in trawls. Seine catches were dominated by Mississippi Silverside (*Menidia audens*), which made up approximately 79% of total seine catch. Threadfin Shad, Bigscale Logperch (*Percina macrolepida*), Striped Bass, and Largemouth Bass (*Micropterus salmoides*) were the next most abundant fishes in seines (Table 2). Overall, total catch per unit effort (CPUE) was higher in 2014 than in 2013 for both trawls and seines (Table 1). Much of this change in trawl CPUE was driven by Threadfin Shad, the CPUE of which doubled in 2014 (Figure 3). Striped Bass CPUE increased by 21%, and Black Crappie CPUE decreased by 41%. The difference in seine CPUE was driven primarily by Mississippi Silverside, but catches for most other fishes were also higher in 2014.

There were strong differences in fish abundance across slough channel networks. Trawl CPUE was higher in the Cache network than in the Lindsey network. This was driven primarily by Threadfin Shad and Striped Bass, but most fish species were more abundant in Cache (Figure 4). The notable exceptions were non-native

fishes associated with SAV, including Redear Sunfish (*Lepomis microlophus*) and Bluegill Sunfish (*Lepomis macrochirus*), which were more abundant in the Lindsey network. Native fish diversity and abundance were higher in Cache than in Lindsey. Every native species except Sacramento Pikeminnow (*Ptychocheilus grandis*) and Sacramento Splittail (*Pogonichthys macrolepidotus*) was more abundant in the Cache network (Table 3), and two native species were present only in the Cache group: Sacramento Blackfish (*Orthodon microlepidotus*) and Threespine Stickleback (*Gasterosteus aculeatus*).

## Discussion

Pelagic fish catch during long-term fish monitoring surveys has historically declined during periods of drought or low flows in the San Francisco Estuary (SFE) (Feyrer et al. 2007, Rosenfield & Baxter 2007). The pelagic fish response to drought in the CSC during 2013 – 14 deviated from this pattern, with fish abundance increasing across the two years of drought (Figure 3). Primary and secondary productivity remained high in both years, with zooplankton densities in Cache Slough two orders of magnitude higher than those reported in other zooplankton surveys (Hennessey & Enderlein 2014, Montgomery et al., this issue). Low-flow conditions may have helped to retain phytoplankton and zooplankton, similar to the retention of sediment in the region (Morgan-King & Schoellhamer 2013), contributing to high local concentrations of plankton biomass. During periods of extended drought and/or low outflow, these regions of high local productivity may be important for supporting native species of interest, such as Longfin Smelt and Delta Smelt (Sommer et al. 2009), as well as non-native species that are in decline elsewhere, such as Striped Bass and Threadfin Shad.

**Table 1 Total catch and CPUE by method and year. CPUE for trawls is defined as the number of individuals per minute. CPUE for seines is the number of individual fish per seine haul.**

| | *Trawls* | | *Seines* | |
|---|---|---|---|---|
| | *Total Catch* | *CPUE* | *Total Catch* | *CPUE* |
| 2013 | 2768 | 2.77 | 1851 | 39.36 |
| 2014 | 4905 | 3.6 | 3533 | 76.76 |
| Total | 7673 | 3.25 | 5384 | 57.89 |

The difference in fish abundance between the Cache and Lindsey networks may be the result of several mechanisms, each of which affects different groups of native fishes. First, native pelagic fishes (Longfin Smelt and Delta Smelt) likely benefit from the high pelagic productivity in the Cache network. Zooplankton are important diet items for native pelagic fishes (Moyle et al. 1992, Feyrer et al. 2003), therefore high zooplankton densities in the Cache network (Montgomery et al. this issue) likely provide more abundant food for native pelagic fishes than in many other places in the upper estuary. Second, average turbidity in the Cache network is much higher than in the Lindsey network, possibly limiting the establishment and proliferation of non-native SAV in Cache. This could have important impacts on SAV-associated fishes, and parallels trends in fish abundance; SAV-associated non-native fishes are much more abundant in the Lindsey group, and SAV-tolerant native fishes (particularly Tule Perch) are able to maintain populations in both slough networks. In addition to SAV-mediated impacts on fish distribution, high turbidity is frequently negatively correlated with the abundance of non-native fishes that primarily detect prey visually (Moyle 2002). Low abundance of non-native fishes may limit predation on and competition with native fishes, which are proposed mechanisms for native fish decline (Moyle 2002). Third, the presence of feeder streams in the Cache network contributes a diversity of habitat types not observed in the Lindsey group. For example, Sacramento Suckers (*Catostomus occidentalis*) were the native fish that exhibited the largest abundance difference between slough groups, largely driven by juvenile fish (< 200 mm standard length). It is likely that Sacramento Suckers spawn in Ulatis Creek, with the resultant juveniles recruiting to lower Ulatis Creek and Cache Slough. Ulatis Creek also may provide spawning habitat for other native fishes, including Hitch (*Lavinia exilicauda*), which may explain differences in Hitch distribution within the complex (Figure 4, Table 3).

The fish assemblage in the Cache Slough network differs greatly from the fish assemblage of the Lindsey Slough network. The Lindsey Slough network resembles a typical SAV-dominated Delta assembly (Nobriga & Feyrer 2005, Brown & Michniuk 2007), while the Cache Slough network includes more native species (e.g., Hitch, Sacramento Blackfish, and Tule Perch) and many non-native species uncommon in the Lindsey network. These

**Table 2 CPUE of all fishes sampled using trawls and seines. Bold * indicates native species.**

| | | *Trawl* | | | *Seine* | | | *All Methods* |
|---|---|---|---|---|---|---|---|---|
| ***Species*** | ***Code*** | ***Total*** | ***CPUE*** | ***% CPUE*** | ***Total*** | ***CPUE*** | ***% CPUE*** | ***Total*** |
| Mississippi Silverside (*Menidia audens*) | MSS | 158 | 0.07 | 2.10% | 4243 | 45.62 | 78.80% | 4401 |
| Threadfin Shad (*Dorosoma petenense*) | TFS | 3552 | 1.5 | 46.30% | 327 | 3.52 | 6.10% | 3879 |
| Striped Bass (*Morone saxatilis*) | SB | 1066 | 0.45 | 13.90% | 135 | 1.45 | 2.50% | 1201 |
| Black Crappie (*Pomoxis nigromaculatus*) | BC | 700 | 0.3 | 9.10% | 37 | 0.4 | 0.70% | 737 |
| **Tule Perch* (*Hysterocarpus traski*)** | TP | 390 | 0.17 | 5.10% | 16 | 0.17 | 0.30% | 406 |
| White Catfish (*Ameiurus catus*) | WCF | 297 | 0.13 | 3.90% | 0 | 0 | 0.00% | 297 |
| Bigscale Logperch (*Percina macrolepida*) | BLP | 79 | 0.03 | 1.00% | 215 | 2.31 | 4.00% | 294 |
| **Longfin Smelt* (*Spirinchus thaleichthys*)** | LFS | 276 | 0.12 | 3.60% | 0 | 0 | 0.00% | 276 |
| American Shad (*Alosa sapidissima*) | ASH | 251 | 0.11 | 3.30% | 16 | 0.17 | 0.30% | 267 |
| **Prickly Sculpin* (*Cottus asper*)** | SCP | 118 | 0.05 | 1.50% | 48 | 0.52 | 0.90% | 166 |
| White Crappie (*Pomoxis annularis*) | WC | 140 | 0.06 | 1.80% | 16 | 0.17 | 0.30% | 156 |
| Shimofuri Goby (*Tridentiger bifasciatus*) | SG | 65 | 0.03 | 0.80% | 47 | 0.51 | 0.90% | 112 |
| **Sacramento Sucker* (*Catostomus occidentalis*)** | SKR | 92 | 0.04 | 1.20% | 3 | 0.03 | 0.10% | 95 |
| Bluegill Sunfish (*Lepomis macrochirus*) | BG | 70 | 0.03 | 0.90% | 19 | 0.2 | 0.40% | 89 |
| Common Carp (*Cyprinus carpio*) | CP | 76 | 0.03 | 1.00% | 8 | 0.09 | 0.10% | 84 |
| Redear Sunfish (*Lepomis microlophus*) | RESF | 66 | 0.03 | 0.90% | 16 | 0.17 | 0.30% | 82 |
| Golden Shiner (*Notemigonus chrysoleucas*) | GSH | 42 | 0.02 | 0.50% | 31 | 0.33 | 0.60% | 73 |
| Largemouth Bass (*Micropterus salmoides*) | LMB | 14 | 0.01 | 0.20% | 58 | 0.62 | 1.10% | 72 |
| Yellowfin Goby (*Acanthogobius flavimanus*) | YFG | 11 | 0 | 0.10% | 50 | 0.54 | 0.90% | 61 |
| **Hitch* (*Lavinia exilicauda*)** | HCH | 53 | 0.02 | 0.70% | 1 | 0.01 | 0.00% | 54 |
| **Sacramento Splittail* (*Pogonichthys macrolepidotus*)** | 27 | 0.01 | 0.4% | 0 | 0.00 | 0.0% | 27 | 0.011433798 |
| **Delta Smelt* (*Hypomesus transpacificus*)** | 16 | 0.01 | 0.2% | 0 | 0.00 | 0.0% | 16 | 0.006775584 |
| Brown Bullhead (*Ameirus nebulosus*) | 18 | 0.01 | 0.2% | 0 | 0.00 | 0.0% | 18 | 0.007622532 |
| Western Mosquitofish (*Gambusia affinis*) | 1 | 0.00 | 0.0% | 0 | 0.00 | 0.0% | 1 | 0.000423474 |
| Channel Catfish (*Ictalurus punctatus*) | 11 | 0.00 | 0.1% | 0 | 0.00 | 0.0% | 11 | 0.004658214 |
| **Sacramento Pikeminnow* (*Ptychocheilus grandis*)** | 5 | 0.00 | 0.1% | 0 | 0.00 | 0.0% | 5 | 0.00211737 |
| **Chinook Salmon* (*Oncorhynchus tshawytscha*)** | 2 | 0.00 | 0.0% | 0 | 0.00 | 0.0% | 2 | 0.000846948 |
| Fathead Minnow (*Pimephales promelas*) | 2 | 0.00 | 0.0% | 0 | 0.00 | 0.0% | 2 | 0.000846948 |
| Goldfish (*Carassius auratus*) | 7 | 0.00 | 0.1% | 0 | 0.00 | 0.0% | 7 | 0.002964318 |
| **Threespine Stickleback* (*Gasterosteus aculeatus*)** | 1 | 0.00 | 0.0% | 0 | 0.00 | 0.0% | 1 | 0.000423474 |
| Warmouth (*Lepomis gulosus*) | 3 | 0.00 | 0.0% | 0 | 0.00 | 0.0% | 3 | 0.001270422 |
| **Sacramento Blackfish* (*Orthodon microlepidotus*)** | 2 | 0.00 | 0.0% | 0 | 0.00 | 0.0% | 2 | 0.000846948 |

non-natives tend to be in general decline (e.g., Striped Bass and Threadfin Shad) or have limited, localized populations throughout the Delta (e.g., Black Crappie, Bigscale Logperch). There is some evidence that the non-native fishes co-exist successfully with natives in the Cache Slough network, creating what amounts to a novel assembly of trophically integrated species (Moyle & Light 1996).

## Conclusion

The CSC is a heterogeneous network of sloughs, each with distinctive habitat characteristics that support different assemblages of native and non-native fishes. The Cache Slough network has distinctive characteristics (e.g., high primary productivity, high turbidity, and disparate inputs) and supports a novel assemblage of native and non-native fishes. This combination of physical attributes likely contributes to the relative success of local native fauna. The Lindsey Slough network more closely resembles other large slough systems elsewhere in the Delta, with dense SAV along slough margins, low primary productivity, and low turbidities. This inherent heterogeneity within the CSC offers the opportunity to conduct research that helps to identify the attributes which support various fish species. This contrast is important given the magnitude of planned restoration projects in the CSC and surrounding region. Sampling during a time of environmental stress, such as the current extended drought, provides insight into the potential effects of future management decisions that may mimic low-outflow conditions (e.g., upstream diversions through the twin tunnels).

## Acknowledgements

The authors would like to acknowledge the following funding sources and support: California Department of Fish and Wildlife Ecosystem Restoration Program (Project #E1183013 00), the State and Federal Contractors Water Agency (Grant #15-19), the California Department of Water Resources, and the Dixon Boat Club.

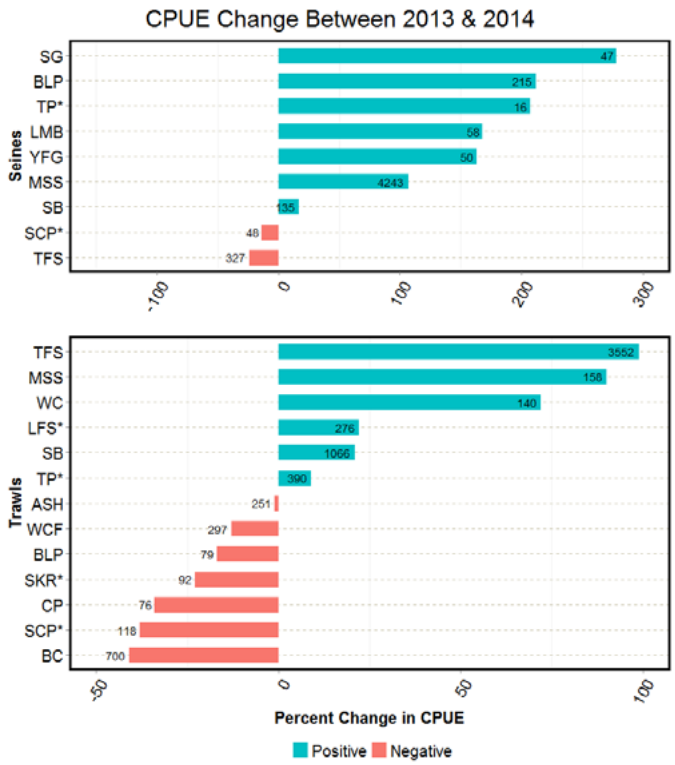


**Figure 3 Percent change in CPUE from 2013 to 2014. The total number of individuals captured across both years is in black text. Species codes are listed in Table 2.**

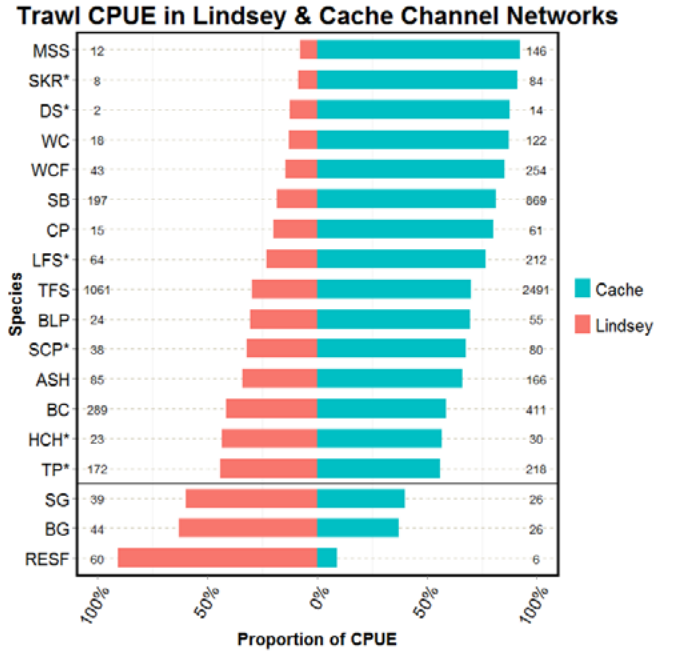


**Figure 4 Proportion of CPUE in the Cache and Lindsey channel networks. The numbers on the borders of the plot represent total catch of each species in each group. Species above the black horizontal line are more abundant in Cache, and below the line are more abundant in Lindsey. Species codes are listed in Table 2.**

**Table 3 CPUE of all native fishes captured in the Cache & Lindsey Slough networks. CPUE is defined as the number of individuals per minute.**

| *Species* | *Cache* | *Lindsey* |
|---|---|---|
| Chinook Salmon | 0.001 | 0.001 |
| Delta Smelt | 0.012 | 0.002 |
| Hitch | 0.025 | 0.019 |
| Longfin Smelt | 0.175 | 0.053 |
| Prickly Sculpin | 0.066 | 0.031 |
| Sacramento Blackfish | 0.002 | 0.000 |
| Sacramento Pikeminnow | 0.001 | 0.003 |
| Sacramento Splittail | 0.009 | 0.013 |
| Sacramento Sucker | 0.069 | 0.007 |
| Threespine Stickleback | 0.001 | 0.000 |
| Tule Perch | 0.180 | 0.142 |

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# Fishes of the Nurse-Denverton Slough Complex: Managed Wetlands and Tidal Waterways in Suisun Marsh

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## Introduction

Suisun Marsh lies at the geographic center of the San Francisco Estuary and is vital habitat for multiple life stages of estuarine and migratory fishes, including threatened and endangered species (O'Rear and Moyle 2014). In 1979, the University of California, Davis (UC Davis) Suisun Marsh Fish Study (SMFS) was initiated in cooperation with the California Department of Water Resources (DWR) to monitor and to study the distribution and abundance of fishes within subtidal sloughs of the marsh (O'Rear and Moyle 2014). While the distribution and abundance of fishes in subtidal sloughs have been thoroughly documented for the past 35 or more years, little sampling of fishes has occurred within the managed wetlands that dominate much of the area of Suisun Marsh. Managed wetlands are diked and tidally muted areas of marsh that are managed for the purpose of promoting intensive growth of vegetation to provide food and habitat for waterfowl. Currently, little is known about the ecological interactions between slough-channel networks and managed wetlands in Suisun Marsh.

Historically, the marsh landscape was dominated by tidal marsh habitat, with vast expanses of intertidal marsh plain that would flood during high tides (Moyle et al. 2014). In 1897, construction of a railroad through the western marsh facilitated rapid development of managed wetlands for waterfowl hunting (Arnold 1996). Today, approximately 340 km (210 miles) of constructed levees separate about 210 $km^2$ (52,000 acres) of managed wetlands from tidal waterways (Moyle et al. 2014). The Suisun Marsh Habitat Management, Preservation, and Restoration Plan mandates (1) conversion of 20 – 30 $km^2$ (5,000 – 7,000 acres) from tidally-muted managed wetlands to tidally-unrestricted wetlands, and (2) the enhancement of 160 – 200 $km^2$ (40,000 – 50,000 acres) of managed wetlands (United States Bureau of Reclamation 2013).

Understanding how managed wetlands influence aquatic organisms of subtidal waterways is important for water management and the development of restoration designs that will benefit aquatic species. To address this knowledge gap, the UC Davis Blacklock Fish Study was initiated in October 2013 to collect and interpret information on the distribution and abundance of fishes in a restoring tidal marsh, a managed wetland, and adjacent tidal waterways. We used catch per unit effort (CPUE)

of fishes collected during monthly trawl and beach-seine sampling conducted by the Blacklock Fish Study to evaluate differences in the distribution and abundance of fishes among target sites.

## Methods

### *Study site*

Suisun Marsh is the largest continuous brackish marsh on the West Coast of the United States, with an area of approximately 470 km$^2$ (120,000 acres) (Moyle et al. 2014). The Nurse-Denverton slough complex is a region of Suisun Marsh defined by unique geomorphology, myriad physical drivers, and high aquatic productivity (Moyle et al. 2014) (Figure 1). It occupies roughly 10% of the total area of Suisun Marsh and includes a mosaic of waterway types, including subtidal sloughs, tidal marsh, a restoring marsh, an embayment, and managed wetlands. The overbite clam (*Potamocorbula amurensis*), a highly invasive species known to deplete pelagic food webs in nearby areas, has been rare in this region (Schroeter 2011).

In 2003, DWR purchased the Blacklock parcel (Blacklock Marsh, Figure 1) within the Nurse-Denverton slough complex with the intent to restore the property to a natural tidal influence (California Department of Water Resources 2007). In 2006, a natural breach occurred in the levee and a second breach was excavated. The goal of the Blacklock restoration project was to increase the acreage of tidal marsh within Suisun Marsh, and thus increase available habitat for various listed and important marsh species (California Department of Water Resources 2007). The parcel currently consists of shallow interior intertidal ponds, a deep perimeter ditch, and a network of historical and newly-forming intertidal channels through the now-tidal marsh.

Arnold Slough is a sinuous, terminal slough that extends along the southern boundary of Blacklock Marsh and continues until it fragments into an array of ditches and mudflats (Figure 1). Arnold Slough and Blacklock Marsh maintain minimal hydrologic connection through a levee via an open water control structure pipe, an artifact from when the property was a managed wetland. Little Honker Bay is a small embayment of approximately 300,000 m$^2$ (80 acres), abutting the northwest boundary of Blacklock Marsh. It is hydrologically connected to Blacklock Marsh through two large levee breaches and is the primary source of tidal exchange.

The Luco Slough complex is found in the northwest quadrant of the Nurse-Denverton complex (Figure 1). Luco Slough is a sinuous channel network with two main branches, modified by the presence of dikes and water control structures connecting to managed wetlands. To the north, Luco Pond, a managed wetland owned by the Potrero Duck Club, covers about 2 km$^2$ (500 acres) and still contains some of its historic channel morphology but is dominated by a mix of open water and large stands of emergent vegetation. It is seasonally flooded and drained via three water control structures that are gated and connected to both branches of Luco Slough (Table 1).

### *Sampling*

The Blacklock Study sampled fishes at 11 trawl sites and three seine sites (Figure 1) once monthly from January through December, 2014 using comparable

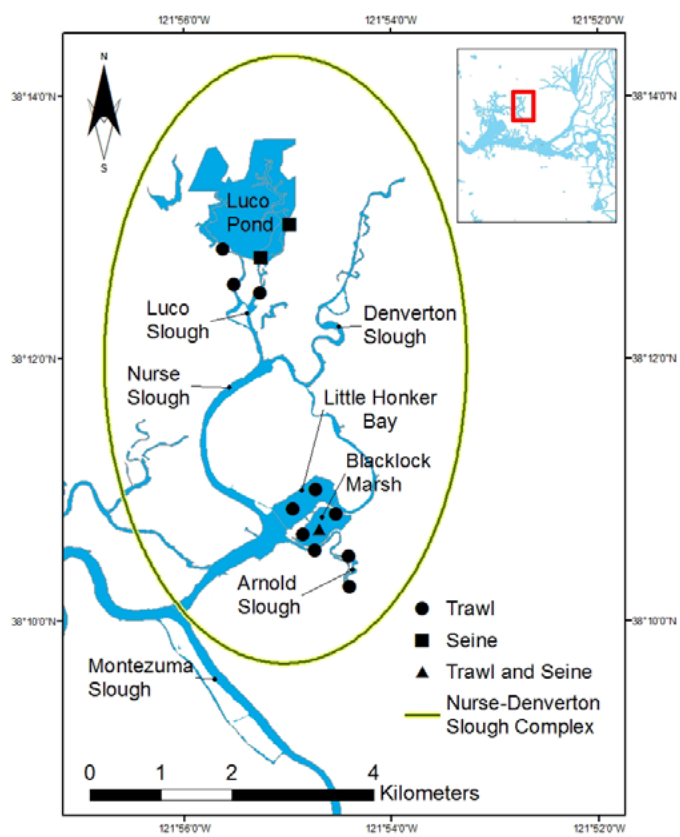


**Figure 1 Map of Blacklock Fish Study sites in the Nurse-Denverton Slough complex, 2014.**

methodologies to the SMFS and North Delta Arc study (O'Rear and Moyle 2014; Young et al. this issue). Monthly trawl catch per unit of effort (CPUE) was calculated by dividing total catch by species per waterway by total number of minutes spent trawling in said waterway. Monthly seine CPUE was calculated by dividing total catch by species per waterway by the number of seine hauls per waterway, resulting in catch per seine haul for each waterway. Three diversity indices were calculated to compare diversity among waterways sampled: the Shannon, Simpson, and Inverse Simpson indices. The Shannon diversity index was calculated as:

$$H' = -\sum_{i=1}^{S} p_i ln(p_i) \qquad \text{(Equation 1)}$$

the Simpson index as:

$$D_1 = 1 - \sum_{i=1}^{S} p_i^2 \qquad \text{(Equation 2)}$$

and the Inverse Simpson index as:

$$D_2 = \frac{1}{\sum_{i-1}^{S} p_i^2} \qquad \text{(Equation 3)}$$

where pi is the proportion of species i and S is the number of species so that

$\sum_{i=1}^{S} p_i = 1$

**Table 1 Waterway description, control structures and sample site number for the Blacklock Fish Study, 2014. WCS = Water Control Structure used to drain or flood water from managed wetland. * indicates WCS present but not in use.**

| *Waterway* | *Waterway Type* | *Number of WCS* | *WCS/ km* | *Diking extent* | *Avg Depth (m)* | *Number of Trawl Sites* | *Number of Seine Sites* |
|---|---|---|---|---|---|---|---|
| Blacklock Marsh | Restoring marsh | 0* | 0 | High | 0.5 – 3 | 3 | 1 |
| Arnold Slough | Small subtidal slough | 3 | 1.3 | Moderate | 1 – 3 | 3 | 0 |
| Little Honker Bay | Embayment | 1 | 0.4 | Moderate | 1 – 2 | 2 | 0 |
| Luco Slough | Small subtidal slough | 12 | 4 | Moderate | 1 – 3 | 3 | 0 |
| Luco Pond | Managed wetland/ pond | 3 | 0.4 | High | 0.5 – 2 | 0 | 2 |

## Results

In 2014, 4,524 fish were captured in trawls and 19,011 fish were captured in seines. The three most abundant species captured in trawls were Mississippi Silverside (*Menidia audens*), Sacramento Splittail (*Pogonichthys macrolepidotus*), and Black Crappie (*Pomoxis nigromaculatus*) (Table 2). The three most abundant species captured in seines were Threespine Stickleback (*Gasterosteus aculeatus*), Mississippi Silverside, and Western Mosquitofish (*Gambusia affinis*) (Table 2).

### *Blacklock Marsh, Arnold Slough, and Little Honker Bay*

Blacklock Marsh was dominated by the invasive Mississippi Silverside — 4,486 individuals were captured, constituting over 75% of the total trawl CPUE (Figure 2) and nearly 95% of the total seine CPUE in Blacklock (Figure 3). Blacklock had the lowest diversity value for all three indices calculated (Table 3). Fish catch in Arnold Slough was diverse and composed of a high proportion of native fishes. Tule perch (*Hysterocarpus traskii*) was the most abundant species, accounting for nearly a quarter of the total CPUE in Arnold Slough (Figure 2). Trawls in Little Honker Bay yielded the fewest fish, but had the highest species diversity for the region in all diversity indices (Table 3), and a greater proportion of pelagic fishes, such as American shad (*Alosa sapidissima*) and Threadfin Shad (*Dorosoma petenense*), than the subtidal sloughs (Figure 2).

### *Luco Slough Complex*

More fish were captured by trawl in Luco Slough than in any other waterway in 2014. The two species with the highest CPUE in Luco Slough were Black Crappie and Sacramento Splittail. During May, there was a spike in abundance of Black Crappie (Figure 2). In Luco Pond, 16,300 fish were captured, total, and seasonal abundance was highly variable throughout the year (Table 3). Fish abundance in this managed wetland was driven primarily by capture of Threespine Stickleback in

**Table 2 Fish species catch and CPUE by trawl and seine of all fishes where more than 50 individuals were sampled combined from Arnold Slough, Blacklock Marsh, Little Honker Bay, Luco Slough and Luco Pond, January – December, 2014. Bold* indicates native species.**

| | | | *Trawls* | | | *Seines* | | |
|---|---|---|---|---|---|---|---|---|
| ***Species Common Name*** | ***Scientific Name*** | ***Total Catch*** | ***Catch*** | ***CPUE*** | ***% CPUE*** | ***Catch*** | ***CPUE*** | ***% CPUE*** |
| Threespine Stickleback* | *Gasterosteus aculeatus* | 12391 | 16 | 0.03 | 0.36% | 12375 | 167.23 | 64.87% |
| Mississippi Silverside | *Menidia audens* | 4486 | 1793 | 3.14 | 40.19% | 2693 | 36.39 | 14.12% |
| Black Crappie | *Pomoxis nigromaculatus* | 2227 | 786 | 1.38 | 17.62% | 1441 | 19.47 | 7.55% |
| Western Mosquitofish | *Gambusia affinis* | 1456 | 0.00 | 0.00 | 0.00% | 1456 | 19.68 | 7.63% |
| Sacramento Splittail* | *Pogonichthys macrolepidotus* | 1123 | 793 | 1.39 | 17.78% | 330 | 4.46 | 1.73% |
| Shimofuri Goby | *Tridentiger bifasciatus* | 495 | 380 | 0.67 | 8.52% | 115 | 1.55 | 0.60% |
| Common Carp | *Cyprinis carpio* | 450 | 45 | 0.08 | 1.01% | 405 | 5.47 | 2.12% |
| Tule Perch* | *Hysterocarpus traskii* | 235 | 234 | 0.41 | 5.25% | 1 | 0.01 | 0.01% |
| Striped Bass | *Morone saxatilis* | 208 | 207 | 0.36 | 4.64% | 1 | 0.01 | 0.01% |
| Prickly Sculpin* | *Cottus asper* | 187 | 46 | 0.08 | 1.03% | 141 | 1.91 | 0.74% |
| Threadfin Shad | *Dorosoma petenense* | 86 | 85 | 0.15 | 1.91% | 1 | 0.01 | 0.01% |
| American Shad | *Alosa sapidissima* | 62 | 62 | 0.11 | 1.39% | 0 | 0 | 0.00% |
| Yellowfin Goby | *Acanthogobius flavimanus* | 58 | 9 | 0.02 | 0.20% | 49 | 0.66 | 0.26% |

February, May, June, and July, accounting for 75% of the total CPUE (Figure 3). During all other months sampled, fewer than 6 fish per seine were captured in Luco Pond each month. Ninety-nine percent of the 1,441 Black Crappie and all of the 108 Sacramento Splittail found in the pond were captured during May and June sampling. Nearly all fish captured in these months were young-of-year.

## Discussion

### *Blacklock Marsh, Arnold Slough, and Little Honker Bay*

Arnold Slough and Little Honker Bay, on either side of Blacklock Marsh, are both in close proximity to Montezuma Slough, a major corridor of Suisun Marsh, but each has unique geomorphic features that influence fish assemblage. Both waterways yielded more diverse catches of estuarine and migratory fishes than Blacklock Marsh (Table 3), despite being adjacent and hydrologically connected. This difference suggests that most fishes present in the area were not utilizing Blacklock Marsh, perhaps because habitat features that attract fish to the other waterways were absent from Blacklock Marsh.

An exception to this pattern is the high abundance of Mississippi Silverside found in Blacklock Marsh year-round (Figure 2). One hypothesis for the abundance of Mississippi Silverside is that the shallow water in the internal ponds warms more quickly than deep subtidal sloughs surrounding Blacklock. Mississippi Silverside flourish in higher water temperatures, with optimal growth and reproduction occurring between 20 °C and 25 °C (Moyle 2002; O'Rear and Moyle 2014). Additionally, during the summer months, the shallow ponds in Blacklock accumulated green filamentous algae that may have provided spawning substrate for Mississippi Silverside. Because Mississippi Silverside is a known predator of native fish species, including Delta Smelt (*Hypomesus transpacificus*) eggs or larvae (Baerwald et al. 2012), further research on conditions that support Mississippi Silverside reproduction and foraging in Blacklock is warranted.

### *Luco Slough Complex*

Luco Slough had relatively high diversity compared to Luco Pond. Splittail were present in both waterways but were much more abundant in Luco Slough. Two notable species seem strongly associated with managed wetlands, Threespine Stickleback and Black Crappie. Both inhabit

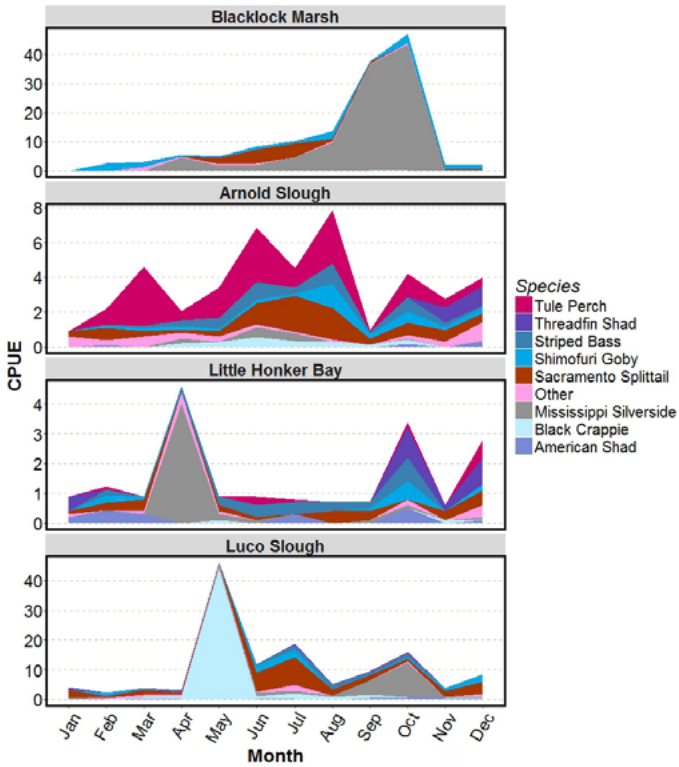


**Figure 2 Monthly trawl CPUE by fish species and waterway, January – December, 2014. Y-axis scale varies by waterway.**

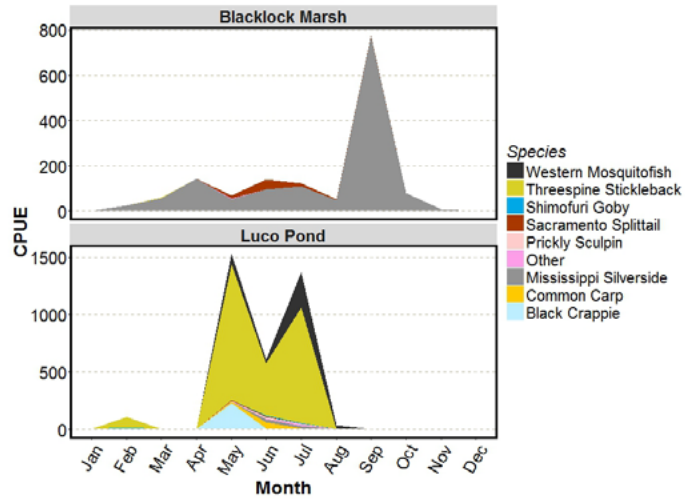


**Figure 3 Monthly seine CPUE by fish species and waterway, January – December, 2014. Y-axis scale varies by waterway.**

Luco Pond and were found in greatest abundances in subtidal sloughs with high connectivity to managed wetlands. Threespine Stickleback hit peak abundance in Luco Pond during the drain cycle in May (Figure 4), and many of these fish were presumably transported to tidal Luco Slough through water control structures. Threespine Stickleback require submerged vegetation for nest building (Moyle 2001), which managed wetlands contain in abundance. Spawning can begin as early as October (Batzer and Resh 1992), which coincides with the start of typical managed wetland flooding (Rollins 1981).

Black Crappie were found in high abundance in Luco Slough and Luco Pond. Peak Black Crappie catch occurred in May in Luco Pond during a period of pond draining (Figure 4), corresponding with peak Black Crappie abundance in Luco Slough, an indication of fish transport from managed wetlands to subtidal sloughs. Spawning occurs from March to July, and while previous research suggests that reproduction only occurs in fresh water (Wang and Reyes 2008), Black Crappie exhibited reproductive behaviors in Luco Pond at salinities > 1 part per trillion (ppt) (personal observations). The upper salinity tolerance for survival is thought to be 10 ppt (Moyle 2002), but Black Crappie were collected in salinities up to 11 ppt in Luco Slough. High densities of food in the form of zooplankton and macroinvertebrates may facilitate the survival and reproduction of Black Crappie in managed wetlands and adjacent tidal sloughs despite physiological stress.

Managed wetlands function as seasonal fish habitat through provision of food, cover, and spawning substrate while flooded from autumn through spring. Luco Pond had a higher percentage of native fish, a greater abundance of fish, and higher diversity index values than Blacklock Marsh. This difference in fish catch and fish diversity between a managed wetland and a breached pond was likely a result of differences in water exchange with the adjacent waterways. In Luco Pond, water is circulated through control structures, which greatly mutes tidal exchange between the pond and subtidal slough, resulting in high water residence time in the pond. Blacklock Marsh has full tidal exchange through two large levee breaches that connect to Little Honker Bay, which results in high water exchange. High water residence time can support phytoplankton and zooplankton blooms, which provide an abundant food source for the early life stages of many fish (Durand 2015), and may also help retain larval fish in suitable conditions. The presence of Threespine Stickleback and Black Crappie that may be reproducing in Luco Pond and the absence of other species (e.g., Mississippi Silverside) indicate that wetland management can influence reproduction and recruitment. The water level in Luco Pond was low or dry during summer months when many non-native species, including Mississippi Silverside, reproduce (Figure 4) (Meng and Matern 2001).

**Table 3 Diversity indices and native fish catch by waterway, January – December 2014. All information is calculated from trawl data, except for Luco Pond where no trawl data is available.**

| *Waterway* | *Total Fish Catch* | *CPUE* | *Species Richness* | *Shannon Diversity* | *Simpson Diversity* | *Inverse Simpson* | *% Native* |
|---|---|---|---|---|---|---|---|
| Blacklock Marsh | 1839 | 11.36 | 17 | 0.82 | 0.38 | 1.60 | 7.60% |
| Arnold Slough | 598 | 3.69 | 17 | 1.99 | 0.80 | 5.04 | 27.90% |
| Little Honker Bay | 163 | 1.53 | 12 | 2.15 | 0.87 | 7.60 | 22.70% |
| Luco Slough | 1924 | 11.04 | 16 | 1.71 | 0.75 | 4.06 | 24.60% |
| Luco Pond | 16300 | 305.10 | 11 | 0.91 | 0.41 | 1.69 | 77.30% |

Seasonal pond draining transports fish and invertebrates to tidal sloughs and increases foraging opportunities for fish in tidal sloughs connected to managed wetlands. For example, White Catfish (*Ameiurus catus*) diets in subtidal sloughs shift seasonally to invertebrates that are transported from managed wetlands (O'Rear 2012).

It is currently unknown why Sacramento Splittail are abundant in Luco Slough and not in Luco Pond, but it may be a result of intake pipes being located high in the water column, limiting the entrainment of benthic-oriented fish. Although size, location, and management strategies may differ among ponds in Suisun Marsh, our results support the idea that managed wetlands can be managed to support food webs and fish diversity in tidal sloughs.

## Conclusion

Considerable differences were seen in the distribution and abundance of fishes among waterways, indicating that unique combinations of characteristics for each waterway determine which fish species inhabit them. Luco Pond yielded a higher percentage of native species, higher fish abundances, and a more diverse catch than Blacklock Marsh. An exploration of the reasons for these differences and their implications for pond restoration are forthcoming in future publications using our data. Intensive management of restoration sites could aid in minimizing negative outcomes and maximizing aquatic productivity. The management of Luco Pond has a great influence on fish in Luco Slough by providing food, cover, and spawning habitat. It is likely that similar dynamics occur in many of the managed wetlands of Suisun Marsh, creating the potential to develop management strategies that continue to attract waterfowl for hunting, while also providing spawning and rearing habitat for select native fishes as well as providing food for fish inhabiting adjacent subtidal sloughs.

## Acknowledgements

Robert Eddings of California Waterfowl Association and John Bessolo, owner of Potrero Duck Club, made access to Luco Pond possible. Particular thanks to Melissa Riley for field assistance and Matthew Young for help creating the "R" code used to generate the figures in this article. Special thanks to California Department of Fish and Wildlife and the United States Fish and Wildlife Service for the Cooperative Endangered Species Conservation Fund (Section 6) Grant P1382003.

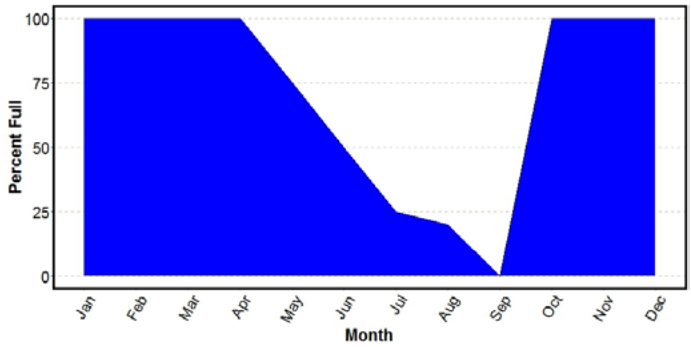


**Figure 4 Monthly pond level (percent full) of Luco Pond, January – December, 2014. Major draining occurred from April – September.**

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