Monitoring the Response of Fish Communities to Salt Pond Restoration: Final Report

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&

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Introduction

When the first European explorers arrived in San Francisco Bay in the 16th Century, the intertidal margins of the South, Central, and much of North Bay were covered in expanses of pickleweed (*Salicornia (Sarcocornia) sp.*) and *Spartina* marsh, providing habitat for migratory waterfowl, shorebirds, and fishes. Historically, pickleweed encompassed approximately 300 square miles of marsh, an area the size of New York City. Beginning in the mid 1800's, much of this habitat was reclaimed for agriculture, development and salt production, resulting in a 90% reduction in tidal marsh habitat.

Salt marshes support vast numbers of shorebirds and are home to endangered species such as the California Clapper Rail and the salt marsh harvest mouse, and historically supported feeding grounds for migratory fishes such as salmon, sturgeon, anchovy, and herring. Salt marshes are also the permanent home of the longjaw mudsucker (*Gillichthys mirabilis*), a small gobiid fish that makes its home in high intertidal creeklets amongst the pickleweed. The mudsucker has adapted to the high marsh by developing the ability to breathe air and by producing a moist, sticky slimecoat to protect against desiccation (Todd and Ebeling 1966). The longjaw mudsucker is found exclusively within these pickleweed marshes and thus have experienced significant habitat loss within San Francisco Bay/Estuary, much like the endangered Clapper Rail and salt marsh harvest mouse.

In 2003, a consortium of state and federal agencies purchased over 15,000 acres of salt ponds from the Cargill, Inc, and began the largest tidal marsh restoration project west of the Mississippi River. The restoration of these former salt-producing ponds to tidal wetlands presumably would benefit shorebirds, waterfowl, and fish populations. To maximize the benefit to a diverse community, the "restoration" of former production salt ponds has taken several forms, each with different management objectives: full breaching of pond levees to tidal flow to create tidal wetlands; "partial breaching" and the placement of a water control structure to create ponds with muted tides for shorebirds and migratory waterfowl; and ponds that have water levels managed by water control structures that create deeper pond habitats for diving ducks. The creation of a mosaic of habitats utilized of existing pond configurations and maximizes the creation of key habitats outlined in the Goals Project (1999). Moreover, restoration actions that provide operational control of water levels afford the application of adaptive management.

Following the acquisition of the former salt ponds, the ponds on Station Island in the Alviso Marsh (formerly A19-21) were breached under the leadership of the Santa Clara Valley Water District in July 2006. More directed restorations began in 2008 with the initiation of the first phase of the South Bay Salt Pond Restoration Program. Phase One consisted of the full restoration of tidal flow to Knapp's Tract (i.e., Pond A6) in the Alviso Marsh (October 2010), to Outer Bair Island (June 2008), and to ponds E9, E8, and E8x within the Eden Landing Complex (November 2011). In addition, Pond SF2 (Ravenswood) was fitted with a water control structure and limited tidal flows were restored to the pond, and Pond A8 was fitted with a tide gate and connected to Alviso Slough during summer months in an attempt to flush out high concentrations of mercury that had accumulated within the sediments.

The goal of this project is to document the species assemblages within the restored salt ponds and to design a monitoring program to assess the effect of pond restoration on fish assemblages inside newly breached ponds and adjacent sloughs.

Fish Community Study

Study Areas

South San Francisco Bay (referred to hereafter as “South Bay”) is a tectonically formed embayment along the southeastern leg of the San Francisco Bay Estuary (Atwater 1979). This basin has a wetted area of 554 square kilometers (km^2) and a mean depth of 3.4 meters (m) at mean low water (Cheng and Gartner 1985). South Bay consists of mostly open-water and sandy- and muddy-bottomed habitat that is bordered by several remnant marsh complexes and active salt ponds owned by Cargill, Inc. Some of these marshes have been or are in the process of being restored to tidal action for the benefit of a suite of biota.

Unlike the northern portions of the San Francisco Estuary, there is not a delay in high tide as you move away from the Golden Gate, but rather tides move as a standing waves, resulting in the near simultaneous occurrence of high slack tides throughout the southern portion of the basin (Cheng and Gartner 1985). In addition, the two principle tidal force components become increasingly out of phase, which, in addition to a decrease in the mean basin depth, results in an increased tidal amplitude in the southern part of the bay (i.e., the Alviso Marsh Complex) (Cheng and Gartner 1985).

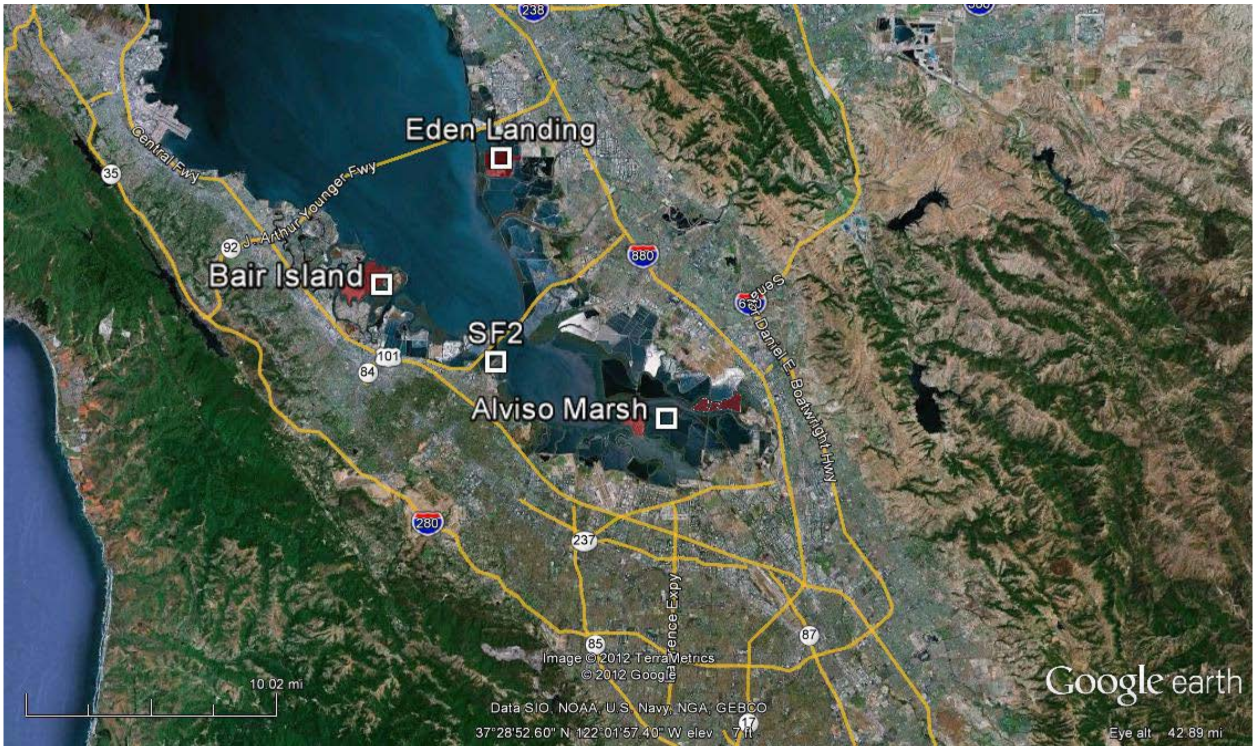


Figure 1. Marsh complexes under study.

Alviso Marsh Complex

The Alviso Marsh Complex is the southernmost marsh of South Bay and is the location of the earliest restoration actions by the South Bay Salt Pond Restoration Program. The Alviso Marsh Complex consists of two major tidal channels and four tributary sloughs (Figure 2a). Alviso Slough is fed by the Guadalupe River at the uppermost end, is shallow (<4-m depth), is relatively narrow (30- to 70-m wide), and is bordered by earthen levees along much of its 8-km length. Alviso Slough contains the Port of Alviso, the home of a small commercial fishing fleet and the Alviso Marina. Alviso Slough has a small brackish marsh (~0.1 km^2) dominated by bulrush (*Schoenoplectus* sp.) located at the Alviso County Park, which is immediately downstream of the port. Alviso Slough is adjacent to Knapp's Tract at its lower end, and two of the Knapp's Tract breaches drain into the slough. The lower 5 km of slough are bordered by marshes dominated by cordgrass (*Spartina* spp.) and pickleweed (*Sarcocornia* spp.).

Figure 2a. Alviso Marsh Complex and sloughs. Breached ponds are shaded red.

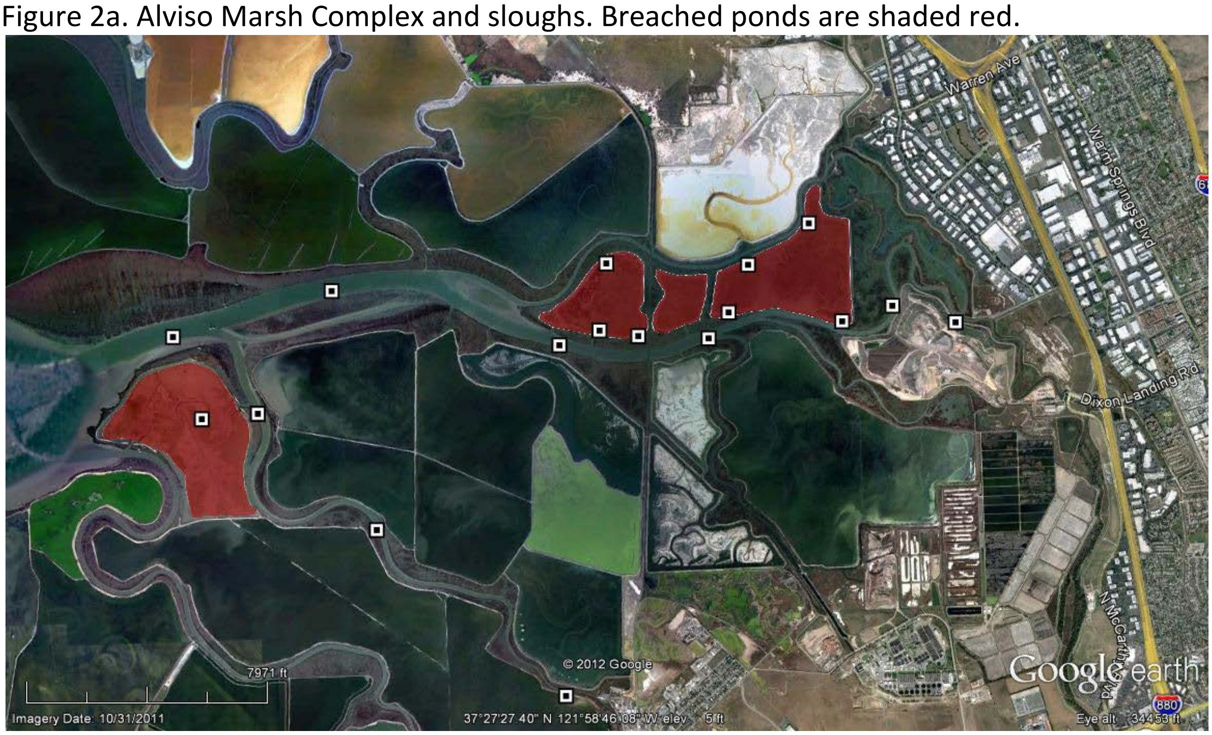


Figure 2b. Otter trawl sampling stations in Alviso Marsh Complex.

Coyote Creek is fed by Coyote Creek at the upstream end and empties into South Bay at its downstream end. Coyote Creek is bordered by the initial restoration areas (Island Ponds), is bordered by the brackish Warm Springs Marsh, and has four tributary sloughs draining into it: Alviso Slough, Mud Slough, Artesian Slough, and Abrae. Coyote Creek (the largest slough in the Alviso Marsh Complex) is ~11-km long, is 65-m wide at its upstream end, is 100-m wide adjacent to Pond A21, and 375-m wide at its lower end; it has maximum depths that range from 5 m (adjacent to South Bay) to 2 m at its uppermost end. Like Alviso Slough, Coyote Creek is bordered by earthen levees, with a narrow band of cordgrass- and pickleweed-fringing marsh along the lower 9 km; however, directly across from Pond A21, Coyote Creek is bordered by the historic Triangle Marsh, a salt marsh about the size of the smallest Pond A21(~0.3 km^2) (Stevenson et al. 1987).

Artesian Slough is the third-largest slough within the Alviso Marsh Complex and is the location of the Santa Clara/San Jose Wastewater Treatment Center, which discharges tertiary treated sewage into Artesian Slough.

There are four fully tidal, restored salt ponds within the Alviso Marsh Complex. In order of increasing wetted area, they are A20, A21, A19, and A6 (Knapp's Tract). All four ponds are ringed by earthen levees, though the levee in A6 has been lowered to facilitate tidal exchange. A19, A20, and A21 (referred to collectively as the "Island Ponds") are located on Station Island adjacent to the former town of Drawbridge and are mostly intertidal. All three are ringed by a "borrow ditch" (so called because the ditch was created by borrowing pond sediment to construct the levees). The borrow ditch is typically 1-2 m lower than the former salt pan, which is the relatively flat surface used to evaporate salt. The borrow ditches get considerably shallower as you move away from the breach. The salt pan on A21 is the highest in elevation and is the most heavily vegetated of the Island Ponds. A19 has the lowest salt pan and has the least amount of vegetation (Fulfrost 2011). A6 was modified prior to breaching, and the former borrow ditch quickly accreted sediment (personal observation). The former salt pan of A6 has begun to vegetate, but coverage is less than 20% that of A21 (Fulfrost 2011). Unvegetated intertidal salt pans support large amounts of green algae in the spring and summer months, which likely provide easily accessible organic material for primary consumers.

Photo 1. Marsh plain of A19 (top) with very little vegetation and A21 (bottom) with considerable amounts of vegetation.

Bair Island Marsh Complex

The Bair Island Marsh Complex is adjacent to the Port of Redwood City. Bair Island consists of three islands (inner, middle, and outer) separated by tidal sloughs. The Bair Island salt ponds were abandoned in the 1970's after less than two decades of salt production (Phillip Williams and Associates, 2000). The central outer pond (Figure 3) was passively recolonized by marsh vegetation and was allowed to return to tidal salt marsh, while the southernmost outer pond was used to deposit supra-tidal dredged material from the adjacent port (Bair Island Restoration and Management Plan appendix A 2000). The vegetation community of Bair Island largely consists of pickleweed and cordgrass. The northernmost pond in outer Bair Island was breached in 2008 and has begun to recruit pickleweed and cordgrass to the marsh surface. The intertidal ponds in outer Bair Island are ringed by a borrow ditch, similar to those at Alviso.

Figure 3a. Bair Island Marsh Complex and adjacent sloughs. Breached ponds are shaded red.

Figure 3b. Otter trawl stations within the Bair Island Marsh Complex.

The sloughs surrounding Bair Island consist of Redwood Creek to the south/southeast, Smith Slough to the south/southwest, Steinberger Slough to the north/northwest, and the central South Bay channel to the east. The Redwood Creek channel is dredged to a depth of about 10 m for shipping. Though the position of the sloughs has not changed since 1857, building of levees and the creation of the Foster City development to the north halved the Steinberger Slough drainage, resulting in a decrease in current velocity and the gradual sedimentation of the slough. Though the slough remains unvegetated, Steinberger Slough and much of Corkscrew Slough are intertidal, with an average depth of ~0.5 m above mean low water (Philip Williams & Associates appendix A 2000). It is likely that the reconnection of former marsh habitat to Steinberger Slough will cause scouring and an increase in average depth. The remnants of earthen levees that were used to construct the salt ponds border Corkscrew, Smith, and Steinberger sloughs; however, Redwood Creek and the adjacent deepwater channel are bounded by mudflat.

Eden Landing

Eden Landing is the site of the oldest commercial salt ponds in San Francisco Bay, and it probably was a salina (a natural salt flat where little or no vegetation occurs) prior to its development in the 1850s (Johnck 2008). The restored Eden Landing Marsh (Figure 4) is bounded on the north by the newly constructed Mt. Eden Creek flood control channel and is bounded on the south by the Old Alameda Creek channel. The lower ends of Mt. Eden Creek and Old Alameda Creek are bounded by riprapped levees, and are bounded by earthen levees with the exception of the pond breaches upstream of the riprapped areas.

Figure 4. Eden Landing Marsh Complex and associated sloughs

Three ponds in Eden Landing were restored to tidal action. The newly breached habitat at Eden Landing has already begun to vegetate, primarily with pickleweed. Eden Landing ponds lack a clearly defined borrow ditch, making them different from the Alviso and Bair Island ponds. The Eden ponds do have some vestigial tidal creeks in some areas that are completely intertidal.

Ravenswood

Ravenswood is a managed pond on the western shore of South Bay, directly below Dumbarton Point. The former salt pond was fitted with water control structures, and the water level is managed to facilitate foraging of shorebirds. Because of the limited tidal range within the pond, very little vegetation has recruited within the pond complex. Ravenswood is adjacent to a fringing salt marsh dominated by pickleweend and gumplant (*Grindelia*). The fringing marsh is between 100-m and 30-m wide and has several 2^{nd} and 3^{rd} order creeklets (small, typically dendritic tidal channels) draining it. The channel that connects the water control structures to the adjacent bay cuts through the marsh and is about 20-m wide and 60-m long. Because of the limited tidal flow, there is poor channel definition within the pond itself, but the remnant borrow ditch is present.

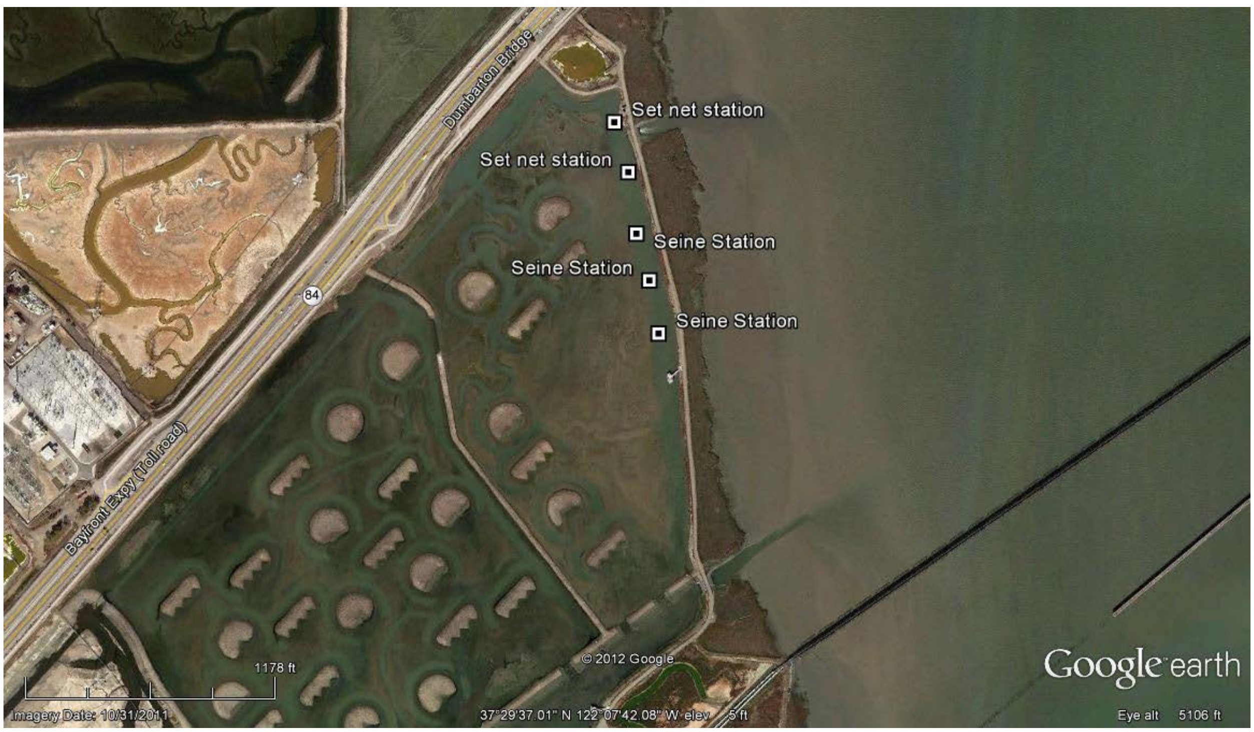


Figure 5. Ravenswood (SF2) and sampling stations.

Sampling Methods

Beginning in July 2010, we began sampling sites within the Alviso, Eden Landing, and Bair Island marshes. Initial sampling trips consisted of otter-trawl surveys in the slough habitats and the deployment of 10-15 baited minnow traps in intertidal creeks on the marsh plain; however, prior to October 2010, no otter trawls were used at Eden Landing. Beginning in October 2010, we began sampling at Ravenswood Marsh using minnow traps and a modified beam trawl. By May 2011, we modified our sampling techniques to maximize safety and improve sampling efficiency.

From July 2010 to May 2011, bimonthly juvenile and adult fish sampling was conducted at standard sites within the Alviso Marsh Complex and the Bair Island Marsh using a four-seam otter trawl with a 1.5 m X 4.3m opening, a length of 5.3 m, and a mesh size of 35-mm stretch in the body and 6-mm stretch in the cod end. Prior to May 2011, between 14 and 20 otter trawls were conducted within the Alviso Marsh Complex, and six to 12 trawls were conducted at Bair Island. Beginning in May 2011, 15 stations were sampled monthly within the Alviso Marsh Complex, with those adjacent to Station Island being sampled twice each sampling trip at high and low tide. Stations were located along Coyote Creek and along Alviso Slough. Two tributary sloughs (Artesian and Mud) to Coyote Creek were sampled over part of this study; however, sampling was intermittent and the stations were eventually abandoned in May 2011. Beginning in July 2011, five stations were sampled at Bair Island using the otter trawl. Otter trawl surveys at Bair Island were expanded to include four additional sites in order to accommodate recently breached habitat in May 2011, and the frequency of surveys was increased to monthly. Sampling at Eden Landing was sporadic because of seasonal navigation hazards and levee closures during favorable tides. Because of the high elevation of the marsh and an increase in navigational hazards originating from construction in Pond E9, otter trawling was abandoned at Eden Landing in May 2011. Eden Landing was sampled approximately quarterly from June 2011 to June 2012 using baited minnow traps, seines, gillnets, and a smaller, less efficient otter trawl. Trawls were towed for 5 minutes in small sloughs (<3-m deep and <70-m wide) and for 10 minutes in larger sloughs (>3-m deep and >70-m wide) to compensate for small catches. Monthly gillnet and trammel-net (referred to as “set nets”) surveys were initiated in May 2011 at both Bair Island and Alviso in an attempt to survey fish species capable of evading trawl surveys. At Pond A6, Alviso Slough adjacent to A6, Pond A8, Eden Landing, and Ravenswood, inshore fishes were sampled using a 30-m, 1.2-m-deep beach seine having a stretched mesh size of 10 mm and a bag size of 1.5 m x 1.5 m. A small four-seam otter trawl with a mouth size of 2.44 m x 0.75 m, a length of 3 m, a mesh size of 32-mm stretch in the body and 6-mm stretch in the cod end was used to augment the seine catches within A6 because depth <1 m precluded the use of larger sampling gear.

For each site, temperature (degrees Celsius, °C), salinity (approximated by practical salinity units, PSU), dissolved oxygen parameters (percent saturation, and milligrams per liter, mg/L), and specific conductance (microSiemens, µS) were recorded using a Yellowstone Springs Instruments (YSI) model 85 meter. Water clarity was measured using a Secchi disk and recorded in centimeters (cm). Depths at which the trawl was towed were also recorded.


Photo 2. Deploying the large otter trawl.

The contents of each trawl, seine, trammel net, or gillnet were placed into large containers of water. Fishes were identified, measured to the nearest millimeter standard length, and released. Sensitive and native species were processed first and immediately released. Numbers of bay shrimp (*Crangon franciscorum, Crangon nigricauda, Crangon nigromaculata*), Oriental shrimp (*Palaemon macrodactylus*), and bivalve mollusks (e.g., *Corbula amurensis*, *Corbicula fluminea*, and *Macoma* sp.), brachyuran decapods (e.g., *Hemigrapsus oregonensis*, *Metacarcinus magister* (formerly *Cancer magister*)) were also recorded. Crustaceans from the order Mysida were pooled into one category, "mysids," and given and abundance ranking: 1 = 1-3 mysids, 2 = 4-50 mysids, 3 = 51-100 mysids, 4 = 101-500 mysids, and 5 = >500 mysids. High numbers of mysids within the restoration areas made the index necessary because otter trawls are not an efficient way to sample mysids, and those that are captured are very difficult to count. A similar index was developed for crustaceans from the order Isopoda: 1 = 1-3 isopods, 2 = 4-10 isopods, 3 = 11-50 isopods, 4 = 51-100 isopods, and 5 = >100 isopods.

Because of an equipment malfunction, no sampling was conducted in February 2012; however, Alviso and Bair Island were sampled in late January and again in early March in an attempt to mitigate the issue.

Data Analysis

Species accumulation curves were used to identify the appropriate amount of effort required to document the species assemblages both within the Alviso Marsh Complex and the Bair Island Marsh and within the slough/restoration areas of the marsh. Cumulative effort was plotted against cumulative number of species captured, and the point at which diversity stopped increasing was deemed the appropriate effort for that region.

For this report, catch-per-unit-effort was calculated for individual trawls as

Equation 1: $$\text{CPUE}_{\text{(trawl)}} = \sum_{i=1}^{j} \left(\frac{i}{n}\right) x5$$

where *i*=is the number of fish species "*i*" that were captured, *j* is the total number of species in each trawl and n is the total number of minutes the trawl was towed. Because the shortest trawl that is currently used in this study is five minutes long, CPUE is standardized for 5-minute trawls (i.e., if one fish from species X is captured in a 5-minute tow, the $\text{CPUE}_{\text{(trawl)}}$ trawl for that species is one, if one fish is captured in a 10-minute tow, the $\text{CPUE}_{\text{(trawl)}}$ for that that species is ½).

Monthly and regional CPUE was determined by:

Equation 2: $$\text{CPUE}_{\text{month or region}} = \sum_{n=1}^{n} \frac{(\text{CPUE (trawl)})}{n}$$

where *n* is the number of trawls. Monthly water quality samples were determined by the same formula, with the water quality parameter of interest being substituted for $\text{CPUE}_{\text{trawl}}$ in Equation 2. Gillnet and trammel net CPUE were computed using Equation 1, with the time the net was deployed being substituted for the trawling time.

Frequency of occurrence was calculated by:

Equation 3: $$\text{Frequency of Occurrence}_{(I)} = \frac{p}{n}$$

where *p* is the number of trawls in which fish species *i* is present and *n* is the number of trawls.

Because the field samples are spatially and temporally autocorrelated, they violate parametric assumptions. This makes "replicate" trawls within a habitat pseudoreplicates as they are not independent. Placing error bars on CPUE and frequency-of-occurrence data is therefore inappropriate (Hurlburt 1984).

Sampling frequency for the fish community surveys were determined using a presence/absence, pairwise comparison between sampling events (Sørensen similarity index, or SSI). These comparisons were blocked by marsh (e.g., Alviso Marsh Complex in December was only compared with Alviso Marsh Complex in November). The SSI is given by:

Equation 4: $$QS=\sum_{n=0}^{n} \frac{2n\text{A}\cap\text{B}}{n\text{A}+n\text{B}} = \sum_{n=0}^{n} \frac{2\text{C}}{\text{A}+\text{B}}$$

where *A* and *B* are the number of species in samples A and B, respectively, *C* is the number of species shared by the two samples, and QS is the similarity index. The SSI was also used to compare restored habitat with unrestored habitat.

In addition to the SSI, the Bray-Curtis similarity index was also used to compare sequential sampling trips as well as restored and unrestored habitats. The Bray-Curtis index accounts for the actual abundance of fish species, not just the presence/absence of species.

Equation 5: $$BC=\sum_{n=0}^{n} \frac{Min(\text{A}\cap\text{B})}{n\text{A}+n\text{B}} = \sum_{n=0}^{n} \frac{2*Min(\text{C})}{\text{A}+\text{B}}$$

where *A* and *B* are the number of individuals from all species in samples A and B, respectively, C is the minimum number individuals of species *n* if that species occurs at both sites, and BC is the similarity index.

In order to simplify the discussion, the water quality section will be limited to the two marshes where otter trawling is the principle sampling method employed (the Bair Island Marsh and the Alviso Marsh Complex). The water quality of Bair Island is similar to that at both Eden Landing and outside of the Ravenswood complex (see Hobbs and others 2011).

Water quality parameters for Central South San Francisco Bay were obtained from the US Geological Survey's water quality survey of San Francisco Bay website. Delta outflow was obtained from the California Department of Water Resources' Dayflow website.

Results and Discussion

Environmental Conditions

Salinity

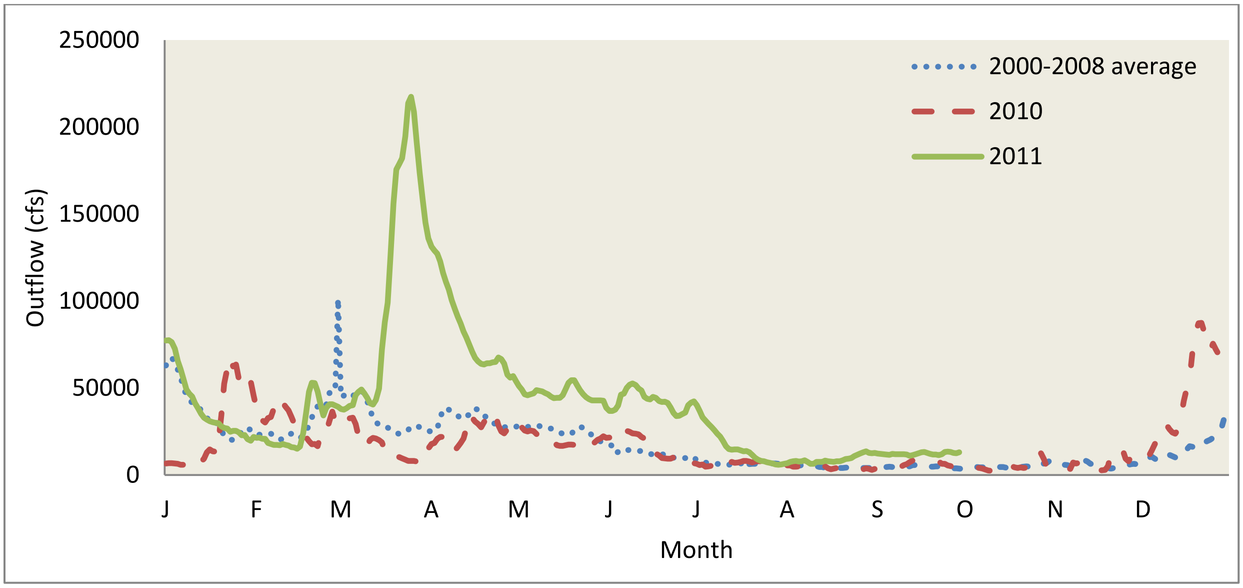


Figure 6. Daily Delta outflow in cubic feet per second (cfs) for 2010, 2011, and the average for the years 2000 - 2008 (Dayflow 2012).

Salinities within South San Francisco Bay are inversely correlated with both Delta outflow and outflow from local creeks (Stevenson et al. 1987), and are typically lowest in the winter and spring months. Historically, Delta outflow explains 85% of the salinity variation in the Alviso Marsh Complex, and local stream flows accounted for 15% of the variation (Stevenson et al. 1987). Reflecting average Delta outflow and local stream runoff, salinities in 2010 were close to average and had already increased to summer highs at the start of this project in July 2010 (Figure 6,7, and 8). In 2011, above-average precipitation in both local watersheds and in the Sacramento-San Joaquin watershed resulted in high Delta outflows and high local stream flows (Figure 6 and 7). This resulted in salinities than were lower than average for a longer time period in 2011 than in either 2010 or 2012 (Figure 7 and 9). Precipitation in all drainages during the 2012 water year has been below average to date and has resulted in salinities that are higher than average.

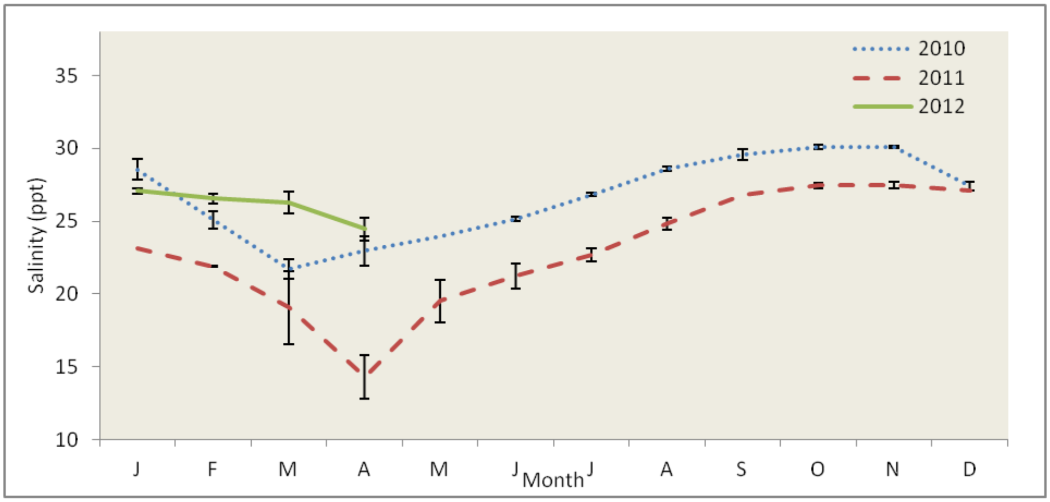


Figure 7. Monthly salinities measured in "central" South San Francisco Bay, adjacent Bair Island (USGS SFB WQ monitoring, accessed July 2012). Error bars are ±1 SD.

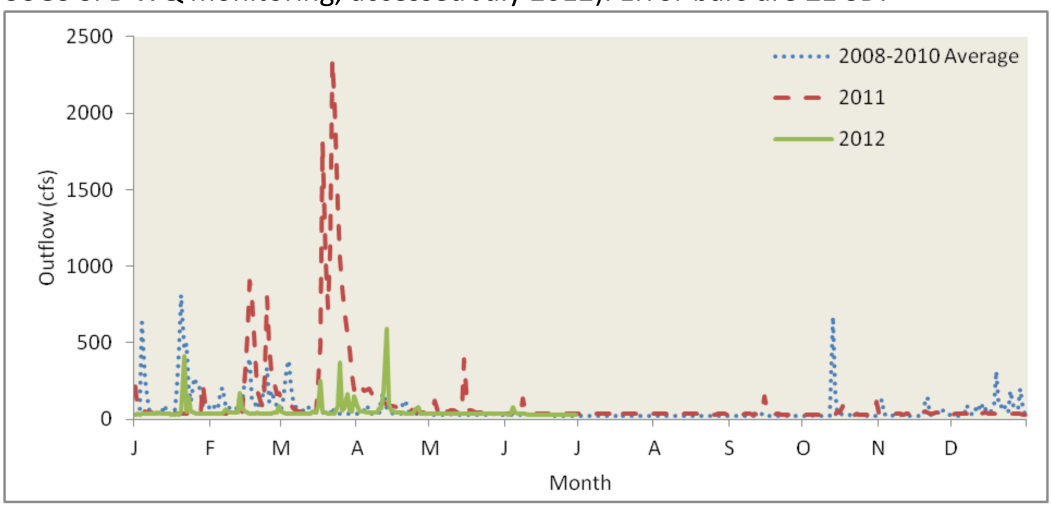


Figure 8a. Daily averages of local stream inflows for the Alviso Marsh Complex from the Guadalupe River.

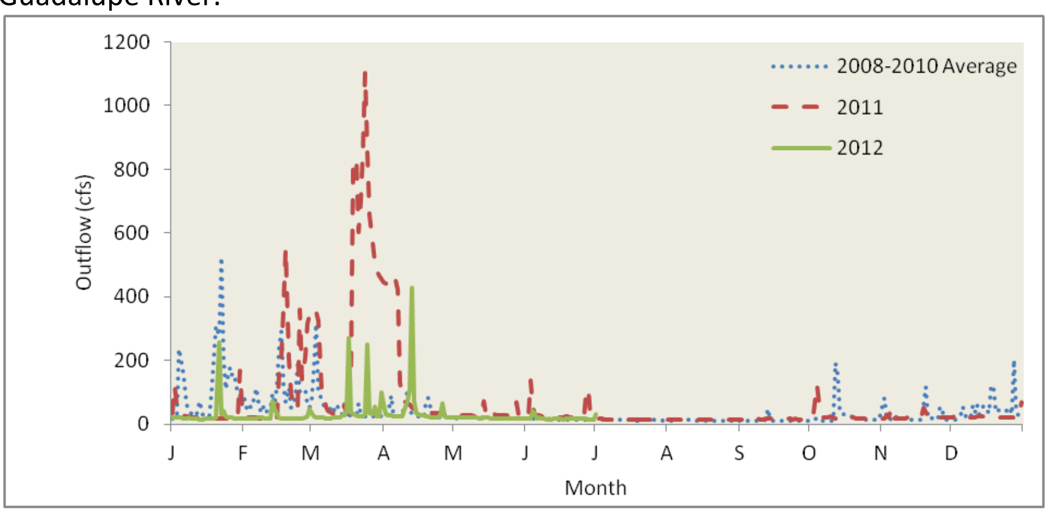


Figure 8b. Daily averages of local stream inflows for the Alviso Marsh Complex from Coyote Creek.

The Alviso Marsh Complex lies downstream of the Guadalupe River and Coyote Creek - two of the three largest tributaries to South San Francisco Bay - and contains the discharge site of the San Jose/Santa Clara wastewater treatment facility, which releases tertiary treated sewage throughout the year at a rate of approximately 200 cubic feet per second (cfs). As a result, this region had lower and more variable salinities than other study sites (Figure 9). There is a distinct geographic gradient in place year-round in the Alviso Marsh Complex, with the lowest salinities consistently located in upper Artesian, upper Alviso, and upper Coyote Creeks and the highest salinities adjacent to South San Francisco Bay. The amplified tidal range in the Alviso Marsh Complex and the perennial input of freshwater from local sources result in salinity swings of over 10 ppt throughout the tide cycle (MacVean and Stacey 2011). These salinity fluctuations likely preclude more stenohaline organisms from all or part of the marsh at certain tides.

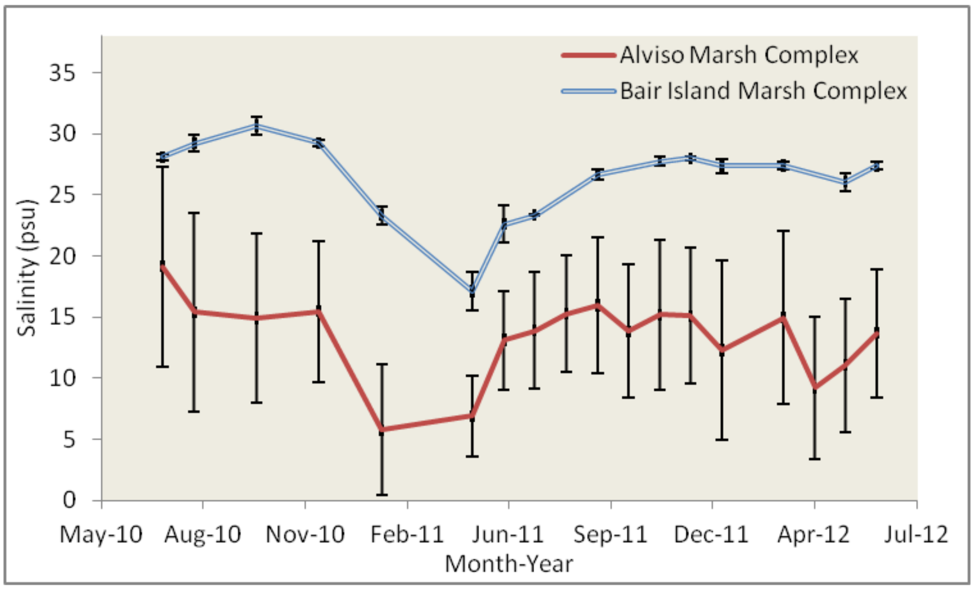


Figure 9. Monthly average salinities within the Bair Island Marsh and within the Alviso Marsh Complex. Error bars are standard deviation for each month.

Bair Island and Ravenswood lack significant freshwater inflow. As a result, these marshes have more stable salinity regimes, both geographically and throughout the tide cycle (Figure 9). Because of these marshes' proximity to the deep water channel of central South Bay, salinities within these marshes tend to be close to the salinities in the adjacent South Bay (Figure 6).

<u>Dissolved Oxygen</u>

Dissolved oxygen (DO) concentrations in salt marshes are typically affected by primary production, decomposition of organic material, salinity, tide regime, nutrient input, and temperature. Typically, DO is the highest in the winter and spring months and lowest in the summer and fall. In early spring, photosynthetically derived oxygen can increase oxygen levels to the point of supersaturation in shallow habitats (e.g., restored salt ponds).

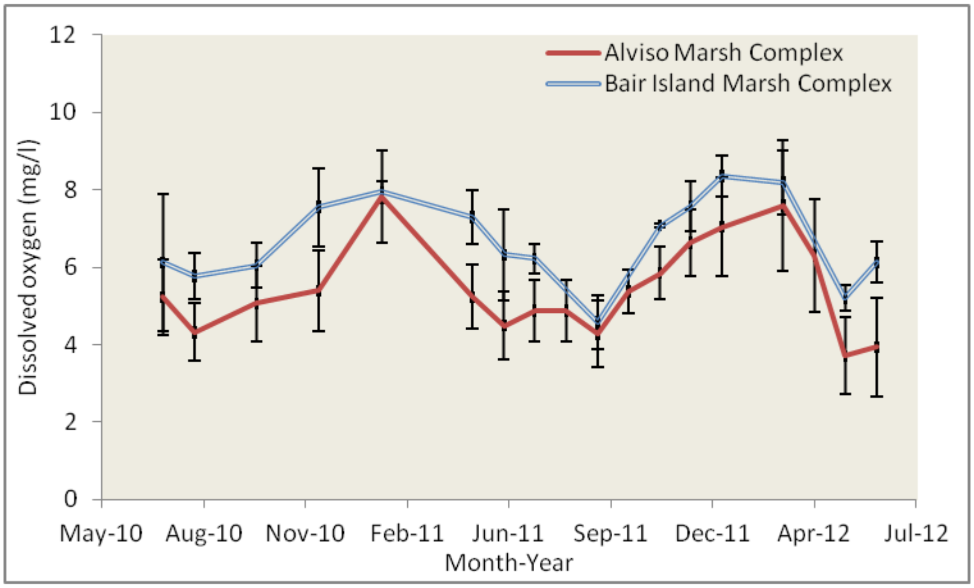


Figure 10. Monthly dissolved oxygen levels at Bair Island Marsh and Alviso Marsh Complex. Error bars are monthly standard deviations.

Nutrient loading of salt marsh habitats has been shown to lead to eutrophication and anoxia in other systems (Deegan 2002). Nutrient levels within South Bay are consistently high, in large part because of the high volume of tertiary treated sewage that is discharged into the basin (USGS SFB Water Quality Monitoring, accessed July 2012). It is apparent that the high nutrient load allows for tremendous algal production within salt-pond habitats, and the subsequent accumulation and decomposition of organic debris within these habitats results in hypoxia (DO levels <30%) in certain areas during the night/early mornings in the summer and fall (S. Poitter, USGS, pers. com, this study).

The monthly average DO in central South Bay showed the expected seasonal patterns but was consistently above 6 ml/L and 80% saturation. The monthly average oxygen concentration within the Bair Island Marsh was more variable over the course of the year and reached lower levels than the adjacent bay. DO concentrations within the Alviso Marsh Complex (Alviso Slough, Coyote Creek, the Island Ponds and Knapp's Tract) were considerably lower than both central South Bay and Bair Island, dropping to levels that are stressful to many fish species at all locations. The Alviso Marsh Complex also had several hypoxic and anoxic (less than 10% saturation) events during our sampling periods: on July 1, 2011, waters with oxygen levels below 1.0 mg/L were observed at the mouth of Pond A19; and on October 20, 2010, storm-water runoff from both Coyote Creek and the Guadalupe River led to hypoxia in upper Alviso Slough and in upper Coyote Creek. Both events resulted in fish mortalities.

Transparency and Temperature

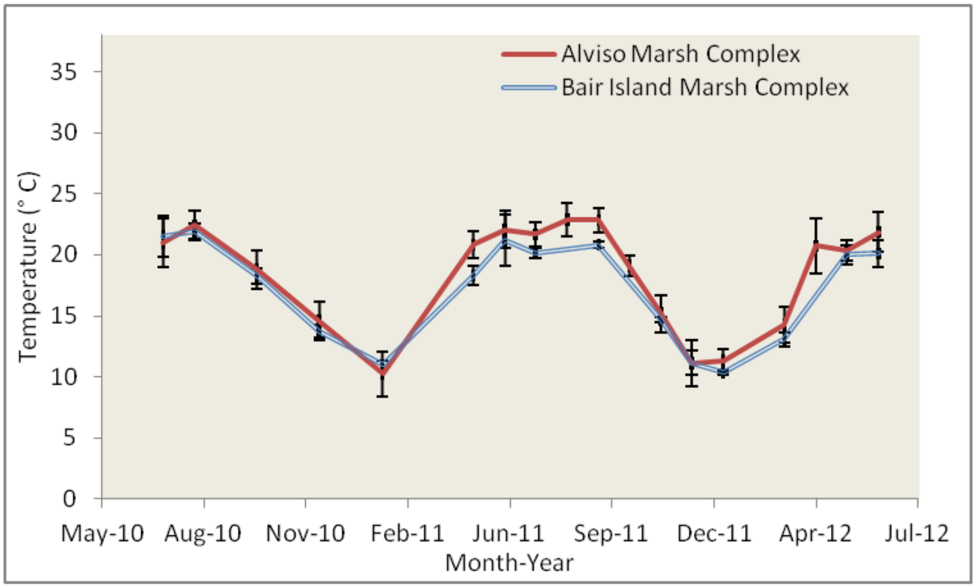


Figure 11. Monthly average temperatures at the Bair Island Marsh and at the Alviso Marsh Complex. Error bars are standard deviation for each month.

Water temperatures in the restoration area exhibit a seasonal pattern: coldest temperatures occur in winter (December to February) and warmest temperatures occur in summer (July and August).

Recorded monthly water temperatures followed the expected seasonal pattern during the course of this study, though several deviations are worth pointing out. First, the 2010/2011 winter was cooler than the 2011/2012. Second, the Alviso Marsh Complex gets consistently warmer in the summer months than the Bair Island Marsh due its shallow depth.

Turbidities can be affected by phytoplankton, total dissolved solids, water speeds, and winds. Overall, turbidity is higher in the southern portion of South Bay, especially below Calaveras Point because increases in tidal energy keep fine sediments in suspension. As a result, turbidities in the Alviso Marsh Complex were consistently high year round (Figure 12). Turbidities within the Bair Island Marsh Complex were typically lowest in the winter months and highest in spring and early summer. Unlike the Alviso Marsh Complex, it is likely that the increased turbidity in the Bair Island Marsh was due to seasonal phytoplankton blooms, which peaked in April of each year (USGS SFB WQ monitoring 2012).

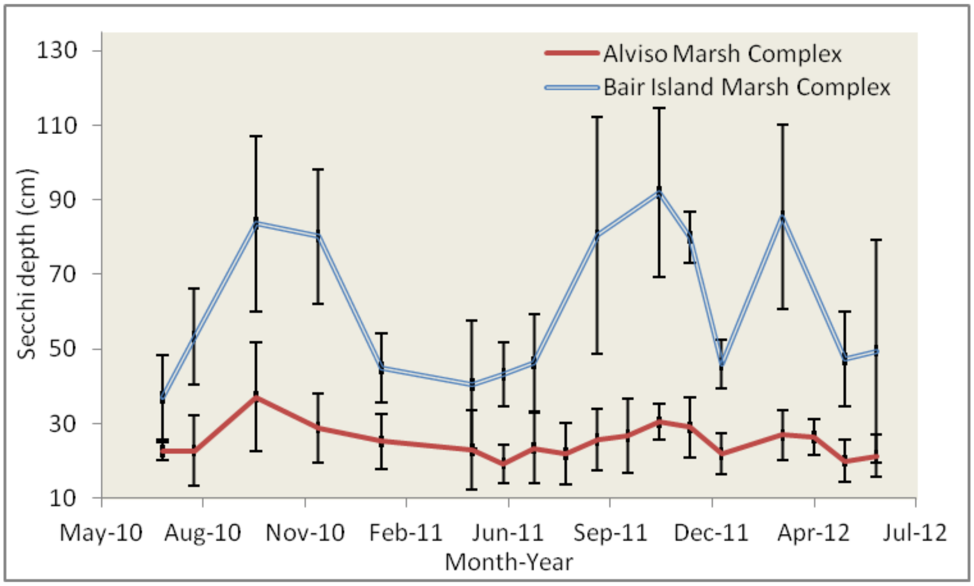


Figure 12. Monthly average transparency from each marsh from July 2010 to June 2012. Error bars are standard deviation for each month.

Invertebrate trends and observations

We have captured 38 species of macroinvertebrates in otter trawling surveys from July 2010 to June 2011. Four planktivores are abundant (California bay shrimp (*Crangon franciscorum*), overbite clam, (*Potamocorbula amurensis*), Oriental shrimp,(*Paleomon macrodactylus*), and black-tailed bay shrimp, (*C. nigricauda*)) in trawl catches, as well as the Oregon mud crab (*Hemigrapsus oregonensis*), the New Zealand opisthobranch (*Philini auriforms*), and the eastern mudsnail (*Ilyanassa obsoleta*). California bay shrimp constituted over 61% of the total individuals captured (excluding isopods and mysids). Of the total species captured, at least 20 (53%) are nonnative to the San Francisco Bay/Estuary; however, only 36% of total individuals captured in otter-trawls were invasive. Overbite clam were introduced into the estuary in the late 1980's and became abundant in 1990. Beginning around 2000, overbite densities began a dramatic decrease in South San Francisco Bay (Cloern et al. 2007), though they are still exceptionally abundant within the Ravenswood Pond and within the Alviso Marsh (this study).

Bay Shrimp

California bay shrimp typically reproduce outside of the Golden Gate and then migrate upstream into the brackish waters of the estuary coincident with salinity incursion in the summer months (Hatfield 1985). Peak abundance in San Francisco Bay/Estuary follows the movement of juvenile shrimp into Suisun and San Pablo Bays and Suisun Marsh in summer months (Hatfield 1985, O'Rear and Moyle 2011). Because sampling began in July 2010, the discussion is broken up into Year 1 (July 2010 to June 2011) and Year 2 (July 2011 to June 2010).

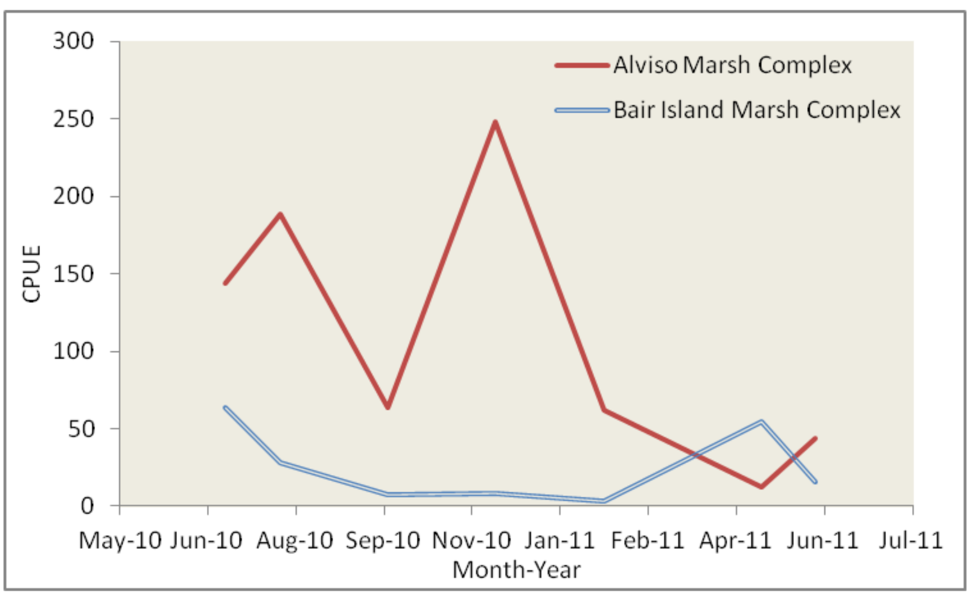


Figure 13. CPUE of bay shrimp from July 2010 to June 2011

Year 1

From July 2010 to June 2011 in the Alviso Marsh Complex, California bay shrimp reached peak abundance in December 2010 and then declined rapidly in the spring months. By June 2011 the arrival of new recruits caused the CPUE of California bay shrimp to increase slightly; however, the catch throughout the marsh was still less than in December. The 2011 cohort never reached high abundance within the Alviso Marsh Complex in this first year, despite lower salinities that attract young shrimp. The apparent paucity of California bay shrimp was possibly caused by the harvest of 24,000 lbs by the local fishing fleet (CA DFG 2011), as the salinities within the Marsh were ideal for young shrimp. At the Bair Island Marsh Complex, the 2010/2011 California bay shrimp CPUE was low during winter months, displayed a peak in May of 2011, and then declined rapidly the following month. It is likely that the bulk of the California bay shrimp observed at Bair Island in May were migrating recruits that rapidly moved out of the area. This hypothesis is corroborated by the arrival of the new recruits in the Alviso Marsh several weeks later. Black-tailed bay shrimp were not particularly abundant in either the Bair Island complex or in the Alviso Marsh during the first year of sampling, presumably due to this species preference for waters in excess of 19 ppt (Wahle 1982). Trends in California bay shrimp catches were similar in both the restored habitats and the adjacent sloughs during the first year of sampling (Figure 14).

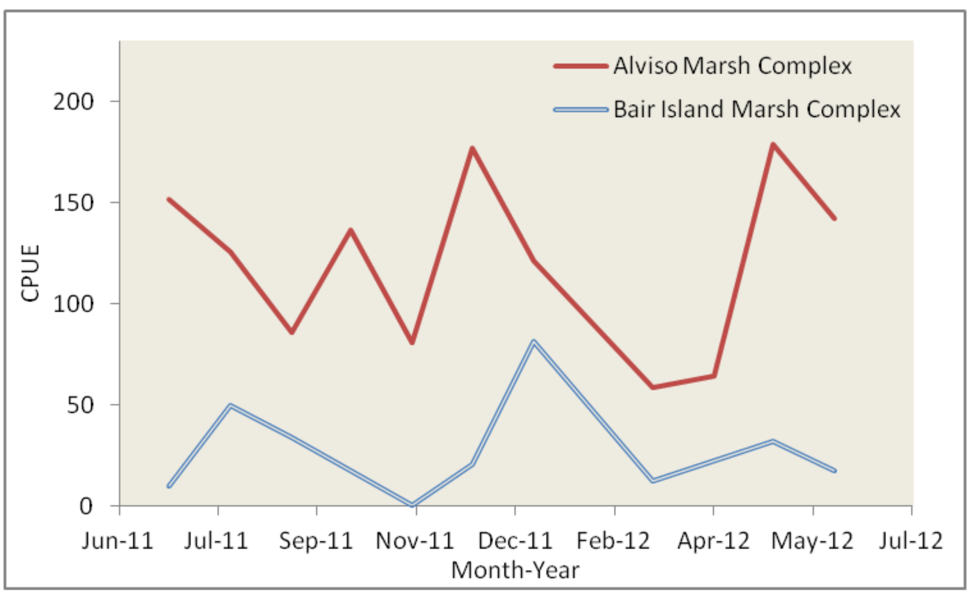


Figure 14. CPUE of bay shrimp from July 2011 to June 2012

Year 2

Overall, California bay shrimp CPUE was higher from August 2011 to June 2012 than from August 2010 to June 2011 (Figure 14). The outmigration of mature adults occurred in March and April 2012 resulted in a decrease in CPUE at both the Alviso and Bair Island Marsh complexes. The recruitment pulse occurred later in 2011 (July) than in 2012 (May), though CPUE of newly recruited bay shrimp in 2012 was comparable to 2011 (Figures 13 and 14). Hatfield (1985) theorizes that in dry years, California bay shrimp may reproduce in South Bay; however, despite the presence of gravid females in the Alviso Marsh from November 2011 to February 2012, no larval or early juvenile bay shrimp were collected in larval surveys within either Alviso or the Bair Island Marsh Complexes (Buckmaster, unpublished data). The absence of young juvenile and larval bay shrimp coupled with the abrupt arrival of recruits make it unlikely California bay shrimp successfully reproduced in the sampled marshes during the 2011/2102 winter. Black-tailed bay shrimp were present in both the Alviso and Bair Island marsh trawls beginning in March 2012. As with the California bay shrimp, the CPUE of black-tailed shrimp was higher within the Alviso Marsh. In addition, two specimens of the black-spotted bay shrimp (*Crangon nigromaculata*) were captured at Bair Island. California Department of Fish and Game surveys in South Bay have found black-spotted bay shrimp primarily in cool, high salinity waters, and much of our sampling habitat is simply outside of this species' apparent habitat (Baxter et al. 1998). The obvious difference in the bay shrimp CPUE between Alviso Marsh and Bair Island seems to reflect the higher productivity associated with the Alviso Marsh (the high production within the Alviso Marsh will be discussed later).

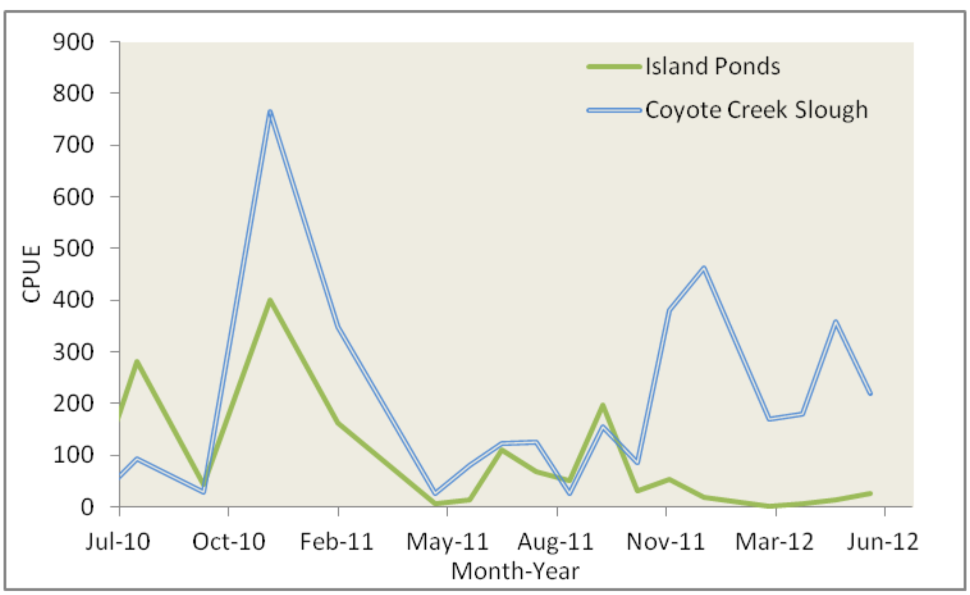


Figure 15. California bay shrimp CPUE for the Island Ponds and the adjacent Coyote Creek (Alviso Marsh Complex)

Trends in bay shrimp abundances remained comparable in restored habitats and slough habitats during the study, with the exception of the Island Ponds in the winter and spring (January to May) of 2012. Despite the apparent abundance of bay shrimp adjacent to the ponds, relatively few were captured inside the ponds. Though measured abiotic parameters taken while trawling the ponds do not explain the absence of shrimp from these habitats, water quality readings taken early-morning showed daily dissolved oxygen swings in excess of 7 mg/l (2.5 mg/l to 9.5 mg/l) during the period during which shrimp were absent from the ponded habitat. Schroeter and Moyle (2004) noted that bay shrimp will avoid water with low dissolved oxygen levels (<2.5 mg/l. Although the diel variations within the Island Ponds keep the pond habitat accessible to sensitive species capable of moving in and out of the habitat rapidly (e.g., surfperch, striped bass), bay shrimp may not be able to move into the pond and escape before the oxygen levels drop.

Other Invertebrate Species

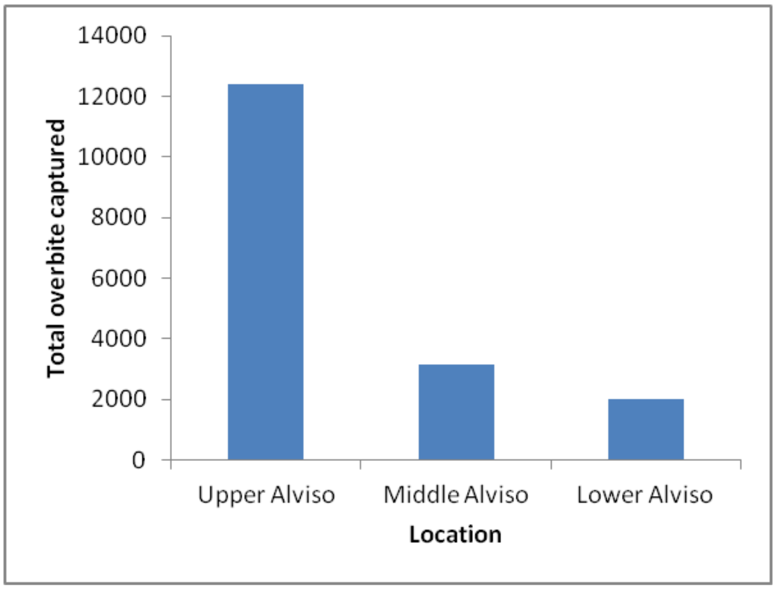


Figure 16. The total overbite clam catch in otter trawls within Alviso Slough.

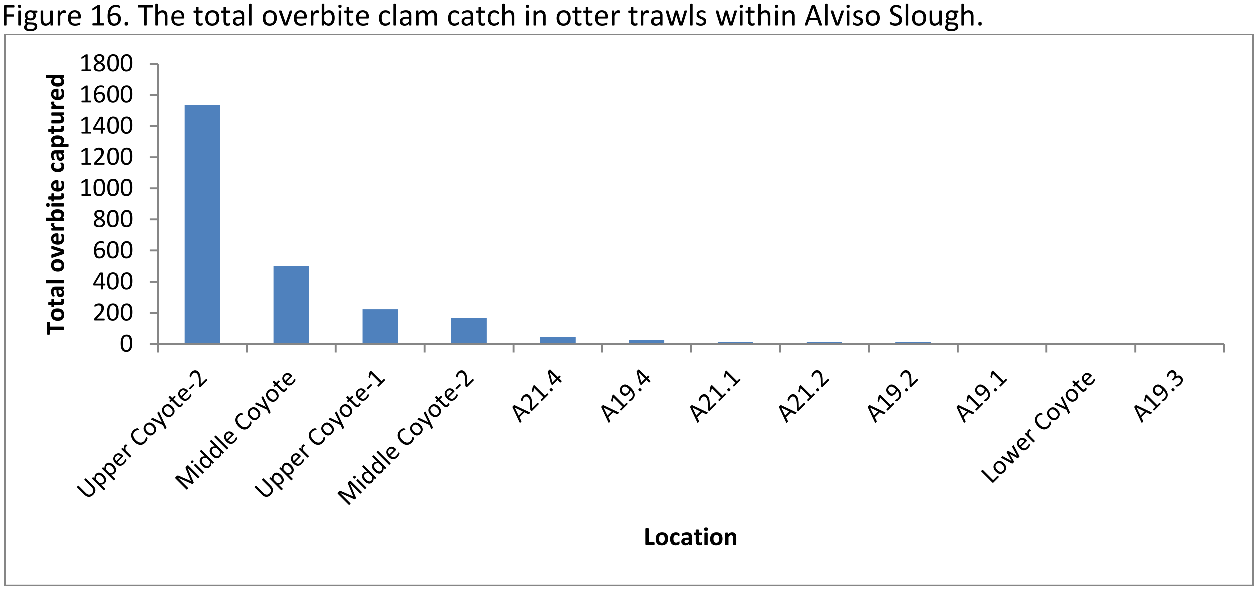


Figure 17. The total overbite clam catch in otter trawls within Coyote Creek and the Island Ponds.

Overbite clam historically were the most abundant bivalve in all of South Bay and have been implicated as causing tremendous declines in macrozooplankton (i.e., mysid shrimp) in San Pablo Bay and the Sacramento/San Joaquin Delta (Kimmer and Orsi 1996, Takakawa et al. 2002). Despite recent declines throughout South Bay (Cloern et al. 2007), our sampling shows overbite clams abundant within the Ravenswood Pond as well as in the Alviso Marsh. Otter trawl CPUE of overbite clam is high within Alviso Slough, especially at the upstream stations adjacent to, but not within, fresh water. Overbite are virtually absent from the lower reaches of Coyote Creek, the Island Ponds, and A6, but they are present in the upper reaches of the tidal portion of Coyote Creek.

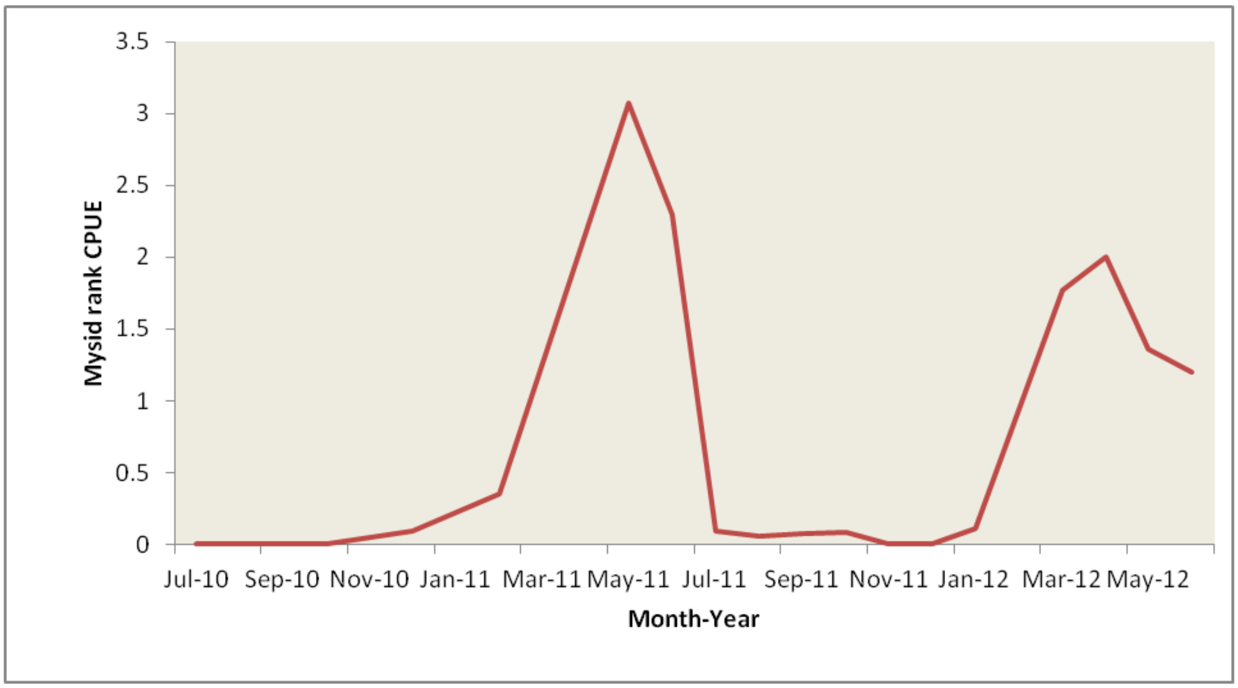


Figure 18. Mysid rank (see methods) CPUE for the Alviso Marsh.

Mysid shrimp were only abundant within the Alviso Marsh and displayed a strong seasonal pattern, reaching maximum abundance in May 2011 and April 2012. Additionally, a bloom of *Alienacanthomysis macropsis*, which is apparently too small to easily capture via otter trawl, was identified in December 2010 and January 2012 (Buckmaster, unpublished data). The dominant mysid shrimp in the spring bloom was the euryhaline species *Neomysis kadiakensis*. Mysid shrimp appeared to be more abundant in the Island Ponds than in the adjacent slough habitats (Figure 19). The bloom appeared to last longer and peak somewhat later in these habitats.

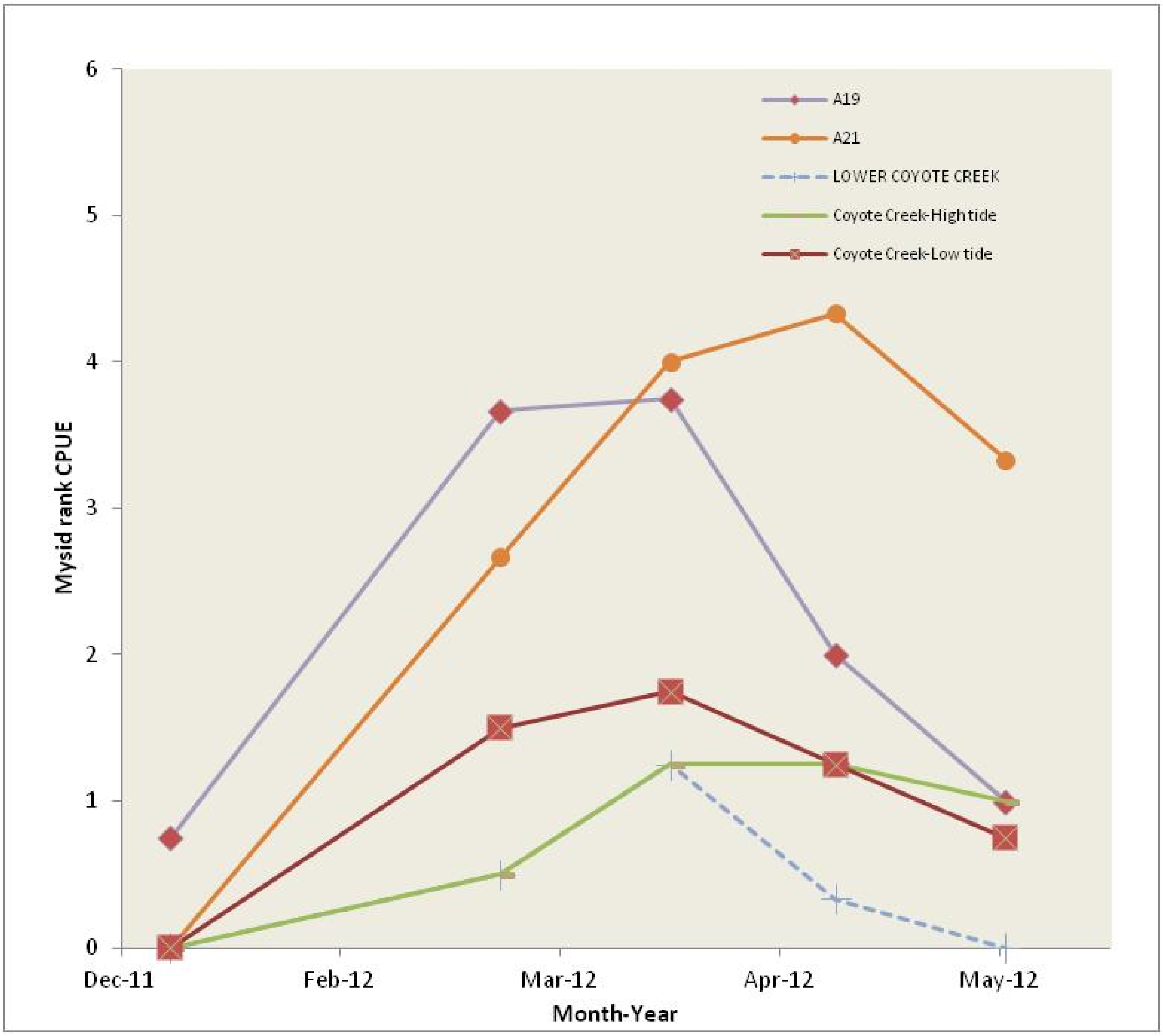


Figure 19. Mysid rank CPUE for Coyote Creek at high and low tide, lower Coyote Creek (adjacent Alviso Slough) and two of the Island Ponds.

In addition to mysid shrimp, amphipods of the family Corophiidae were more abundant within the Island Ponds than in the adjacent slough habitat, presumably due to an increase in organic material in the sediment. Corophiid amphipods tend to be detritivores and are known to filter feed. These amphipods probably forage in the accreted organic material within the restored salt ponds. Corophiid amphipods appear to be tolerant of extremely low DO levels, an adaptation that suites a benthic grazer.

Fish Community Sampling Results

Summary and Marsh Complex comparisons

Because the first year of sampling was largely experimental, most of the discussions will focus on the second year (June 2011 to June 2012). These are abbreviated descriptions of the sampled fish faunas at the study marshes, with some broad comparisons drawn between them. Eden Landing will not be discussed here, and the species captured at Eden can be found in the appendix. Approximately 30,000 fish from 41 species have been captured in the fish community study.

Alviso Marsh Complex

The Alviso Marsh Complex has yielded more species than any other complex and has a higher average otter trawl CPUE than Bair Island or Eden's Landing. Otter trawl CPUE was highest in March 2012, when juvenile fish were rearing within the marsh, followed by September 2011, when the dominant species in the marsh were threespine stickleback and staghorn sculpin (Figure 20, 21). Because of the habitat diversity within the marsh, especially the presence of freshwater inflow, we have found several euryhaline freshwater-dependent fish species within the Alviso Marsh Complex that we have not seen elsewhere [i.e., prickly sculpin(*Cottus asper*) Sacramento sucker (*Catostomus occidentalis*)]. Migratory and resident juvenile fish CPUE within the Alviso Marsh Complex were considerably higher than any of the other sampled habitats, including the shoals and channel of the central South Bay, indicating that Alviso might be important as a nursery for some species [English sole (*Parophrys vetulus*) staghorn sculpin (*Leptocottus armatus)* Pacific herring (*Clupea pallasii*) and others]. In addition, CPUE for threespine stickleback within the Alviso Marsh Complex was higher than any other marsh by three orders of magnitude. A distinct pelagic-fishes assemblage was also abundant in winter months and was only found in the Alviso Marsh Complex. This assemblage included the state-threatened longfin smelt (*Spirinchus thaleichthys*), American shad (*Alosa sapidissima*), and threadfin shad (*Dorosoma petenense*) (Figure 20). Finally, all (71 individuals) striped bass (*Morone saxatilis*) captured via otter trawl were captured within the Alviso Marsh Complex.

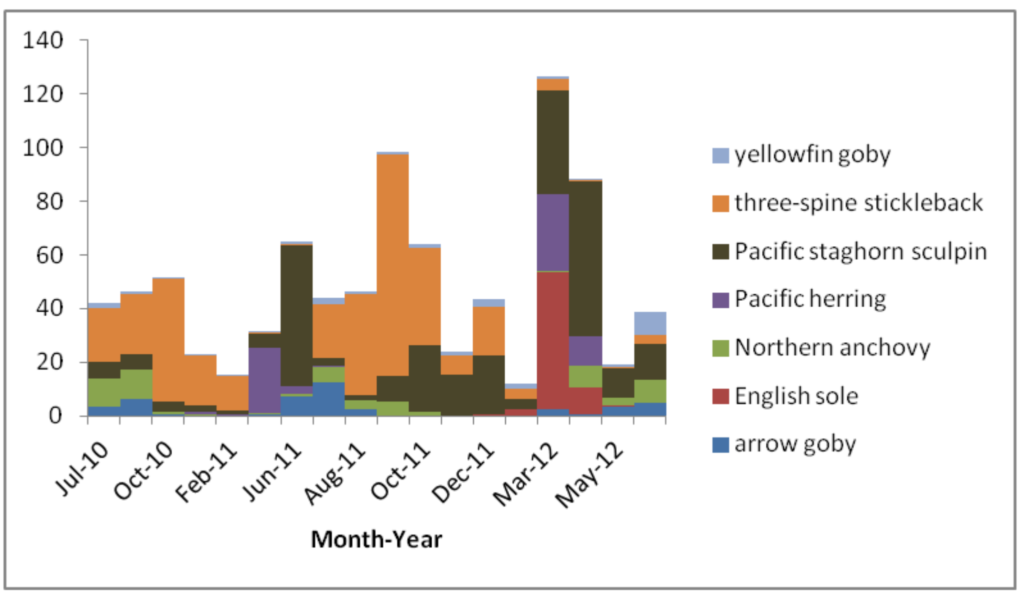


Figure 20a. CPUE of most abundant fishes within the Alviso Marsh Complex for the entire study period.

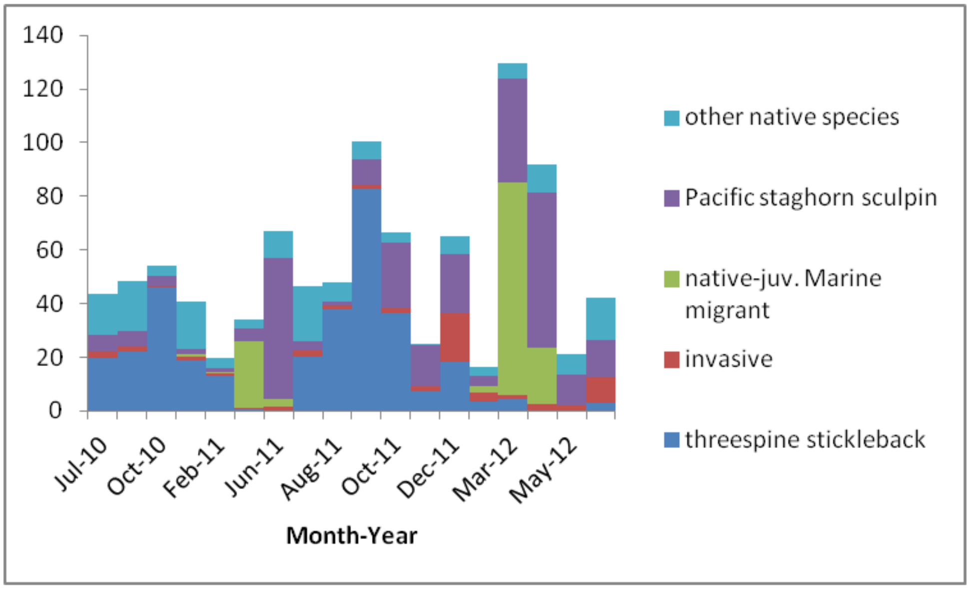


Figure 20b. Total CPUE of all fish in the Alviso Marsh Complex for the entire study. Fish are separated by general classifications: invasive/non-native species, threespine stickleback, Pacific staghorn sculpin juvenile native marine species, and other native species.

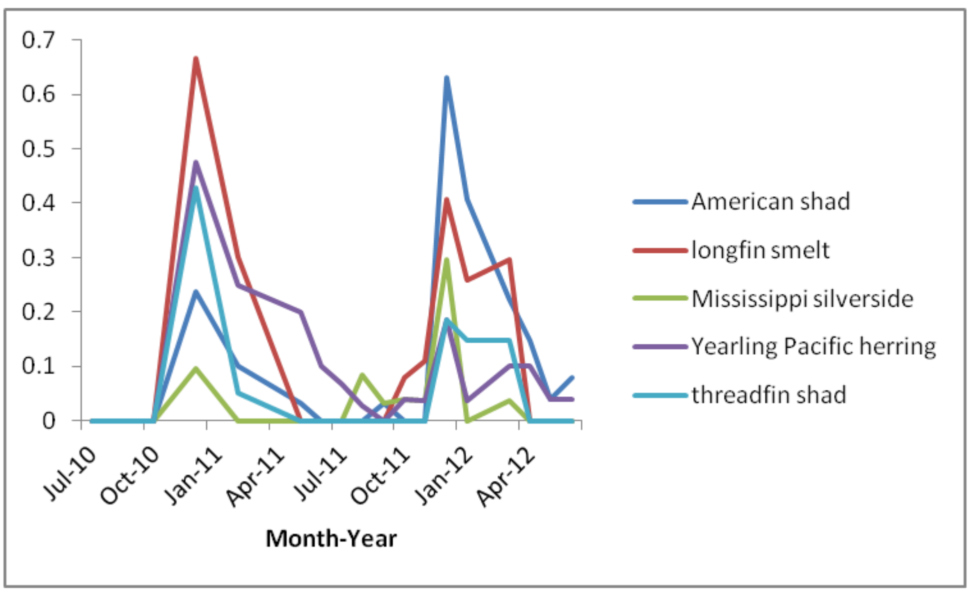


Figure 21. Frequency of occurrence for pelagic fishes in the Alviso Marsh Complex.

Bair Island

On average, the Bair Island Marsh Complex has yielded fewer species than the Alviso Marsh Complex and has a lower CPUE; however, the newly restored Outer Bair Island pond had a CPUE that was comparable to the Alviso Marsh Complex and was considerably higher than elsewhere within the Island. Bair Island CPUE showed a strong seasonal pattern, with lows in both diversity and CPUE occurring in the winter months (December 2010 and November 2011) (Figure 22, 23). Marine and polyhaline fish species had a higher CPUE at Bair Island than at Alviso, but only four species were not found at Alviso [white croaker (*Genyonemus lineatus*), chameleon goby (*Tridentiger trigonocephalus*), brown smoothound (*Mustelus henlei*), and dwarf perch (*Micrometrus minimus*)]. Unlike the Alviso Marsh Complex, Bair Island lacks the dramatic pulse of juvenile fish in the spring months (Figure 23), though species found at Alviso Island are typically present in lower abundance around Bair Island. The juvenile fish most abundant at Bair Island are Pacific herring and staghorn sculpin, followed by English sole and shiner surfperch (*Cymatogaster aggregata*).

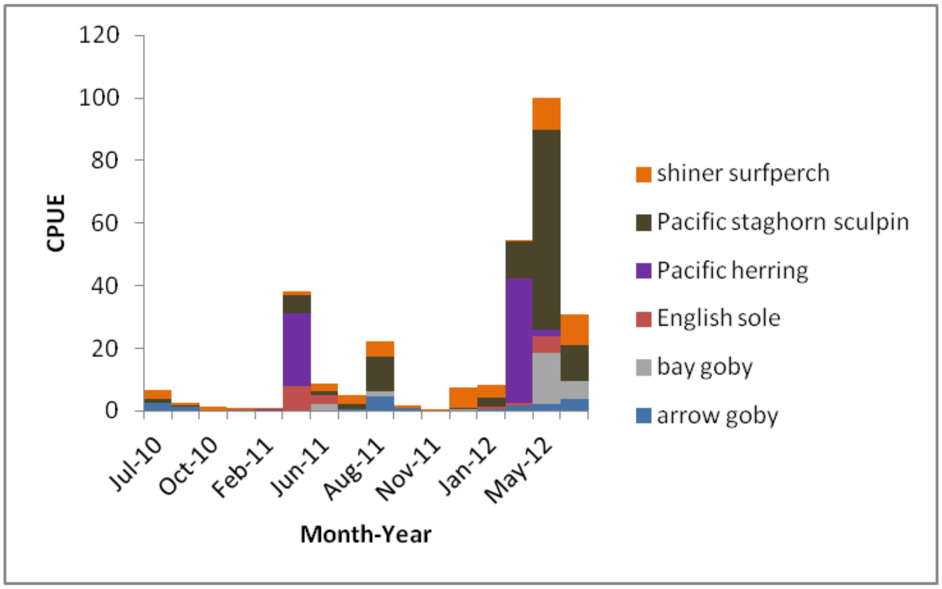


Figure 22. CPUE of the most abundant fish species within the Bair Island Marsh Complex

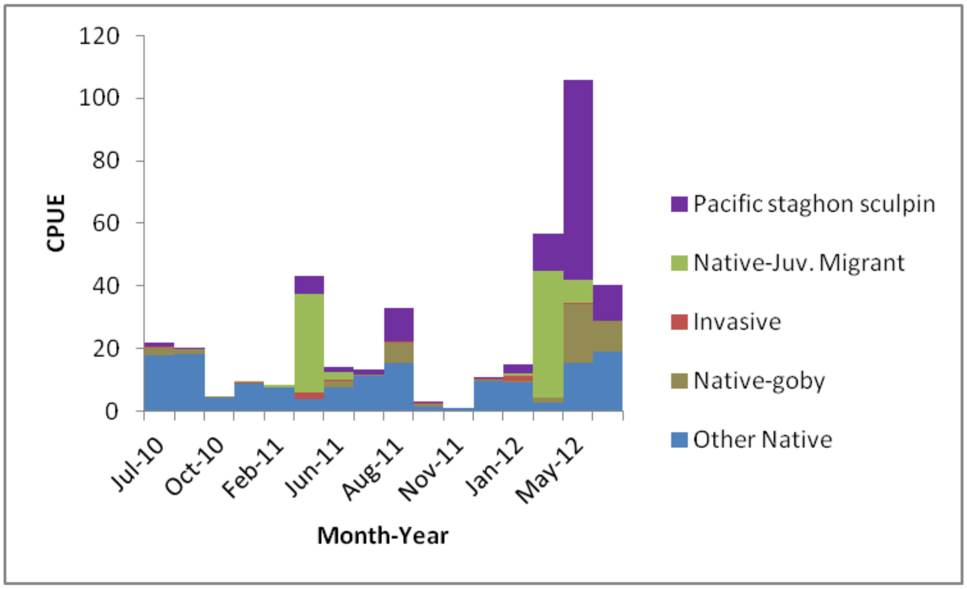


Figure 23. CPUE of all species within the Bair Island Marsh Complex for the last year of the study. Fish are separated by general classifications: Pacific staghorn sculpin, native-juvenile marine migrant, invasive/non-native, native gobiid, and other native fish species. The high catch of Pacific staghorn sculpin in March and May 2012 is due to the initiation of sampling within middle Bair Island.

Ravenswood

CPUE at Ravenswood was highest in the summer season, though the peak seine catch (September 2011) was three months after the peak set-net catch (June 2011), and diversity was highest in February 2011. Because Ravenswood was only sampled with set nets and seines, direct comparisons of CPUE to the Alviso and Bair Island otter trawl surveys are limited; regardless, the use of set nets and seines at the Alviso Marsh Complex and Bair Island makes it possible to compare the communities there to those at Ravenswood. The species assemblage at Ravenswood differs substantially from both Alviso and Bair Island, both in species composition and relative abundances. The dominant species at Ravenswood are atherinopsids [jacksmelt (*Atherinopsis californiensis*) and topsmelt (*Atherinopsis affinis*)] and gobiids [longjaw mudsucker, yellowfin goby, arrow goby (*Clevelandia ios*)]. Pacific herring juveniles were captured in the pond in both February and May 2011; however, they were not abundant during the period and were apparently absent from May 2011 to December 2011. The diversity of the fish community within the Ravenswood pond was extremely low, despite reaching phenomenal abundances in summer months. The warm temperature (26 C<) and low dissolved oxygen levels at night (<1 mg/L) (RWQCB 2011) exceed the lethal limits of fish species common in the adjacent bay. It is clear that poor water quality within the pond precludes most species from entering and remaining in this habitat throughout much of summer and fall. The species observed in Ravenswood during summer months closely resembles the species observed in low-salinity salt ponds still owned and operated by Cargill (Lonzarich and Smith 1997).

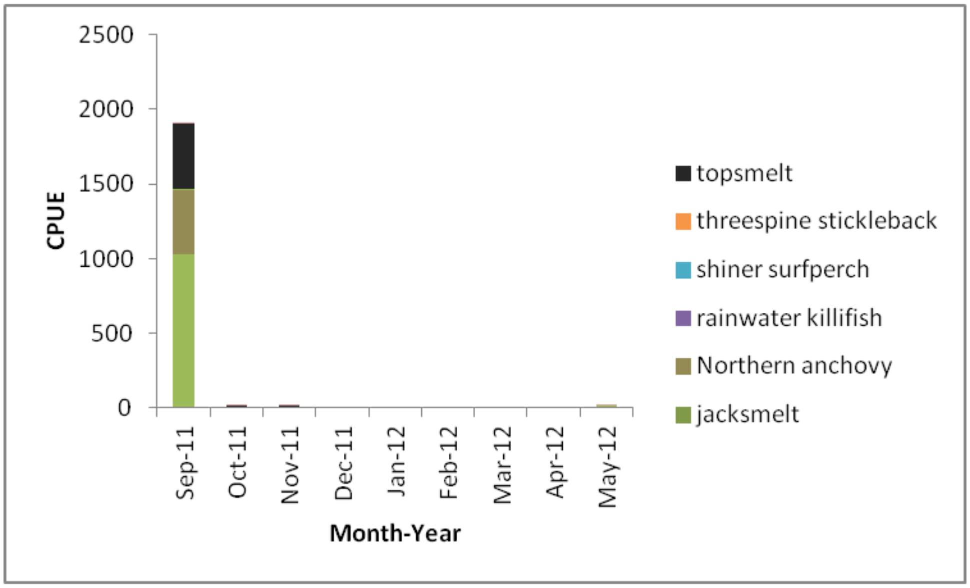


Figure 24. Catch-per-seine-haul at Ravenswood. All species captured are shown.

Species of Concern:

Our surveys have documented the presence of several species of conservation and commercial importance within the sampled marshes: longfin smelt, Chinook salmon California halibut, and white sturgeon.

Longfin smelt

Longfin smelt are an anadramous true smelt (Osmeridae) and are listed as threatened under the California Endangered Species Act. Longfin smelt were present only in the Alviso Marsh Complex and were captured in December 2010 and February 2011 of the first year of sampling and from October 2011 to March 2012. Longfin smelt were the 7th most abundant species in trawls during that period and were captured in all major sloughs and tributary sloughs within the Alviso Marsh Complex. Longfin abundance peaked in December of both years (2010 and 2011), when the catch-per-trawl was over 3.5 individuals. Length-frequency plots indicate two or three modes were present in the Alviso Marsh Complex in December 2011 corresponding to three age classes (0+, 1+ and 2+). The 2011 cohort was the most abundant from October 2011 to December 2011; however, only the larger, reproductively mature cohort remained within the marsh through March 2012.

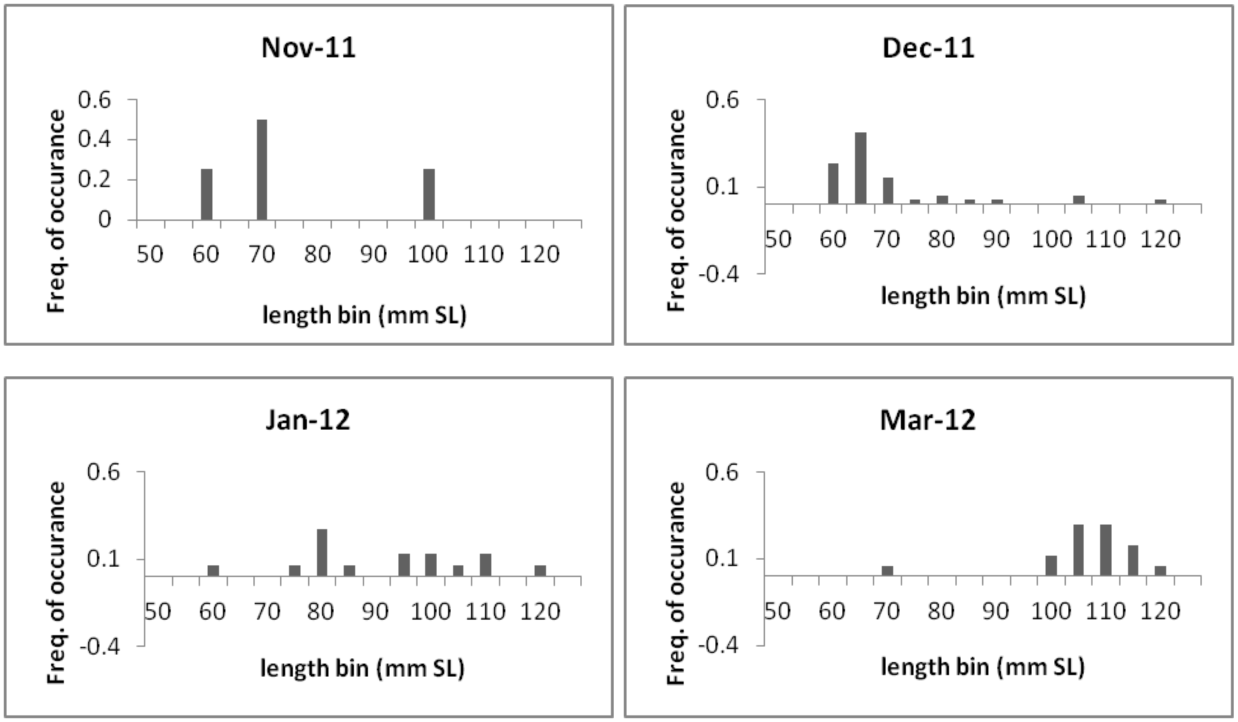


Figure 25. Length frequency distribution of longfin smelt in the Alviso Complex. Bin size is 5mm (e.g., 50-54.99=50).

In late March 2012, Delta outflow increased and caused San Francisco Bay to freshen and likely drew the mature smelt out of South Bay and towards Suisun Bay and the Delta. It is possible that fresh water coming out of local tributaries and the wastewater plant produced enough of a low salinity signature that mature smelt remained around the Alviso Marsh Complex until Delta outflow increased, since they require freshwater to spawn (Emmet 1991). In addition, mysid shrimp (upon which longfin smelt feed almost exclusively) were beginning to increase rapidly in the Alviso Marsh Complex during this period, which undoubtedly increased the attractiveness of this habitat to longfin smelt. Because mysid shrimp have decreased elsewhere in the Bay/Delta, their abundance within the Alviso Marsh Complex presents a compelling explanation for longfin smelt's presence and abundance in this area (especially immature fish). In spite of gravid adult smelt being captured within the Alviso Marsh Complex, larval fish surveys of the Alviso Marsh Complex did not indicate successful spawning occurred in either the winter of 2010/2011 or 2011/2012.

Photo 3. Longfin smelt captured via otter trawl in Coyote Creek (Alviso Marsh Complex) in December, 2010. Photo: Amy Chandos.

Salmon and Steelhead

Chinook salmon have been known to spawn in both Coyote Creek and the Guadalupe River (Liedy 2007). It is likely that these fish are strays from northern streams, as the persistence of an anadromous salmonid population in the Alviso Marsh Complex would have been unlikely given the chronic, year-round hypoxia (<3mg/L) that persisted in the sloughs from ~1900 to ~1970 (USGS SFB WQ monitoring 2012 and Skinner 1962). A single Chinook smolt that was fall-run size was captured in Coyote Creek adjacent to Pond A19 on March 19, 2012. No other salmonids have been captured or observed during our surveys.

All Chinook salmon that enter Coyote Creek and the Guadalupe River do so at the same time fall-run fish enter the Sacramento/San Joaquin river drainages (Leidy 2007), implying that fish in these systems are all fall run. Garcia-Rossi and Hedgecock (2002) found that Chinook in the Guadalupe drainage were strays from the Central Valley and Oregon stocks, and it is likely that the same is true of Coyote Creek. Chinook were absent from both drainages until the 1980's when flow increases for groundwater recharge allowed adult fish to ascend the streams (Leidy 2007). In the early 2000's, over 200 adult Chinook spawned in the Guadalupe River, though the run has tapered off since (Leidy 2007). Run sizes on Coyote are largely unknown, but the possibility of a run becoming established in that drainage cannot be discounted.

Coyote Creek was one of the last streams to support a population of the now-endangered Coho salmon (*Onchorynchus kisutch*). The Coho run on Coyote Creek lasted until the mid-1950's, when the construction of Coyote dam prevented them from reaching their spawning grounds (Leidy 2007). In addition to Coho, spawning pairs of Chum salmon (*O. keta*) also ascended the Guadalupe River in 2002, 2003, 2004 and 2005, raising the question of whether a small run of chum salmon has become established in the drainage (Leidy 2007).

There is historical evidence that steelhead spawned in both Coyote Creek and the Guadalupe Rivers as late as the 1950's (Leidy 2007), and remnant steelhead populations still exist in both Anderson and Coyote reservoirs, as well as in the streams of both drainages.

Because *O. mykiss* is a polymorphic species, with a stream-resident life history (i.e. rainbow trout) and a migratory life history (if anadromous it is called a steelhead), resident “rainbow trout” can give rise to anadromous “steelhead” at any point. With viable trout populations in both drainages, the possibility of steelhead occurring in either drainage is fairly high (however, few surveys have been conducted). In fact a single steelhead smolt was captured by East Bay Regional Parks in the spring of 2012 in lower Alameda Creek (which drains into Eden Landing), which is a system virtually identical to Coyote Creek. Two adult steelhead also returned to Alameda Creek in the winter of 2008, and successfully spawned after being transported around the BART weir.

Photo 4. Chinook salmon from Coyote Creek.

California halibut

California halibut are one of the most popular game fish in San Francisco Bay, in-spite of only limited spawning within the bay and no spawning occurring on the coastal shelf (Baxter et al. 1999). None were captured in our field areas until March 2012, when juveniles were captured at both Alviso and Bair Island. Halibut have remained in both marshes and have been found as far upstream as Warm Springs Marsh in Coyote Creek. California halibut have been captured inside Pond A21 (Alviso Marsh Complex) but not inside any other restored ponds.

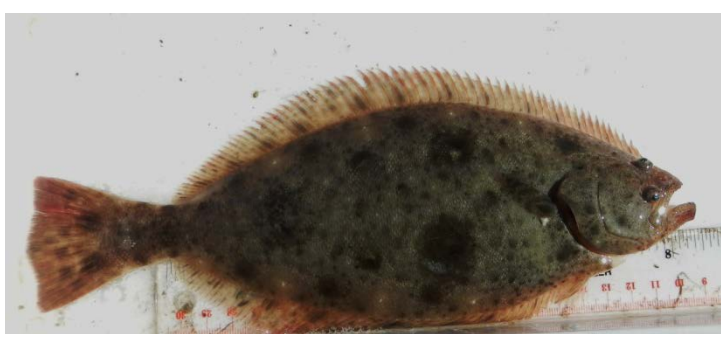


Photo 5. Juvenile California halibut from Bair Island.

White sturgeon

White sturgeon is another popular game fish in San Francisco Bay and is heavily targeted by anglers in the Alviso Marsh Complex. Though not captured in large numbers, our preliminary surveys indicate that adult sturgeon are considerably more abundant in the Alviso Marsh Complex than at any other restoration marshes in South Bay. Though a single white surgeon has entered the Guadalupe River in recent times, the paucity of spawning gravel and of large, sustained flows in both Coyote Creek and the Guadalupe River make it extremely unlikely that sturgeon reproduce in this area (D. Salsbery, personal communication). Instead, it appears that the high sturgeon population in the Alviso area is due this area's historic inaccessibility (and therefore shelter from fishing pressure) and high densities of overbite clam and *Crangon* shrimp, both favorite prey of sturgeon.

Photo 6. White sturgeon captured in Coyote Creek. The animal had a prominent wound on its back, probably from a collision with a prop.

Fish species of interest:

Here we will highlight the seasonal abundance patterns of fish commonly found in and around restored habitats. This provides a background with which to view the subsequent comparative analysis of the communities found within the restored ponds. As with the invertebrate section, only the second year of sampling when effort was standardized will be discussed here unless otherwise noted.

Threespine stickleback

Threespine stickleback (*Gasterosteus aculeatus*) was the most numerous fish captured in the otter trawl surveys and constituted 31% of the total catch (8435 individual stickleback). Threespine stickleback (referred to as stickleback hereon) are one of the most abundant bait fish in the Alviso area. Several species of fish (e.g., striped bass) and birds (egrets, herons, terns) have been observed feeding on them during the summer and fall months. The vast majority of stickleback were captured within the Alviso Marsh Complex; only a single individual was captured at Bair Island, and less than 20 were captured at Eden Landing. Within the Alviso Marsh Complex, stickleback were most abundant within the Island Ponds and in upper Coyote Creek, directly adjacent to Warm Springs lagoon. The Alviso stickleback population appears to be annual, and the CPUE is highest in late summer (Figure 26a), following a period of spawning and recruitment that begins in May (Figure 26b).

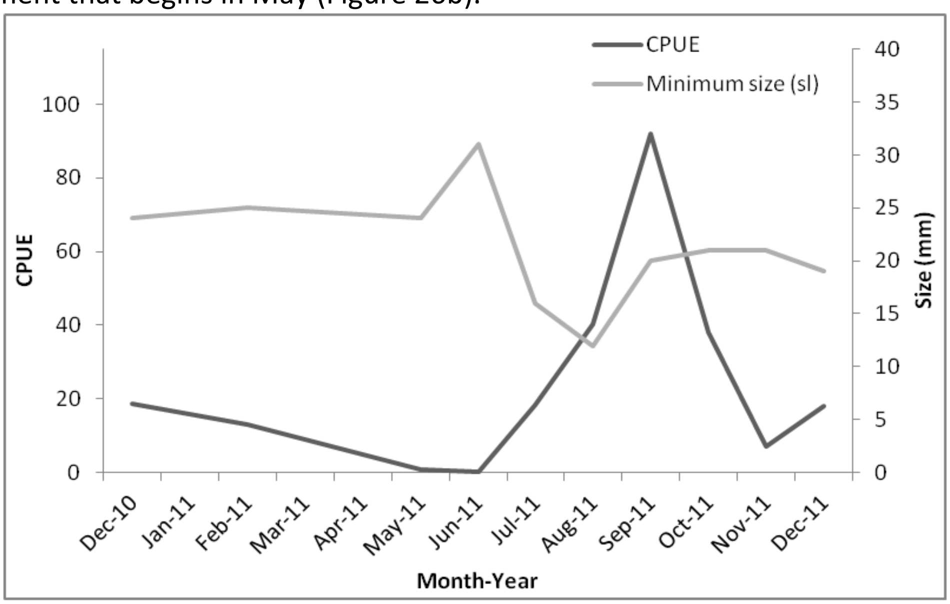


Figure 26. Annual pattern of CPUE for threespine stickleback in the Alviso Marsh Complex and the minimum size of stickleback captured via otter trawl in the Alviso Marsh Complex. Smaller fish indicate ongoing recruitment to the trawl (i.e. July and August, 2011 and April to June 2012), while the absence of small stickleback indicate there is no recruitment.

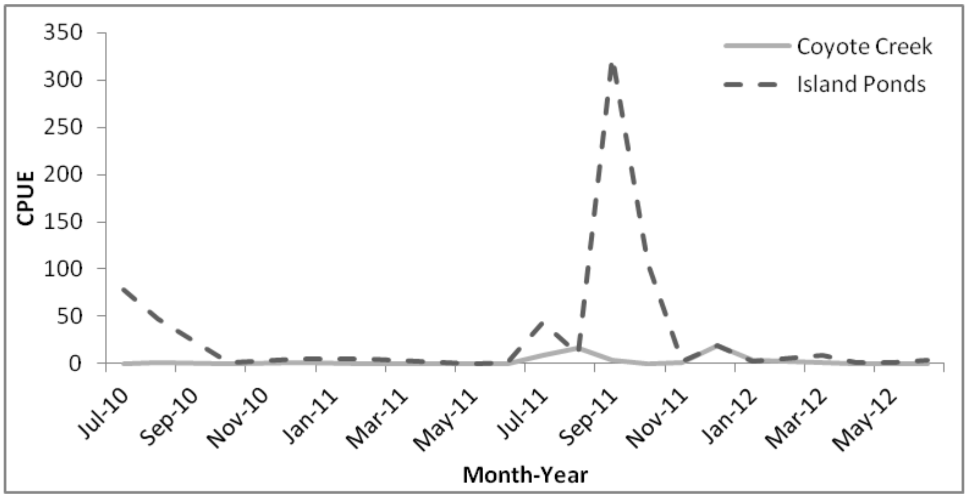


Figure 27. CPUE of threespine stickle back in the Island Ponds and Coyote Creek.

As an annual, physiologically tolerant species, threespine stickleback are one of the fish species most likely to benefit from the initial stages of tidal marsh restoration. Because threespine stickleback are an important prey item both within the Alviso Marsh Complex and in Suisun Marsh (O'Rear and Moyle 2011). Ultimately, increased populations of threespine stickleback benefit piscivorous fish and birds.

Pacific staghorn sculpin

Photo 7. Pacific staghorn sculpin adult captured via otter trawl in Alviso Slough.

Pacific staghorn sculpin (staghorn) are the second most abundant species in our otter trawl surveys and make up a significant portion of the minnow trap catch as well. Staghorn are one of the few fish species to increase in abundance in San Francisco Bay since 1973 (Moyle 2002 and Baxter et al. 1999). Because staghorn are abundant throughout the year at Alviso but only seasonally at Bair Island, the two marshes will be discussed separately.

Bair Island Marsh Complex:

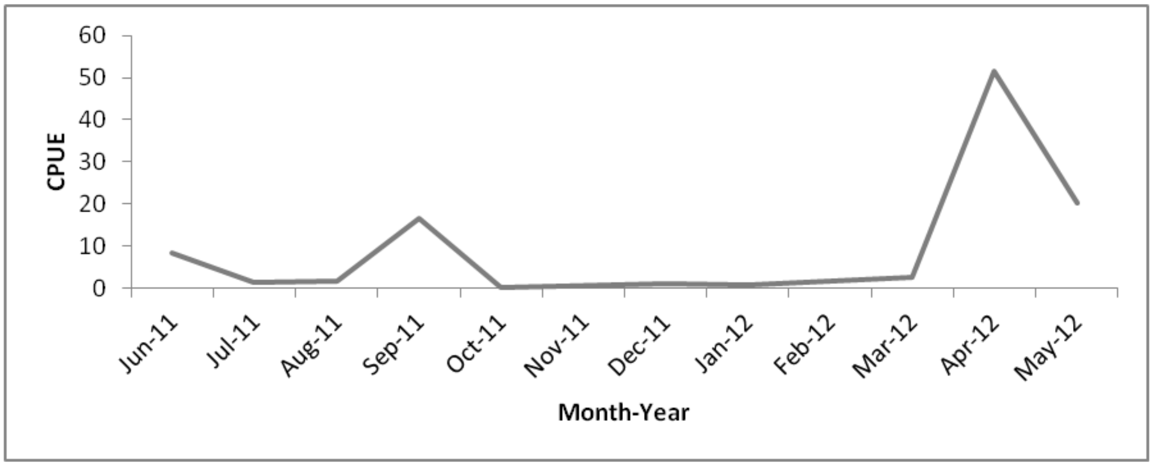


Figure 28. Pacific staghorn sculpin CPUE at Bair Island for the duration of the study.

Staghorn catch within Bair Island and the adjacent sloughs (excluding Outer Bair Island) was relatively low, and peak in CPUE occurred in April 2012 (following settlement of the 2012 cohort). The diked saltmarsh east of Outer Bair Island is the oldest restored habitat in the area and did not support many staghorn despite the appearance of quality habitat. In addition, staghorn captured in this pond showed several deformities, including scoliosis and the formation a second jaw. Presumably, dredge tailings from the Port of Redwood City contaminated the central pond and thus limited its effective value for staghorn.

Outer Bair Island, however, was heavily used by staghorn sculpin young-of-year during the winter and spring of 2011/2012. CPUE of staghorn in this habitat was one to two orders of magnitude higher than in the adjacent Steinberger Slough, indicating that staghorn sculpin were not only using this habitat but almost certainly breeding in it as well. CPUE patterns in the newly restored habitats indicate that following recruitment and a brief rearing period, staghorn sculpin emigrated from the pond.

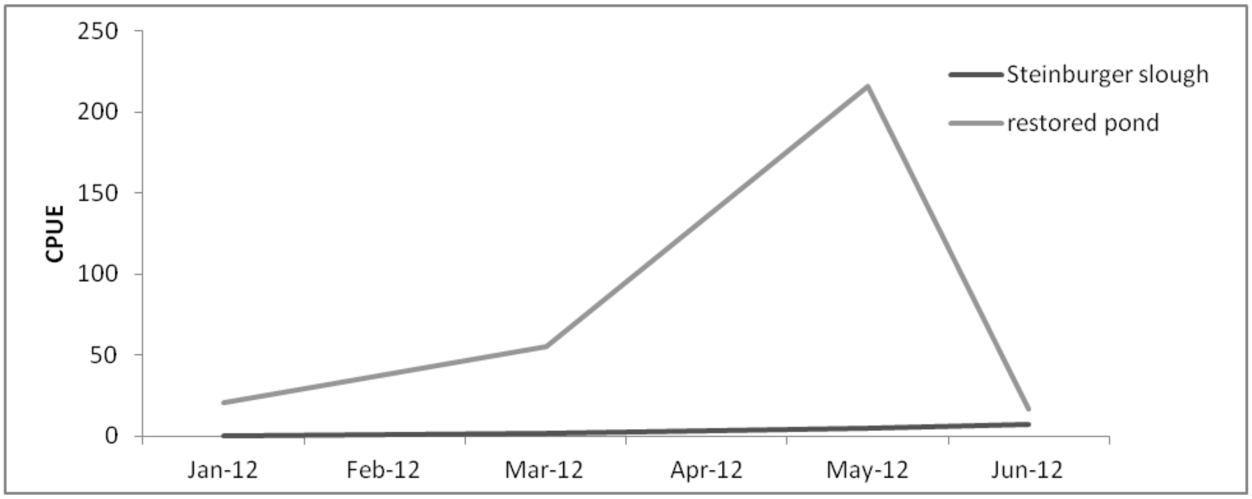


Figure 29. CPUE of Pacific staghorn sculpin in Steinberger Slough and the newly restored pond, Outer Bair Island.

Alviso Marsh Complex:

Staghorn sculpin were phenomenally abundant in the Alviso Marsh Complex throughout the year and have been harvested by the bait industry based out of the Port Alviso (CDFG 2012). The CPUE of staghorn sculpin in the second full year of sampling peaked in March, following the settlement of the 2012 year class (Figure 30). Staghorn sculpin had a protracted spawning period within the Alviso Marsh Complex, and newly transformed sculpin were abundant in otter trawls from December to April and peak recruitment occurred from January to March (Figure 31). Like the newly breached pond at Bair Island, large numbers of young staghorn were observed in Knapp's Tract (Pond A6).

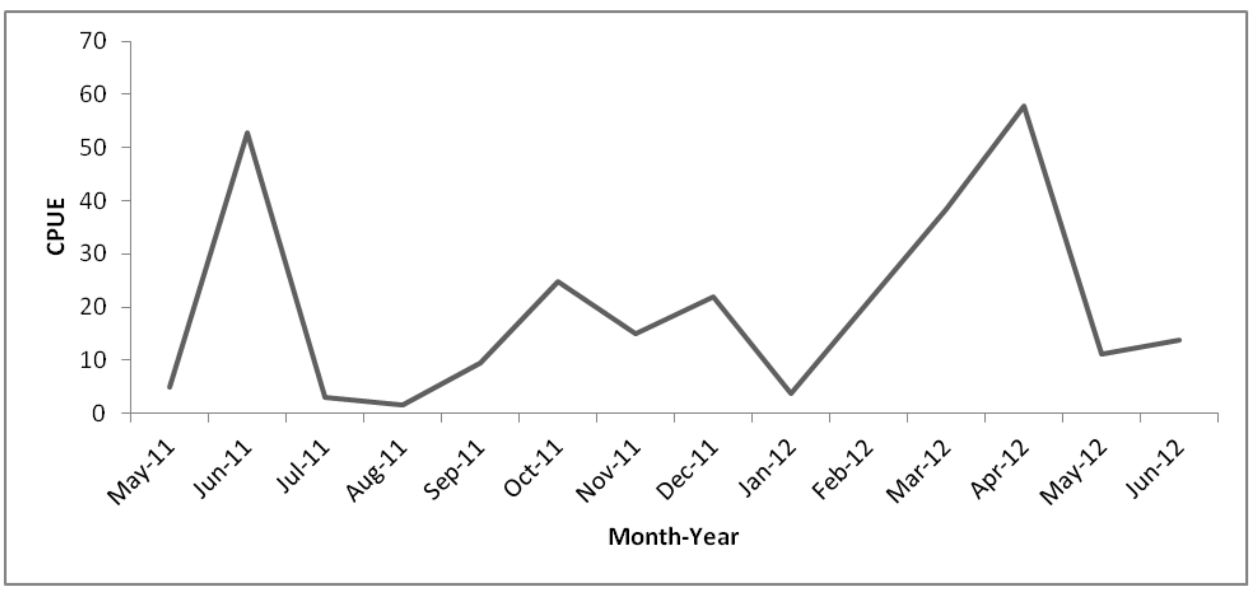


Figure 30. CPUE of Pacific staghorn sculpin (all size classes) within the Alviso Marsh

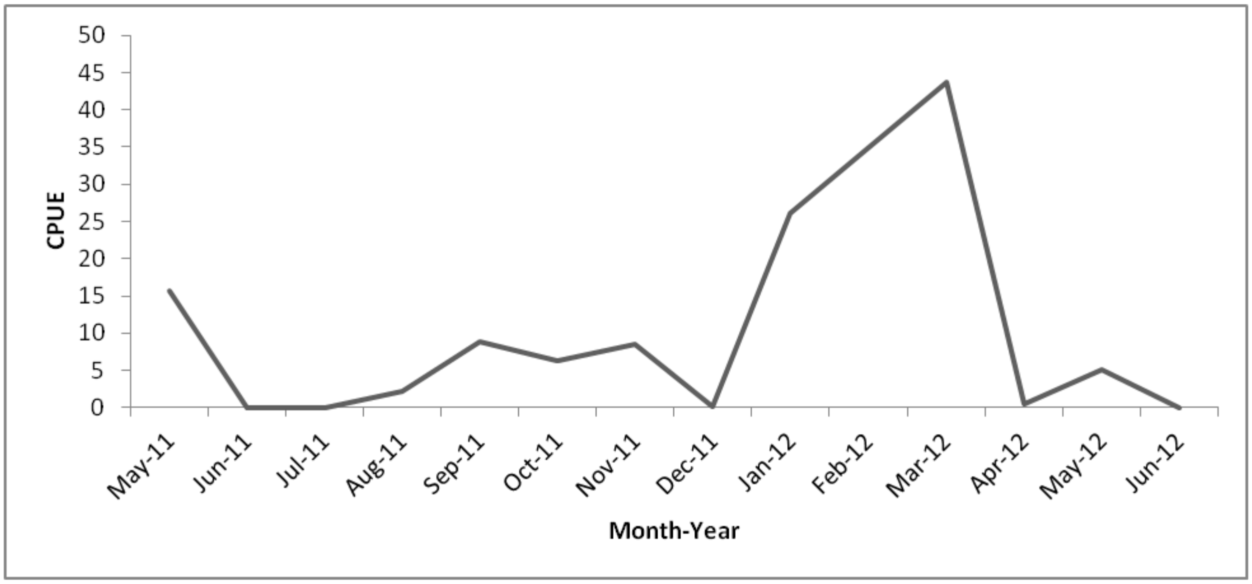


Figure 31. CPUE of newly transformed (<25mm SL) staghorn sculpin within the Alviso Marsh.

The CPUE of adult staghorn sculpin increased within the Alviso Marsh Complex in September and remained above average through November (Figure 30). Presumably, these staghorn were moving into the area to spawn, and examinations of mortalities revealed fully developed ovaries in females. The presence of newly transformed staghorn in otter trawls during this period corroborates this. However, commercial harvest of staghorn decreased during this period, and the observed increase in CPUE might have been impacted by this (i.e., there was a continual immigration of staghorn into the marsh, but commercial harvest kept abundances constant over this period).

Staghorn sculpin young-of-year actively seek out fresh water (Jones et al. 1962, Moyle 2002), and the distribution of young-of-year staghorn sculpin within Coyote Creek and Alviso sloughs reflected this, with higher abundances at upstream locations during spring and summer. Because of the position of the A8 notch, adjacent to the Guadalupe River, it is likely that this upstream movement makes staghorn likely candidates to invade this habitat when the notch is opened at the beginning of summer of both 2011 and 2012. When the notch in A8 opens the salinity of Alviso Slough increases, and staghorn sculpin CPUE declines. This decline is due to emigration from Alviso Slough into A8, or the reduced attractiveness of Alviso Slough for Staghorn sculpin.

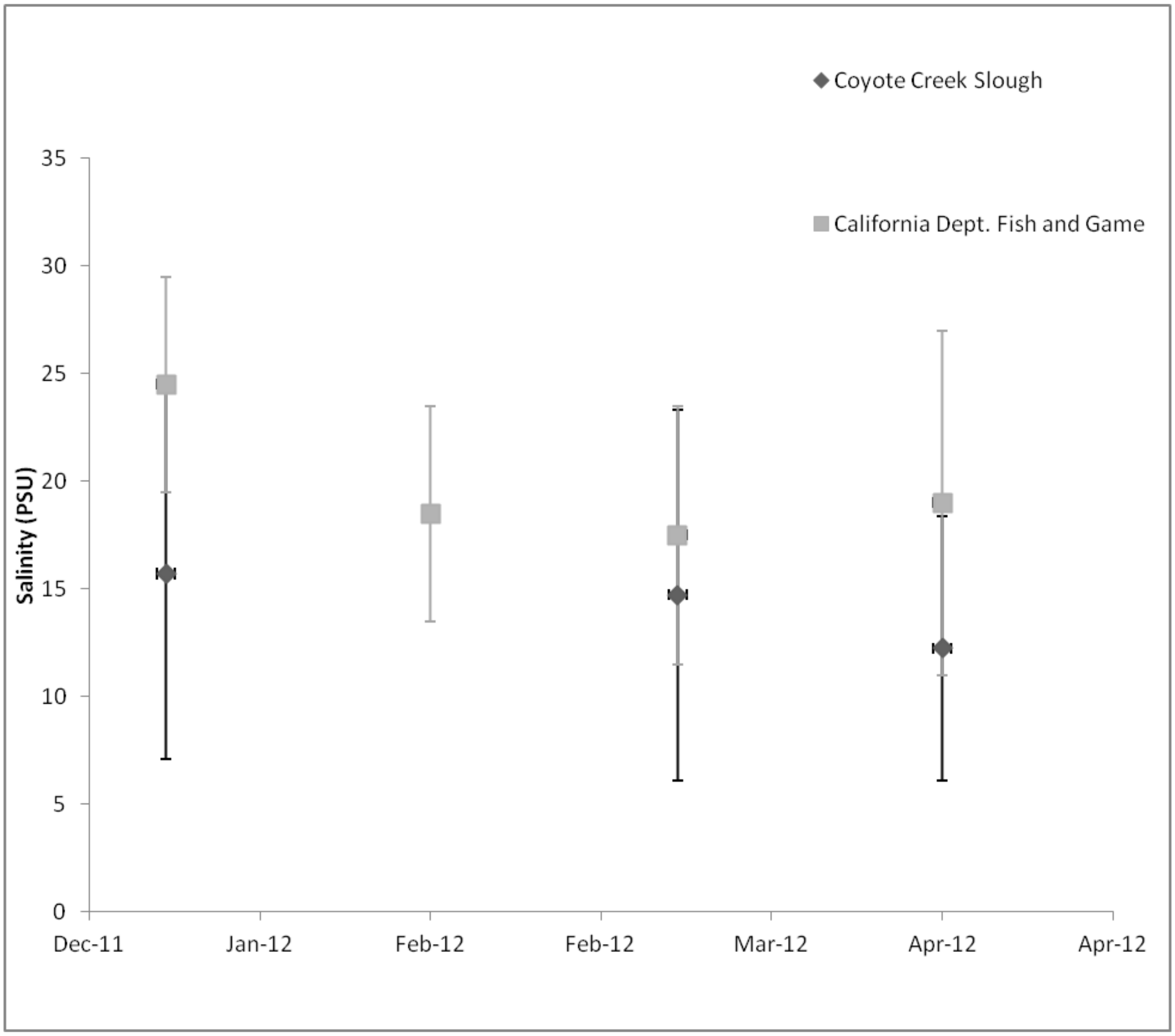
Like threespine stickleback, Pacific staghorn sculpin are a common prey item for predatory fish such as striped bass and leopard sharks and for wading birds such as egrets and herons. High numbers of staghorn in and around the restoration areas ultimately will provide increased foraging opportunities for these species.

English Sole

Photo 8. Young-of-year English sole captured via otter trawl in Alviso Slough. Photo: Matt Young.

Adult English sole are marine oriented; prefer cool, deep channels; and are rarely captured in our surveys. Young-of-year English sole, however, migrate in large numbers into San Francisco Bay and rear in Central, San Pablo, and South Bay (Orsi et al 1998). This facultative estuarine rearing strategy is common among California marine fishes, as there are few truly estuarine-dependent fish species, leaving little completion for small juveniles. English sole are one of the most common of such fish in our surveys, but there are numerous others (e.g., California halibut, speckled sanddab, Pacific herring, leopard shark, and starry flounder). English sole were most abundant within the Alviso Marsh Complex, although in both 2011 and 2012, there was a brief increase in English sole CPUE at Bair Island the month following their decline at the Alviso Marsh Complex. This pattern is consistent with the observation that English sole move into coastal waters after their first year of life, though in low outflow years larger sole will remain in Central San Francisco Bay (Rooper et al. 2002 and Baxter et al. 1999).

What makes English sole relevant to our questions pertaining to salt pond restoration was their location within the Alviso Marsh Complex. English sole are very rarely collected below 18 ppt throughout most of their range (Rooper et al 2002), though CDFG surveys from San Francisco Bay report that sole will frequent waters from 13-24 ppt in spring months. However, within the Alviso Marsh Complex, English sole were most abundant adjacent to the Island Ponds and Knapp's Tract in water that is fresher (as low as 6ppt) than their apparent preferences. In regions of the marsh where salinities are closer the reported optimal, English sole are considerably less abundant.



Fiugre 32. CPUE-weighted average salinity of English sole capture in Coyote Creek and the entire San Francisco Bay (reported by CDFG in Baxter et al. 1999). Error bars are ±1 SD.

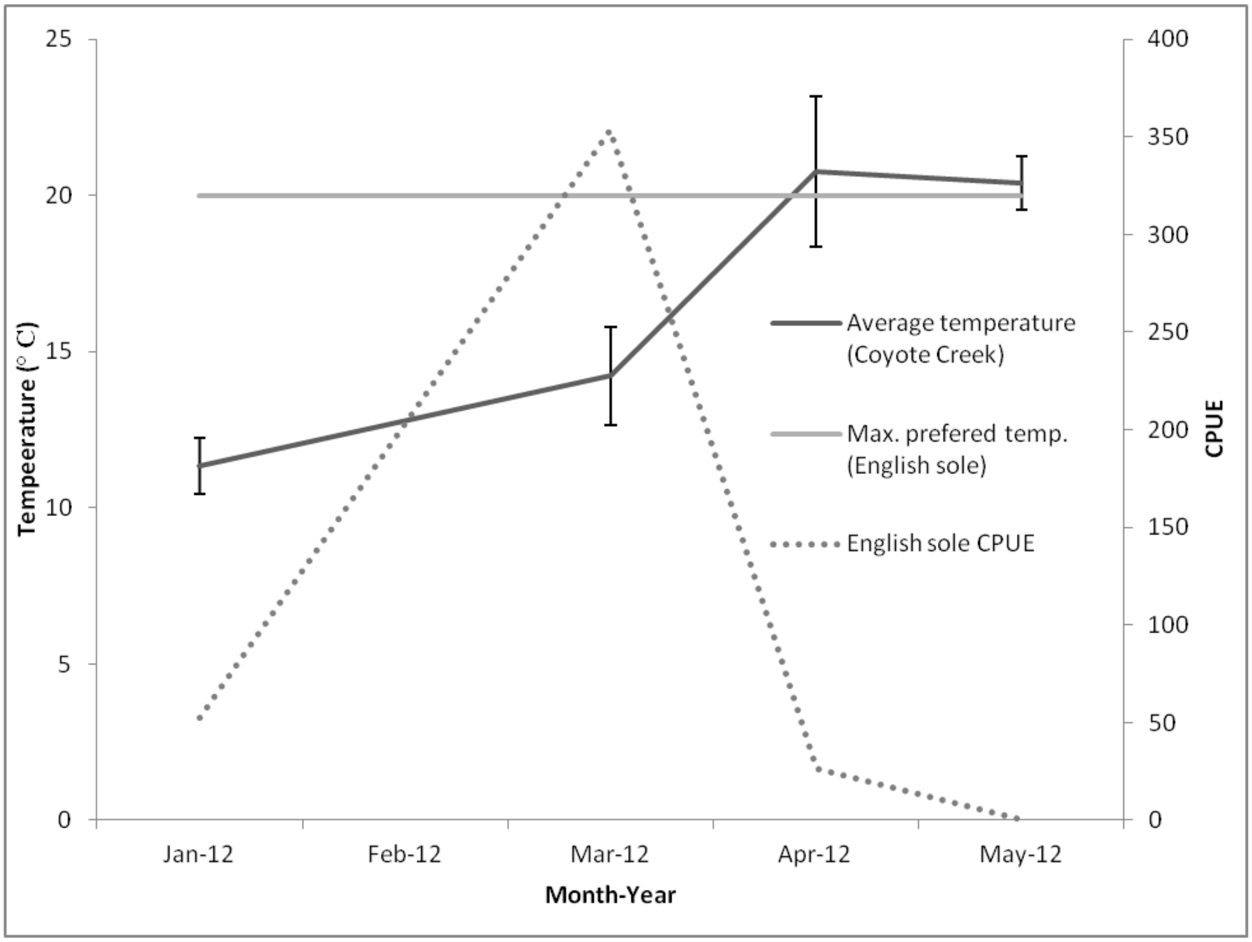


Figure 33. English sole remain in Coyote Creek until the temperature exceeds 20° C, at which point they move into cooler waters.

English sole are a species that frequently uses the marine portions of estuaries as nursery habitats, but within the Alviso Marsh Complex it appears as though English sole are moving into, and remaining in, lower-salinity water adjacent to restoration areas. Other studies have found similar patterns in flatfish across the Pacific, including one definitive study of stone flounder (*Platichthys bicoloratus*), in Japan. Yamashita et al.(2003) showed that stone flounder young-of-year rearing in low salinity habitats had increased stress hormones; however, these fish only remained in these osmotically stressful environments when prey was sufficient to support extremely rapid growth. As a result, the most stressed individuals also grew the fastest and had the best survival index.

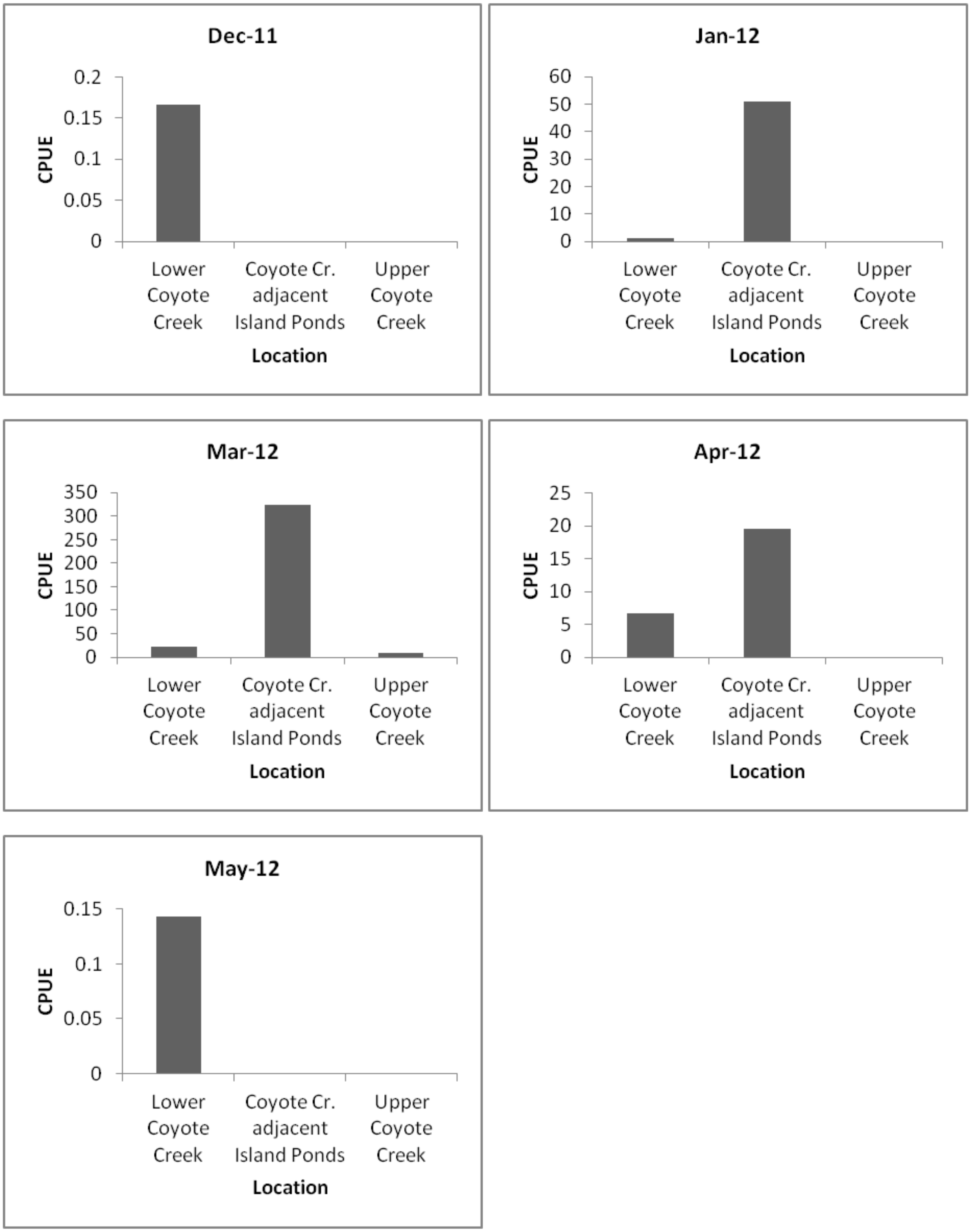


Figure 34. CPUE of English sole within the Alviso Marsh. The axes are scaled to account for drastic differences in CPUE. Because English sole catch within the borrow ditches of the Island Ponds was dependent on tide stage (when the surface of the ponds were inundated, no sole were captured), the ponds are excluded from the above diagram.

Pacific herring

Photo 9. Pacific herring captured via otter trawl in Alviso Slough. Photo: Matt Young.

Pacific herring are another marine immigrant that uses bays and estuaries of the Pacific Coast as rearing habitat. Herring are a commercially important species harvested for meat as well as roe. Unlike English sole, which move into San Francisco Bay as juveniles, Pacific herring adults actually spawn inside of the Golden Gate, and the larvae are present throughout the bay (Alderice and Velsen 1971, Orsi et al 1998). Like English sole, Pacific herring recruits are more abundant within the Alviso Marsh Complex than at Bair Island, Eden Landing, or SF2, though recruits are present at all locations.

Like English sole, Pacific herring generally select waters of higher salinity (21 ppt) in which to rear. Within San Francisco Bay, newly transformed herring were found in salinities ranging from 13-28 ppt (Orsi et al. 1998) and salinities below 10 ppt were extremely stressful to juvenile herring (Holliday and Blaxter 1961, Garrison and Miller 1982). As Pacific herring increased in size, the salinity at which they occurred in also increased (Orsi et al. 1998). However, similar to English sole, Pacific herring CPUE was higher in the low-salinity areas adjacent to the Island Ponds and up Coyote Creek to Warm Springs Marsh. April and May are typically when Pacific herring young-of-year begin to migrate towards the higher salinities and cooler temperatures of Central Bay (Orsi et al. 1998). However, Pacific herring CPUE in the Alviso Marsh Complex was highest within A19 and Warm Spring Marsh, where salinity was nearly fresh (<5 ppt). This would also indicate that Pacific herring juveniles are moving into and utilizing restored marshes, despite these environments being osmotically stressful.

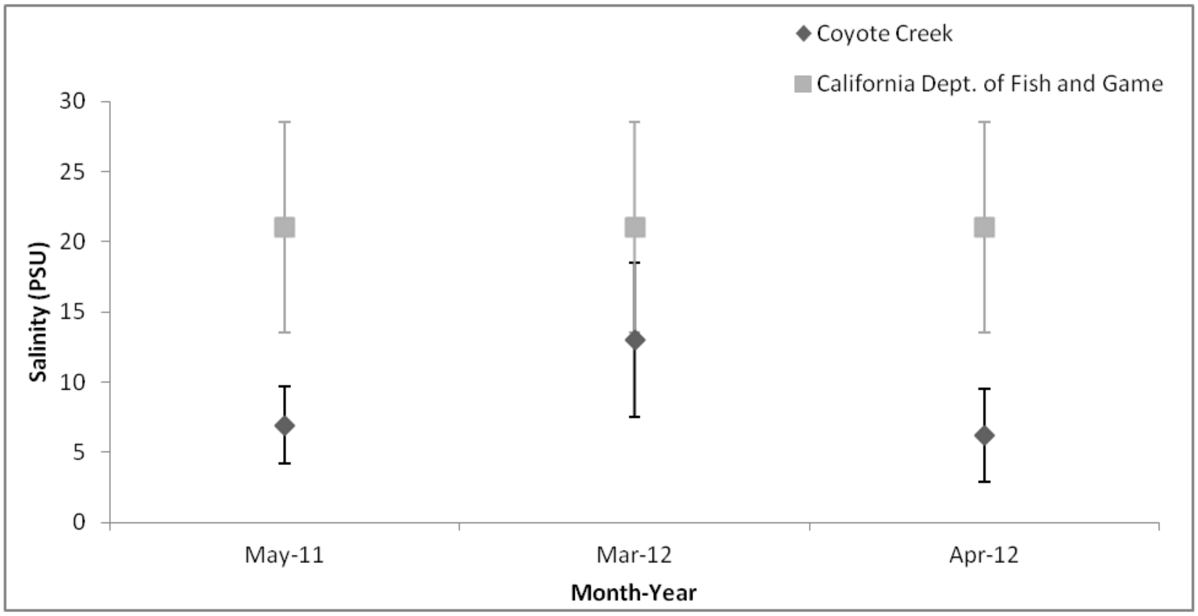


Figure 35. CPUE weighted average salinities where young (~30-40 mm SL) Pacific herring were captured in Coyote Creek and the long-term average salinities where comparably sized Pacific herring were captured in San Francisco Bay (Orsi et al. 1998). Pacific herring are only abundant in Alviso Marsh for ~2-3 months a year. Error bars are ±1 SD

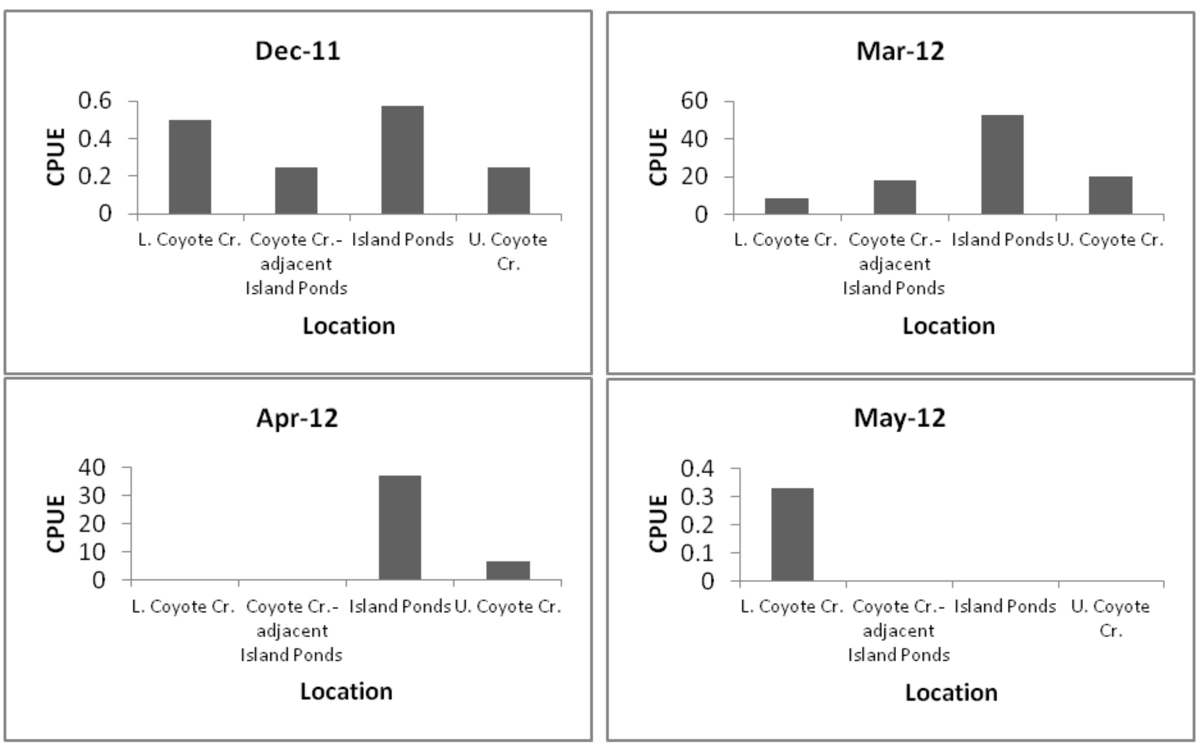


Figure 36. CPUE of Pacific herring in Coyote Creek and the Island ponds. Axes are scaled to account for monthly differences in CPUE. The high CPUE of Pacific herring in Upper Coyote Creek in April occurred in our inaugural sampling of Warm Springs Lagoon.

The high CPUE of juvenile marine immigrants such as Pacific herring and English sole within the Alviso Marsh Complex, and their position within the marsh, indicates that the Alviso Marsh Complex (especially adjacent to restored salt ponds) might actually function as nursery habitat for several species. Whether this is due to salt pond restoration has not been determined; however, seasonal surveys conducted immediately prior to the Island Pond restoration (Takekawa et al. 2005) did not document either species in the area. Historical surveys from 1980-1986 (Stevenson et al. 1987) documented both species in South Bay, but not upstream of Calaveras Point, implying that these fish might have not been using this area as extensively during this time. However, less frequent sampling, different methods, and bay-wide changes in fish communities make this conclusion tenuous. Further investigation into possible mechanisms underlying the relationship between breached ponds and fish communities is needed.

Salt Pond Restoration: Community level

Using similarity indices provides a quantitative method that allows us to determine if restored salt ponds support similar fish species assemblages, both between salt ponds and between restored ponds and sloughs. Such indices also give the extent to which communities differ. Should salt ponds support different assemblages, the species colonizing the habitat will reflect the conditions created by the salt pond and be indicative of the fish communities' response to restoration. Alternatively, should the assemblages be identical between the ponds and sloughs, it is likely salt pond restoration has very few effects on slough fish and provides habitat that is identical to the sloughs. Future, more complex analysis will seek to further address this question, depending on the ability of the data to meet the requisite assumptions. Because of sampling consistency, the Island Ponds in the Alviso Marsh will be used as an example.

The Islands Pond fish assemblage is most similar to the adjacent Coyote Creek in winter and spring, and least similar in summer and fall, as seen in both 2010/2011 and 2011/2012. Most fish found in Coyote Creek were also found in the adjacent Islands Ponds, which is reflected in a consistently high Sørensen similarity index between the two habitats; however, fewer species are shared during the summer and fall months (Figure 37a). The relative abundances of the fish species that comprise the two communities are rarely similar in both the restored ponds and the slough, and in the summer to fall period the dominant community members are extremely different, as indicated by a low Bray-Curtis similarity index during this period (Figure 37b). Because the spring of 2011 was cooler and wetter than the spring of 2012, this "summer" pattern began later in the season.

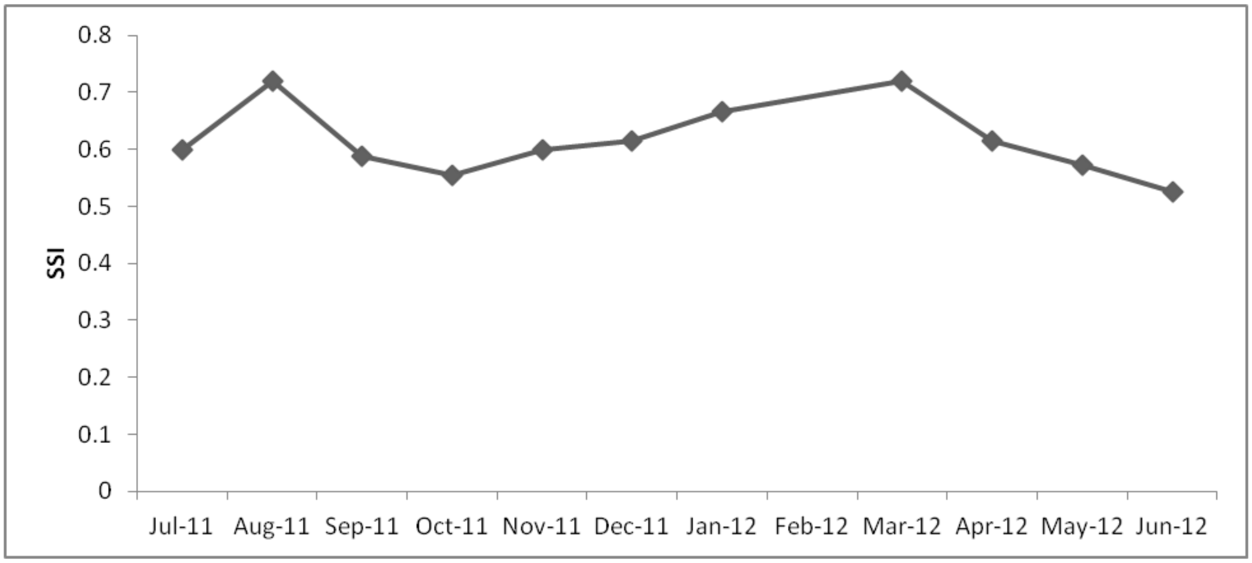


Figure 37a. Sørensen similarity index (SSI) comparing the Island Ponds with the adjacent reach of Coyote Creek. The SSI only operates on a species/presence or absence.

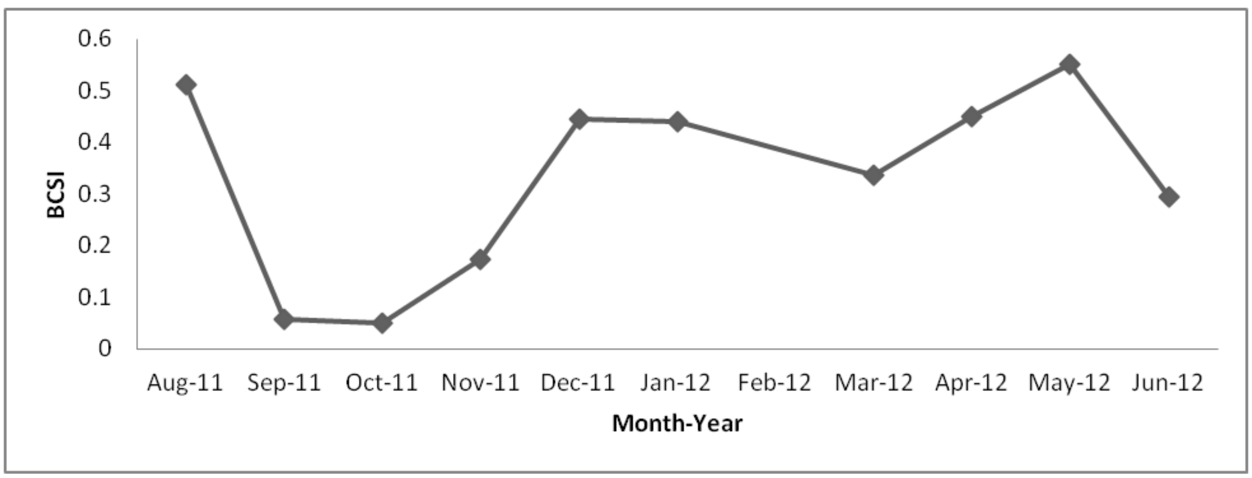


Figure 37b. Bray-Curtis similarity index (BCSI) comparing the Island Ponds and the adjacent stretch of Coyote Creek. The BCSI accounts for the relative abundance of species in each community.

Throughout much of the year, most of the fish present in the slough appear to utilize the restored habitat, resulting in communities that are fairly similar. The difference in fish communities that is observed in summer months is due in large part to the stressful conditions that exist in the Island Ponds during that time. Because the Island Ponds are large, shallow bodies of water, they get considerably warmer than the adjacent slough. The high temperatures, coupled with the large daily fluctuation in dissolved oxygen, create an environment that inhospitable to many fish species. However, these are extremely productive environments, and, as our invertebrate surveys have shown, the ponds have large numbers of potential prey items. Because of this, fish species that are capable of tolerating the abiotic stressors in these habitats reach extraordinary abundances (i.e., Pacific staghorn sculpin and threespine stickleback).

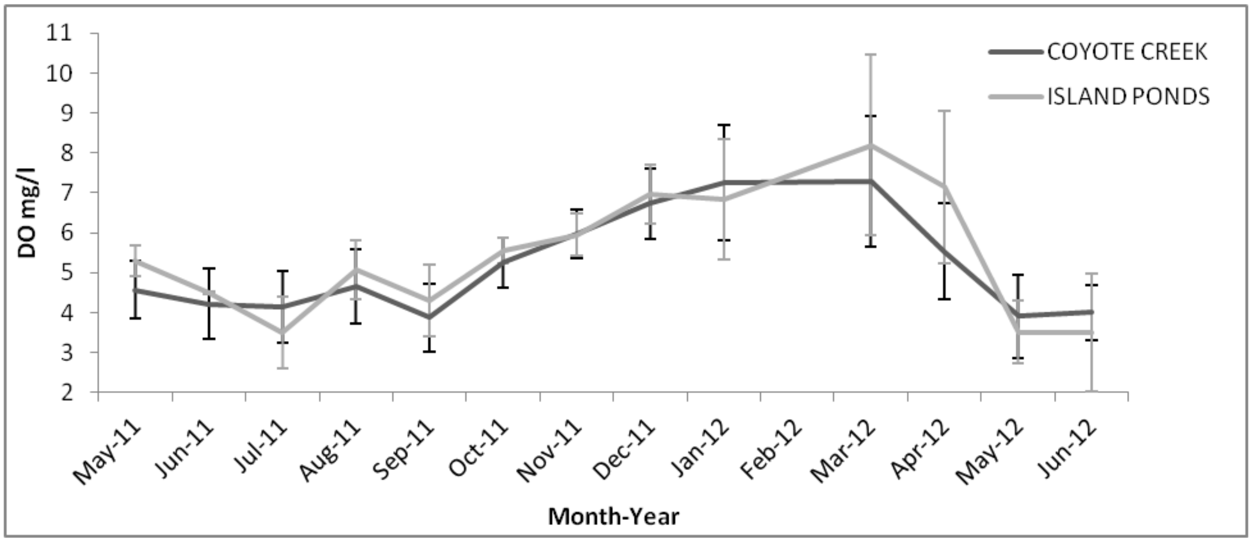


Figure 38a. Average monthly dissolved oxygen recorded in the Island Ponds and in Coyote Creek. Error bars are ±1 SD.

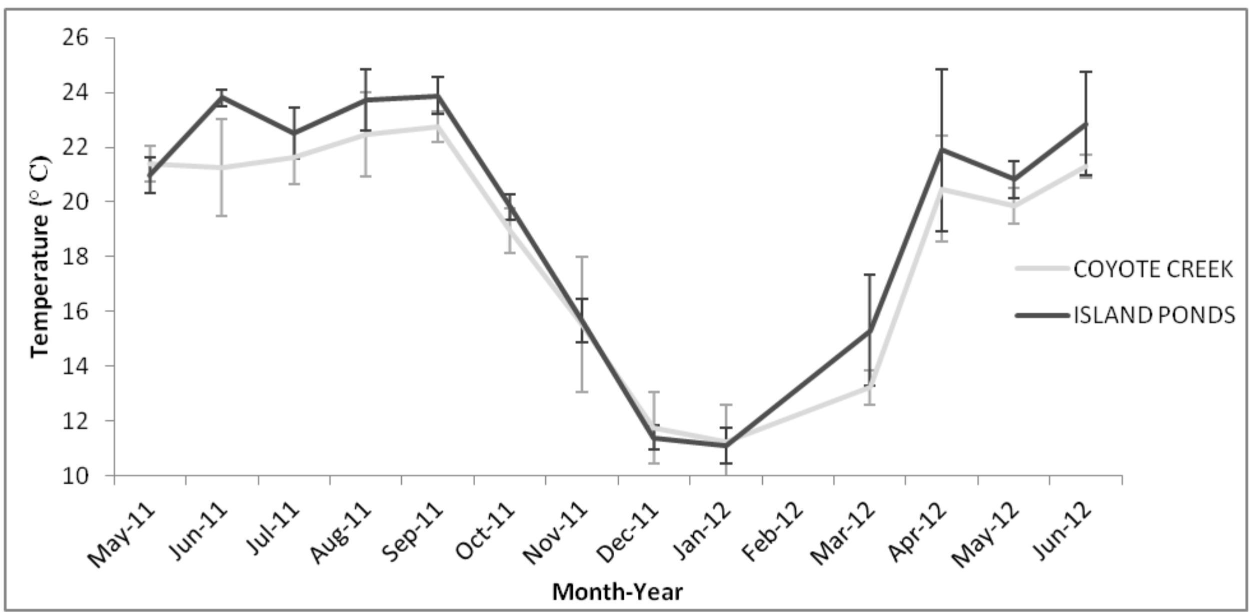


Figure 38b. Average monthly temperature recorded in Coyote Creek and the Island Ponds. Error bars are ±1 SD.

The fish species found in both Pond A19 and Pond A21 were similar throughout the year, which is reflective of the similar abiotic conditions in both habitats (i.e., high temperature and low dissolved oxygen in summer and relatively good water quality in winter). The only time when the fish species composition differed was following a runoff event in Coyote Creek in November, 2011 (Figure 39). This changed the salinity (an important abiotic factor) of Pond A19 more than that of Pond A21, resulting in a changed fish fauna.

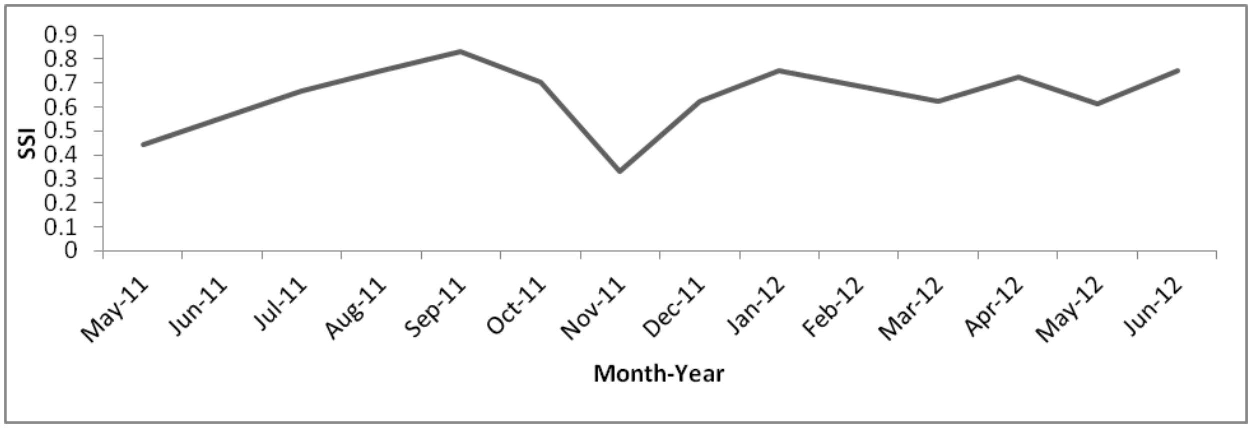


Figure 39. Sørensen similarity index (SSI) comparing Ponds A19 and A21 with the adjacent reach of Coyote Creek. The SSI only operates on a species/presence or absence.

In spite of similar species in both habitats, the dominant members of the two communities differed in summer and early fall (Figure 40), as indicated by a consistently low Bray-Curtis similarity index. The dominant member of the fish community found in Pond A21 was the Pacific staghorn sculpin, and the dominant fish species in Pond A21 was the threespine stickleback (see appendix).

Because of the relative elevations of the surface of Pond A19 and A21 and their position along Coyote Creek, A21 has become more vegetated and accreted more sediment than A19 (Brand et al. 2012). This slow habitat evolution creates more habitat for intertidal marsh specialists (such as Pacific staghorn sculpin) and less habitat for pelagic fishes (northern anchovies, threespine stickleback). The difference in the communities observed in A21 and A19 are reflected by this.

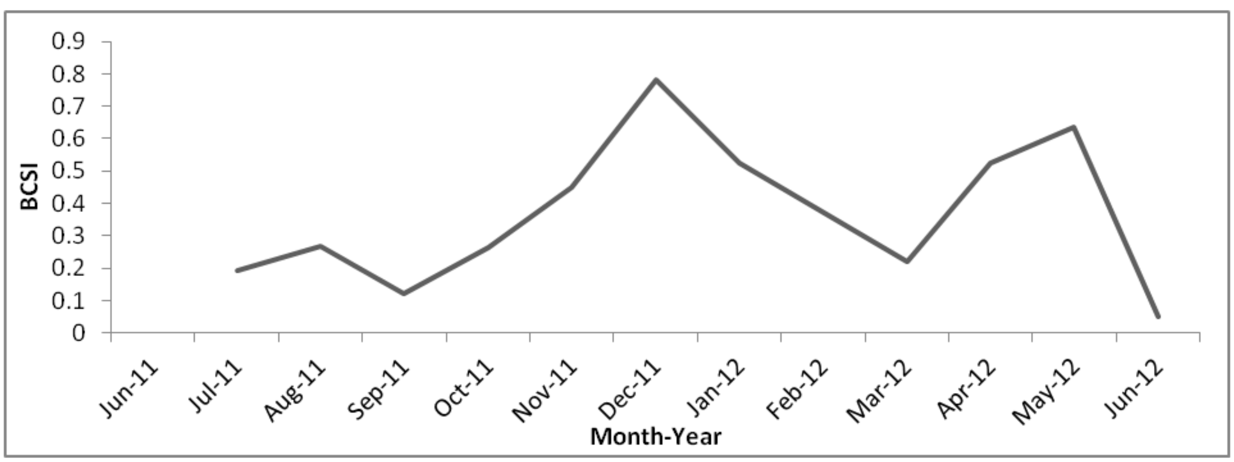


Figure 40. Bray-Curtis similarity index comparing the Ponds A19 and A21.

The two ponds increased in similarity in the late fall to spring months (October 2011 to April 2012). The two ponds were less similar in March 2012, when large numbers of Pacific staghorn sculpin began to recruit to the trawl inside pond A21. By April 2012, Pacific staghorn sculpin were also abundant inside A19, thus increasing the similarity index.

Sentinel Species Health Monitoring

Approach

Sentinel species health monitoring is an important and ecologically relevant approach for determining the effect of environmental stressors on a community of organisms. Although it is impossible to determine the precise factors contributing to the health of a free-ranging species found at a certain site, the use of an integrated approach incorporating somatic (whole body) condition indices, in concert with assessments of growth, nutritional status, disease status, and population abundance are good indicators of the general health of a species (Adams et al., 1989). The nutritional status of fish can mediate contaminant and disease impacts in susceptible species. Fish nutrition and growth may reflect overall food quantity, food quality, and availability of good habitat (Brinkmeyer and Holt, 1998; Gaspasin et al., 1998; Ashraf et al., 1993). Moreover, the presence of disease in wild fish populations is a significant health indicator because it represents the cumulative effects of multiple stressors and variables in the aquatic environment, many of which are unknown or poorly defined (Hedrick 1998). Seasonal, and interannual trends in adult abundance and the numbers of juvenile recruits has been used to track the population health status of many species in San Francisco Bay and is one of the most common metrics used to monitor fish (Honey et al., 2004). In this task, we monitor the health of a sentinel indicator species of salt-marsh habitat quality, the longjaw mudsucker (*Gillichthys mirabilis*), in restoration salt ponds and remnant marshes in South San Francisco Bay.

The longjaw mudusucker is a resident estuarine fish, ranging from Mexico to Humboldt Bay, California, USA, and is one of the most abundant fishes in high intertidal salt-marsh habitat (Desmond et al., 2000; Talley 2000; West and Zedler 2000). The Longjaw mudsucker depends on high intertidal creeks in marshes dominated by pickleweed [*Salicornia* (*Sarcocornia*)]. The fish reside within burrows in soft sediments and is the only fish species that can remain in intertidal creeks during low tide when the creeks completely de-water. The mudsucker can tolerate life out of water by having vascularized buccal cavities for uptaking oxygen from the air. Mudsuckers have a wide environmental tolerance, and are able to tolerate freshwater and salinities as high as 90-ppt for periods of a few days to a week, and temperatures from 9-35 C° (Lonzarich and Smith 1997, Moyle 2002). Longjaw mudsuckers are benthic consumers, most commonly eating bottom-dwelling invertebrates, such as amphipods, isopods, and small fish. Males will guard burrows and display their long maxillae, hence their common name, to attract females. Spawning occurs predominantly from late winter to early spring, with pelagic larvae settling to the benthos approximately two months after hatching. Juveniles (<80mm) spread out into many different habitats during summer, while adults tend to spend most of their lives in a single creek habitat, not straying more than a few meters from their burrows. With such a high degree of site fidelity, longjaw mudsucker completes its life cycle in a single marsh

(Yoklavich et al., 1992), making it an excellent candidate as a sentinel species of saltmarsh habitat quality.

The longjaw mudsucker has been used as a sentinel species of ecosystem health for saltmarsh habitats in San Francisco Bay, Tomales Bay, and Carpenteria Marsh in Southern California. The Pacific Estuarine Ecosystem Indicators Project (www.bml/PIEER.org) developed indicators of health for longjaw mudsucker with an emphasis on biochemical and ecological indicators in contaminated marshes. In San Francisco Bay, individuals from highly contaminated habitats exhibited poor liver quality, high levels of apoptosis (programmed cell death), and had large tumors on gonads (Anderson et al., 2006). Furthermore, populations in highly altered habitats had poor recruitment, low survival and lower abundances than more pristine marsh habitats (McGourty et al. 2009).

To assess the population status and general health of longjaw mudsucker inhabiting restoration ponds and adjacent remnant marsh habitats, we took an integrated approach by incorporating the monthly abundance of adult and juvenile recruits via catch per unit effort (CPUE) and estimated annual abundance and survival using a mark-recapture study from monthly minnow trap surveys. Health status was evaluated from monthly surveys by quantifying individual condition factor (length-weight measurements) and examining fish for structural deformities and incidence of external disease or parasite infection. Once a year in the fall, a subset of individuals (N= 8-10) were sacrificed and fish health was assessed from seasonal otolith growth, condition factor, hepatosomatic index (liver weight), incidence of disease and parasites, and proximate body composition analysis (% moisture, lipid-protein).

Study Areas

Alviso Marsh Complex

Pond A6 is a fully tidal pond with two breaches along Alviso Slough that were opened in November 2010. We chose 4 reference creeks (A6_O) along the remnant marsh outside the second northernmost breach to the pond. Initially, our first creek occurred where the breach was made, and we were forced to abandon this location. This area is characteristic of a remnant marsh that was altered by pond formation, with a levee built at the uppermost edge. Creek habitats are relatively intact, with short meandering reaches creating steep undercut banks which provide habitat for the longjaw mudsucker. Creeks are 30-40 meters in length and average a depth of 1.5 meters. The marsh plain (A6_I) is dominated by pickleweed with small patches of cordgrass growing on the marsh plain. Inside A6, the margins of the borrow ditch are forming pickleweed marsh; however, creek formation has not yet occurred.

Pond A8 (A8_I) is a managed pond, and is tidally muted from June 1 to November 30, with the water levels dictated by flood-control during winter months. Depths are usually between 1-3 meters. The pond is surrounded by rip-rap levees with very little pickleweed marsh. One small patch of pickleweed occurs at the old boat launch just north of the tide gates; however, this area is de-watered approximately half the year due to fluctuating water levels, rendering this location as a long-term study site difficult. We chose three lines (~30m length) along the southeast levee along the road, and when inundated we sampled the pickleweed marsh adjacent to the boat launch east levee. In May 2012, we began sampling just outside the tide gate along the edge to monitor for recruitment of juvenile longjaw mudsucker.

Pond A21 was the most extensively surveyed breached tidal salt pond, since it has the highest marsh plain and has pickleweed filling in much of the marsh plain with pockets of cordgrass occurring as well. We have sampled extensively along the borrow ditch edges (east, west, and north levees), along the inside of the large slough forming within the middle of the marsh, and along the marsh plain along the northeastern edge. Here we identified four reference creeks of about 60-meters (A21_I) length with pickleweed beginning to line the banks. We began consistently sampling these locations in May 2012. Sites within the interior of the marsh plain did have ample populations of longjaw mudsucker; however, access to this area was very limited and navigation has been dangerous. Because of the difficulties associated with access, we decided not to continue sampling the interior of the marsh plain. We selected five creeks outside the northern levee (A21_O) along Mud Slough as our remnant pickleweed marsh reference site. The creeks here are only about 10 meters in length and less than one meter in width.

Ponds A19 and A20 were sampled extensively in the first year of the study, and catches were sporadic, but were relatively high in the summer, averaging 1-3 per trap when juveniles were searching intertidal habitat. In both ponds no pickleweed marsh has begun to grow on the marsh plain and only a very narrow fringing marsh exists. Since very little habitat existed in these ponds, we decided to abandon A19 and A20 to focus more effort in A21.

Ravenswood

We chose three reference creeks along the outside of Pond SF2 (SF2_O), which average 30-60 meters in lengths and are less than one meter in depth. One of the three creeks is less than 0.3 meters in depth and is only inundated on the highest spring tides of the month. The first creek (nearest the Dumbarton Bridge) is a long meandering creek that is bifurcated into two first-order creeks and, as a result, is given twice the trap effort as the other two creeks. Inside SF2 (SF2_I) we chose 3 lines of about 30 meters in length along the east edge of the levee and the walking path, one before the breach and two after the breach.

Bair Island Marsh Complex

We extensively sampled outside Outer Bair Island, north side of Corkscrew Slough (OB_O) and Outer Bair Island (OB_I) beginning July 2010. We found very few longjaw mudsuckers given the extensive effort, and it was not until June 2012 that we began consistently (monthly) collecting mudsuckers in one creek outside of the easternmost breach, where a small patch of pickleweed marsh exists. We also sampled inside the restoration pond along the borrow-ditch edge and the marsh plain where pickleweed has been recruiting over the last year.

Eden Landing Mash Complex

We extensively sampled many pilot sites within and outside ponds E9_I, E8_I, E8X at the Eden Landing complex prior to breaching of these ponds in 2012. Initial sampling occurred in July 2010 when restoration ponds were drawn down for construction. We sampled the ponded waters adjacent to culverts and collected many longjaw mudsuckers; however, these sites were drained and bulldozed in the construction process. Two short creeks (~10m) along the Whales Tail Marsh (WT1) on the northwest corner outside the E9 breach were chosen as long-term sites. These sites have mature pickleweed marsh but are littered with trash from the bay. South of WT1 within the Whales Tail Marsh, we selected a second creek site with mature marsh and meandering channels. We have yet to establish consistent trapping sites inside the restoration ponds, but in June 2012 we successfully collected longjaw mudsucker from the northeast corner where water flows into E13 from E9, making this site a candidate for our long-term inside-pond site for Eden Landing.

Sampling Methods

Minnow Trapping

Collection of the longjaw mudsucker was accomplished using baited minnow traps in first-order channels (high intertidal creeks) of mature pickleweed marsh and along fringes of ponded water inside newly breached ponds (Figure 41).

Figure 41. (Left) Image of a first-order creek with minnow trap. (Right) a Gee Style Minnow Trap from Wildco.com.

The study began in July 2010, with sampling taking place approximately bi-monthly (July, August, October, November, and December) at several pilot sites to determine optimal locations for long-term study sites (Figure 42). We chose reference sites with remnant pickleweed marsh on the outside levees of restoration ponds, where at least 3 traps could be spaced evenly at approximately 5 meters apart along creek habitats to represent the source population for fish immigrating into restoration ponds. This was not possible for many sites as very few remnant marsh creeks remained, or were overgrown with cordgrass (*Spartina*) or tules (*Schoenoplectus*) (e.g., outside ponds A8, A19, A20, and A21; Figure 42). We searched restoration ponds for creek habitat and only pond A21 had pickleweed on the marsh plain where creek habitat was beginning to form; therefore, we selected fringing pickleweed along the borrow-ditch edges as test sites for most pond sites. Several sites were only sampled once or infrequently during the pilot period due to no catch or difficulty of access.

Figure 42. Map of all sample sites for minnow trapping of longjaw mudsuckers during the pilot phase. Sites labeled as _O represent reference locations outside restoration ponds in adjacent remnant *Salicornia* (i.e. pickleweed) marsh, while sits labeled as _I are sites within the restoration ponds. Blue dots show different creek sites.

Study Design

We selected long-term study sites at several restoration ponds that provided the opportunity to monitor abundance trends of longjaw mudsucker within restoration ponds and in reference remnant pickleweed marshes immediately outside restoration ponds (Figure 43).

Figure 43. Monthly survey sites (top left) Pond A8, (top right) A21, (bottom left) SF2, and (bottom right) A6.

We selected 3-5 replicate creek habitats per site. Each site was sampled with 1-5 baited minnow traps (depending on creek length) for a minimum of 12 hours overnight during the full-moon spring tide, when the highest monthly tides occur. Monthly sampling began in May 2011 and has been ongoing at ponds A6, A8, and A21 in the Alviso Marsh Complex and at SF2 at Ravenswood (Figure 42). Quarterly sampling has been occurring at Outer Bair Island and the Eden Landing Complex because of overall low catch. All fish species collected were counted and measured for standard length, and all invertebrate taxa were identified to species and enumerated. All longjaw mudsucker were weighed, sexed, and inspected for the presence of any morphological deformities, infections, and parasites (microsporidia and external parasites) (Figure 44).

Figure 44. (Top) Longjaw mudsucker with an abnormally developed right maxilla. (Middle) longjaw mudsucker with an infection of the micrscoporidian parasite (yellowish spots on the head). (Bottom) microscopy image of the microsporidian parasite *Kabatana* sp.

Abundance Trends

A monthly abundance (catch-per-unit-effort, CPUE) index was calculated by averaging the number of longjaw mudsucker per trap (1-5 traps) for each creek (3-5) and then averaging the mean catch per trap across the replicate creeks for each site (A8, A6_I, A6_O, A19-21_I, A21_O, SF2-I, SF2_O, Bair Island, and Eden Landing). The nested design, with replicated traps per creek and replicated creek per site, allows for accounting of spatial variation within a site. We calculated the monthly abundance index for adults, (>80mm) and juvenile recruits (<80mm standard length). Comparisons for adults and juveniles were made across all sites (ANOVA) and between site types (inside restoration pond vs. outside the pond in remnant marsh). The lengths of longjaw mudsucker at each site where compiled into length-frequency histograms using Origin 8.5.1 to allow comparisons of the size structure between sites and years.

Mark-Recapture

We conducted a mark-and-recapture study using the sentinel species longjaw mudsucker at sites in the Alviso Marsh complex (ponds A8, A6, A21, A20 & A19), the Ravenswood complex (SF2), Eden Landing (Whales Tail Marsh and E9), and at the restoration outer Bair Island pond to estimate abundance and survival rates. Initial marking began in May 2011 and was concluded in July, 2012. We conducted monthly minnow trap surveys at all sites during this period to recapture tagged individuals. During each survey, captured longjaw mudsuckers were measured to the nearest 1 mm (standard length), sexed (adults only >80mm SL), weighed (wet weight 0.1g), assessed for deformities, the presence of microsporidian parasites was noted, and (if untagged) injected with a Northwest Marine Technologies alpha numeric tag (Figure 45). During subsequent surveys, recaptured fish were measured as above and the unique tag identification number recorded.

Figure 45. Longjaw mudsucker with an alpha numeric tag.

Marking dates and the numbers of tagged fish varied among site in association with the numbers of individuals captured monthly. For the sites A6_O and SF2_O marking began in May 2011 and continued monthly through July 2012, while site A21_O began in October 2011 and A21_I began in November 2011 and continued through July 2012 (Table 1). Due to the theft of field journals and a laptop computer from our laboratory, data for marked individuals was lost for the months of Jan-April 2012. However, tagged individuals first captured during this time period were determined based on recapture site and the sequence of individual alpha-numeric tags. For abundance and survival estimates we pooled January to April for analysis.

Sites	5/6/2011	6/18/2011	7/2/2011	7/15/2011	7/17/2011	8/4/2011	8/16/2011	9/12/2011	10/10/2011	11/10/2011	12/10/2011	1/1/2012	2/2012-4/2012	5/5/2012	6/3/2012	6/29/2012	6/30/2012	7/1/2012
A6_O	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
A6_I			●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
A8_I								●	●	●	●	●	●	●	●	●	●	●
A19_I	●			●		●		●		●								
A20_I	●	●		●		●		●		●								
A21_O									●	●	●	●	●	●	●	●	●	●
A21_I										●	●	●	●	●	●	●	●	●
SF2_O	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
SF2_I						●			●	●		●	●	●	●	●	●	●
Eden	●	●	●			●			●	●				●	●			●
Bair	●		●			●				●								

Table 1. Minnow trapping sites and sampling dates for mark-recapture study, regardless of whether longjaw mudsuckers were captured. Each black dot represents a sampling event.

Abundance was estimated using a closed population capture-recapture model (Higgins model) in program MARK (White and Burnham 1999). In this model, the population abundance is estimated using a full maximum-likelihood probability approach with the following parameters: p_i is the probability of first capture, c_i is the probability of recapture conditional on having been previously captured and tagged, and N is the abundance. The closed population model assumes the population of interest is closed to immigration and emigration during the sampling period and no births or deaths occur. We fit models with the parameters for the probability of capture p_i and recapcture c_i being constant over time and with a variable time component. However, a fully variable model is only possible when the final p_i of the survey is made equivalent to the final c_i , thus only three models rather than four were examined. Model fits were assessed with Akaiki's Information Criterion (AIC), which compares the model likelihood and accounts for the number of parameters estimated (Kutner et al.2004).

Annual survival and capture probability was estimated for longjaw mudsucker from monthly mark and recapture at four sites (A6_O, SF2_O, A21_O and A21_I). Marking dates and recaptures occurred as described above. Survival was estimated using the Cormack Jolly Seber (CJS) model in program MARK (White and Burnham 1999). In this model, survivial (ϕ, phi) and capture probability (*p)* from consecutive surveys were estimated from marked and recaptured individuals using the maximum likelihood probability. The CJS model assumed survival and catchability probabilities for all individuals (marked and unmarked) were the same. We fitted models with both constant ϕ and *p* and time-varying ϕ and *p* that resulted in four models fit. Model fits were assessed with AIC.

Health

To assess the health of the longjaw mudsucker, we examined all fish collected in minnow traps from the monthly surveys for condition factor and the incidence of infection and parasitism. We also collected a subsample of up to 10 individuals from several sites (A6_I, A6_O, A8, A21_O, A21_I SF2_O and E9_O) during fall of 2011. Fish were euthanized with an overdose of MS-222 (Trimethyl sulfate), numbered individually, and frozen in dry ice. Upon returning from the field, fish were stored in -20^{o}C. Necropsies were conducted within two weeks of returning from the field. Standard length (1-mm) and wet weight (0.1g) were recorded and were of the presence of internal parasites and external deformities was noted. The liver was dissected whole and weighed, allowing for the computation of the hepatosomatic index. Gonads were also removed and weighed when present. Otoliths were dissected and stored in individual labeled trays for growth analysis. All contents of the body were returned to the individually labeled bags and stored at -20^{o}C for proximate analysis.

Condition Factor

The wet weight of each individual was measured in the field with an Acculab EC-411 portable balance (0.1g). The condition factor was calculated using Fulton's Condition Factor Index. This was done for each longjaw mudsucker collected from monthly surveys (May 2011 to July 2012). In addition, we measured condition factor in the lab for the subsample collected for otoliths and proximate analysis.

Equation 6: Fulton's Condition Factor Index (FCFI)

FCFI = $weight \frac{10,000}{length^3}$

Hepatosomatic Index

The wet weight of liver was weighed for the subsample of longjaw mudsucker, the hepatosomatic index was calculated as follows:

Equation 7: Hepatosomatic index

Hepatosomatic index $= \frac{liver\ weight}{length^3} 10000.$

Disease and parasites

All longjaw mudsuckers were examined in the field for the presence of microsporidia. The degree of infection was quantified with an infection scale of 1 to 3, with a score of 1 representing individuals with a few distinct nodules located around the abdomen and the head, a score of 2 representing many nodules located throughout the body, and a score of 3 for individuals with extensive infection and in an emaciated state. External gill parasites and hookworms were also noted in the field. Skeletal deformities were also noted for body parts, but no ranking score was conducted.

<u>Proximate Analysis</u>

Proximate analysis refers to the measurement of the major constituents of the body, including moisture (water), lipids, proteins, minerals, and carbohydrates, and is reported as percentage of the total body weight. Whole carcasses, minus the otoliths, were freeze-dried in a furnace for approximately 7 days and weighed. The dried carcass was then ground to a powder and baked in a drying oven at 120^{o}C for 72 hours to remove the residual carbon ash. Ash-free samples were weighed and used as a proxy for the remaining lipid and protein content.

<u>Otolith Growth</u>

Otoliths were mounted onto glass slides with Crystal Bond thermoplastic resin in the sagittal plane, ground to the core on both sides with wet-dry sandpaper, and polished with a polishing cloth and 0.3-micron polishing alumina. Otoliths were digitized with a digital camera at a magnification of 100X. Otolith increments were enumerated, and the distance from the core to each daily ring was measured using Image-J NIH software. Growth rates were quantified using several approaches. The size at each daily increment was estimated using the Biological Intercept Model (BIM) method previously developed for delta smelt (Hobbs et al. 2007). Seasonal growth rates were quantified from the settlement check mark, which is formed when the larva transitions from the pelagic to benthic environment approximately two months post hatch, to the edge of the otolith or the point at which daily increment formation was difficult to interpret.

Results

Abundance Trends

The abundance Index (CPUE) of longjaw mudsucker varied considerably on a monthly and seasonal basis, with the months of June-August (summer) having the highest abundance and the winter months the lowest abundance (ANOVA: MS 37.5, df=26, F-Ratio=8.9,5 p <0.001 (Figures 6-9). The seasonal abundance trend did not vary between years (2010-2012) with high abundance in summer months and lows in winter months. Abundance varied between sites, with A6_O having the highest abundance and A8 the lowest (ANOVA: MS 76.9, F-Ratio =12.9, df=6, p <0.001); however, sites where longjaw mudsucker populations were not persistent, such as Outer Bair Island and Eden Landing were excluded from the analysis . Sites inside restoration ponds tended to have much lower catch (ANOVA: MS 227, F-Ratio=33.7, df=1, p<0.001) compared to outside remnant marsh sites, although sites inside A21 (A21_I) and A6 (A6_I) had equivalent CPUE compared to outside reference sites (A6_O and A21_O) in summer months, exceeding an average of 3 adults per trap. Abundance was lower for ponds with a muted tide stage (A8 and SF2_I) compared to ponds that were fully tidal (ANOVA: MS 324.8, F-Ratio=51.2, df=1, p < 0.001). The abundance of longjaw mudsucker increased during the surveys for adults at sites A6_O and A21_I and A21_O while declining at A6_I; they also increased during 2011 at SF2_O and A8, but then declined in 2012.

Recruitment of Juveniles

Longjaw mudsucker recruitment (CPUE of fish <80mm SL) varied among inside-outside restoration pond comparisons (ANOVA: MS 56.4, F-Ratio=15.2 df=1 $p<0.001$) and between sites in 2011 and 2012 (ANOVA: MS 21.4, F-Ratio=6.1 df=6 $p<0.001$) (Figures 46-49). Recruits were observed at all sites but were in greater abundance at sites outside restoration ponds. At stations A6_O and SF2_O, recruits were observed during each survey, and at A21_O they were observed at all but four surveys. Recruits were most abundant during the summer months (May-Aug) at all sites, declined during the fall months ,and were rare during winter. This pattern reflects the reproductive timing, and the subsequent mortality and recruitment into the adult size class. In 2011, the abundance of recruits was similar among all sites, averaging approximately 2 fish per trap. In 2012, the CPUE for recruits was higher at all sites than in 2011, and were in greater abundance inside ponds A6 (A6_I) and A21 (A21_I) relative to outside A6 (A6_O) and A21 (A21_O). The abundance of recruits was similar to adults at most sites and surveys; however, the abundance of recruits was greater at A6_I in August 2011 and July 2012, at A21_I in July and August 2011, at A21_O in July 2012, at SF2 in June and July 2011, and in July 2011 at A8.

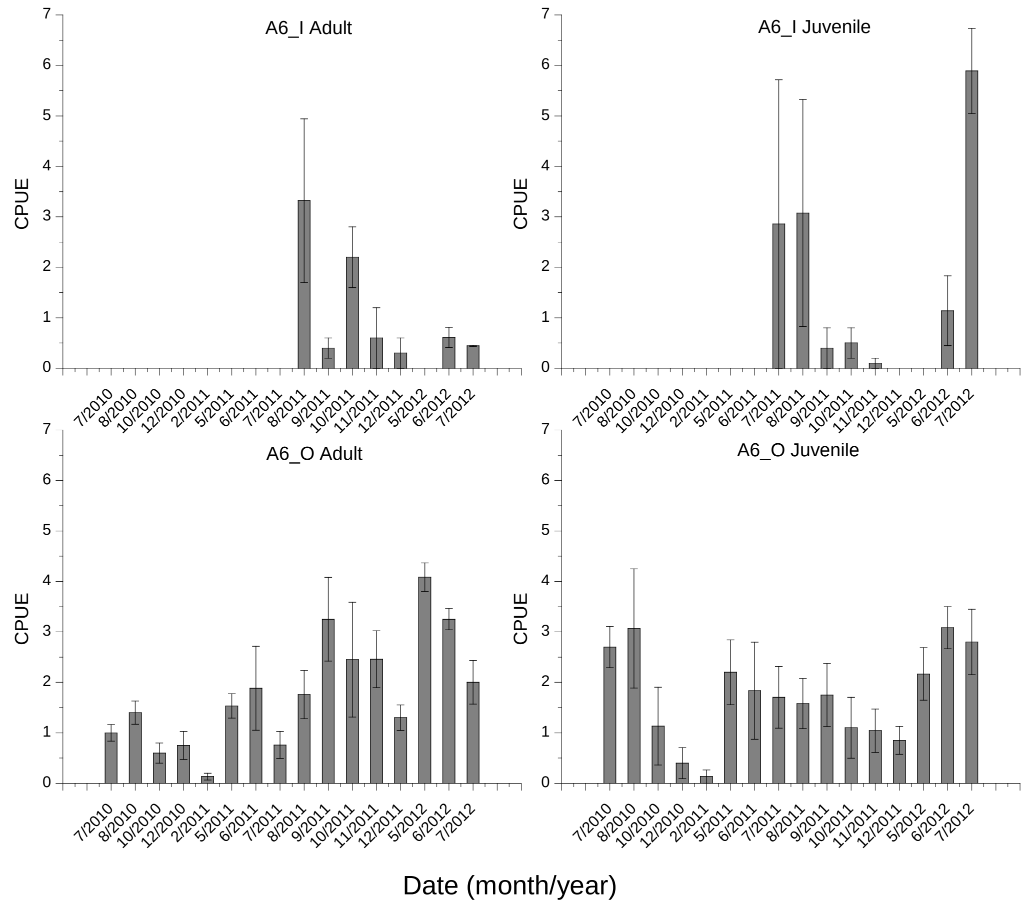


Figure 46. Monthly CPUE for the sites A6_I and A6_O for adult and juvenile longjaw mudsucker. Error bars depict 1 SE.

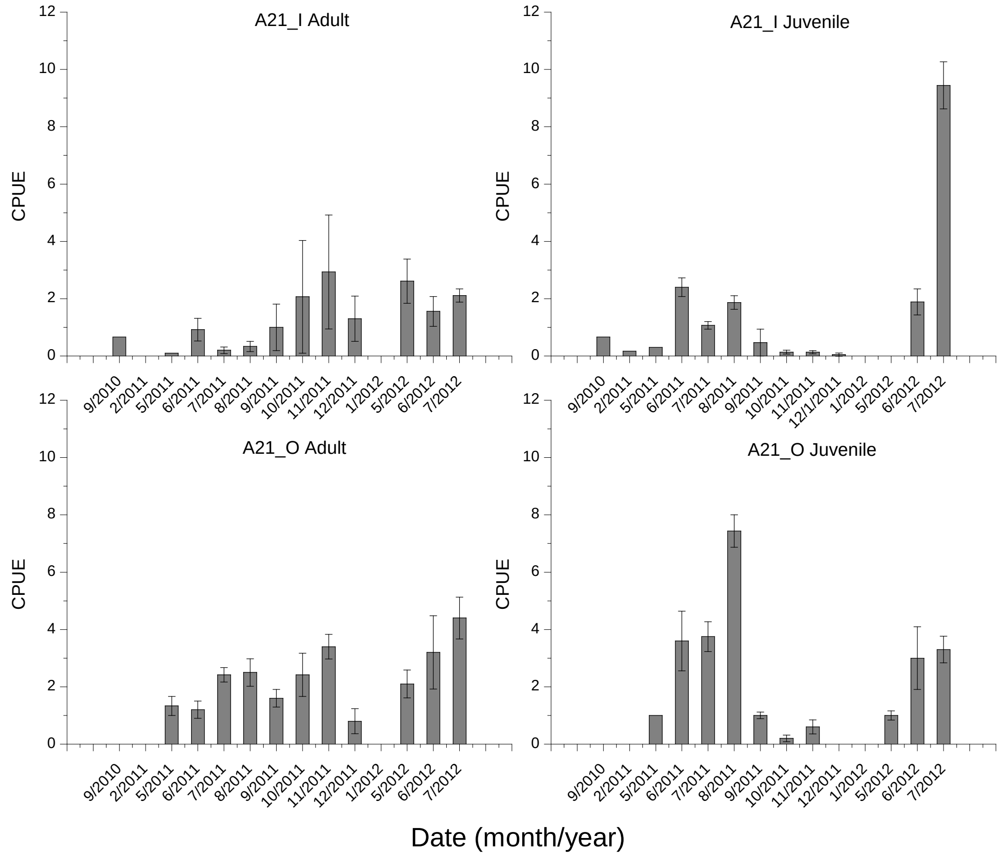


Figure 47. Monthly CPUE for the sites A21_I and A21_O for adult and juvenile longjaw mudsucker. Error bars depict 1 SE

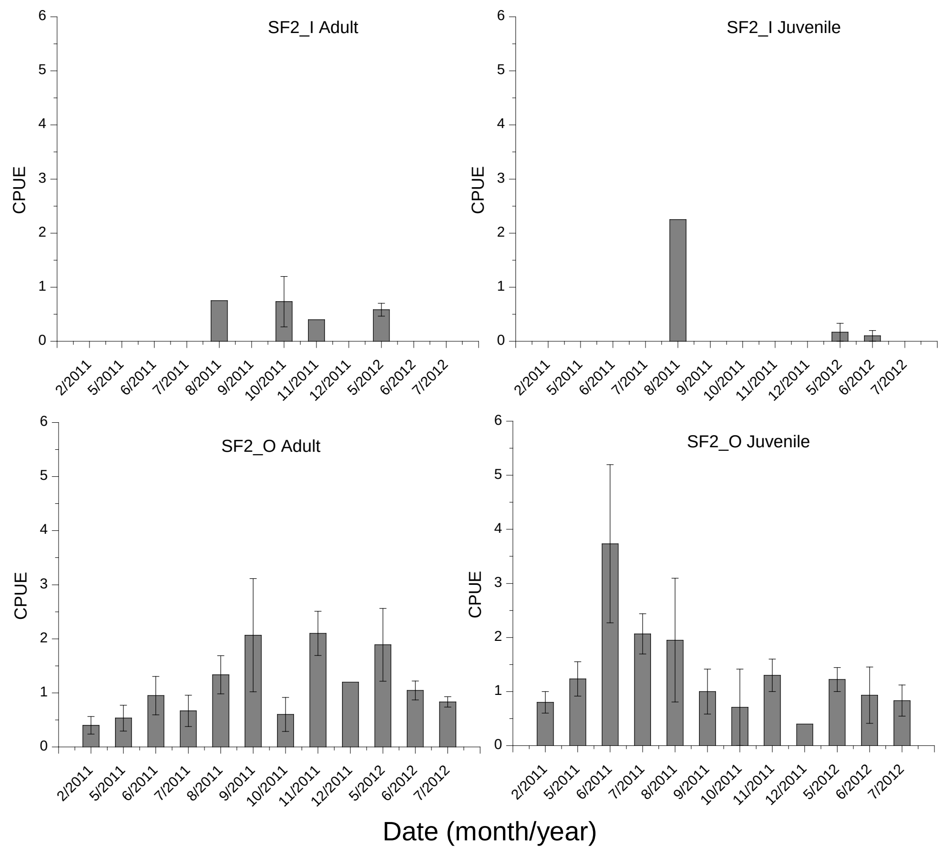


Figure 48. Monthly CPUE for the sites SF2_I and SF2_O for adult and juvenile longjaw mudsucker. Error bars depict 1 SE.

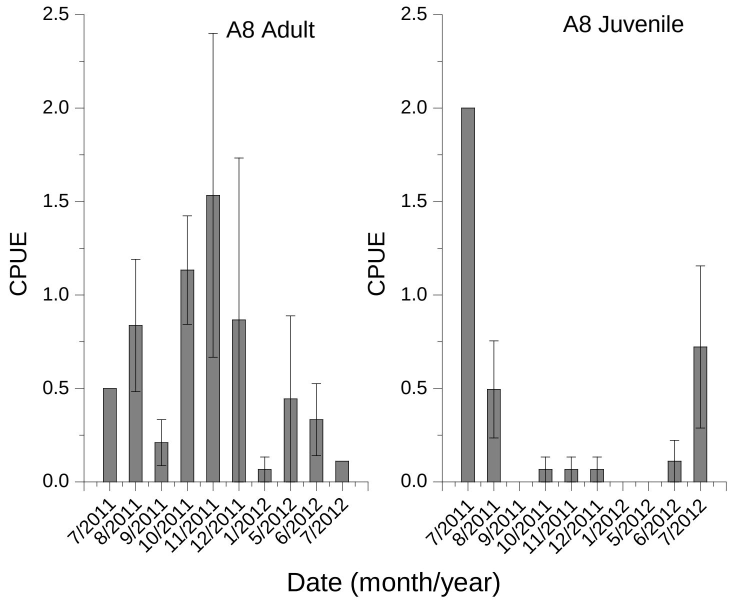


Figure 49. Monthly CPUE for the sites A8_I for adult and juvenile longjaw mudsucker. Error bars depict 1 SE

Length Frequency

The timing of peak recruitment varied by one month between sites and years, with new young-of-the-year (YOY) recruits (45-60 mm SL) entering the minnow traps in May for sites A21_I (Figure 10) and A6_O for 2011 (Figure 51), while sites A21_O (Figure 50) and SF2_O (Figure 12) had recruits first appearing in June. Sites A6_I (Figure 51) and A8 (Figure 53) did not receive these small size classes until July 2011. With length-frequency histograms, the change in size of the YOY recruits can be followed from each monthly survey. Recruits at all sites had reached a length of ~90 mm by December of their first year. Adults did not appear to grow as quickly as YOY recruits, and fish beginning the year at a length greater than 90 mm reached a length of ~110-mm SL by December, and fish greater than 120-mm SL were rarely observed . Growth rates approximated from length-frequency changes were consistent with otolith growth data from this study and from our previous work in central San Francisco Bay and Tomales Bay (Hobbs, unplublished data). YOY grew approximately 10-15 mm per month in the summer up to a length of 90 mm, at which point growth slowed to less than 10 mm a year, with fish reaching a maximum size of 135 mm at an age greater than 4 years. Site A6_I was first breached in November 2010, and, in the following spring, recruits began to utilize this habitat and appeared to grow rapidly, reaching greater than 90 mm by October, although they were not found in November or December 2011. We began catching fish again in June 2012; however, very few individuals from the 2011 cohort were observed. The range and variation in length distributions were often greater for sites outside restoration ponds compared to sites inside restoration ponds; however, the length variation within A21 (A21_I) was larger then the adjacent reference site (A21_O) (or any other site) from May to August 2011.

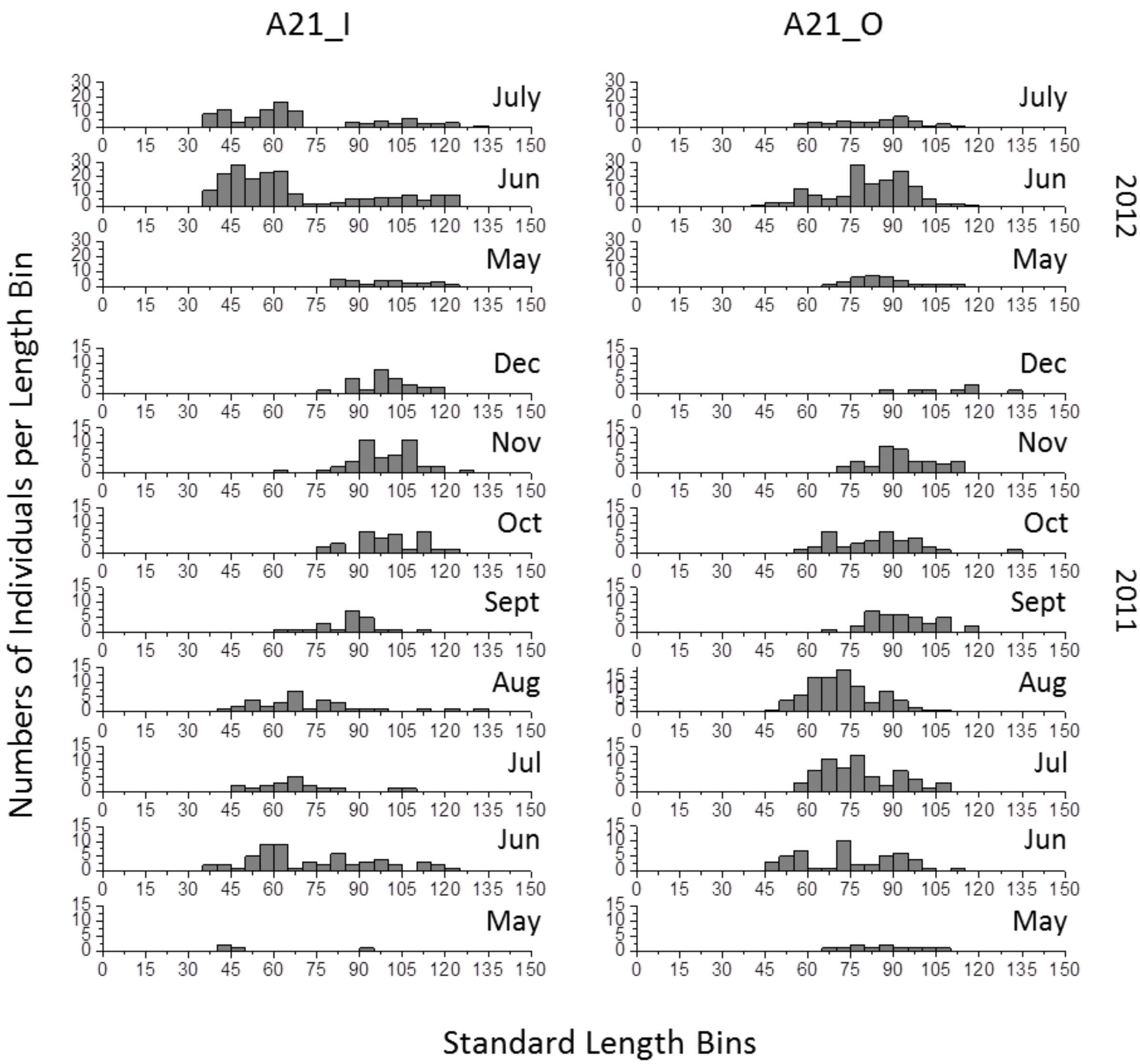


Figure 50. Length-frequency (number of fish per length bin) distributions for longjaw mudsucker collected from monthly minnow trap surveys at sites A21_I and A21_O for May-Dec 2011, and May-July 2012.

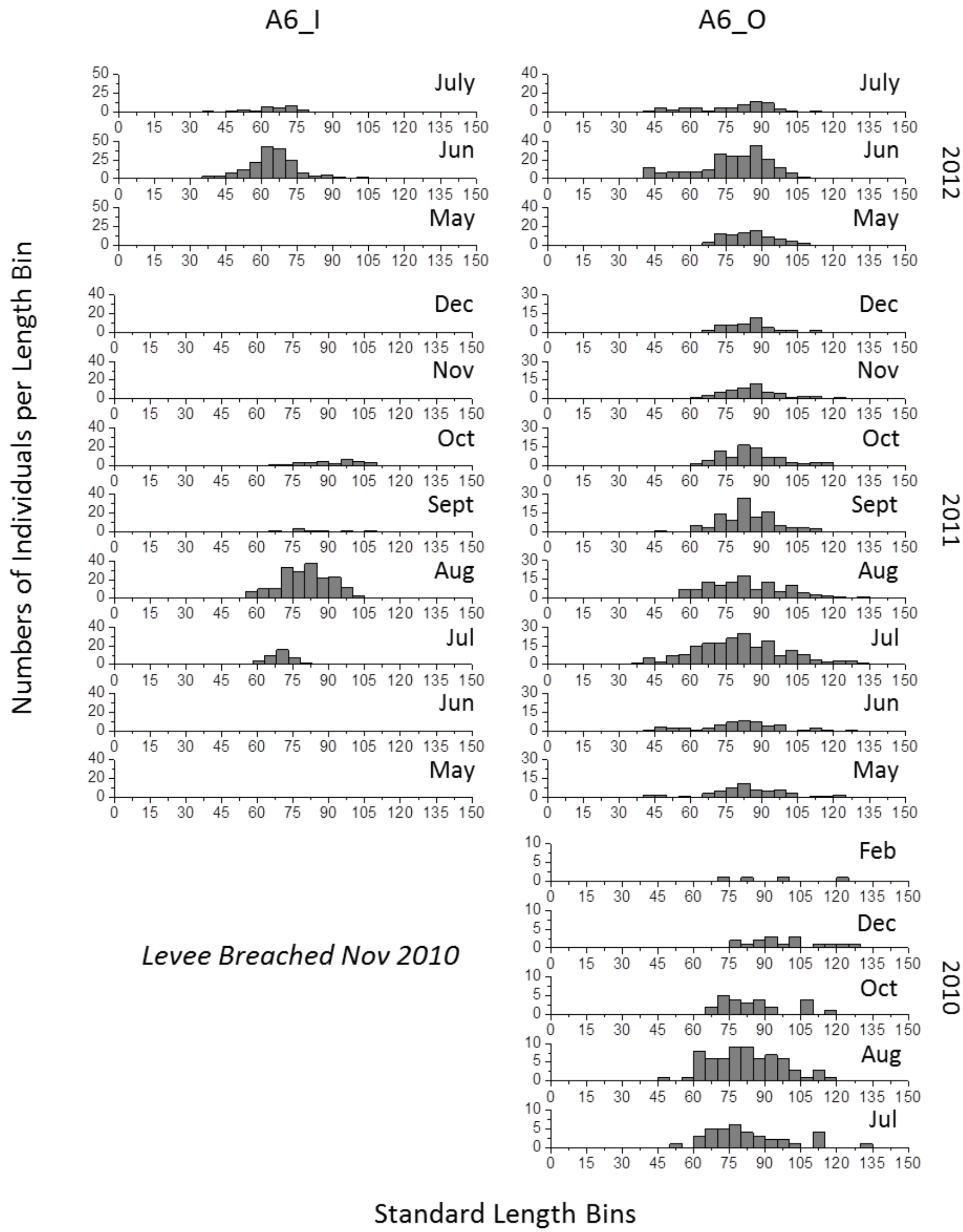


Figure 51. Length-frequency (number of fish per length bin) distributions for longjaw mudsucker collected from monthly minnow trap surveys at sites A6_I and A6_O for the pilot period Jul-Feb 2010-2011, May-Dec 2011, and May-July 2012.

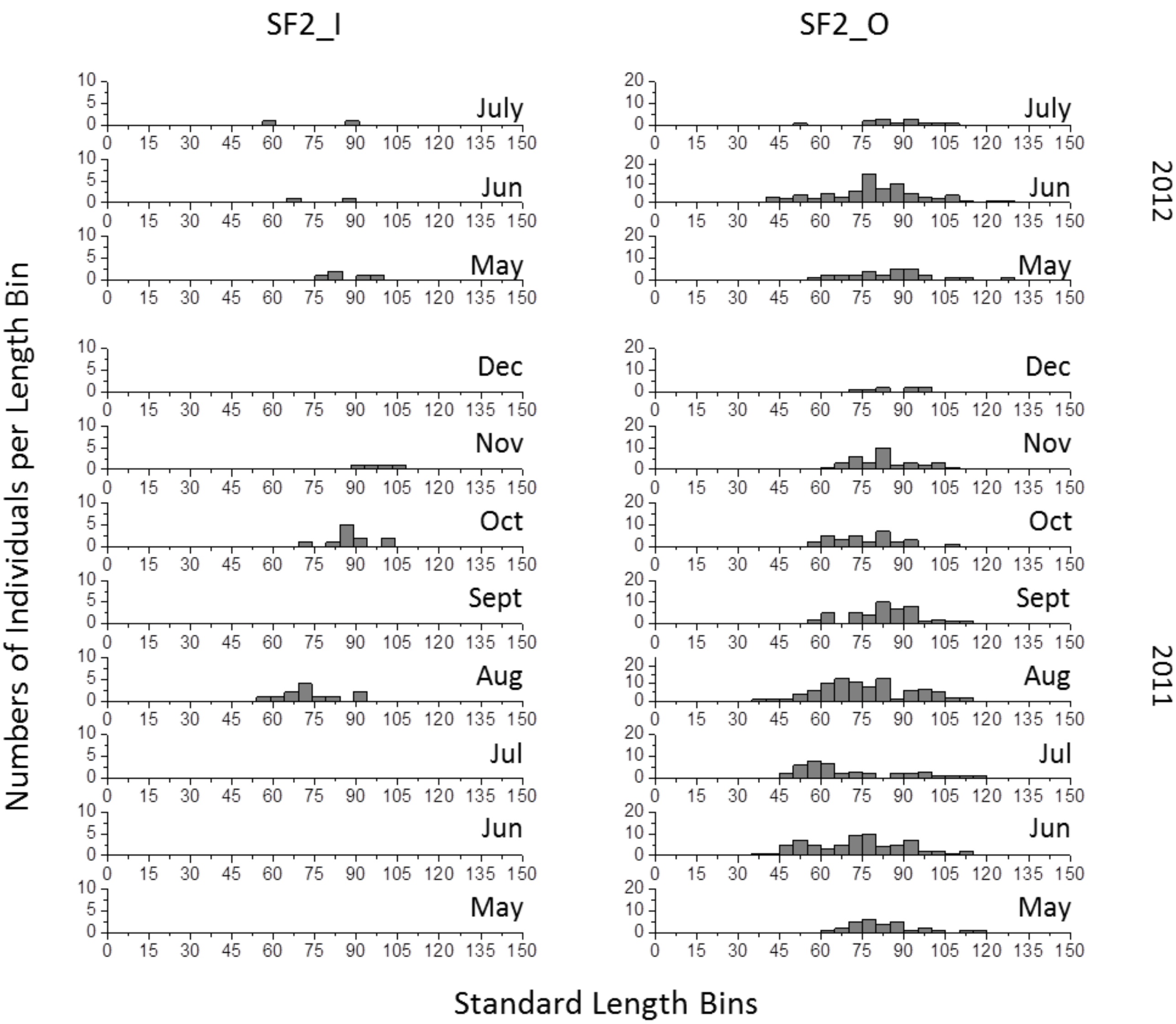


Figure 52. Length-frequency (number of fish per length bin) distributions for longjaw mudsucker collected from monthly minnow trap surveys at sites SF2_I and SF2_O for May-Dec 2011 and May-July 2012

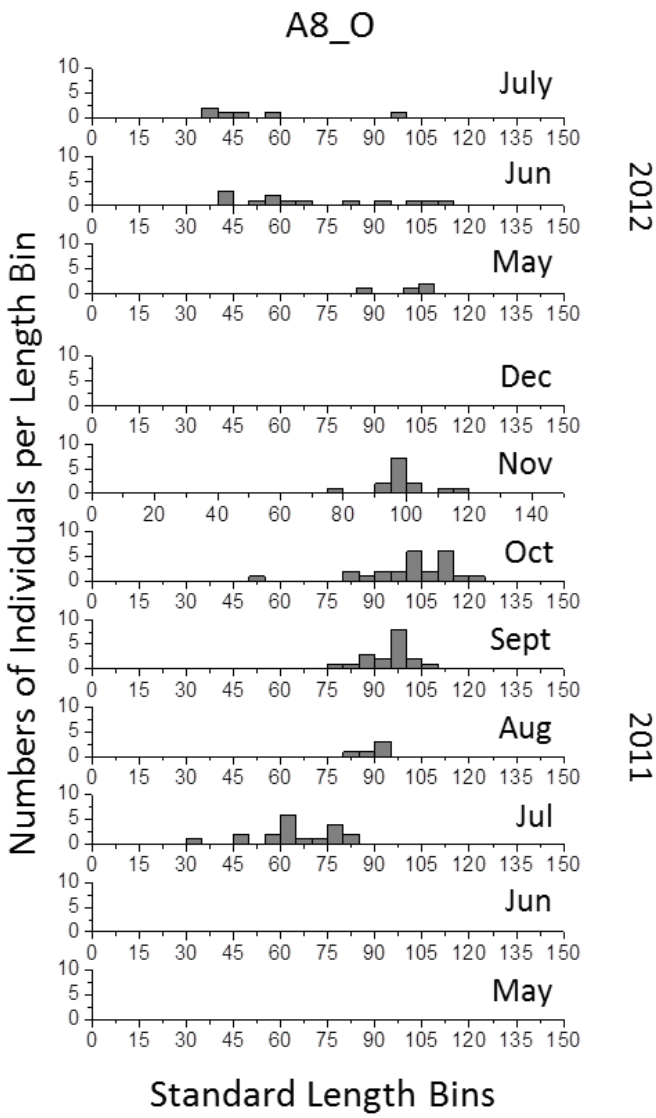


Figure 53. Length-frequency (number of fish per length bin) distributions for longjaw mudsucker collected from monthly minnow trap surveys at site A8 for May-Dec 2011 and May-July 2012

Annual Abundance Estimates

The numbers of tagged and recaptured individuals with unique capture histories varied between sites and years, with the A6_O site having the largest number of tagged and recaptured individuals in both 2011 and 2012. Note that many individuals at all sites were recaptured more than once. Table 2.

	2011		2012	
Sites	Tagged	Recaptured	Tagged	Recaptured
A6_O	446	104	205	73
SF2_O	300	26	64	18
A21_O	67	28	100	52
A21_I	62	7	192	33

Overall, the model with time-varying first capture probability($p)_i$ was the model best fitting the data for each site and year except for site A21_O in 2011, reflecting the seasonal patterns of activity or abundance of the fish, with activity and catch per unit effort being greater in summer than winter months (Table 3).

	A6_O		A21_O		A21_I		SF2_O	
Model Type	2011	2012	2011	2012	2011	2012	2011	2012
Constant first capture	-1042.76	-544.20	47.41	-86.37		-1021.50	-1071.02	-34.30
Time varying first capture	-862.78	-514.21	35.15	-65.37		-888.33	-931.96	-28.65
Differing first capture and recapture	-693.70	-509.81	138.56	-63.22		-862.51	-716.20	-26.78

Table 3. AIC for closed-capture models fit to mark-recapture encounter histories. Greater values (more positive and more negative) depict the best fit to the data given the number of parameters estimated.

Annual abundance estimates varied among sites, with the high abundance occurring at A6_O (N = 783) and SF2_O (N = 863) and low abundance at A21_O (N = 89) for 2011 (Figure 54). No estimate was calculated at A21_I due to the low numbers of recaptures. Annual abundance estimates for 2012 were calculated only for the May-July months at the four sites, as data was missing for the January-April months. The shorter time interval precludes directly comparing abundance between 2011 with 2012, however relative differences between sites within years could be used to assess abundance trends. Abundance was high for A21_I (N = 689), while A6_0 was lower (N = 308) and SF2 (N = 107) and A21_O (N = 106) were the lowest for the year. In 2012, abundance was much lower for SF2_O relative to the A6_O site, in comparison to 2011, suggesting abundance was likely much lower overall at SF2_O in 2012.

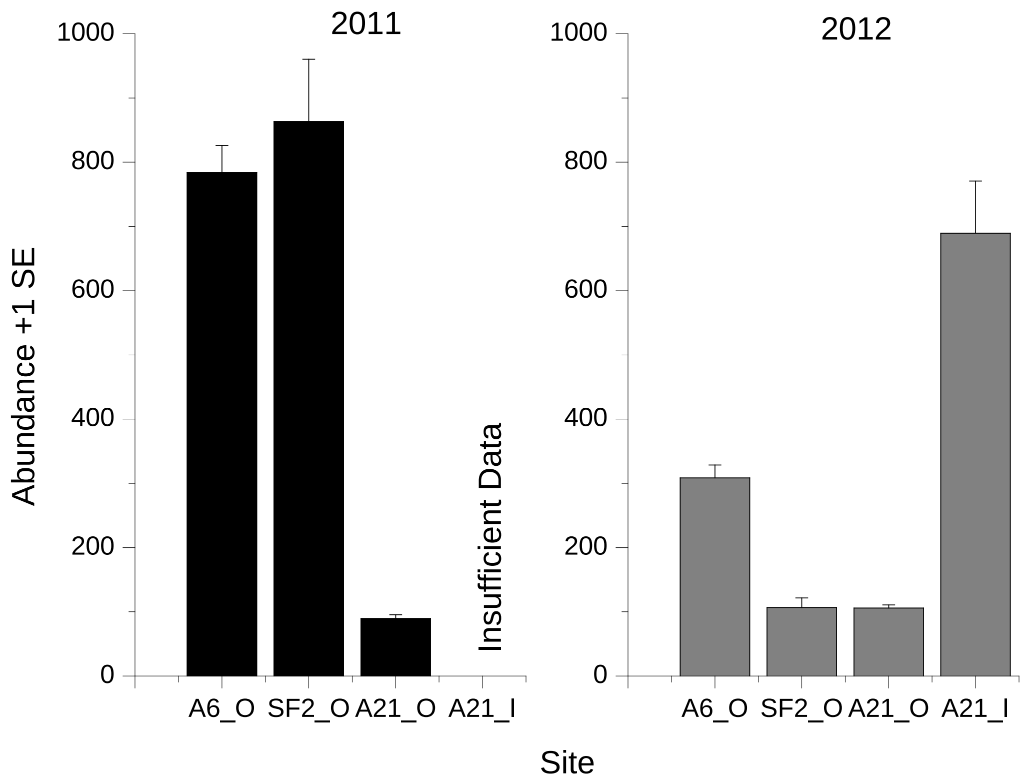


Figure 54. Annual abundance estimates from a closed capture model ± 1 standard error. Note for 2012 estimates include data for only May-July, while 2011 estimates are based on data from May-December.

Survival

At all sites, the models with constant survival were selected as the best-fitting model. Models with variable capture probability best fit all sites in 2011 (except A21_I, which was not calculated for 2011 due to low recaptures); however, constant capture probability provided a better fit to 2012 data. A constant survival probability model, suggests that for the annual scale, seasonal survival differences could not be detected, and again the variable capture probability reflects the seasonal abundance patterns. Survival probability varied from 0.48 at A21_I in 2012 to 0.73 at A21_O 2011 and did not vary statistically among sites. (Figure 55). Differences in parameter error likely reflect the sample sizes for each site and year.

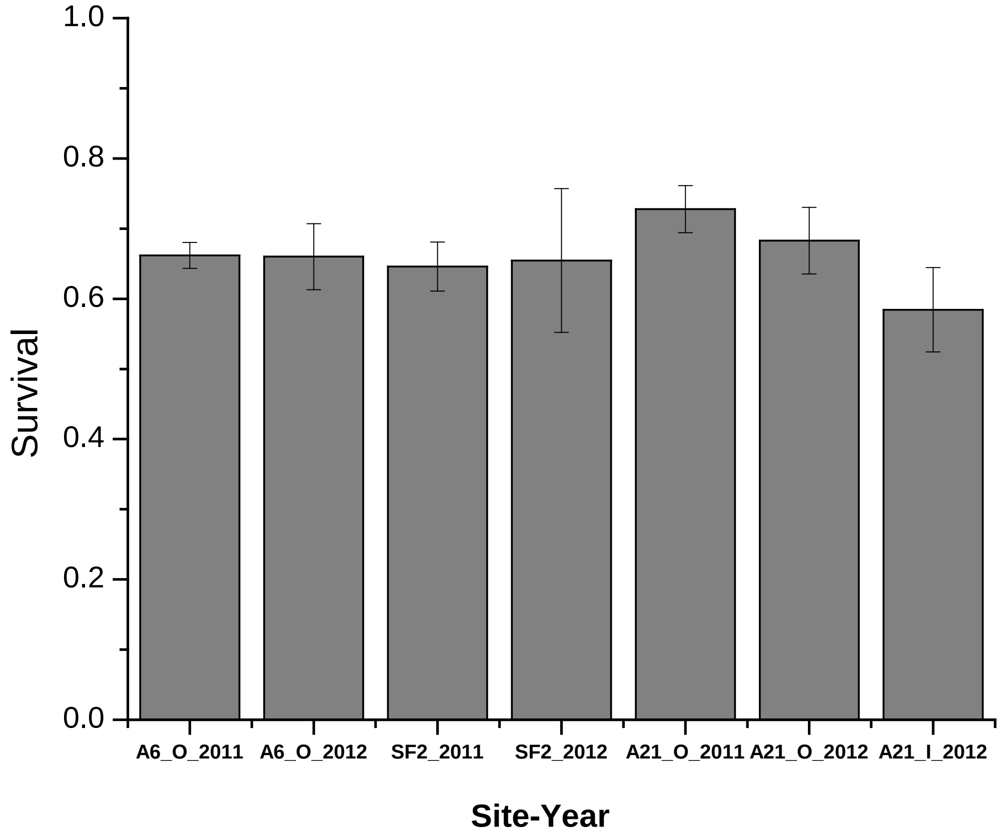


Figure 55. Survival estimates ± 1 standard error from Cormack Jolly Seber model.

Capture Probability

Capture probability was highest during the summer months (0.2- 0.6) and was lowest during the winter (<0.1) (Figure 56). Pond A6_O exhibited a higher capture probability during the summer months than the October to November period. Capture probability tended to be lower for SF2_O and ponds A21_O and A21_I. (Note that recapture probability for the latter two sites was only possible for the December 2011 to July 2012 period.)

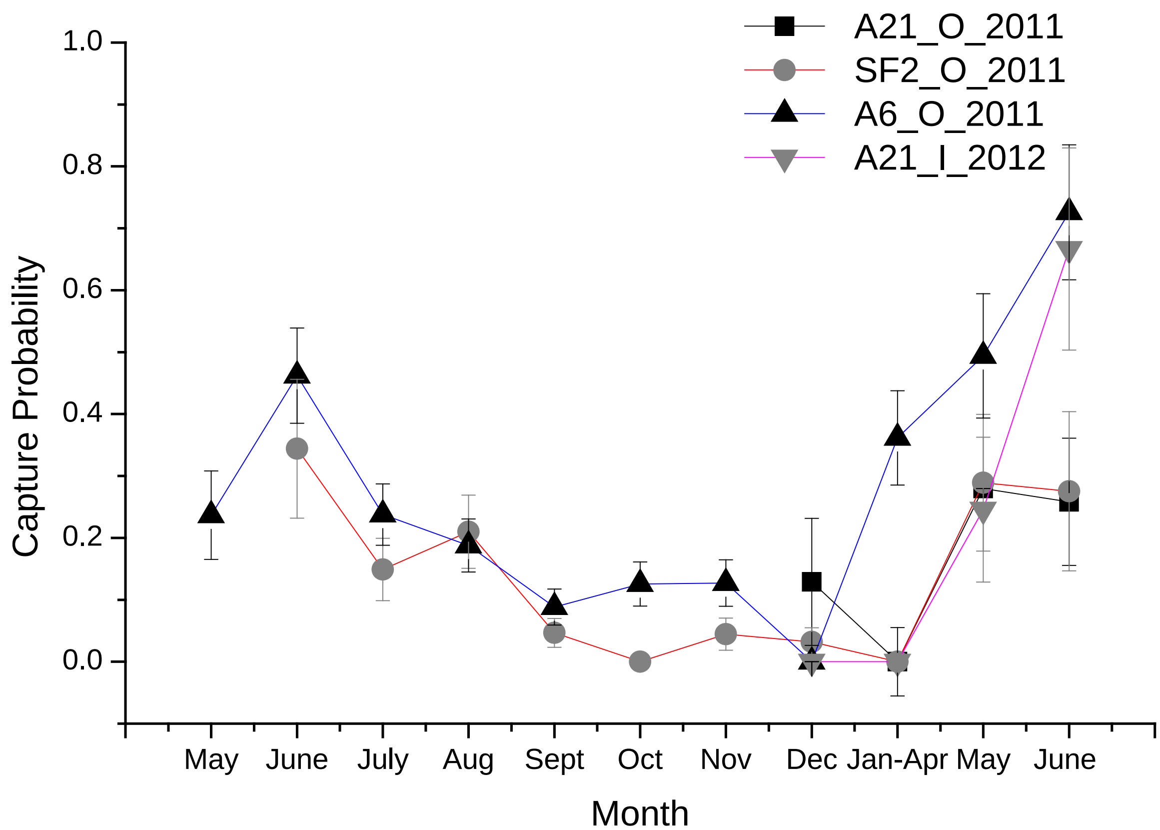


Figure 56. Monthly probability of capture derived from a Cormack Jolly Seber model. Error bars depict 1 standard error.

Condition

We measured the condition factor (Fulton's Index) for 3,135 longjaw mudsuckers collected during monthly surveys. Condition varied seasonally among all sites, with the spring months having a lower condition factor compared to all other months (ANOVA: MS=2.1, F-Ratio=10.4, df=3, p<0.001) (Figure 57). In comparing ponds, we did not find a difference among sites (ANOVA: MS=0.5, F-Ratio=2.2, df=4, p<0.65). Condition factor was higher inside restoration ponds compared to outside adjacent remnant marshes (ANOVA; MS=13.9, F-Ratio=69.1, df=1, p<0.001) and was higher in ponds with a muted tide stage compared to fully tidal ponds (ANOVA; MS=2.1, F-Ratio=10.4, df=1, p<0.001) (Figure 57).

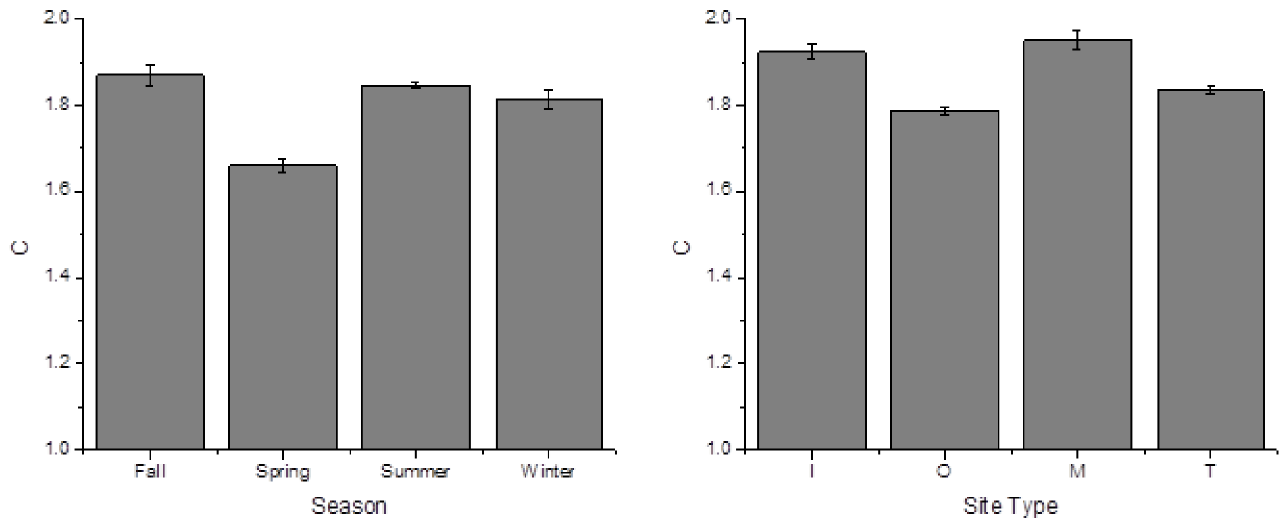


Figure 57. Condition factor for longjaw mudsucker collected during monthly surveys. (Left) season trends and (Right) different restoration types (I= inside restoration ponds, O= outside restoration ponds, M = muted tide-stage ponds A8 and SF2, and T = fully tidal ponds). Error bars depict 1 SE.

Otolith Growth

Growth rates estimated from otolith increment widths and back-calculated from the BIM ranged from 0.5mm/day at A21_I to 0.7mm/day at SF2_O. Overall, sites did not vary significantly (ANOVA: MS=0.034, F-Ratio=1.618, df=6, p=0.156), and no significant difference was found for the comparison between the inside of the restoration ponds compared to adjacent marsh habitats (ANOVA; MS=0.01, F-Ratio=0.028, df=1, p= 0.867) (Figure 58).

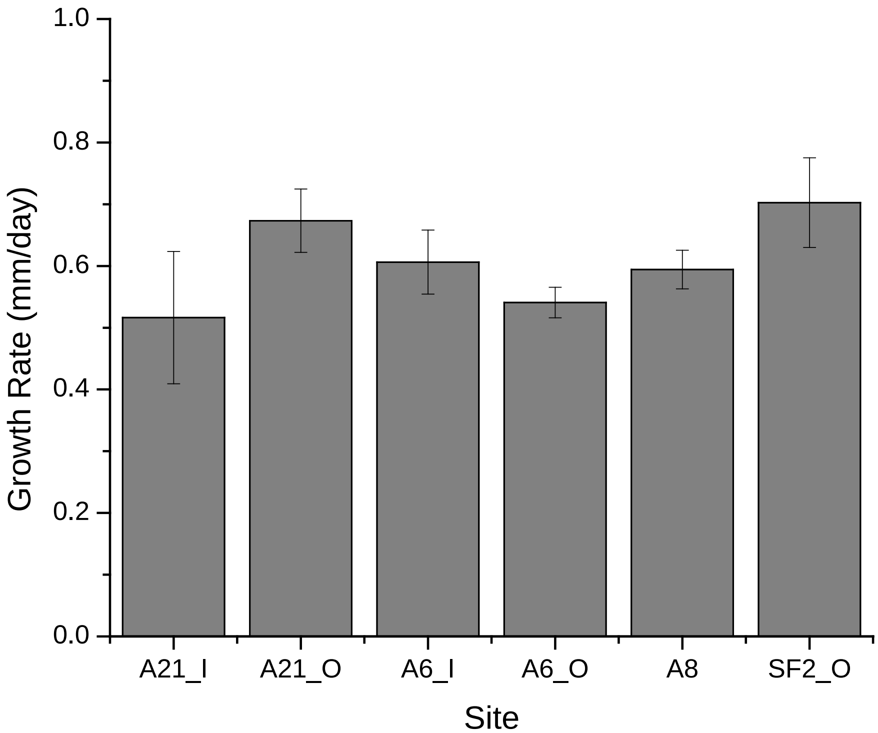


Figure 58. Summer otolith daily growth rate back-calculated from otolith increment widths from the settlement check to the edge of the otolith or the point at which daily increments were not visible. Error bars depict 1 SE.

Proximate Body Composition

The proximate analysis of body composition for % moisture and % lipid was variable between sites; however, we found no statistical significance (ANOVA: MS=0.034, F-Ratio=1.618, df=5, p=0.156), due to the large within site variation (Figure 59). Regardless of statistical significance, we did observe relevant patterns of variation with Pond A8 having the highest % moisture and lowest % lipid content of all the sites, while A6_O and SF2_O exhibited similar overall patterns. Condition factor was also not different between sites and showed considerable variation among individuals. Hepatosomatic index was generally lower at Pond A8 and SF2_O, but due to individual variation no statistical differences were found. All analyses failed to detect statistically significant patterns due to the high within site variation. The failure to detect a statistically significant pattern was likely due to low sample sizes with only 8 individuals analyzed per site. A small sample size was deliberately chosen to minimize the impact of removing individuals from small populations, where mark and recapture studies were being conducted.

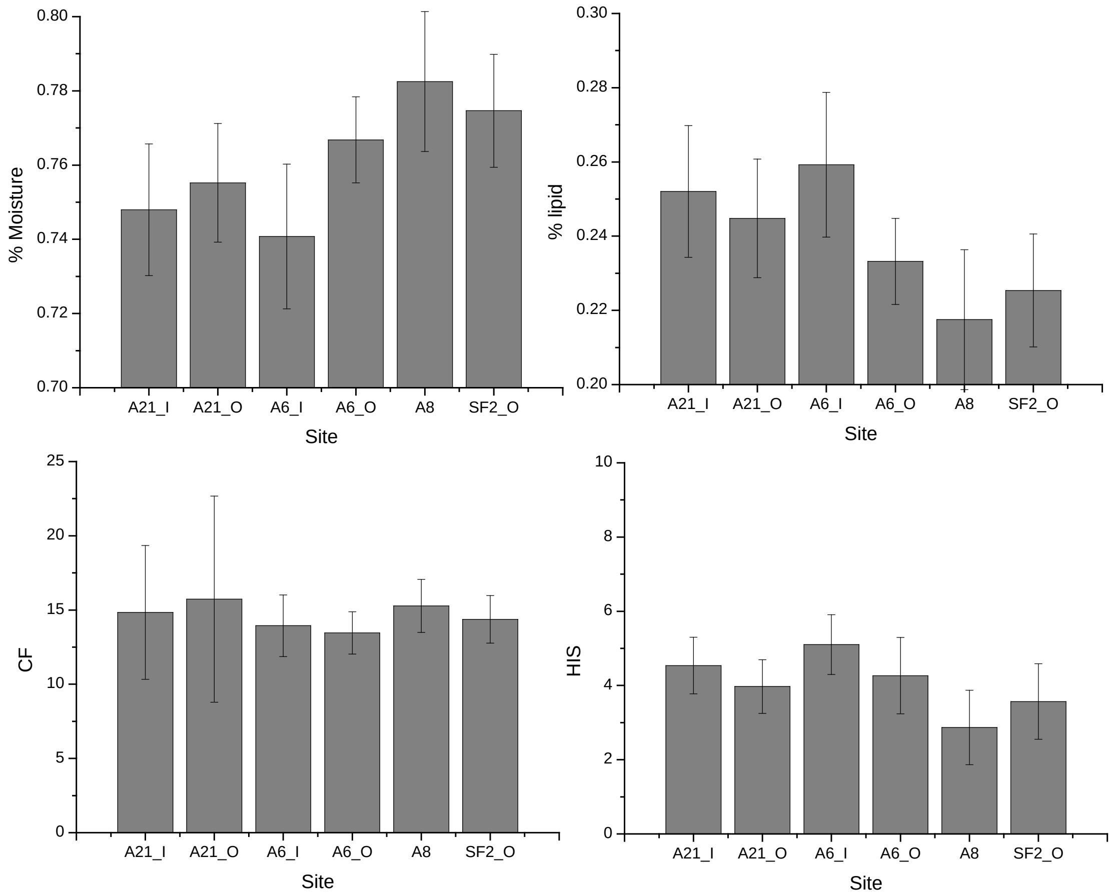


Figure 59. (Top-Left) The percent body moisture for a sample of 8 individuals collected in fall of 2011. (Top-Right) The percent lipid content, (Bottom-Left) Fulton's condition factor, and (Bottom-Right) the hepatosomatic index. All error bars a ±1 SD.

Disease and deformities

The incidence of the internal microsporidian parasite *Kabatana* sp. was low overall with a total of only 46 incidences out of the 3,135 longjaw mudsuckers examined. The sites outside A6 in the remnant pickleweed marsh had the highest incidence with 26 infected individuals, Pond A8 had 6 individuals, SF2_O had 7 individuals, A6_I and A21_O both had 3 individuals, and Outer Bair Island only had 1 individual. We also observed very few fish with visible deformities, with only 18 deformed individuals observed out of the 3,135 longjaw mudsuckers examined. Deformities observed included maxilla skeletal curvatures and eye hemorrhage. The site outside SF2 and the Ravenswood marsh had the highest incidence of deformities, with a total of 6 individuals, while ponds A8 and A6_O had 3 individuals, A21_I and A21_O had 2 individuals, and Eden Landing's pond had a single individual. No incidence of scoliosis or other structural deformities or other external parasites were observed.

Discussion

Monitoring the sentinel species population and individual health status has revealed that most restoration ponds have yet to provide permanent habitat for the longjaw mudsucker, an obligate intertidal pickleweed marsh specialist. At all but one restoration pond, the mean catch per unit effort and abundance was greater at reference sites in remnant pickleweed marsh habitats outside, than at sites inside restoration ponds. However, we did find that condition factors of fish occupying restoration ponds, including those managed for a muted tide regime, was better than remnant marsh sites. Pond A21 was the only pond that supported longjaw mudsuckers year round. In addition, Pond A21 has shown the greatest recovery of pickleweed and cordgrass, with large sections of marsh beginning to form in the interior of the pond and intertidal creek habitats beginning to scour. At most of the restoration ponds, pickleweed has begun to grow extensively along the leveed side of the borrow ditches, but very little vegetation has grown in the interior mudflats and no creek habitats exist. The longjaw mudsucker is a species that burrows into the bottoms and the vertical banks of intertidal creeks and remains in these habitats during low tides when these areas are dewatered. While the mudsucker has been found in deeper slough habitats at times, these observations are very rare, supporting the idea that this species depends on intertidal creeks to thrive. Based on our observations, it is likely that pond restorations will not support populations of adult longjaw mudsucker without extensive pickleweed marsh and creek habitats for this species.

The restoration ponds did receive large numbers of juveniles during the summer months when new recruits were seeking out intertidal creek habitats; however, very few individuals appeared to overwinter inside restoration ponds and recruit to the adult population the following year. Since, lonjaw mudsuckers can burrow into soft sediments, and the restoration pond sites provide an abundance of soft sediment habitat, it is not clear why these habitats do not support long-term residence of longjaw mudsucker. Predation may be an important factor explaining the low numbers of longjaw mudsuckers in restoration ponds. While burrowing into soft sediment would protect mudsuckers from predation by most piscivorous fishes, the major fish predators in this system are the leopard shark and bat ray, which can use electroreception to find prey buried in sediments, and most wading birds are adept at locating borrowed fish as well. Food abundance may also be a factor affecting the use of restoration ponds; however, condition factors for fish collected inside ponds was greater than sites outside ponds, which does not support food abundance as an explanation for low numbers inside restoration ponds.

A third, behavioral hypothesis also exists: longjaw mudsuckers simply may not prefer open mudflat habitat, and seek out intertidal marsh creek habitats, thus abandoning the restoration pond habitats that do not have proper habitat.

Individual condition and health metrics suggest that conditions for feeding and growth inside restoration ponds was satisfactory for the small number of fish collected there; however, at locations along Alviso Slough, other stressors may affect the condition of longjaw mudsucker. For example, while the wet-weight condition was high for Pond A8, those individuals also had high moisture content that suggests these fish were experiencing some stressor and retaining body water to compensate. Pond A8 is located at the upper end of Alviso Slough and experiences larger salinity fluctuations than other ponds and could explain the higher moisture contents. While the longjaw mudsucker can tolerate salinities from freshwater to three times the concentration of seawater, they tend to occur in salinities between 16-22 psu (Moyle 2002). Pond A8 is often below 10 psu and fresh at times during winter, suggesting osmotic stress may be important in A8. The hepatosomatic index was also low for fish collected in A8, which could suggest that fish are utilizing energy storage in the liver to compensate for an environmental stressor such as contaminants, but additional work would be needed to confirm the cause of lower health metrics for these fish. Similarly, fish in Alviso Slough inhabiting the remnant pickleweed marsh outside pond A6 had poor condition metrics; however, salinity is consistently higher at this site and typically in the preferred range for longjaw mudsuckers, so the poor condition of fish at this site is not likely due to osmotic stress. The abundance of longjaw mudsucker at this site was much higher than Pond A8, and the reduced condition of these fish may be due to the high densities of fish inhabiting the creeks and the competition for limiting resources. Alternatively, this site also had a higher prevalence of a microsporidian parasite that was first observed in tidewater goby and has been shown to cause severe health issues for host fish that often results in mortality (McGourty et al 2007). The microsporidian, *Kabatana* sp., has been observed in longjaw mudsucker from Walker Creek and Toms' Point marsh, both in Tomales Bay, and at China Camp State Park in San Pablo Bay and Stege Marsh in central San Francisco Bay; however, the prevalence in Alviso Slough was much lower than that seen in Tomales Bay marshes (Hobbs unpublished data). The infection status is only observable in the field once the fish has become severely infected, with large nodules of the parasite visible under the epidermis of the fish. The prevalence may be much greater than we observed and could explain the reduced condition of fish in Alviso Slough.

Skeletal deformities can often depict nutritional and contaminant stress. We found very few deformities overall in this study and found no evidence of the common deformity, scoliosis, which is often associated with poor feeding conditions. We did observe a few individuals with deformed maxilliae, which may be associated with contaminant stress. In Tomales Bay, the prevalence of maxillae deformities was high at sites along Walker Creek, which receives metallic mercury from an abandoned cinnabar mine. Similarly, Alviso Slough receives metallic mercury from cinnabar mines; however, we observed only three individuals in Alviso Slough with maxilla deformities and thus mercury contamination may not be as severe in Alviso Slough as previously observed in Tomales Bay.

Our individual health metrics from the fall sampling (% moisture, %lipid, otolith growth) were not statistically different between sites, due to the high within site variation among individuals and the small sample sizes used for the analyses. However, the patterns we observed likely reflect meaningful trends. While condition factor for fish collected during the fall subsampling for health metrics was not statistically different, the large sample set of condition factors measured during the monthly surveys did provide for a more robust analysis of condition differences among restoration ponds and seasons, revealing that condition did vary seasonally, with lower condition during the spring. Low spring condition factors likely reflect the post-spawn condition of the fish; however, we did not observe ripe females during our monthly surveys. Condition factors did not differ among the reference sites for the breached fully-tidal ponds (A6, A21); however, we did observe higher condition for fish collected inside muted tidal ponds compared to reference sites, specifically at SF2 and A8 , where the tidal stage is modified to keep the pond inundated for shorebird use. This effectively keeps the tide stage high and allows longjaw mudsuckers to forage for longer periods of time relative to habitats that are dry at low tide.

Abundance and survival estimates from the mark-recapture study did not appear to provide useful information regarding the population status of longjaw mudsucker in restoration ponds, as most pond sites had insufficient numbers of individuals tagged and recapture to calculate either metric. We did recapture sufficient number of individuals at several reference sites, outside the restoration ponds, and inside one restoration pond (A21), and were able to calculate annual abundance and survival estimates. Abundance patterns were similar to the catch per unit effort, except for the reference site outside A21, where the abundance estimate from mark-recapture was much lower than other sites, although catch per unit effort was relatively high at this site. This could be explained by the length of the creeks. The reference site at A21 has much shorter creek lengths (~5 m) as compared to the other reference sites and inside A21 (~40 m). Since we space the minnow traps out at 5 m distances, the total number of traps and thus effort at the site outside A21 is lower and represents less overall creek habitat. The catch per unit effort represent the relative density of fish for a length of creek habitat, thus the catch per unit effort is similar among the reference sites, when scaled to length of creek habitat, while the abundance estimate from the mark-recapture study are independent of habitat amount. These observations suggest creek habitats may have a limit to the number of longjaw mudsuckers they can support. At three sites with relatively similar lengths (50-75-m) we observed similar abundances (800-900) fish for four replicate creeks or approximately 200 fish per creek. If longjaw mudsucker are habitat limited and in most cases creeks are near capacity, the most appropriate and cost effective means to assess population status may be the use of presence/absence surveys with minnow traps at many creek habitats within a study area, rather than the more intensive catch-per-unit-effort approach with mark-recapture estimation. Moreover, given the seasonal patterns of fish activity and juvenile recruitment, targeted samplings in the late summer fall months only, may provide the best means to assess the status of longjaw mudsucker in restoration salt pond habitats.

The use of baited minnow traps to capture longjaw mudsucker, while the most reliable means to collect these fish, does pose logistical problems for monitoring the catch per unit effort year round and for conducting mark recapture studies. First, the sampling method is passive, requiring the fish to select a trap to enter primarily based on scent attraction to the bait. This results in an estimate of relative abundance that is dependent on the hunger level or at least the attraction to bait. In the winter months, the catch per unit effort declined dramatically and was more likely the result of decreased activity of the fish when water temperatures were cold, rather than a true decrease in abundance. This is apparent when conducting mark-recapture studies where each individual is given a unique tag and followed through a season within a creek habitat. Longjaw mudsuckers are known to not move long distances and usually do not leave their adult creek habitats. We observed in several instances individuals trapped multiple times at a single trap location within a creek during the summer and fall that were then not observed during the winter months but were subsequently recaptured in the spring the following year at the exact same trap location. Either these fish vacated these habitats in winter, which we do not think is the case, or they do not choose to enter the traps as readily when water temperature in the winter is low. Moreover, the capture probabilities from the mark-recapture study clearly showed low capture probabilities during the winter months, suggesting conducting minnow-trap-based surveys during winter months may not be appropriate for monitoring the relative abundance of this fish. The second problem with using baited minnow traps is that individuals learn quickly that food is available in the traps without consequence of predation and thus become “trap happy." We caught many of our uniquely marked individuals up to 7 consecutive monthly, while a majority of marked individuals were only observed once, or not at the same frequency. These differences in catch suggest that we had trap-happy fish. This can create bias in mark-recapture abundance and survival estimates as the capture-recapture probabilities are not equal among all individuals, which is an important assumption of most mark recapture models. Therefore abundance and survival rates in this study are likely biased by violating these assumptions

We conducted several intensive surveys at Bair Island and Eden Landing restoration ponds and reference sites using 60-80 minnow traps during 2010 and 2011 and observed very few longjaw mudsuckers. Both sites have large expanses of pickleweed marsh, with what we would consider appropriate habitat for this species; however, we found very few mudsuckers or other fish species. We did observe large numbers of the native mud crab *Hemigrapsus oregonensis,* which often averaged > 20 individuals per trap at both Eden and Bair. When high numbers of mud crabs were observed in the remnant marsh at SF2, we observed many dead, mostly consumed mudsuckers and other fish species, followed by a decrease in CPUE on the following survey. It is not clear whether mud crabs could actively prey upon the longjaw mudsucker, or if when trapped in high densities the crabs can cause significant mortality and scavenge the carcasses. The large numbers of crabs at these locations seem to be excessively high for the small creek habitats and may inhibit the longjaw mudsucker from establishing populations. Since the mud crab is a filter-feeder that can also scavenge detrital materials including dead organisms, the ponds may provide high abundances of prey for the crabs. Moreover, the pond habitats may support the retention of their pelagic larvae in the area and provide large numbers of recruits to adjacent remnant marsh. Further research would be required to discern causative mechanisms for the low numbers of longjaw mudsuckers at Eden Landing and Bair Island.

Conclusions:

We have developed a comprehensive and flexible monitoring regime for fish communities associated with salt-pond restoration (see appendix A). Using large seine nets that are deployed via small craft, set nets (i.e., gillnets and trammel nets), minnow traps, and otter trawls, we have documented the fish community that resides within the restoration areas and the adjacent sloughs in the Alviso Marsh Complex, the Bair Island Marsh Complex, and Ravenswood.

Of the 41 species of fish captured, only one (longfin smelt) is a listed species while several others are of commercial and conservation importance. The most numerous fish in the restored salt ponds are the physiologically tolerant threespine stickleback and Pacific staghorn sculpin, as well as the pelagic northern anchovy. Though the fish communities of the different restoration areas differed substantially between the studied complexes, the high CPUE within restored ponds was notable.

Restored and muted tidal salt ponds are harsh environments in summer and fall, when water temperatures reach extreme highs during the day and dissolved oxygen levels reach extreme lows at night. As a result, the species assemblages of these restored ponds are depauperate during these months, and only fish species tolerant of extreme physiological stress (i.e., Pacific staghorn sculpin, longjaw mudsucker, threespine stickleback) or able to move in and out of restoration areas on a daily basis (e.g. northern anchovy, leopard shark) commonly occur. In spite of the physiological stresses, the CPUE within the restored ponds (and occasionally in muted ponds) is extraordinarily high during these periods.

Several of the restored ponds and the immediately adjacent sloughs have higher densities of juvenile fishes in them than the surrounding area. Without further study investigating these juveniles' growth, survival, and recruitment into the adult population, it is premature to classify the restored ponds as nurseries. But there is no question that juvenile fish from several important species are using these habitats more than they are using adjacent ones, in spite of sub-optimal conditions within these areas. It is extremely likely that these fish are remaining in these physiologically stressful environments because prey densities are higher.

Both the abundance of juvenile fish within these habitats in spring and the abundance of tolerant adult fish in the summer indicate that these restored habitats are attracting and holding fish from several species. Otter trawl bycatch and limited invertebrate sampling indicate that several invertebrate taxa commonly preyed upon by fish elsewhere (e.g., mysid shrimp and amphipods) are considerably more abundant within the restored ponds than in the adjacent sloughs and mudflats. Presumably, many of these fish are attracted to these areas to forage, and if possible, will remain in and around these restored ponds for quite some time.

Monitoring the population and individual health of the sentinel fish species, the longjaw mudsucker, has revealed that recently restoration ponds have yet to provide permanent habitat for the longjaw mudsucker, an obligate intertidal pickleweed marsh specialist. However, pond A21 of the Island Pond complex, which was first breached in 2006, does support large numbers in the sections of the pond that have developed pickleweed marsh habitat. Recently restoration ponds, A6, A8, and SF2 did receive large numbers of juveniles during the summer months when new recruits were seeking out intertidal creek habitats; however, very few individuals appeared to overwinter inside restoration ponds and recruit to the adult population the following year.   If these ponds begin to develop marsh habitats, juvenile recruits should be able to take advantage of newly formed habitats and establish new populations.

Individual condition factors suggest that conditions for feeding and growth inside restoration ponds were satisfactory, however we did observe some evidence for environmental stress effects.   Health metrics associated with nutritional state and growth were not statistically significant, primarily due to low sample sizes. We observed very few visually diseased or deformed individuals in restoration ponds or reference sites; however we did find a microsporidian parasite that is known to have deleterious effects on its' host. Overall, the condition and health of the sentinel species in restoration ponds and reference sites were in good health condition, and very little effects of environmental stressors were found. Additional research will be required to further investigate health indicators in restoration ponds, including increasing samples sizes where possible.

Population abundance estimation and catch per unit effort data collected at the restoration pond and reference sites suggest that the population abundance of longjaw mudsucker may be limited by the amount of available creek habitat. Catch per unit effort data appeared to be a good indicator of fish density, and that creeks of different size supported different numbers of individuals that scaled with creek length. Longjaw mudsucker are known to reside in high intertidal burrows within creeks, and depend solely on picklweed marsh creeks to thrive. Given we observed similar density of fish among the many creeks we sampled, effective monitoring of this species may take a different approach than the one we used in this study. The presence/absence of the longjaw mudsucker in creeks of restoration ponds and reference sites may be a more efficient means of assessing the status of the species. Quantifying the presence/absence status would require much less effort for a single creek and would provide for more sampling to occur spatially. In addition, we had very low catch and capture probability of tagged individuals in winter months and high catch in summer to fall months suggesting efforts could be focus more within the summer and fall.

Several sites produced very few longjaw mudsuckers, including the restoration pond on Outer Bair Island and among the remnant picklweed marshes at Bair Island, and the ponds at Eden Landing (E9, E8, and E8X), including references creeks in the Whales Tail Marsh.   The sites in the remnant marsh at Bair Island and Eden Landing had vast expanses of pickleweed marsh with creek habitats that should support large number of longjaw mudsuckers, however we found very few fish. It isn't clear why we don't find many longjaw mudsuckers in these reference sites but this suggests establishing populations in recently restoration ponds at Bair Island and Eden Landing would take much longer than expected. Further research may be needed at these sites to elucidate the cause of absence or extremely low numbers of longjaw mudsuckers

Regarding the lost data from January-April 2012 for minnow trapping efforts

Note that while we do not report minnow trap data for January-April 2012, we did sample using our standard monthly survey protocol, but datasheets were stolen from this time period and no data were reported. Catch of longjaw mudsucker was low during this period overall (Hobbs pers. obs.), and likely had little effect on our ability to discern patterns regarding comparisons between restoration ponds and reference sites.   We did mark 221 individuals during this time period at four sites and were able to determine where each tag was used during the interval and were able to use the recapture of these individuals in abundance and survival estimates. Because we found little difference in the survival estimates among sites, we feel the data loss would have had very little effect on these estimates. The abundance estimates were also likely not significantly affected by the data loss as error on the estimates was small and patterns were robust. The data loss occurred during the winter period when catch is low and recapture probabilities are at a minimum. In addition to the minnow trapping data loss, we also lost data for beach seining at pond A8 and A6, however we collected very few fish during those surveys. We had also started implementing the use of a smaller otter trawl deployed from our 14 foot Jon boat, to be used inside A6, where it is difficult to sample with our larger boat and trawl. We had conducted two trawls inside A6 in March, which we lost data for. From memory, we caught several hundred newly recruited staghorn sculpin, however we saw large numbers of staghorn in the large boat otter trawl during the same month in Alviso Slough, thus the information loss was likely minimal.

Recommendations for future studies

Fish Community Study

The goals of the fish community study were to determine a flexible and comprehensive monitoring program to assess the impacts of salt pond restoration on fish communities and to document the fish communities within restored salt ponds and the adjacent habitats. We were successful in developing a monitoring technique using a combination of otter trawling, seining and gill/trammel netting (see appendix 1). The appropriate amount of effort required to document the communities within the restoration areas was also determined for all locations except Eden Landing. We make the following recommendations to for the continuation of the community study:

Continue on-going studies with some modifications:

1. Continue monthly sampling using seines, trammel/gill set nets and otter trawls within the Alviso Marsh Complex and Bair Island Marsh Complex. Because fish communities within the restoration marshes are extremely dynamic, monthly sampling is necessary to determine the communities present throughout the year, and the extent of similarity between restored and unrestored habitats. Given the potential presence of several listed species within these habitats (steelhead, green sturgeon, spring-run Chinook salmon, longfin smelt), sampling as frequently as possible maximizes our likelihood of detection.

2. We recommend bi-monthly sampling at Ravenswood and Eden Landing for two different reasons:

Ravenswood is tidally muted, and the water is not completely exchanged within the Bay. Our preliminary sampling data for this area indicates that the species assemblage in this pond is not as dynamic as in fully tidal systems, and monthly sampling is not needed to accurately assess the communities present in this pond.
The Eden Landing restoration area has an extremely high marsh plain, and rarely has enough water for fish species to move into the restoration area, and it has not accrued sufficient pickleweed to facilitate mudsucker populations. This results in very few fish utilizing the restored ponds, besides leopard sharks in the scour hole at the E9 breach. Sloughs surrounding the restoration ponds have been sampled with the 14ft Jon boat and small otter trawl with abundance of fish collected however access is prohibitive of consistent sampling until a secure launch is created. We therefore recommend sampling Eden Landing bi-monthly.

New Study Concepts

1. Leopard shark and other large predator abundance and diet surveys:
   We recommend continuing a pilot project we initiated in August 2011 examining leopard shark, striped bass and bat ray stomach contents in restored marshes and adjacent sloughs. These three predators are the apex of the non-mammalian aquatic food-web in the restoration marshes. Diet analysis of these predators allows us to determine the quantity and quality of food that is provided to large predatory fishes in the restoration marsh compared to unrestored sloughs.

2. Additional fully tidal sites:
   We recommend including new fully tidal sites (Middle Bair Island and Pond A17) in the sampling regime to allow for the further assessment of recently breached habitats. The analysis of fish communities colonizing habitats immediately following restoration is of immediate concern for managers in SFE, given the possibilities of levy failure elsewhere in the Bay/Delta. The ongoing restoration of salt ponds provides an excellent venue to assess the immediate response of aquatic communities to restoration. Because we have two years of data collected adjacent these restoration locations, we are ideally situated to monitor the early stages of restoration. Because of our sampling methods (entirely boat-based) the addition of two more locations is extremely feasible and can be accomplished with minimal additional effort.

3. Additional muted or managed ponds:
   We recommend the addition of at least one longterm managed pond site per complex (e.g. A5/7, E12-13) as well as conducting intermittent sampling at other managed ponds during monthly surveys. Our research focuses heavily on full tidal and muted ponds, however we currently don't sample ponds that are managed for water levels for ducks and shorebirds. Salinities in managed ponds can be very high at times (>80ppt) which precludes many fish, but some ponds can be much lower, and be similar to adjacent sloughs. Monitoring the fish communities of these ponds across different salinity

regimes would provide us a better understanding how these managed systems effects fish populations in relation to the muted and fully tidal systems. In addition we would like to add the new muted pond A16 given its similar configuration to SF-2, which we will continue to monitor bi-monthly.

4. We also intend on further analysis of the first two years' data using time series regression of individual fish species' population growth rates , cluster analysis to determine the geographic similarities in observed species assemblages, and ordination (CCA, DCA, NMDS) to identify the principle abiotic factors responsible for observed assemblage shifts.

Sentinel Species Monitoring

The goal of this study was to gather baseline information on the individual and population health of a sentinel species for salt pond restoration. The longjaw mudsucker is the only fish species that depends on pickleweed marsh, and has a small enough home-range to reveal effects of individual salt pond restoration actions. However, we found too few individuals in many of the restoration ponds to effectively utilize the species health status as an indicator of the restoration actions. At these sites, pickleweed marsh had not developed significantly and likely explains the low numbers of fish. Furthermore, the small population sizes made it difficult to collect enough individuals to quantify many of the health metrics. Given the limitations of using the longjaw mudsucker as a sentinel species for fish health, we make recommendations to improve study designs to continue the use of this species as an indicator. Our recommendations also take into consideration new decisions regarding the use of baited minnow traps for collecting longjaw mudsuckers in pickleweed marsh, as the use of this gear type can have adverse impacts to the endangered salt-marsh harvest mouse, and sampling some marsh sites may be precluded by the endangered clapper rail.

1. Annual sampling – Our monthly sampling efforts clearly revealed a seasonal pattern to the relative abundance, such that effort should be focused in the summer months. Recruitment of juveniles to the populations appeared to be complete by August, therefore to represent annual abundance index, we recommend focusing sampling efforts to a single survey during the months of August or September during the spring tide series.

2. Minnow trapping - Very few individuals were collected in beach seine or otter trawl gears so we recommend using minnow traps to collect longjaw mudsucker. To minimize the impact to harvest mice we recommend only trapping during the high tide, and removing traps before the next high tide, to avoid drowning trapped mice. (*Although incidentally trapping an endangered fish would still constitute take under the Federal Endangered Species Act)*. This would preclude sampling multiple sites on the same tide because it takes too much time to reliably collect traps before the next tide. Therefore

an annual sampling at many sites may be possible during the 3-5 days available for sampling during the spring high tide series. Sampling in the months of August or September would also preclude issue with Clapper Rail as currently sampling is allowed after during this period.

3. Health monitoring – First, we recommend increasing the sample size for individual health metrics during the August-September sampling period. In this study we attempted to minimize the numbers of fish sacrificed for health metrics because we were using the same sites for mark-recapture studies. Several metrics should be included in the health portfolio, including biomarkers of contaminant exposure, particularly for mercury exposure in the Alviso Marsh as mercury is a known issue in this area.

4. Sampling sites- During the study we only found significant numbers of longjaw mudsuckers inside pond A21. Pond A21 has the most pickleweed marsh of all the restoration ponds and this species is dependent on pickleweed marsh habitat. It will likely take many years for other ponds to develop pickleweed marsh habitat, therefore, monitoring may take place at long time intervals to allow for the recovery of pickleweed marsh. Given the species life-span (2-3) years in San Francisco Bay, we recommend sampling at a 3 year time interval.

5. Focusing studies at larger spatial scales- Pond restoration will not only create new marsh habitats, but will benefit adjacent habitats by increasing primary and secondary production. We have sites along Alviso Slough and Coyote Creek in the fringing marsh outside restoration ponds A6 and A21 that could be monitored for sentinel species for groups of restoration ponds within a slough. For example the site outside A6 could be monitored for restoration effects of both pond A8 and A6. However this study design would require a slough site that does not have restoration ponds. The Newark Slough Marsh would be a good candidate as a “control” site.

Other sentinel species

There are other species that could be used as sentinel species of health, although residence time within a particular pond would not be similar to the longjaw mudsucker. The staghorn sculpin is a native estuarine species that occurs in high abundance in many of the restoration ponds. Otter trawl data suggests that staghorn may select pond restoration sites Coyote Creek (A21 & A19). However, this species can be found in slough habitats and the bay, and probably only utilizes ponds during high tides and may move around too much to be an indicator of a single pond restoration. The three-spine stickleback is small native estuarine fish that occurs in shallow water habitats, and has been found in large numbers inside restoration ponds, but could be found in slough and shallow bay habitat as well. The top-smelt is another small native estuarine fish that can be found frequently inside restoration ponds. However, like the staghorn sculpin, the residence time within the restoration ponds is unknown and they are often found outside the ponds along the sloughs, thus making it difficult to associate the health of the fish to any particular restoration.

Using multiple sentinels

Another approach may be to utilize many species for indicators of health. Combining multiple species within a small spatial scale could provide another means to monitor the health of fish in association with restoration ponds. Using species with different life history or habitat requirements could provide a powerful approach for assessing the overall restoration benefits to fish health. Combining species that utilize different micro-habitats created by restoration could give you a more inclusive perspective on how restoration may benefit a community of species. Health metrics could be chosen to best reflect each species use of the restoration ponds. Given the short residence time of most fish species within the restoration sites, quick responding health indicators could be used. For example, stomach fullness could be used to determine how well a fish is feeding over a few hours, and daily otolith increment widths could be used as a proxy for growth over a few days. Enzyme biomarkers of contaminant stress can reflect very short term exposure. Combining short term metrics with some long term metrics such as condition factor can provide for a power tool to examine fish health in the restoration ponds.

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Appendix A:

Otter Trawling Efficiency

Species accumulation curves were plotted for Coyote Creek, directly adjacent to the Island Ponds and within the Island Ponds themselves (Figure a1 and a3), in order to determine the appropriate sampling effort in a representative slough habitat and a representative restored habitat. Species such as longjaw mudsuckers, which rarely leave intertidal creeklets, remaining even at low tide, and Mississippi silverside (*Medina audens*), which inhabits inshore shallow habitat nearly exclusively, were not represented in the communities sampled via otter trawl. Neither were large, fast-swimming species such as white sturgeon.

Four months' trawl catches from Coyote Creek were compared (Figure a1). By the time 30 minutes of trawling was conducted, no additional species were captured, regardless of the overall diversity of the assemblage within Coyote Creek. Based on the smooth, asymptotic shape of the species accumulation curve, we inferred that the sampled habitat was relatively homogenous and that few species emigrated/immigrated from the sampling area while we were conducting surveys (Magurran 2004).

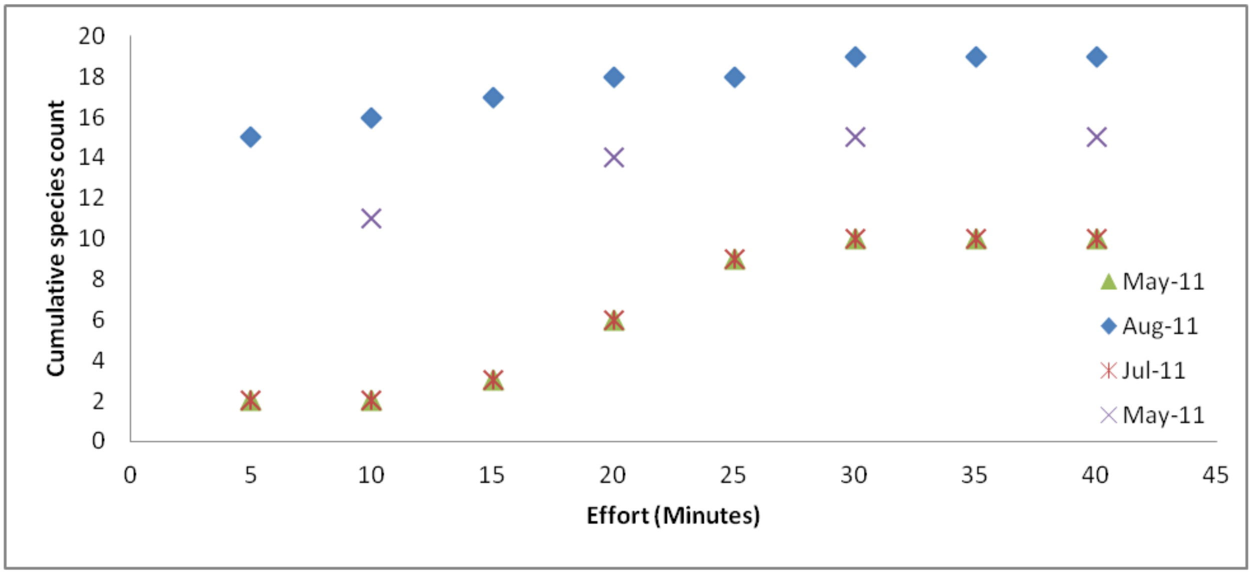

Figure a1. Species accumulation curve within Coyote Creek for four representative months (Months were chosen to maximize differences in diversity and abiotic conditions). May is exactly the same as Jul.

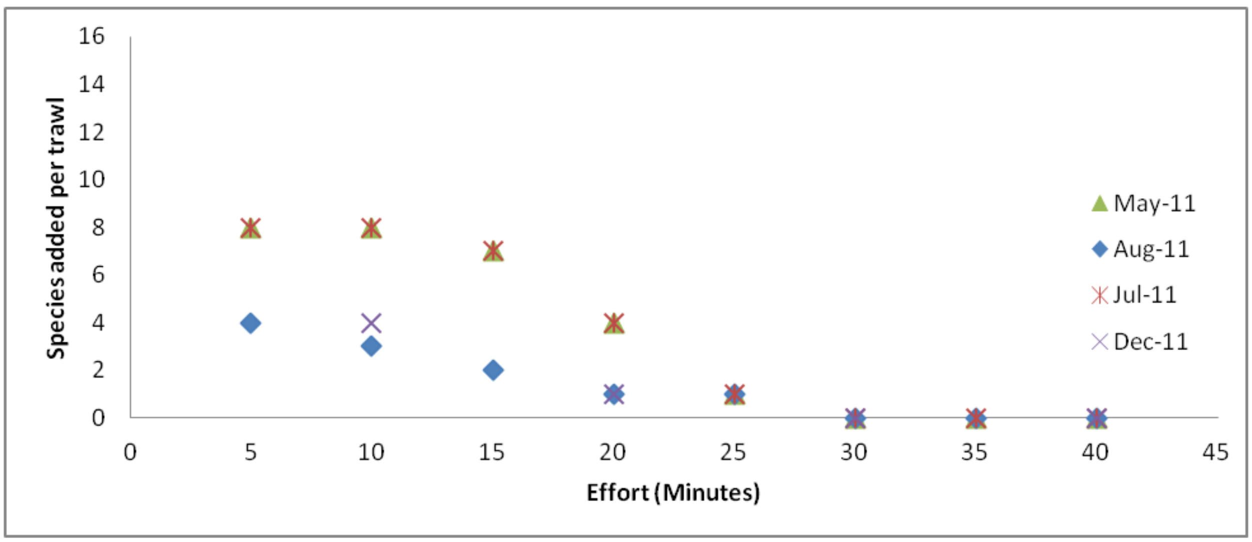

Figure a2. Additional species documented per trawl within Coyote Creek for four representative months.

Trawl catches from within the Island Ponds were also compared from the same months. The Island Ponds species accumulation curves showed considerably more variation than did the adjacent slough, which indicates that the habitat is more heterogeneous or more species immigrated into the ponds while sampling was taking place. Empirical observation shows that the Island Ponds are a more heterogeneous environment: they are bordered by both mudflat and newly vegetated marsh plain, have depths ranging from decimeters to meters, and have extremely variable water quality parameters due to tidal trapping and mixing (Maclean and Stacey 2011). This heterogeneity undoubtedly explains some of the variation in the accumulation curves, though the movement of species into these habitats cannot be discounted. In spite of this variation, it appears that 35 minutes of trawling effort document all but the rarest species. In two months (August 2011 and December 2011), 10 additional minutes of effort (two trawls) was expended and no additional species were detected.

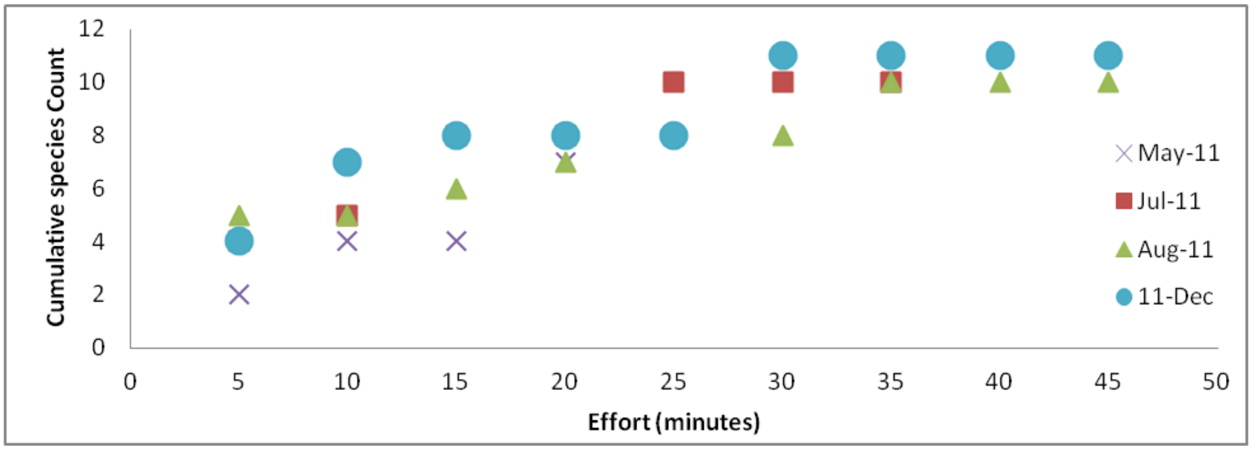

Figure a3. Species accumulation curve for the Island Ponds for four representative months .

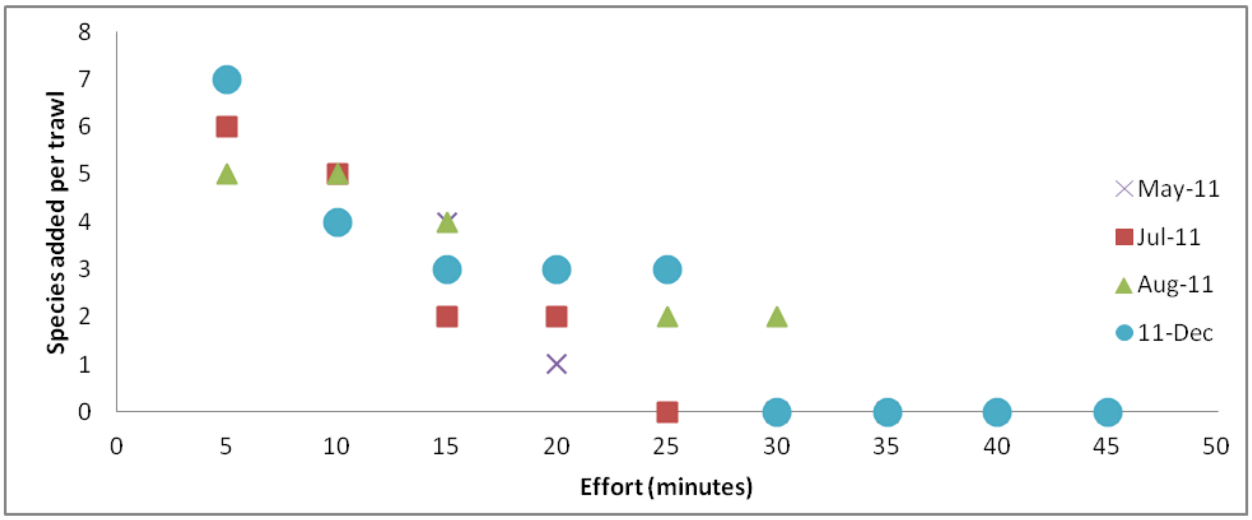

Figure a4. Additional species documented per trawl within the Island Ponds for four representative months.

The ability to use such a simple method to determine appropriate effort is only possible because estuaries are typically a low-diversity, high-abundance environment with a depauperate native community, especially on the tectonically active Pacific Coast.

Because long trawls dramatically increase fish mortalities the appropriate amount of effort (in minutes) was divided into multiple shorter trawls (5 or 10 minutes). Typically five minute trawls are used in smaller sloughs and restored ponds and 10 minute trawls are used in larger slough habitats.

<u>Limitations of otter trawling:</u>

Otter trawls were used to sample intertidal and sub-tidal sloughs (depths >0.75m); however, because otter trawls run along the bottom, sample a fixed volume of water, and are pulled a fixed speed, intuition states that the effectiveness will be limited. There are three questions regarding otter trawl effectiveness that we have addressed: (1) Are there marsh resident species, which rarely/never enter the sloughs sampled with the otter trawl, but inhabit the marsh habitat? (2) Are there surface-oriented/peripheral habitat specialists that never enter the water column? (3) Are some species capable of evading the otter trawl?

Are there marsh resident species?

The intertidal marsh was sampled using minnow traps placed in creeklets adjacent to otter trawling locations. The only fish species in the sample area that was captured in the creeklets but not in the sloughs was the longjaw mudsucker. Longjaw mudsuckers are residents of intertidal marsh and rarely leave high-intertidal habitat (Williams and Zedler 2000). Longjaw mudsucker is a native gobiid that is being used as a sentinel species for salt-pond habitats and are sampled using minnow traps placed in the intertidal creeklets (see Sentinel species report). Mudsuckers comprise over 2/3 of the minnow trap catch and constitute less than 1% of the otter trawl catch. Other fish species (e.g., staghorn sculpin) captured in minnow traps were also captured in sloughs at low tide.

Are there surface-oriented/peripheral-habitat specialists?

30 years of Suisun Marsh fish sampling has demonstrated the limitations of otter trawl sampling when it comes to the near-shore assemblages: the communities observed via otter trawl differ substantially from those in beach seine hauls (Matern et al. 2002). Mississippi silversides are the most notable species that is under-sampled by otter trawl in Suisun Marsh, although the littoral assemblage of Suisun is different even without including the silversides (O'Rear and Moyle 2011). In the South Bay, there are three silverside species that are known to be common and yet are uncommon in trawl catches. Seines are the preferred method for sampling these near-shore fishes; however, the poorly consolidated sediment of the South Bay makes traditional beach seining dangerous (pers. obs, Photo 10). After much experimentation, we have determined that a large seine (30 m) deployed from a boat and retrieved by two people standing clear of the mud is the best and most effective way to sample these habitats. Seine catches were typically less speciose than otter trawls, but they effectively sample all three of the silverside species, juvenile fish common in otter trawl catches, and other near-shore species that are relatively uncommon in trawls such as rainwater killifish (*Lucania parva;* Appendix Fish) Because seine surveys were only initiated in the fall of 2011, they will not be discussed in detail in this report, other than to note that we have begun implementing them and have circumvented the problems posed by the poorly consolidated South Bay sediments.

Photo 10: Hazards of walking on mudflats. Photo: Georgia Ramos.

Do some species evade the trawl?

Because trawls are towed at a speed of about 2.5 knots, fast-swimming fish species will inevitably swim out of the trawls path and evade capture. Gill- and trammel nets (set nets) have been used to determine what species are capable of evading the trawl, with surveys beginning in May 2011. 14 species were captured by gillnet over the year that they have been employed, and all of them were also captured, at some point, in trawl surveys. However, four species captured in set nets were only captured as juveniles in trawl surveys (leopard shark, American shad, jacksmelt, and striped bass), and one additional species (white sturgeon) was much more common in set nets than in the trawl. Set nets are useful for determining which species are present within the marsh, but low catches make them less suitable for documenting species assemblages even in a depauperate community.

Photo 11. White sturgeon can usually evade otter trawl surveys and are thus rarely captured.

Species	Adults in trawl?	Adults in set nets?	Juv. In trawl?
American shad	**No**	**Yes**	**Yes**
barred surfperch	Yes	Yes	Yes
CA bat ray	Yes	Yes	Yes
diamond turbot	Yes	Yes	Yes
English sole	Yes	Yes	Yes
jacksmelt	**No**	**Yes**	**Yes**
leopard shark	**No**	**Yes**	**Yes**

Northern anchovy	Yes	Yes	Yes
Pacific staghorn sculpin	Yes	Yes	Yes
shiner surfperch	Yes	Yes	Yes
starry flounder	Yes	Yes	Yes
striped bass	**Occasional**	**Yes**	**Yes**
topsmelt	Yes	Yes	Yes
white sturgeon	**Rare**	**Yes**	**n/a**
yellowfin goby	Yes	Yes	Yes

Table 1. Species captured in set nets and their presence in otter trawl surveys. Discrepancies between the two are in bold.

Frequency of sampling

Ideally, each sampling trip will perfectly document the species community that is present at that time, as well as document the seasonal variation that occurs. Aquatic communities are unfortunately extremely dynamic and are sensitive to a suite of abiotic and biotic factors that vary at many spatial and temporal scales. Initially we began sampling the marsh bimonthly; however, sampled communities were extremely dissimilar between these trips (Figure a5). Because the inter-month differences between sampled communities exceeded the intra-complex differences (i.e., the community sampled in August 2010 and October 2010 was more different than any of the areas sampled on either trip), any sort of consistency within the data set was deemed impossible. In addition, our ability to account for short-term stochastic events (e.g., storm systems that alter abiotic factors such as temperature and salinity and thus affect the fish community) was hindered. To compensate, we adopted a monthly sampling protocol in order to better document the effects of restoration on the annual assemblage in the marsh and to have some semblance of insurance against short-term perturbations. Monthly sampling increased the similarity between sampling trips (Figure 37) in both presence/absence and relative-abundance metrics.

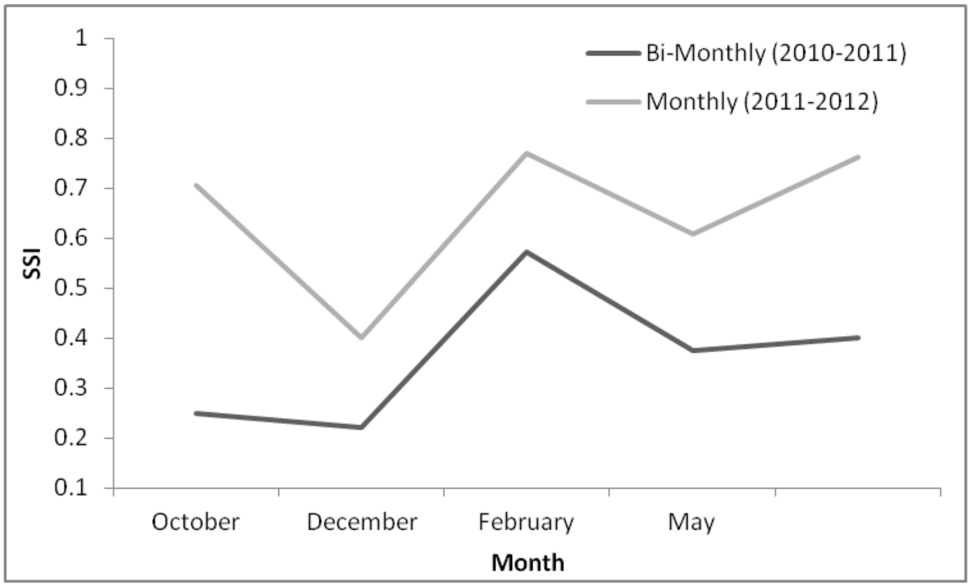

Figure a5-A. Sørensen pair-wise similarity index between consecutive sampling expeditions to the Alviso Marsh Complex. The Sørensen index operates using only the presence/absence of species.

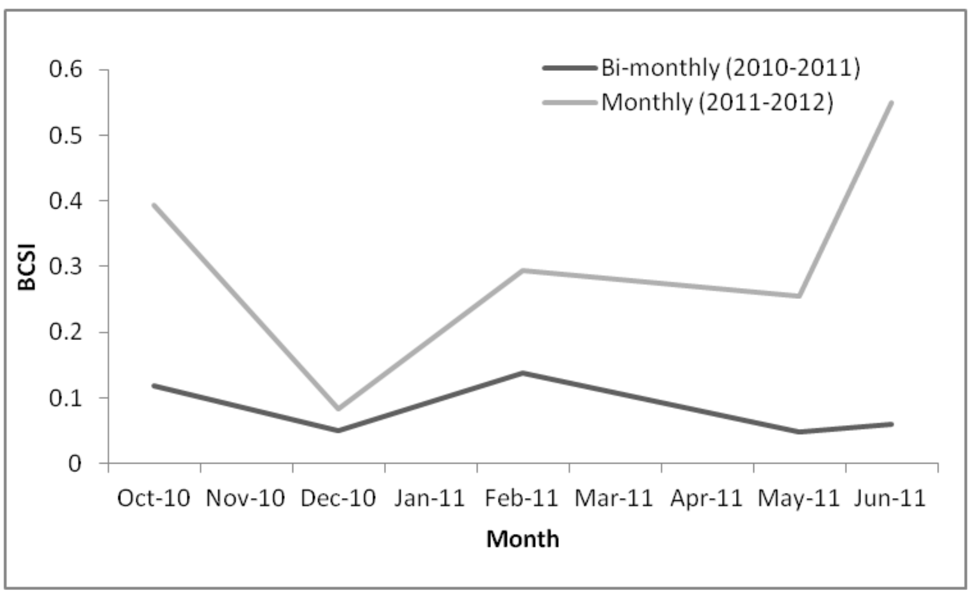

Figure a5- B. Bray-Curtis pair-wise similarity index between consecutive sampling expeditions to the Alviso Marsh Complex. The Bray-Curtis index operates using both presence/absence and the relative abundance of species.

Appendix B:

Total fish captured via otter trawl for the duration of the study at the Alviso Marsh Complex and Bair Island and associated restored ponds.

Alviso Marsh	Jul-10	Aug-10	Oct-10	Dec-10	Feb-11	May-11	Jun-11	Jul-11	Aug-11	Sep-11	Oct-11	Nov-11	Dec-11	Jan-12	Mar-12	Apr-12	May-12	Jun-12	total
three-spine stickleback	236	223	828	392	261	19	3	604	1370	2484	912	200	496	99	119	10	8	76	8340
Pacific staghorn sculpin	74	59	68	43	27	151	527	89	55	284	617	407	589	104	1038	1564	292	343	6331
Pacific herring				23	11	733	28	2	1		1	1	8	1	771	296	1	1	1878
English sole					1	8							2	65	1369	270	2	1	1718
Northern anchovy	130	110	17	8		15	8	178	133	151	34			1	24	223	78	206	1316
arrow goby	39	60	6	2		9	74	374	81	6	1		5		70	9	92	122	950
yellowfin goby	25	13	8	5	8	9	12	73	23	29	40	40	68	53	28	18	23	220	695
topsmelt	2		29	294	2	2			4	2		1	26	11	1		1		375
Mississippi silverside				2					3	11	1	8	313		2				340
longfin smelt				61	7						2	4	99	15	17				205
starry flounder		1	10	1	2		2	8	3	4	20	11	23	16	23	12	9	48	193
American shad				8	4	2				3			85	26	10	5	1	3	147
jacksmelt								49	21	6	14		4						94
speckled sanddab				4	60	1	1							3	2	3			74
prickly sculpin	9	1			3	9	9	5	4	3	2	2	4	11	4	2	2	3	73
striped bass		1				4	1	2	1			1			1	32	20	8	71
shiner surfperch	2		1	1		16	2				1	3	6	2	11	12	1	1	59
bay pipefish		7				3	1	3	4	5	7	1	4	6	5	3	1	2	52
rainwater killifish	2	1	5	1	4	1		2	14		3		11					2	46
CA bat ray	4	4	1					1	3	18		1			1	1	1	3	38
threadfin shad				12	1								7	8	5				33
longjaw mudsucker		1			1			8	1	5	2		2				4		24
California halibut																9	6	7	22
Pacific lamprey					4									18					22
Sacramento sucker	1										2	1			1	1	3	4	13
bay goby																8	2	1	11
plainfin midshipman								2		2								1	5
leopard shark		1	2																3
shokahaze goby				1													2		3
shimofuri goby	1															1			2
barred surfperch													1						1
Chinook salmon																	1		1
diamond turbot						1													1
surf smelt															1				1
white sturgeon																1			1

COYOTE CREEK	Jul-10	Aug-10	Oct-10	Dec-10	Feb-11	May-11	Jun-11	Jul-11	Aug-11	Sep-11	Oct-11	Nov-11	Dec-11	Jan-12	Mar-12	Apr-12	May-12	Jun-12	Total
Pacific staghorn sculpin	2	4	1	6		22	2	5	28	20	22	15	342	63	369	293	72	39	1305
English sole					1								2	51	971	79			1104
three-spine stickleback		2		6	1	2		74	280	28	2	9	157	30	7			2	600
Northern anchovy	6	2					4	23	35	25					9	193	3	30	330
Pacific herring				5	2	70	1		1				2		145	1		1	228
arrow goby	4	5		1			10	32	57	1	1				13		6	8	138
yellowfin goby		1				3	1	3	15	17	1	5	35	8	4	1	4	24	122
longfin smelt				17								1	67	5	7				97
American shad				2	4								48	13	3	1	1	1	73
speckled sanddab					39	1								2	1	1			44
starry flounder			1		1		1	3	1		1		9	2	6	6	2		33
striped bass						3		2	1			1				13	5		25
shiner surfperch						7							5	1	6	4			23
bay pipefish								3	3	1	2		3	3	3		1	2	21
California halibut																6	6	5	17
rainwater killifish						1		1	14										16
topsmelt				1	1				1	2			5						10
CA bat ray		1						1	2	5									9
jacksmelt									6	1	2								9
Unidentifiable						5											3		8
Mississippi silverside									1				6						7
prickly sculpin									3	1			2		1				7
threadfin shad													2		2				4
bay goby																	1	1	2
Pacific lamprey														2					2
Chinook salmon																	1		1
diamond turbot						1													1
longjaw mudsucker													1						1
shimofuri goby																1			1

ISLAND PONDS	Jul-10	Aug-10	Oct-10	Dec-10	Feb-11	May-11	Jun-11	Jul-11	Aug-11	Sep-11	Oct-11	Nov-11	Dec-11	Jan-12	Mar-12	Apr-12	May-12	Jun-12	Total
three-spine stickleback	234	141	10	28	38		1	304	99	2268	745	18	132	19	65	4	5	22	4733
Pacific staghorn sculpin	8	25	20	1	16	49	31	35	14	172	337	234	50	19	186	513	103	223	3341
Pacific herring				11	6	361		1				1	4		370	259			1241
English sole														2	16	1			1123
Northern anchovy	96	67	8	1		6	1	88	77	89	24			1		9	11	97	905
arrow goby	24	7				1	47	131	16	1					30	7	78	48	528
yellowfin goby	8	10	3		6		6	48	6	3	9		3		12	4	10	179	429
longfin smelt				20	6						1	2	5	5	3				139
starry flounder		1	9	1				5	1	3	10	2	5	1	1	5	5	39	121
American shad				1									6	6	1	1			88
topsmelt	2		2	49	1				3				12	4					83
speckled sanddab				2	6														52
Unidentifiable						37													45
jacksmelt								6	15	2	7		4						43
shiner surfperch	2					6	2									2		1	36
striped bass						1										6	2	1	35
bay pipefish						1	1		1		2					3			29
rainwater killifish					1			1			1		1						20
California halibut																		1	18
prickly sculpin						6					2					1			16
threadfin shad				6	1								1	2	2				16
bay goby																6	1		9
CA bat ray																			9
Pacific lamprey					1									6					9
longjaw mudsucker		1						2			2						2		8
Mississippi silverside									1										8
leopard shark			1																1

Bair Island Marsh	Jul-10	Aug-10	Oct-10	Dec-10	Feb-11	May-11	Jun-11	Jul-11	Aug-11	Sep-11	Nov-11	Dec-12	Jan-12	Mar-12	May-12	Jun-12	total
Pacific staghorn sculpin	7	2				51	9	11	66	1		6	24	120	638	115	1051
Pacific herring					4	209							1	395	21		657
Northern anchovy	78	140	9	30	37	9	30	49	56	3	1	21	28	16	25	52	584
shiner surfperch	17	9	7	1	3	12	14	17	29	3	2	65	30	4	101	98	412
bay goby							12		11			3	1		166	59	253
English sole				1		72	16						6	8	54		157
arrow goby	16	14	2	1			1	2	27	3		1	3	18	20	37	145
topsmelt	3	21	13	21	3	8						4		1	8	30	112
chameoleon goby						4	1		1	2		4	7	1	5	2	27
yellowfin goby	3			1		15			1				2				22
white croaker									4				1		11	2	18
dwarf perch													12			2	14
barred surfperch	1	2							1			1	1	3	2	2	13
leopard shark	3	2				2			1						1	2	11
brown smoothhound		5													3		8
CA bat ray	3	3													1	1	8
speckled sanddab			1	1		4									1	1	8
starry flounder	1	1							2					1			5
Mississippi silverside												4					4
plainfin midshipman		1				1	1	1									4
three-spine stickleback												1					3
jacksmelt															1	1	2
threadfin shad													2				2
bay pipefish													1				1
California tonguefish															1		1
diamond turbot														1			1
longfin smelt													1				1
shokahaze goby				1													1

MIDDLE BAIR					
	Jan-12	Mar-12	May-12	Jun-12	Total
Pacific staghorn sculpin	21	110	432	34	576
Pacific herring		156	1		157
shiner surfperch			3	67	70
arrow goby		4	11	17	32
Northern anchovy	17	4			4
English sole	2	2			2
diamond turbot		1			1
dwarf perch				1	1
barred surfperch					0
bay goby					0
CA bat ray					0
jacksmelt					0
leopard shark					0
threadfin shad	1				0
topsmelt					0
yellowfin goby	1				0

STEINBURGER					
	Jan-12	Mar-12	May-12	Jun-12	Total
Pacific herring		17	20		37
topsmelt			4	28	32
Pacific staghorn sculpin		4	10	14	28
Northern anchovy	4		6	15	21
arrow goby	2		5	12	17
shiner surfperch			4	5	9
barred surfperch	1			2	2
CA bat ray			1	1	2
English sole	3	2			2
jacksmelt			1	1	2
leopard shark				2	2
bay goby	1				0
diamond turbot					0
dwarf perch					0
threadfin shad					0
yellowfin goby					0

Appendix C

Total number of minutes otter trawled each month in each slough

	Jul-10	Aug-10	Oct-10	Dec-10	Feb-11	May-11	Jun-11	Jul-11	Aug-11	Sep-11	Oct-11	Nov-11	Dec-11	Jan-12	Mar-12	Apr-12	May-12	Jun-12	Total
A6	0	0	0	5	0	0	0	10	0	0	0	0	10	10	5	0	0	0	40
ALVISO SLOUGH	15	15	15	15	15	25	20	20	20	20	20	20	20	20	15	15	15	10	315
ARTESIAN	0	0	10	10	10	10	0	0	0	0	0	0	0	0	0	0	0	0	40
COYOTE CREEK	10	10	20	20	20	35	20	40	85	45	35	30	40	40	40	40	40	40	610
ISLAND PONDS	15	15	30	25	35	30	10	35	50	35	35	35	35	35	35	35	35	35	560
LOWER COYOTE CREEK	20	10	10	20	10	30	0	40	20	40	20	30	10	20	20	20	20	20	360
MUD SLOUGH	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
Upper Coyote Creek	0	0	5	5	10	20	0	5	5	10	15	20	20	10	20	25	20	20	210
EDEN LANDING	0	0	15	10	10	0	0	0	0	0	0	0	0	0	0	0	0	0	35
BAIR ISLAND	20	30	25	20	30	25	10	10	10	10	0	5	30	30	30	0	30	30	345
BAIR-DEEPWATR CHANNEL	10	20	10	10	10	20	20	20	20	10	0	10	20	10	20	0	20	20	250

Appendix D

Total number of fish captured via beach seine in 2012 (since seining was standardized)

Month/Species	ALVISO	RAVENSWOOD	EDEN
January			
No Catch	1		
rainwater killifish	1		
three-spine stickleback	1		2
topsmelt			25
March			
bay pipefish	1		
Mississippi silverside	12		
Pacific herring	37		
Pacific staghorn sculpin		9	
shiner surfperch		1	
topsmelt	1	7	
May			
bay pipefish	2		
diamond turbot		1	
English sole	7		
Mississippi silverside	27		
Northern anchovy	17		
Pacific staghorn sculpin	35	47	6
rainwater killifish	12		
shiner surfperch	1		
three-spine stickleback	18	10	10
topsmelt	64		20
yellowfin goby	6	3	3
June			
longjaw mudsucker	4		
Mississippi silverside	14		
Northern anchovy	10		
Pacific herring	1		
Pacific staghorn sculpin	19	14	
rainwater killifish	16		
shiner surfperch	1		
three-spine stickleback	28		
topsmelt	39	1	
yellowfin goby	27	48	