Comparison of Nekton Assemblages Among Restoring Salt Ponds in the Alviso Marsh, San Francisco Estuary

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Contents

Supplemental Figures and Tables.

Introduction

Coastal salt marshes and wetlands are among the most productive and economically important habitats, yet most degraded and threatened aquatic habitats worldwide (Lotze et al. 2006). Loss of salt marsh habitat in estuaries impairs ecosystem functions; degrading nutrient cycling, food web support, and rearing habitat for fishes and invertebrates (Vernberg 1993, Sousa et al. 2010). Impaired ecosystem function reduces the viability of many estuarine fish populations, impacting growth and survival of early life stages (Jung and Houde 2003, Valiela et al. 2004, Weinstein et al. 2014). The major cause of saltmarsh loss is direct human use and modification of the landscape (Kirwan and Megonigal 2013). Water control structures (e.g. culverts, tidegates, dikes) are commonly used to prevent tidal flooding of adjacent land for urban or agricultural development. Tidal restriction with man-made structures has been well documented to have detrimental effects on water quality, nutrient cycling, species diversity, fish abundance and overall nursery function (Ritter 2008, Moreno-Valcarcel 2016).

Since the California Gold Rush in 1848, the San Francisco Estuary has lost approximately 95% of its wetland habitats as a result of land reclamation for agriculture, urban and industrial development (Atwater et al. 1979, Nichols et al. 1986), resulting in the decline of fish, birds, and shellfish resources (Skinner 1962). In South San Francisco Bay, salt marshes were dredged, leveed, and transformed into commercial solar evaporation ponds for salt production, limiting access for fish and destroying habitat for marsh-dependent wildlife (Josselyn 1983). In 2003, approximately 9,600 acres of solar evaporation ponds were purchased by the U.S. Fish and Wildlife Service and the California Department of Fish and Game (now Fish and Wildlife) for tidal marsh restoration under the auspices of the South Bay Salt Pond Restoration Project (SBSPRP). The SBSPRP is the largest wetland restoration project in the western United States, with approximately 15,000 acres of former solar evaporation ponds available for conversion to a variety of wetland habitat with benefits to fish, wildlife, rare plants, and the public (http://www.southbayrestoration.org/)). These evaporation ponds are located along the Pacific flyway and have been considered important wintering grounds for migratory and breeding birds. The SBSPRP is restoring these ponds to a mosaic of tidal marsh and managed (tidally restricted) pond habitats (EDAW et al. 2007) to benefit many species of salt marsh-dependent biota, including several species listed as threatened or endangered under the Federal Endangered Species Act (ESA) including as the California Ridgway's rail (*Rallus obsoletus obsoletus*, formerly California clapper rail, *Rallus longirostris obsoletus*), Western Snowy Plover (*Charadrius alexandrines nivosus*), Salt Marsh Harvest Mouse (*Reithrodontomys raviventris*), Central California steelhead trout (*Oncorhynchus mykiss*) and green sturgeon (*Acipenser medirostris*) (Takekawa et al. 2001, Warnock et al. 2002, Strong et al. 2004, EDAW et al. 2007).

The effect of pond management on water quality, phytoplankton, fish diversity, abundance and food web dynamics in South Bay remains a one of the primary uncertainties for adaptive management of the South Bay Salt Pond Restoration Project. This effect is of particular concern in the pond A8 complex where a legacy of mercury mining in the Guadalupe River watershed has left a large amount of mercury tailings in the pond. Restoration of this pond is being done iteratively, using an adaptive management approach. Monitoring of water, fish and bird eggs for mercury contamination following successive openings of an operable tide gate on pond A8 is being used to inform managers of potential impacts to species. If no adverse impacts are found in mercury concentrations, additional gates are removed until all gates to the pond are opened. The present study was conducted to improve our understanding of the structure, function, and diversity of aquatic species assemblages inhabiting restored tidal ponds, managed ponds, and sloughs in the Alviso Marsh, including the A8 complex and slough sites used for the mercury monitoring. We conducted three seasonal surveys (Summer 2015, Fall 2015 and Winter 2016) of fish and macro-invertebrates to compare species assemblages, diversity and relatively abundance between the two types of pond restoration (tidal vs. managed) and the adjacent sloughs, which act as donor habitats to the restorations. We also monitored water quality in managed ponds and compared these data to a slough sites to determine the effect of pond management on water quality, species assemblages and diversity in managed ponds.

Methods

Site description

Restoration of former salt pond habitats is being conducted using an adaptive management framework to monitor the progress of tidal and managed pond restorations to guide future restoration decisions. In the Alviso Marsh, a total of 7,485 acres of former industrial production salt ponds have been restored to tidal and managed ponds. The tidal ponds differ from managed ponds in several ways. In tidal ponds, earthen levees surrounding the pond were breached with an excavator, approximately 10-30 meters in width at one to three locations per pond (Figure 1; yellow boxes) allowing unaltered tidal exchange with the adjacent sloughs (Figure 1A). Due to the extreme tidal range (> 4-meters) (Cheng and Gartner 1985), tidal ponds de-water during most low-tides. In managed ponds, water depths are maintained by water control structures which limit tidal exchange and connectivity with sloughs.

There were five tidal restored ponds included in this study: A6 (360-acres), A17 (130-acres), A19 (265-acres), A20 (65-acres), and A21 (150-acres) (Figure 1). Restoration of these pond consisted of one to three breaches (10-30m width) of the levees separating the pond from the adjacent sloughs (Figure 1A) The “Island Ponds” (A19, A20, and A21) were breached in March 2006, pond A6, on Alviso Slough, was breached in December 2010 and pond A17 was breached in October 2012. The ponds are intertidal and feature a "borrow ditch" along the inside perimeter of the surrounding levee. Borrow ditches are typically 1-2 m lower than the former salt pan, and were formed when material was removed from the salt pan to construct the levees. Borrow ditches function as slough-like habitats when tidal ponds are inundated, and are completely dewatered at tides below +4.0 mean lower low water (MLLW).

There were four managed ponds included in this study. The 1,280 acre A8-complex consists of three ponds (A5, A7, and A8) (Figure 1). The internal levees separating the ponds were breached at multiple locations creating an interconnected pond habitat.   Pond A8 is connected to upper Alviso Slough by an operable tide gate system consisting of eight, 5-ft wide removable tide gates (Figure 1B). Tidal flows enter the complex through this gate system located at the upper end of Alviso Slough, but overall volume of water exchanged on tides is small relative to the volume of the ponds and thus water elevation changes little with daily tides. Additional water control structures are located at the north ends of ponds A5 (Figure 1C) and A7 consisting of two 4-ft diameter pipes with tidal flapper gates, one set for inflow and the other outflow, (Figure 1D); A5 exchanges water with Guadalupe Slough, while A7 with Alviso Slough. The water control structures in the A8 complex are managed to maintain proper depths for winter waterfowl hunting and to avoid entrainment of steelhead trout during their outmigration from December through June. The A8 complex was initially opened to tidal flows in 2011 with only a single 4-ft gate open from April to closing November 30th. During this study the tide gates to pond A8 were opened with three gates year-round. The A5 and A7 water control structures were operated bi-directionally from June 1st through November 30th and are exporting water only from December 1st through May 30th. The 240-acre Pond A16 has two water control structures; one is located at the northwest corner of the triangular-shaped pond, which connects with tidal pond A17 through a 63-inch culvert and three independent inclined traveling belt fish screens (Figure 1E). The second is located along the southeast levee with a 4 x 8 cast-in-place box culvert 80-ft in length 6-ft cement culvert, with bi-directional flow into Artesian/Mallard Slough (Figure 1F). Because Pond A16's water elevation is managed for shorebirds, tidal fluctuations are minimal. There were three slough sites included in this study. The Mallard/Artesian Slough (MAL) site was located at the upper end of Artesian Slough, which is heavily influenced by wastewater effluent from the San Jose-San Clara Wastewater Treatment Facility. The upper Alviso Slough site (ALV2) was located at the Alviso Municipal Boat Launch and the creeklet immediately adjacent to the east. The Guadalupe Slough (GUA) site was located in the slough downstream of the Sunnyvale Wastewater Treatment Facility.

Figure 1 Map of the sample sites. Tidal ponds in yellow, managed ponds in blue, slough sites denoted by yellow triangles. Top images show individual seine haul sites. Blue stars depict the location of water quality sondes. Note, the MAL site in Artisian Slough may also be labelled as ART in this draft.

Sampling

We surveyed habitat types; 5 managed ponds (A5, A7, A8, A16), 3 sloughs (Alviso Slough-ALV2 and ALV3, Artesian/Mallard Slough-MAL/ART, Guadalupe Slough-GUA), and 5 tidal ponds (A6, A17, A19, A20, A21) during Summer, Fall 2015 and Winter 2016 (Table X). Small fish (20-mm to approximately 3-cm) and macroinvertebrates (>5-mm) were sampled using a 30-m beach seine, 1.5-m depth with 0.32-cm stretch mesh to assess species assemblage differences among restoration sites. At each pond or slough site a minimum of three to four seine hauls were manually pulled along the shoreline sampling a rectangular area to a depth of approximately 1.5-m. Seine hauls swept an area of 81-m^2 ± 16-m 1-standard deviation. Seine hauls conducted on each survey date within managed and tidal ponds were distributed around the accessible perimeter of each pond typically greater than 50-m apart (Figure 1; top panel). In sloughs, replicate seine haul sites occurred in closer proximity (~10-m) due to the limited shallow shoreline in these habitats. All sampling occurred during daytime hours from approximately between 8-am and 8-pm.

Table 1 Survey dates for the three seasonal surveys within managed ponds, tidal ponds and sloughs

Survey Dates	Managed Ponds				Tidal Ponds					Sloughs			
Summer	**A16**	**A5**	**A7**	**A8**	**A17**	**A19**	**A20**	**A21**	**A6**	**ALV2**	**ALV3**	**GUA**	**MAL**
6/25/2015													X
6/26/2015		X										X	
6/27/2015			X	X						X	X	X	
6/28/2015										X			
6/30/2015										X			
7/24/2015	X			X									
7/25/2015		X	X	X	X								
8/1/2015							X	X	X				
8/2/2015						X							
Fall													
9/26/2015										X		X	X
9/27/2015												X	
9/28/2015											X		
9/29/2015											X		
10/23/2015		X	X	X					X				
10/24/2015	X					X	X	X					
10/25/2015	X			X	X				X				
Winter													
2/13/2016												X	
2/14/2016											X		
2/16/2016										X			X
2/17/2016	X	X		X						X			X
3/12/2016			X		X	X		X	X				

At the end of each seine haul, all fish were quantified and identified to species. Large invertebrates (clams, shrimps, snails) >5-mm were quantified and identified to species, while smaller invertebrates (amphipods, isopods, and mysid shrimp) <5-mm were assinged a rank abundance from 0 to 5 based on visual inspection of catch (0=absent, 1 = 1-3, 2 = 4-10, 3 = 11-50, 4 = 51-100 and 5 = >100 individuals).Water quality was recorded before the seine was deployed at each seine haul site with a handheld YSI Pro Plus. Water quality parameters included temperature (°C), salinity (parts-per-thousand, ppt), conductivity (microsiemens, μm), dissolved oxygen concentration (mg/L). Sampling depth (m) and turbidity (Secchi depth in cm) was measured with a meter stick with a white disk mounted to the bottom for Secchi depth. Water quality variability among the seasonal surveys and sites was explored using Principle Component Analysis (PCA). PCA is an ordination technique that creates composite variables (PC axis) of continuous, linear and often correlated variables that maximizes the variance in the dataset. Water quality variables are often correlated with each other and vary on different spatial or temporal scales.

Because site water quality was only recorded during daytime surveys, and manage pond water quality can often exhibit diel patterns we also deployed water quality sondes (YSI 6500) in three of the managed ponds included in this study (A5, A7, and A16) (Figure 1; blue stars). The sondes were mounted below a buoy anchored to the pond bottom with probes located approximately 1-m below the surface. Prior to deployment, all probes were tested and calibrated against stock solutions for accuracy. Each sonde was programmed to record specific conductivity, temperature, salinity, dissolved oxygen, and depth at 15-minute intervals.

Species Assemblage Comparisons in Tidal Restored Ponds, Managed Ponds, and Sloughs

To understand how the species assemblages varied between managed ponds, tidal ponds and adjacent slough habitats we employed several non-parametric based statistical procedures commonly used for species community data. Each beach seine haul was included as an independent sample unit and raw catch per haul for each taxa was 4th root transformed to diminish the influence of numerically dominant taxa, a common problem when comparing habitats supporting many taxa with varying density.

Bray-Curtis dissimilarity coefficients were calculated from 4^{th} root transformed species raw catch data to construct a sample-by-species matrix that is used for ordination and statistical testing. The raw data were 4^{th} root transformed to reduce the influence of dominant taxa. The Bray-Curtis dissimilarity coefficient is a numerical index used to characterize differences in species and their abundances between samples, in this case beach seine hauls. Differences in Bray-Curtis dissimilarity among seine hauls were explored using non-metric multi-dimensional scaling (NMDS). NMDS is an ordination technique used in species community analysis for graphical representation of non-normal or discontinuous species assemblage data (Clarke 1993, McCune et al. 2002). We visually represented species assemblage differences among the three seasons surveyed and the three habitat types (managed pond, tidal pond, and slough) with one NMDS plot for each of three seasons (summer 2015, fall 2015, and winter 2016). NMDS arranges samples in a multi-dimensional space so that the rank-order correlation between distance measures and distance in ordination space is maximized, while also minimizing stress: a measure of fit between ordination space and multi-dimensional space (McCune et al. 2002). To reduce the impact of rare species which is a common issue in species assemblage studies, we restricted our statistical treatment of samples to species comprising 90% of the total catch. Stress levels less than 0.2 were considered reasonable for our analysis (Clarke and Warwick 2001).

To determine the statistical significance of group differences between seasons, habitat types and habitat type by season we used permutational multivariate analysis of variance (PERMANOVA) (Anderson 2001). The first test (PERMANOVA-1) was a 2-factor test for differences between the three seasonal surveys (Summer, Fall, Winter), the three habitat types (managed pond, tidal pond, sloughs) and the interaction between season and habitat type by season Seine hauls within the managed ponds (A5, A7, A8, and A16), tidal ponds (A6, A17, A19, A20, and A21) and slough sites (Artesian Slough-MAL, Guadalupe Slough-GUA, upper Alviso Slough-ALV2, and middle Alviso Slough-ALV3) were pooled by habitat type to increase sample size for statistical testing of habitat type effects on species assemblages. Pairwise tests were conducted by habitat type and season and significance between pairs accepted at the p-value <0.001 to account for the number of pairwise comparisons. A second test (PERMANOVA-2) was a 2-factor test for differences again between the seasons, the individual ponds and slough sites and the interaction.

Water quality attributes recorded during each seine haul and species 4th root transformed catch data were used to explain species assemblage differences using the non-parametric BIOENV analysis (Clarke and Ainsworth 1993). BIOENV determines the suite of environmental variables or species catch data to show the greatest rank correlation with sample dissimilarities. We conducted BIOENV for each season separately and include all normalized water quality attributes and the top five most abundant species for each season. Euclidean distances among samples were calculated as part of each BIOENV procedure; this distance measure can be applied to both categorical and continuous data (McCune et al. 2002). A Spearman's correlation coefficient (rho) was calculated for the best fitting suite of taxa and environmental data. All multivariate community analysis were conducted in PRIMER 7.0.

Results

We conducted three seasonal surveys within five fully tidal restored ponds, four muted-tidal managed ponds, and four slough sites adjacent to pond restorations in summer 2015, fall 2015, and winter 2016, completing a total of 144 beach seine hauls; 51 within tidal ponds, 45 within managed ponds, and 48 in adjacent sloughs (Table S1). We counted and identified a total of 64,799 aquatic organisms consisting of five phyla including Arthropoda (crabs, shrimp, amphipods, isopods), Annelida (worms), Mollusca (clams, snails, seaslugs), Chordata, subphylum urochordata (tunicates) and subphylum vertebrata (fish) and Cnidaria (jellyfish) (Table 1).

Fishes dominated the catch comprising 70% of all organisms counted. We collected a total of 24 species of fish during our surveys, 16 of which were native to California and 8 non-native (Table 1). The majority of fish species (n = 20) were marsh resident taxa. Fishes considered migratory or transient included Northern anchovy (*Engraulis mordax*), Pacific herring (*Clupea pallasii*), striped mullet (*Mugil cephalus*) and American shad (*Alosa sapidissima*). Pelagic taxa dominated the total catch (>90%) and consisted of 9 of the 16 native fishes and 4 of 7 non-native species (Table 1). Total catch was dominated (>90%) by only 8 species and included only two native species, topsmelt (*Atherinops affinis*) and Northern anchovy. Mississippi silverside (*Menidia audens*) was the most abundant species encountered followed by rainwater killifish (*Lucania parva*), yellowfin goby (*Acanthogobius flavimanus*), threespine stickleback (*Gasterosteus aculeatus*), arrow goby (*Clevelandia ios*) and Pacific herring (*Clupea pallasii*).

Three species of clams were collected during the study, the majority of which were overbite clam (*Potamocorbula amurensis*), a non-native species that dominates the benthos in Suisun Bay. The majority of overbite clams were captured during the summer survey in tidal restored ponds, followed by sloughs and then managed ponds (Table S1). The non-native Japanese littleneck clam (*Venerupis philippinarum*), was the second must numerous clam, however it was found in a single beach seine haul in pond A7 as small juveniles during the summer survey (Table S1). The other clam species was a softshell clam of the genus *Macoma* consisting of a single individual. Gastropod snails consisted primarily of only a single non-native species, eastern mudsnail (*Ilyanassa obsoleta*), that was most abundant in managed ponds during the summer survey. Crabs consisted of only two species, the native Oregon mudcrab (*Hemigrapsus oregonensis)* and the non-native European green crab (*Carcinas maenas*) which consisted of only three specimens observed. The shrimps included three taxa, the non-native Oriental shrimp (*Paleomon macrodactylus*) was the most abundant shrimp and 5th most abundant taxa overall. The native grass shrimp (*Crangon franciscorum*) and non-native Siberian prawn (*Exopalaemon modestus*) comprised the remainder of the shrimp species. Mussels included the non-native Asian mussle (*Musculista senhousia*) and the ridge mussel (*Geukensia demissa*). Other taxa, counted in the surveys included taxonomic groups not identified to species, including jellyfish, worms, tunicates, amphipods, isopods and mysid shrimp (Table 1).

Table 2 Species list with total catch and % of total catch. Non-native species in red text and taxa with multiple species of unknown origin in grey text.

Common Name	Latin name	Taxonomic Group	Habitat	n	%
Mississippi silverside	*Menidia audens*	*Fish*	*Pelagic*	21933	34%
topsmelt	*Atherinops affinis*	*Fish*	*Pelagic*	14241	22%
rainwater killifish	*Lucania parva*	*Fish*	*Pelagic*	12048	19%
Overbite clam	*Potamocorbula amurensis*	*Clam*	*Benthic*	6938	11%
Oriental shrimp	*Paleomon macrodactylus*	*Shrimp*	*Benthic*	2791	4%
Japanese littleneck clam	*Tapes japonica*	*Clam*	*Benthic*	2001	3%
Northern anchovy	*Engraulis mordax*	*Fish*	*Pelagic*	1101	2%
European mudsnail	*Illyanasa obsoleta*	*Snail*	*Benthic*	1077	2%
yellowfin goby	*Acanthogobius flavimanus*	*Fish*	*Benthic*	546	1%
Oregon mudcrab	*Hemigrapsus oregonensis*	*Crab*	*Benthic*	307	0%
threespine stickleback	*Gasterosteus aculeatus*	*Fish*	*Pelagic*	263	0%
comb jelly	*Pleurobrachia bachei*	*Jelly*	*Pelagic*	256	0%
arrow goby	*Clevelandia ios*	*Fish*	*Benthic*	245	0%
Pacific herring	*Clupea pallasii*	*Fish*	*Pelagic*	167	0%
tunicates	*Unk multiple sp.*	*Sea Squirt*	*Benthic*	138	0%
Asian mussel	*Musculista senhousia*	*Mussle*	*Benthic*	114	0%
staghorn sculpin	*Leptocottus armatus*	*Fish*	*Benthic*	110	0%
longjaw mudsucker	*Gillichthys mirabilis*	*Fish*	*Benthic*	85	0%
western mosquitofish	*Gambusia affinis*	*Fish*	*Pelagic*	80	0%
shimofuri goby	*Tridentiger bifasciatus*	*Fish*	*Benthic*	78	0%
cheekspot goby	*Ilypnus gilberti*	*Fish*	*Benthic*	61	0%
shokihaze goby	*Tridentiger barbatus*	*Fish*	*Benthic*	54	0%
largemouth bass	*Micropterus salmoides*	*Fish*	*Pelagic*	45	0%
bay pipefish	*Syngnathus leptorhynchus*	*Fish*	*Pelagic*	33	0%
California halibut	*Paralichthys californicus*	*Fish*	*Benthic*	27	0%
grass shrimp	*Crangon spp.*	*Shrimp*	*Benthic*	12	0%
Striped mullet	*Mugil cephalus*	*Fish*	*Pelagic*	10	0%
starry flounder	*Platichthys stellatus*	*Fish*	*Benthic*	9	0%
bat ray	*Myliobatis californica*	*Fish*	*Benthic*	7	0%
ridge mussle	*Geukensia demissa*	*Mussle*	*Benthic*	6	0%
pileworms	*Unk multiple sp.*	*Worm*	*Benthic*	4	0%
green crab	*Carcinus maenas*	*Crab*	*Benthic*	3	0%
shiner perch	*Cymatogaster aggregata*	*Fish*	*Pelagic*	2	0%
Siberian prawn	*Exopalaemon modestus*	*Shrimp*	*Benthic*	2	0%
softshell clam	*Unk Macoma spp.*	*Clam*	*Benthic*	2	0%
American shad	*Alosa sapidissima*	*Fish*	*Pelagic*	1	0%
jacksmelt	*Atherinopsis californiensis*	*Fish*	*Pelagic*	1	0%
pile perch	*Rhacochilus vacca*	*Fish*	*Pelagic*	1	0%
Small invertebrates-ranked abundance					
amphipods	*Unk multiple sp.*	*Amphipoda*			
isopods	*Unk multiple sp.*	*Isopoda*			
mysid shrimp	*Unk multiple sp.*	*Shrimp*			

Did Species Assemblage Vary Between Habitats and Seasons?

NMDS ordinations were conducted on the 8 most abundant taxa (excluding the Japanese littleneck clam since it was encountered in only a single seine haul) data from the 144 beach seine hauls in summer and fall 2015 and winter 2016 (Table 1). The NMDS plots showed clear differences in species assemblage by season (Figure 2A-C), with a 2-D representation of the n-dimensional space having a stress value of 0.19 indicating the two dimension representation marginally displayed the overall variability in multidimensional space.

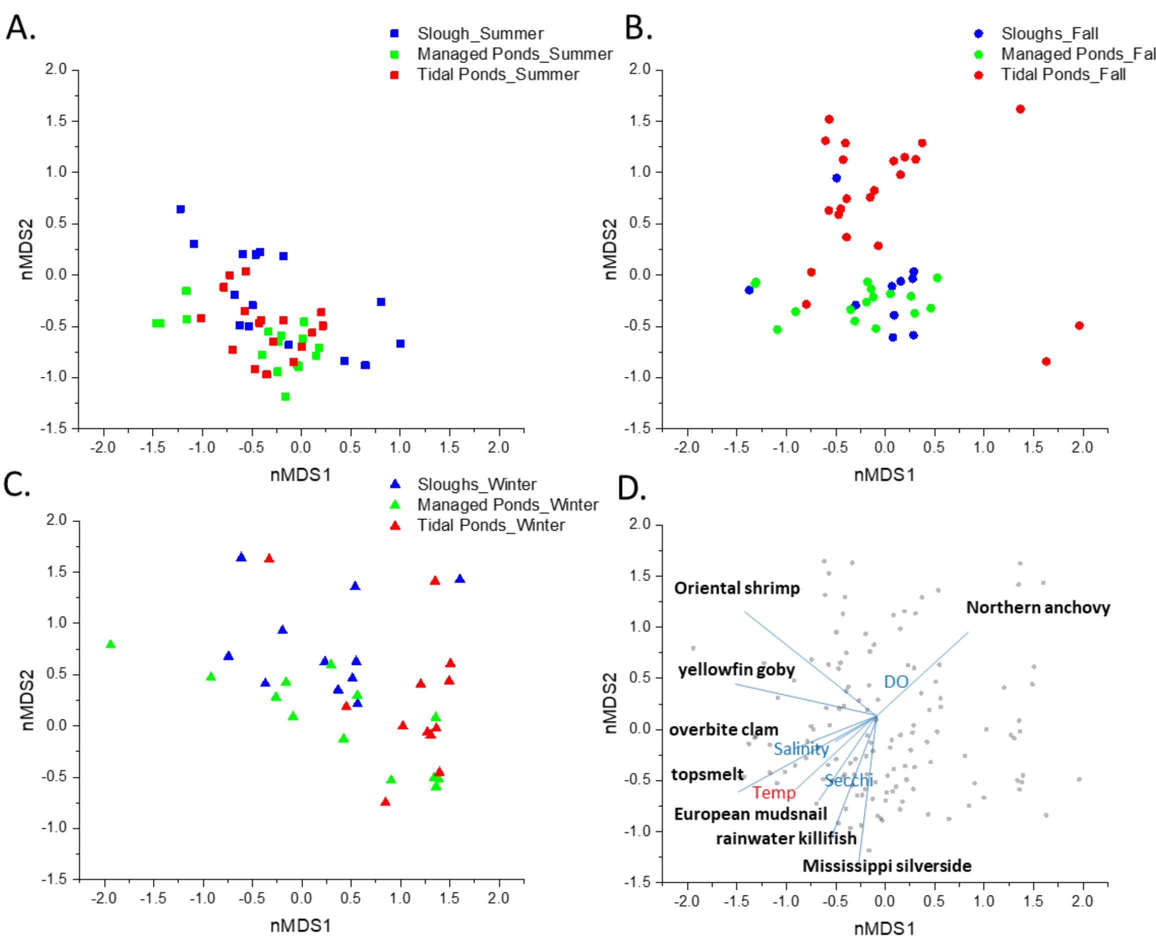

Figure 2 Non-metric multidimensional scaling (nMDS) ordinations of seine hauls conducted over three seasons in muted ponds, tidal ponds, and slough habitats in the Alviso Marsh. A. nMDS ordination on the three seasonal surveys. Arrow vectors depict direction and strength of water quality drivers. Ordinations from A with symbology representing site-type in colored symbols and sites as labels for A. Summer, B. Fall, C. Winter, D full ordination with top 8 species and water quality variables overlayed as vectors depicting the correlation between species assemblage ordination with species and water quality.

The PERMANOVA results were consistent with the visual assessment of the nMDS ordination. The PERMANOVA-1, effect of season (*Psuedo-F*=3.81 *df*= 2 p <0.029) and habitat type (*Psuedo-F*=7.12 *df*= 2 p<0.001) and their season by habitat type interaction (*Psuedo-F*=4.44 *df*= 4.44 p <0.001 were highly significant, thus species assemblages differed between restoration types and slough habitats in each seasonal season. Pairwise tests comparing species assemblage across seasons showed that Summer vs. Winter (t = 2.4, p<0.001) and Fall vs. Winter (t = 1.9, p = 0.002) were significantly different, however; the comparison between Summer vs. Fall was not statistically different (t = 0.1, p <0.159). Tidal ponds during the fall appeared to be different than other habitat types and all habitat types during the summer survey (Figure 2B).

Pairwise tests for habitat type by season showed habitat-types during the Summer survey showed that all pairwise group comparisons were statistically significant; sloughs assemblages were different than managed ponds (t = 3.24, p<0.001), and tidal ponds (t = 4.89, p <0.001), and the assemblages in managed ponds were different than those in tidal ponds (t = 3.46, p <0.001). In Fall, the tidal pond species assemblages were different than the manage ponds (t = 2.2, p<0.001) and sloughs (t = 2.6, p < 0.001), but there were no differences between sloughs and managed (t = 1.13, p = 0.286). In winter, species assemblages were not different between sloughs and managed ponds (t = 2.01, p = 0.009), while sloughs differed from tidal ponds (t = 2.62, p = 0.001) and managed ponds differed from tidal ponds (t = 2.15, p<0.008).

The PERMANOVA-2 test comparing species assemblage differences between Season (*Psuedo-F*=28.7 *df*= 2 p <0.001) and sites (each managed and tidal pond and slough sites)(*Psuedo-F* = 6.8 *df*= 12 p <0.001) and the interactions term was highly significant (*Psuedo-F* = 3.4, *df* = 23 p <0.001). However, the majority of pairwise comparisons were not significantly different likely due to the small sample size (number of seine hauls, 2-4) within sites by season (Table S2). Due to the large number of tests among sites considered p-values less than 0.01 rather than the traditional 0.05 value as significant, although this is somewhat arbitrary.

In summer, 5 of the 16 comparisons between slough and manage ponds were significantly different; Guadalupe Slough (GUA) was significantly different than all the A8 complex ponds and the Mallard Slough (MAL) was different than managed ponds A5 and A8, but not A7. There were 5 out of 20 managed pond vs. tidal pond comparisons that were significantly different; Pond A5 was different than tidal ponds A6, A19 and A21 and A7 was different than tidal ponds A19 and A21. Guadalupe Slough was different than Mallard Slough, and pond A16 was different than the A8-complex ponds (A5, A7, and A8) and pond A7 with pond A8 were statistically significant (Table S2). In fall, only the comparison of tidal pond A20 was different from managed ponds A5 A7 and A16. No pairwise comparisons were different during the winter survey.

Species Assemblage Differences by Season and Habitat Type?

Catch of all species declined from the Summer survey to the Winter survey among habitat types (Figure 3A-B). Catch of all nekton taxa in the manage ponds tended to be slightly greater than in tidal ponds and sloughs, however, catch patterns were not statistically different among any habitat type within a season. Overall, catch of taxonomic groupings were highly variable among beach seine hauls precluding our ability to conduct parametric tests on most species. Catch patterns among native and non-native fishes (Figure 3B-E) appeared to be similar by habitat type within seasons, while invertebrate catch was dominated by non-native taxa (Figure 3B,D and F).

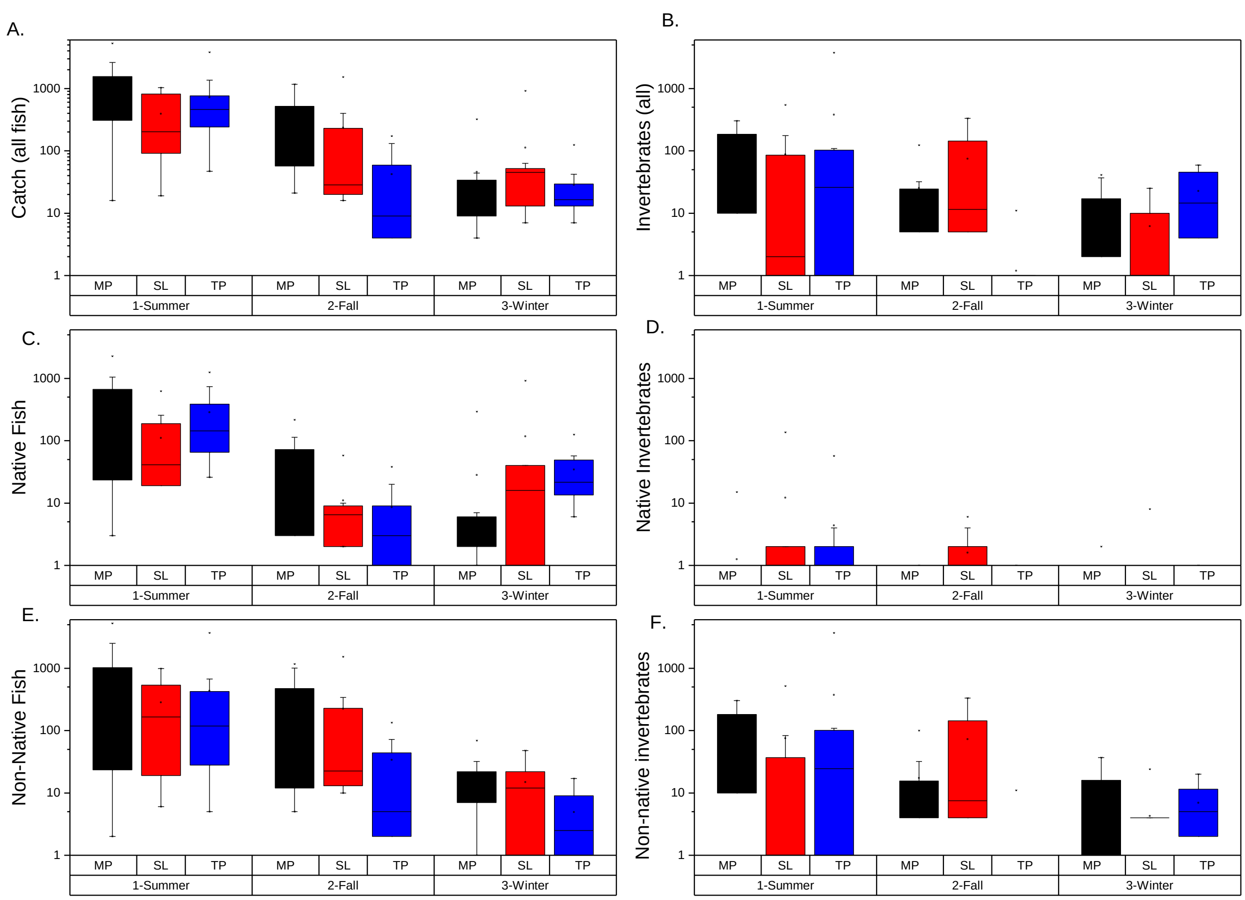

Figure 3 A. Catch (log10) of all fish B. invertebrates, C. native fish, D. native invertebrates, E. non-native fish, and F. non-native invertebrates by seasonal surveys and habitat types (MP = managed ponds, SL = sloughs and TP = tidal ponds). Boxplots depict the 25th and 75th percentiles, medians are horizontal lines within boxes and error bars 1.5 standard deviations.

According the the BIOENV routine the rank order of species importance contributing to seasonal and habitat type differences (for the top 8 taxa) included in the species assemblage analyses (nMDS and PERMANOVA) included topsmelt as the most important taxa followed by Northern anchovy, yellowfin goby, Mississippi silverside, rainwater killifish, overbite clam, Oriental shrimp and European mudsnail (Figure 2D). Topsmelt were more abundant during the Summer survey in the managed and tidal ponds and were nearly non-existent by winter (Figure 4B). In contrast, Northern anchovy were more abundant in sloughs than managed or tidal ponds and showed no overall seasonal trend in abundance (Figure 4F). Mississippi silverside were more abundant in the Summer and Fall surveys and showed similar abundance among habitat types (Figure 4A).

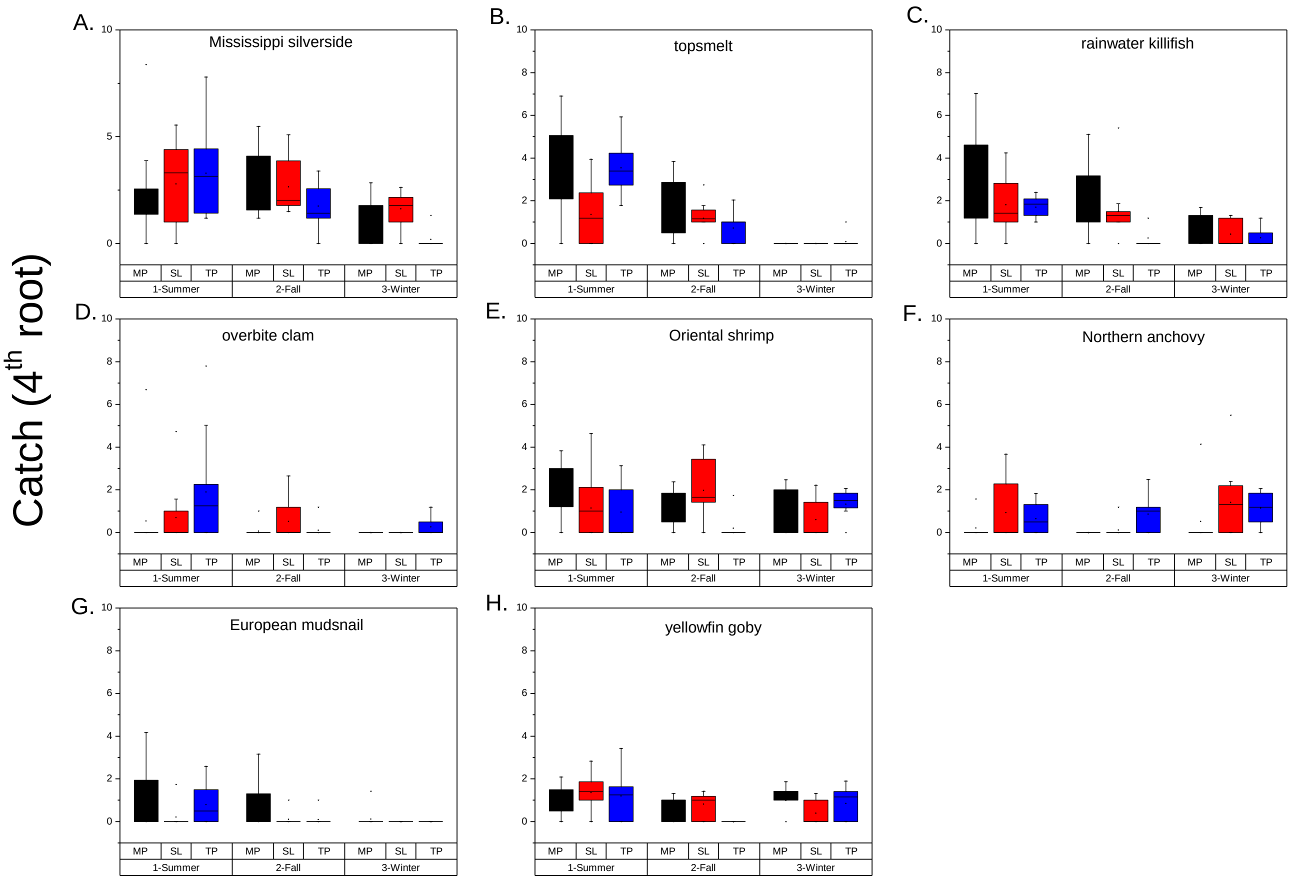

Figure 4 A. Catch of the eight most abundant taxa in order of total abundance that were included in nMDS and PERMANOVA, by seasonal surveys and habitat types (MP = managed ponds, SL = sloughs and TP = tidal ponds). Boxplots depict the 25^{th} and 75^{th} percentiles, medians are horizontal lines within boxes and error bars 1.5 standard deviations.

Water Quality Variability

Water quality conditions varied strongly between winter and summer-fall surveys (Figure 4). Winter was characteristically cooler, less saline, and had higher dissolved oxygen concentrations than summer and fall, which were not different. This variability was summarized with PCA. The first principle component axis explained 36.3% of the variance in the water quality data and distinguished the summer and fall samples from the winter. Salinity and temperature were strongly negatively correlated and dissolved oxygen concentration postivitly correlated to the first PC (Figure 4). Principal component 2 (PC2) was driven by turbidity as measured with Secchi depth.

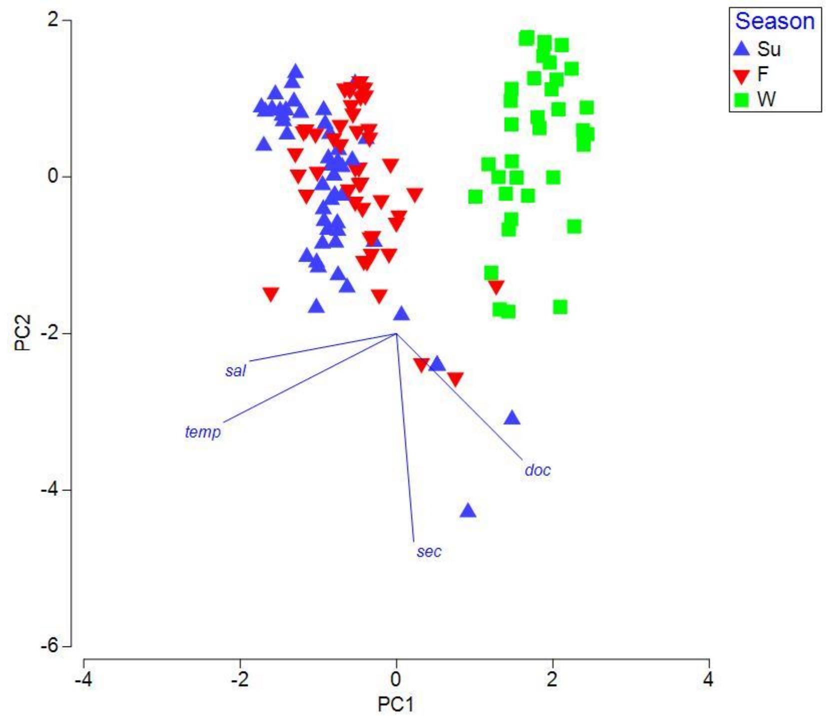

Figure 5 Principle component analysis (PCA) plot of water quality variables measured during seine hauls. Symbols represent each of the three seasonal surveys. Length and direction of water quality vector represent the correlation with seasonal PCA scores, doc= dissolved oxygen concentration (mg/L), sec = Secchi depth (cm), temp = water temperature (°C) and sal = salinity (ppt)

According to the BIOENV routine, the best fitting model of water quality variables explaining species assemblage differences between habitat types included dissolved oxygen concentration, salinity and temperature and had a Spearman rho of 0.341, and $p < 0.001$ (Figure 2D). Mean water quality conditions varied by site and season within the Alviso Marsh (Figure 5). Water clarity indexed from Secchi depth was consistently higher in the managed ponds, except for the Mallard/Artesian Slough site which is heavily influenced by wastewater effluent with high water clarity. Salinity exhibited a seasonal decline from summer to winter and tended to be slightly saltier in the managed ponds. Salinity at the Mallard/Artesian Slough site, which receives tertiary treated wastewater from the Santa Clara-San Jose wastewater facility, was consistently fresher than all other sites in the study. Water temperature also exhibited a seasonal decline from summer to winter but was similar among the habitat types (Figure 5).

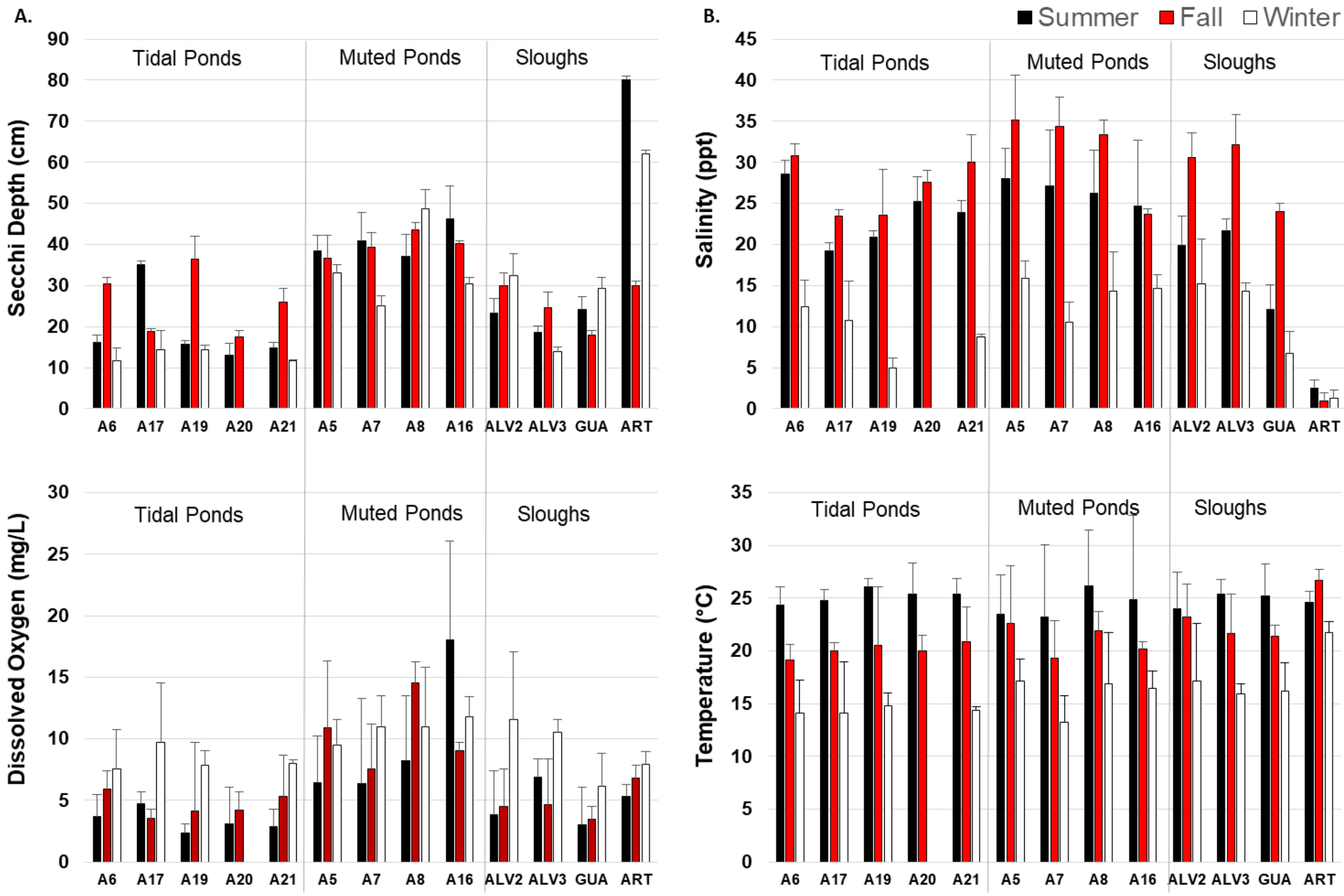

Figure 6 Mean water quality from spot samples measured during seine surveys in upper Alviso Slough-ALV2, middle Alviso Slough-ALV3, Mallard/Artesian Slough-ART, and Guadalupe Slough (GUA). A. Secchi Depth, B. Salinity C. Dissolved Oxygen D. Temperature.

High Frequency Water Quality Data

Water quality data from continuous 15-minute intervals in Alviso Slough and three of the muted ponds demonstrated the high frequency daily and seasonal variability within the slough and managed ponds (Figure 6). 2015 was an extreme dry year and salinity measured as specific conductance was generally high, with Alviso Slough having the highest conductivity, and increased from spring through fall (Figure 6A). Conductivity in pond A16 was also much higher than the other muted ponds (A8, A7) and was similar to Alviso Slough. Due to persistent fouling in pond A16 data from deployments after July 30th were excluded from the analysis. Conductivity in ponds A7 and A8 were similar through July, then A7 increased and stabilized at an elevated conductivity (Figure 6A). Variability in daily mean conductivity for the A7 and A8 ponds likely reflected changes in management operation of water control structures. Pond water elevations varied little during deployments (Pond A8 $\bar{X}$ = 0.27 ± 0.14-1σ, Pond A7 $\bar{X}$ = 0.20 ± 0.08-1σ, Pond A16 $\bar{X}$ = 0.16 ± 0.05-1σ), thus minimal water is exchanged with the sloughs during tide cycles.

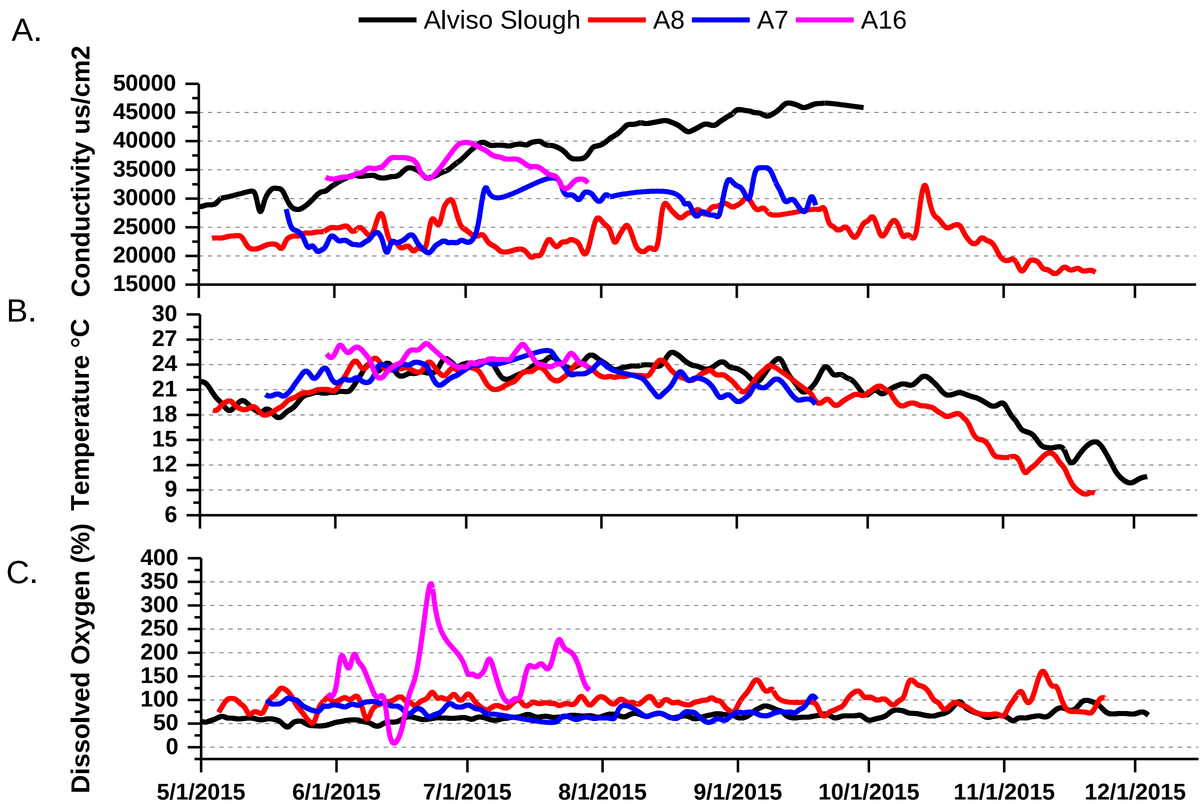

Figure 7 A. Daily mean Conductivity, B. Temperature, and C. Dissolved Oxygen from continuous water quality sonde deployments. Data from Alviso Slough was retrieved from the USGS database.

Daily mean water temperature varied seasonally, and during several days was warmer in pond A16 than other muted pond sites (Figure 6B). Pond A16 is the shallowest of the muted ponds monitored for water quality, thus short durations of warming are likely due to a period of warm atmospheric temperature and less thermal buffering. Dissolved oxygen measured as percent saturation was generally low for Alviso Slough ($\bar{X}$ = 65% ± 10%-1σ), and higher in the A7 ($\bar{X}$ = 77% ± 14%-1σ), A8 ($\bar{X}$ = 96% ± 19%-1σ) manage3d ponds, but was super oxygenated for much of the study period in A16 (Figure C). In addition, Pond A16 experienced several days of anoxic conditions in mid-June, followed by a rapid increase to nearly 350%. Low dissolved oxygen concentrations in Alviso Slough occur typically during low tides and is thought to be the result of high demand in the sediments.

Species Richness

Mean species richness per seine haul for native and non-native species varied seasonally and spatially among sites (Figure 7). Managed pond sites had higher mean species richness, largely due to the high non-native richness in the Fall survey (Figure 7B). Tidal pond species richness declined in the Fall survey but increased again during the Winter survey and was generally similar between native and non-native taxa. Species richness among slough sites was similar to managed ponds and tidal ponds during the Summer and Winter surveys and was greater than tidal ponds in the Fall. The Mallard/Artesian Slough site tended to have lower species richness and generally higher non-native richness during the Summer and Winter surveys.

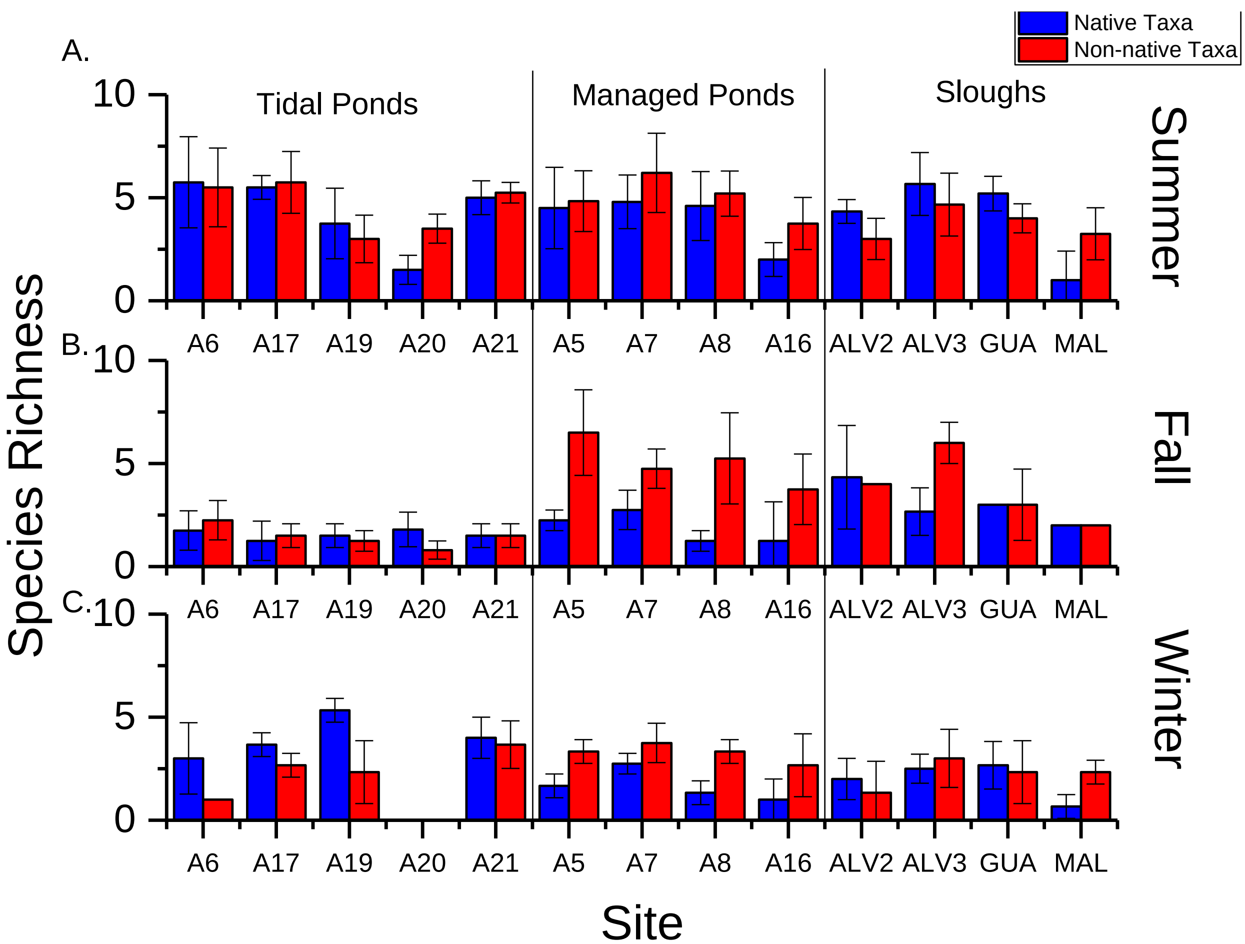

Figure 8 Mean species richness per seine haul for native and non-native species by habitat types and individual sites. Error bars are ± 1 standard deviation.

Discussion

The effects of artificial tidal restriction with water control structures on ecosystem structure and function have been well documented worldwide (Roman et al. 1984, Burdick et al. 1996, Roman et al. 2002, Raposa and Talley 2012). The impacts include declining abundance of native species, proliferation of invasive non-native species, prolonged periods of hypoxia or anoxia and overall habitat and biodiversity loss (Portnoy 1991, Daehler and Strong 1996, Zedler et al. 2001, Raposa and Roman 2003, Gedan et al. 2009). In this study, we documented differences in nekton species assemblages between tidally-restricted managed ponds, full-tidally restored ponds, and slough sites adjacent to water control structures in the Alviso Marsh over three seasonal surveys in 2015-2016. The density of native and non-native species was similar among the habitat types but declined from Summer to Winter (Figure 3). Managed ponds had the highest species richness among the three site types due in part to the greater number of non-native taxa (Figure 7), thus in this case the addition of non-native taxa served to increase biodiversity in managed ponds. The non-native taxa were comprised primarily of small, short-lived pelagic forage species (e.g. Mississippi silverside and rainwater killifish), thus impacts on native species would likely come from competition for food resources. However, the Mississippi silverside is a known voracious predator of larval fishes, thus this species could have an impact via predation as well as competition, a phenomenon known as intraguild predation (Baerwald et al. 2012). Regardless, the non-native taxa were abundant and available as prey for piscivorous avian predators, supporting an important ecosystem function targeted by restoration of the salt ponds.

Water control structures can alter species assemblages by limiting the movement of nekton between habitats thereby reducing connectivity with adjacent habitats. In Summer, species assemblages in the managed ponds differed from the slough and tidal pond habitats, however; in the Fall and Winter surveys, species assemblages in the managed ponds were similar to the sloughs. Overall only 8 (California halibut, shiner perch, striped mullet, Pacific herring, American shad, largemouth bass, softshell clam, Siberian prawn) out of 43 total taxa identified to species were absent in the managed ponds during our surveys (Table S1). Several of these species were either migratory species or seasonal residents in the Alviso Marsh. Pacific herring recruit as larvae to the Alviso Marsh and rear there during the late-winter and spring months before moving out to Central Bay. American shad is a highly migratory species that will utilize estuarine habitat for rearing before migrating to the ocean and is typically only found in the Alviso Marsh in the winter months. Shiner perch migrate into the Alviso Marsh in the spring to give birth to live young which rear through the spring. Striped mullet is a species common to Southern California estuaries and is rarely found in San Francisco Bay. In addition to species not found in managed ponds, Northern anchovy, a migratory species that moves into the estuary during the summer rarely occurred in managed ponds during this study. The lack of these seasonal or migratory taxa in the managed ponds suggests water control structures may limit the movement of the species into managed pond habitats.

Water control structures can also alter species assemblages by affecting water quality. Tidal gates or other water control structures that cause permanent inundation of marsh habitat have been shown to exhibit similar impacts on water quality, including reduced tidal energy and increased water clarity, greater evaporation causing elevated salinity, greater solar irradiation through the water column and warmer temperature and greater periods of low dissolved oxygen or hypoxia. Water quality conditions in the managed ponds was different than tidal ponds and sloughs during this study. As expected the managed ponds tended to have greater water transparency (Secchi depth), were generally warmer and saltier. However, we did not observe hypoxic conditions in the managed ponds during our seasonal nekton surveys and DO was generally higher in the managed ponds than tidal ponds and slough during Summer and Fall. The continuous water quality monitoring revealed more pronounced differences in dissolved oxygen levels in the managed ponds. The A8 complex was generally more oxygenated than the adjacent Alviso Slough, but pond A16 experienced a period of severe hypoxia in mid-June, prior to our first survey in that pond and was followed by a prolonged period of super oxygenation (>100% saturation). Such extreme variability in the oxic environment can be highly stressful to aquatic organisms, both from periods of anoxia/hypoxia and hyperoxia (Ross et al. 2001, Lushchak and Bagnyukova 2006, Pollock et al. 2007). This hypoxic event was likely exacerbated by wastewater with high nitrate concentrations entering the pond from the water control structure in Artesian/Mallard slough. While we did not directly quantify primary production in pond A16, the water was often very green suggesting phytoplankton production was very high in this pond.

Pond A16 species assemblages differed from the other managed ponds during the Summer survey (Table S2). Total catch was also much greater in pond A16 than all other study sites in the Summer and Fall surveys, suggesting the high primary productivity supported greater abundance in this pond. Unfortunately our first survey occurred after the hypoxic event thus we cannot fully assess the impact of this event on abundance and diversity. Productive marsh environments have been documented to experience dissolved oxygen concentrations below 5-mg/L over diel (Tyler et al. 2009) and seasonal cycles (Eby and Crowder 2002). The Alviso Marsh (including Alviso Slough and Coyote Creek and its surrounding marsh and pond habitats) is one of the most productive marshes in the San Francisco Estuary, in part due to the input of nutrients from the largest wastewater facility in the estuary (Senn and Novick 2014). The addition of managed restoration ponds to the Alviso Marsh system may exacerbate eutrophication issues in this system by providing warm, shallow conditions conducive to phytoplankton production. Indeed, in this study Pond A16 is located immediately downstream of the discharge location for the Santa Clara-San Jose WWF and can intake effluent directly from Artesian Slough on flooding tides via a 4-ft box culvert (Figure 1F).

Nekton assemblages did vary between the tidal restoration ponds and adjacent slough sites during each survey, but was extremely different based on ordination plots for the Fall Survey (Figure 4B). The species contributing to assemblage differences in each seasonal survey varied (Figure 4) and overall species richness declined during the Fall survey. It’s not clear what caused the change in species assemblage, relative abundance and species richness in the tidal ponds during Fall. Water quality conditions at most slough sites (except Mallard/Artesian) were similar to the tidal ponds (Figure 5). Dissolved oxygen concentrations in tidal ponds and sloughs were low in the fall, but would have likely influence assemblages in both locations similarly. Tidal ponds occur at a higher mean tidal elevation than the slough sites and during most low-tide events (< 4-ft MLLW) the tidal ponds dewater while water remains at all slough sites. However, tidal inundation and dewatering would have been greater during the Summer survey, occurring closer to the summer solstice when tidal amplitude is greater. It’s likely that the catch patterns observed during the Fall survey in the tidal ponds was due to highly variable movement patterns in nektonic organisms suggesting greater effort may be required to fully assess species assemblage in tidally dynamic habitats.

Assessing Restoration Actions with Regards to the South Bay Salt Pond Restoration Adaptive Management Plan.

The primary objective(s) of the South Bay Salt Pond Restoration Project was to create, restore, or enhance habitats of sufficient size, function and appropriate structure to 1) promote restoration of native special-status plants and animals that depend on South San Francisco Bay habitat for all or part of their life cycle. This study demonstrated that managed and tidal pond habitats in the Alviso Marsh can provide habitat for a large number of aquatic species. Special status aquatic species include, ESA listed Central Coast Steelhead and green sturgeon, as well as the state threatened longfin smelt. Additional species of management importance or special concern include Pacific herring and shiner perch. During this survey we did not encounter any Steelhead, green sturgeon or longfin smelt. Tidal restoration ponds did support a large number of juvenile Pacific herring during the Winter survey but only two shiner perch were found (Table S1).

The second objective 2) was to maintain current migratory bird species that utilize existing salt ponds and associate structures such as levees. While we did not quantify avian taxa during our surveys, we did observe large numbers of winter waterfowl utilizing the tidal ponds A19 and A21, and piscivorous birds (cormorants, terns) utilizing the A8 complex.

The third objective 3) was to support increasing abundance and diversity of native species in the various South San Francisco Bay aquatic and terrestrial ecosystems for plants, invertebrates, fish, mammals, birds, reptiles and amphibians. The abundance of non-native species utilizing the managed ponds is troubling, however; given the degree to which the San Francisco Estuary is already impacted by non-native species, it may be impossible to devise restoration strategies that support native species while discourages non-native species.

In the adaptive management plan, several key uncertainties were also outlined. Key uncertainty #13. What is the effect of a) pond management, including increased pond flows and associated managed pond effects and b) tidal prisms from tidal habitat restoration on water quality, phytoplankton and fish diversity and abundance and food web dynamics in South Bay? Managed ponds provided habitat for a greater diversity of species than adjacent sloughs and tidal ponds and nekton density was high. However, we did document a period of severe hypoxia in pond

A16. Unfortunately our sampling events in this pond began after this period. We did not observe a significant impact to the aquatic species assemblages in this pond following the hypoxic event. We did find many dead fish along the shoreline in the A8 complex during this survey and during other sampling events in this pond. Also, in other surveys we documented hypoxic periods in the A8 pond, thus water quality remains an important issue for managed ponds.

Recommendations

This study was conducted over only a single year (summer to winter) during the height of prolonged drought in California (Swain et al. 2014, Diffenbaugh et al. 2015). As a result, salinity was likely elevated during our surveys and species assemblages may not be representative of "normal" conditions in the Alviso Marsh. The majority of taxa encountered were euryhaline estuarine species, thus the species encountered would have likely found the marsh to be suitable rearing habitat. However, habitat suitability and environmental tolerances to the described conditions has not been established for the majority of the taxa encountered in this study. Future studies should include years of differing hydrologic conditions to gain a better understanding of the species assemblage structure of managed pond habitats. Furthermore, due to the inherent spatial and temporal variability of species abundance (catch) in this system we recommend increasing sampling effort within any one pond site and survey period to determine full demographic effects of restoration aquatic species. Based on rarefaction curves from our data, we estimate that a minimum of 40 samples be taken from a site to be sure to detect all species encountered in this study (Figure S1). Since the majority of species and catch occurred in the Summer to Fall surveys we recommend focusing on a single survey period. Furthermore, ponds within the A8 complex could be pooled since these ponds function as a single unit. Additional monitoring and research efforts should be focused on the impacts of hypoxia within the managed ponds. It is likely they have much more severe impacts on aquatic species that we observed in this study.

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Table S 1 Summary of catch and water quality from the three seasonal surveys

Summer-2015

		Managed Ponds				Tidal Ponds					Sloughs			
		A16	A5	A7	A8	A17	A19	A20	A21	A6	ALV2	ALV3	GUA	MAL
Effort	Number of replicate hauls	4	4	4	4	4	4	2	4	4	4	4	4	4
	Mean area sampled m2	78.3	81.4	91.7	78.5	88.3	88.6	77.2	87.3	87.0	86.5	72.3	80.2	77.9
Water Quality	Secchi depths (cm)	46	44	47	42	35	16	13	15	16	23	19	24	80
	Salinity (ppt)	24.7	29.1	27.8	27.2	19.2	20.9	25.3	23.9	28.6	19.9	21.6	11.9	2.5
	Temperature (°C)	24.8	22.5	23.1	26.2	24.8	26.1	25.4	25.4	24.4	24.0	25.3	25.2	24.6
	Dissolved oxygen concentration (mg/L)	18.1	5.5	5.9	8.2	4.7	2.4	3.1	2.9	3.7	3.9	6.9	3.0	5.3
	Benthic													
Native Fishes	bat ray	0	0	0	0	0	0	0	0	0	0	0	0	0
	arrow goby	13	12	7	19	8	9	0	16	118	3	4	5	0
	California halibut	0	0	0	0	0	0	0	1	1	0	3	4	0
	cheekspot goby	0	6	7	0	0	0	0	0	8	0	0	0	0
	starry flounder	0	0	0	0	0	0	1	0	0	0	0	5	0
	longjaw mudsucker	2	8	4	16	6	2	0	1	16	0	0	6	0
	staghorn sculpin	1	0	1	0	0	0	0	0	7	0	0	0	0
	Pelagic													
	pile perch	0	0	1	0	0	0	0	0	0	0	0	0	0
	bay pipefish	0	4	3	5	4	1	0	0	1	1	2	5	0
	threespine stickleback	0	14	2	5	22	38	5	126	39	0	0	0	0
	topsmelt	29	1562	4112	2263	1024	261	104	1875	1442	646	34	5	15
	shiner perch	0	0	0	0	0	0	0	0	1	0	1	0	0
	jacksmelt	0	1	0	0	0	0	0	0	0	0	0	0	0
	Striped mullet	0	0	0	0	0	0	0	0	0	0	0	0	10
	Northern anchovy	0	0	0	5	1	4	0	15	11	5	297	270	0
	Pacific herring	0	0	0	0	0	0	0	0	0	0	0	0	0
	Benthic													
Non-Native Fishes	yellowfin goby	0	26	12	14	28	37	0	19	146	1	18	69	71
	shimofuri goby	0	0	1	46	0	0	0	0	4	0	0	0	0
	shokihaze goby	0	0	0	0	0	0	0	0	0	0	0	0	0
	Pelagic													
	American shad	0	0	0	0	0	0	0	0	0	0	0	0	0
	Mississippi silverside	5733	75	29	63	17	4892	177	139	2111	849	120	190	2004
	western mosquitofish	0	0	0	0	0	0	0	0	0	0	0	0	73
	Largemouth bass	0	0	0	0	0	0	0	0	0	0	0	0	45
	rainwater killifish	4673	942	64	2536	66	78	2	14	56	441	130	13	289
Native Invert	softshell clam	0	0	0	0	0	0	0	1	0	0	0	0	0
	Oregon mudcrab	0	15	10	0	16	1	0	2	59	2	154	26	0
	grass shrimp	0	0	0	0	0	0	0	0	0	1	0	0	0
Non-Native Invertebrates	Overbite clam	0	0	21	0	7	1915	1	710	3711	0	3	508	0
	Japanese littleneck clam	0	0	2001	0	0	0	0	0	0	0	0	0	0
	green crab	1	0	0	2	0	0	0	0	0	0	0	0	0
	comb jelly	0	0	0	0	0	0	0	0	0	0	3	0	0
	ridge mussle	6	0	0	0	0	0	0	0	0	0	0	0	0
	Asian date mussel	5	22	46	0	4	0	0	0	0	0	0	0	0
	Oriental shrimp	0	209	319	360	158	0	0	1	110	4	569	29	1
	Siberian prawn	0	0	0	0	0	0	0	0	0	0	0	1	0
	European mudsnail	500	161	153	3	1	0	1	103	7	0	13	0	0
Multi-species	tunicates	0	5	10	0	0	0	0	0	0	0	0	0	0
	pileworms	0	1	1	0	1	0	0	0	1	0	0	0	0
	worms	0	0	0	0	0	0	0	0	0	0	0	0	0
	amphipods	3	3	20	2	4	8	0	7	4	0	2	2	6
	isopods	0	15	19	14	5	3	0	4	9	6	11	3	0
	mysid shrimp	0	12	2	15	7	0	0	2	5	0	3	9	7
	Totals:	**10,966**	**3,093**	**6,845**	**5,368**	**1,379**	**7,249**	**291**	**3,036**	**7,867**	**1,959**	**1,367**	**1,150**	**2,521**
	Pond Type Totals:				**26,272**					**19,822**				**6,997**

Fall-2015

		Managed Ponds				Tidal Ponds					Sloughs			
		A16	A5	A7	A8	A17	A19	A20	A21	A6	ALV2	ALV3	GUA	MAL
Effort	Number of replicate hauls	4	4	4	4	4	4	5	4	4	4	4	4	4
	Mean area sampled m2	80.1	72.7	86.7	82.9	91.7	83.1	76.4	54.2	82.1	82.6	77.5	83.4	85.2
Water Quality	Secchi depths (cm)	40	37	39	44	19	37	18	26	31	30	25	18	30
	Salinity (ppt)	23.7	35.2	34.4	33.4	23.5	23.6	27.6	30.0	30.8	30.6	32.2	24.0	0.9
	Temperature (°C)	20.2	22.6	19.3	22.0	20.0	20.5	20.0	20.9	19.2	23.2	21.7	21.4	26.7
	Dissolved oxygen concentration (mg/L)	9.1	10.9	7.6	14.5	3.6	4.2	4.2	5.4	5.9	4.5	4.7	3.5	6.8
	Benthic													
Native Fishes	bat ray	0	2	0	0	0	0	2	0	0	2	1	0	0
	arrow goby	1	5	0	0	0	0	0	0	0	0	0	2	1
	California halibut	0	0	0	0	4	0	1	0	0	6	2	0	0
	cheekspot goby	0	9	2	0	1	0	0	0	0	0	0	0	0
	starry flounder	0	0	0	1	0	0	0	0	0	0	0	0	0
	longjaw mudsucker	3	1	4	1	0	0	0	0	0	0	0	0	0
	staghorn sculpin	0	0	0	0	1	0	0	0	0	0	0	0	0
	Pelagic													
	pile perch	0	0	0	0	0	0	0	0	0	0	0	0	0
	bay pipefish	0	0	1	0	0	0	0	0	0	0	2	1	0
	threespine stickleback	0	0	0	0	0	0	0	0	0	2	0	1	1
	topsmelt	1	338	138	263	0	2	3	7	34	4	19	59	0
	shiner perch	0	0	0	0	0	0	0	0	0	0	0	0	0
	jacksmelt	0	0	0	0	0	0	0	0	0	0	0	0	0
	Striped mullet	0	0	0	0	0	0	0	0	0	0	0	0	0
	Northern anchovy	0	0	0	0	2	95	2	24	0	2	0	0	0
	Pacific herring	0	0	0	0	0	0	0	0	0	0	0	0	0
	Benthic													
Non-Native Fishes	yellowfin goby	2	4	2	4	0	0	0	0	0	7	4	3	0
	shimofuri goby	0	18	4	2	0	0	0	0	0	0	0	0	0
	shokihaze goby	0	2	8	0	0	0	0	0	0	0	10	2	0
	Pelagic													
	American shad	0	0	0	0	0	0	0	0	0	0	0	0	0
	Mississippi silverside	1952	78	20	302	8	224	8	159	304	34	62	562	673
	western mosquitofish	0	0	1	0	0	0	0	0	0	0	0	4	0
	Largemouth bass	0	0	0	0	0	0	0	0	0	0	0	0	0
	rainwater killifish	1737	41	2	34	0	0	0	2	2	11	7	12	855
Native Invert	softshell clam	0	0	0	0	0	0	1	0	0	0	0	0	0
	Oregon mudcrab	1	0	2	0	0	0	1	0	1	12	2	1	0
	grass shrimp	0	0	0	0	0	0	0	0	0	0	0	1	0
Non-Native Invertebrates	Overbite clam	0	1	0	0	3	0	0	0	0	0	54	0	0
	Japanese littleneck clam	0	0	0	0	0	0	0	0	0	0	0	0	0
	green crab	0	0	0	0	0	0	0	0	0	0	0	0	0
	comb jelly	0	0	0	0	0	1	0	0	2	0	0	0	0
	ridge mussle	0	0	0	0	0	0	0	0	0	0	0	0	0
	Asian date mussel	3	23	5	5	0	0	0	0	0	0	1	0	0
	Oriental shrimp	0	61	38	14	12	0	0	0	2	19	625	29	0
	Siberian prawn	0	0	0	0	0	0	0	0	0	0	0	0	0
	European mudsnail	102	19	1	6	0	0	0	0	2	0	1	0	0
Multi-species	tunicates	122	1	0	0	0	0	0	0	0	0	0	0	0
	pileworms	0	0	0	0	0	0	0	0	0	0	0	0	0
	worms	0	0	0	0	0	0	0	0	0	0	0	0	0
	amphipods	2	1	1	0	0	0	0	0	0	0	0	0	0
	isopods	1	15	12	8	0	0	0	0	0	10	4	3	0
	mysid shrimp	0	3	1	5	10	1	0	0	0	14	8	6	0
	Totals:	**3,927**	**622**	**242**	**645**	**41**	**323**	**18**	**192**	**347**	**123**	**802**	**686**	**1,530**
	Pond Type Totals:				**5,436**					**921**				**3,141**

Winter-2016

		Managed Ponds				Tidal Ponds				Sloughs			
		A16	A5	A7	A8	A17	A19	A21	A6	ALV2	ALV3	GUA	MAL
Effort	Number of replicate hauls	3	3	4	3	3	3	3	3	4	4	4	4
	Mean area sampled m2	84.3	79.0	80.6	85.8	88.1	87.7	90.1	57.8	80.6	76.5	81.5	84.2
Water Quality	Secchi depths (cm)	30	33	25	49	14	14	12	12	32	14	29	62
	Salinity (ppt)	14.7	15.9	10.5	14.3	10.7	5.0	8.7	12.4	15.2	14.4	6.7	1.3
	Temperature (°C)	16.4	17.1	13.3	16.9	14.1	14.8	14.4	14.1	17.1	15.9	16.2	21.7
	Dissolved oxygen concentration (mg/L)	11.8	9.5	11.0	11.0	9.7	7.9	8.0	7.6	11.6	10.6	6.2	7.9
	Benthic												
Native Fishes	bat ray	0	0	0	0	0	0	0	0	0	0	0	0
	arrow goby	0	0	13	1	1	3	4	0	0	0	0	0
	California halibut	0	0	0	0	2	1	1	0	0	0	1	0
	cheekspot goby	0	1	8	0	0	9	9	1	0	0	0	0
	starry flounder	0	2	0	0	0	0	0	0	0	0	0	0
	longjaw mudsucker	0	0	1	3	0	11	0	0	0	0	0	0
	staghorn sculpin	34	2	6	2	11	9	8	0	0	0	27	1
	Pelagic												
	pile perch	0	0	0	0	0	0	0	0	0	0	0	0
	bay pipefish	0	0	0	0	0	0	1	1	0	0	1	0
	threespine stickleback	0	0	0	0	0	6	1	0	1	0	0	0
	topsmelt	0	0	0	0	0	0	0	1	0	0	0	0
	shiner perch	0	0	0	0	0	0	0	0	0	0	0	0
	jacksmelt	0	0	0	0	0	0	0	0	0	0	0	0
	Striped mullet	0	0	0	0	0	0	0	0	0	0	0	0
	Northern anchovy	0	298	0	0	8	11	3	48	0	0	0	0
	Pacific herring	0	0	0	0	3	114	2	11	17	2	18	0
	Benthic												
Non-Native Fishes	yellowfin goby	5	17	10	3	7	13	18	0	1	0	3	2
	shimofuri goby	0	1	2	0	0	0	0	0	0	0	0	0
	shokihaze goby	0	0	19	0	0	0	12	0	0	1	0	0
	Pelagic												
	American shad	0	0	0	0	0	1	0	0	0	0	0	0
	Mississippi silverside	16	23	8	91	0	4	0	0	951	36	19	0
	western mosquitofish	0	0	0	0	1	0	0	0	0	0	0	1
	Largemouth bass	0	0	0	0	0	0	0	0	0	0	0	0
	rainwater killifish	6	8	1	14	1	1	2	0	2	1	0	5
Native Invert	softshell clam	0	0	0	0	0	0	0	0	0	0	0	0
	Oregon mudcrab	0	0	0	0	1	0	0	0	0	1	0	0
	grass shrimp	2	0	0	0	0	0	0	0	0	0	8	0
Non-Native Invertebrates	Overbite clam	0	0	0	0	1	1	2	0	0	0	0	0
	Japanese littleneck clam	0	0	0	0	0	0	0	0	0	0	0	0
	green crab	0	0	0	0	0	0	0	0	0	0	0	0
	comb jelly	0	51	0	0	5	0	88	96	10	0	0	0
	ridge mussle	0	0	0	0	0	0	0	0	0	0	0	0
	Asian date mussel	0	0	0	0	0	0	0	0	0	0	0	0
	Oriental shrimp	0	7	88	11	17	1	35	26	0	41	5	0
	Siberian prawn	0	0	0	0	0	0	0	0	0	0	1	0
	European mudsnail	4	0	0	0	0	0	0	0	0	0	0	0
Multi-species	tunicates	0	0	0	0	0	0	0	0	0	0	0	0
	pileworms	0	0	0	0	0	0	0	0	0	0	0	0
	worms	1	0	0	0	0	0	0	0	0	0	0	0
	amphipods	0	0	0	0	0	0	0	0	0	0	1	1
	isopods	0	1	9	1	1	0	0	0	0	0	3	0
	mysid shrimp	10	7	20	4	9	15	9	12	16	0	15	2
	Totals:	**78**	**418**	**185**	**130**	**68**	**200**	**195**	**196**	**998**	**82**	**102**	**12**
	Pond Type Totals:				**811**				**659**				**1,194**

Table S 2 Pairwise PERMANOVA tests among sites for each seasonal survey. Tests considered significant at p <0.01 in bold

Pairwise Comparison	Summer		Fall		Winter	
	t	P(perm)	t	P(perm)	t	P(perm)
Sloughs vs. Managed Ponds						
ALV2, A16	2.5827	0.035	4.2448	0.029	1.731	0.080
ALV2, A5	2.2338	0.011	1.9335	0.061	1.4643	0.090
ALV2, A7	2.2562	0.020	2.2835	0.028	4.0801	0.034
ALV2, A8	2.6721	0.018	2.6044	0.032	2.6417	0.132
ALV3, A16	3.4539	0.021	3.8318	0.024	2.0356	0.102
ALV3, A5	2.0974	0.012	1.6675	0.033	1.6227	0.188
ALV3, A7	1.8059	0.011	1.9778	0.035	6.1685	0.063
ALV3, A8	2.4069	0.018	2.0929	0.029	1.6419	0.085
GUA, A16	3.1496	0.014	1.9961	0.025	1.1828	0.224
GUA, A5	2.2211	**0.002**	1.3482	0.062	1.3181	0.102
GUA, A7	2.0824	**0.008**	1.3289	0.083	2.1013	0.026
GUA, A8	2.3282	**0.006**	1.2119	0.152	1.7684	0.097
MAL, A16	2.1559	0.027	0.83986	0.586	1.1936	0.388
MAL, A5	2.7038	**0.005**	1.7699	0.199	1.7211	0.119
MAL, A7	2.6201	0.012	2.5653	0.223	3.888	0.033
MAL, A8	2.955	**0.009**	2.5389	0.207	1.23	0.306
Manged vs. Tidal Ponds						
A16, A17	3.7801	0.032	2.6968	0.026	1.517	0.190
A16, A19	2.4876	0.027	3.6218	0.039	1.5287	0.096
A16, A20	2.4844	0.069	2.6631	**0.009**	NA	NA
A16, A21	3.2682	0.022	3.3051	0.017	1.8367	0.108
A16, A6	2.6921	0.021	3.2215	0.029	2.6149	0.107
A5, A17	1.2445	0.130	1.9935	0.034	1.0754	0.329
A5, A19	2.5854	**0.006**	3.2093	0.027	1.7566	0.112
A5, A20	2.4678	0.028	2.3199	**0.003**	NA	NA
A5, A21	2.3039	**0.006**	2.876	0.029	1.1206	0.294
A5, A6	1.7696	**0.004**	2.7032	0.034	1.42	0.101
A7, A17	1.4437	0.047	2.1477	0.035	2.1576	0.026
A7, A19	2.1724	**0.007**	3.6023	0.028	2.8519	0.040
A7, A20	2.1294	0.051	2.2664	**0.008**	NA	NA
A7, A21	1.763	**0.008**	3.1127	0.038	1.9677	0.040
A7, A6	1.5968	0.017	2.8572	0.038	6.8379	0.033
A8, A17	1.7659	0.010	2.1115	0.034	1.6734	0.207
A8, A19	2.7897	0.011	3.5396	0.020	1.9758	0.098
A8, A20	3.221	0.046	2.4278	0.013	NA	NA
A8, A21	2.6874	0.013	3.0122	0.040	1.9522	0.106
A8, A6	1.7472	0.014	2.5969	0.027	3.0496	0.098
Sloughs vs. Tidal Ponds						
ALV2, A17	2.4273	0.023	1.5186	0.048	2.2627	0.099
ALV2, A19	1.3125	0.040	4.0932	0.020	1.6515	0.114
ALV2, A20	2.0291	0.097	2.3116	0.017	NA	NA
ALV2, A21	2.3956	0.027	3.7773	0.022	2.1412	0.111
ALV2, A6	1.3432	0.128	4.1521	0.022	2.1903	0.077
ALV3, A17	1.7777	0.024	1.498	0.025	2.1949	0.089
ALV3, A19	2.5042	0.021	3.685	0.021	2.7346	0.100
ALV3, A20	2.7511	0.112	2.2446	0.020	NA	NA
ALV3, A21	2.2666	0.034	3.3027	0.030	2.1245	0.098
ALV3, A6	1.8274	0.024	3.2033	0.023	4.2758	0.093
GUA, A17	1.5052	0.058	1.3715	0.087	1.35	0.204
GUA, A19	2.0026	0.018	1.9507	0.066	1.4117	0.107
GUA, A20	1.9679	0.044	1.5227	0.058	NA	NA
GUA, A21	1.7943	0.027	1.7341	0.027	1.7738	0.101
GUA, A6	1.7635	0.021	1.4811	0.101	2.4357	0.113
MAL, A17	2.8375	0.034	1.3673	0.186	2.2545	0.106
MAL, A19	1.9184	0.034	2.2565	0.191	2.5221	0.094
MAL, A20	1.833	0.066	1.4166	0.373	NA	NA
MAL, A21	2.6768	0.031	2.0251	0.194	2.5437	0.108
MAL, A6	2.0488	0.040	2.2677	0.192	3.9785	0.101

Pairwise Comparison	Summer		Fall		Winter	
	t	P(perm)	t	P(perm)	t	P(perm)
Slough						
ALV2, ALV3	2.2593	0.102	2.4098	0.098	3.049	0.105
ALV2, GUA	2.2268	0.022	1.5133	0.116	1.6161	0.097
ALV2, MAL	2.2099	0.034	4.4291	0.258	2.7903	0.108
ALV3, GUA	1.7162	0.036	1.2392	0.090	2.4693	0.100
ALV3, MAL	2.7385	0.029	3.0989	0.228	2.0991	0.110
GUA, MAL	2.1909	**0.009**	1.035	0.500	2.0127	0.117
Managed Ponds						
A16, A5	3.183	**0.007**	2.6613	0.021	1.5388	0.115
A16, A7	3.0299	**0.006**	3.7046	0.028	2.2374	0.024
A16, A8	3.9415	**0.007**	3.3124	0.037	1.1779	0.189
A5, A7	1.5796	0.034	1.1431	0.358	2.3168	0.025
A5, A8	0.87903	0.658	1.0727	0.365	1.3508	0.283
A5, A17	1.2445	0.130	1.9935	0.034	1.0754	0.329
A7, A8	1.7896	**0.007**	1.3051	0.205	2.7465	0.024
Tidal Ponds						
A17, A19	2.2862	0.036	2.2132	0.025	1.8004	0.095
A17, A20	2.6312	0.058	1.7831	0.019	NA	NA
A17, A21	2.0959	0.024	2.2724	0.029	0.99499	0.702
A17, A6	1.5808	0.036	2.3778	0.033	2.1996	0.107
A19, A20	1.6246	0.075	1.3856	0.108	NA	NA
A19, A21	1.9791	0.024	1.0593	0.310	1.7418	0.101
A19, A6	1.1683	0.198	2.019	0.025	2.4918	0.098
A20, A21	2.2421	0.068	1.0151	0.389	NA	NA
A20, A6	1.8771	0.071	1.5818	0.035	NA	NA
A21, A6	1.28	0.090	1.3126	0.174	1.8063	0.105

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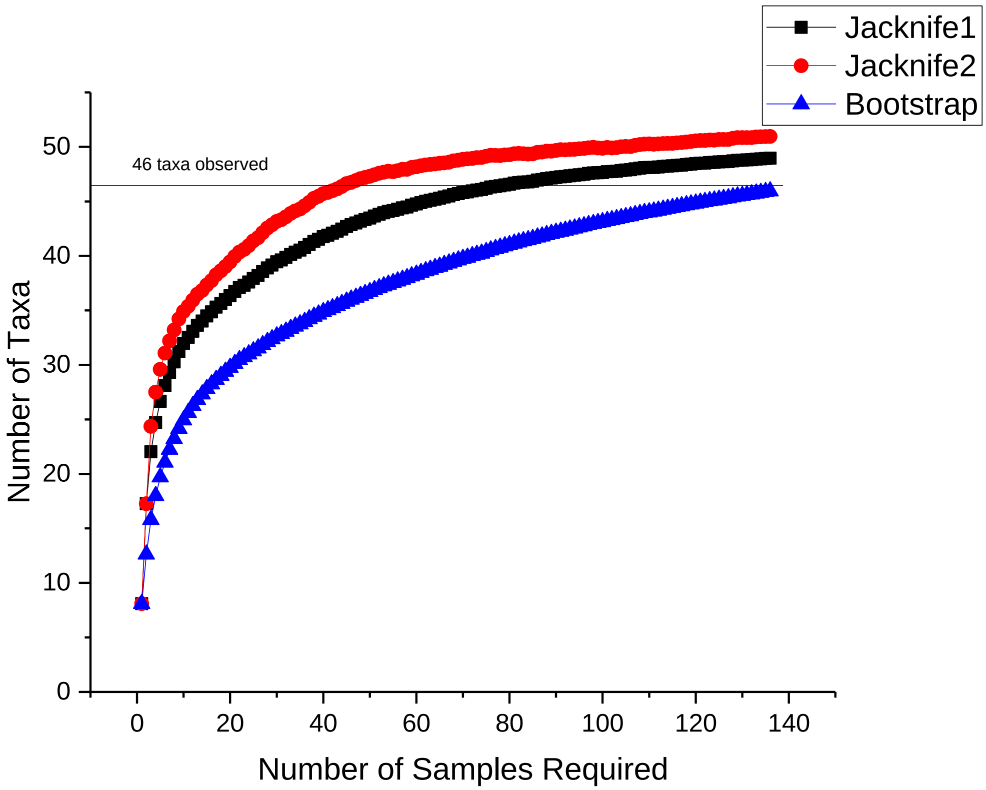

Figure S 1 Rarefaction curve for beach seine sampling in managed, tidal and slough habitats in the Alviso Marsh. During our study we encounted a total of 46 species. To reliably detect all species at any one site would require 40-140 samples depending on the analytical technique employed in rarefaction.