RELATION BETWEEN SPECIES ASSEMBLAGES OF FISHES AND WATER QUALITY IN SALT PONDS AND SLOUGHS IN SOUTH SAN FRANCISCO BAY

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ABSTRACT—This study was conducted to characterize fishery resources inhabiting salt-evaporation ponds and sloughs in South San Francisco Bay, and to identify key environmental variables that influence distribution of fishes. The ponds, which were originally constructed and operated for commercial production of salt, have undergone preliminary modifications (installation of culverts, gates, and other water-control structures) in preparation for full restoration to mostly tidal wetlands over the next 2 decades. We sampled fish from two salt-pond complexes (Alviso complex and Eden Landing complex), each consisting of several pond systems and their associated sloughs. Cluster analysis of species of fish indicated that at least two species assemblages were present, one characteristic of ponds and the other characteristic of sloughs and slough-like ponds. The slough-like ponds exhibited water-quality conditions (especially salinity) that resembled conditions found in the sloughs. Pond fishes were represented by 12 species, whereas slough fishes were represented by 22 species. Except for bay pipefish (*Syngnathus leptorhynchus*), which was unique to ponds, all species present in ponds also were in sloughs and slough-like ponds. These results indicated that species of fish in ponds originated from the sloughs. According to canonical-discriminant analysis, four environmental variables were useful for discriminating between the two species assemblages. Most discriminatory power was contributed by the index of habitat connectivity, a measure of minimum distance that a fish must travel to reach a particular pond from the nearest slough. Apparently, as fish from sloughs enter and move through interconnected salt ponds, environmental stress factors increase in severity until only the more tolerant species remain. The most likely source of stress is salinity, because this variable was second in importance to the index of habitat connectivity in discriminating between the two species assemblages. Water temperature and concentration of dissolved oxygen also seemingly influenced spatial distribution of fishes, although they were less important than salinity.

RESUMEN—Este estudio fue conducido para caracterizar los recursos pesqueros en salinas y barrizales de la Bahía de San Francisco y para identificar las principales variables del medio ambiente que influencian la distribución de peces. Las salinas que fueron construidas y operadas originalmente para la producción de sal comercial han pasado por modificaciones preliminares (instalación de alcantarillas, esclusas, y otras estructuras para el control del agua) en preparación para su restauración total a humedales regulados por la marea durante las 2 próximas décadas. Colectamos peces en dos conjuntos de salinas (Alviso y Eden Landing), cada conjunto consistiendo de varios sistemas de salinas y barrizales asociados. El análisis de grupos de las especies de peces indicó que al menos dos ensamblajes de especies estuvieron presentes, uno característico de las salinas y otro de los barrizales y charcas parecidas a barrizales. Las charcas parecidas a barrizales presentaron condiciones de la calidad del agua (especialmente la salinidad) parecida a las condiciones encontradas en barrizales. Los peces de las salinas fueron representados por 12 especies mientras que los peces de los barrizales fueron representados por 22 especies. Excepto por el pez pipa de bahía (*Syngnathus leptorhynchus*), encontrado únicamente en las salinas, todas las especies presentes en las salinas también fueron encontradas en barrizales y en charcas parecidas a barrizales. Estos resultados indican que las especies de peces en las salinas se originaron en los barrizales. De acuerdo al análisis de discriminación canónica, cuatro variables del medio ambiente fueron útiles para la discriminación entre los dos ensamblajes de especies. El índice de conectividad de hábitat tuvo el poder discriminatorio más alto, una medida de la distancia mínima que un pez debe viajar para alcanzar una determinada salina desde el barrizal más cercano. Aparentemente, una vez que un pez procedente de un barrizal entra y atraviesa las salinas interconectadas, el pez experimenta factores estresantes que se intensifican hasta que sólo los peces más tolerantes de factores ambientales permanecen en dichas salinas. La fuente más importante de estrés es la salinidad, porque esta variable fue segunda en importancia al índice de conectividad de hábitat en discriminar entre los dos ensamblajes de especies. La temperatura del agua y la concentración de oxígeno disuelto también parecieron haber influido en la distribución espacial de los peces, aunque sus efectos fueron menos pronunciados que los de la salinidad.

Coastal salt ponds, sometimes referred to as salinas or solar saltworks, are shallow manmade depressions where seawater is trapped and allowed to evaporate until salts are crystallized and harvested for use by humans. Due to the universal need for salt, salt ponds are throughout the world, requiring only access to salty water and a climate that favors high evaporation rates (breezy conditions and a hot sun). By some estimates, commercial salt ponds produce as much as one-third of the worldwide production of salt, or ca. 63.5 million metric tons/year (Davis, 1999). However, in addition to its economic value, salt ponds are ecologically important as centers of biodiversity, with a growing number of countries especially in North America, Europe, and Australia now attempting to actively manage salt-pond systems as nature reserves and wildlife refuges.

The ecological importance of coastal salt ponds stems from their shallow depths and nutrient-rich waters, which attract high numbers of migratory shorebirds and waterfowl. Often times, due to loss of natural wetlands from anthropogenic activities, the salt ponds may be the only significant habitats remaining for such birds. This is largely the situation in San Francisco Bay, California, on the Pacific coast of North America. According to Nichols et al. (1986), over the past 150–200 years, >90% of original tidal marshes and mud flats in San Francisco Bay have been lost to diking, draining, and filling. In this highly urbanized estuary, the need to protect and manage remaining wetlands was so great that the San Francisco Bay National Wildlife Refuge was created in 1974. This refuge consists of a variety of habitats, including open bay, mud flats, salt marsh, and managed salt ponds.

Commercial salt production in San Francisco Bay began in the mid-1850s with conversion of natural marsh lands to salt-evaporation ponds (San Francisco Bay Conservation and Development Commission, in litt.; http://www.bcdc.ca.gov/pdf/planning/reports/salt_ponds.pdf). By 1959, salt production had increased to nearly 0.91 million metric tons from 16,605 ha of salt ponds (San Francisco Bay Conservation and Development Commission, in litt.). In 1965, >16,800 ha of salt ponds were held under private ownership in the Bay Area (San Francisco Bay Conservation and Development Commission, in litt.). However, beginning in the 1970s, public agencies began to acquire the privately owned salt ponds. In March 2003, a partnership of federal, state, and nonprofit agencies purchased nearly 6,116 ha of salt ponds from Cargill, Inc., to initiate the South San Francisco Bay Salt Pond Restoration Project (California Department of Fish and Game and United States Fish and Wildlife Service, in litt.; http://www.southbayrestoration.org/pdf_files/ISPJun2003.pdf). Under this project, the salt ponds are mostly destined for conversion to tidal wetlands over the next 2 decades. However, through 2006, the salt ponds were largely unchanged except that additional water-control structures were installed to allow better regulation of flows between the ponds and adjacent sloughs, or the bay.

A number of studies in the South San Francisco Bay salt ponds have pointed out the importance of these habitats to migratory shorebirds and waterfowl (e.g., Anderson, 1970; Warnock et al., 2002; Hickey et al., 2007). By comparison, little is known about fish that use the ponds and adjacent sloughs. Carpelan (1955, 1957) and Lonzarich and Smith (1997) listed several species of fish that they captured in a few salt ponds, but sampling effort in these studies was superficial. Although Orsi (1999) summarized findings from fish surveys conducted by the California Department of Fish and Game over a 15-year period in the South Bay, the sampling sites were located in offshore waters where environmental conditions can differ considerably from those found in inshore waters such as salt ponds and sloughs.

The purpose of the present study was to improve our understanding of fishery resources that use salt ponds and sloughs in South San Francisco Bay, and identify the key environmental variables that influence distribution of fish. Specific objectives were to document species assemblages of fishes in selected salt ponds and sloughs, and if two or more species assemblages were present, determine if the assemblages were associated with water quality or other environmental variables. Results from this study will serve as historic baseline information for assessing potential changes in species assemblages of fishes following completion of activities to restore salt ponds.

MATERIALS AND METHODS—*Study Area*—The study area consisted of two salt-pond complexes and associated sloughs in South San Francisco Bay—the Alviso complex in Santa Clara and Alameda counties, and the Eden Landing complex in Alameda County (Fig. 1). The Alviso complex is located ca. 16 km NW San Jose, whereas the Eden Landing complex is located ca. 8 km W Union City.

The Alviso complex contained seven pond systems (A2W, A3W, A7, A14, A16, island ponds, and A22), and the Eden Landing complex contained five pond systems (B2, B2C, B6A, B8A, and B11). In general, each pond system was composed of at least two ponds, an intake pond (receives water during high tide from a slough) and an outlet pond (discharges water during low tide into a slough or South San Francisco Bay). Intake and outlet ponds were designed to provide water circulation through each pond system to control water quality (especially high salinity) during the summer evaporation season. Outlet ponds also allowed drainage of excess water accumulated during heavy winter rains that would otherwise erode or damage the earthen levees. If more than two ponds were included in a pond system, the additional ponds were referred to as interior ponds because they received water from an intake pond and not directly from a slough.

Within the Alviso complex, we sampled six ponds as follows: pond A9 (intake pond), ponds A2E, A10, A11, and A12 (interior ponds), and pond A2W (outlet pond). In addition, we sampled Stevens Creek, Alviso Slough, and Coyote Creek. Within the Eden Landing complex, we sampled six ponds as follows: pond B1 (intake pond), ponds B4, B5, B6C, and B7 (interior ponds), and pond B2 (outlet pond; this pond also served as an inlet pond whenever resource managers needed dilution water from the bay to control high levels of salinity). We also sampled Coyote Hills Slough and Old Alameda Flood Control Channel.

Field Sampling—Field work began in March 2004 and continued at 3-month intervals through June 2005

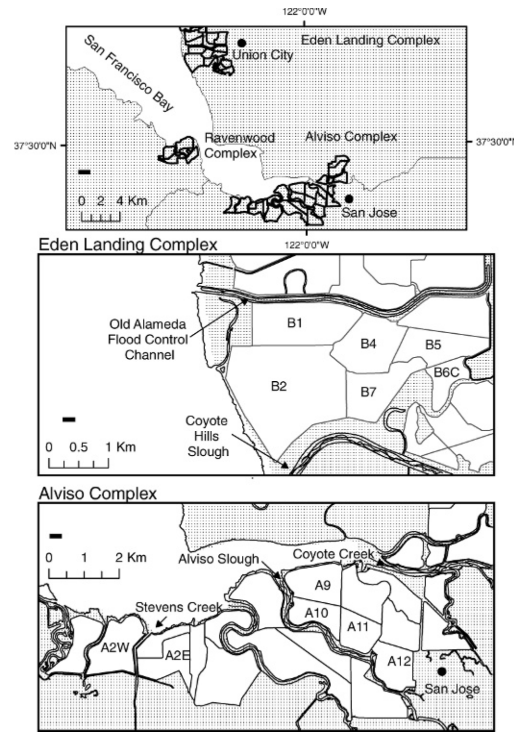

FIG. 1—Map of the study area showing locations of 17 salt ponds and sloughs in the Alviso and Eden Landing complexes, California.

at four fixed sites in each pond or slough. The sites were initially selected at random within a pond or located in a longitudinal (upstream-downstream) pattern within a slough such that the sites bracketed adjacent ponds.

Fish were sampled from each site with two floating variable-mesh monofilament gill nets fished for 2 h and five baited minnow traps fished for 1 h. Gill nets were 38-m long by 1.8-m deep, and consisted of square-mesh measuring 12.7, 25.4, 38.1, 50.8, and 63.5 mm (Nylon Net Company, Memphis, Tennessee). Minnow traps were 25.4-cm high, 25.4-cm wide, and 43.2-cm long, with 3.2-mm square mesh (AMT-F, Netco, LLC, Memphis, Tennessee). Each minnow trap was baited with fish-flavored canned cat food (Special Kitty Tuna Dinner Premium Cat Food, marketed by Wal-Mart Stores, Inc., Bentonville, Arkansas). Due to concerns over incidental take of steelhead trout (*Onchorhynchus mykiss*), a federally listed threatened species, we did not sample fish from sloughs in the Alviso and Eden Landing complexes in March 2004, and from sloughs in the Alviso complex in March 2005. Excessively shallow water prevented sampling in some ponds during September 2004 (ponds B2 and B4), November 2004 (pond B4), and June 2005 (ponds A2E, A9, B2, B4, B5, and B6C). In addition, minnow traps were not fished on a consistent basis until November 2004 (minnow traps were not used in March 2004 and only in sloughs and a few ponds during June 2004 and

September 2004). Sampling times in sloughs occurred only during slack high tide when velocity of current was negligible. By comparison, sampling times in ponds were not affected by tidal cycles.

At each site, captured fish were identified to species, counted, then either released alive or sacrificed by preservation in 99% isopropyl alcohol for verification of identification and to obtain other measurements. Water temperature, dissolved oxygen, pH, and salinity were measured at 1.0-m intervals from surface to bottom if the site was deeper than 2.0 m; otherwise, only surface readings were taken. Measurements were made with a Hydrolab DataSonde 3 multiprobe (Hach Environmental, Loveland, Colorado; http://www.hydrolab.com/) calibrated according to instructions provided by the manufacturer. Salinity was expressed as a dimensionless unit in accordance with the Practical Salinity Scale of 1978, which defines this variable as the conductivity ratio of a sample of sea water to a standard solution of potassium chloride (United Nations Educational, Scientific, and Cultural Organization, 1981).

Fish require an unobstructed aquatic corridor (e.g., a channel, culvert, siphon tube, or tidal gate) to move from a slough into an adjoining pond system, or from a pond system into a slough or the bay. During our study, water from sloughs (source water) typically circulated through pond systems by first flowing into an intake pond at high tide, then moving by gravity or pumps through one or more interior ponds until reaching an outlet pond. From the outlet pond, water discharged into a receiving slough or the bay during low tide by flowing through a one-way tidal gate that opened only during falling tides. To assess influence of habitat connectivity on composition of species, we assumed that accessibility of a particular habitat was inversely related to distance that fish had to travel to reach that habitat. To generate an index of habitat connectivity for a particular slough or pond, we designated the nearest culvert or channel linking a slough to an intake pond as the reference point, then measured the shortest unobstructed distance from this reference point to the culvert, channel, or siphon tube of a downslope pond. Thus, during our study, values for index of habitat connectivity ranged from zero (maximum connectivity; characteristic only of source-water sloughs) to 3.3 km (minimal connectivity; characteristic of a downslope pond located a considerable distance from its source-water slough).

Statistical Analyses—Chi-square analysis of counts of the eight most abundant species–leopard shark (*Triakis semifasciata*), northern anchovy (*Engraulis mordax*), topsmelt (*Atherinops affinis*), rainwater killifish (*Lucania parva*), Pacific staghorn sculpin (*Leptocottus armatus*), striped bass (*Morone saxatilis*), yellowfin goby (*Acanthogobius flavimanus*), and longjaw mudsucker (*Gillichthys mirabilis*)–plus a general category consisting of all other species combined, was used to determine if proportions of species differed among catches by gill nets and minnow traps. Cluster analysis was used to identify species assemblages, whereas discriminant analysis was used to determine if species assemblages were associated with selected environmental variables (Green and Vascotto, 1978). Ward's method of cluster analysis was performed by using presence-absence data. According to Jackson and Harvey (1997), use of presence-absence data obtained with multiple gears fished in a variety of habitats is more likely to yield unbiased information on structure of fish communities than data on relative abundance obtained with a single gear. The number of significant clusters was determined by plotting semi-partial R^2-values with their corresponding cluster numbers, where the number of significant clusters corresponded to the largest observed reduction in semi-partial R^2-values (Khattree and Naik, 2000). Canonical-discriminant analysis was conducted with logarithmically transformed means of the index of habitat connectivity and water-quality variables. Pearson's product-moment correlations were used to identify and select intercorrelated environmental variables for exclusion from the canonical-discriminant analysis.

All statistical computations were conducted with SAS software for Windows, version 9.1 (SAS Institute, Inc., Cary, North Carolina). In general, results of statistical tests were deemed significant when $P \leq 0.05$. However, the Bonferroni correction ($P = 0.05/n$, where n = number of simultaneous comparisons) was used to determine significance during correlation analysis of environmental variables.

RESULTS—A total of 5,142 fish represented by 16 families and 23 species was examined during this study (Table 1). Gill nets yielded 4,289 fish and 18 species, whereas minnow traps yielded 853 fish and 9 species.

Selectivity of gear was evident in the combined-catch statistics from salt ponds and sloughs. Proportions of captured species differed significantly between gill nets and minnow traps (χ^2 = 4,595.4, $df = 8$, $P < 0.001$), with gill nets catching mostly topsmelt (65.1%), northern anchovy (20.1%), and leopard shark (6.6%), and minnow traps catching mostly longjaw mudsuckers (45.7%) and rainwater killifish (40.2%).

Distribution of Fish—Topsmelt was the most ubiquitous species, occurring in all ponds and sloughs (Table 2). Northern anchovy, striped bass, and yellowfin goby occurred in all sloughs, but were not captured in one or more ponds. Several species were not captured in ponds (e.g., threadfin shad, *Dorosoma petenense*; common carp, *Cyprinus carpio*; Sacramento sucker, *Catostomus occidentalis*; longfin smelt, *Spirinchus thaleichthys*; and shimofuri goby, *Tridentiger bifasciatus*), whereas other species were not captured in sloughs (e.g., Pacific herring, *Clupea pallasii*; and bay pipefish, *Syngnathus leptorhynchus*). Alviso Slough was unique in supporting several freshwater species (threadfin shad, common carp, and Sacramento sucker) that were not captured elsewhere during this study.

TABLE 1—Number (n) and percent (%) of fishes captured with gill nets and minnow traps from the Alviso and Eden Landing complexes, California, March 2004–June 2005.

			Gill net		Minnow trap	
Family[a]	Species	Common name	n	%	n	%
Triakidae	*Triakis semifasciata*	Leopard shark (native)	282	6.6	0	0.0
Myliobatidae	*Myliobatis californica*	Bat ray (native)	3	0.1	0	0.0
Engraulidae	*Engraulis mordax*	Northern anchovy (native)	862	20.1	0	0.0
Clupeidae	*Alosa sapidissima*	American shad (introduced)	46	1.1	0	0.0
	Clupea pallasii	Pacific herring (native)	15	0.4	0	0.0
	Dorosoma petenense	Threadfin shad (introduced)	2	<0.1	0	0.0
Cyprinidae	*Cyprinus carpio*	Common carp (introduced)	1	<0.1	0	0.0
Catostomidae	*Catostomus occidentalis*	Sacramento sucker (native)	3	0.1	0	0.0
Osmeridae	*Spirinchus thaleichthys*	Longfin smelt (native)	6	0.1	0	0.0
Atherinopsidae	*Atherinops affinis*	Topsmelt (native)	2,793	65.1	9	1.1
	Atherinopsis californiensis	Jacksmelt (native)	3	<0.1	0	0.0
	Menidia audens	Mississippi silverside (introduced)	0	0.0	6	0.7
Fundulidae	*Lucania parva*	Rainwater killifish (introduced)	0	0.0	343	40.2
Gasterosteidae	*Gasterosteus aculeatus*	Threespine stickleback (native)	0	0.0	2	0.2
Syngnathidae	*Syngnathus leptorhynchus*	Bay pipefish (native)	1	<0.1	0	0.0
Cottidae	*Leptocottus armatus*	Pacific staghorn sculpin (native)	48	1.1	5	0.6
Moronidae	*Morone saxatilis*	Striped bass (introduced)	107	2.5	0	0.0
Embiotocidae	*Cymatogaster aggregata*	Shiner perch (native)	24	0.6	0	0.0
Gobiidae	*Acanthogobius flavimanus*	Yellowfin goby (introduced)	72	1.7	93	10.9
	Clevelandia ios	Arrow goby (native)	0	0.0	4	0.5
	Gillichthys mirabilis	Longjaw mudsucker (native)	10	0.2	390	45.7
	Tridentiger bifasciatus	Shimofuri goby (introduced)	0	0.0	1	0.1
Pleuronectidae	*Platichthys stellatus*	Starry flounder (native)	11	0.3	0	0.0
		Total	4,289	100.0	853	100.0

[a] Although not caught with gill nets and minnow traps, the chameleon goby (*Tridentiger trigonocephalus*) was captured during supplemental sampling with a bag seine in ponds B1, B2, and B4.

Assemblages of Fish—According to cluster analysis, the 17 sampling sites were divided into two major clusters or groups (Fig. 2). The existence of two groups was suggested by a plot of semipartial R^2-values, which exhibited a maximum rate of change at the two-cluster location (Fig. 3). Group 1 was composed entirely of ponds (A10, B2, B6C, A11, A2E, A12, B4, B5, and B7) whereas Group 2 was composed of a mix of ponds (A2W, A9, and B1) and sloughs (Old Alameda Creek Flood Control Channel, Coyote Hills Slough, Stevens Creek, Alviso Slough, and Coyote Creek).

Fish in Group 1 were represented by 12 species of which 3 were native, whereas fish in Group 2 were represented by 22 species of which 8 were native. The proportions of native and introduced species in these two groups were not significantly different ($\chi^2 = 0.458$, $df = 1$, $P = 0.499$). Except for bay pipefish, which was unique to Group 1, all species found in Group 1 also were present in Group 2. Thus, Group 1 included northern anchovy, Pacific herring, topsmelt, jacksmelt (*Atherinopsis californiensis*), Mississippi silverside (*Menidia audens*), rainwater killifish, bay pipefish, Pacific staghorn sculpin, yellowfin goby, arrow goby (*Clevelandia ios*), longjaw mudsucker, and starry flounder (*Platichthys stellatus*). By comparison, Group 2 did not contain bay pipefish, but included all other species plus leopard shark, bat ray (*Myliobatis californica*), American shad (*Alosa sapidissima*), threadfin shad, common carp, Sacramento sucker, longfin smelt, threespine stickleback (*Gasterosteus aculeatus*), striped bass, shiner perch (*Cymatogaster aggregata*), and shimofuri goby.

Water Quality and Other Environmental Variables—Water quality varied considerably among the 17 sampling sites, with larger variations generally occurring in salt ponds than in sloughs (Fig. 4). On average, water temperatures were higher in the Alviso complex than in the Eden Landing complex, whereas concentrations of dissolved oxygen were higher in the Eden

TABLE 2—Occurrence of fish (+ = present; − = absent) in various ponds and sloughs within the Alviso and Eden Landing complexes, California, March 2004–June 2005: ALV, Alviso Slough; COY, Coyote Creek; CHI, Coyote Hills Slough; OAF, Old Alameda Flood Control Channel; and STE, Stevens Creek.

	Alviso complex									Eden Landing complex							
	Pond						Slough			Pond						Slough	
Fish	A2E	A2W	A9	A10	A11	A12	STE	ALV	COY	B1	B2	B4	B5	B6C	B7	CHI	OAF
Leopard shark	−	+	+	−	−	−	+	−	−	+	−	−	−	−	−	+	+
Bat ray	−	+	−	−	−	−	−	−	+	−	−	−	−	−	−	−	+
Northern anchovy	+	+	−	+	+	+	+	+	+	+	+	+	+	−	+	+	+
American shad	−	−	−	−	−	−	+	+	+	+	−	−	−	−	−	+	−
Pacific herring	−	+	−	−	−	−	−	−	−	+	−	−	−	−	+	−	−
Threadfin shad	−	−	−	−	−	−	−	+	−	−	−	−	−	−	−	−	−
Common carp	−	−	−	−	−	−	−	+	−	−	−	−	−	−	−	−	−
Sacramento sucker	−	−	−	−	−	−	−	+	−	−	−	−	−	−	−	−	−
Longfin smelt	−	−	−	−	−	−	−	+	+	−	−	−	−	−	−	−	−
Topsmelt	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Jacksmelt	−	−	−	+	−	−	−	−	−	−	−	−	−	−	−	−	+
Mississippi silverside	+	+	−	−	+	−	−	−	−	−	−	−	−	+	−	−	−
Rainwater killifish	+	+	+	+	+	+	−	+	+	+	−	+	−	−	+	−	+
Threespine stickleback	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	+	+
Bay pipefish	−	−	−	−	−	−	−	−	−	−	−	−	−	−	+	−	−
Pacific staghorn sculpin	+	+	+	−	+	+	−	+	+	+	−	+	+	−	+	+	+
Striped bass	−	−	+	−	−	−	+	+	+	−	−	−	−	−	−	+	+
Shiner perch	−	+	+	−	−	−	−	−	+	−	−	−	−	−	−	+	+
Yellowfin goby	+	+	+	+	+	+	+	+	+	+	+	+	+	−	+	+	+
Arrow goby	−	+	−	−	+	−	−	−	−	−	−	−	−	−	−	−	−
Longjaw mudsucker	+	+	+	+	+	+	+	+	−	−	+	+	+	+	+	+	+
Shimofuri goby	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	+
Starry flounder	−	−	+	−	−	−	−	−	+	+	+	−	−	−	−	−	−

Landing complex than in the Alviso complex. Generally, pH-values were higher in ponds than in sloughs, with larger variations occurring in the Eden Landing complex (especially pond B1) than in the Alviso complex. Mean salinities varied between ponds and sloughs, with higher values typically occurring in ponds (in some Eden Landing ponds, salinities exceeded 90 in March 2004) than in sloughs.

Seasonal patterns were observed for water temperature and concentration of dissolved oxygen, with highest temperatures and lowest concentrations of dissolved oxygen typically occurring during summer or early autumn. By comparison, pH and salinity did not exhibit recognizable seasonal patterns.

Relation Between Species Assemblages and Environmental Variables—Canonical-discriminant analysis was conducted with environmental variables, such as index of habitat connectivity, water temperature, dissolved oxygen, and salinity. Hydrogen-ion concentration (pH) was excluded from the canonical-discriminant analysis because this variable was moderately intercorrelated with index of habitat connectivity ($r = 0.77$, $P < 0.001$) and salinity ($r = 0.73$, $P < 0.001$), indicating that its contribution to the canonical-discriminant analysis would have mostly duplicated contributions by the other two variables. According to canonical-discriminant analysis, the Wilks' lambda statistic was significant ($\lambda = 0.20$, $F_{4,\ 12} = 11.77$, $P < 0.001$); thus, the canonical-discriminant-analysis model was useful for discriminating between the two groups of salt ponds and sloughs (Fig. 5). Moreover, the canonical-discriminant analysis correctly classified ponds and sloughs into their respective groups.

Mean values for index of habitat connectivity and salinity differed significantly between the

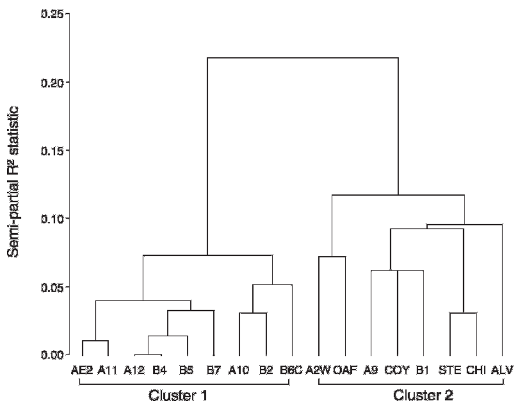

FIG. 2—Dendrogram for cluster analysis (Ward's minimum-variance method) of presence-absence data for 23 species of fish from 17 sampling sites in California: ALV, Alviso Slough; COY, Coyote Creek; CHI, Coyote Hills Slough; OAF, Old Alameda Flood Control Channel; and STE, Stevens Creek.

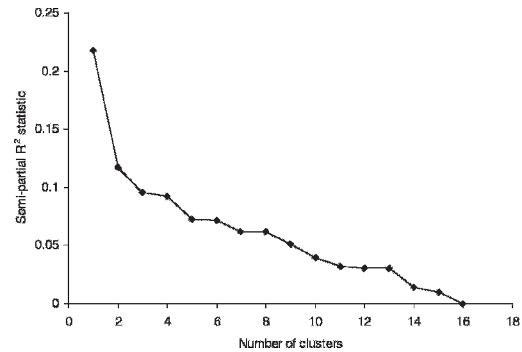

FIG. 3—Plot of semi-partial R^2-values and number of clusters. In this study, the significant number of clusters, which corresponds to the largest reduction in semi-partial R^2-values, occurred at the two-cluster level.

two groups, whereas mean values for temperature and dissolved oxygen were not significantly different (Table 3). Nevertheless, according to their standardized-canonical coefficients, all four environmental variables collectively contributed toward differentiating between the two groups, with index of habitat connectivity being most important, followed by salinity, then by dissolved oxygen, and lastly by temperature.

DISCUSSION—During 1980–1995, extensive surveys were conducted by the California Department of Fish and Game in open-water areas of the San Francisco Estuary from the Sacramento-San Joaquin Delta downstream to San Francisco Bay (Orsi, 1999). These surveys yielded at least 126 species of freshwater, estuarine, and marine fish, including anadromous taxa. However, relatively little is known about species of fish inhabiting shallow shoreline habitats such as salt ponds and tidally influenced reaches of sloughs in the South Bay. Until now, these shoreline habitats have been largely overlooked by fishery managers because they are difficult to sample with conventional fish-collecting gear, and public access by road is almost nonexistent (which detracts from use by visitors, especially by fishermen and others who might be interested in the fishery resources). Carpelan (1957) reported that topsmelt, threespine stickleback, Pacific staghorn sculpin, and longjaw mudsucker were captured in the Alviso salt ponds during sampling trips made in 1951. In addition, Lonzarich and Smith (1997) collected 15 species of fish from the Alviso salt ponds during 1985–1986, of which only two (bay goby, *Lepidogobius lepidus*; and English sole, *Parophrys vetulus*) were not caught during our study. In June 2002, cursory collections with variable-mesh gill nets in Alviso Slough and Coyote Creek yielded large numbers of northern anchovy and topsmelt, along with smaller numbers of Sacramento sucker and striped bass (B. A. Martin, in litt.).

A handful of surveys conducted in salt ponds and sloughs elsewhere in San Francisco Bay documented several of the same species of fish that we found in salt ponds of South Bay (e.g., Wild, 1969; Woods, 1981; Takekawa et al., 2006; Visintainer et al., 2006; K. A. Hieb, in litt.). In Hayward Marsh, leopard shark and topsmelt were the most abundant species caught with gill nets, whereas threespine stickleback and longjaw mudsucker were the most abundant species caught with minnow traps (Woods, 1981). Collections with a specially designed trap in Plummer Creek yielded mostly topsmelt (Wild, 1969). Beach-seining in various localities within the South Bay during 1980–1987 captured mostly northern anchovy, topsmelt, and jacksmelt (K. A. Hieb, in litt.). Northern anchovy also constituted most of the midwater-trawl catch during 1980–1999, whereas a more diverse catch was reported for otter trawls fished during the same time (>50% of the catch was composed of white croaker, *Genyonemus lineatus*; shiner perch; bay goby; and English sole; K. A. Hieb, in litt.). In several Napa-Sonoma salt ponds located in North

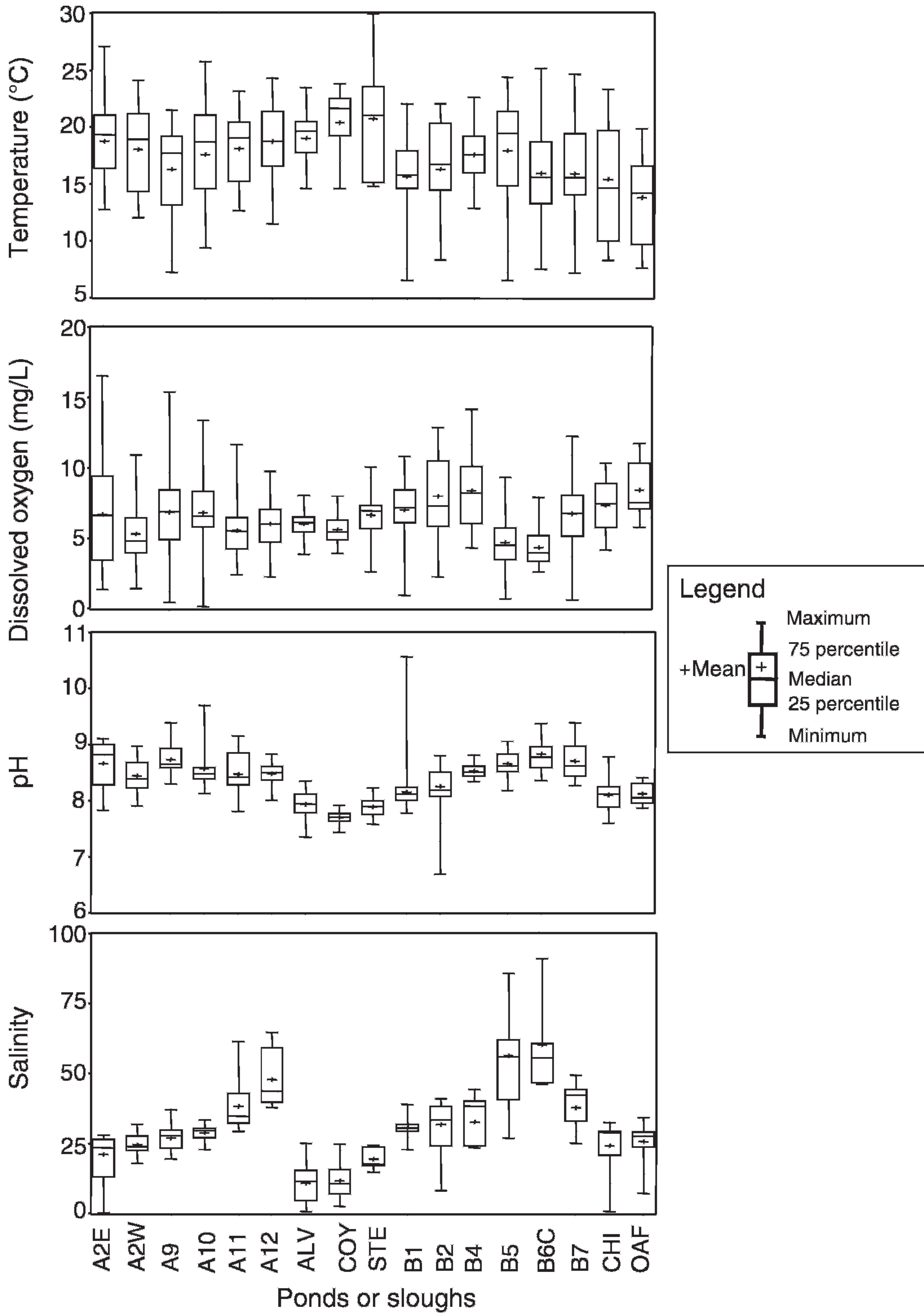

FIG. 4—Box plots of water temperature, concentration of dissolved oxygen, pH, and salinity measured on six occasions during March 2004–June 2005: ALV, Alviso Slough; COY, Coyote Creek; CHI, Coyote Hills Slough; OAF, Old Alameda Flood Control Channel; and STE, Stevens Creek.

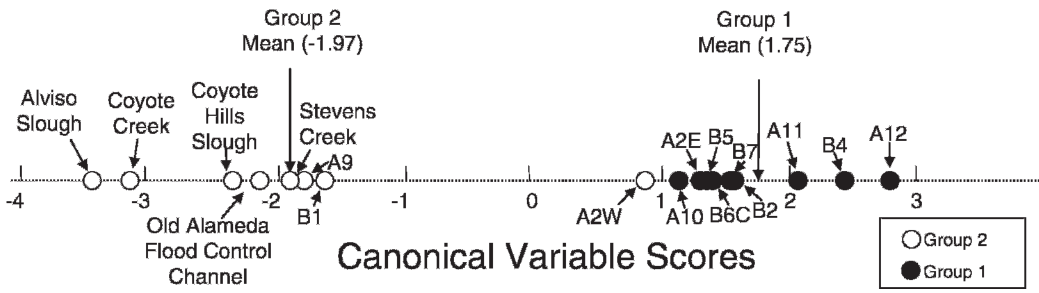

Fig. 5—Results of canonical-discriminant analysis for two groups of salt ponds and sloughs determined by cluster analysis. Canonical-discriminant analysis was conducted with the following environmental variables: index of habitat connectivity (IHC); water temperature; dissolved oxygen; and salinity. All 17 ponds or sloughs were correctly classified into their assigned groups (i.e., there was no misclassification).

San Francisco Bay, sampling with gill nets and bag seines yielded a total of 16 species of fish (Takekawa et al., 2006). According to Takekawa et al. (2006), gill nets captured mostly American shad, striped mullet (*Mugil cephalus*), striped bass, yellowfin goby, and longjaw mudsucker, whereas bag seines captured mostly Mississippi silverside (identified by these authors as inland silverside, *Menidia beryllina*; however, according to K. A. Hieb, in litt., taxonomic criteria given by Suttkus et al., 2005, indicates that only the Mississippi silverside occurs in the San Francisco Estuary), Pacific staghorn sculpin, yellowfin goby, longjaw mudsucker, and shimofuri goby. In China Camp Marsh, also located in the North Bay, sampling with modified fyke nets yielded 22 species, but >75% of the catch (reported as numbers of individuals) was comprised of three species–topsmelt (50.2%), Mississippi silverside (identified as inland silverside, 13.4%), and Pacific staghorn sculpin (14.9%; Visintainer et al., 2006).

Cluster analysis of presence-absence data from our study indicated that at least two species assemblages were present in salt ponds and sloughs in South San Francisco Bay, one consisting of species characteristic of ponds and another consisting of species characteristic of sloughs. Nevertheless, differences between species assemblages in ponds and sloughs were subtle because several ponds (e.g., A2W, A9, and B1) were clustered with the sloughs. Inspection of our catch data indicated that inclusion of ponds A2W, A9, and B1 with sloughs was due to presence of one or more species (e.g., leopard shark, bat ray, American shad, striped bass, and shiner perch) characteristic of the species assemblage of sloughs.

The species assemblage characteristic of salt ponds consisted of 12 species, whereas the assemblage characteristic of sloughs consisted of 22 species, including 11 species characteristic of ponds. These results strongly suggest that pond species were derived from the larger array

Table 3—Summary of results from canonical-discriminant analysis for two groups of sampling sites. Geometric means (95% confidence intervals in parentheses), *F*-statistics, *P*-values, and standardized canonical coefficients are shown for each environmental variable.

Environmental variable	Group 1 (n = 9)	Group 2 (n = 8)	$F_{1,\ 15}$	P	Standardized canonical coefficient[a]
Water temperature (°C)	17.08 (16.19–18.02)	17.35 (15.62–19.26)	0.10	0.752	0.306
Dissolved oxygen (mg/L)	6.33 (5.36–7.49)	6.58 (5.90–7.34)	0.19	0.672	0.361
Salinity	37.96 (29.11–49.50)	20.81 (14.95–28.95)	11.22	0.004	0.575
Index of habitat connectivity (km)	1.37 (0.90–2.07)	0.02 (0.004–0.09)	48.14	<0.001	0.865
Mean canonical variable	1.75	−1.97			

[a] Standardized canonical coefficients indicate the importance of environmental variables to the overall canonical-discriminant analysis.

of slough species. Moreover, these findings indicate that environmental limiting factors probably are preventing some species in sloughs from colonizing ponds.

According to canonical-discriminant analysis, four environmental variables were useful in discriminating between the species assemblage characteristic of salt ponds and sloughs. The variable contributing the most discriminatory power was index of habitat connectivity (standardized canonical coefficient = 0.865). Apparently, as fish from sloughs enter and move through a pond system, environmental stress factors progressively increase in severity until only the more tolerant species remain. The most likely source of stress is salinity, because this variable was second in importance to index of habitat connectivity in discriminating between the pond species assemblage and the slough species assemblage (standardized canonical coefficient = 0.575). Concentration of dissolved oxygen (standardized canonical coefficient = 0.361) and water temperature (standardized canonical coefficient = 0.306) also seemingly influenced spatial distribution of fishes, although their effects were less important than salinity.

Previous studies indicated that some species can reproduce successfully in salt ponds of South San Francisco Bay. For example, Carpelan (1955) noted that eggs of topsmelt hatched successfully in water from the Alviso ponds at salinities as high as 72. Lonzarich and Smith (1997) also reported evidence of natural reproduction by rainwater killifish in Alviso ponds where salinities averaged 55. However, even in absence of reproduction, some species might populate ponds by passing through culverts and channels from adjacent sloughs. For example, anecdotal evidence strongly suggests that leopard sharks move from Charleston Slough into ponds A1 and A2W by traversing culverts and siphons that link these habitats (P. Malpelli, pers. comm.). In Mugu Lagoon, a small estuary in southern California, gray smoothhound (*Mustelus californicus*), a species similar to leopard shark, also commonly were observed passing through culverts that linked the western basin with the greater lagoon (Saiki, 1997).

In South San Francisco Bay, habitat connectivity is an especially important determinant of species composition in salt ponds. Long-term persistence of species in these ponds probably is dependent on a continuous influx of recruits from adjacent sloughs and the greater San Francisco Bay area. As distance from sloughs increases, fewer species of fish are able to successfully colonize a given salt pond. Thus, intake ponds (e.g., ponds A9 and B1) often exhibit a species assemblage that is characteristic of sloughs. Environmental conditions, especially salinity, in intake ponds are also most similar to those found in sloughs. By comparison, interior and outlet ponds often exhibit a species assemblage that diverges from that in sloughs, mainly by excluding species that cannot tolerate hypersaline conditions. Pond A2W was exceptional because this outlet pond supported a species assemblage and environmental conditions similar to the sloughs. We suspect the slough-like environmental conditions in pond A2W are associated with an unusually high flushing rate from Charleston Slough (facilitated by a 1.5-m diameter gate connecting the slough to pond A1 and a 1.8-m diameter siphon connecting pond A1 to pond A2W) that prevented elevated salinities and other potentially stressful water-quality conditions (Fig. 4).

Although beyond the scope of our study, other unmeasured environmental variables and ecological interactions (e.g., depth of water, composition of substrate, complexity of channel, predator-prey relations) might influence composition of species assemblages in South San Francisco Bay. In North San Francisco Bay, Visintainer et al. (2006) determined that complexity of tidal channel within China Camp Marsh, particularly presence of low-order and high-order channel systems, influenced species composition, abundance of fish, and diets of fish. In Western Australia, Molony and Parry (2006) argued that even salt-tolerant predators eventually can be eliminated from solar salt ponds if they experience starvation following loss of their prey base from high salinities.

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