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DISSOLVED OXYGEN IN SOUTH SAN FRANCISCO BAY: VARIABILITY, IMPORTANT PROCESSES, AND IMPLICATIONS FOR UNDERSTANDING FISH HABITAT

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ABSTRACT

Dissolved oxygen (DO) is a key water quality parameter that is related to nutrient enrichment in estuaries around the world. In 2017-2018, the San Francisco Estuary Institute (SFEI) launched a study to investigate the potential effects of low-DO on habitat quality in Lower South Bay (LSB) to inform decisions about nutrient regulation. The goal of the study was to understand where and when regions of LSB provide adequate DO to support resident fish species. The study approach involved convening a team of experts to advise on methods, analyzing high frequency DO measurements from seven mooring stations in LSB, and partnering with researchers from UC Davis to interpret several years of monthly fish abundance data in LSB relative to DO and other factors.

Analysis of high-frequency measurements indicates that low DO concentrations occur in LSB and likely originate in sloughs and other perimeter habitats. In particular, sloughs that receive treated wastewater or pond discharge with elevated organic matter have higher oxygen demand. As a result, water in the sloughs is depleted of its DO as it is transported through the estuary by diurnal tides. DO concentrations typically meet the Basin Plan water quality objective of 5 mg/L in the deep channels. However, in the sloughs, DO concentrations fell below 5 mg/L for 11-65% of the observations throughout the year and as much as 90% of the summer months at some stations. At most stations, it appears that low-DO events occur on rapid time scales that are consistent with the major drivers of tidal advection and diurnal factors. Excursions below 5 mg/L were typically the shortest at the Dumbarton Bridge (1-2 hours) and longest in Guadalupe Slough (7-20 hours). Certainly, the high-frequency measurements provided useful insights into DO concentrations in LSB. However, there is still a major data gap, which is knowing the DO concentrations at other locations in LSB which may have more important fish habitat than at the mooring stations.

Cumulative catch curves and generalized additive models were used to examine relationships between the abundances of 12 fish species and water quality metrics (DO, temperature, salinity, clarity) in the LSB, providing insights regarding potential drivers of species abundance patterns and whether hypoxia appears to limit fish abundance within the system. Our results suggest that most species abundances responded strongest to seasonal variation in temperature and salinity, and to a lesser extent, variation in DO and water clarity. However, DO co-varied with temperature and season, thus complicating assessment of its individual effects. Cumulative catches as functions of DO indicated that different species exhibit positive, negative, or neutral responses to DO; therefore, fishes in the LSB exhibit diverse responses to variation in DO, likely driven by a variety of potential mechanisms (e.g., physiology, population dynamics, and ecological interactions). Though species-habitat relationships provide important inferences regarding habitat quality, such studies alone cannot resolve the true mechanisms behind observed patterns. Mechanistic models of DO concentrations throughout LSB and additional analyses and targeted studies of fish responses to environmental conditions would be needed to advance our

understanding of the drivers of abundance and the relative importance of hypoxia to AMC fish communities.

Alternative approaches for deriving protective thresholds for DO in LSB are also possible. For example, it is possible to develop site-specific DO objectives for LSB using the Virginian Province Approach (USEPA 2000). This approach uses information on the species of fish of management interest in LSB and a database of species-specific tolerances to derive protective thresholds. Another approach would be to investigate the link between temperature, DO and the metabolic requirements of fish. Increasing temperature reduces oxygen solubility and increases respiratory oxygen demand, and could therefore lead to habitat compression for fish species in the San Francisco Bay. Predictions of fish responses to increasing temperature can be developed based on the thermal tolerances of target species and DO conditions.

CHAPTER 1

INTRODUCTION

San Francisco Bay (SFB) is the largest estuary on the west coast of California and is home to over 7 million people (Figure 1). The Bay is rimmed with 42 publicly owned wastewater treatment facilities that collectively discharge approximately 450 million gallons of treated waste into the bay daily. The estuary has been described as a nutrient-enriched water body, with large inputs of nitrogen and phosphorus from both urban and agricultural sources. However, unlike other estuaries with comparable levels of nutrient loads, the SFB has not suffered the same degree of eutrophication impacts (Cloern and Jassby 2012). This ecosystem resilience to excess nutrients is likely facilitated by several biological and physical processes such as high filtration rates by suspension-feeding bivalves, light limitation from suspended sediments, and strong turbulent mixing of the water column (Cloern 1982, 1999, Cloern and Jassby 2012). However, recent monitoring has revealed some water quality conditions in the Bay that have been associated with nutrient over-enrichment in other estuaries (e.g., recurring low dissolved oxygen in some margin habitats and consistent detection of multiple toxins produced by harmful algae). There have also been recent fluctuations in the abundances of phytoplankton, invertebrates, and fishes (Cloern et al. 2007; Sommer et al. 2007, Baxter et al. 2010, Cloern and Jassby 2012, Crauder et al. 2016, Feyrer et al. 2015). Growing concern over high nutrient loads from wastewater and changing ecosystem responses has spurred efforts to understand the effects of nutrients on water quality in the Bay through the San Francisco Bay Nutrient Management Strategy (http://sfbaynutrients.sfei.org/). Low dissolved oxygen (DO) is one of the focus areas of this strategy as it is an important indicator of habitat quality and eutrophication.

Excess nutrients resulting in algal blooms and subsequent hypoxia can have profound effects on the abundance and diversity of estuarine communities including fish (Bowen and Valiela 2001; Breitburg 2002; Brietburg et al. 2009; Wazniak and Glibert 2004). Hypoxia can be characterized based on the frequency, duration, and intensity of low oxygen events, all of which may affect the responses of fishes and sessile fauna (Diaz and Breitberg 2009). Events that are infrequent but large in magnitude and duration can cause mass mortality of sessile fauna and fish, while shorter but persistent events can lead to fish avoidance of habitats, and reduced growth and reproductive output of fauna utilizing the impacted habitats. More profound impacts on fish populations may occur when frequent hypoxia occurs in fish nursery habitats reducing overall population replenishment (Coutant 1990, 2012; Breitberg et al. 2009; Kemp et al. 2005). Frequently occurring hypoxic events are most often associated with diel productivity cycling, which is driven by oxygen production during daylight by photosynthesizing algae and subsequent consumption at night. Therefore, when assessing hypoxia, it is important to characterize the frequency, duration, and intensity of low-DO events.

In many estuaries and coastal systems, frameworks have been established to assess DO-related condition and inform management decisions aimed at lessening the severity and frequency of low-DO events (Devlin et al. 2011). In some estuaries, low-DO events occur due to natural processes, and well-adapted resident biota employ a variety of strategies to limit physiological effects from inhospitable conditions. In other cases, high nutrient loads and excessive primary production introduce low oxygen or hypoxic (<2 mg/L, <~30% saturation) zones that adversely impact resident biota that are poorly-adapted to such conditions. Parsing natural and anthropogenic DO dynamics requires an understanding of the spatial extent, temporal duration, and mechanisms driving low-DO events in an estuary. Insight into how resident fish react to low DO can come from studies that observe their behavioral or physiological responses to varying DO levels either in the wild or in controlled experiments. Both approaches have strengths and limitations but offer complementary information.

Presently in SFB, the Regional Water Quality Control Board's Basin Plan has specified a DO objective for all tidal waters down-estuary of the Carquinez Bridge of 5 mg/L and > 80% DO saturation for the running three-month median in any SFB sub-embayment (SFBRWQCB 2017). While waters in SFB's deep, subtidal habitats generally satisfy this DO objective, early data from some habitats in Lower South Bay (LSB, Figure 2) suggest that DO levels frequently fall below 5 mg/L (Crauder et al. 2016; Sutula, et al. 2017; Senn and Novick 2014). Initial work on identifying nutrient-related science priorities in SFB identified expanded DO monitoring and improved understanding of habitat utilization by biota in LSB sloughs as important data gaps. These priorities prompted deployment of moored sensors to characterize DO-related condition in LSB and fish trawl studies.

The goal of this document is to present analyses of the moored sensor and fish catch datasets across diverse habitats in LSB to understand where and when regions of LSB provide adequate DO to support resident fish species. The first part is an analysis of continuous measurements by moored sensors of DO, temperature, salinity, and tidal stage at seven LSB locations made by the San Francisco Estuary Institute (SFEI). These data provide insights into the trends and variability of DO in the system (Chapter 2). The second part is a summary of recent work by the University of California Davis (UCD), in which fish abundances and co-located instantaneous measurements of water quality were used to assess preferred water quality conditions for 12 species of LSB fishes (Chapter 3). UCD also constructed a statistical model of fish abundance based on water quality conditions to predict water quality conditions corresponding to low and high abundance for the focus species.

These analyses contribute to answering one of the priority questions of the Nutrient Management Strategy (NMS) Science Plan: “What conditions in different San Francisco Bay habitats would indicate that beneficial uses[1] are being protected versus experiencing nutrient-related impairment?” The report closes with an overview of remaining uncertainties or data gaps, and proposed approaches for how these gaps could be addressed.

[1] The definition of beneficial uses is provided in the Basin Plan for San Francisco Bay, https://www.waterboards.ca.gov/sanfranciscobay/water_issues/programs/planningtmdls/basinplan/web/bp_ch2.html.

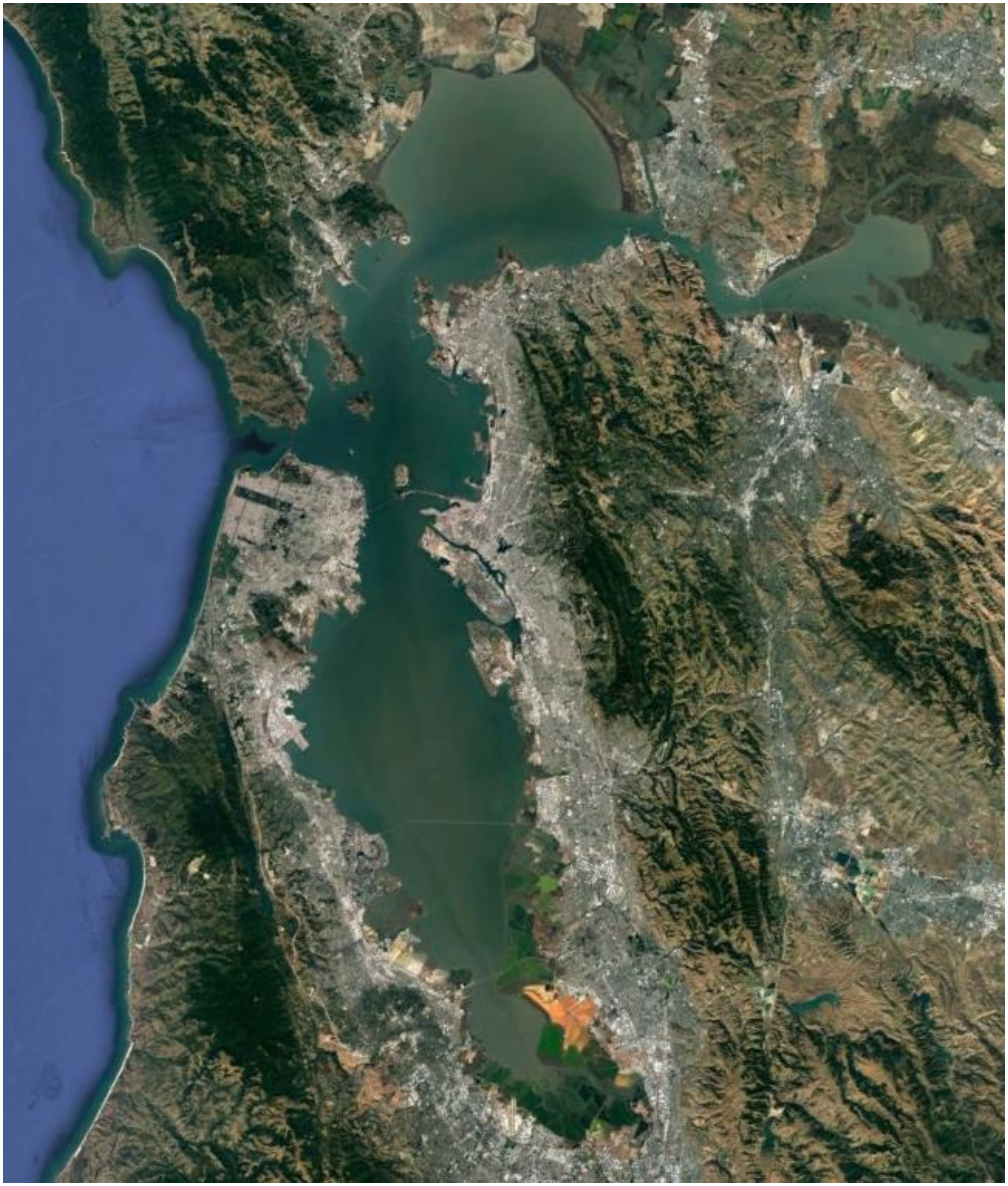

Figure 1: San Francisco Bay in California, USA. Lower South Bay is south of the southernmost bridge. Freshwater inflow enters the Bay from the Sacramento-San Joaquin Delta to the east and a series of smaller rivers that surround the Bay. Tidal exchange with the ocean occurs through the Golden Gate (37°48' N, 122°30' W).

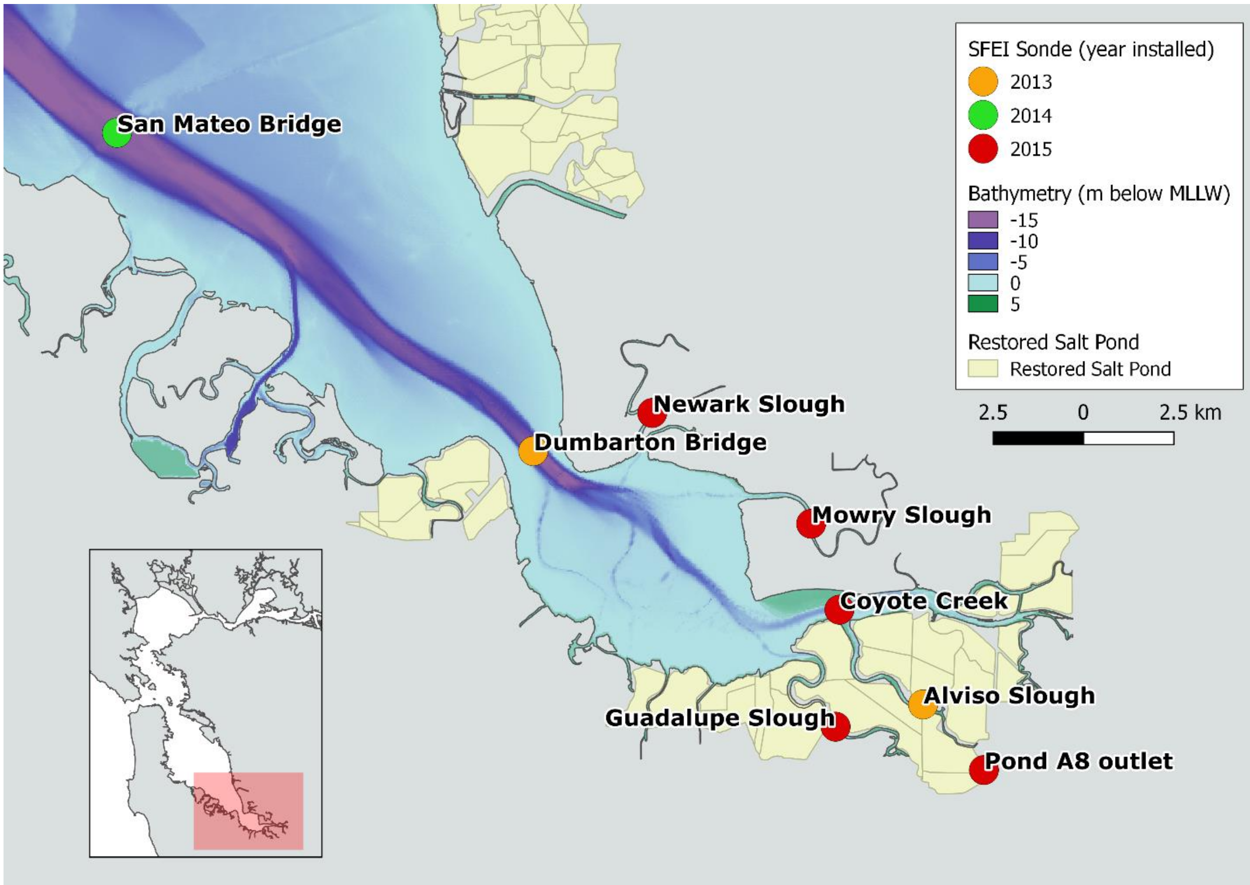

Figure 2: Lower South San Francisco Bay with high-frequency mooring locations indicated. Colors correspond to year established.

PHYSICAL AND BIOLOGICAL CONTEXT

Physical Environment

San Francisco Bay - the largest estuary on the West coast of the United States - is a highly altered system surrounded by a densely populated urban center. The Bay receives freshwater from the Delta formed by the confluence of the Sacramento and San Joaquin rivers, which drain California's Central Valley, many local tributaries, and discharges from over 40 wastewater treatment plants. The climate is Mediterranean, with warm, dry summers and cool, wet winters. The Bay exchanges with the Pacific Ocean to the west.

LSB is a shallow, macrotidal environment with most of its summer freshwater inflow from wastewater treatment plants located on its perimeter. The South Bay generally functions as a "marine lagoon strongly influenced both by inputs from an urban landscape and connectivity to a coastal ocean" (Cloern and Jassby 2012). More than half of the area of LSB is intertidal; at low tide, vast mudflats are exposed to air. The perimeter of LSB constitutes a network of tidal sloughs and active and former salt ponds. The native salt marsh that once occupied the low-lying areas adjacent to LSB was leveed off for industrial salt production beginning in the early 20th century. Approximately 16,000 acres of these ponds have been acquired by a consortium of state and local agencies to be breached to tidal action as part of an ongoing habitat restoration project. Some of the breached ponds exchange fully with the Bay, but others have a large subtidal volume due to subsidence and flow control structures at the breaches.

According to published data (MacVean 2010, Schraga and Cloern 2017, www.enviz.org), salinity in LSB typically varies from 15 Practical Salinity Units (PSU) in the winter to 33 PSU in summer, but can become almost completely fresh during extreme wet weather. Water temperatures vary annually from about 7 to 23 ^{o}C in the main channel, but can reach summertime highs of 27 ^{o}C in the shallow sloughs. DO varies over a fairly narrow range in the deep channel, and generally remains between 80 and 100% saturation. In the sloughs and near the former salt ponds, however, DO varies over a much greater range, reflecting hotspots of primary productivity in some managed ponds.

Conceptual Model of DO-related Habitat Quality for Fish

The physical, biological, and biogeochemical processes that control the degree to which the estuarine environment is supportive of animals are numerous and complex. This is especially true in LSB, where vast intertidal areas are exposed to air twice per day, and tidal currents can exceed 0.5 m/s in sloughs and 1 m/s in pond breaches, effectively making the *volume* of habitat a dynamic quantity. In addition to the variable existence of habitat, water quality varies tidally and seasonally and the habitat requirements of organisms change with life stage.

For locations with physical features that are beneficial to a particular species/life-stage (such as refuge from predators, substrate material, and flow), water quality can become important for determining habitat quality. Temperature, salinity, DO and turbidity are water quality parameters that are generally important to fish. Seasonal fluctuations in temperature, salinity, and turbidity can also influence primary productivity in an estuary, which in turn affects DO concentrations. Light, nutrients, and tides are also important factors. Unraveling the needs of each species at each life-stage, and reconciling those with the physically and biogeochemically dynamic environment requires careful consideration of covariance between factors and an understanding of naturally-occurring conditions that may arise on a daily, neap-spring tidal cycle, or seasonal basis.

CONTEXT FOR THIS REPORT

SFEI staff worked with a panel of scientific and regulatory experts to identify tractable approaches for evaluating DO condition and quality of fish habitat in LSB. Work began with a two day workshop in April 2017 at SFEI. The panel proposed that the scientific basis for assessing habitat must integrate (1) the needs of the species that reside in the estuary, or of a targeted subset of those species, and (2) the frequency, severity, spatial extent, and drivers of low-DO events.

The group asserted that the components of a determination of habitat quality should include:

- Characterizing the extent and duration of low-DO conditions;
- Establishing the implications of different DO levels for biota using fish as the target species;
- Combining the previous two efforts to assess how much of the estuary is suitable habitat.

This report uses existing information on DO and fish abundance to provide an initial assessment of the first two bullets and outlines recommendations for future work.

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CHAPTER 2

Characterization of Dissolved Oxygen in Lower South San Francisco Bay

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Abbreviation	Definition
CHLA	Chlorophyll-a
CIMIS	California Irrigation Management Information System
DO	Dissolved Oxygen
fDOM	Fluorescent Dissolved Organic Matter
LSB	Lower South Bay
NMS	Nutrient Management Strategy
PSU	Practical Salinity Units
SAL	Salinity
SFB	San Francisco Bay
SFBRWQCB	San Francisco Bay Regional Water Quality Control Board
SFEI	San Francisco Estuary Institute
TEMP	Temperature
TMDL	Total Maximum Daily Load
UCD	University of California Davis
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
YSI	Yellow Springs Instruments

INTRODUCTION

San Francisco Bay (SFB) receives high nutrient loads from a range of sources, and studies have been underway since 2012 to understand the effects of these loads and to identify potential nutrient management needs through the San Francisco Bay Nutrient Management Strategy (NMS, http://sfbaynutrients.sfei.org/).

Dissolved oxygen (DO) is a critical parameter for assessing ecosystem condition, in particular in nutrient enriched and eutrophic systems worldwide. Presently in SFB, the Regional Water Quality Control Board's Basin Plan has specified a DO objective for all tidal waters down-estuary of the Carquinez Bridge of 5 mg/L and > 80% DO saturation for the running three-month median in any SFB sub-embayment (SFBRWQCB 2017). While waters in SFB's deep subtidal habitats generally satisfy this DO objective, early data from some habitats in Lower South Bay (LSB, Figure 1) suggest that DO levels frequently fall below 5 mg/L (Crauder, et al. 2016; Sutula, et al. 2017; Senn and Novick 2014). Initial work on identifying nutrient-related science priorities in SFB identified expanded DO monitoring and improved understanding of habitat utilization by biota in LSB sloughs as important data gaps (Senn and Novick 2014).

In order to address the information gap regarding DO concentrations, the San Francisco Estuary Institute (SFEI) installed seven moored sensors in LSB between 2013 and 2015. The sensors have been continuously deployed and maintained since their initial installment. As one component of examining DO-related ecosystem health in LSB, this section analyzes the moored sensor data from 2013-2017 to characterize spatial and temporal variability of DO in LSB sloughs, in particular from the perspective of habitat quality.

METHODS

A. Collection of High-Frequency In-Situ Observations of Dissolved Oxygen

Continuous water quality monitoring in the sloughs and main channel of LSB was initiated in 2013, with additional stations added in 2015 (Figure 1). Each station has one YSI EXO2, measuring conductivity (which is converted to salinity or SAL), temperature (TEMP), DO (optical method), turbidity, fluorescent dissolved organic matter (fDOM), chlorophyll-a (CHLA), and pressure to measure depth. The locations, deployment dates, and distance between the sensor and the bed for each station are presented in Table 1. The sampling interval at all locations is 15 minutes. Water quality measurements were downloaded from instruments’ internal memory every 3-5 weeks during routine maintenance trips (sensor cleaning, calibration). Data were then quality assured using the algorithms described in Appendix B.

Table 1: Details of water quality moorings in Lower South Bay

Station	Lat (deg N)	Lon (deg W)	Approximate Distance Above Bed (m)	Date Installed	Latest QA'ed Data used in this report	Overlying Water Depth (m)	Habitat Type
Dumbarton Bridge	37.504	122.119	12.6	July 2013	December 2017	1.5-4.5	Main Channel
Alviso Slough	37.44	121.998	0.5	Sept 2013	December 2017	0.75-3.75	Slough
Newark Slough	37.513	122.082	1.3	April 2015	December 2017	0.25-3	Slough
Coyote Creek	37.464	122.024	1.3	May 2015	December 2017	2-5	Slough
Mowry Slough	37.485	122.033	0.5	June 2015	December 2017	0.25-3	Slough
Guadalupe Slough	37.435	122.026	0.5	June 2015	December 2017	0.25-3	Slough
Pond A8 Outlet	37.423	121.98	0.5	July 2015	December 2017	0.5-3	Pond-Slough Connector

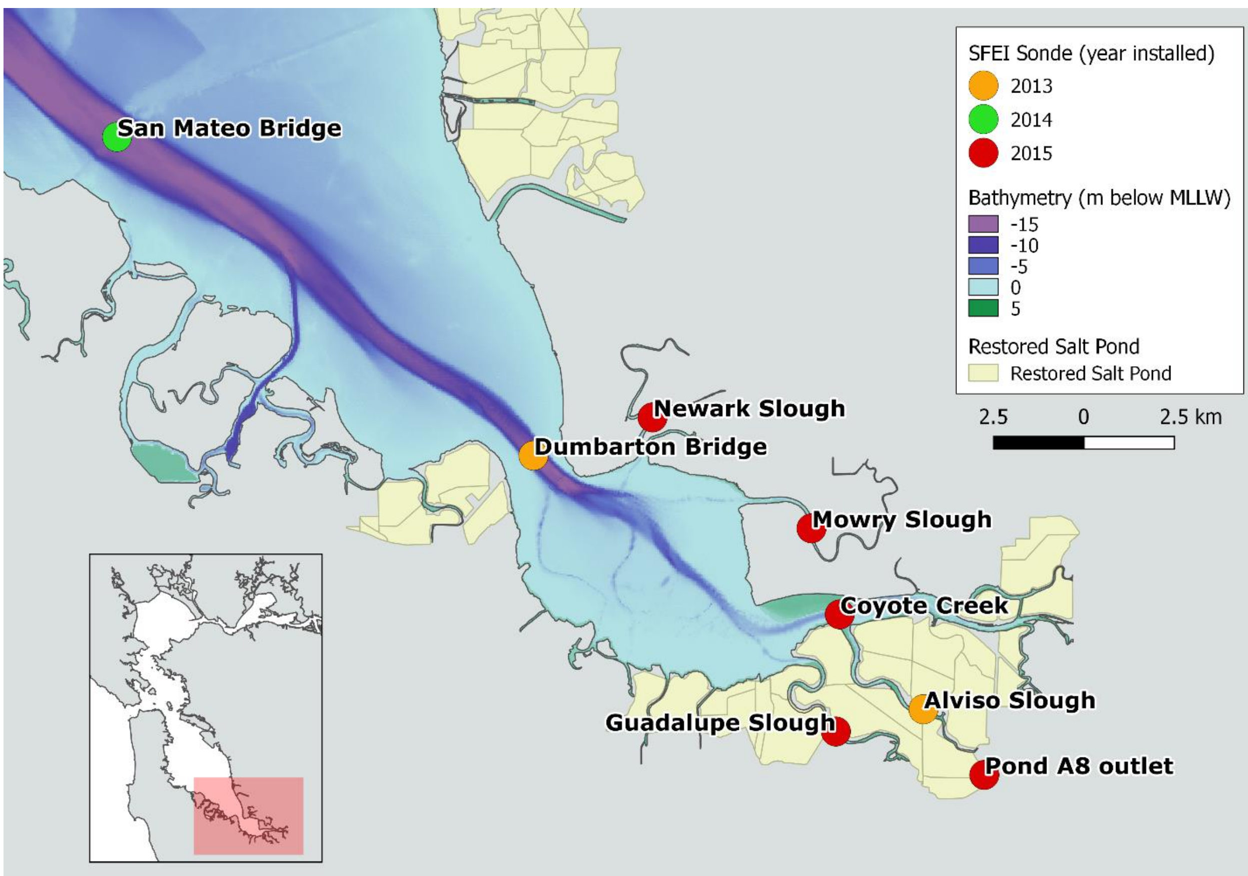


Figure 1: Lower South San Francisco Bay with high-frequency mooring locations

B. Analysis of High-Frequency In-Situ Observations of Dissolved Oxygen

Continuous data were analyzed to assess spatial and temporal trends. Temporal patterns were evaluated for the following scales: diurnal and tidal fluctuations, neap-spring tides, seasons, and between year variance due to freshwater inflows. The data were evaluated by visual interpretation of time series plots, correlation analysis, and Kruskal-Wallis tests.

In order to evaluate DO concentrations relative to tides, the tide stage was estimated from the sensor depth readings. Slack high, peak ebb, slack low, and peak flood tides were identified from inflection points in the depth readings. Tide stage at other times was assigned by interpolation between these points. Chi-squared contingency tables (2x2) were used to test for independence between tide stage and occurrence of DO concentrations below thresholds.

Measured DO concentrations were compared to water quality objectives for SFB, specifically the existing Basin Plan water quality objective (>5 mg/L) and site-specific objectives for Suisun Marsh (>5 mg/L as a 30-day average and 3.8 mg/L as a daily average) were used for this calculation. The metric that was used for these comparisons was the percent of the period of record for which the DO was lower than an objective. To identify and illustrate how these low DO events varied temporally, the percent of observations below a threshold was plotted for each month during the period of record if there were data for at least 80% of that month. Reasons for missing data include failure, fouling, or removal of the sensors.

Finally, the duration of low DO events was calculated. For these calculations, the measured DO concentrations (1-hour averaged data based on at least three 15-minute readings in each hour) were compared to the Basin Plan objective (5 mg/L) and a threshold representing potential acute impacts to fish (2.3 mg/L from US EPA, 2000). Each unique excursion below these thresholds was identified through an algorithm that cut the DO time series into unique strings of continuous data above or below the threshold. A second algorithm was used to splice together excursions which were separated by a gap of two hours or less. This latter step was added to avoid treating single long excursions as multiple shorter ones due to a few missing data points.

RESULTS AND DISCUSSION

Measurements at a set of biogeochemically-diverse habitats within LSB (Figure 1) demonstrate that DO concentrations vary substantially within the system. The variability in DO concentration is evident at multiple temporal and spatial scales. The following sections characterize DO variability in time, space, and relative to water quality objectives.

A. Temporal Variability

Diurnal and Tidal Fluctuations

Many surface water systems experience pronounced daily (or diel) cycles in DO concentrations caused by day-night changes in the balance between DO production via photosynthesis and DO consumption via respiration. At first glance, the data from LSB show a similar pattern (Figure 2). At the Dumbarton Narrows during summer months, DO showed once-daily sharp (but short-lived) drops of ~2 mg/L or a 30% change in saturation. At some slough sites, there were 2-fold changes in DO concentration within a day.

However, something other than production and respiration appears to be causing this hourly time-scale variability in the DO signals. In fact, Figure 3 illustrates that the periodicity and timing of the DO variations at some LSB stations are synchronized with tidal fluctuations. Therefore, the daily fluctuations at these stations are mostly driven by strong tidal currents transporting biogeochemically-distinct water masses past fixed locations. While Figure 3 shows only a small portion of the dataset, it is representative of typical conditions. In the following section on spatial variability (starting on page 2-11), a statistical analysis using all of the data supports this finding.

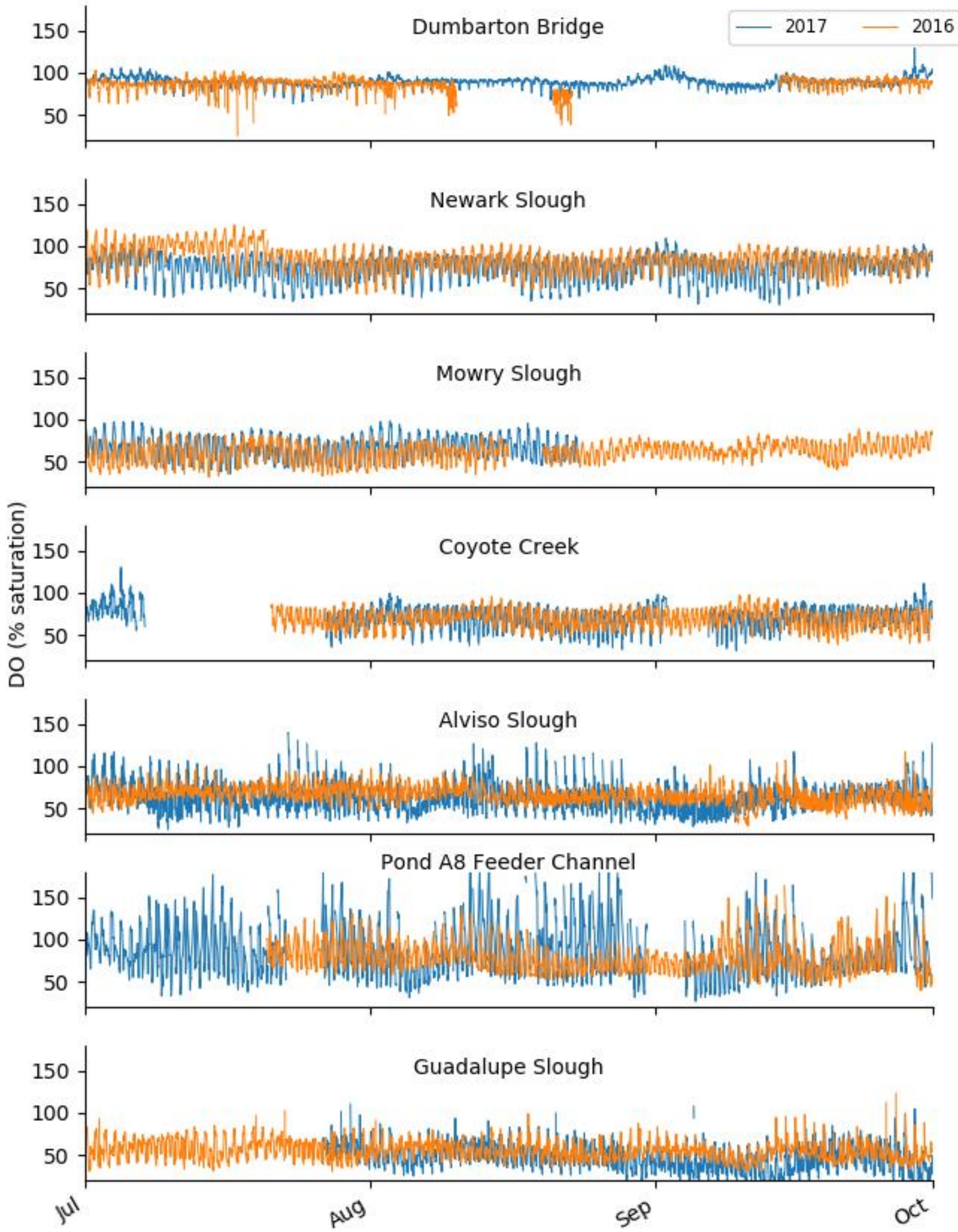


Figure 2: Dissolved oxygen saturation measurements from all stations at 15-minute increments. Summer data are shown (July-Sept) from 2016 (orange) and 2017 (blue). Missing data are due to sensor failure or failure of the data to pass quality assurance criteria.

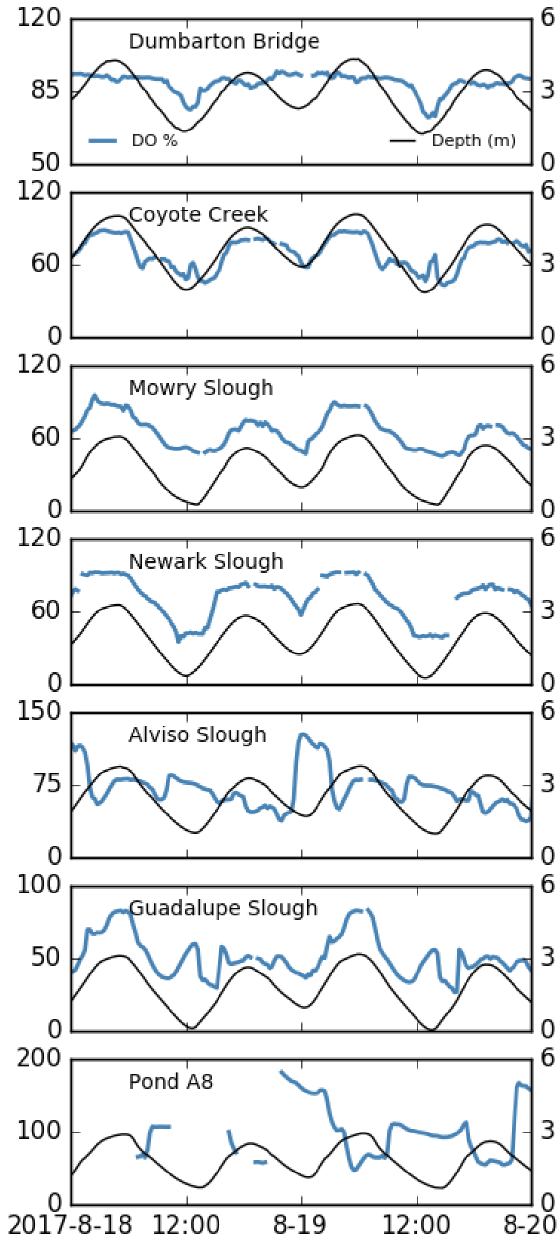


Figure 3: Dissolved oxygen (blue, left axis, in units of percent saturation) and depth (black, right axis, in units of meters) at mooring stations over a two-day tidal cycle. At all the stations besides Alviso Slough and Pond A8, low DO and low tide are concurrent, suggesting that ebb tides transport the low-DO water mass to the sensor package.

Spring-Neap Tidal Cycle

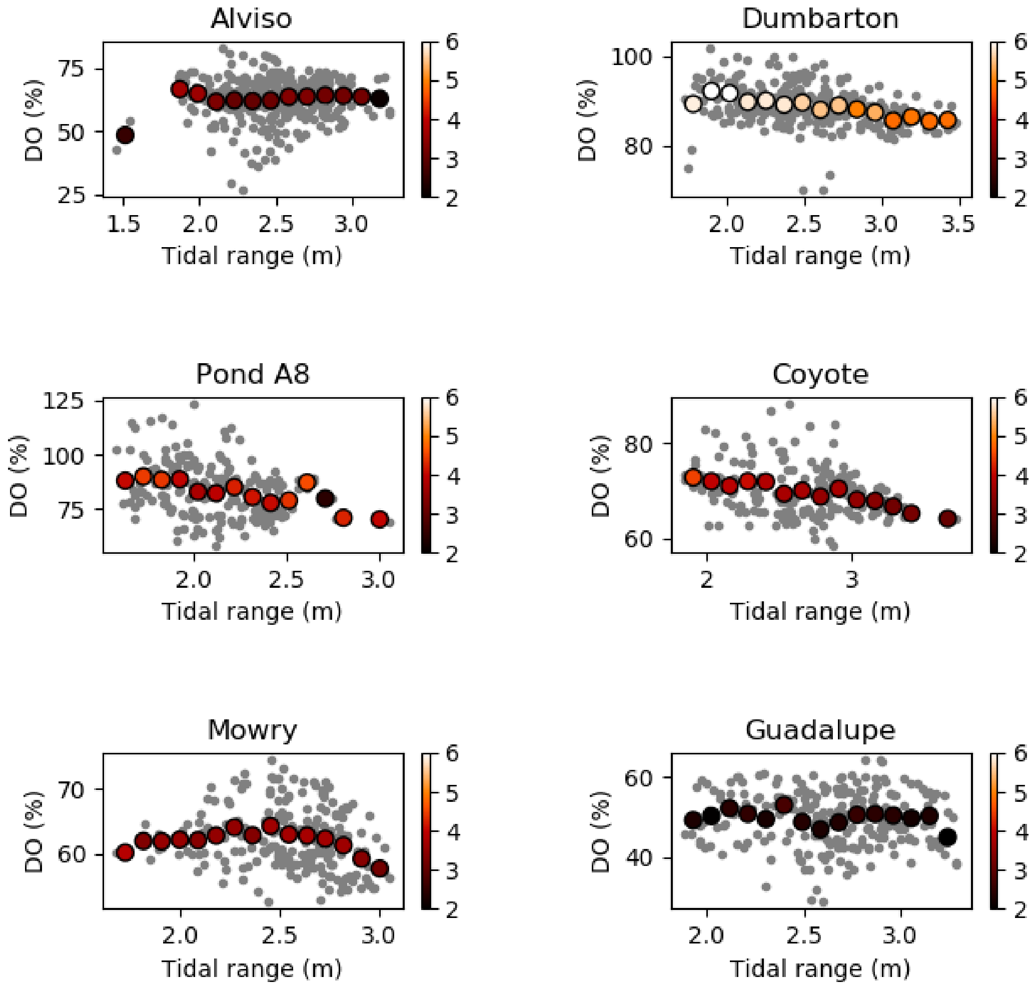
Tides also appear to influence DO concentrations at weekly time-scales related to the spring-neap cycle. Hints of this influence are initially evident in the gradual change in the daily maximum and minimum values in the summer time series (Figure 2). To explore these variations in a more targeted way, we plotted daily-averaged DO saturation (%) vs. the daily tide range for all summer data (Figure 4). Daily tidal range, calculated as the difference between the 24-hour maximum and minimum tidal stages, provides an indication of spring-neap phasing, with low values indicating neap tides, and high values corresponding to springs.

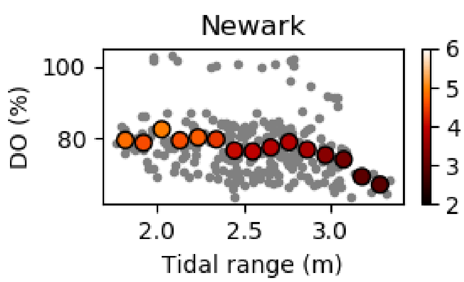
While there is considerable scatter among the daily average values (gray dots), at some sites interesting patterns emerge from the binned data (circles, where the color represents the minimum daily DO concentration in mg/L). At five of the seven sites (Dumbarton, Newark, Mowry, Coyote, Pond A8), statistically significant lower DO values were associated with larger tidal ranges (i.e., spring tides). A possible explanation for the patterns observed in Figure 4 is that spring tides allow for the transport and entrainment of water from poorly exchanging habitats (including wetlands and interstitial waters) having lower DO or more reducing conditions.

The mechanistic relationship causing the observed patterns in Figure 4 is uncertain. Many other factors co-vary with tides. These factors, and not the tidal range could be causing the observed pattern. The amount of variance explained by tidal range is low (2-12%) indicating that other factors are more important. Finally, Crauder et al. (2016) documented the opposite relationship at Alviso Slough (lower DO during neap times) in 2012 but the gates controlling the flow out of Pond A8 were operated differently then.

Seasonal Variability

Both DO concentrations (in mg/L) and DO saturation (in % sat) exhibited strong seasonal variability at LSB mooring sites (Figure 5). The seasonal variations in DO concentrations (in mg/L) are expected, since DO solubility increases with decreasing temperature and salinity, leading to a seasonally-varying 'baseline' DO concentration. However, DO percent saturation also varied in consistent seasonal patterns at all sites, with lowest values occurring in summer and fall and highest during winter and spring. Since DO saturation already takes into account the underlying variations in DO solubility, the lower values during summer and fall probably result from a combination of greater amounts of labile organic matter and higher rates of oxygen demand by metabolic processes (e.g., respiration). The higher DO saturation during winter and spring are likely due to the slower respiration rates in these seasons, combined with episodic increases in primary production photosynthesis. A Kruskal-Wallis test confirms that for each station, winter and summer DO saturation levels are statistically distinct ($p < 0.001$).





Station	Slope	R^2	P-value
Dumbarton Bridge	-3.6	0.12	<0.05
Newark Slough	-5.2	0.05	<0.05
Mowry Slough	-2.4	0.02	<0.05
Coyote Creek	-3.8	0.08	<0.05
Alviso Slough	1.5	0.003	0.31
Pond A8 Outlet	-13.8	0.10	<0.05
Guadalupe Slough	-1.4	0.005	0.29

Figure 4: Daily average DO saturation (%) versus daily tidal range (m) for all summer data (gray dots). Large circles indicate binned averages by day, with color scaled by minimum daily DO concentration in units of mg/L (ranging from 2 mg/L to 6 mg/L). Table shows linear regression statistics for daily DO (% saturation) and daily tidal range (m).

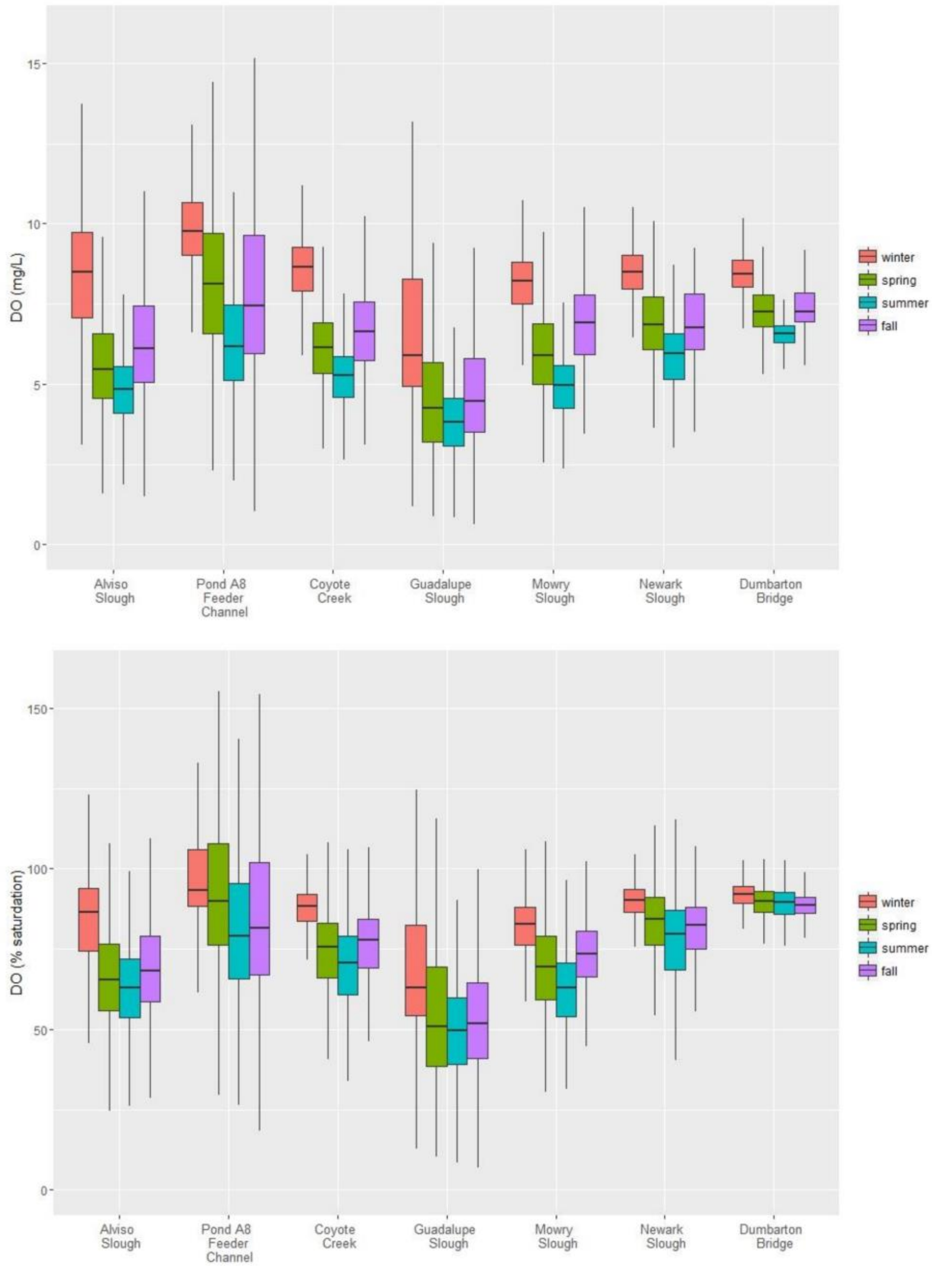


Figure 5: Distributions of DO concentration (in mg/L, top plot) and percent saturation (bottom plot) measurements at each station by season. Filled boxes show the interquartile range of measurements, with the horizontal line indicating the median value. Gray lines show 5th and 95th percentile values. Winter = December-February; Spring = March-May; Summer = June-August; Fall = September-November.

Interannual Variability

DO concentrations can also be affected by variability in weather between years. In California, the amount of winter rainfall is the dominant weather variable that changes between years. The role of freshwater inflow is difficult to separate from seasonal trends since most runoff events occur during winter and spring when DO saturations are high. Freshwater inflows may influence DO by injecting oxygenated water into the system or by creating stratification, which stimulates productivity. Figure 6 shows a time series of monthly-averaged Guadalupe River flow, which discharges to Alviso Slough, and DO saturation levels in Coyote Creek and at the Dumbarton Bridge. The time-series suggests that runoff from winter storms is correlated with high DO conditions during the winter and spring at Coyote Creek and to a lesser extent at the Dumbarton Bridge. However, given that there has only been one strongly wet winter since the moored sensors were deployed, it is not possible to isolate the effect of freshwater flows on DO in the sloughs. A longer time series is needed to know how much of an effect wet winters have on DO concentrations in LSB relative to the normal seasonal patterns for water temperature, productivity, and respiration.

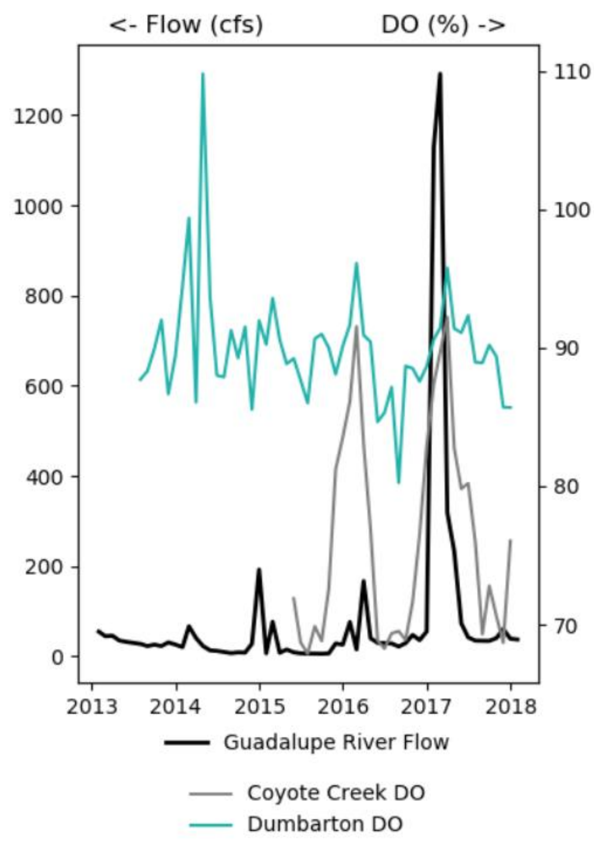


Figure 6: Monthly-averaged DO at Coyote Creek and Dumbarton Narrows, with freshwater flow from the Guadalupe River.

B. Spatial Variability

Horizontal Gradients

The phasing of DO concentrations relative to the tide can offer insights as to the horizontal spatial gradients of DO in LSB. At most stations, the lowest DO concentrations tend to occur at low tide or during ebb tides, suggesting that a low-DO water mass has been advected from up-estuary to the sensor package. This implies that an along-estuary DO gradient exists in which DO is higher down-estuary and lower up-estuary. Therefore, the temporal variability in DO on tidal time scales (see discussion starting on page 2-4) reflects spatial variability in DO between the open Bay and the sloughs.

One way to visualize the differences in DO concentrations due to tidal advection is to select measurements taken 2-3 hours on either side of high and low tides and calculate summary statistics on the two groups of data for each station (Figure 7, Table 2). The metric that will be used for this comparison is the percent of observations where DO was below 5 mg/L.

In general, DO concentrations fell below 5 mg/L more frequently at low tide than during high tide. The sensor at Dumbarton rarely experienced DO below 5 mg/L at either high or low tide. However, at the slough stations, between 2 and 74% of the observations were less than 5 mg/L. The slough sensors will be discussed in three groups:

- Newark and Mowry Sloughs;
- Coyote Creek, Alviso Slough, and Pond A8; and
- Guadalupe Slough.

At the Newark and Mowry slough stations DO fell below 5 mg/L for approximately one-third of low tides (typically in summer). However, at high tide, the DO tended to return to >5 mg/L. This pattern is consistent with a relatively small spatial gradient in DO between the open Bay and the sloughs. Water from the open Bay with higher DO concentrations enters the slough on flood tides. Lower DO concentrations occur in the upper reaches of the slough where there is more biological oxygen demand from organic material. These sloughs are not connected to restored salt ponds and do not receive wastewater discharges, so there are no major inputs of either high or low oxygen water to the upstream portions of the sloughs.

The pattern of DO at Pond A8, Alviso Slough, and Coyote Creek stations indicates sources of DO to the slough from both the open Bay and the restored salt pond upstream. At the Coyote Creek station, the DO concentrations were higher at high tide than at low tide. This pattern is similar to the Newark and Mowry slough stations and is indicative of advection of lower DO water from the sloughs to the open Bay on ebb tides. However, the pattern was different at the Alviso Slough station in the middle of the slough and at the Pond A8 station at the head of the slough. At the Alviso Slough station, there was no difference in the percent of observations below 5 mg/L at low tide than at high tide. At the Pond A8 station, the DO concentrations were actually higher at low tide. These patterns suggest that the Alviso complex of salt ponds, located between Guadalupe and Alviso sloughs, is highly productive and supplies the sloughs with oxygen-enriched water, as well as organic material that contributes to oxygen demand as it is respired during transit down the slough. In other words, the Pond A8 complex, which has muted velocities and long residence times, appears to supply the connected sloughs with both: 1) high DO water during times of elevated productivity, and 2) organic matter that results in oxygen demand farther down the slough. Respiration of the organic material as it is advected down the slough results in lower DO concentrations at the Alviso Slough and Coyote Creek stations. Chlorophyll fluorescence (units of RFU) at the Alviso complex are an order of magnitude higher than the maximum values observed at the Dumbarton Bridge which supports the hypothesis of high productivity in the pond.

DO concentrations in Guadalupe Slough were more frequently below 5 mg/L than the other stations. Concentrations at low tide were lower than at high tide, but the 5 mg/L threshold is exceeded the majority of the time regardless of the tide stage. This slough experiences the same tidal advection signal as the Newark and Mowry Sloughs. It also receives some discharge from Pond A8. What is different about this slough is that it also receives treated effluent from the Sunnyvale wastewater treatment facility, which may add lower DO and higher biological oxygen demand water into the upper reaches of the slough. The combination of these factors results in DO concentrations that are frequently below the 5 mg/L water quality objective from the Basin Plan.

Vertical Gradients

Grab samples of DO at the top and bottom of the water column at trawl sites indicate that conditions were generally well mixed at all sites with limited evidence for stratification throughout the year (see Chapter 3, Appendix 3). However, limited targeted measurements with in-situ sensors (not shown) suggest that, within sloughs, DO decreases toward the sediment surface. The dependence of DO on vertical position within the water column could be an important factor, but additional observations will be needed to characterize it. This data-gap will be discussed further in the recommendations at the end of the report.

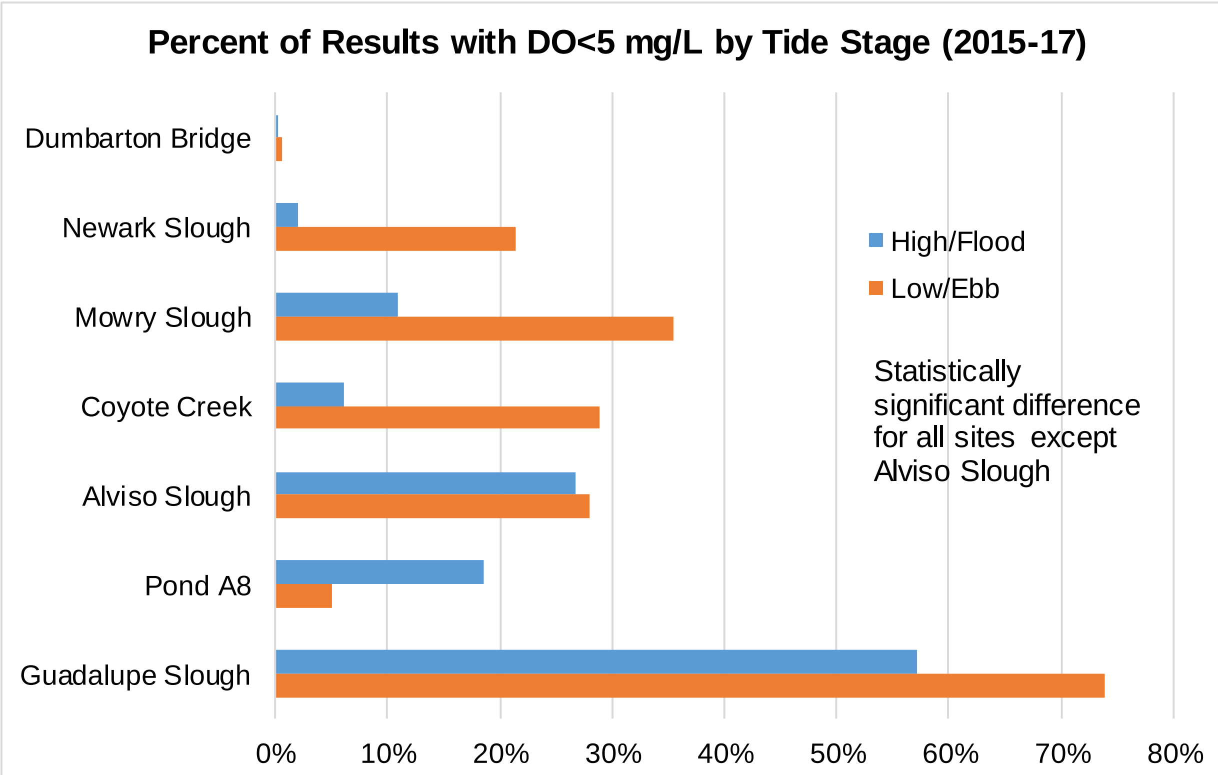


Figure 7: Percent of dissolved oxygen readings (1-hour averaged data) from 2015-2017 that are less than 5 mg/L by tide stage. Tide stage was determined using inflection points in the depth readings at each moored sensors. Differences are statistically significant for all sites except Alviso Slough.

Table 2: Number of dissolved oxygen readings (1-hour averaged) from 2015-2017 that are above or below 5 mg/L by tide stage. Results for Chi-squared test for independence are shown in the far right column.

Station	Tide Stage	Number of 1-hr averages with DO<5 mg/L	Number of 1-hr averages with DO>5 mg/L	Percent of 1-hour averages with DO<5 mg/L	Chi-squared Test Results
Dumbarton Bridge	High/Flood	3	11691	0%	P<0.05
	Low/Ebb	56	11139	1%	
Newark Slough	High/Flood	169	8066	2%	P<0.05
	Low/Ebb	1782	6550	21%	
Mowry Slough	High/Flood	919	7489	11%	P<0.05
	Low/Ebb	3110	5662	35%	
Coyote Creek	High/Flood	596	9037	6%	P<0.05
	Low/Ebb	2753	6776	29%	
Alviso Slough	High/Flood	3156	8656	27%	P=0.52
	Low/Ebb	3523	9089	28%	
Pond A8	High/Flood	1675	7393	18%	P<0.05
	Low/Ebb	492	9251	5%	
Guadalupe Slough	High/Flood	4763	3577	57%	P<0.05
	Low/Ebb	6460	2278	74%	

C. Frequency of Low-DO Concentrations Relative to Water Quality Objectives

The Basin Plan water quality objective for DO in Lower South Bay is 5 mg/L. This objective was intended for the waters of the open Bay, not necessarily the tidal sloughs, but it still provides a useful threshold for comparison.

The moored sensor data show that DO typically meets the water quality objective of 5 mg/L in the deep channels (Figure 8). At the Dumbarton Bridge, DO only fell below 5 mg/L for 0.3% of the observations in the period of record. However, in the sloughs, DO concentrations fell below 5 mg/L between 11 and 65% of the period of record. Table 3 and Figure 9 show the results for each station in the different sloughs. Out of all the slough sites, the station at the Pond A8 Outlet had the lowest percent of observations below the objective. The station in Guadalupe Slough had the highest percent of observations below the objective.

The new site-specific objectives for Suisun Marsh provide another set of thresholds for comparison (SFBRWQCB 2018). These objectives were developed by the San Francisco Bay Regional Water Quality Control Board using the Virginian Province Approach with the assistance of an expert panel. The objectives are 5 mg/L for chronic exposures (evaluated as a 30-day running average of daily averages) and 3.8 mg/L for acute exposures (evaluated as a daily average). There are also objectives for salmonid migratory periods, which apply to specific locations in Suisun Marsh that have been identified by the resource agencies.

Application of the Suisun Marsh site-specific objectives to the LSB data shows that the acute standards were typically met in all locations except Guadalupe Slough. In this location, DO fell below the acute objective 32% of the days in the period of record. The chronic objective was always met at the Dumbarton Bridge, Newark Slough, and Pond A8 outlet stations. However, this objective was not met in the other locations to various degrees ranging from 4% to 75% of the calculated 30-day averages, most commonly in Guadalupe Slough. The objectives for salmonid migratory periods were not applied to the data from LSB because they pertain to specific habitats in Suisun Marsh.

Therefore, measurements indicate that DO typically meets the Basin Plan objective of 5 mg/L at the Dumbarton Bridge, which reflects conditions in the deep channel. DO concentrations in the sloughs, taken in aggregate, fall below 5 mg/L for 26% of their cumulative period of record. Guadalupe Slough has the lowest and most frequent low-DO excursions. DO in Guadalupe Slough is commonly less than 5 mg/L (65% of the time since the mooring was established), less than the acute objective for Suisun Marsh (32% of period of record), and less than the Suisun Marsh chronic objective (75% of calculated 30-day averages from the period of record).

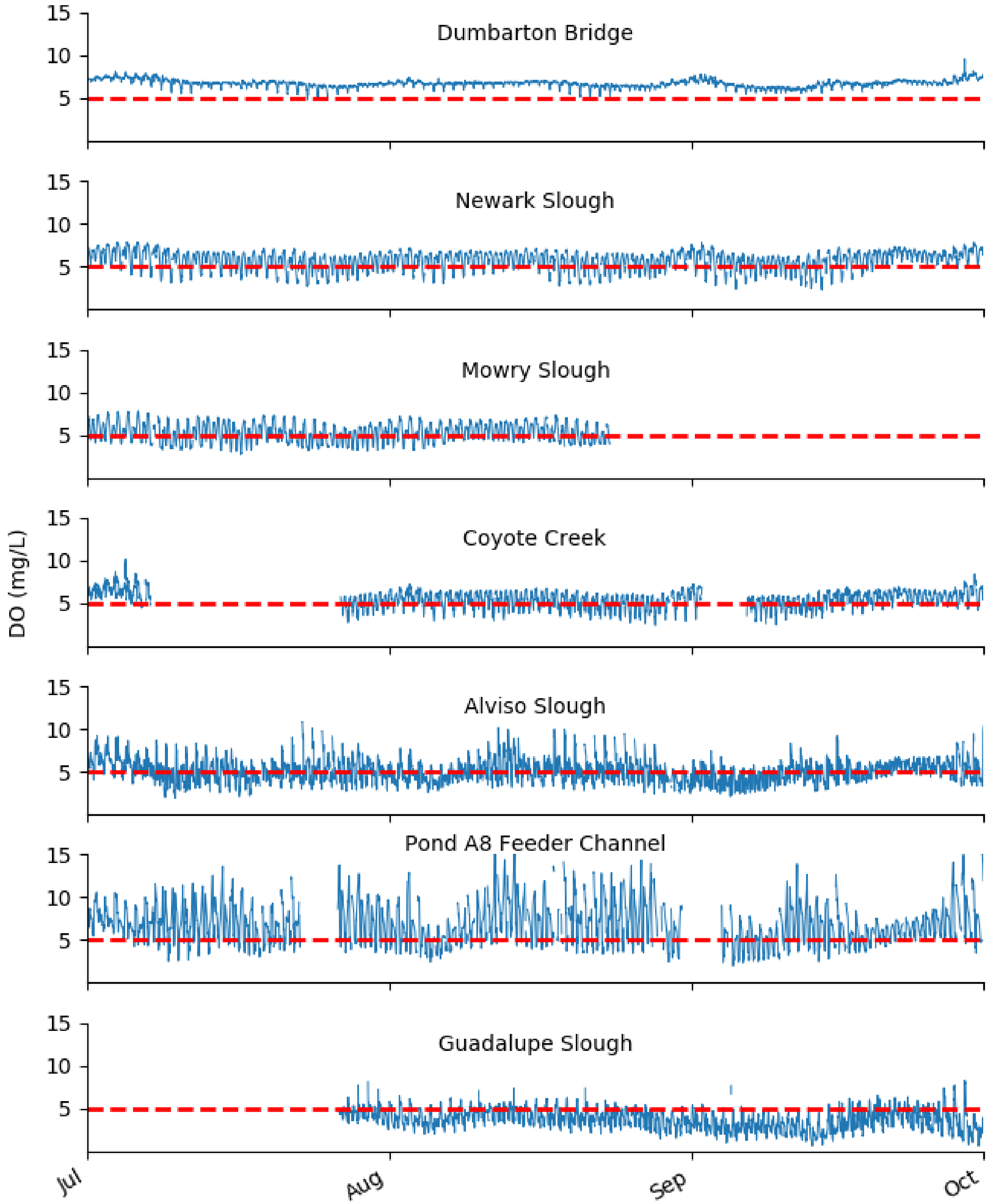


Figure 8: Dissolved oxygen concentration (mg/L) from July 1 to September 30, 2017, based on 15-minute data. Dashed red line depicts the 5 mg/L SFB Basin Plan objective. Missing data are due to sensor failure or failure of the data to pass quality assurance criteria.

Table 3: Frequency that DO concentrations measured by in-situ sensors were below water quality objectives from the Basin Plan and the Suisun Marsh Site-Specific Objectives.

Monitoring Station	Percent of Period of Record* below 5 mg/L (1-hour averages)+	Percent of Period of Record below 3.8 mg/L (daily averages)#	Percent of 30-day Running Averages in Period of Record below 5 mg/L#
Dumbarton Bridge	0.3%	0% (1591)	0% (1310)
Newark Slough	12%	0% (833)	0% (568)
Mowry Slough	23%	0% (791)	18% (536)
Coyote Creek	17%	0% (886)	4% (664)
Alviso Slough	30%	3% (1471)	25% (1188)
Pond A8 Outlet	11%	0% (835)	0% (488)
Guadalupe Slough	65%	32% (789)	75% (560)

Calculations provided by Richard Looker, SFBRWQCB

*The period of record for each station is shown in Table 1.

+ The percentages are the same if instantaneous (15-minute) data are used for this calculation.

Site-specific objectives from Suisun Marsh TMDL. The number of samples or averages computed is shown in parentheses.

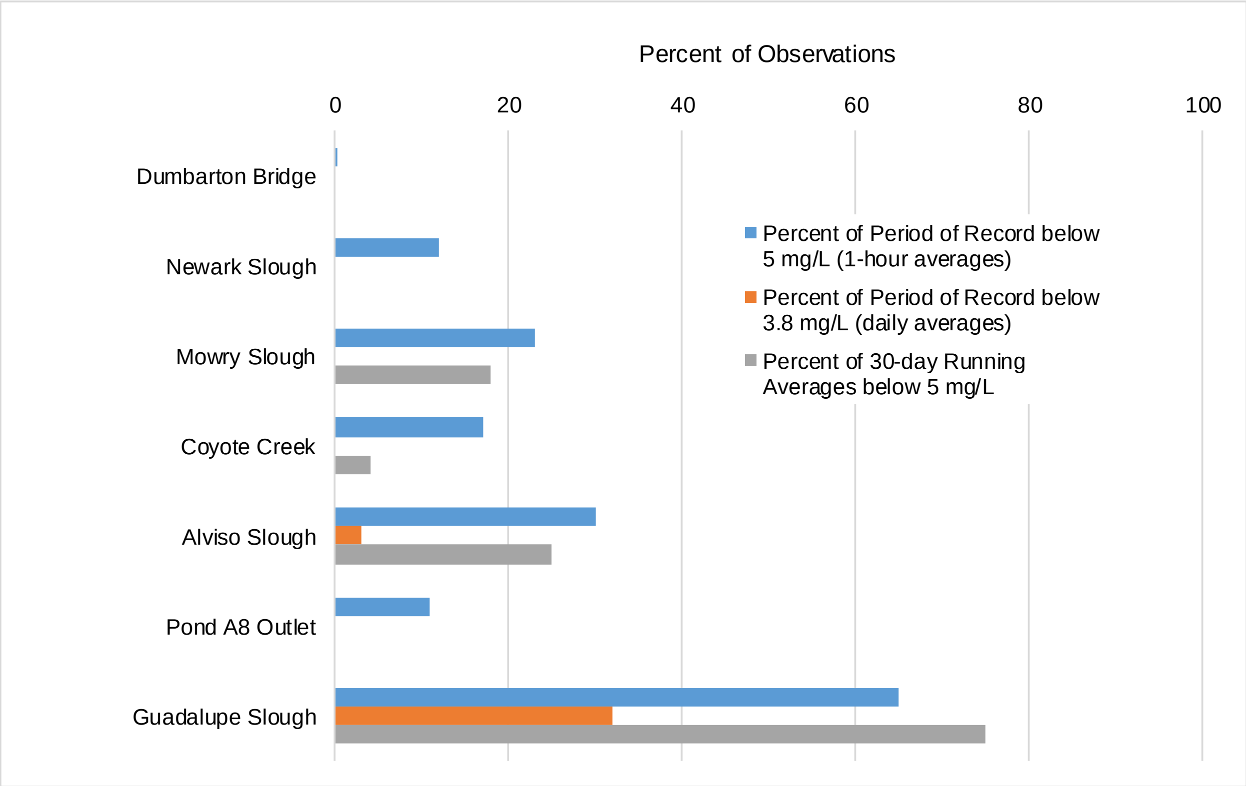


Figure 9: Frequency of DO measurements by moored sensors below water quality objectives from the Basin Plan and the Suisun Marsh Site-Specific Objectives. Results are shown as the percent of observations in the period of record shown in Table 1 that were below the objectives.

D. Seasonality of Low-DO Events

The comparisons to water quality objectives in the previous section examined the whole period of record in aggregate; however, in reality, low DO typically occurs during the summer season. Figure 10 shows how the percent of time with DO less than 5 mg/L varied by month for all Lower South Bay stations. Guadalupe Slough has the highest frequency of low DO during summer, reaching between 80 and 100% in late summer months. In comparison, the Pond A8 Outlet station experiences a maximum of 30% of low-DO events during these months. At this station, which is located just outside the largest breach of Pond A8, the generally high levels of DO saturation suggest that the DO-enriched water exiting the productive pond offsets local DO demand such that the two are largely in balance. Evidently, at stations farther from the breach but within the tidal excursion, DO demand often outpaces supply, possibly due to respiration of organic material.

While DO concentrations exhibit a predictable seasonal dependence, variability is also great on inter-annual timescales. For example, at the station in Alviso Slough, there is a noticeable difference in the summer time series across years. One possible factor in this change is the operation of gates controlling flows from Pond A8 (see Appendix A). These gates control tidal exchange between the slough and the pond and, therefore, can affect residence time and mixing in the pond. Between 2015 and 2017, the number of gates open was increased, which presumably increased tidal exchange. There are other factors possibly contributing to this variability, including but not limited to meteorological forcing (freshwater inflows, temperature differences, wind characteristics), and the drivers of phytoplankton blooms themselves, such as nutrient loads, the light field, and grazer populations.

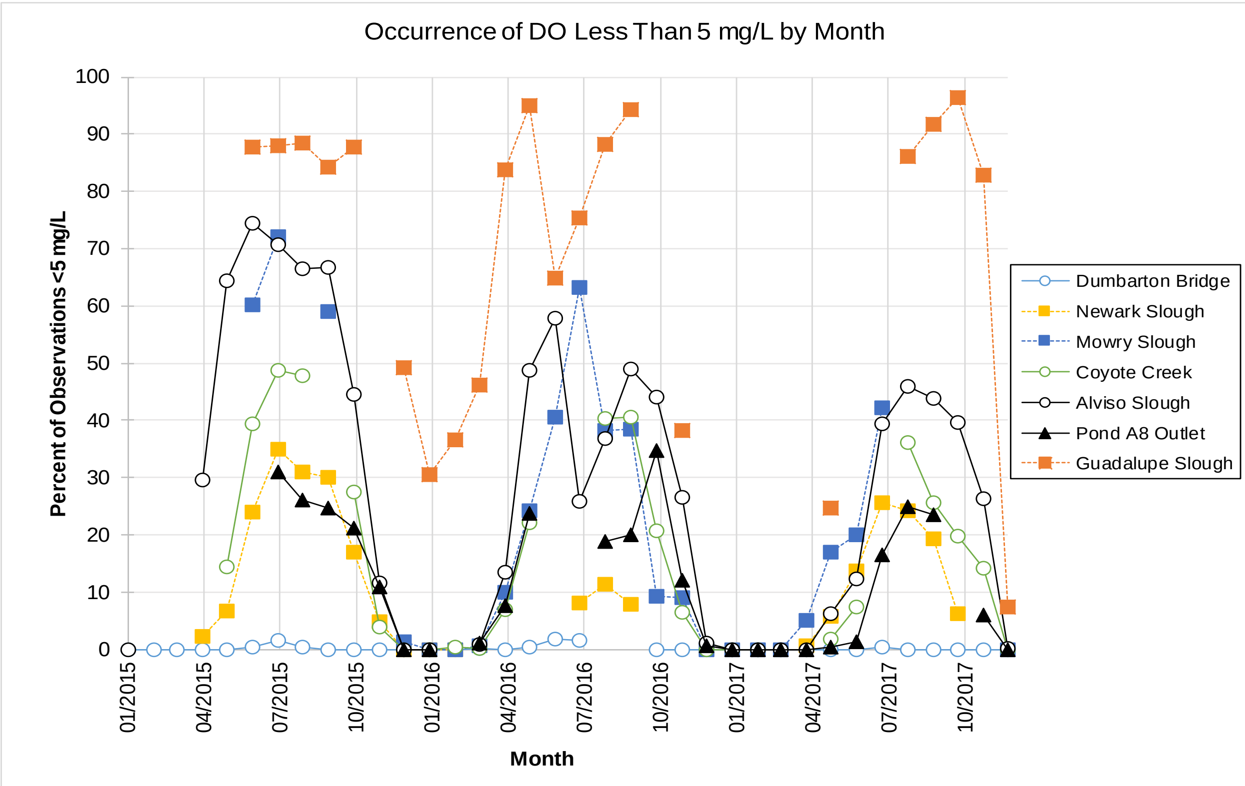


Figure 10: Percent of time each month for which hourly average dissolved oxygen was less than 5 mg/L. Months with incomplete data (<80% of possible observations) are not shown.

E. Duration of Low-DO Events

In addition to observations of instantaneous low-DO occurrences, the duration of exposure to low DO is particularly relevant to the question of habitat quality. For this analysis, 1-hour averaged DO concentrations and thresholds of 5 mg/L and 2.3 mg/L were used to calculate unique “low DO excursions”, which are periods of time when DO was continuously below a threshold. The 5 mg/L threshold is the water quality objective from the Basin Plan. The value of 2.3 mg/L is a threshold for impacts for fish after 24-hour exposures that is recommended for the Virginian Province of the East Coast (USEPA 2000). It is not known whether this threshold is applicable to the fish species in LSB but it provides a useful benchmark for evaluating the data for obvious concerns on short time scales.

At most stations, low DO events occur on rapid time scales that are consistent with the major drivers of tidal advection and diurnal production/respiration. Excursions below 5 mg/L were typically the shortest at the Dumbarton Bridge (1-2 hours) and longest in Guadalupe Slough (7-20 hours). The excursion durations at the other stations fell in between these two end members (Figure 11, Table 4).

During the spring and summer months, the excursions lasted longer, with peak durations occurring in July through October. This pattern is especially strong in Guadalupe Slough where the average excursion duration peaked above 30 hours in the late spring and late summer (Figure 12).

For all stations except Guadalupe Slough, 99% of excursions lasted less than 24 hours. In Guadalupe Slough, 90% of the excursions were less than 24 hours (Figure 13). However, some longer excursions were observed at this site, such as one lasting 12 days.

Importantly, the measurements do not show any instances at any stations where DO fell below 2.3 mg/L for 24 hours, which would be indicative of acute impacts on fish (Table 4, Figure 14). Guadalupe Slough and Alviso Slough were the only stations where DO concentrations fell below 2.3 mg/L for a non-trivial duration. At Guadalupe Slough, the typical excursion lasted 2 hours. The longest excursion lasted 18 hours.

The excursion durations calculated here are likely an underestimate. The algorithm used to identify excursions below a threshold was reset every time the DO concentration went above the threshold or there was a break in the dataset lasting more than 2 hours. As a result, there were potentially cases where a single excursion below 5 mg/L was broken into two or three by missing data points or a sudden fluctuation above the threshold. It is not clear whether these brief upswings in DO represent an actual “reset” in the DO conditions for fish habitat.

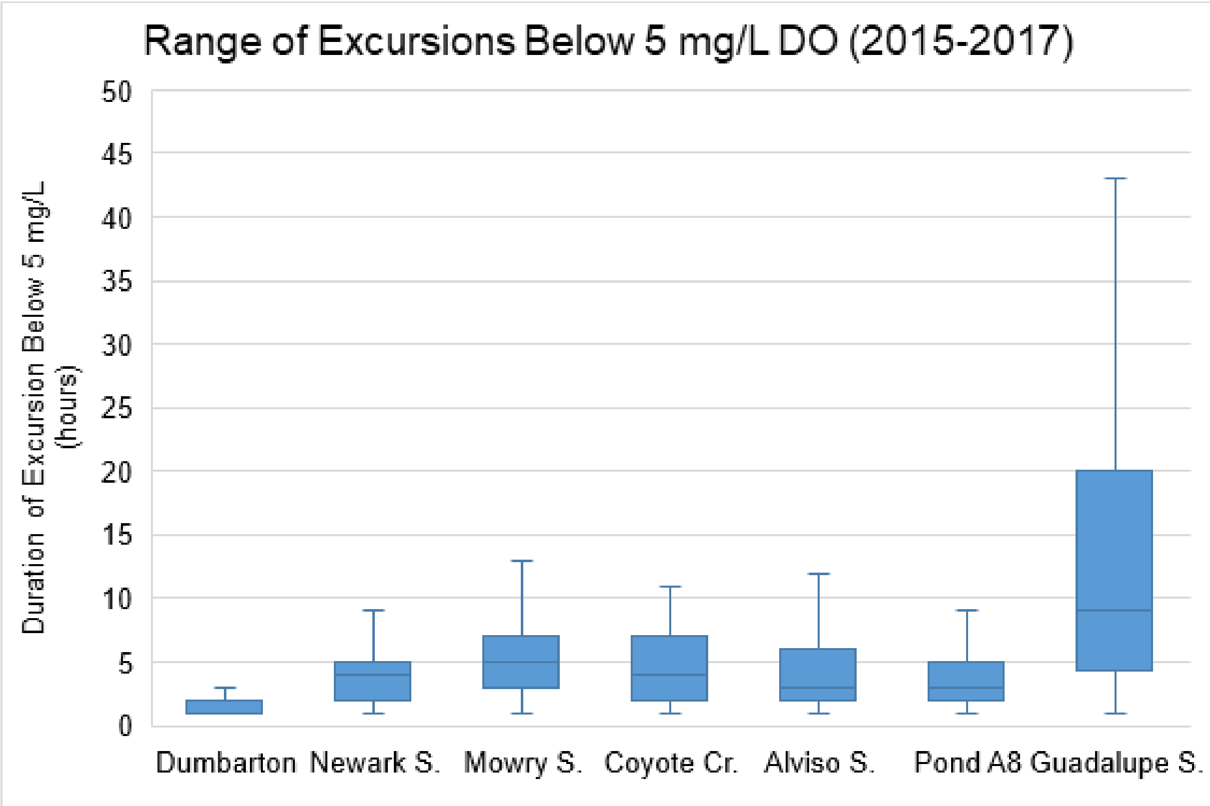


Figure 11: Range of durations when dissolved oxygen was continuously less than 5 mg/L at moored sensor stations in 2015-2017. Excursions below 5 mg/L were identified using 1-hour averaged data. The boxes show the interquartile range with the median represented as the middle line. The lines extending from the boxes show the 5th and 95th percentiles.

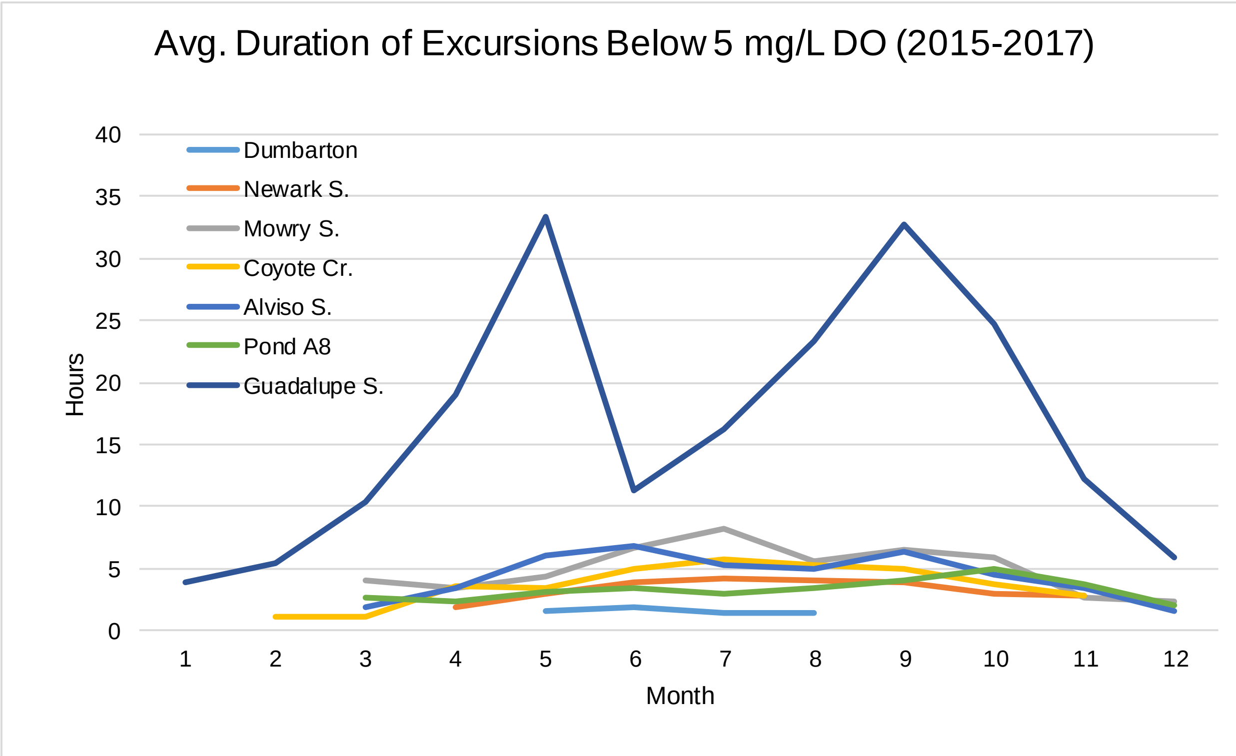


Figure 12: Average durations when dissolved oxygen was less than 5 mg/L by month at moored sensor stations in 2015-2017.

Table 4: Summary statistics for the durations of unique excursions of dissolved oxygen concentrations below thresholds at moored sensor stations in 2015-2017. The column for N indicates the number of unique excursions. The columns for Min, 25th %ile, Median, 75th %ile, and Max represent the distribution of excursion durations in hours.

(a) Duration of Excursions of Dissolved Oxygen below 5 mg/L

Moored Sensor	N	Min (hours)	25th %ile (hours)	Median (hours)	75th %ile (hours)	Max (hours)
Dumbarton Bridge	40	1	1	1	2	3
Newark Slough	516	1	2	4	5	9
Mowry Slough	657	1	3	5	7	44
Coyote Creek	741	1	2	4	7	11
Alviso Slough	1297	1	2	3	6	121
Pond A8 Outlet	598	1	2	3	5	67
Guadalupe Slough	704	1	5	9	20	293

(b) Duration of Excursions of Dissolved Oxygen below 2.3 mg/L

Moored Sensor	N	Min (hours)	25th %ile (hours)	Median (hours)	75th %ile (hours)	Max (hours)
Dumbarton Bridge	0					
Newark Slough	0					
Mowry Slough	1	1	1	1	1	1
Coyote Creek	0					
Alviso Slough	29	1	1	1	2	6
Pond A8 Outlet	3	1	1	1	1	1
Guadalupe Slough	349	1	1	2	4	18

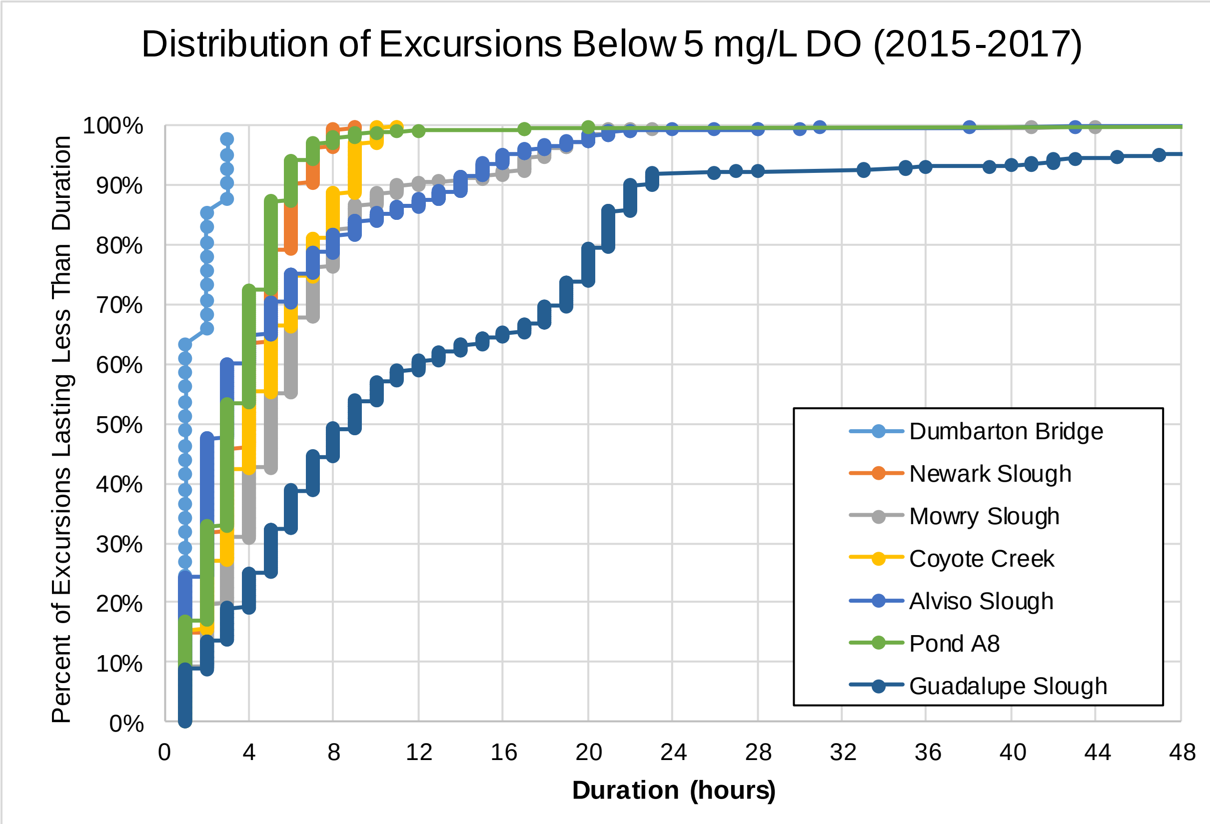


Figure 13: Quantile plot (Weibull distribution) showing the distribution of time that dissolved oxygen (1-hour averaged) was continuously less than 5 mg/L at moored sensor stations in 2015-2017. At the site with the longest excursions, Guadalupe Slough, 90% of the excursions below 5 mg/L lasted less than 24 hours.

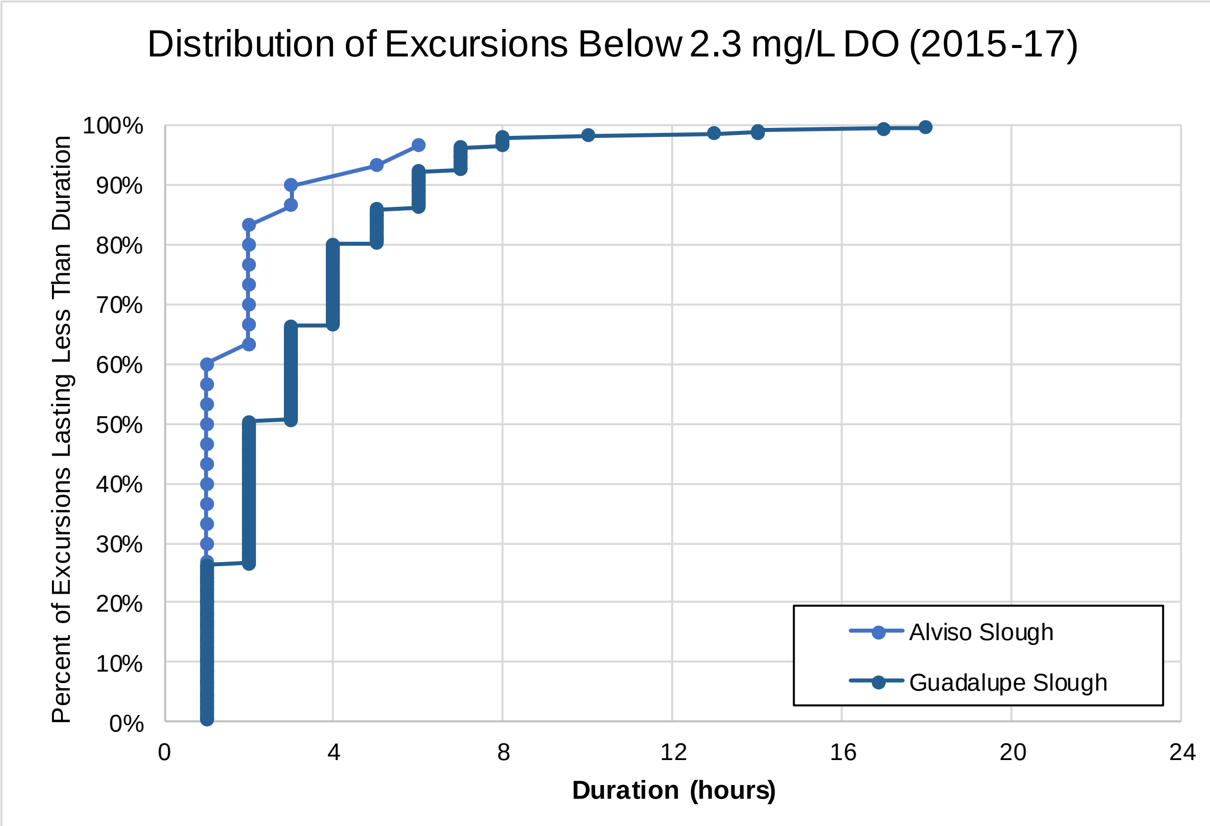


Figure 14: Quantile plot (Weibull distribution) showing the distribution of time that dissolved oxygen (1-hour averaged) was continuously less than 2.3 mg/L at moored sensor stations in 2015-2017. All of the excursions below 2.3 mg/L lasted less than 18 hours. All other stations had no excursions of DO below 2.3 mg/L.

F. Comparison of Water Quality Measured by Moored Sensors to Discrete Measurements Made During Fish Trawls

A key objective for this overall report is to bring together observations from the SFEI mooring program with fish data collected by researchers from University of California Davis (UCD) to advance our understanding of DO-related habitat quality in LSB. UCD has been conducting fish surveys and collecting data on DO and other water quality parameters during, approximately, monthly fish trawls in LSB. The variations in catch relative to water quality measured during the trawls are explored in detail in Chapter 3. Therefore, it is important to know whether the discrete measurements of water quality during the trawls are representative of typical conditions at these sites.

There is limited direct overlap between the fish trawl locations and the moored sensors both in space and time, which makes comparisons between the datasets difficult. Two of the seven moored sensors, Coyote Creek and Alviso Slough, are in the vicinity of the fish trawl sites. The data from fish trawls were collected between 2010 and 2016. The data for moored sensors at Coyote Creek and Alviso Slough were collected between 2015 and 2017 (mostly in 2016-2017). Therefore, using the data from Alviso Slough and Coyote Creek for 2016-2017 would provide the best "apples to apples" comparison but the sample size for the trawl measurements would be too small. Instead, we chose to compare the moored sensor data from Alviso Slough and Coyote Creek in 2016-2017 to all of the trawl data knowing that the mismatch in time would introduce some uncertainty.

In general, the distributions of temperature, salinity, and DO observations during trawls appear to be comparable to those measured by moored sensors (Figure 15), suggesting that conditions during fish trawls were similar to those sampled continuously by water quality moorings. The trawl conditions appeared to be slightly lower in DO compared with the continuous monitoring, possibly due to sampling in shallower parts of LSB. Given the limited direct overlap in space and time for these two datasets, it is not possible to conclude anything with certainty, however the data do not indicate large differences that would raise concerns about the validity of using the temperature, salinity, and DO measurements during the trawls to assess the relationship between fish abundance and water quality.

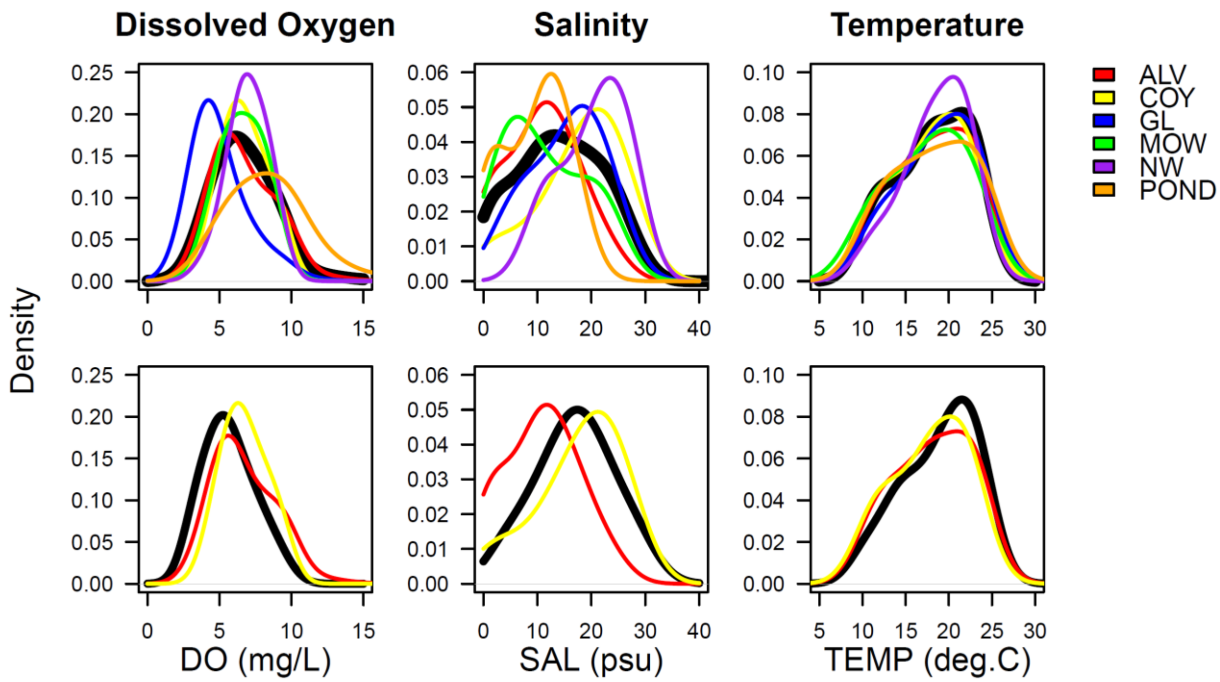


Figure 15: Comparison of water quality measurements made during fish trawls and measurements made by nearby moored sensors. Top panel: Distributions of dissolved oxygen, salinity, and temperature measured by moored sensors in 2016-2017. Results for individual moored stations are shown with colored lines. Results for all stations pooled are shown with the black line. Results from the Dumbarton Bridge station were not included. Bottom panel: Distributions of dissolved oxygen, salinity, and temperature measured during fish trawls by UD Davis in Lower South Bay in 2010-2017. The black line shows the results for all fish trawl stations pooled together. The yellow and red lines are the distributions for the moored sensors for Alviso Slough and Coyote Creek from the top panel. These moored sensors are in the vicinity of the trawl sites and, therefore, are the best comparisons to the data from the trawl sites. (Graph courtesy of Levi Lewis, UCD)

CONCLUSIONS & RECOMMENDATIONS

Dissolved oxygen in Lower South Bay exhibits high variability across diurnal, seasonal, and annual timescales, as well as across space. In this chapter, we describe the broad trends observed in the DO concentrations in LSB.

Low DO concentrations occur in LSB and likely originate in sloughs and other perimeter habitats. In particular, sloughs that receive treated wastewater or pond discharge with elevated organic matter have higher oxygen demand. As a result, water in the sloughs is depleted of its DO as it is transported through the estuary by diurnal tides. Low-DO events that occur in down-estuary locations (e.g., Dumbarton Bridge) have been linked to tidal advection of slough waters (Crauder, et al. 2016). Accordingly, the Alviso and Guadalupe Slough sites, which are down-estuary from the salt pond complex containing Pond A8 and some wastewater discharges, show the greatest likelihood of low-DO events. The fluctuations in DO were more moderate at the other three slough sites (Newark Slough, Mowry Slough, and Coyote Creek).

The moored sensor data show that DO typically meets the Basin Plan water quality objective of 5 mg/L in the deep channels. However, in the sloughs, DO concentrations fell below 5 mg/L for 11-65% of the observations throughout the year and as much as 90% of the summer months at some stations. The most persistent low DO concentrations were in Guadalupe Slough. DO in Guadalupe Slough is commonly less than 5 mg/L (65% of the period of record), less than acute objective for Suisun Marsh (32% of period of record), and less than the Suisun Marsh chronic objective (75% of calculated 30-day averages from the period of record). In Alviso Slough, the DO concentrations are not as low as in Guadalupe Slough presumably because the oxygen demand is offset by discharges of super-saturated water from Pond A8. This balance is dependent on management practices in use at Pond A8. If those management practices were changed, DO concentrations in Alviso Slough could change – for the better or the worse.

At most stations, it appears that low-DO events occur on rapid time scales that are consistent with the major drivers of tidal advection and diurnal factors. Excursions below 5 mg/L were typically the shortest at the Dumbarton Bridge (1-2 hours) and longest in Guadalupe Slough (7-20 hours). During the summer months, the excursions lasted longer, with peak durations occurring in July through October. The longest continuous excursion below 5 mg/L was 12 days in Guadalupe Slough. Excursions below 2.3 mg/L were observed in Alviso and Guadalupe Sloughs but, importantly, lasted less than a day. The value of 2.3 mg/L is a threshold for impacts for fish after 24-hour exposures that is recommended for the Virginian Province of the East Coast (USEPA 2000). It is not known whether this threshold is applicable to the fish species in LSB but it provides a useful benchmark for evaluating the data for obvious concerns on short time scales.

In general, the distributions of temperature, salinity, and DO observations during fish trawls appear to be comparable to those measured by moored sensors suggesting that conditions during fish trawls were similar to those sampled continuously by water quality moorings. This finding dispels concerns that water quality measurements used to assess fish abundance in Chapter 3 could be biased. A greater concern is that DO concentrations show strong variability with tide stage and season. Fish abundance, behavior, and life stage also vary with tides and seasons. The covariance of DO with all of these factors that are important for fish creates a challenge for isolating the effects of DO (and water quality in general) on fish habitat. The statistical models relating fish abundance to water quality in Chapter 3 included seasonal terms to account for this fact. Chapter 3 contains further discussion of this issue.

The analyses presented in this chapter focus on the seven moored sensor stations. The near continuous measurements of DO and other water quality parameters at these stations illustrate patterns at temporal scales that could not be evaluated using monthly discrete measurements. However, there is still a major data gap, which is knowing the DO concentrations at other locations in LSB. To address this data gap, a dynamic representation of DO in space and time from a coupled biogeochemical-hydrodynamic model is needed. Producing this dynamic DO field for the entirety of Lower South Bay will require continued moored sensor monitoring, model development, and studies to determine the rates for biogeochemical processes from different habitats in the estuary.

Continued analysis and synthesis of the moored sensor data from LSB is also warranted. Inter-annual variability was not assessed in this report because there were too few years of data. Changes in winter rainfall, changes in gate operations, and restoration of former salt ponds can have profound impacts on DO concentrations in nearby sloughs. Analysis of moored sensor data collected before and after these changes will yield valuable insights.

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APPENDIX A: GATE OPERATIONS

Table A1: Gate operations for ‘the notch’ on A8 at the Alviso Slough feeder channel, and elsewhere in the Alviso complex.

Pond	Slough	Date	Action
A8	Alviso Slough	June 2011-December 2011	1/8 gates open (5 ft)
A8	Alviso Slough	December 2011-June 2012	closed
A8	Alviso Slough	June 2012-December 2012	3/8 gates open (15 ft)
A8	Alviso Slough	December 2012-June 6, 2013	closed
A8	Alviso Slough	June 6, 2013-December 6, 2013	3/8 gates open (15 ft)
A8	Alviso Slough	December 6, 2013-March 6, 2014	closed
A8	Alviso Slough	March 6, 2014-September 29, 2014	3/8 gates open (15 ft)
A8	Alviso Slough	September 29, 2014-June 2, 2017	5/8 gates open (25 ft)
A8	Alviso Slough	June 2, 2017-present	8/8 gates open (40 ft)
A3W	Guadalupe Slough	September 2016-present	open

APPENDIX B: MOORED SENSOR DATA: QUALITY CONTROL

Data are quality assured using several automated procedures, and the results are verified (and corrected, as needed) by inspection. Specific tests used for QAQC of SFEI's moored sensor data include:

- Screen for absolute outliers: ranges of possible values for each parameter are enforced. Data that lie outside of this range are replaced by null values. For DO, this range is 0 to 30 mg/L. Regions of super-saturation (e.g. near Pond A8) result in high, real values of DO and require that this limit not be restrictive.
- Screen for relative outliers: each data point is compared to the mean +/- one standard deviation of the surrounding two hours' worth of data, excluding its own value. Data outside this range are replaced with null values.
- The variance of a one-week window of data is compared to that of its neighbors. If the variance is too low (characteristic of a broken sensor pin and of sediment fouling) or too high (characteristic of biological fouling), the window of data is replaced with null values.
- Limits on the rate of change for each parameter are enforced: if gradients exceed parameter- and site-specific limits, those data are replaced with null values. Slow changes in a parameter value with time could indicate clogging of the sensor, while rapid changes could indicate a mechanical or electrical failure within the instrument.
- If null values were recorded for T or conductivity, or if other screening processes resulted in nulls for these parameters, the DO concentration value (which depends on T, S, and DO saturation) is corrected using data from a co-located or nearby sensor. EXO2 sensors each have a thermometer, so co-located T is almost always available (barring sonde failure). Nearby sensors (at the same horizontal location; possibly offset vertically) are maintained by the USGS at the Dumbarton Bridge, Coyote Creek, and Alviso Slough. If no nearby conductivity data are available, missing conductivity values are replaced by the linear interpolation of the reliable values surrounding the missing data for the purpose of correcting the DO concentration estimate. Note that conductivity data replaced in this manner are used only for correcting DO, and are not distributed. Instrument-specific equations are applied to recalculate the DO concentration if null values of T and/or conductivity were replaced.
- The DO concentrations were plotted for the entire period of record for each sonde. The plots were reviewed for suspect data such as when the DO concentration had a large offset between the end of one deployment and the beginning of the next. Suspect data were removed for the periods shown in the Table B1.
- Finally, the data were checked for the level of completeness on a monthly basis by comparing the number valid observations to the total possible observations. Months where valid observations covered less than 80% of the time were excluded from plots showing the seasonality of low DO events.

Table B1: Suspect data for dissolved oxygen that were manually removed from the moored sensor time series.

Moored Sensor	Period Start	Period End	Comment
Newark	4/12/2016	5/13/2016	Suspected fouling
Newark	10/9/2016	12/6/2017	Suspected fouling
Newark	10/7/2017	10/11/2017	Anomalously low and offset data
Guadalupe	11/4/2015	12/3/2015	Suspected fouling
Mowry	7/30/2015	8/12/2015	Anomalously high and offset data
Coyote	6/28/2016	7/20/2016	Anomalously high and offset data

Table B2: Percent of each month for which there are valid DO data from the moored sensors. Cells in blue are >80%. Cells in orange are <80%.

Station	Year	J	F	M	A	M	J	J	A	S	O	N	D
Alviso Slough	2013									20	25	99	99
	2014	98	98	98	97	95	88	73	98	83	77	80	0
	2015	81	65	78	95	98	98	98	95	95	96	97	97
	2016	99	73	97	97	98	96	97	97	98	97	96	98
	2017	97	96	97	93	98	95	97	97	97	93	98	98
Coyote Creek	2015					98	96	94	95	29	95	91	95
	2016	95	94	93	93	95	79	33	96	96	96	97	97
	2017	96	93	58	30	96	88	34	96	81	93	96	95
Dumbarton	2013							95	94	94	94	93	94
	2014	94	42	85	70	93	95	93	94	95	94	82	62
	2015	93	94	93	92	80	94	94	94	94	92	95	93
	2016	95	91	93	92	93	92	92	33	53	94	94	94
	2017	96	95	95	94	93	93	93	94	95	95	95	96
Guadalupe Slough	2015						97	96	96	98	98	13	90
	2016	97	98	95	96	97	96	96	97	97	48	97	33
	2017	40	24	60	30	96	38	16	96	97	97	97	96
Mowry Slough	2015						97	89	59	98	43	0	92
	2016	97	98	91	95	94	87	96	85	96	81	97	97
	2017	97	97	91	91	95	81	96	70	0	15	0	95
Newark Slough	2015				95	96	95	94	97	97	97	95	96
	2016	94	95	26	0	55	93	96	97	96	27	0	0
	2017	41	29	57	93	97	95	96	94	95	81	38	1
Pond A8 Feeder	2015							97	95	98	99	99	99
	2016	99	78	94	86	98	78	36	98	92	91	82	99
	2017	98	96	98	95	98	98	86	90	87	31	92	98

CHAPTER 3

Habitat Quality and Fish Abundance in the Alviso Marsh Complex 2010-2016

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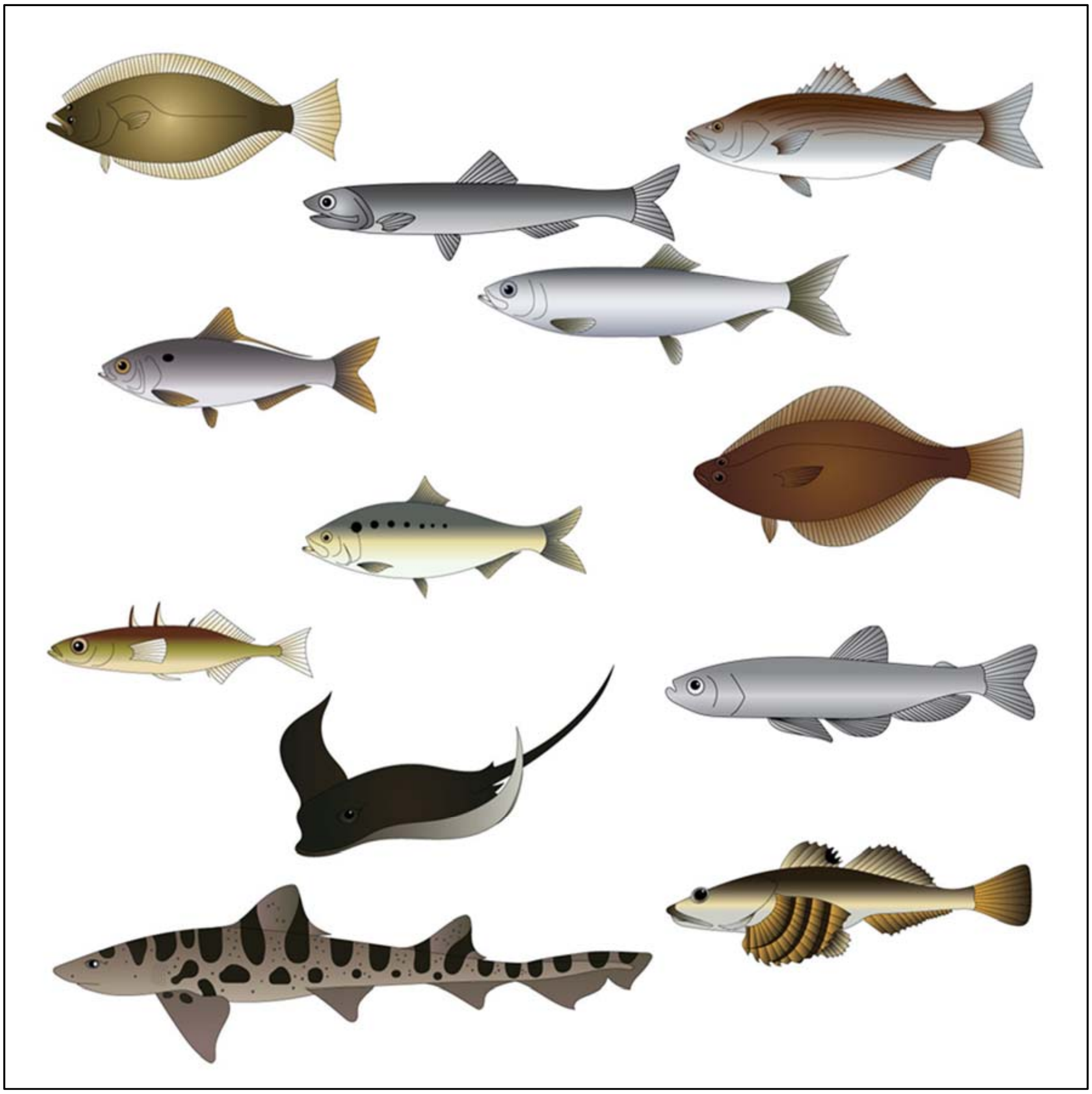

Artwork by Adi Khen

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AMC	Alviso Marsh Complex
SFE	San Francisco Estuary
SJ-SC RWF	San Jose-Santa Clara Regional Wastewater Facility
UCD	University of California, Davis
SFEI	San Francisco Estuary Institute
GAM	generalized additive model
GLM	generalized linear model
TEMP	water temperature in degrees Celsius (°C)
SAL	salinity in practical salinity units (psu)
DO	concentration of dissolved oxygen in water in mg per liter (mg/L)
SEC	Secchi depth in cm (cm)
OST	Oxygen, Salinity, and Temperature (one of several GAM models)
OSTN	Oxygen, Salinity, Temperature, and Secchi depth (one of several GAM models)
Catch	raw number or fish collected in a trawl sample
CPUE	catch per unit effort (count per tow duration)
Relative catch	proportional change in catch relative to the proportional change in effort
Y	Year (factor)
M	Month
d	trawl duration (min.)
t	trawl
s	fish species
m	metric (SAL, TEMP, DO)
x	binned unit of water quality metric (m)
ALV	Alviso Slough
COY	Coyote Creek
ART	Artesian Slough
LSB	Lower South Bay
DMP	Dump Slough
UCOY	Upper Coyote Creek

INTRODUCTION

Coastal salt marshes and wetlands are among the most productive and economically important habitats that strongly influence nutrient cycling, food production, and spawning and rearing of estuarine species (Vernberg 1993, Sousa et al. 2010). These coastal habitats are also the most degraded and threatened aquatic habitats worldwide, resulting in impairment of the numerous ecosystem services they provide (Lotze et al. 2006). Degradation of estuarine habitats can strongly influence the viability of many estuarine and marine fish populations by impacting spawning, growth, condition, and survival during early life stages. Human disturbance can also favor the invasion of non-native species (Jung & Houde 2003, Valiela et al. 2004, Weinstein et al. 2014). The San Francisco Estuary (SFE) in Central California, USA has experienced myriad perturbations including the draining of wetland habitats, diversion of freshwater flows, nutrient loading from fertilizer and wastewater effluent, and the introduction of alien species which have all likely contributed to significant changes in the functioning of the estuary (Glibert et al. 2011, Cloern & Jassby 2012). For example, declines of many species of zooplankton and fishes in the northern SFE are believed to be linked to human activities (Kimmerer 2002, Sommer et al. 2007, Cloern & Jassby 2012, Feyrer et al. 2015). Much less is known about trends in fish assemblages and species abundances in South and Lower South San Francisco Bays, with work to date having primarily explored associations with large-scale climate patterns (Cloern & Jassby 2012, Feyrer et al. 2015) and presence in restored salt marshes (Saiki & Mejia 2009).

As part of a broader effort evaluating the impacts of anthropogenic nutrients on the ecological health of the SFE (Crauder et al. 2016), we analyzed fish trawl data from Lower South Bay to identify factors that influence fish abundance, with a particular focus on evaluating relationships between abundance and dissolved oxygen levels. Since 2010, the Hobbs Lab at the University of California, Davis has conducted monthly otter trawl surveys in the sloughs and restored marshes of the Alviso Marsh Complex (AMC) to assess spatial and temporal (seasonal and interannual) variation in fish and macro-invertebrate assemblages (Buckmaster 2014, Cook 2016). These data are valuable for assessing the potential effects of large-scale salt pond restoration (South Bay Salt Pond Restoration Project) and inputs of wastewater effluent into the AMC on estuarine fish and invertebrate communities. These survey data can be also be used to develop models describing how abundances of fishes (catch per unit effort) covary with water quality attributes (e.g., salinity, temperature, clarity, and dissolved oxygen). Model outputs can then be used to assess habitat quality (i.e., predicted abundances) from continuous records of environmental conditions throughout the AMC. Here, we examine variation in the abundance of fishes in the Alviso Marsh Complex in relation to salinity, temperature, clarity, and dissolved oxygen, each measured at the time of capture, to develop predictive models for estimating habitat suitability for a select subset of estuarine fishes. By providing a refined understanding of the environmental drivers and the potential impacts of human activities on fish communities, we can better assess the current ecological state of the AMC and develop more effective strategies to restore and conserve this highly modified and valuable ecosystem.

METHODS

Study region

This study was conducted in the Alviso Marsh Complex (AMC) located at the terminus of Lower South San Francisco Bay (LSB) (Fig. 1). It is a shallow (mean depth of 3.4 m MLLW), meso-tidal (2.5-3.0 m), lagoon-type estuarine sub-embayment of the SFE (Gartner & Walters 1986). The AMC receives intermittent freshwater from three small tributaries, Coyote Creek, Guadalupe River and Stevens Creek in winter months resulting in fresh to oligohaline conditions during years of high precipitation and meso-polyhaline conditions in summer and year-round during dry years. The marsh vegetation community is a mix of cordgrass (*Spartina foliosa*), saltgrass (*Distilichlis spicata*), alkali bulrush (*Bolboschoenus maritimus*), and pickleweed (*Sarcocornia pacifica, Sarcocornia depressa*). Beginning in the early 1900s much of the historic tidal salt marsh habitat was converted to commercial salt ponds, upstream watersheds were urbanized, and freshwater inputs reduced due to upstream capture and diversions for urban, agricultural, and industrial use.

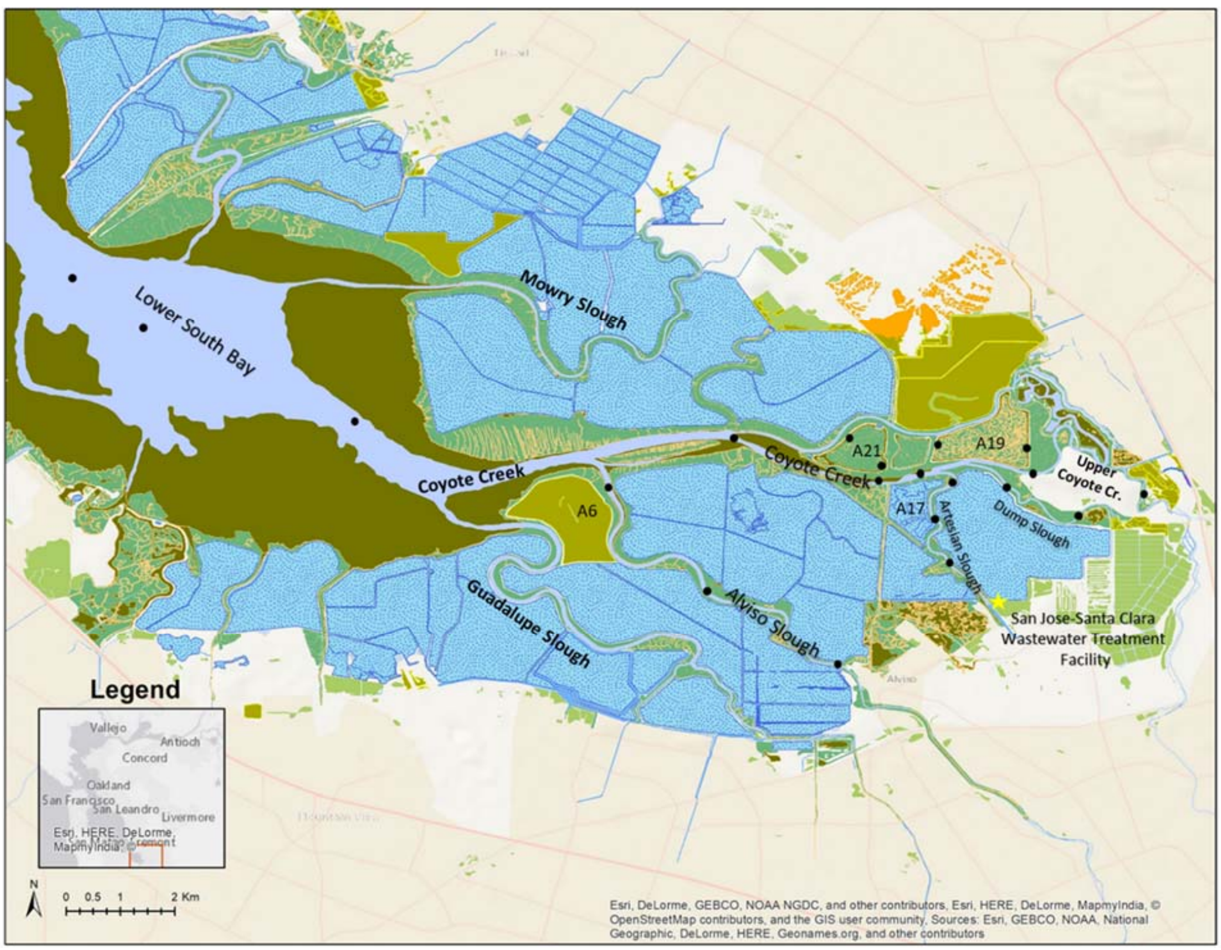

Figure 1. Map of the Alviso Marsh Complex (AMC) and sampling stations, including the fully-tidal restored ponds (A6, A17, A19, A21), Dump Slough, Artesian Slough, Alviso Slough, Coyote Creek, and Lower South Bay.

In 2003, 15,100 acres of industrial salt production ponds were purchased by the state of California for restoration to a mix of tidal and muted tidal ponds in accordance with the South Bay Salt Pond Restoration Program (EDAW et al. 2007). Phase 1 of the restoration resulted in over 3,400 acres of restored tidal habitat, with additional restoration actions planned for Phase 2. Two tidally-restored salt ponds (A19 and A21) in the "island pond" complex were regularly sampled throughout this study. These island ponds are bounded by Coyote Creek to the south and Mud Slough to the north (Fig. 1). Two breaches ~20 m wide were cut along the southern border of each pond in March 2006, allowing complete inundation and tidal flushing from Coyote Creek. The arrangement of the breaches resulted in significant tidal trapping along the eastern shore of Coyote Creek, increasing residence times and reducing the mixing of pond and slough waters (MacVean & Stacey 2011). Removal of sediment for levee creation resulted in borrow ditches surrounding the interior of each pond that were up to 60 m wide and 2-3 m deep at high tide. Borrow ditches provided deeper habitats within tidally-restored ponds that could be sampled using standard sampling gear (otter trawls) during high spring tides.

Sampling design

Monthly sampling was conducted from July 2010 to December 2016 at multiple permanent stations including four tidally-restored salt ponds (A6, A17, A19 and A21), 5 sloughs (Mainstem Coyote Creek-COY, Upper Coyote Creek-UCOY; Alviso Slough- ALV; Artesian Slough-ART; and Dump Slough-DUMP) and 2 stations in the Lower South Bay (LSB) (Fig. 1). To quantify the abundance of fishes and macroinvertebrates (> 12-mm), a four-seam otter trawl with a 1.5 m by 4.3 m (6.4 m^2) opening, length of 5.3 m, and mesh size of 3.5 cm in the body and 0.6 cm in the cod end, was deployed and towed against the prevailing tide at 2-5 km/h for 5-10 minutes. Otter trawls are commonly used for assessing variation in the abundances of different fish taxa in space and time. It is important to note, however, that the relative abundances observed in otter trawls (conducted on flat, muddy bottoms in the center of sloughs and channels) likely differ from those adjacent to the shoreline (e.g., sampled using beach seines) or within more complex habitats (e.g., tules, rocks, and woody debris). Furthermore, catchability may vary among species and size classes—small (e.g., < 15 mm) species and life stages are less likely to be retained by otter trawl mesh and large, highly mobile taxa (e.g., adult leopard sharks and striped bass) are likely able to avoid the trawl. Despite these caveats, trawl data are excellent for assessing relative changes in the abundances of fishes in space and time.

Given that tows could not be conducted instantaneously at all sites, sampling was conducted throughout the day. Tidal regimes varied among months such that all sites were sampled at a variety of tidal heights. Due to bathymetry, however, sites had to be monitored in a consistent order to prevent stranding of the research vessel in shallow waters. Thus, slightly higher tides were generally sampled in fall-winter versus spring-summer; Alviso and Artesian Sloughs were generally sampled at slightly lower tides (median ~ 4ft) than other slough sites (median ~ 6 ft), and tidal ponds (A19 & A21) were generally sampled when flooded at higher tides that provided ample access to the tidal floodplain (median ~ 2m) (Appendix 3). Environmental conditions can vary in both space and time, and we used this spatiotemporal variation to model fish abundance patterns in the AMC and assess the responses of focal species to changes in water quality.

Trawls and Catch Calculations

During the study period (2010-2016), a total of 1,267 trawls were conducted, of which 1,212 were included in final analyses (Fig. 2). Trawls were removed from analyses due to questionable water quality values (identified by QAQC procedures). Fishes were identified to species, counted, and standard lengths of the first 30 individuals of each species were recorded.

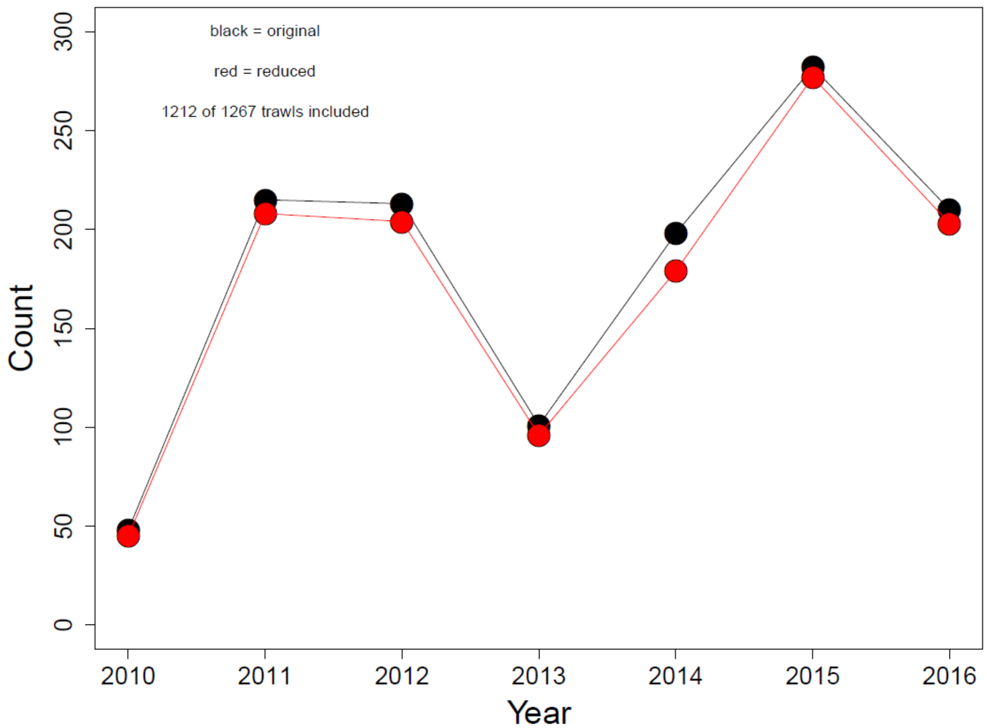

Figure 2. Number of trawls included in the analysis. All trawls (black) were inspected for quality assurance and only the trawls that met quality criteria were included in analyses (red).

Fish counts were summed for each trawl (total catch = $catch_t$) or by species for each trawl (species catch = $catch_{t,s}$) and scaled to a standard tow duration (d) of 10 min per trawl ($catch_{10}$) using:

$$catch_{10} = catch * \frac{10}{d}, 10 \geq d \geq 4. \quad (1)$$

Proportional catch (*p_catch*) and effort were calculated for 20 consecutive bins equally distributed across the range of each environmental variable (DO, SAL, TEMP), and used to create cumulative distribution curves for visualizing and contrasting proportional catch. By using standardized proportional binning for each variable, catch curves could be contrasted directly across equivalent bins that were each 5% of the range of each predictor variable. Proportional catch was calculated for each bin (x) of each environmental metric (m) (and for each fish species, s) using:

$$p\_catch_{m,x} = \frac{\sum_{t=1}^{n} catch_{10,m,x,t}}{\sum_{t=1}^{n} catch_{10,t}}, \qquad (2)$$

where m = mth environmental metric (dissolved oxygen-mg/L, salinity-psu, and temperature-°C), x = xth binned range (1:20) for the environmental metric m, and t = tth trawl per unit bin. Proportional effort (*p_effort*) was calculated as the total number of trawls (*effort* or N) for each bin (x) of each environmental metric (m) using:

$$p\_effort_{m,x} = \frac{\sum_{t=1}^{n} effort_{m,x,t}}{\sum_{t=1}^{n} effort_{t}} = \frac{N_{m,x}}{N}. \qquad (3)$$

Relative catch (r_*catch*) was used to explicitly contrast differences between catch (or species catch) and effort in relation to environmental conditions. Relative catch was calculated as the difference between proportional catch and corresponding proportional effort for each bin (x) of the environmental variable (m):

$$r\_catch_{m,x} = p\_catch_{m,x} - p\_effort_{m,x}. \qquad (4)$$

Water Quality Measurements

Water quality (temperature in ˚C, salinity in psu, and dissolved oxygen in mg/L) was measured using Yellow Springs Instruments (YSI 85 and Pro 2030 2010-2014; YSI 6600 2015-2016) at the beginning and/or end of each tow at a depth of approximately 1 m sub-surface. YSI meters were calibrated quarterly. When depths were greater than 10 m, additional water quality measurements were often taken at 1 m above the bottom. Water clarity (Secchi depth in cm) and trawl depth (in m) were also recorded for each trawl. Examination of top and bottom tows indicated weak, if any, stratification (Appendix 2); thus, for tows with multiple water quality measurements (beginning/end, top/bottom), all values were compared and averaged to provide a single integrated value for each tow.

Species selection and aggregation

Over 73,000 individuals of more than 50 distinct species of fish were captured in otter trawls in the Alviso Marsh Complex, with 58% of the total catch dominated by just three native species (Threespine Stickleback, Northern Anchovy, and Pacific Staghorn Sculpin) (Fig. 3). Juveniles (approximately 15-90 mm) of these three species recruited in large numbers during spring-summer months, thus resulting in their numerical dominance. The non-native Yellowfin Goby was the fourth most abundant taxa, also exhibiting large spring-summer recruitment events. All other species were considerably less abundant; however, many were commonly present as larger juveniles or adults. No salmonids were observed in the > 1,200 tows conducted or this study. Though steelhead have been observed in upstream portions of the watershed and adult Chinook salmon have been observed within tidally-muted ponds in Alviso Marsh, no salmonids were captured in our otter trawl surveys. Though large adult salmonids may be able to evade the sampling gear, other large mobile fishes (e.g. Striped Bass) were regularly caught in trawls, and juvenile salmonids (e.g., out-migrating par and smolts) should be highly susceptible to the sampling gear. Therefore, the absence of adult and juvenile salmonids in the trawl dataset suggests that they were absent or rare in the system during the study period.

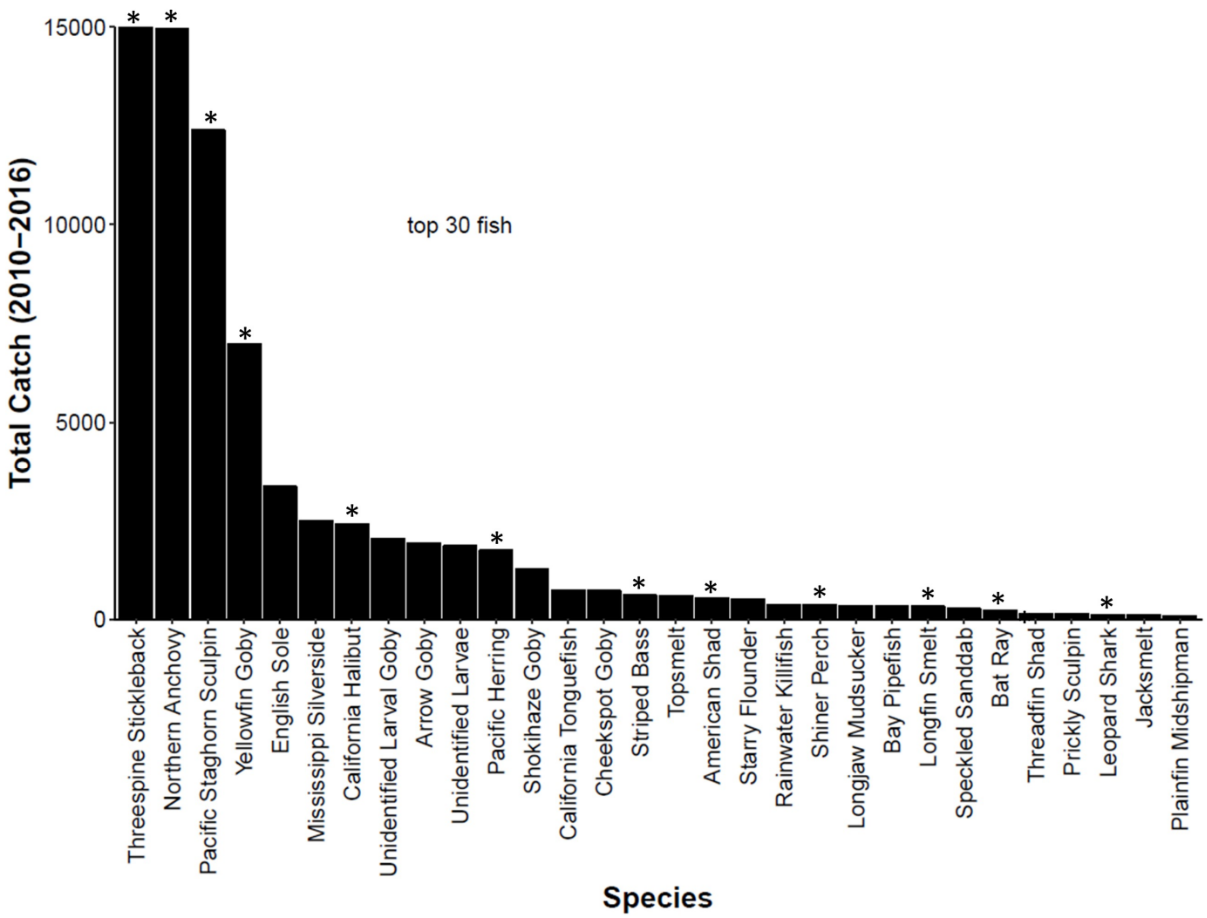

Figure 3. Total raw counts of the 30 most abundant fish species collected in otter trawls in the Alviso Marsh Complex. Asterisks indicate focal species modeled individually in the current study.

To assess relationships between water quality and the abundances of individual fish species, several criteria were used to select a subset of 12 focal species that were either numerically dominant or exhibited unique characteristics that afforded greater significance over other candidate taxa (Fig. 3, Table 1). Given the numerical dominance of Threespine Stickleback, Northern Anchovy, Pacific Staghorn Sculpin, and Yellowfin Goby, these were all included as focal species. Two clupeids, Pacific Herring (native) and American Shad (non-native) exhibited lower abundances but were included due to their economic importance in recreational and commercial fisheries. Striped Bass, Leopard Sharks, California Halibut and Bat Rays were less common, but were included due to both their importance as top predators in the system and their importance to recreational fisheries. Shiner Perch was included as the only estuarine-obligate embiotocid seaperch and its value as a baitfish in recreational fisheries, and Longfin Smelt was included due to its socio-political importance as a listed (threatened) species under the California Endangered Species Act. These 12 species accounted for greater than 76% of the total catch.

Table 1. Species of fish selected for individual analyses, their characteristics, and raw total counts. All taxa except for Longfin Smelt and Threespine Stickleback are fished recreationally or commercially for food or bait. Habitats are L-littoral, B-benthic, and P-pelagic. Seasons of maximal abundance are Su-Summer, Sp-Spring, and W-Winter.

No	Common	Scientific	Family	Abundant	Fishery/Bait	Top Predator	Threatened	Marsh Resident	Native/Exotic	Habitat	Season	Count
1	Threespine Stickleback	*Gasterosteus aculeatus*	Gasterosteidae	x				x	N	L	Su	14996
2	Northern Anchovy	*Engraulis mordax*	Engraulidae	x	x				N	P	Su	14963
3	Pacific Staghorn Sculpin	*Leptocottus armatus*	Cottidae	x	x			x	N	B	Su	12395
4	Yellowfin Goby	*Acanthogobius flavimanus*	Gobiidae	x	x			x	E	B	Su	6977
5	California Halibut	*Paralichthys californicus*	Bothidae		x	x			N	B	Su	2414
6	Pacific Herring	*Clupea pallasii*	Clupeidae		x				N	P	W	1741
7	Striped Bass	*Morone saxatilis*	Moronidae		x	x			E	L	Su	604
8	American Shad	*Alosa sapidissima*	Clupeidae		x				E	P	W	530
9	Shiner Perch	*Cymatogaster aggregata*	Embiotocidae		x				N	L	Sp	358
10	Longfin Smelt	*Spirinchus thaleichthys*	Osmeridae				x		N	P	W	320
11	Bat Ray	*Myliobatis californica*	Myliobatidae		x	x			N	B	Su	217
12	Leopard Shark	*Triakis semifasciata*	Triakidae		x	x			N	B	Su	116
								sum				55631
								% of total catch				76.2

Visualizing catch relative to environmental metrics (CCCs)

We used cumulative catch (distribution) curves (CCCs) to visualize general relationships between fish abundance and environmental predictors (Perry & Smith 1994, Simpson & Walsh 2004). Given the high degree of zero-inflation (many trawls with zero catch for a given species) that is common in fish trawl datasets (i.e., fish are patchy in nature), CCCs provide an assumption-free overview of the conditions under which relative catch is maximized for a species. CCCs plot the cumulative proportion of catch at discrete sampling intervals of a predictor variable. By also plotting cumulative effort at the same discrete intervals of each predictor (Fig. 4), the relative difference between cumulative catch versus effort can be visualized across the full range of each predictor variable. Furthermore, proportional changes in catch versus effort between each interval can be contrasted to determine where changes in proportional catch are disproportionately high or low relative to the change in effort. CCCs provide simple visualizations of the environmental conditions at which relative catch is high or low, thus indicating the conditions under which a species or aggregate community is most and least abundant (i.e., the habitat is most or least suitable).

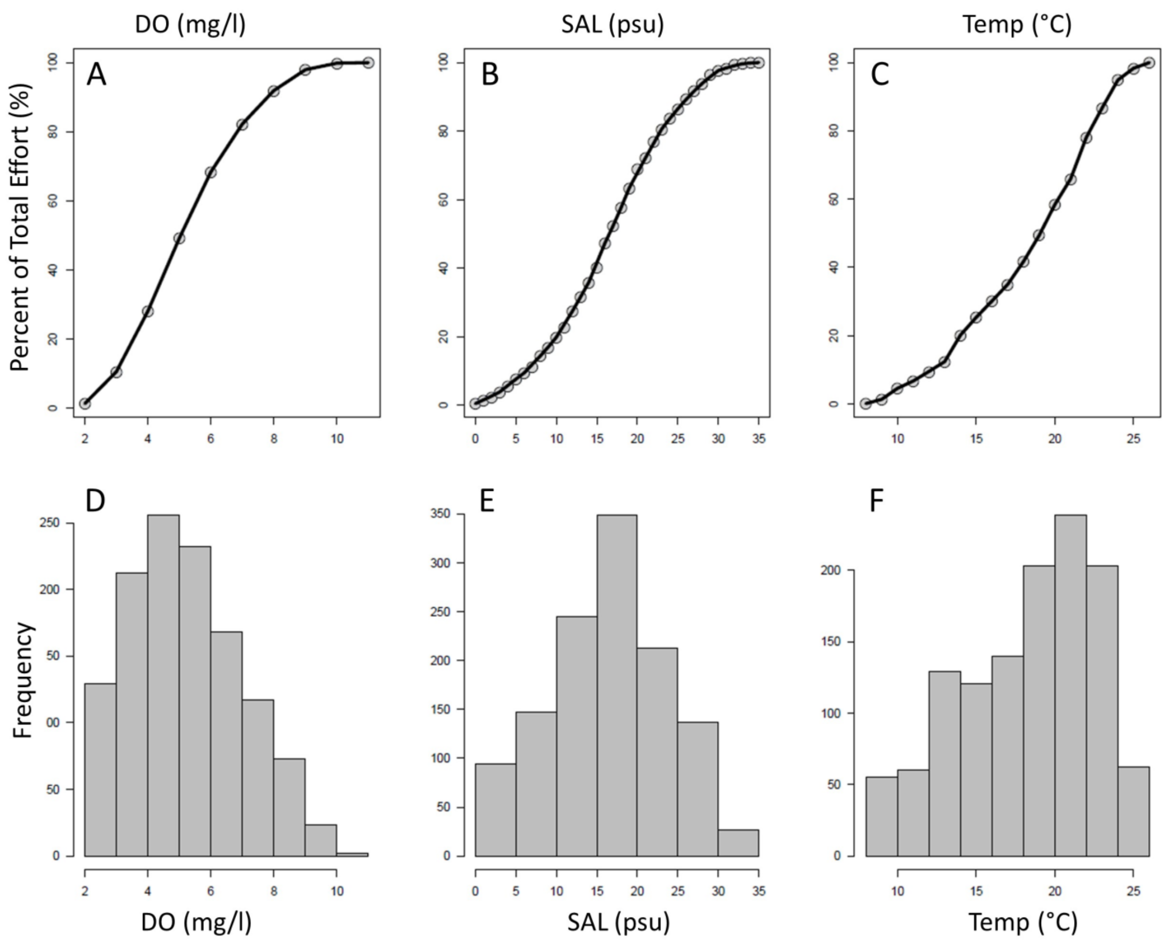

Figure 4. Distribution of sampling effort across the three environmental metrics (dissolved oxygen-DO, salinity-SAL, temperature-Temp): proportional cumulative effort curves (A-C) and histograms of the number of trawls conducted (D-F) across the full range of each environmental metric.

Sampling effort was unevenly distributed with respect to water quality attributes, with most trawls occurring at intermediate values of dissolved oxygen, salinity, and temperature. Dissolved oxygen ranged from around 2 to 11 mg/L, salinity from 0 to 35 psu, and temperature from 8 to 27 °C. Because effort was not uniformly distributed across predictors, the cumulative effort curves (Fig. 4) were used as null distributions to contrast patterns in cumulative catch with expected values given the assumption of catch proportionality (i.e., that catch is directly proportional to effort).

Modeling catch relative to environmental metrics (GAMs)

We used generalized additive models (GAMs) (Wood 2011) to model the abundances (catch per 10 minute tow) of fishes as functions of physical environmental properties (salinity, temperature and dissolved oxygen). GAMs use smoothers, here a thin-plate regression spline (Wood 2003), to describe relationships between predictor and response variables. Splines of multiple independent variables are used additively to predict response variables. The nonparametric splines can describe any functional shape, thus providing a key advantage over parametric models (e.g., GLM) for complex, non-linear relationships between predictor and response variables. Random factors (e.g., Year) are included to account for random variation that is not directly related to the functional responses of interest. GAM analyses were conducted using (restricted) marginal likelihood (REML) generalized cross validation (GCV) in the mgcv package (Wood 2004, 2017) in R version 3.2.2 (RCoreTeam 2015). Catch was modeled using a negative binomial distribution with a log link function to account for zero inflation that is common in fish trawl studies due to the patchy distribution of organisms in nature (Barry & Welsh 2002, Simpson & Walsh 2004, Drexler & Ainsworth 2013).

To explore which factors and combinations of factors best predicted the abundances (rescaled counts = ccounts) of each focal species, we fit 20 generalized additive models (Table 2) incorporating variation in time and water quality. Smooth complexity was limited to a basis dimension of k=6 to prevent over-parameterization and the thin-plate regression spline basis (bs= “tp”) was used. Simple smooths of year (y) and month (m) were fit to examine inter-annual and intra-annual (seasonal) variation in species abundances. Individual smooths of dissolved oxygen (o), salinity (s), temperature (t), and turbidity (n) were also fit separately, as well several pairwise (e.g., os, ot, st, sn, tn) and more complex combinations. To incorporate temporal variability into models of water quality month (smooth effect) and year (random effect) and were also included in several mixed effects GAM models (GAM, bs= “re”), thus explicitly examining the influence of random interannual variability, seasonal patterns, and environmental variability.

Table 2. Generalized Additive Models (GAMs) examined in the current study

```
y <- as.formula(ccount~s(year, k=k, bs=bs))
m <- as.formula(ccount~s(Month, k=k, bs=bs))
o <- as.formula(ccount~s(do, k=k, bs=bs))
s <- as.formula(ccount~s(sal, k=k, bs=bs))
t <- as.formula(ccount~s(temp, k=k, bs=bs))
n <- as.formula(ccount~s(sec, k=k, bs=bs))
os <- as.formula(ccount~s(do, k=k, bs=bs) + s(sal, k=k, bs=bs))
ot <- as.formula(ccount ~ s(do, k=k, bs=bs)+ s(temp, k=k, bs=bs))
st <- as.formula(ccount ~ s(sal, k=k, bs=bs) + s(temp, k=k, bs=bs))
sn <- as.formula(ccount ~ s(sal, k=k, bs=bs) + s(sec, k=k, bs=bs))
tn <- as.formula(ccount ~ s(temp, k=k, bs=bs) + s(sec, k=k, bs=bs))
ost <- as.formula(ccount ~ s(do, k=k, bs=bs )+ s(sal, k=k, bs=bs) + s(temp, k=k, bs=bs))
stn <- as.formula(ccount ~ s(sal, k=k, bs=bs )+ s(temp, k=k, bs=bs) + s(sec, k=k, bs=bs))
ostn <- as.formula(ccount ~ s(do, k=k, bs=bs )+s(sal, k=k, bs=bs )+ s(temp, k=k, bs=bs) + s(sec, k=k, bs=bs))
most<- as.formula(ccount ~ s(Month, k=k, bs=bs) + s(do, k=k, bs=bs )+ s(temp, k=k, bs=bs) + s(sec, k=k, bs=bs))
mstn<- as.formula(ccount ~ s(Month, k=k, bs=bs) + s(sal)+ s(temp, k=k, bs=bs) + s(sec, k=k, bs=bs))
yost<- as.formula(ccount ~ s(year, k=k, bs="re") + s(do, k=k, bs=bs )+ s(sal, k=k, bs=bs) + s(temp, k=k, bs=bs))
ystn<- as.formula(ccount ~ s(year, k=k, bs="re") + s(sal, k=k, bs=bs )+ s(temp, k=k, bs=bs) + s(sec, k=k, bs=bs))
ymost<- as.formula(ccount ~ s(year, k=k, bs="re") + s(Month, k=k, bs=bs) + s(do, k=k, bs=bs )+ s(sal, k=k, bs=bs) + s(temp, k=k, bs=bs))
ymstn<- as.formula(ccount ~ s(year, k=k, bs="re") + s(Month, k=k, bs=bs) +s(sal, k=k, bs=bs )+ s(temp, k=k, bs=bs) + s(sec, k=k, bs=bs))
```

RESULTS & DISCUSSION

Water quality

Water quality metrics varied greatly in time and space and exhibited moderate covariation with each other and additional trawl-specific characteristic (Fig. 5). Dissolved oxygen (DO) ranged from 2 to 11 mg/L and was negatively correlated with temperature (TEMP) which ranged from 8 to 26 °C. Salinity (SAL) ranged from 0 to 35 psu and was weakly correlated with TEMP and DO. Tide height (TIDE) ranged from 0.6 to 4 m (2 to 12 feet) and was positively correlated with

SAL and depth, and negatively correlated with TEMP. Secchi depth ranged from 10 to > 100 cm, but was generally below 50 cm. Though several correlations among tow and water quality metrics were statistically significant (e.g., due to large sample sizes), the strength of these relationships were moderate to weak, with low percent variation explained by each variable: DO versus TEMP ~ 40%, SAL versus TIDE ~ 13%, TEMP vs TIDE ~10%, and most other relationships < 5%.

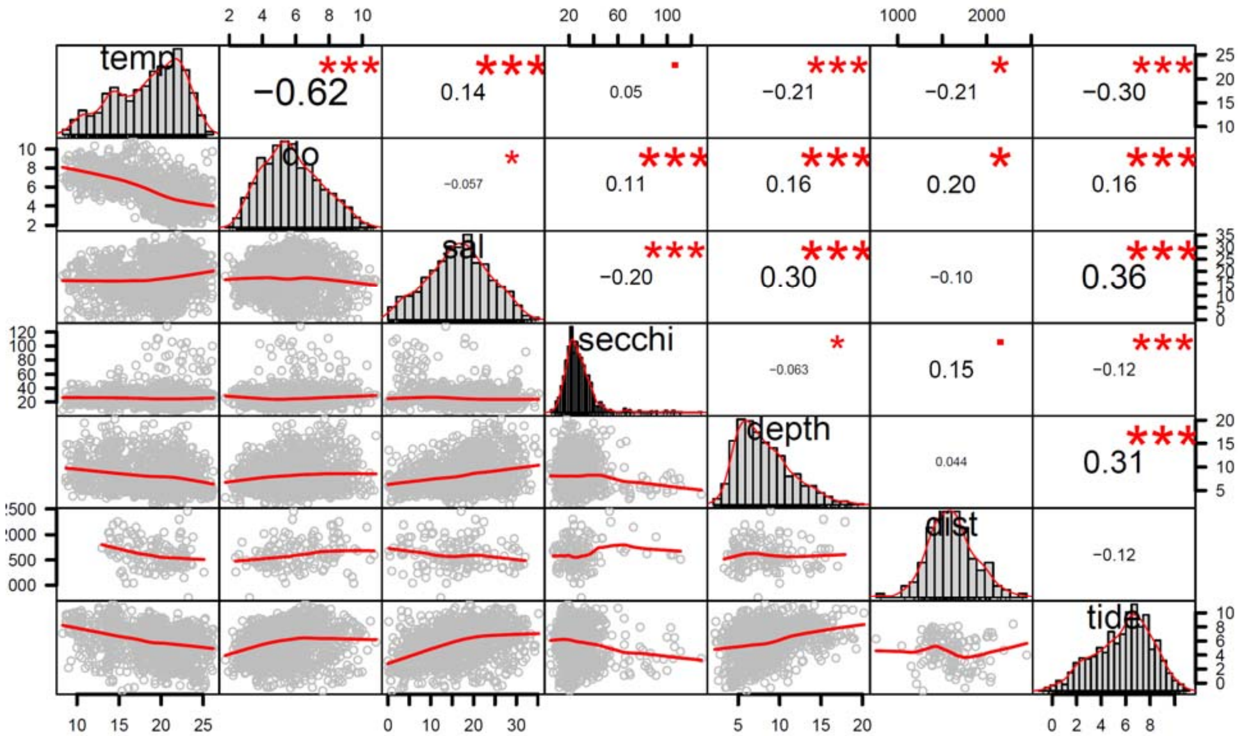

Figure 5. Comparison of the distributions and relationships between water quality (temperature-temp, dissolved oxygen-do, salinity-sal, clarity-secchi) and sampling (depth, trawl distance-dist, and tide height-tide) parameters. Smoothers are shown in red with Pearson correlation coefficients and significance indicated by * P < 0.05, **P < 0.001, *** P < 0.001.

Water quality varied little among years, but greatly among months (Fig. 6). Because tidal sampling varied among months (Appendix 3), seasonal variation in water quality was examined as a function of both month and tide (to account for monthly variation in tidal sampling) (GAM, k=10, bs= "tp", fam=gaussian). Seasonal (monthly) variation was large for temperature (~80%), moderate for DO (~50%) and salinity (~35%), and weak for Secchi depth (~10%) when also accounting for weak effects of tides (Appendix 3). Thus temperature and DO exhibited strong seasonal variation, whereas other metrics appeared to vary less among months, and all water quality metrics generally varied less among years (Figure 6) and sites (Appendix 3).

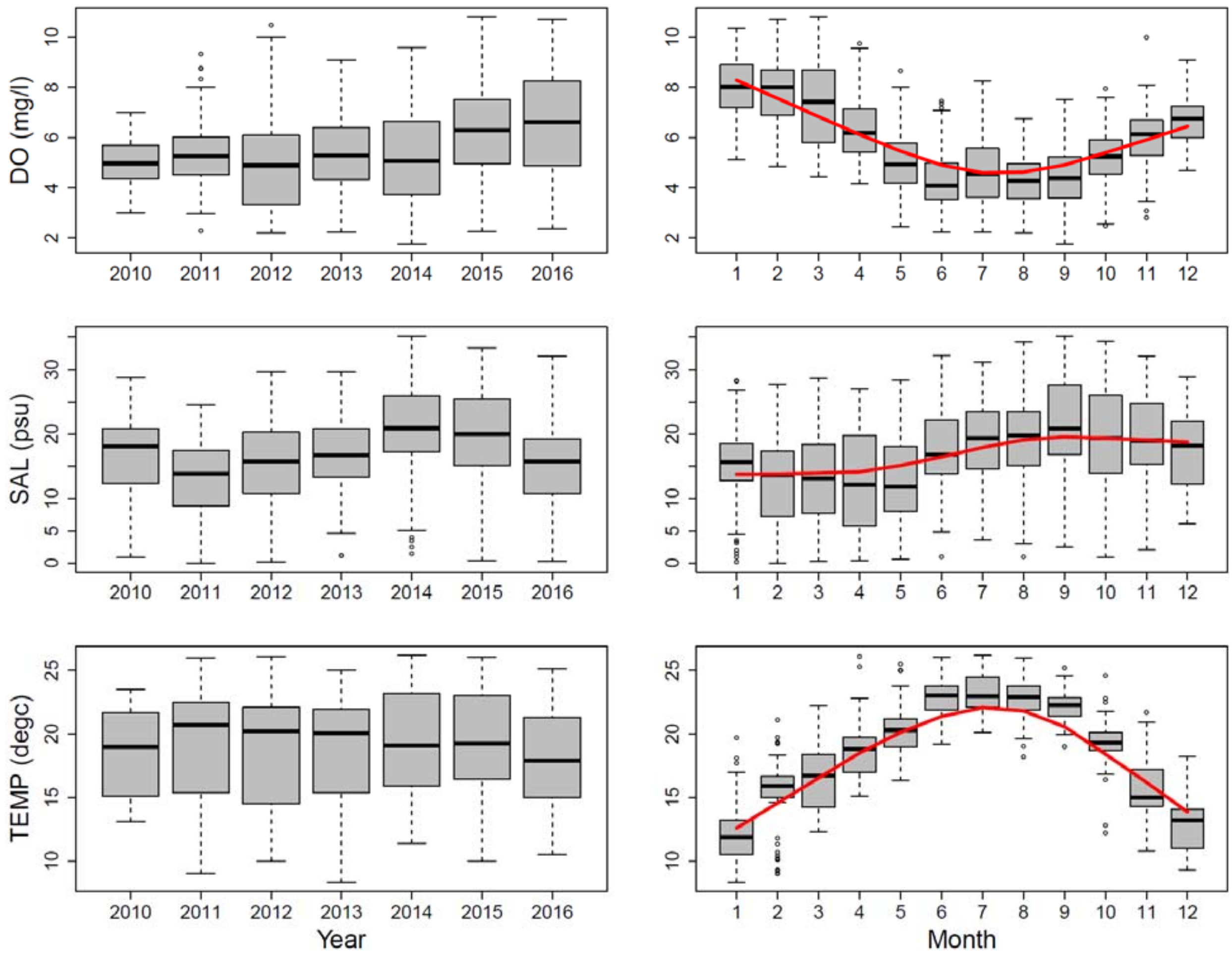

Figure 6. Variation in water quality among years and months.

Fish abundance

Catches of focal species varied greatly among months (Fig. 7) and years (Fig. 8), likely reflecting responses to seasonal and interannual variation in environmental conditions and temporal variation in population dynamics. Species exhibited unique patterns in abundance, making it difficult to group taxa into simple functional groups. Nevertheless, certain species appeared to consistently be most abundant within the AMC during either summer-fall (e.g., Threespine Stickleback) or winter-spring (e.g., Longfin Smelt). Species catches included numerous zeros and occasional, anomalously-large catches (indicating patchy distributions in space and time); therefore, catch distributions were highly right skewed and zero-inflated. These distributions precluded the use of simple linear models based on Gaussian distributions, thus requiring use of generalized models with an appropriate distribution (e.g., negative binomial). Though such complex data could be reduced and simplified to binary occupancy (i.e., presence/absence), explicit inclusion of large catches can greatly enhance model outputs and inferences with respect to habitat quality for fishes. For example, occupancy would treat catches of 1 and 4000 equivalently, whereas a generalized negative binomial model would explicitly account for such large variation in catch values.

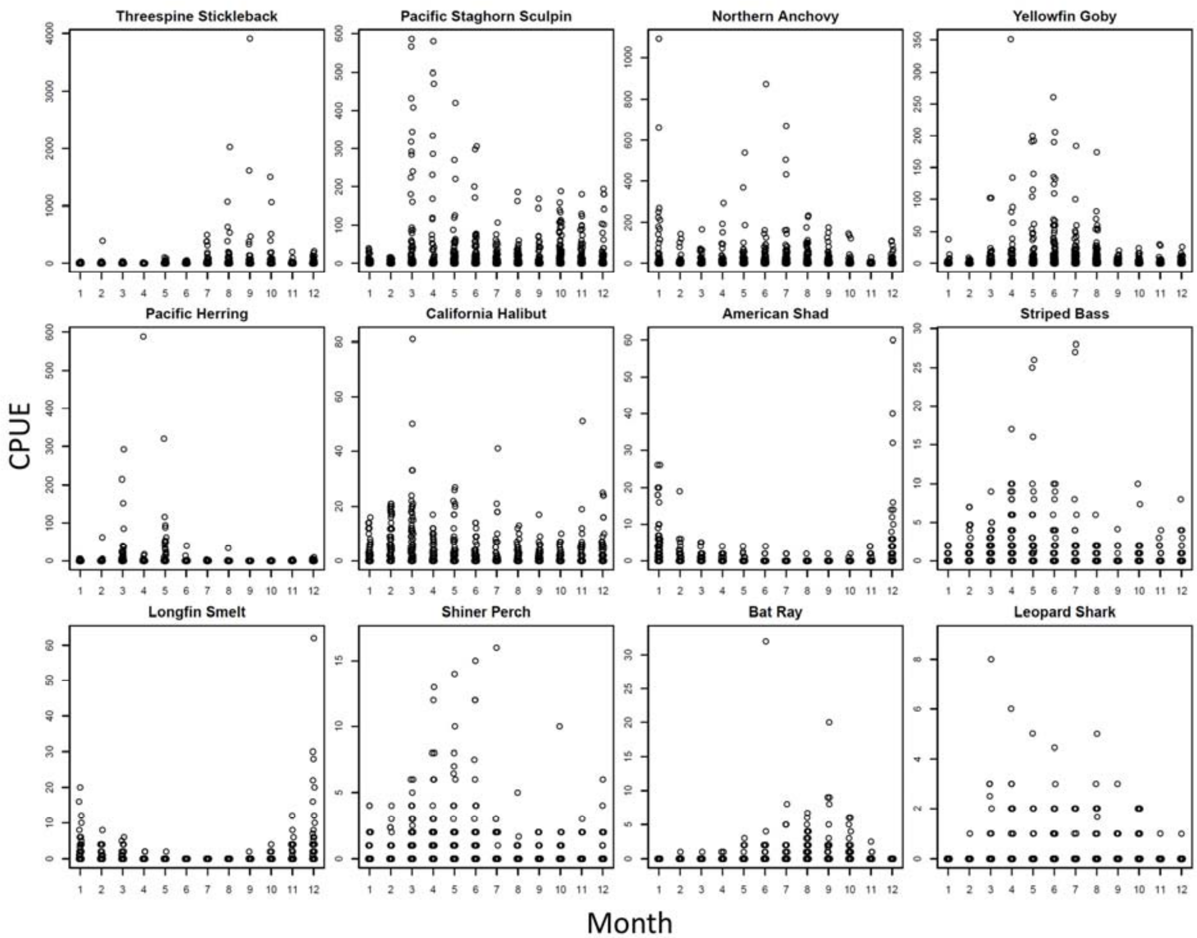

Figure 7. Catch per unit effort (catch per 10 min tow) by month for each focal species.

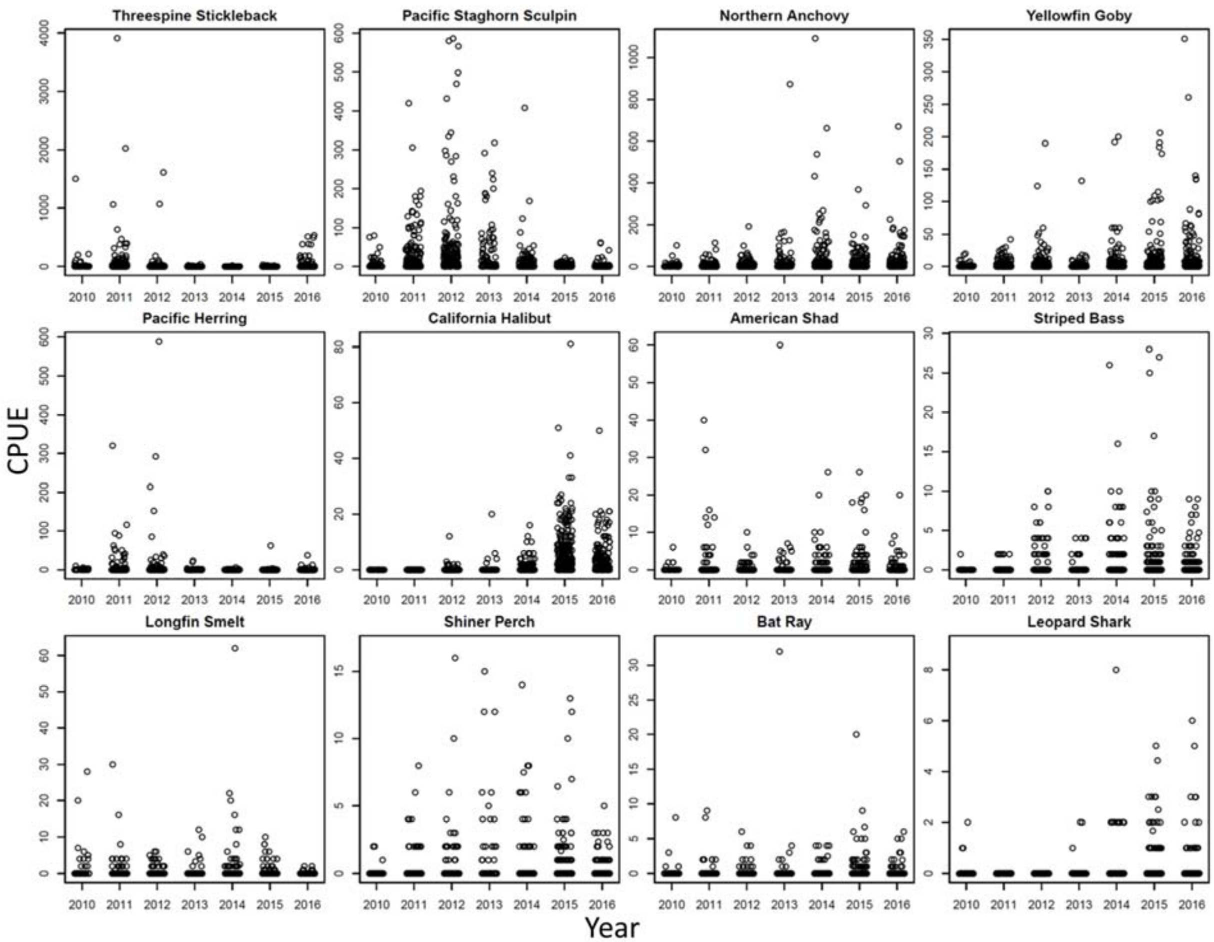

Figure 8. Catch per unit effort (catch per 10 minute tow) by year for each focal species.

Fish-habitat associations: Cumulative Catch Curves (CCCs)

Total (aggregate) cumulative catch cures

Cumulative catch curves of total catch (all species in aggregate, Fig 9) exhibited distributions similar to effort for all three water quality parameters (dissolved oxygen, salinity, and temperature), suggesting that aggregate fish abundance did not vary significantly with these environmental predictors. This is likely due to diverse species-specific responses to environmental conditions that can result in enhanced spatiotemporal stability in abundance. Overall, trends indicated slightly higher catches in warmer, fresher waters with low (2-6 mg/L) DO. This trend, however was likely driven by highly abundant, marsh-adapted summer species (e.g., sticklebacks and yellowfin gobies, Fig. 3).

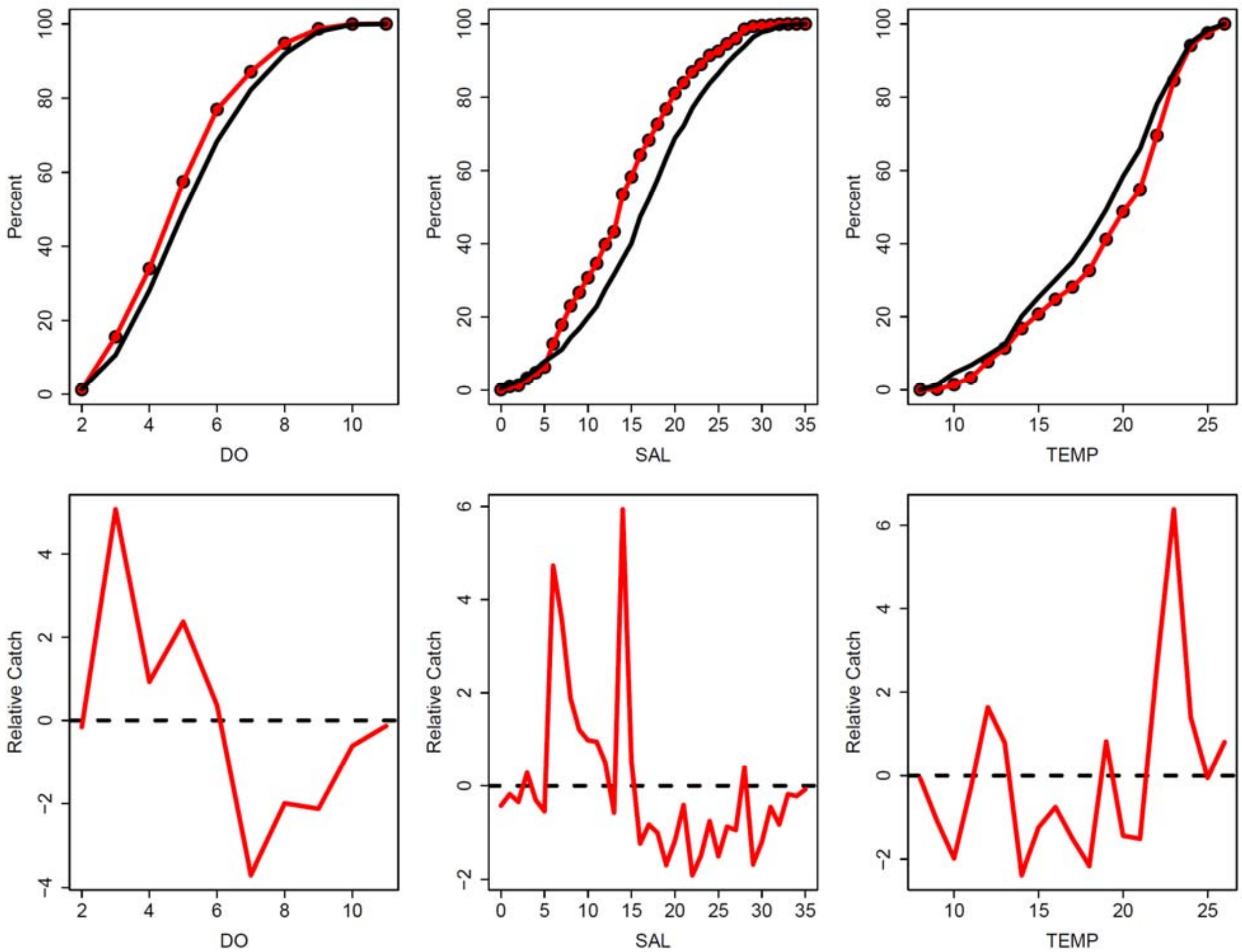

Figure 9. Cumulative catch (distribution) curves (top row) and relative catch (bottom row) of all fishes across full ranges (1-unit bins) of dissolved oxygen (left), salinity (center) and temperature (right). The cumulative distribution of effort (top row) is shown in black for contrast. For relative catch (bottom), regions of each curve above zero (black dashed line) reflect disproportionately high increases in cumulative catch versus effort for corresponding proportional ranges in x, whereas values below zero indicate disproportionately low changes in cumulative catch.

Species Cumulative Catch Curves

Individual cumulative catch distributions varied greatly among focal species for salinity and temperature, though less so for dissolved oxygen (Figs 10-12). Merging of cumulative catch curves provided for direct contrast among species for each metric (Fig. 13).

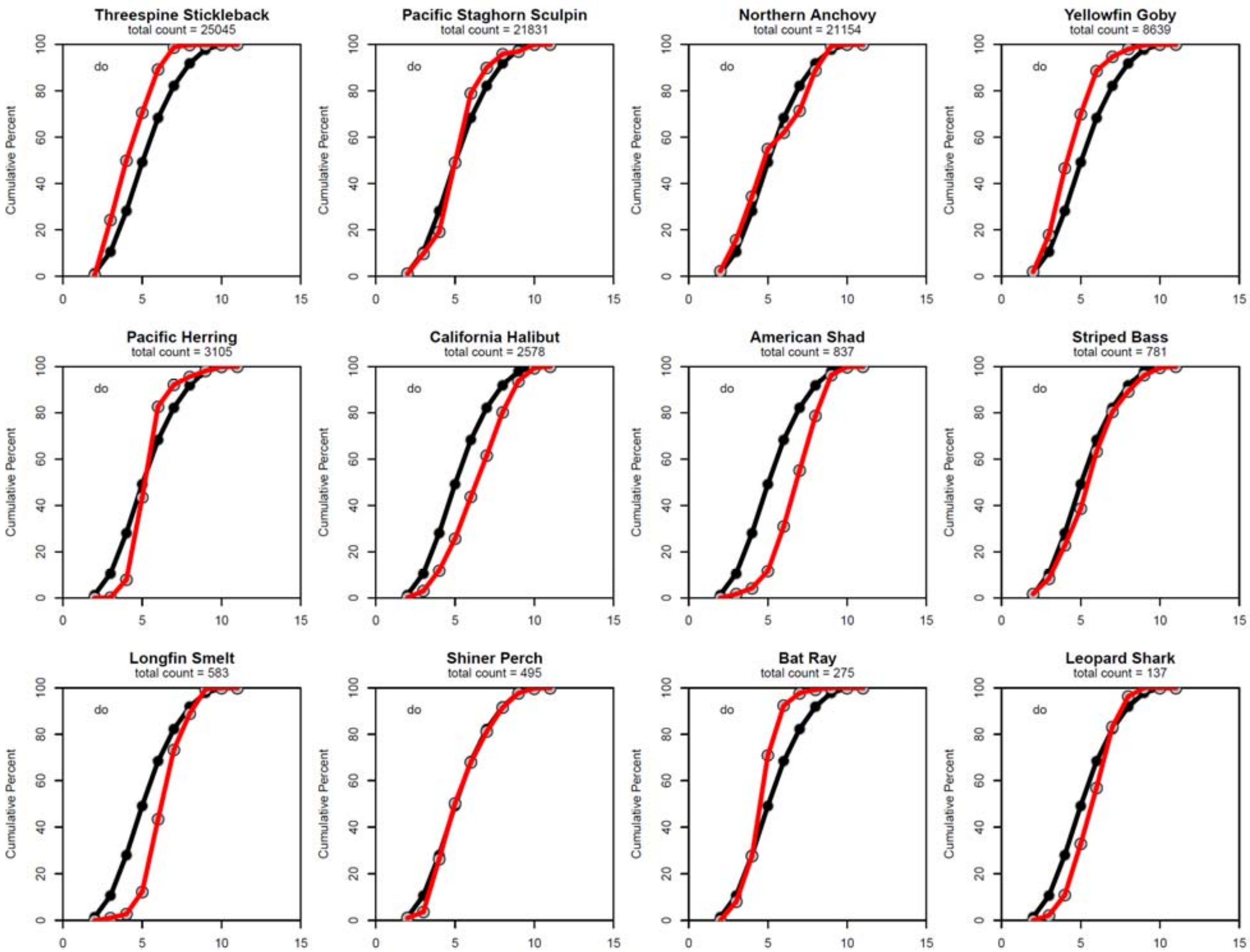

Figure 10. Cumulative catch (red) and effort (black) versus dissolved oxygen (mg/L, x-axis) for each of the 12 focal species.

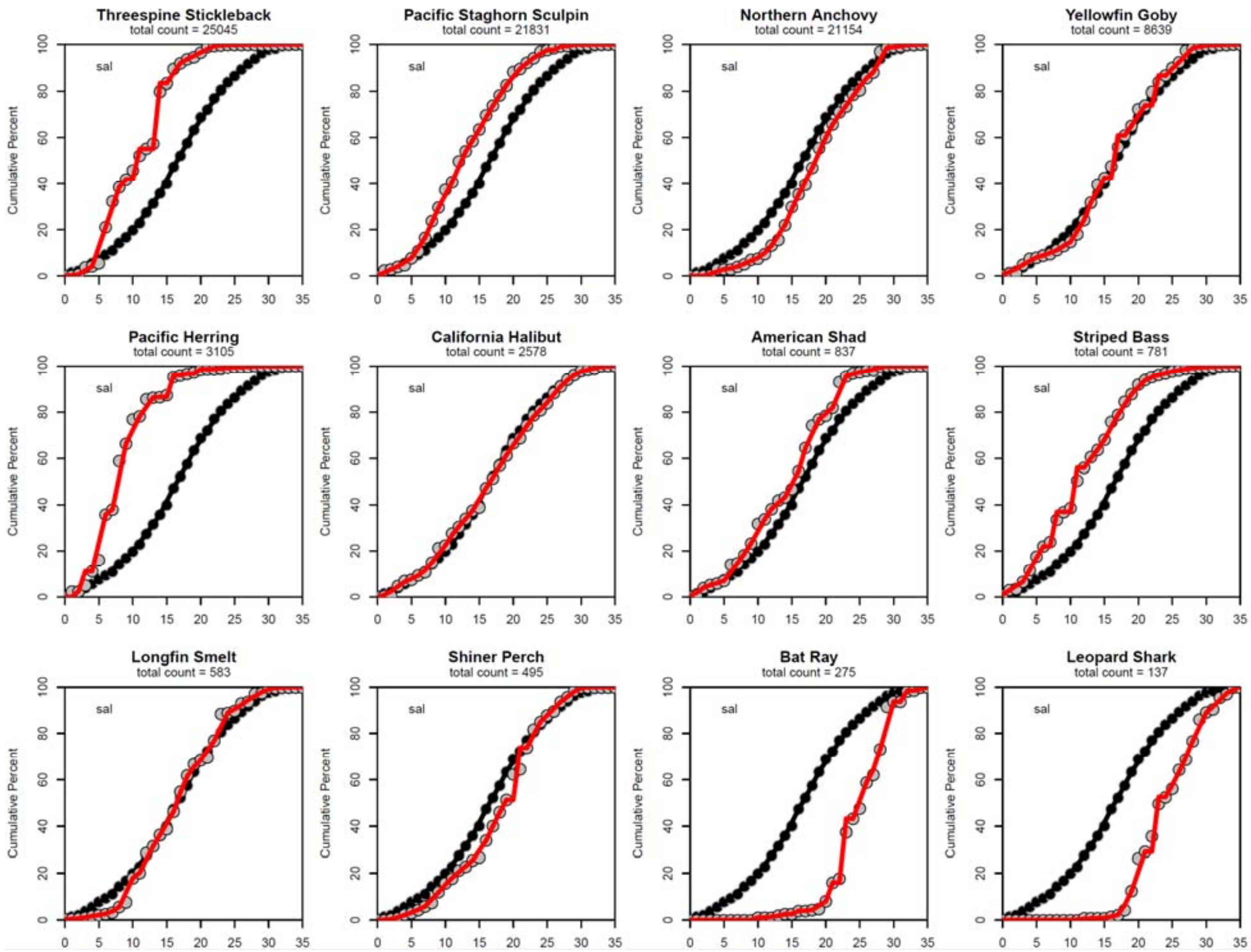

Figure 11. Cumulative catch (red) and effort (black) versus salinity (psu, x-axis) for each of the 12 focal species.

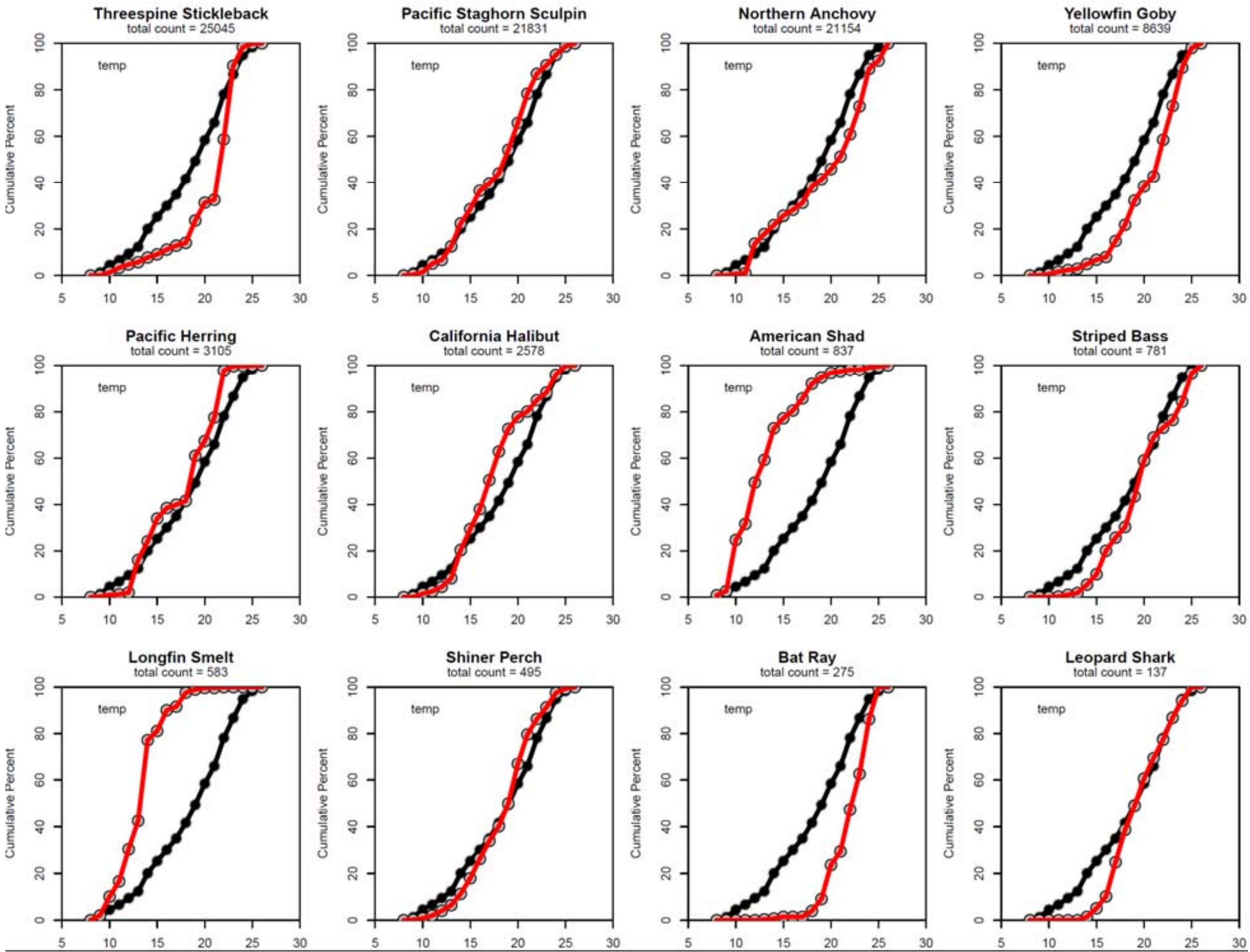

Figure 12. Cumulative catch (red) and effort (black) versus temperature (°C, x-axis) for each of the 12 focal species.

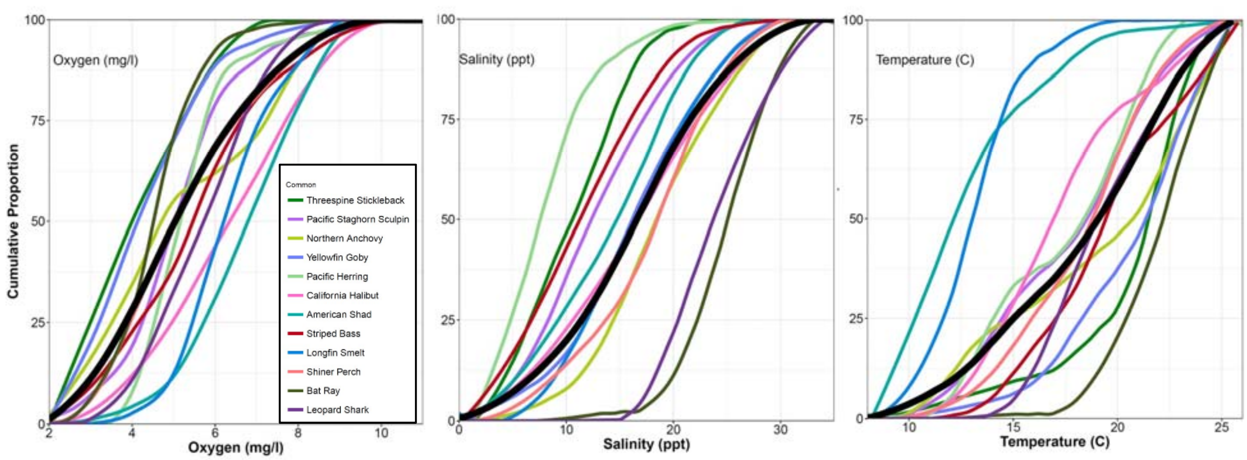

Figure 13. Smoothed, merged cumulative catch (colors) and effort (black) curves for all focal taxa across ranges of oxygen (left), salinity (center) and temperature (right).

Relative Catch Curves

Examination of relative changes in catch across proportional ranges of water quality variables provided for simultaneous comparisons of the relative strength of species' responses to each water quality metric (Fig. 14). American Shad, Pacific Herring, Bat Rays, Longfin Smelt, and Leopard Sharks appeared to be the most sensitive to water quality conditions; however, each responded in a unique way to the environment. American Shad were most abundant during cool and high DO conditions, whereas Longfin Smelt were most responsive to temperature. Bat Rays, Yellowfin Gobies, and Threespine Sticklebacks were more abundant during warmer conditions and lower DO, whereas catches of Leopard Sharks and Striped Bass responded greatest to salinity (with opposite responses). In contrast to Leopard Sharks, Pacific Herring, Striped Bass and Threespine Sticklebacks were more abundant in fresher waters. Pacific Staghorn Sculpin and Shiner Perch appeared to be influenced less by water quality. Catch of California Halibut appeared to be positively correlated with higher DO levels.

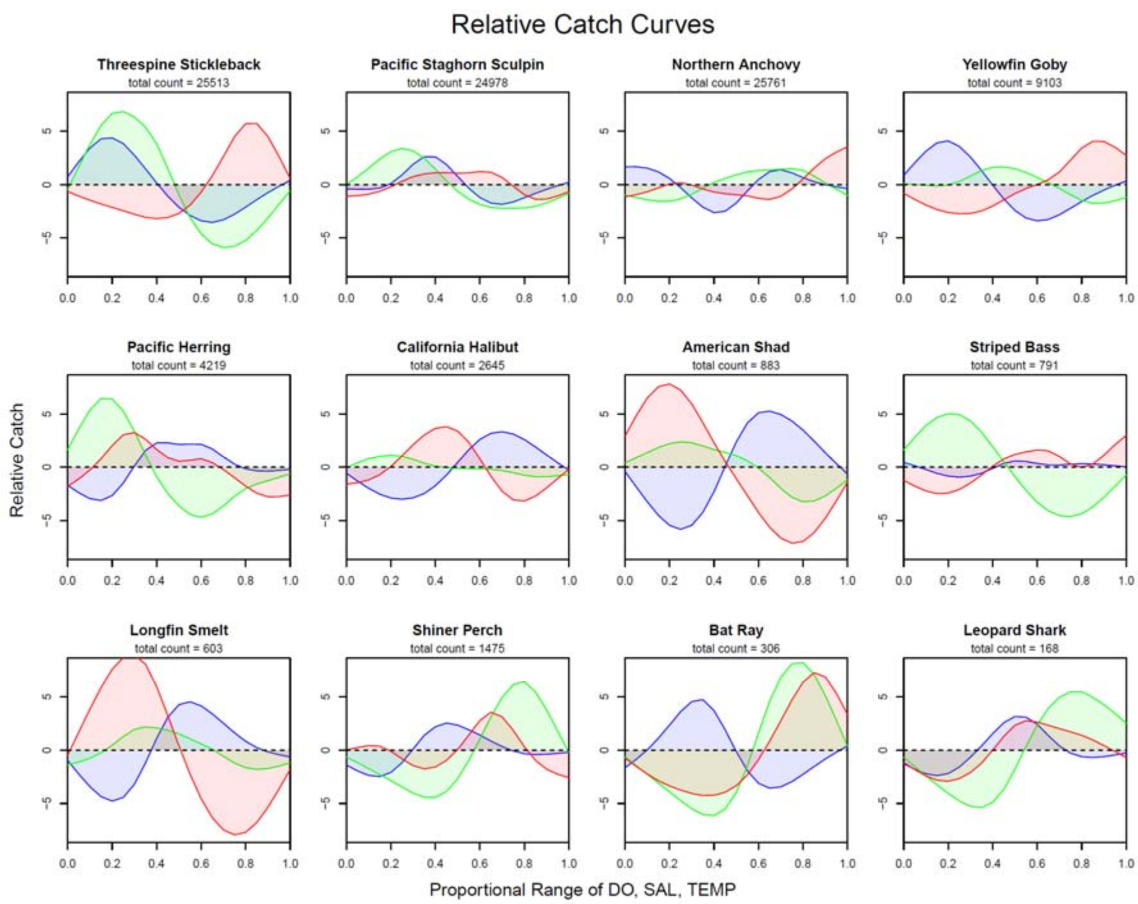

Figure 14. Smoothed (cubic spline, df = 5) relative catch curves for all focal taxa across the full ranges of oxygen (blue), salinity (green) and temperature (red). Relative catch (y-axis) was calculated as the difference in step-wise changes (slopes) between cumulative catch and effort curves. The x-axis reflects the proportion of the total range in each x variable from low to high. Regions of each curve above zero (black dashed line, where catch directly

reflects effort) reflect disproportionately high increases in cumulative catch versus effort for corresponding proportional ranges in x, whereas values below zero indicate disproportionately low changes in cumulative catch.

Fish-habitat associations: Generalized Additive Models (GAMs)

We compared model performance by qualitatively examining variation in deviance explained across GAM models with increasing levels of complexity (Figs. 15,16) and quantitatively using Akaike information criteria (AIC) scores which penalize the strength of models by their complexity (Fig. 17, Table 3). Stronger models are indicated by higher deviance explained given lower EDF (complexity) and overall lower AIC values. Model complexity ranged from 1 to 20 estimated degrees of freedom (Fig. 15) while deviance explained ranged from 0 to 60% (Fig. 16).

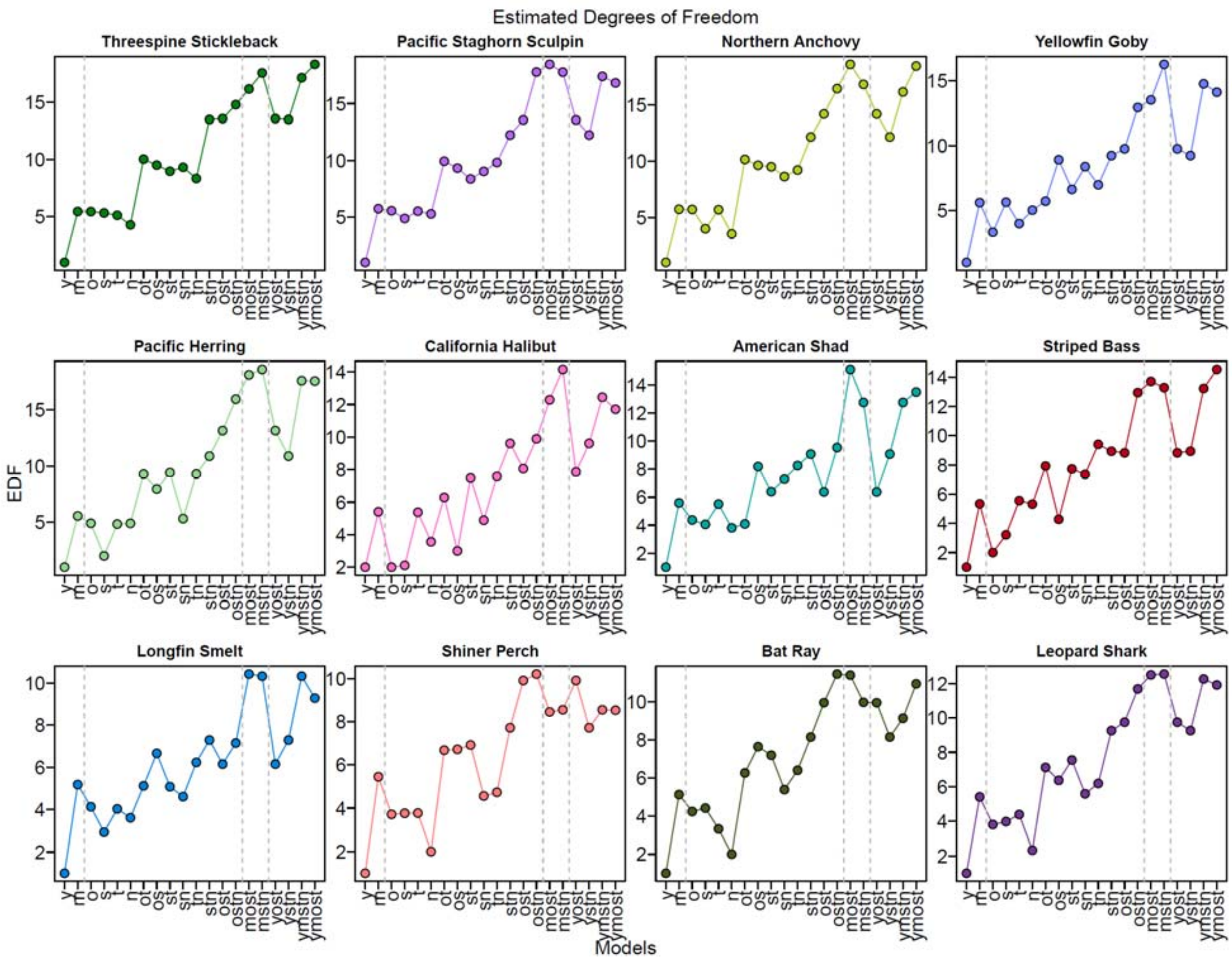

Figure 15. Plot of model complexity (estimated degrees of freedom, edf) for 20 Generalized Additive Models of fish abundance for each of the 12 focal species. Models are in order of increasing number of independent terms (left to right); however, the estimated degrees of freedom were more variable due to variation in smooth parameters. Vertical dashed lines delimit models with temporal (Year, Season) terms.

For some species, a single environmental variable was sufficient to account for much of the deviance in abundance (e.g., temperature for Longfin Smelt); for others (e.g., Leopard Shark), combinations of variables yielded the best model. Temporal variation appeared to be a strong driver of variation in abundances for several species, with variation among years (e.g., California Halibut, Threespine Stickleback) and months (e.g., Shiner Perch, American Shad and Longfin Smelt) explaining much of the variance in catch. Environmental predictors, however, were also strongly correlated with seasonal variation among months (high concurvity), suggesting a possible mechanism for the strong seasonal patterns in abundance for many species. In additional to temporal variation, spatial variation also likely contributed to patterns in water quality and species abundances (Appendix 3).

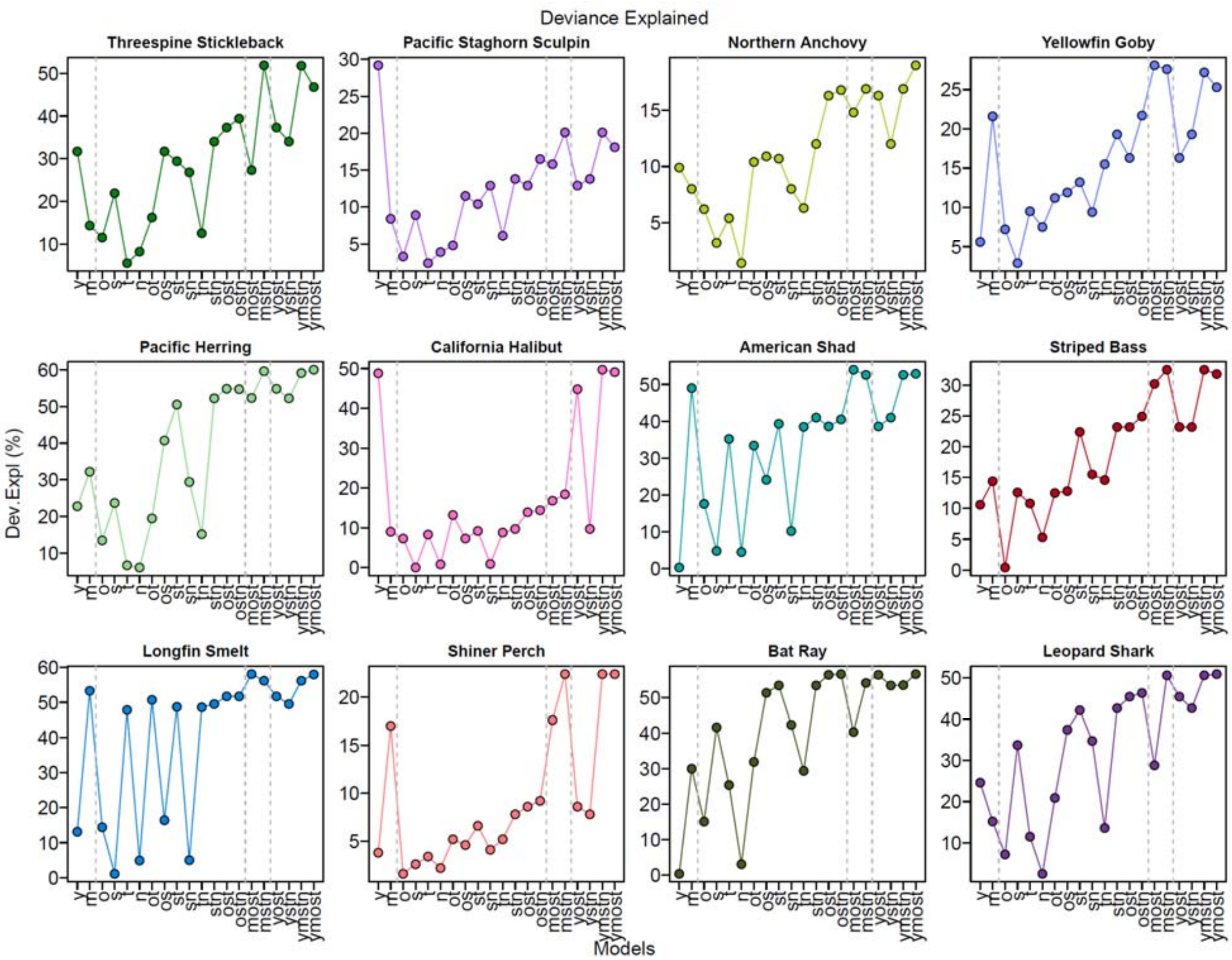

Figure 16. Plot of goodness of fit (percent deviance explained) for 20 Generalized Additive Models of fish abundance for each of the 12 focal species. Models are in order of increasing number of independent terms (left to right); however, the estimated degrees of freedom were more variable due to variation in smooth parameters. Vertical dashed lines delimit models with temporal (Year, Season) terms.

AIC values (Table 3) were strongly, negatively correlated with deviance explained for all species (e.g., $n = 16$, $r = 0.99$, $p < 0.001$ for Threespine Stickleback), suggesting that differences in explanatory power between models were more influential than penalties based on model complexity. Models including temporal terms (month, year) exhibited the lowest AIC scores, either alone or in combination with water quality parameters, thus indicating that seasonal (e.g., American Shad) and interannual (e.g. California Halibut) variability were relatively large for several species. Of the water quality-only models, the most complex yielded the greatest deviance explained and lowest AIC, suggesting species are influenced by most water quality parameters. However, several simpler models yielded similar explanatory power (e.g., t for Longfin Smelt), suggesting that selection based on AIC might lead to overparameterization (Hurvich & Tsai 1989). Alternative criteria such as AICc or BIC might provide improved inference regarding the most efficient models for each taxon.

Table 3. Akaike Information Criteria (AIC) for 20 Generalized Additive Models (GAMs) for each of the 12 focal species. Models are ordered by the number of terms and are defined in Table 2: y-year, m-month, o-dissolved oxygen, t-temp, s-salinity, n-Secchi depth. Bold values are lowest AIC overall and grey-shaded values are the lowest values for water quality-only models.

Model	Threespine Stickleback	Pacific Staghorn Sculpin	Northern Anchovy	Yellowfin Goby	Pacific Herring	California Halibut	American Shad	Striped Bass	Longfin Smelt	Shiner Perch	Bat Ray	Leopard Shark
y	4127	**6513**	7034	5486	1610	**3097**	1710	2036	1224	1565	951	672
m	4279	6798	7057	5302	1574	3523	1459	2014	1062	1505	874	699
o	4301	6860	7080	5472	1641	3530	1641	2090	1219	1575	918	716
s	4216	6791	7115	5524	1600	3588	1696	2022	1254	1571	828	639
t	4345	6871	7090	5447	1663	3529	1550	2037	1088	1566	886	707
n	4323	6852	7136	5471	1665	3586	1696	2070	1245	1568	945	724
ot	4274	6852	7037	5432	1631	3489	1559	2032	1075	1566	871	688
os	4136	6768	7029	5430	1553	3532	1617	2022	1220	1569	791	631
st	4159	6781	7035	5409	1523	3526	1528	1966	1086	1560	779	614
sn	4182	6750	7067	5457	1587	3589	1681	2012	1247	1566	827	640
tn	4301	6836	7088	5382	1646	3530	1536	2022	1090	1560	879	706
stn	4126	6746	7022	5340	1525	3527	1522	1963	1088	1557	780	617
ost	4091	6760	6968	5379	1505	3488	1533	1962	1072	1558	769	606
ostn	4076	6722	6966	5318	1507	3488	1527	1960	1074	1556	772	607
most	4193	6733	6997	**5232**	1506	3472	**1441**	1926	1046	1509	851	677
mstn	**3991**	6673	6966	5246	1462	3462	1448	1903	1058	1484	782	588
yost	4091	6760	6968	5379	1505	3162	1533	1962	1072	1558	**769**	606
ystn	4126	6746	7022	5340	1525	3527	1522	1963	1088	1557	780	617
ymstn	3991	6672	6965	5248	1463	3103	1448	**1903**	1058	1483	782	588
ymost	4001	6699	**6939**	5272	**1459**	3108	1447	1914	**1043**	**1483**	770	**585**

GAM SMOOTH FUNCTIONS: Oxygen, Salinity, Temperature, Secchi (OSTN)

To illustrate responses of each species to environmental metrics, here we present smooth functions of fish abundance based on the OSTN model. As expected, given the cumulative and relative catch curves, species exhibited large variability in responses to environmental variation (Table 3, Fig. 17). California Halibut were more abundant in warmer waters with higher dissolved oxygen, whereas abundances of Longfin Smelt and American Shad corresponded with cooler, higher DO conditions (Fig. 17). The two elasmobranchs (Leopard Sharks and Bat Rays) exhibited positive relationships with salinity and temperature. Pacific Herring appeared in cooler waters with higher dissolved oxygen, whereas Threespine sticklebacks appeared most common in fresher, warmer waters, with lower dissolved oxygen levels. Pacific Staghorn Sculpin and Yellowfin gobies were more abundant in warmer, fresher, low-DO waters. Some species exhibited negative relationships with Secchi depth (e.g., Staghorn Sculpin and Shiner Perch), suggesting they prefer more turbid waters; however, many showed no response (e.g., Bat Ray and Longfin Smelt) or even a slightly positive response (e.g., sticklebacks, anchovies, and Striped Bass) suggesting a preference for clearer waters. We note that patterns in GAM smooth relationships may differ from relative catch curves due to interactions or concurvity among partially correlated variables (e.g., TEMP & DO).

Further exploration of the data is warranted, but unlikely to substantially alter species responses described above or the overall fit of GAM models for most taxa. Inclusion of additional parameters (e.g., depth, tide height, station, habitat, etc.) could possibly be informative, but would increase model complexity and concurvity, thus complicating interpretation. Furthermore, interactions between multiple continuous predictors could be explored further in developing the best model for individual species. Nevertheless, the GAM models described herein are useful for assessing spatial and temporal variation in habitat suitability (predicted abundance) for a given species using continuous measurements of water quality.

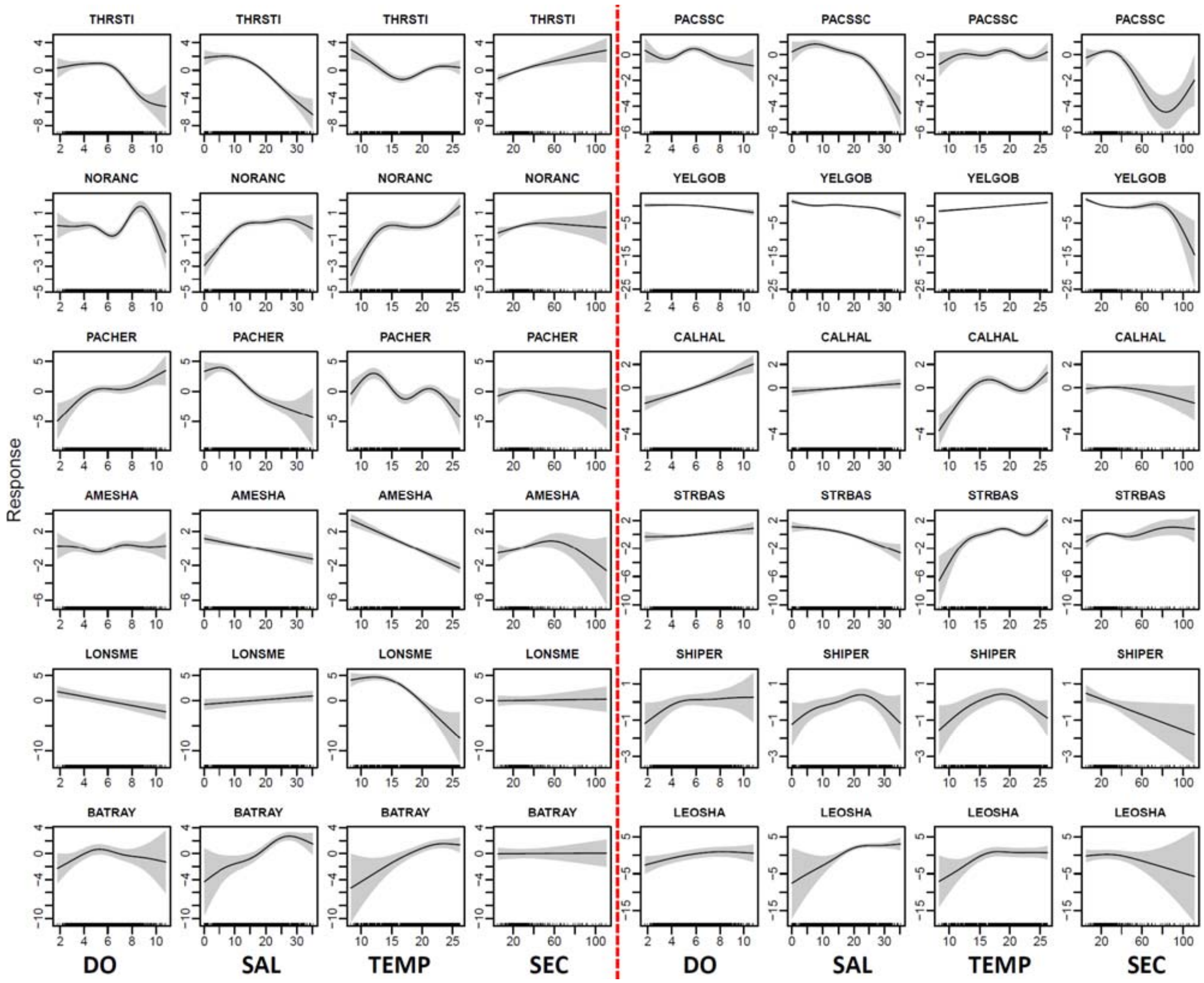

Figure 17. GAM smooth functions for the OSTN model. Smooth functions for each of the four environmental predictors (dissolved oxygen-DO, salinity-SAL, temperature-TEMP, and Secchi depth-SEC) are shown for each of the 12 focal species. Species are labeled using the first three letters of each common name (e.g., Longfin Smelt = LONSME, Table 1), except for Pacific Staghorn Sculpin (PACSSC).

SUMMARY

Fish communities and habitat quality in the AMC

We observed over 50 species of fish in the Alviso Marsh Complex during the study period and abundances appeared relatively stable despite seasonal variation in environmental conditions and fish community structure. Diversity (richness) overall was 20% lower during summer months, likely due to the absence of transient winter species (Fig. 18). Species assemblages were dominated by native species and exhibited a diverse community structure including: pelagic, littoral, and benthic species; marsh transients (e.g., Longfin Smelt) and residents (e.g., sticklebacks, mudsuckers); numerous forage fish (e.g., silversides, anchovies, herring, and shad); several top predators (Leopard Sharks, Bat Rays, Striped Bass, California Halibut); and a threatened estuarine-obligate species (Longfin Smelt). Alviso marsh is utilized by many recreationally and commercially important fish species, some of which may be sensitive to dissolved oxygen levels.

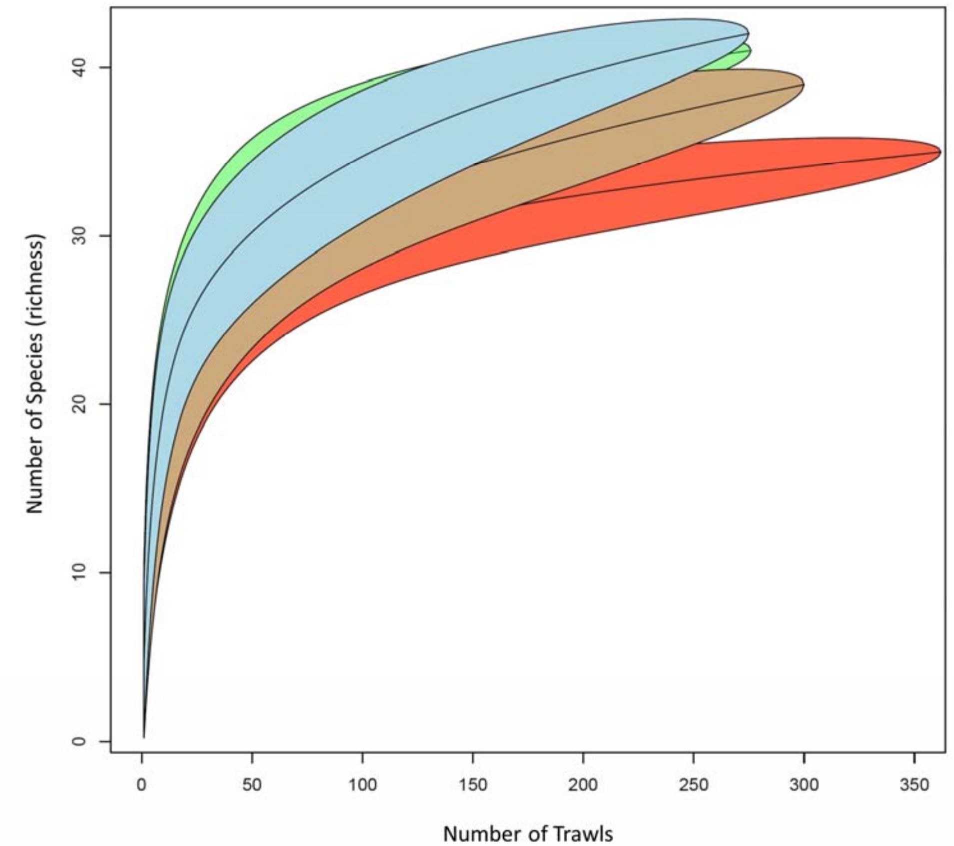

Figure 18. Species accumulation curves for the AMC by season (winter-blue, spring-green, fall-light orange, summer-dark orange).

This study focused on soft-bottom tidal sloughs and ponds navigable with our boat and suitable for otter trawling; thus, alternative habitats that are shallower or contain aquatic vegetation or rocky structure may provide different results. To the best of our knowledge, all species we might expect to find in marshes throughout the SFE appeared to be present in the AMC, suggesting that the system, as a whole, is supporting a diverse fish community. Though many species are present, it is unclear without data from reference marshes whether species abundances appear natural or impacted, and whether certain species would remain in the estuary throughout summer and fall (when hypoxia and respiratory stress are greatest) given reductions in nutrient loading. Environmental conditions did not strongly predict species abundances at the individual trawl level, with maximum deviance explained at approximately 60% for certain species using different combinations of temperature, salinity, dissolved oxygen and Secchi depth. However, the distribution of fishes is patchy in nature and the deviance explained in our models are similar to those observed in other studies using negative binomial GAMs to model trawl data (Simpson & Walsh 2004). Temperature and salinity contributed greatest to predictions of abundance for most species (Figs. 14,16), with only two species exhibiting a prominent response to dissolved oxygen. Yellowfin Gobies responded positively to more hypoxic conditions while Halibut was the only species exhibiting a dominant (albeit weak), positive response to DO. Given these results, DO did not appear to be a dominant driver of fish abundance patterns in the AMC trawl catch dataset. However, the independent effect of each metric is difficult to detangle in GAMs due to co-variation between metrics (e.g., temperature, oxygen) and with seasons, thus responses of organisms to variation in DO could be exaggerated or partially masked by responses to other co-varying factors. Additional analyses of interactions among predictor variables for individual focal species could shed further light on the relative contributions of individual metrics to species abundance patterns.

Though our results do not demonstrate strong effects of DO on fish abundance, the independent effects of low DO on fish communities could be important. For example, many fish species (e.g., California Halibut, Longfin Smelt, Striped Bass, American Shad) exhibited disproportionately low catches where oxygen concentrations were low (≤ 5 mg/L), suggesting that DO may be limiting at this lower range (Figs. 19,20). Maximal abundances generally occurred at much higher (6-7 mg/L) concentrations for most taxa, suggested that even 5 mg/L may be suboptimal for these species. However, several fish species also exhibited higher catches in waters with low (≤ 5 mg/L) DO (e.g., Threespine Stickleback, Yellowfin Goby, and Bat Ray), suggesting that low DO conditions in Alviso Marsh may be favorable for these taxa. The diverse responses of fishes to environmental conditions highlights the importance of selecting appropriate focal species for assessing marsh health and the effects of hypoxia.

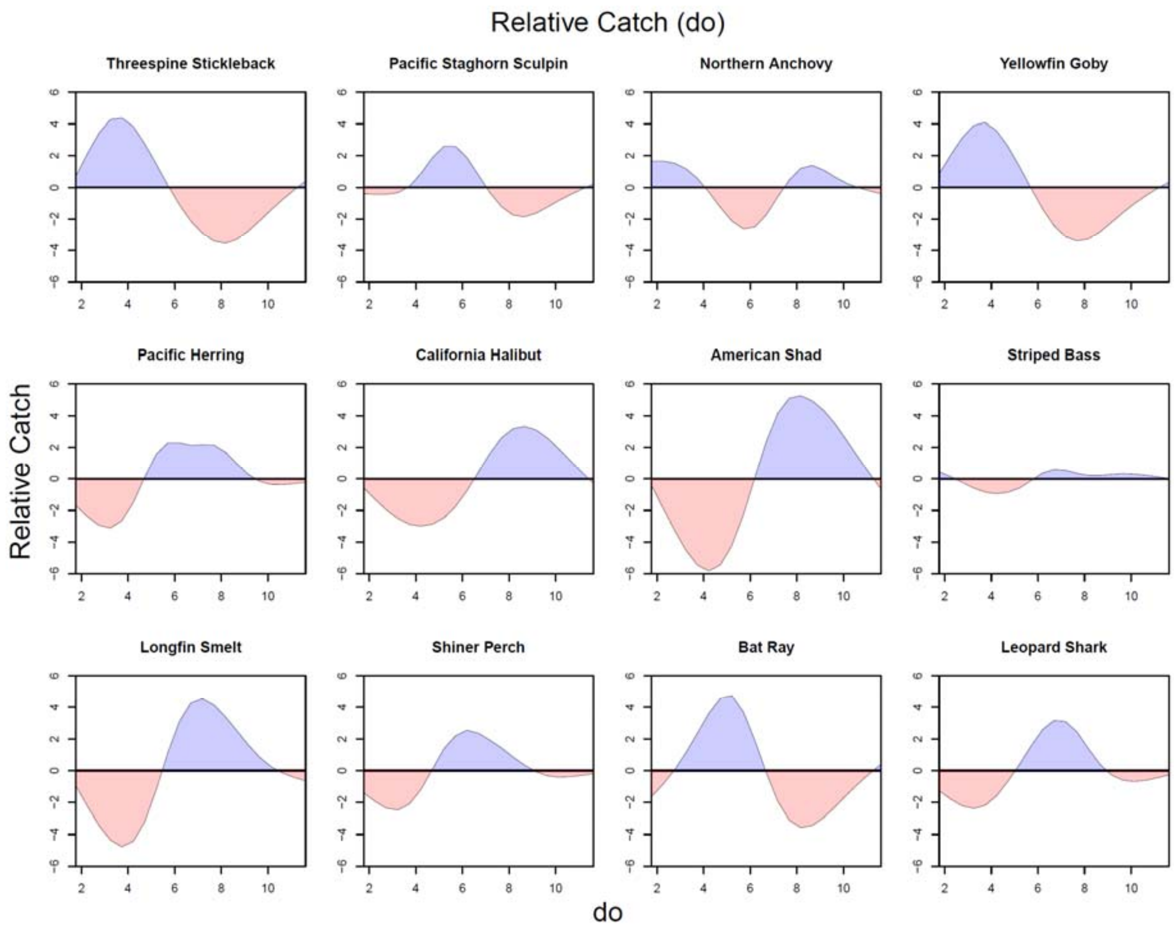

Figure 19. Smoothed (cubic spline, df=5) relative catch curves across the full range of dissolved oxygen concentrations (mg/L). The black horizontal zero line indicates where changes in catch were proportional to effort. Above this line, catch was disproportionately high (blue area) and, below this line, catch was disproportionately low (red area) for corresponding values of dissolved oxygen.

The identification of meaningful thresholds from catch data remains an important field of inquiry. Here, we used GAMs to describe the complexity in species responses to the environment and to develop a predictive model of abundance and habitat quality. To simplify the assessment of DO, we used relative catch, calculated from cumulative catch curves, to describe overall patterns in catch with respect to water quality. In particular, we described the DO concentrations in which catch was minimized and maximized for these focal species (Figs. 19,20). In addition to these extreme values, another important value to consider is the inflection point where habitat in the DO dimension changes from low quality (disproportionately low catches) to high quality (disproportionately high catches) (Figs. 19,20). These inflection points may represent biologically-meaningful DO values for each species based on overall patterns of abundance throughout the estuary; however, they cannot alone be used to assess whether DO is a primary driver of abundance.

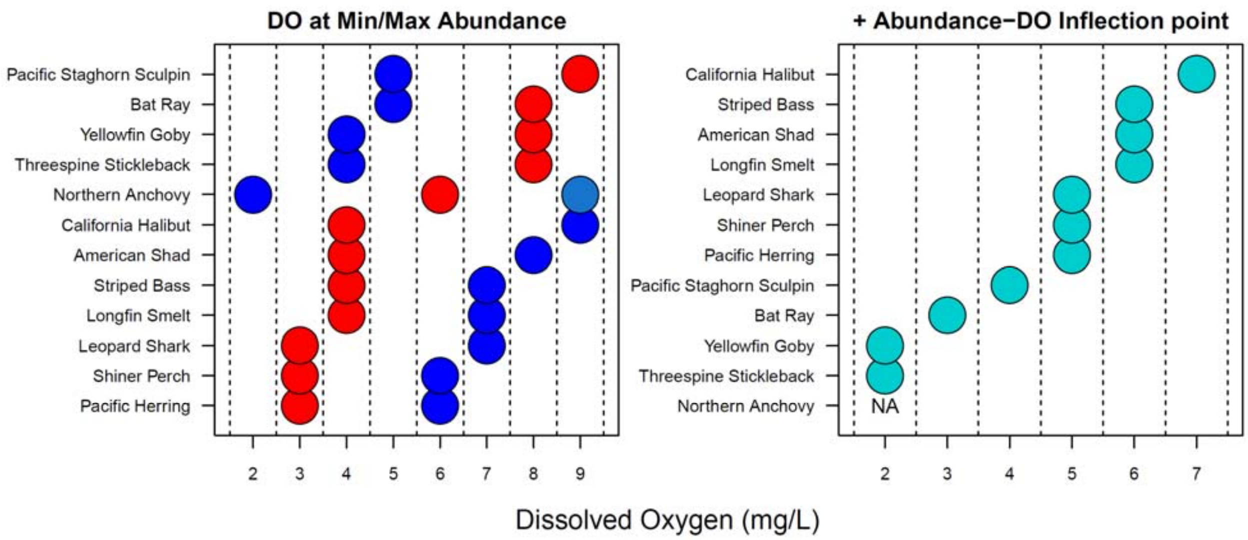

Figure 20. Summary of species' responses to dissolved oxygen. (LEFT) Dissolved oxygen levels at which smoothed relative catch was minimal (red) or maximal (blue) for each focal species. Northern Anchovy exhibited a bimodal distribution, with peaks in abundance at both 2 and 9 mg/L. For DO sensitive taxa (the lower 7 species), DO values ≤ 5 mg/L were generally "poor" quality whereas "good" conditions were generally ≥ 6 mg/L. (RIGHT) Dissolved oxygen levels at which relative catch changed from negative to positive, indicative of a transition from poor to desirable habitat with respect to DO. Conservative values were estimated for sticklebacks and yellowfin gobies; no inflection was provided for anchovies due to the bimodal distribution. See Fig. 19 for details.

Management Implications

Abundances of fishes in the AMC responded to several measures of water quality, providing insights regarding the likely drivers of species abundance patterns and whether hypoxia appears to limit fish abundance within the system. Our results suggest that species respond strongest to variation in temperature and salinity, and least to variation in turbidity and dissolved oxygen in the AMC. Examining cumulative catches across the full range of dissolved oxygen observed during surveys, it appears that different species exhibit positive, negative, or neutral responses to DO; therefore, fish communities in the AMC appear to be a diverse collection of species that exhibit diverse responses to variation in dissolved oxygen. Such diversity is a hallmark of biocomplexity with patterns likely driven by a variety of potential mechanisms (e.g., physiology, population dynamics, and ecological interactions).

The patterns observed in this study, therefore, are informative, but not conclusive. Though species-habitat relationships provide important inferences regarding habitat quality, such mensurative studies alone cannot resolve the true mechanisms behind observed species abundance patterns. For example, catches of the Threespine Stickleback, Yellowfin Goby, and Pacific Staghorn Sculpin, typically present as small (30-60 mm) forage fish, were highest in low-DO waters where top predators (e.g., Striped Bass, Leopard Sharks, and Halibut) were less common. Thus, low-DO water may function as a refuge from predation for prey species that are adapted to hypoxic conditions, even if it is otherwise poorer quality habitat (Robb & Abrahams

2003, Altieri 2008, Vanderploeg et al. 2009). Additional analyses and studies (e.g., physiology, selection/avoidance, growth, tracking) are needed to disentangle the true drivers of abundance and the relative importance of hypoxia to AMC fish communities.

Results of this work are directly relevant to management of the AMC and may also have broad implications for the greater San Francisco Estuary. The AMC receives wastewater effluent from the SJSCRFW and the greater SFE receives effluent from over 40 additional wastewater treatment facilities; therefore, the entire estuary experiences levels of nutrient loading that commonly cause algal blooms and hypoxia in other estuaries throughout the United States (Cloern & Jassby 2012). Though the SFE has appeared resilient to such eutrophication, largely due to high filtration rates by invertebrates and light limitation due to high turbidity, impacts of eutrophication on dissolved oxygen concentrations remain a valid concern throughout the estuary, including the AMC. Our data suggest that fishes in the SFE respond strongest to variation in temperature and salinity, and exhibit diverse responses to variation in dissolved oxygen (across the ranges measured in this study). In addition to eutrophication, temporal variation in ocean conditions may also contribute to variation in productivity and population dynamics of fishes in the SFE. For example, recruitment of several species of marine fishes to the SFE shifted in concert with regional changes in the NPGO (North Pacific Decadal Oscillation) (Cloern et al. 2007) and chl-a in the SFE appears to respond to changes in coastal upwelling in the Gulf of the Farallons (Raimonet & Cloern 2017). Similarly, our results also revealed large interannual variability in species abundances that may reflect variation in ocean conditions (e.g., Halibut, Anchovy, Leopard Shark) or regional climate (e.g., Sticklebacks). Therefore, consideration of temporal variation in regional ocean and climate conditions appears important for assessing water quality, productivity, and fish community dynamics in the AMC.

How do we develop DO criteria that will preserve the health and integrity of marsh habitats in the SFE? In the absence of local data, this is often addressed using data from other systems that may not be directly applicable to the system of interest. For example, hypoxia often drives fish abundance patterns in vertically-stratified systems with limited tidal mixing (Coutant 1990, Pothoven et al. 2012); however, the shallow AMC experiences significant mixing and flushing due to large (> 3 m) semi-diurnal tidal fluctuations. Fortunately, we have collected a long-term dataset of abundance patterns for over 50 species of fish and associated environmental conditions exists within the AMC. Given this biodiversity, we might average responses among a subset of abundant taxa with the objective of protecting the majority of individuals or their ecological functions in the system. However, catches in the AMC were dominated by hypoxia-tolerant taxa (e.g., sticklebacks), suggesting that averaging may not be the best strategy. Alternatively, the cautionary principle might suggest managing for the most sensitive species in order to protect the greatest number of species. Species such as Longfin Smelt might appear like good candidates in this regard; however, their temperature sensitivity may result in avoidance of the marsh during summer, when hypoxic conditions are most likely to occur. Another approach might be to focus on a subset of 'desirable' species (native and non-native) most likely to be impacted by hypoxic conditions where and when they appear to overlap in space and time. For example, Striped Bass, American Shad, Leopard Sharks, Staghorn Sculpin, and Halibut might be species of interest for establishing summertime DO thresholds. Additional species not assessed in this report (but present in trawl surveys) might also be included for specific questions or management objectives (e.g., flatfish species). The selection of appropriate focal species remains a key step in developing meaningful thresholds for DO concentrations in a given system. Fish habitat-abundance patterns for the current subset of focal taxa suggest that maintaining DO concentrations above the current open-water minimum concentration (5 mg/L) could be somewhat protective for several sensitive fish species in the AMC. For example, species that were more abundant at higher levels of DO exhibited positive inflections at 5-6 mg/L and minimal abundances at concentrations < 5 mg/L. Further refinement of the subset of focal taxa and temporal range included in models may provide improved inferences regarding the most appropriate DO criteria for the AMC.

The decline of dissolved oxygen in coastal waters is a global problem (Breitburg et al. 2018). Oxygen is essential to most aquatic life and thus remains an important metric of ecosystem health. However, to fully assess the effects of wastewater effluent on the health of estuarine organisms and ecosystems, it is important to consider multiple ecological criteria (e.g., secondary production, fish abundance/production, and biodiversity) in addition to changes in DO concentrations (Breitburg 2002, Bergstrom et al. 2004, Alexander & Dunton 2006). While effluent-fueled algal blooms and hypoxia are worthy of concern, the ecological benefits of freshwater and nutrient inputs to the estuary could also be significant (Alexander & Dunton 2006, Breitburg et al. 2009). Natural freshwater inputs into the AMC have been greatly reduced due to extensive capture, diversion, and consumption of surface and groundwater water from surrounding watersheds; therefore, effluent now provides the majority of freshwater inputs to the AMC, without which, many of the aquatic species we observed would likely be unable to persist year-round, especially during drought conditions (Alexander & Dunton 2006). Furthermore, while the food web in the northern SFE has collapsed, resulting in the decline of many fish species (Kimmerer 2006, Sommer et al. 2007), the food web in the AMC appears to be robust. Contrasts between fish densities in the AMC and surveys conducted with identical gear in marshes of the northern SFE (San Pablo Bay) have indicated that the AMC contains approximately10-fold greater abundance and 2-fold greater diversity of fishes than marshes in the less productive northern SFE (Hobbs, *unpublished data*). The discharge of nitrate-rich freshwater from the SJSCRWF likely fuels much of this excess production, supporting an abundance of invertebrates and forage fish that subsequently support vibrant bird and gamefish populations in the AMC (Breitburg et al. 2009). Thus, in addition to remaining vigilant regarding the risks of nutrient-induced hypoxia, our results suggest that management strategies for the AMC may also benefit from considering the benefits of treated freshwater effluent in this hydrologically-impacted, productive, and resilient estuarine ecosystem.

Recommendations

The analysis of habitat quality for fishes in the AMC has provided some initial insights into the factors that may determine abundances of fishes in the AMC. These insights can be used to assess marsh health, establish habitat quality targets (e.g., minimum DO concentrations), and highlight key uncertainties that warrant further exploration.

Is hypoxia currently compromising fish populations within the AMC?

- Diurnal discrete DO concentrations ranged from 2-11 mg/L, with 5-6 mg/L being the most commonly-observed values year-round. The lowest DO values were more common during summer, when fish abundance was often higher. Individual response functions (e.g., catch curves or single variate GAMs) suggested that some species may be sensitive to low concentrations of DO, and occasional observations of fish kills (e.g., Striped Bass) suggest that acute hypoxic events could impact fishes in the marsh. Most fishes that exhibited a positive DO-abundance relationship exhibited peaks in abundance ≥ 6 mg/L, inflections between 5-6 mg/L and minimum abundances ≤ 5 mg/L. Thus it appears that 5-6 mg/L may be an important criterion for maintaining populations of hypoxia-sensitive species in the AMC.

- However, variation in dissolved oxygen contributed least to abundance patterns for most species of fish examined using multivariate GAMs, thus DO was generally a poorer predictor of abundance than temperature and salinity for most species. Furthermore, several species also exhibited negative DO-abundance relationships, suggesting they are more abundant in low-DO habitats in the AMC. Though periodic hypoxia could compromise habitat quality for some fish species, the abundance-habitat GAMs developed herein do not provide strong evidence for this.

- GAMs and catch curves from field observations can provide key insights regarding the conditions that maximize fish abundance; however, these cannot alone determine the mechanisms (e.g., physiology, predation/competition, population dynamics) driving abundance patterns. Additional studies are needed to truly determine whether hypoxia is a driver of fish abundance in the AMC, especially during the summer DO-minimum period.

What are the remaining key uncertainties and how might future studies address them?

- It is not possible to discern “natural” versus “impacted” conditions (water quality and biotic community) without comparable data from reference marshes to provide appropriate context for fish and water quality metrics.
    - *Comparative studies of water quality and biotic properties in mash habitats throughout the SFE could greatly enhance the interpretation of data from the AMC in relation to wastewater influence, species assemblages, and environmental conditions.*
- The definition of “healthy” fish communities of fishes remains unclear. There are many native and non-native eury-oxic, -haline, and -thermal estuarine fishes that are abundant during summer-fall periods of high respiratory stress. Selection of appropriate focal species is central to establishing and assessing habitat quality targets.
    - *Definition of ‘desirable’ summertime fish assemblages (species & age classes) would clarify the metrics, methods, and values to be used for assessing habitat quality.*
    - *Assessments of benthic and nektonic invertebrate communities (e.g., in trawl data) may yield additional valuable information on habitat quality for forage species in relation to environmental conditions.*
- The current study incorporates seasonal variation in habitat quality, thus assuming that seasonal variation in fish abundance reflects habitat quality. However, the effects

of seasonal population dynamics (e.g., recruitment) could drive catch trends independent of adult sensitivities to habitat quality.
  - *Assessments of fishes filtered by life stage (e.g., in trawl data).*
  - *Assessments of habitat use filtered by season (e.g., in trawl data).*
- Though periodic hypoxia occurs in the AMC, due to tidal flushing, it is possible that hypoxia duration/intensity is not severe enough to significantly impact marsh-adapted native and non-native species. The hypoxia time-intensity limits, and interactions with other stressors (e.g., temperature and salinity), of focal fish species in the AMC remain uncertain.
  - *Physiological studies of time-intensity responses of focal species with respect to oxygen, temperature, salinity, and their interactions, would greatly enhance inferences regarding mechanisms behind observed variation in abundance and distribution.*
- Sites were only sampled once per month without replication, thus limiting geospatial inferences about habitat quality within shorter time periods.
  - *Intensive spatial & temporal sampling (with replication) in summer-fall would provide greater resolution for determining habitat use in relation to temporal and spatial variation in environmental conditions during periods of maximum respiratory stress.*
- Otter trawls sample flat substrate in the middle of channels; several species are likely much more abundant nearshore in more complex habitats and may exhibit different patterns than observed using otter trawls.
  - *Assessments of fishes using multiple gear types (e.g., seine, gill net, hook and line, fyke, minnow trap and plankton nets) to target key habitats (e.g., pelagic, littoral, marsh), life-stages (e.g., juvenile, adult) and taxa (e.g., Longjaw Mudsuckers, Sturgeon, Adult Striped Bass and Leopard Sharks) would provide a more robust and meaningful assessment of habitat quality for focal species.*
- Otter trawls select for small species and juvenile life stages; larger top predators (e.g., leopard sharks, striped bass, sturgeon) were likely under-sampled).
  - *Other gear types (e.g., gill nets, hook and line, fyke nets) could be used to assess habitat use by large fishes. Tagging/tracking the movement patterns and monitoring the abundance of large summer-time predators (leopard sharks, bat rays, striped bass) would provide for explicit testing of the geospatial preference and avoidance of certain habitats at certain times and, combined with paired water quality monitoring, could provide key insights into the effects of DO and other water quality parameters on predator abundance, behavior, and ecosystem dynamics (e.g., top-down control of prey) in the AMC.*
- Otter trawls were conducted during daily spring tides and did not sample Guadalupe Slough, thus omitting the times and locations where hypoxic stress is likely most severe.
  - *Additional sampling at night, during neap tides, and within Guadalupe Slough may provide additional information of fish responses to the most extreme hypoxic conditions in the AMC.*

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APPENDICES

Appendix 1: R Code for running GAM analyses

```
###############################################################################################
#            SETUP
###############################################################################################

# FIRST, set working directory to correct folder

rm(list = ls())                              #clear console
par(mfrow=c(1,1))                            #single graph arrangement

# useful libraries
library(plyr)
library(dplyr)
library(tools)
library(ggplot2)
library(mgcv)
#library (gamm4) (needs to be installed still)

# color pallet

ll_scale <- c("#008210","#b667f1","#afcd1c","#6a7dff","#91d78e","#ff6dcc","#00aaa4","#bd001b",
      "#0084e1","#ff787d","#45591f","#733794","#9a2738","#f3b0ef","#844640"
      )

# read in data
sbdata <- read.csv("sbdata.csv", stringsAsFactors = FALSE)
sbdata$Year <- as.factor(sbdata$Year)   # works with random effects gam

# Focal Species

selsp <- c("Threespine Stickleback", "Pacific Staghorn Sculpin", "Northern Anchovy" , "Yellowfin Goby",
   "Pacific Herring", "California Halibut", "American Shad", "Striped Bass" , "Longfin Smelt",
   "Shiner Perch" , "Bat Ray" , "Leopard Shark")

# about mgcv and gamms (gamm4)
# mgcv = a GAM package by Simon Wood, uses gam() call
# mgcv cannot use lowess smoothers...uses tp or cubic splines
            # mgcv uses gcv to automatically choose degree of smoothing, with REML
                        # tensor products, te() and ti() in mgcv, or t2() in gamm4, can be used to include interactions
                        # s(x, by= "factor") can be used for smoothing separately across different levels of a factor
            # gamm4 = updated version of gamm; better for complex random effects (re) GAM models (t2 tensors only)

# set params

bs <-  "tp"                                  #thin plate regr. spline (default); cc might be better for cyclical patterns, M
fam <- nb(theta = NULL, link = "log")  #negative binomial distribution with log link
k <-6                                        # max complexity of smoothing (1 = line, 2 = peak, 3+ = polynomial, 8= mid/high)
re <- "re"                                   # for random effects basis


# MODELS

y <- as.formula("ccount ~ s(Year, k=k, bs=re)") # should only include as random variable (re)
m <- as.formula("ccount ~ s(Month, k=k, bs=bs)")
```

```
o <- as.formula("ccount ~ s(do, k=k, bs=bs)")
s <- as.formula("ccount ~ s(sal, k=k, bs=bs)")
t <- as.formula("ccount ~ s(temp, k=k, bs=bs)")
rc1 <- as.formula("ccount ~ s(RC1, k=k, bs=bs)")
rc2 <- as.formula("ccount ~ s(RC2, k=k, bs=bs)")
os <- as.formula("ccount ~ s(do, k=k, bs=bs)+s(sal, k=k, bs=bs)")
ot <- as.formula("ccount ~ s(do, k=k, bs=bs)+s(temp, k=k, bs=bs)")
st <- as.formula("ccount ~ s(sal, k=k, bs=bs)+s(temp, k=k, bs=bs)")
rc12 <- as.formula("ccount ~ s(RC1, k=k, bs=bs)+s(RC2, k=k, bs=bs)")
ost <- as.formula("ccount ~ s(do, k=k, bs=bs) + s(sal, k=k, bs=bs) + s(temp, k=k, bs=bs)")
most <- as.formula("ccount ~ s(Month, k=k, bs=bs) + s(do, k=k, bs=bs) + s(sal, k=k, bs=bs) + s(temp, k=k, bs=bs)")
yost <- as.formula("ccount ~ s(Year, bs=re) + s(do, k=k, bs=bs) + s(sal, k=k, bs=bs) + s(temp, k=k, bs=bs)")
ymrc12 <- as.formula("ccount ~ s(Year, bs=re) + s(Month, k=k, bs=bs) + s(RC1, k=k, bs=bs)+s(RC2, k=k, bs=bs)")
ymost <- as.formula("ccount ~ s(Year, bs=re) + s(Month, k=k, bs=bs) + s(do, k=k, bs=bs) + s(sal, k=k, bs=bs) + s(temp, k=k,
bs=bs)")

mod <- c("y", "m", "o", "s","t","rc1","rc2","os","ot","st","rc12","ost","most","yost","ymrc12","ymost")  # list of models
(characters for get())


##########################################################################################################
#      GAM ANALYSIS
##########################################################################################################

dev.summary <- data.frame(sp = selsp, y = rep(0, length(selsp)))              #table for deviance explained values
aic.summary <- data.frame(sp = selsp, y = rep(0, length(selsp)))              # table for aic values based on AIC(b)
aic2.summary <- data.frame(sp = selsp, y = rep(0, length(selsp)))             # table for aic values based on b$aic
edf.summary <- data.frame(sp = selsp, y = rep(0, length(selsp)))              # table for aic values based on b$aic

sink("gams.txt")  # print all stats to text file "gams.txt"
pdf("gamplots.pdf") # save all plots to single pdf "gamplots.pdf"

for(i in mod){   # start GAM MODEL forloop

par(mfrow=c(4, 4))
par(mar=c(2,5,2,1))

for(sp in selsp){                                                   #start GAM for loop

print(paste("##########################################################################################"))
print(paste("        ",sp, " (",i,")           ", sep=""))    # List sp & model being evaluated
print(paste("##########################################################################################"))

 ldf <- sbdata[sbdata$Common == sp, ]                               # subset by sp

 b <- gam(get(i), family=fam, data=ldf)                                     #gam analysis (using mgc)

print(summary(b))                                                   # gam results (saved/sinked to gam_raw.txt)
print(paste("dev.expl = ", round(summary(b)$dev.expl, 3)))                  # print dev expl
print(paste("AIC = ", round(b$aic, 1)))                             # print aic
print(paste("edf = ", round(sum(b$edf), 1)))                        # print edf

concurvity(b,full=TRUE)                                             # test for concurvity
# paste(gam.check(b, old.style=FALSE))                                      # gam.check (basis dimension, k; plots) [on/of for
speed]

dev.summary[dev.summary$sp==sp, i] <- 100*round(summary(b)$dev.expl, 3) # automatically save deviance explained to
dev.summary table
aic.summary[aic.summary$sp==sp, i] <- round(AIC(b), 0)              # automatically save aic to aic.summary table
aic2.summary[aic2.summary$sp==sp, i] <- round(b$aic, 0)                     # automatically save aic to aic.summary table
edf.summary[edf.summary$sp==sp, i] <- round(sum(b$edf), 2)                  # automatically save edf to edf.summary table
```

```
plot(b,pages=0,scheme=1, main=paste(sp, "(",i,")" ), cex.main=1, seWithMean=TRUE) ## `plot smoothers with SE

 }                                                  # End GAM SPECIES forloop
 }                                                  # End GAM MODEL forloop

dev.off()                                           # stop saving figures to single pdf
sink()                                              #stop printing stats to .csv

#########################################################################
#   EDF
#########################################################################

# melt dev.summary for plotting

edf.melt <- melt(edf.summary, "sp", colnames(edf.summary)[2:length(colnames(edf.summary))])
edf.melt <- edf.melt[order(edf.melt$sp, edf.melt$variable),]
edf.melt$mod <- rep(seq(1:(length(colnames(edf.summary))-1)),length(unique(edf.melt$sp)))

# individual edf explained plots (best)

par(mar=c(4,4,2,2))
par(mfrow=c(3,4))
for(i in unique(edf.melt$sp)){
 temp <- edf.melt[edf.melt$sp==i, ]
 plot(temp$value~temp$variable, ylim=c(min(temp$value), max(temp$value)), main=i, las=2, xlab=NULL, ylab="edf",
type="l")
 lines(temp$value~temp$variable, col=ll_scale[which(unique(edf.melt$sp)==i)], lwd=2)
 abline(v=c(2.5,12.5, 13.5), lty=2, col="grey")
}
dev.copy(pdf, "edf_plots.pdf",width=11, height=8.5)
dev.off()

#########################################################################
#   DEVIANCE EXPLAINED
#########################################################################

dev.summary # summary of deviance explained for all models and all species

# melt dev.summary for plotting

dev.melt <- melt(dev.summary, "sp", colnames(dev.summary)[2:length(colnames(dev.summary))])
dev.melt <- dev.melt[order(dev.melt$sp, dev.melt$variable),]
dev.melt$mod <- rep(seq(1:(length(colnames(dev.summary))-1)),length(unique(dev.melt$sp)))

# individual dev explained plots (best)

par(mar=c(4,4,2,2))
par(mfrow=c(3,4))
for(i in unique(dev.melt$sp)){
 temp <- dev.melt[dev.melt$sp==i, ]
 plot(temp$value~temp$variable, ylim=c(min(temp$value), max(temp$value)), main=i, las=2, xlab=NULL, ylab="Dev.
Explained", type="l")
 lines(temp$value~temp$variable, col=ll_scale[which(unique(dev.melt$sp)==i)], lwd=2)
 abline(v=c(2.5,12.5, 13.5), lty=2, col="grey")
}
dev.copy(pdf, "dev_plots.pdf",width=11, height=8.5)
dev.off()

#########################################################################
#   AIC
#########################################################################
```

```
aic.summary # AIC summary table

# melt aic.summary for plotting

aic.melt <- melt(aic.summary, "sp", colnames(aic.summary)[2:length(colnames(aic.summary))])
aic.melt <- aic.melt[order(aic.melt$sp, aic.melt$variable),]
aic.melt$mod <- rep(seq(1:(length(colnames(aic.summary))-1)),length(unique(aic.melt$sp)))
aic.melt

# individual AIC plots (best)

par(mar=c(4,4,2,2))
par(mfrow=c(3,4))
for(i in unique(aic.melt$sp)){
 temp <- aic.melt[aic.melt$sp==i, ]
 plot(temp$value~temp$variable, ylim=c(min(temp$value), max(temp$value)), main=i, las=2, xlab=NULL, ylab="AIC(b)",
type="l")
 lines(temp$value~temp$variable, col=ll_scale[which(unique(aic.melt$sp)==i)], lwd=2)
 abline(v=c(2.5,12.5, 13.5), lty=2, col="grey")
}
dev.copy(pdf, "aic1_plots.pdf",width=11, height=8.5)
dev.off()
```

Appendix 2. Evidence for stratification

By contrasting spot water quality data taken at both the surface and bottom of the water column, we were able to observe the degree of stratification and variation in water quality parameters with depth. Based on these data, we observed little evidence of persistent stratification in the AMC. Surface-bottom measurements suggest that DO and TEMP are slightly elevated (median difference < 0.1 mg/L and °C) in surface waters, whereas salinity was slightly elevated (median difference < -0.1 psu) in bottom waters (Fig. S2.1). Though these patterns match expected patterns based on water density and irradiance, the small magnitudes and centering around 0 indicate that the water column was generally well-mixed and exhibited weak, if any, stratification. This is likely due to dynamic tidal action that rapidly mixes marsh waters over relatively short timescales.

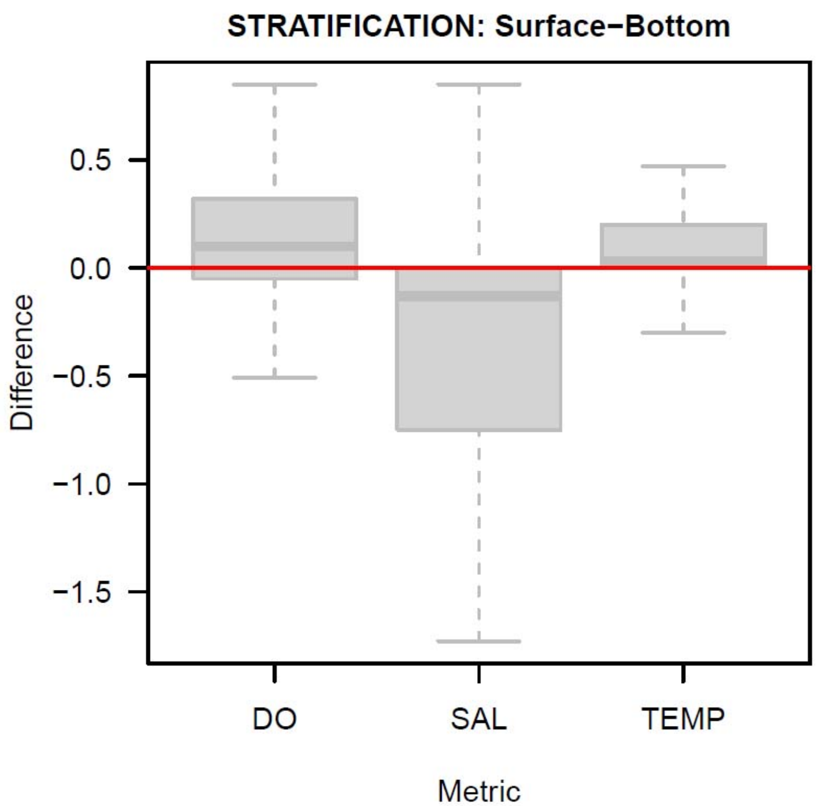

Fig. S2.1. Evidence for stratification in the Alviso Marsh Complex. Values reflect the difference between surface and bottom measurements for DO (mg/L), SAL (psu), and TEMP (°C).

Though stratification can vary among sites and among months, the variation we observed remained quite small, generally < 1 unit in any water quality metric across all sites and months (Figs. S3.2-3); however occasional observations of stratification could be observed in Artesian slough (e.g., salinity, due to fresh wastewater effluent) or across sites in August.

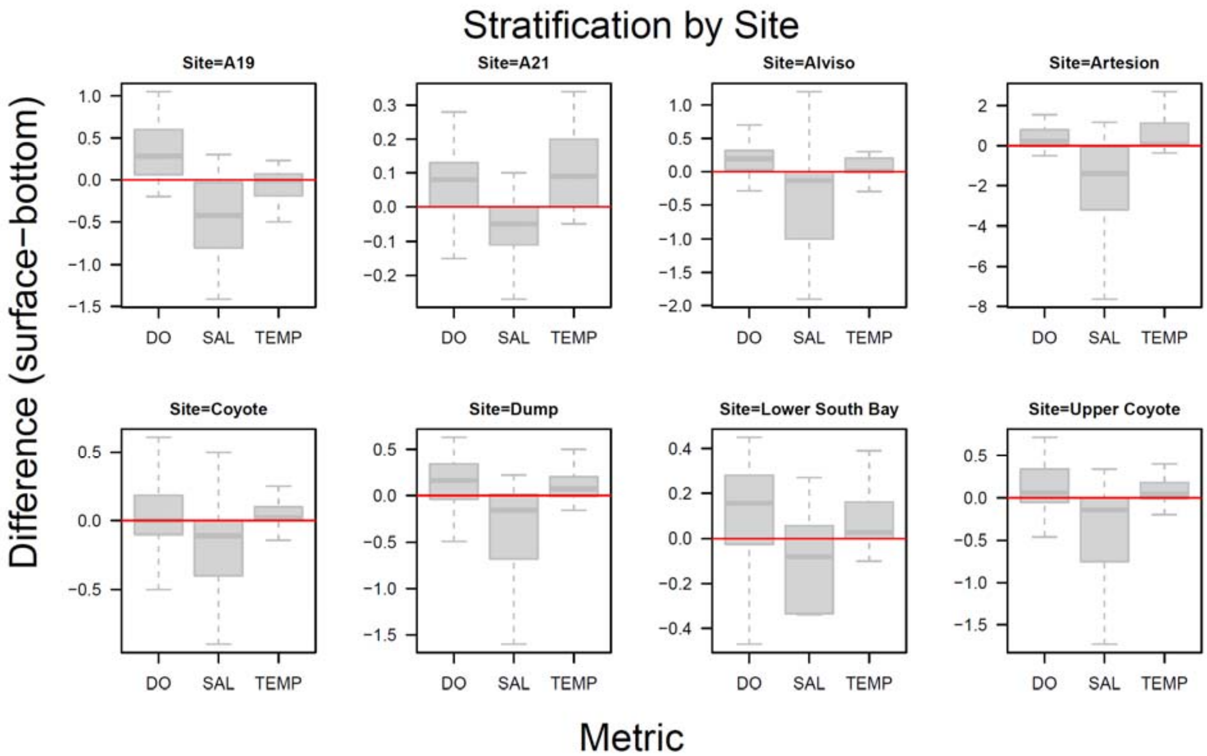

Fig. S2.2. Evidence for stratification by site. Values reflect the difference between surface and bottom measurements for DO (mg/L), SAL (psu), and TEMP (°C).

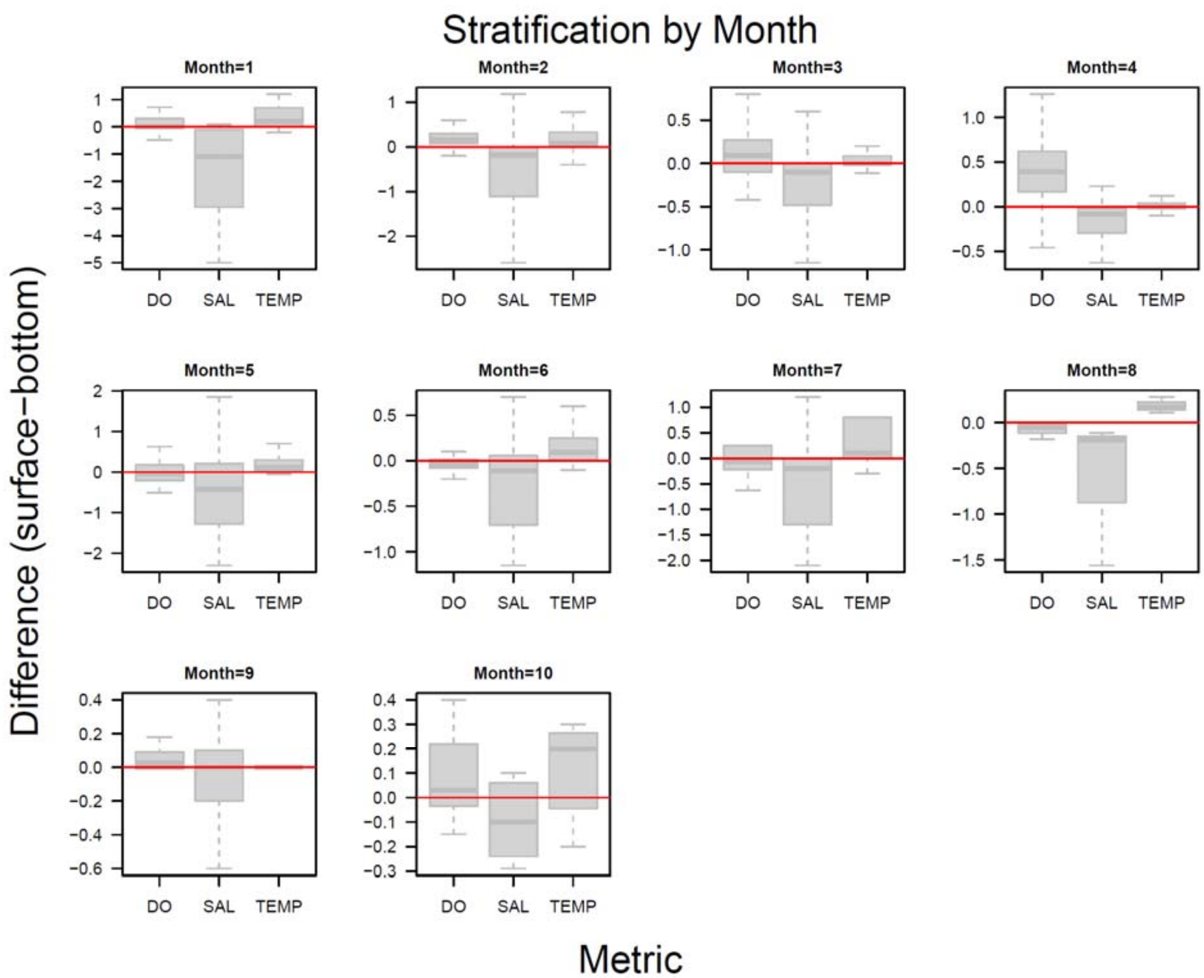

Fig. S2.3. Evidence for stratification by month. Values reflect the difference between surface and bottom measurements for DO (mg/L), SAL (psu), and TEMP (°C). Note: bottom measurements not collected in months 11-12.

Appendix 3. Spatial variation in water quality and catch data

We examined relationships between water quality and fish abundance, with variation in environmental conditions occuring in both time (e.g., months and years) and space (e.g. sites). We did not explicitly incorporate variation in space in our model, as variation in the spatial distribution of fishes likely reflected variation in water quality. To examine this further, we plotted variation among sites with respect to the tidal heights and depths sampled, and observed water quality measurements (do, sal, temp, and sec) (Fig. S3.1). Overall, tide heights, depths, and water quality varied greatly, with sites exhibiting large degrees of overlap in conditions; however, some general differences among sites are apparent. Median tide heights in most sloughs were ~ 6 ft, however tide heights in Alviso and Artesian slough were generally 2 ft lower (~ 4ft), reflecting their proximity to launch sites and the necessity for beginning surveys at low tides to capture the daily high, necessary for sampling shallow sites. Subsequently ponds (A19 and A21) were sampled at higher tides (~ 7ft) that ensured access and sufficient depths for sampling these intertidal habitats. Most sites exhibited median depths of 5-10 ft, with pond habitats being the shallowest (median ~ 5 ft) and outer bay (LSB and lower Coyote) habitats being the deepest (median ~ 10 ft). Coyote exhibited the greatest intra-site variation in depth due to the dispersion of 4 stations upstream to downstream. Salinity varied the greatest spatially, with Artesian and Upper Coyote exhibiting the most freshwater input (median salinity 8-10 psu), and bay habitats (LSB) exhibiting the most ocean influence (median salinity ~ 27 psu). In general, temperature and Secchi depth varied least among sites, however Secchi was consistently higher in Artesian Slough likely due the persistent inflow of clear, fresh wastewater.

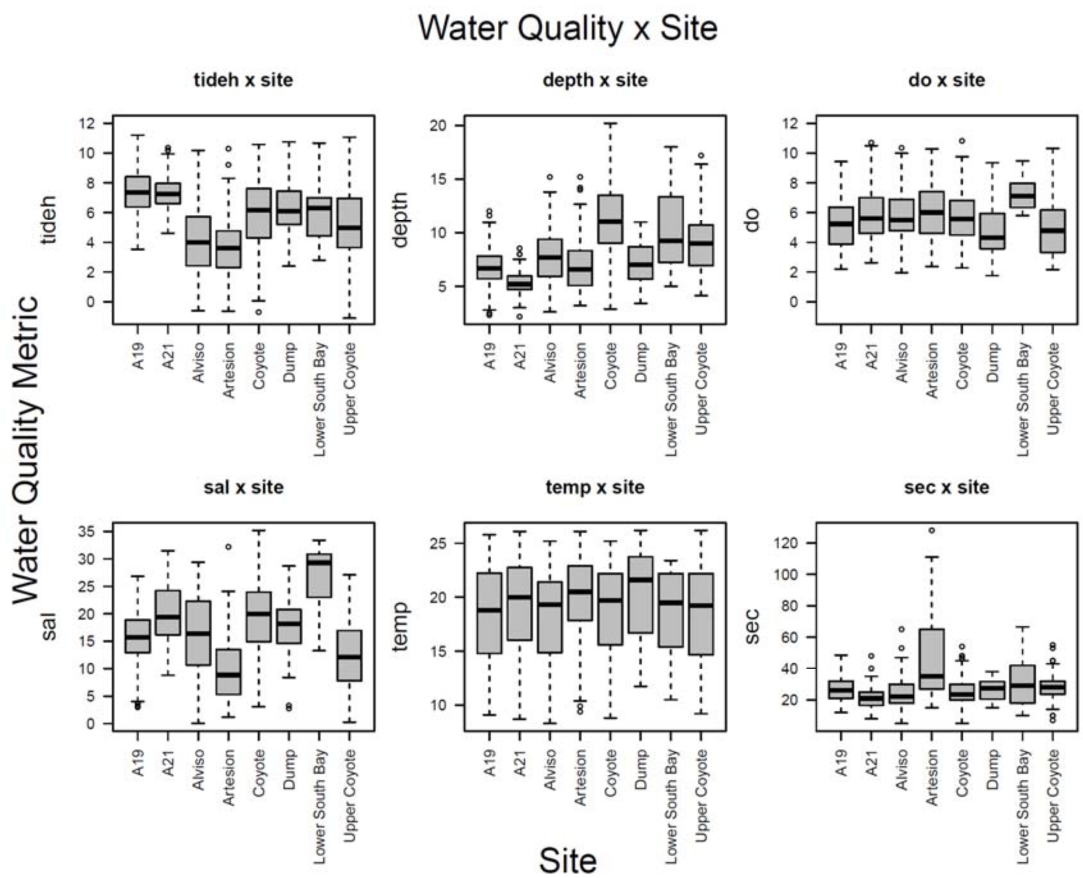

Figure S3.1. Spatial variation in tow and water quality metrics.

Similarly, catch per unit effort varied greatly for each site; however, some sites exhibited lower or higher catches for certain species. Lower South Bay, in general, exhibited lower catches for most species except Bat Rays, Halibut, Leopard Sharks, and Anchovies. Dump slough exhibited low caches of Leopard Sharks, Longfin Smelt, Herring, Shiner Perch, and Striped Bass. Artesian Slough also exhibited lower catches of several species (e.g., Bat Rays, Leopard Sharks, Longfin), but the highest catches of Striped Bass. This spatial variation in abundance covaries with spatial variation in water quality, which likely drives both spatial and temporal variation in habitat quality and use for each species.

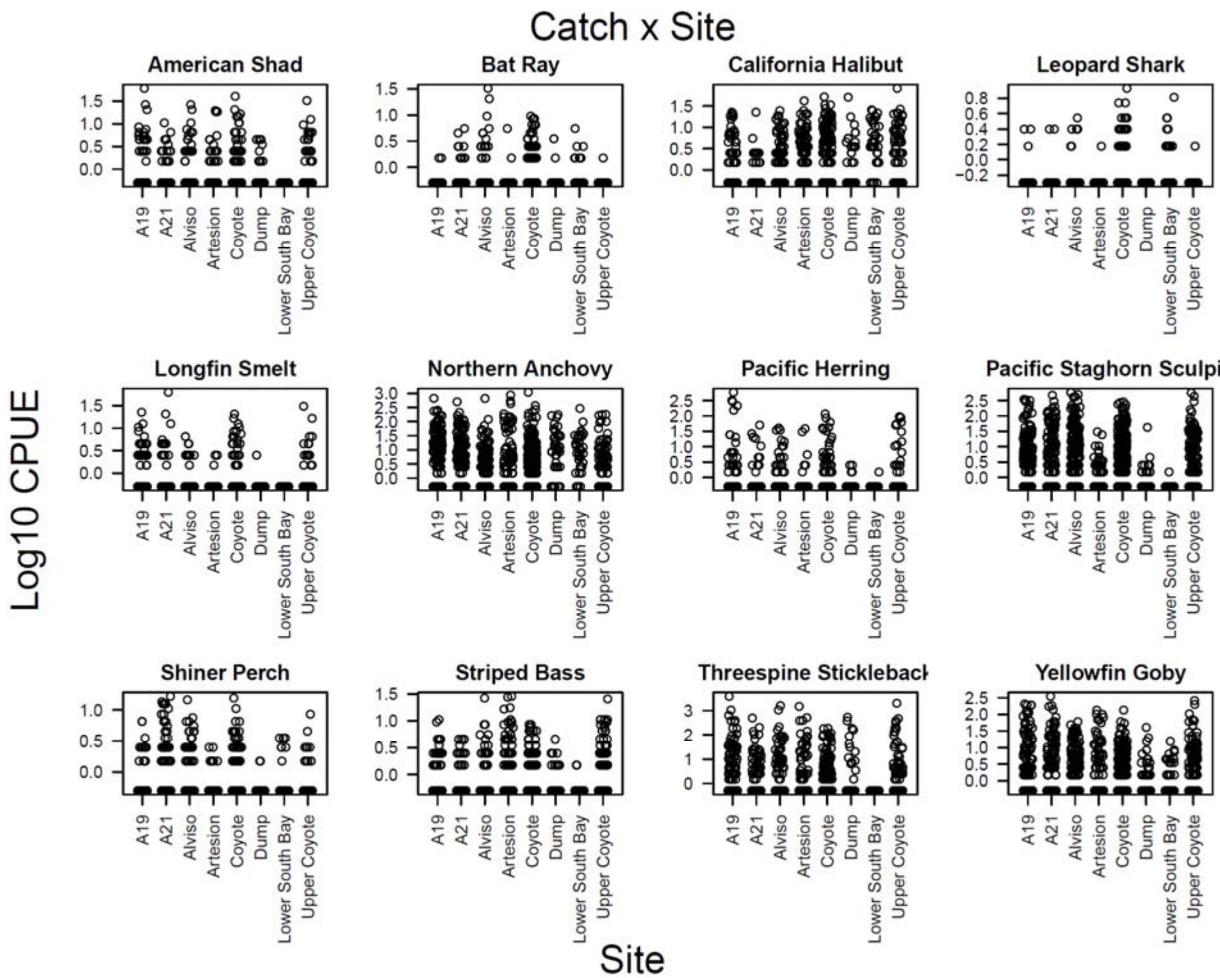

Figure S3.2. Spatial variation in CPUE for each focal species. Values were log10(x+0.5) transformed to facilitate comparisons.

CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

The goal of this report is to present analyses of the moored sensor and fish catch datasets across diverse habitats in Lower South Bay to understand where and when there is adequate dissolved oxygen (DO) to support resident fish species. The first part was an analysis of continuous measurements by moored sensors of DO, temperature, salinity, and tidal stage at seven stations in Lower South Bay (Chapter 2). The second part was an analysis of fish abundances and co-located instantaneous measurements of water quality that were used to assess preferred water quality conditions for 12 species of fish in Lower South Bay (Chapter 3). The following sections outline the joint conclusions and recommendations from these analyses.

Conclusions

Characterization of Dissolved Oxygen

- Dissolved oxygen in Lower South Bay exhibits high variability across diurnal, seasonal, and annual timescales, as well as across space.
- Low DO concentrations occur in LSB and likely originate in sloughs and other perimeter habitats. In particular, sloughs that are connected to restored salt ponds or receive treated wastewater have higher oxygen demand.
- The moored sensor data show that DO typically meets the Basin Plan water quality objective of 5 mg/L in the deep channels. However, in the sloughs, DO concentrations fell below 5 mg/L for 11-65% of the observations throughout the year and as much as 90% of the summer months at some stations.
- At most stations, it appears that low DO events occur on rapid time scales that are consistent with the major drivers of tidal advection and diurnal factors. Excursions below 5 mg/L were typically the shortest at the Dumbarton Bridge (1-2 hours) and longest in Guadalupe Slough (7-20 hours). During the summer months, the excursions lasted longer, with peak durations occurring in July through October. The longest continuous excursion below 5 mg/L was 12 days in Guadalupe Slough. Excursions below 2.3 mg/L were observed in Alviso and Guadalupe Sloughs but, importantly, lasted less than a day. The value of 2.3 mg/L is a threshold for impacts for fish after 24-hour exposures that is recommended for the Virginian Province of the East Coast (USEPA 2000). It is not known whether this threshold is applicable to the fish species in LSB but it provides a useful benchmark for evaluating the data for obvious concerns on short time scales.

Characterization of Fish Abundances

- Alviso Marsh is utilized by many recreationally and commercially important fish species, some of which may be sensitive to dissolved oxygen levels. Over 50 species of fish were observed during the study period and fish communities appeared to be more abundant and diverse than in reference marshes in the northern SFE.
- Overall, fish abundance was highest at lower DO concentrations, reflecting the numerical dominance of hypoxia-tolerant native and non-native species. However, we also observed substantial variation among species in their relationships between catch and DO concentrations, and these patterns could be driven by a variety of potential mechanisms (e.g., physiology, population dynamics, and ecological interactions).
- Fishes were patchy in nature, exemplified by many zero catches and occasional large catches that fit a negative binomial distribution. Negative binomial GAMs using environmental conditions (temperature, salinity, dissolved oxygen and Secchi depth) as predictors explained up to 60% of the deviance for some species. Abundance varied greatest with temperature and salinity for most species; however, DO and temperature co-varied with seasonal changes, thus complicating their independent effects.
- The current minimum DO criterion for open water habitat in the Bay is 5 mg/L, and our results suggest that maintaining concentrations above this threshold could be somewhat "protective" for many fish species encountered in surveys.
- This analysis focused on a subset of focal species selected in relation to their abundance and societal and management relevance. Though these species are valued by many stakeholders, it would be reasonable and advisable to consider a different suite of focal taxa to address specific management objectives.

Recommendations

Additional studies are recommended before drawing conclusions about where and when regions of LSB provide adequate DO to support resident fishes. The additional research is needed because of:

- the lack of information on DO at locations other than at the mooring stations,
- the uncertainty in the species-specific tolerances of LSB fish to low DO, and
- the covariance between DO and other water quality parameters.

Studies to Improve Characterization of Dissolved Oxygen

- **A dynamic representation of DO in space and time from a coupled biogeochemical-hydrodynamic model of LSB**. Producing this dynamic DO field for the entirety of Lower South Bay will require continued moored sensor monitoring, model development, and special studies to determine the rates for biogeochemical processes from different habitats in the estuary.
- **Continued analysis and synthesis of the moored sensor data from LSB**. Inter-annual variability was not assessed in this report because there were too few years of data.

Changes in gate operations and restoration of former salt ponds can have profound impacts on DO concentrations in nearby sloughs. Analysis of moored sensor data collected before and after these changes will yield valuable insights.

Studies to Improve Characterization of Fish Abundances and Habitat Suitability

- **Additional studies of fish abundances patterns could provide additional data to determine the mechanisms driving fish abundance patterns in the LSB**. Studies could assess additional reference and impacted marshes, examine macro-invertebrate communities, track top-predators, use multiple sampling gear types, and intensively sample during periods of greatest hypoxia.
- **Further development of GAMs could provide additional inferences regarding biological responses to environmental conditions**. Additional models could include a refined subset of species and life stages, invertebrate community dynamics, interactive effects of predictors (e.g., DO, TEMP, season), and variation among sites or habitat types.

Alternative Approaches for Assessing Habitat Suitability

- An alternative approach for developing site specific objectives for DO objective is the Virginian Province Approach (VPA), as has been done in other Californian estuaries. The VPA is based on a synthesis of peer-reviewed studies on the biological effects of DO and the application of a mathematical model to integrate effects over time (USEPA 2000). Protective thresholds are developed for distinct life stages (e.g. larvae, juveniles, and adults). Information on low-DO tolerance of local species can be added when possible and appropriate. In Suisun Marsh, adjacent to the eastern-most embayment of the San Francisco Bay, the VPA was used to propose DO objectives of 3.8 mg/L (acute), 5.0 mg/L (chronic), and 6.4 mg/L (chronic for salmonids) by associating Suisun Marsh species to the VPA database by family or genus (SFBRWQCB 2018). A similar process could be used for LSB.

- Dissolved oxygen and community responses of fish also need to be assessed in the context of changing ocean conditions. Increases in water temperatures simultaneously reduce oxygen solubility and increase the respiratory oxygen demand of fish, limiting aerobic scope. These changes to dissolved oxygen concentrations and metabolic requirements as a result of increasing temperature may compress available habitat for fish and other marine organisms. The metabolic index of a marine organism is a metric that has been developed to determine acceptable species distribution using the ratio of oxygen supply to the resting metabolic oxygen demand. The metabolic index could be applied to fish species in the SFB to predict tolerance to increasing temperatures and whether fish habitat may be restricted in the future.

LITERATURE CITED

SFBRWQCB. 2018. Establish Water Quality Objectives and A Total Maximum Daily Load for Dissolved Oxygen in Suisun Marsh and Add Suisun Marsh to SF Bay Mercury TMDL. Tech. rep., San Francisco Bay Regional Water Quality Control Board, Oakland, CA. Published online: https://www.waterboards.ca.gov/sanfranciscobay/water_issues/programs/TMDLs/suisunmarshtmdl.html.

USEPA. 2000. Ambient Aquatic Life Water Quality Criteria for Dissolved Oxygen (Saltwater): Cape Cod to Cape Hatteras. EPA-822-R-00-012. US Environmental Protection Agency, Office of Water, Washington, DC.