Eelgrass, Herring, and Waterbirds in San Francisco Bay: Threats and Opportunities

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Overview

The San Francisco Bay is an ecologically rich estuary, significant for its large eelgrass (*Zostera marina*) beds, spawning areas for Pacific herring (*Clupea pallasii*), and tens of thousands of wintering waterbirds and other wildlife. Herring is a significant food source for many species of marine wildlife, yet habitats such as eelgrass on which they depend are in decline. Without the eelgrass-herring ecosystem, tens of thousands of wintering and migrating birds would lose a vital energy source, which could jeopardize bird populations across the Pacific Flyway (a major north-south migration route along the Pacific Coast). Many species of waterbirds forage on and in eelgrass beds, including Brant geese (*Branta bernicla*) and Surf Scoters (*Melanitta perspicillata*), underscoring the value of the eelgrass food web. The purpose of this paper is to synthesize current research pertaining to the eelgrass, herring, and waterbird ecosystem in San Francisco Bay and propose conservation opportunities.

Key Findings

- Eelgrass is the foundation for a unique and valuable food web in San Francisco Bay, but is threatened by human activity (e.g., dredging, boating, and anchoring), climate change (including impacts from sea level rise and warming ocean temperatures), limited restoration success, and a lack of both formal valuation and community understanding of its benefits.
- Herring spawn provides energy-rich food to birds that winter in and migrate through the San Francisco Bay and herring supports the Bay's last commercial fishery. However, oil spills, dredging, invasive species, habitat decline, and fishing pressures herring.
- Without the eelgrass-herring ecosystem, tens of thousands of birds would be in jeopardy, affecting species persistence and recovery at a hemispheric scale. Migratory waterbirds are threatened by lack of food availability (through impacts to eelgrass and herring) and human disturbance (e.g., unauthorized moorings in priority habitats).
- There is a significant lack of research specific to San Francisco Bay pertaining to relationships between eelgrass, herring, and birds, which limits conservation efficacy.

Recommendations

Eelgrass and herring resources are a priority for winter waterbird conservation in the San Francisco Bay. To expand our understanding of subtidal habitats in San Francisco Bay, we recommend conducting the following monitoring activities: annual eelgrass surveys and estimates of shoot density, analyses to relate waterbird census data to environmental conditions, analyzing relationships between eelgrass coverage and herring biomass, investigating phenological changes in spawn events, and assessing existing waterbird data to identify relationships with spawning events.

Opportunities to address key threats listed above include management strategies that promote eelgrass resilience at local and regional scale, and an evaluation of factors that influence spawning activities in Richardson Bay. With the second largest eelgrass bed in San Francisco Bay and consistent spawn activity every year, Richardson Bay is a priority for future eelgrass conservation and restoration efforts. Communities that live in and adjacent to Richardson Bay must be involved in eelgrass, herring, and waterbird conservation initiatives. Conservation will be easier to implement if local communities are aware of the eelgrass-herring-waterbird food web and understand its value for the Pacific Flyway. As local, state, and regional agencies prepare and adapt to climate change, enhanced community engagement will help protect natural resources across the bay and along the flyway.

Western Grebe
Photo: Leslie Scopes Anderson

EELGRASS, HERRING, AND WATERBIRDS IN SAN FRANCISCO BAY: THREATS AND OPPORTUNITIES

1. Introduction

With its large eelgrass beds, spawning grounds for Pacific herring (*Clupea pallasii*; hereafter herring), tens of thousands of wintering waterbirds, and robust wildlife, the San Francisco Bay Area is a hotspot for biodiversity. Herring is a significant food source for many species of marine wildlife, yet habitats on which the fish depend, namely eelgrass, are in decline. In this paper, we examine the factors affecting eelgrass, herring, and waterbirds in San Francisco Bay, California. We reviewed literature on eelgrass and other submerged aquatic vegetation (SAV) that support herring spawning in the Bay, herring ecology specific to San Francisco Bay, and waterbird use of habitats and resources where herring spawn. Here we define "waterbirds" as birds that use the open bay waters for resting and foraging during the winter months as part of their annual migration.

We assessed the biological and ecological factors that regulate eelgrass and herring populations at broad scales. These factors include direct and indirect effects of changes in temperature, salinity, pH, nutrients, turbidity, sedimentation, currents, sea level rise, SAV, grazers, epiphytes, invasive species, physical disturbance, increased human recreational and industrial use, and fishing and aquaculture. The waterbird assessment focused specifically on bird use of eelgrass and herring habitats. We provide recommendations for ongoing monitoring to help clarify how waterbirds rely on these resources in San Francisco Bay. Lastly, we identified specific and interactive threats to eelgrass, herring, and waterbirds and highlighted opportunities to limit these threats when possible

2. Eelgrass

Seagrasses are a unique group of flowering plants that exist fully submerged in ocean environments. Seagrasses provide valuable ecosystem services, such as food for herbivores and critical habitat for fish species (Orth et al. 2006). Eelgrass (*Zostera marina*) is a species of seagrass distributed throughout the northern hemisphere and is the primary species of seagrass present along the Pacific coast (Ort et al. 2014). Eelgrass provides spawning habitat for commercially important fish, in addition to providing food for other marine animals and birds (Ort et al. 2012). Here we introduce eelgrass ecology, biological interactions, and human-related impacts, as well as threats to eelgrass ecosystems.

2.1 Eelgrass Ecology

Temperature and Light Availability

Temperature and light are the most critical environmental variables controlling eelgrass growth, biomass, and phenology (Zimmerman et al. 1989, Poumian-Tapia and Ibarra-Obando 1999). The optimal temperature range for eelgrass growth is 10-20°C. Beyond this range there is limited capacity for acclimation and growth, survival may be reduced, and life cycles may change from perennial to annual (Phillips 1974, Zimmerman et al. 1989). Eelgrass in the northern portion of its range suffers decline following heat stress events (Winters et al. 2011, Franssen et al. 2011). Warmer temperatures during El Niño years can reduce eelgrass biomass, decrease shoot density, and increase flowering shoot density (Cabello-Pasini et al. 2003, Thom et al. 2003, Ward et al. 2005, Thom et al. 2014). While high temperatures can increase mortality 12-fold, as well as lower growth and photosynthetic rates (Nejrup and Pederson 2008), low water temperatures do not affect mortality.

Eelgrass growth is limited by light availability, which can be altered by sedimentation, competition with phytoplankton and epiphytes, and water depth (Zimmerman et al. 1995). Light availability controls the lower depth limit of eelgrass. Decreased irradiance causes rapid reductions in eelgrass density and standing stock (Backman and Barilotti 1976, Dennison 1979, Dennison and Alberte 1982). The deepest eelgrass found in San Francisco Bay is in Richardson Bay at -3 m, but this is a baywide anomaly. Ninety-four percent of eelgrass mapped in the Bay occurred between -1.6 and 0 m and 99% occurred between -1.77 and 0.4 m MLLW (Merkel and Associates 2004). While microalgae blooms can reduce light availability by shading eelgrass

leaves (Sand-Jensen 1977), turbidity is more often the cause of low light conditions in San Francisco Bay. During storm events, water turbidity increases, as do sediment and nutrient inputs. During the summer in San Francisco Bay, sustained sea breeze events re-suspend local sediments, which reduces water clarity. Low light conditions are a common cause of reduced eelgrass survival, and can negatively affect adults and seedlings. Single flooding events can cause losses, and month-long pulses in turbidity accounts for losses of transplanted vegetation and recruitment failures (Zimmerman et al. 1991, Moore et al. 1997).
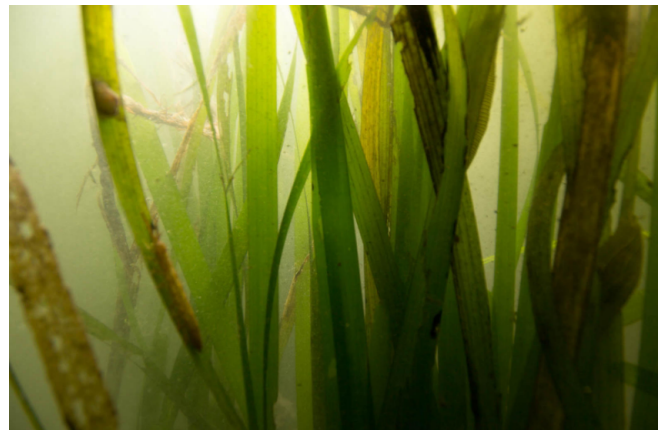
Eelgrass (*Zostera marina*) in San Francisco Bay
Photo: Eric Heupel

Salinity and Nutrients

The optimum salinity range for eelgrass is 10-30 parts per thousand (ppt), although they can survive in salinities ranging from freshwater (< 0.5 ppt) to 42 ppt. Low salinities (4.5-9.1 ppt) associated with winter and spring precipitation generally enhance germination, but eelgrass will not grow in persistent fresh water and can be stunted at 6 ppt (Kikuchi and Peres 1977, Phillips 1984, Nejrup and Pederson 2008). However,

populations subjected to reduced salinity (10 ppt) are more resistant to wasting disease (see below). In the San Francisco Bay, eelgrass extends east into Carquinez Strait and even western Suisun Bay in extended periods of drought (when salinities in the Bay increase), but retracts again in high rainfall years.

Experimenting with Eelgrass planting techniques
Photos: Audubon California

Nutrients can have direct and indirect effects on eelgrass. Water column nitrate enrichment causes decline of eelgrass, especially under increasing or high temperatures (Neckles et al. 1992). This is a direct physiological effect unrelated to light attenuation and may be related to nutrient imbalances that cause accumulation of ammonia (Moore and Wetzel 2000). Under nutrient enrichment, seagrass decline is abrupt, and includes indirect effects such as sediment re-suspension, oxygen stress, light competition with algae, anoxic sediments, and herbivore loss that also accelerate decline (Burkholder et al. 2007).

Currents and Sediments

The healthiest eelgrass occurs in currents of 1.8 m/s or 3.5 knots (Phillips 1972, 1974). Currents within San Francisco Bay range from 0.1-1.5 m/s maximum (Merkel and Associates 2004). When eelgrass leaves interact with current flow, the boundary layer is broken and access to CO_2 and nutrients increases (Conover 1968). However, high current velocities can remove leaves or erode the substrate and low velocities foster algal growth (Fonseca and Kenworthy 1987).

Effects of sedimentation include an alteration of light availability and even burial of seedlings and transplants during extreme events such as prolonged storms. Increased suspension and delivery of sediments to eelgrass systems can create a feedback loop that limits expansion of meadows, potentially leading to dieback (Maxwell et al. 2016). For example, from 2005-2006, eelgrass decline in San Francisco Bay was attributed to burial by sediments following increased natural inputs during storms (Merkel and Associates 2015). However, eelgrass itself can increase water column clarity by reducing current speeds, trapping sediment (which can reduce erosion), and by increasing organic content (Phillips 1984). Therefore, persistent eelgrass beds can be critical to buffering against negative erosive effects of nearshore coastal development.

Characteristics of the sediment itself are particularly important during eelgrass restoration efforts. Determining the suitability of grain size, nutrients, and organic content is a key aspect influencing the likelihood of success. In San Francisco Bay, restoration at sandy sites with low organic content may be enhanced by inoculating sediments with donor site material (K. Boyer, unpubl. data).

2.2 Climate Change Impacts

Sea Level Rise

Based on state-of-the-science policy guidance released by the California Ocean Protection Council in 2018, California is likely to experience between 2.4 and 3.4 ft of sea level rise by the year 2100 (66% probability), with a potential of reaching between 3.2 to 4.4 ft (5% probability; OPC 2018). Based on these changes, suitable habitat for eelgrass within San Francisco Bay

will be altered as water depths increase above existing meadows and light conditions are reduced. Rising sea levels may favor landward expansion of seagrass habitats (Short and Coles 2001) however, hardened shorelines may inhibit shoreward expansion (e.g. the 'coastal squeeze,' Kairis and Rybczyk 2010). Meadows with room to expand are likely to tolerate sea level rise, but this effect may be countered by increased summer die-offs in response to the number of days exceeding temperature thresholds (Carr et al. 2012).

Ocean Acidification

Research on the effects of increasing ocean acidification (OA) on seagrasses including *Zostera marina* indicates a two- to three-fold increase in photosynthesis and 25% increase in biomass under conditions of elevated CO_2, including higher reproductive output and vegetative proliferation of new shoots (Thom 1996, Zimmerman 1997, Invers et al. 2001, Palacios and Zimmerman 2007). However, the positive response does not occur under light limiting conditions, and increased CO_2 can reduce the daily period of light-saturated photosynthesis from seven to three hours (Zimmerman et al. 1997). Because temperature and CO_2 fundamentally influence the physiology and biochemistry of seagrasses, the combined effects are likely to influence photosynthesis and growth responses (Koch et al. 2013). Although studies indicate that CO_2 stimulates seagrass productivity, most studies are short-term and unable to account for adaptation or acclimation to CO_2. Thus, duration of the increased productivity effect is poorly understood (Anderson et al. 2015).

2.3 Biological Interactions between Eelgrass and Co-Occurring Species

Gracilaria spp.

The red macroalga *Gracilaria spp.* co-occurs with eelgrass. In Richardson Bay, the relative abundance of the two species has been shown to alternate. *Gracilaria spp.* dominated from the late 1970s to 1980s, while eelgrass has dominated since the late 1980s (Spratt 1981, California Department of Fish and Game [CDFG] 1998). The underlying mechanisms for these shifts have not been determined. However, El Niño storms may play a role in dislodging *Gracilaria spp.* from the

substrate. Unlike eelgrass, *Gracilaria spp.* are not rooted to the sediment. In Tomales Bay, researchers tested the effects of adding *Gracilaria spp.* to eelgrass beds and found that negative effects to eelgrass occurred at high macroalgal loads (Huntington and Boyer 2008). In Tomales Bay, the natural biomass of *Gracilaria spp.* was three times higher in the back bay compared to the mouth, indicating that environmental conditions towards the back of estuaries may be more favorable to *Gracilaria spp.*

Grazers

Grazers can affect eelgrass in various ways depending on the grazer species (Lewis and Boyer 2014). Some grazers benefit eelgrass through epiphytic algae removal, whereas amphipods negatively affect eelgrass through direct consumption (Lewis and Boyer 2014). When upper trophic level predators are reduced through overfishing or hunting, smaller predators proliferate and increase predation on epiphyte grazers. This leads to increased epiphyte growth and reduced plant growth (Heck et al. 2000, Heck and Valentine 2007). In some cases, when top predators are reintroduced, eelgrass can proliferate, as has been seen with the return of otter populations to Elkhorn Slough (Hughes et al 2013). Migratory Canada Geese (*Branta canadensis*) in San Francisco Bay feed directly on eelgrass and can remove all eelgrass mass so that plants only return from seed the following year (K. Boyer pers. comm.).

Non-Native Species

Though not yet found in San Francisco Bay, invasive Japanese or dwarf eelgrass (*Zostera japonica*) has been documented in Humboldt Bay (Schlosser 2007) and poses a potential threat to native eelgrass. Its risk to herring is currently unknown. It is smaller in size than eelgrass and spreads quickly in stressful, variable intertidal environments (Ruesink et al. 2010). Japanese eelgrass occurs at higher tidal elevations than native eelgrass and can transform naturally unvegetated tidal flats above the elevation of native eelgrass. Japanese eelgrass is native to tropical and subtropical latitudes and grows better at higher temperatures (Shafer et al. 2007). Japanese eelgrass also adapts to an annual life

history when environmental conditions are less favorable (Shafer et al. 2008).

Disease

Wasting disease can devastate eelgrass populations. The disease was reported on the Pacific coast in the late 1930s and eelgrass significantly declined in 1941; however, the effects were not as widespread as in the Atlantic (Short et al. 1987). The slime mold *Labrinthula* that leads to wasting disease is inhibited by low salinity, and eelgrass populations in low salinity (10 ppt) regions are less likely to decline and quicker to recover (McKone and Tanner 2009). In most years, wasting disease is not prominent in San Francisco Bay, though localized outbreaks have been reported as recently as 2014 (K. Boyer, pers. comm.).

2.4 Direct Human-Related Impacts to Eelgrass in San Francisco Bay

In the San Francisco Bay, direct human impacts on eelgrass pose a large threat to vulnerable eelgrass beds and should be considered during conservation planning. This assessment highlights two priority impacts from dredging and boating-related activities, but we recognize that these are not the only human-related impacts to eelgrass.

Dredging

Sediments suspended and redeposited during dredging activities bury eelgrass plants, reduce water clarity, and decrease plant density in San Francisco Bay (Thayer et al. 1975, Phillips 1978). Loss of plants and water clarity creates a positive feedback that inhibits recovery because eelgrass is no longer there to trap sediment. Channel dredging to support recreational and commercial boat activity can negatively affect eelgrass by sedimentation (Short et al. 1991). Sedimentation associated with dredging and construction within San Francisco Bay is controlled by the placement of silt curtains within 250 m of essential fish habitat. Monitoring of direct impacts is required within 50 m and to date there have been no apparent impacts to adjacent eelgrass (Reine and Schroeder 2015).

Boats and Docks

Boat operation and storage can impact eelgrass. Boat docks shade the substrate and cause light-limiting conditions (Burdick and Short, 1995). Mooring and anchoring can create holes in seagrass meadows caused by the swing of the anchor chain, which uproots eelgrass plants. In Richardson Bay, each "anchored out" boat (i.e., boats illegally anchored in the open waters of the Bay) causes nearly half an acre, or 2,000 m^2 of damage to eelgrass on average (Audubon California, unpubl. data).

In Richardson Bay, the number of illegally anchored boats has risen dramatically in recent years, from 98 unauthorized vessels in 1998 to over 200 by 2016 (Mercury News 2016). Many of these vessels are derelict or abandoned and are concentrated along Sausalito's shoreline and in Marin County waters, home to the Bay's highest concentration of remaining eelgrass beds (Mercury News 2016). Recent analysis quantifying the impact of ground tackle from these boats conservatively estimated nearly 57 acres of direct damage, nearly 30% of the eelgrass bed where these vessels are distributed (Audubon California, unpubl. data).

Damage to eelgrass from anchors, chains, and other ground tackle in Richardson Bay.
Photo: 111th Group Aerial Photography

Alternates to the single anchor mooring strategy may reduce damage to eelgrass (Walker et al. 1989, Short et al. 1991). Recent analyses have addressed mooring field effectiveness on seagrass conservation and results indicated that seagrass meadows in mooring fields were

still fragmented. Seagrass cover within mooring fields was found to be 50-60% as compared to 80-90% cover in control sites where no anchoring or mooring was allowed (La Manna et al. 2015). In terms of mooring hardware, both swing and cyclone moorings were detrimental to seagrass, whereas screw moorings were not (Demers et al. 2013).

Figure 1. Extent of eelgrass in Richardson Bay (*Audubon California*)

2.5 Eelgrass in San Francisco Bay

Extent

The largest eelgrass beds have consistently been in the shallow subtidal areas of San Pablo and Richardson Bays (Boyer and Wyllie-Echeverria 2010). A habitat suitability model for eelgrass in San Francisco Bay based on bathymetry, water current speed, wind wave exposure, residence time, and extant bed location predicts maximum coverage of eelgrass at 23,440 acres, or 9% of the bay (Merkel and Associates 2005). However, model results suggest only about half of that area is moderately or highly suitable.

Since baywide assessments began in 2003, maximum extent of eelgrass was 3,700 acres in 2009, roughly 1% of the San Francisco Bay (Merkel and Associates 2005). Sidescan sonar survey of eelgrass in San Francisco Bay in 2014 found Richardson Bay and San Pablo Bay/Point Pinole have the most persistent eelgrass beds (Merkel and Associates 2015). The Richardson Bay bed was 335 acres in 2014, representing 12% of all eelgrass in the San Francisco Bay, as compared to 675 acres in 2009 (Figure 1). This survey also found eelgrass occurring 0.25-2.0 m below mean lower low water (MLLW), with the deepest eelgrass found at the entrance of Richardson Bay (deeper than 3.0 m).

The shallower portions of Richardson Bay that supported eelgrass in 2009 did not support it in 2014 (Merkel and Associates 2015). The eelgrass decline in the winter of 2005-2006 was related to significant sediment loading in San Francisco Bay, and beds were buried in fine sediment up to several cm (Merkel and Associates 2015). Merkel and Associates conducted a bay-wide eelgrass survey in 2017 and are currently processing those data. Preliminary results indicate that eelgrass extent in Richardson Bay increased in 2017 (Keith Merkel pers. comm).

Restoration

San Francisco Bay has been the site of numerous eelgrass restoration efforts. Extensive restoration work conducted by Dr. Katharyn Boyer and colleagues at San Francisco State University (SFSU) is reviewed in detail in the San Francisco Bay Subtidal Habitat Goals Report (Boyer and Wyllie-Echeverria 2010). Eelgrass restoration
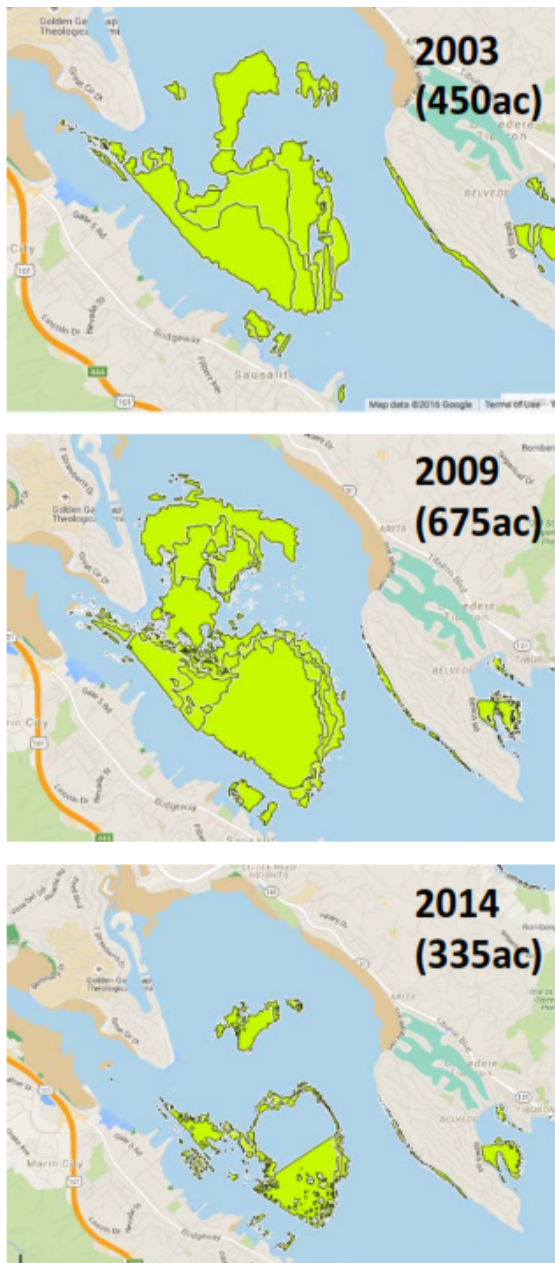
has been underway for several years through recovery funds following the *Cosco Busan* oil spill, and has focused on planting methods and site selection.

In 2012, a living shorelines project with oyster shell reefs and eelgrass plantings was installed by Boyer and colleagues in San Rafael. This goal of this project is to assess both habitat value and the potential for beneficial physical effects on shorelines such as wave attenuation. Researchers are monitoring performance of post-restoration ecological metrics, as well as the effects of the oyster reefs on wave energy and sediment accumulation (Boyer et al. 2014).

Preliminary results from this effort indicated increased invertebrate species richness and abundance after the eelgrass restoration was implemented, with additional benefits conferred by the presence of restored oyster reefs (Boyer et al. 2014).

Valuation

Marine systems including seagrass beds compose 63% of the world's ecosystem services and are valued at US$2.3 trillion year^{-1} (Costanza et al. 1997). Due to the carbon storage potential of coastal ecosystems such as eelgrass, there is an emerging desire to quantify eelgrass' role in climate change mitigation. The majority of research into coastal carbon pools (also known as 'blue carbon') has occurred in wetlands and mangroves. Seagrass beds are relatively understudied, despite their high potential for carbon sequestration.

Until recently, no formal valuations for eelgrass in San Francisco Bay existed, and estimates of eelgrass value based on ecosystem services has been derived from other systems. For example, one of the few valuations of eelgrass comes from Sweden, where estimated annual values were developed based on nutrient cycling, carbon sequestration, and essential fish habitat services (Cole and Moksnes 2016).

Audubon California recently partnered with the Smithsonian Environmental Research Center to assess carbon uptake and storage in eelgrass beds and produced an initial Verified Carbon Standard (VCS) calculation of carbon sequestration for Richardson Bay eelgrass beds (Schile-Beers 2017).

In Schile-Beers' analysis, total carbon sequstered in Richardson Bay was calculated based on the acreage of extant eelgrass patches in the surveys performed in 2003, 2009, and 2014, with carbon storage ranging between 324.9 and 655.3 Mg C (1,191.4 to 2,402.9 Mg CO_2 equivalent).

Based on the habitat suitability analysis conducted in 2004 for Richardson Bay, a potential of 750 hectares of suitable habitat could exist in Richardson Bay. If restoration efforts were successful for this area, an estimated 1,801.1 Mg C or 6,604.0 Mg CO_2 equivalent could be sequestered in the soil. An issue to consider in understanding this valuation, however, is the large loss of eelgrass density and distribution observed in Richardson Bay between 2009 and 2014, which raises questions about the permanence of soil carbon pools (Schile-Beers. 2017).

Based on values of $520/acre/year from Cole and Moksnes (2016), and minimum and maximum eelgrass extent (2,628 acres in 2003, 3,707 acres in 2009), San Francisco Bay's eelgrass value ranges from $1.4-$1.9 million/year.

2.6 Eelgrass Existing Data and Data Gaps

Insufficient sampling frequencies of eelgrass growth rates, biomass, and extent currently limit our understanding of the appropriate conservation measures needed to ensure eelgrass habitat is sustained in San Francisco Bay. Sidescan sonar surveys conducted during the winter of 2003, 2009, and 2014 provide a comprehensive summary of eelgrass acreage in San Francisco Bay, including beds in Richardson Bay and at Pt. Richmond (Merkel and Associates 2015). In the interim years (2006, 2007, 2008 and 2010, 2011, and 2013), additional data were collected using a transect method (Merkel and Associates 2014). In 2017, Audubon California contracted the 111th Aerial Survey Group to map the eelgrass bed during a maximum low tide (-1.36 ft) when there was minimal wind and reduced glare conditions. We recommend developing a framework to relate these datasets to build a more continuous long-term record and description of eelgrass in San Francisco Bay over the past 15 years.

Satellite imagery should be considered for future monitoring efforts across sites in California and the U.S.

west coast, with limited data collection expenses. The GeoEye-1 satellite collects 0.5-meter resolution data from this region approximately six times a month during low tide when eelgrass is visible, and images date back to 2008. Analysis of this dataset would need to include ground-truthing with sidescan sonar and transect data.

The California Department of Fish and Wildlife (CDFW) collects data on eelgrass biomass per square meter (a proxy for eelgrass density) during winter herring spawning surveys. These data can be useful in identifying potential causes of eelgrass decline as indicated by annual changes to eelgrass biomass. This dataset covers 2006-2016 for Richardson Bay and surrounding areas, as well as Pt. Richmond (Ryan Bartling, pers. comm.). Additional data exist for other spawning locations back to at least 1980. Compilation of these sources can provide insights about the inter-annual fluctuations and relationship between eelgrass biomass and herring biomass.

The San Francisco Bay National Estuarine Research Reserve (NERR) recently installed a sonde (a collection of sensors that measure and transmit physical conditions such as chlorophyll a, water temperature, turbidity, salinity, pH, and dissolved oxygen) in Richardson Bay that can provide the environmental data to support a more detailed analysis of what drives eelgrass growth and decline. NERR also operates a weather station at the same location in Richardson Bay, yielding standard meteorological data including wind speed and direction, relative humidity, barometric pressure, precipitation, and radiation. Data from NERR's five other monitoring stations are available online and real-time Richardson Bay data should be available soon (http://www.nerrsdata.org).

2.7 Recommendations for Eelgrass Research and Monitoring

Aerial Extent

The timing and methods of collecting eelgrass extent data are inconsistent among years. The existing record has gaps that limit an understanding of annual changes to eelgrass cover. We recommend an independent assessment of aerial extent be conducted annually at a minimum, ideally during the summer period when the

Monitoring and Research Recommendations
Conduct annual aerial extent surveys in summer and winter
Estimate eelgrass shoot density per m^2
Use data being collected on vegetative and flowering shoot density, epiphyte loads, and epifauna sorting at restored vs. natural beds to inform conservation actions
Investigate response of eelgrass growth to temperature and light conditions at multiple intertidal and subtidal sites

eelgrass extent is at its maximum (May–July). An annual *winter* survey would allow for an assessment of available herring habitat in addition to an intra-annual bed variation analysis.

Biomass and Shoot Density

Though CDFW collects data on eelgrass biomass per square meter as a proxy for eelgrass shoot density, the accepted metric among seagrass researchers is shoot density per m^2. We recommend that CDFW partner with an organization to estimate shoot density. These data will be more directly relatable to other long-term studies and would help enable a better understanding of annual changes in eelgrass shoot density.

Additionally, in partnership with the Smithsonian's MarineGEO program, Dr. Boyer and associates have collected vegetative and flowering shoot density, epiphyte loads, and are working on the epifauna sorting for one natural bed location and one restored bed location in Richardson Bay. We recommend using these data to inform future eelgrass conservation actions.

Eelgrass Growth

Research on the response of eelgrass growth to temperature and light conditions at multiple intertidal and subtidal sites would inform a mechanistic understanding of how eelgrass responds to underlying environmental conditions. Conducting this research would require monitoring of leaf elongation rates on a semimonthly basis, would inform restoration, and would generate knowledge about what underlies the extreme variation in eelgrass coverage in San Francisco Bay.

Environmental Variables Critical to Eelgrass

To understand controls on eelgrass expansion and contraction among years, we recommend additional monitoring of temperature and light within the area of eelgrass maximum extent (Merkel and Associates 2014). We suggest placing temperature data loggers at multiple intertidal and subtidal locations to capture temperature variation that may constrain the intertidal distribution of eelgrass. Secchi disks should also be used to measure water transparency (light attenuation potential) when water levels are at least 1 m above eelgrass fronds.

2.8 Threats to Eelgrass and Opportunities for Conservation

Based on this review of eelgrass ecology and from interviews with stakeholders, we identified the major threats to eelgrass in San Francisco Bay. We also identified opportunities to conserve or protect eelgrass. In some cases, identified opportunities are for specific conservation actions. In other cases, more research and monitoring will help inform future conservation and restoration.

Table 1. Eelgrass Threats and Opportunities

Threat	Opportunity
Direct Damage	
Boat mooring abrasion reduces eelgrass acreage.	• Limit mooring to fewer sites or identify restricted areas to reduce eelgrass disturbance. • Conduct regular anchor-out surveys (e.g., for location and registration). • Measure eelgrass extent seasonally and annually to monitor damage caused by boat moorings and use results to inform policy decisions related to anchor-outs.
Increased sediment load buries eelgrass and reduces water clarity.	• Assess regulations for silt-filtering dredging curtains and limit duration and timing. • Examine 250 m buffer zone requirement for use of silt curtains to reduce deposition and 50 m zone requiring surveys to ensure no direct impacts.
Shipping lanes near Richardson Bay involve regularly moving large amounts of soil to maintain depth. Shipments may be increasing, which may threaten eelgrass habitat.	• Study the impact of increased shipping through the Bay to understand how these activities impact eelgrass and fish species. • Examine policies to re-route shipping lanes away from eelgrass beds.
Oil spills can damage grazers that control microalgae/epiphytes.	• Monitor eelgrass epiphytes as well as invertebrates following oil spill events.
Climate Change	
Changing frequency of episodic warm temperature events, storms, and El Niño increases susceptibility to degradation.	• Improve forecasting of susceptible populations and identify refugia sites, sites for conservation, sites for new transplants, and sites where biomass is increasing. • Develop management strategies that promote eelgrass resilience (such as genetic diversity) at both local and regional scales. • Reduce flow of pollutants into the Bay and enhance water quality so that eelgrass is more resilient to changing climatic conditions.

Threat	Opportunity
Shoreline development and hardening/armoring may limit shoreward expansion with sea-level rise.	• Designate sea-level rise refugia for eelgrass. • Encourage shoreline restoration projects that involve natural 'soft' material rather than shoreline hardening. • Determine the extent to which eelgrass beds reduce nearby shoreline erosion by dampening waves and slowing currents (e.g., Living Shorelines adaptation).
Wasting disease has devastated Atlantic populations in the past and could become a threat in San Francisco Bay.	• Include metric for eelgrass stress response in regular monitoring surveys. • Identify refugia that show decreased wasting disease where salinity is low. • Track temperature in local eelgrass populations.
Limited Restoration Success	
Restoration success is limited by factors such as unpredictable changes in water quality.	• Emphasize conservation and expansion of existing beds over restoration of new areas. • Assess input of nutrients (especially inflows to Richardson Bay) and take action to reduce inflow of nutrients that may harm eelgrass. • Increase network of marine protected areas (MPAs) that could benefit eelgrass, including coastal estuaries. • Add eelgrass abundance as a criterion for assessing water clarity.
Low genotypic diversity can limit productivity.	• Sustain genetic diversity during restoration projects. • Examine genetic diversity within eelgrass beds to determine where to improve diversity.
Other	
Lack of formal valuation of eelgrass ecosystem services in San Francisco Bay constrains leveraging support for eelgrass conservation.	• Estimate eelgrass ecosystem services using existing methodology. • Estimate carbon sequestration potential of eelgrass through the eelgrass blue carbon project in collaboration with Audubon California, Smithsonian Environmental Research Council, and Silicon Valley Community Foundation.
Lack of community awareness of the waterbird-herring-eelgrass ecosystem limits support for conservation.	• Engage local communities in eelgrass conservation and restoration. Several groups should be included that have become valuable partners in protecting eelgrass, especially people who live on or around Richardson Bay, those with mariner experience, or those that depend on the Bay for their livelihoods. • Partner with San Francisco State University's Sustainable Communities and Local Environments Lab to address social and environmental challenges associated with people living on boats within Richardson Bay. • Provide opportunities for community engagement in learning about, protecting, and valuing the abundant resources of the Bay, through events at Richardson Bay Audubon Center & Sanctuary, community science opportunities, social media, and local workshops and meetings.

3. Herring

Herring is a medium-sized (approximately 15 in long) schooling species of fish known to occur in the Pacific Ocean of North America and northeast Asia. Herring provide energy-rich food to birds that winter in, and migrate through, the San Francisco Bay. Herring supports one of the Bay's last commercial fisheries (CDFW 2015). Understanding herring ecology can shed light on relationships between herring and waterbirds in the Bay and may help us determine the factors that can contribute to herring decline.

3.1 Herring Ecology

Reproduction

The number and size of herring spawns is a function of age class (Lambert 1987) and determines spawn timing where older fish spawn earlier than younger fish. In Canada, while the overall timing of herring spawning has not changed, the relative frequency of early and late spawns has diminished, effectively decreasing the spawn window (Therriault et al. 2009). Throughout their range, herring exist as a metapopulation, blinking on and off at individual sites (Ware and Tovey 2004), and evidence from tagging studies indicate 80% of returns on average were from the same sub-district after six years following release (Blaxter and Hunter 1982).

Pacific herring (*Clupea pallasii*).
Photo: Ryan Bartling, CDFW

Stock Recruitment

Observed density-dependent processes that affect herring abundance include decreased survival of eggs when spawning stock biomass is high (Zheng 1996) and decreased embryo survival when egg layers stack up (Taylor 1971). Density-dependent and independent processes operate at different life history stages, and interannual variation can affect mortality rates differently (Lasker 1985, Ainsworth et al. 2008, Reum et al. 2013). For example, egg production can be high but larval survival low due to nutritionally-poor larval food sources (Lasker 1981). Likewise, temperature can be highly important for August fish size, while population abundance has a strong effect on October fish size (Reum et al. 2013).

Temperature

Catch statistics suggest that population abundance is associated with 5-9°C spawning temperatures, with a maximum 10°C for spawning and a lower tolerance of 4 5°C (Alderdice and Velson 1971). Evidence for the effect of temperature on herring comes from research that looks at the correlation of environmental variables with stock assessment data and herring growth. Variation in sea surface temperature (SST) has accounted for 40% of the variation in herring recruitment in Alaska (Zebdi and Colli 1995). Temperature affects spawning timing, which has occurred earlier in years with positive SST anomalies (Paulson and Smith 1977, Lambert 1987, Zebdi and Colli 1995).

Breaking down long-term records into warm and cool regimes indicates high primary and secondary productivity during cool regimes, and reduced productivity during warm regimes (Rose et al. 2008). Although SST has been found to have positive effects on indicators of recruitment, more recent research indicates decreased growth during warm periods that drive zooplankton productivity (Stocker et al. 1985, Ito et al. 2015). Warm winter temperatures associated with El Niño can increase size-specific fecundity, however egg size goes down. Variation in fecundity is best predicted by the temperature 60-90 days prior to spawning (Tanasichuk and Ware 1987).

Salinity

While herring occupy a salinity range of 4-45 ppt, lab and field observations indicate spawning occurs at 8-28 ppt and the optimal range for fertilization is 12-24 ppt (Alderdice and Velsen 1971, Griffin et al. 1998). At low and high salinities, hatching progression is delayed, but the role of salinity in fertilization and embryonic development is questioned because of the broad range of salinities occurring at spawning sites (5-35 ppt) (Griffin et al. 1998). Low salinity can induce spawning and may be important in some locations. However, some adults spawn at sites where salinity approaches full strength seawater (Griffin et al. 1998).

Tides

In San Francisco Bay, spawning timing was connected to the tidal cycle. Records from 1973 – 1976 indicate 88% of all spawn activity occurred when daily high tide was at night (Spratt 1981).

Sediments

High sediment loads have negative effects on herring, but low levels of suspended sediments may provide a refuge from predation (Boehlert and Morgan 1985). Sub-lethal effects of sedimentation are found within the first two hours of egg deposition and effects include increased precocious larval hatch, higher percentages of abnormal larvae, and increased larval mortality (Griffin et al. 2009). Alternatively, larval exposure to suspended sediment during early post-hatch stages does not decrease larval survival, growth, or condition; nor heart rate, critical swimming speed, or prey capture (Griffin et al. 2012). Sediment concentrations in San Francisco Bay can reach 600 mg/L and are more likely to peak from 200-400 mg/L under the most adverse conditions (Schoellhamer 2011).

Storms

Winter Ekman transport (the movement of surface waters controlled by wind) had a negative relationship with herring recruitment in San Francisco (Aleaziz 1997). Weak recruitment occurred when Ekman transport was offshore (i.e., winds blowing out to sea), whereas strong recruitment occurred when onshore Ekman transport was high (Aleaziz 1997). The comparisons between environmental data and recruitment included a two-

year time lag because herring in San Francisco Bay recruit at age two. Storms can cause up to 25% of localized egg losses through increased wave activity (Hay and Miller 1980).

3.2 Climate Change Impacts

Ocean Acidification

Ongoing research indicates OA effects on fish can include increased embryo mortality, reduced length at hatching, and increased mortality at low pH levels (Sewall 2017). Studies on other forage fish indicate that acidification can increase the sensitivity of fishes to hypoxia (Miller et al. 2016). Food web analyses, which account for OA effects on lower trophic levels, suggest that changes in copepod productivity can have indirect effects on herring, including a 10% reduction in fishery yields when crustaceans are affected by OA, as simulated by Ecopath/Ecosim models (Busch et al. 2013).

3.3 Biological Interactions between Herring and Co-Occurring Species

Non-Bird Predators

Predators, including gray whales (*Eschrichtius robustus*), humpback whales (*Megaptera novaeangliae*), orcas (*Orcinus orca*), and Steller sea lions (*Eumetopias jubatus*), have been recorded foraging at herring spawning sites (Wilson and Womble 2006). Some predators can have dramatic effects on herring, reducing larval herring abundance in the spring by 50%, although the effect varies greatly among years (Moller 1984).

Herring egg predation by non-bird predators varies from as low as 4% by greenlings in Alaska (Rooper and Haldorson 2000) to 90% in fur seals (Taylor 1971). Herring found in Alaska, Washington, and Canada fur seal stomachs collected during 1958-65 represented 25-90% of the diet volume, depending on the time of year and location. California fur seals (*Callorhinus ursinus*) stomachs contained no herring, presumably because the offshore distribution of fur seals in California does not overlap with nearshore herring (Taylor 1971, Perez and Bigg 1986). In Washington, harbor seals (*Phoca vitulina*) shift their diet from juvenile herring during the

spawning season to adults during the post-spawn season (Thomas et al. 2011).

In British Columbia, herring and Pacific cod (*Gadus macrocephalus*) fluctuations are consistent with simple predation models, with cod causing an instantaneous mortality rate of 75%. Peak cod abundance in the 1950s may partly be responsible for the collapse of the herring fishery in the 1960s (Walters et al. 1986). In British Columbia, herring and euphausiids are the major components of Pacific hake (*Merluccius productus*) diet. In the 1980s, herring consumption increased during warm summers due to changes to hake migration and decreased euphausiid productivity (Ware and McFarlane 1995). Near San Francisco Bay, herring have dominated salmon diets during February and March (Merkel 1957).

Pacific herring (*Clupea pallasii*) eggs on eelgrass (*Zostera marina*) in San Francisco Bay.
Photo: Ryan Bartling, CDFW (2014).

Herring and Submerged Aquatic Vegetation

Research comparing the expected versus observed occurrence of herring spawn on SAV indicates that herring spawn is related to SAV habitat area (Shelton et al. 2014). Egg survival was also highest on eelgrass although this pattern varied among sites. Eelgrass, when compared to more than a dozen other SAV species, had the most robust values for herring condition based on several metrics (rates of hatching and viability, length, weight, yolk volume, condition

factor) at different sites and under different egg densities (Hourston et al. 1984).

3.4 Human-Related Impacts to Herring in San Francisco Bay

Oil Spills and Creosote

Oil spills have significant, negative impacts on herring stocks across their range, as when herring populations collapsed in Alaska following the 1989 *Exxon Valdez* oil spill and have yet to recover. Disease, predation, and poor recruitment contribute to the continued suppression of the herring population there and the Prince William Sound fishery has been closed for 19 of the 25 years since the spill (Exxon Valdez Oil Spill Trustee Council 2017). The impacts of the 2007 *Cosco Busan* oil spill in San Francisco Bay was studied at three months and at two years following the event. At three months, caged herring embryos at oiled sites showed sub-lethal cardiac toxicity. Embryos sampled two years later from the oiled sites showed modest cardiotoxicity but no elevated neurosis or mortality (Incardona et al. 2012).

In San Francisco Bay, pier pilings and other wood structures were historically treated with creosote to reduce rot. There is documented evidence that contaminants in creosote pier pilings negatively impact herring (Werme at al. 2010). Embryos that adhere to creosote-treated pilings show toxicity, ranging from morphological deformities to reduced heart rates and hatching rates; the effect of creosote was amplified at low salinities comparable to San Francisco Bay during spawning periods (9 ppt; Vines et al. 2000).

Fishing

Commercial fisheries for herring have taken place in San Francisco Bay for over 100 years. Exploitation rates have ranged from 0-20% of spawning biomass. Currently, the DFW is preparing a fishery management plan (FMP) for herring with a harvest control rule for San Francisco Bay. The adoption of the FMP will ensure the continuation of the current regime of precautionary fisheries in the Bay to protect the stock from overfishing and ensure a forage reserve for predators.

3.5 Herring in San Francisco Bay

General Information

Herring enter San Francisco Bay about three weeks prior to spawning. Fecundity is 220 eggs per gram of body weight, and a large female can release 40-50,000 eggs after the males release the sperm (milt). The strip of eggs is 2-3 eggs wide and can be 4-5 layers thick. Eggs generally occur in shallow water (< 30 ft), but have been found up to 60 ft in San Francisco Bay. Large spawning events can last a week and cover a shoreline for 20 mi with a 30 ft wide band of eggs (CDFG 2001).

Incubation of the eggs is about 10 days and dependent on water temperature. The juveniles remain in the Bay until summer or early fall at which time they migrate to the ocean. Some fish mature when they reach 2 years or 7 inches and all fish mature by 3 years. The maximum length is 11 inches and the maximum age is 10 years, but fish older than 7 years are rare. Evidence from fish

parasites used to distinguish spawning stocks indicates the San Francisco Bay non-breeding stock is found nearshore and in Monterey Bay, whereas the Tomales Bay stock is offshore (Moser and Hsieh 1992).

Temperature

Within San Francisco Bay, herring is associated with cool regimes (Feyrer et al. 2015). Herring's association with the North Pacific Gyre Oscillation (a climate pattern in the northeast Pacific) in other locations indicates that upwelling or water temperature is a more meaningful variable for herring than salinity (Reum et al. 2011). El Niño conditions, which tend to bring warmer waters, tend to have a negative impact on herring in the area. The area's lowest biomass estimates have occurred during or just after El Niño as was the case during 1997-98 (CDFG 2001).

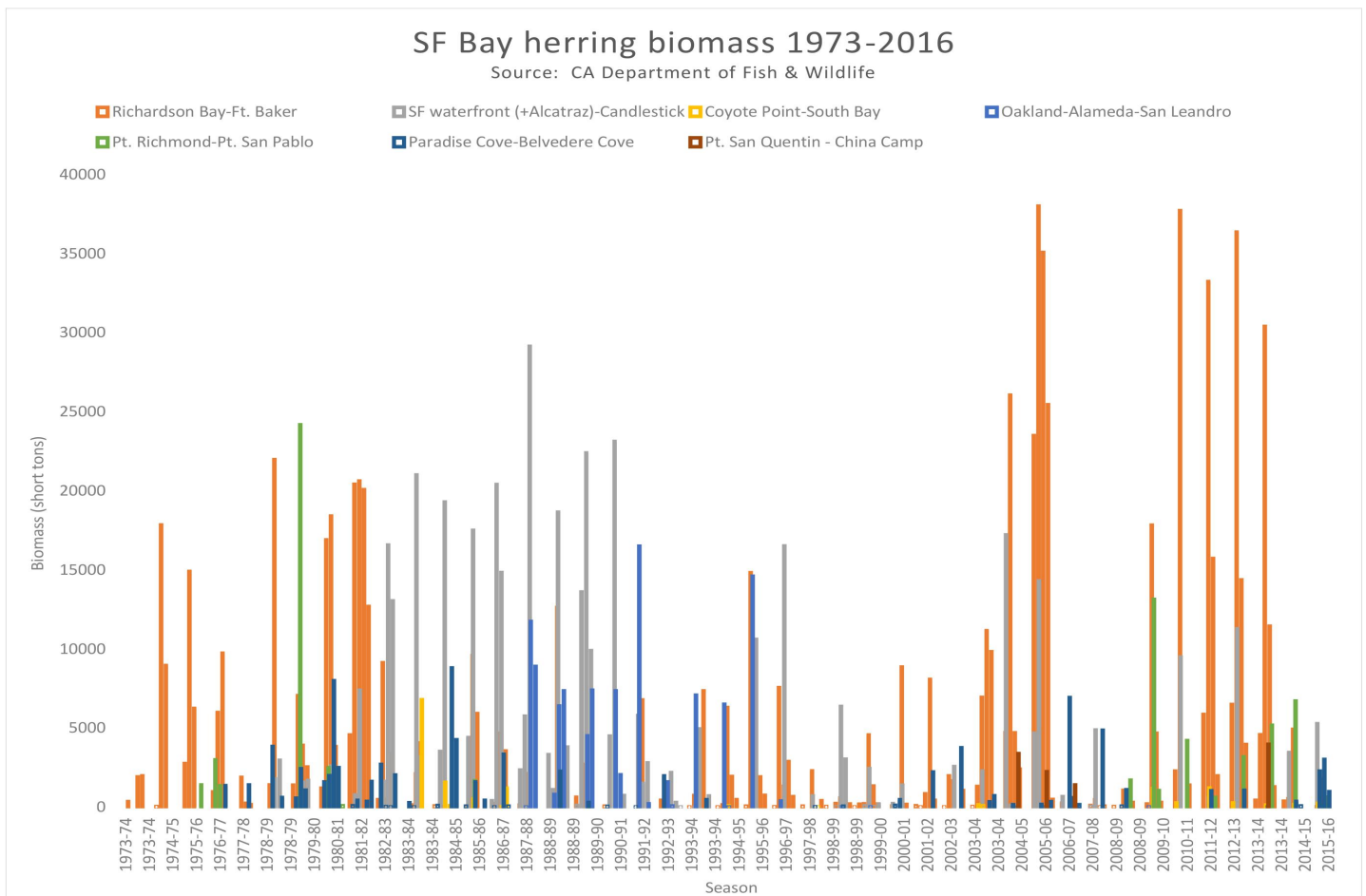The most dramatic effect was in Tomales Bay, where a 90% decline followed the 1983 El Niño. The population

Figure 2: Herring Spawning Biomass in San Francisco Bay during the past 35 years.
Notice consistently (though variably) high biomass at Richardson Bay (orange).

was unstable and declined during the 1987-1992 drought. Following the drought, the fishery closed, but low numbers of 5-year-old fish suggested the decline was likely related to ocean conditions. It is important to note that effects of El Niño besides temperature were reported by CDFW as potential explanations for reduced herring stocks, including altered oceanic currents that may have displaced herring.

Salinity

Salinity levels within San Francisco Bay were reviewed by Kimmerer et al. (2013) and freshwater pulses in February-March 1982 may have pushed herring from San Pablo Bay to the central San Francisco Bay (Levine-Frick 2004). Egg and juvenile survival can be higher during high-flow years compared to low-flow years (Kimmerer 2002).

Spawning events in San Francisco Bay

Within San Francisco Bay, Richardson Bay consistently shows the greatest amount of spawn activity on average (Figure 2; CDFW 2017). For example, during January 13-16 of 2017, spawn total was estimated to be 17,225 short tons of biomass compared to 252 short tons estimated for Pt. Richmond from January 6-9, 2017 (CDFW 2017). The 2017-18 winter season marked the fourth year in a row of below average herring returns. Spawning biomass was estimated at 15,300 tons in 2017-18 compared to the historical (1979-present) average of 48,500 tons (CDFW 2018).

3.6 Herring Existing Data and Data Gaps

Research Recommendations
Explore the relationship between eelgrass acreage and herring biomass.
Investigate potential changes to the timing of the first major spawn.
Examine the relationship between ocean condition and fish biomass and fish condition.
Integrate other existing data sets that are also known to be coupled to ocean condition, including seabird productivity data.

Spawn deposition data are collected by CDFW and survey methods have been employed consistently since 1979 (Watters et al. 2004). Existing data include the date and location of spawning, and the calculated biomass. From 1989-2003 methods included additional hydroacoustic surveys, but these are no longer used because the spawn survey provides a better estimate of biomass (MacCall et al. 2003).

The adult biomass assessment methods are reviewed by Watters et al. 2004. Spawns are identified by the appearance of marine birds and mammals, and the presence of milt in the water. The bottom surface is raked to check for eggs and vegetation, SAV density is quantified, and the boundaries of the spawning area are geo-located. Samples of vegetation with eggs are collected randomly along a transect, the total number of eggs in the spawn are calculated as per Watters et al. (2004), and the number of eggs is scaled up to the spawning adult biomass using a conversion factor.

Since 1980, CDFW has also collected mid-water trawl data for juvenile and adult herring at 52 stations throughout San Francisco Bay at monthly intervals throughout the year (Baxter et al. 1999). Larval fish data was collected in 1980-1989 from plankton tows. Size data exist for this dataset, but need to be requested from CDFW. Additional CDFW data on fish condition (both research-based and fishery-based data) and age composition are available but have not been reviewed in detail. This information would be useful for comparison with oceanographic data for understanding fisheries independent drivers of fluctuations in herring stock condition.

Based on their nearshore juvenile rockfish surveys, which occur in late spring, NOAA Fisheries has data on the occurrence of adult herring off the California coast from 1983-present (though pre-2004 data only covered Monterey Bay to Point Reyes). The use of this dataset is limited because herring were not the target species, and their oceanic habitat is not reliably included in the survey area.

Recently, CDFW contracted the Centre for Environment, Fisheries, and Aquaculture Science to conduct a formal stock assessment that is currently under review and not yet released. The information from this assessment will

be useful to understand herring population dynamics in San Francisco Bay.

Analysis of existing data, independent of the stock assessment, can address current data gaps and target questions about what drives herring population dynamics. We recommend using existing data to explore the relationship between eelgrass acreage and herring biomass. We recommend investigating potential changes to the timing of the first major spawn and examining the relationship between ocean condition, fish biomass and fish condition. Other existing data sets can be coupled with ocean condition, including the seabird productivity data from the Farallon Islands that is collected by Point Blue Conservation Science.

3.7 Threats to Herring and Opportunities for Conservation

We identified key threats to herring in San Francisco Bay based on our literature review and interviews with stakeholders. We offered opportunities to conserve these important resources in Table 2. In some cases, opportunities are for specific conservation actions, and in other cases, opportunities focus on research and monitoring needs that will inform future conservation and restoration.

Table 2. Herring Threats and Opportunities

Threat	Opportunity
Direct Impacts	
Oil spills have immediate negative effects. Large spills can have long lasting effects on population dynamics.	• Identify and support multiple protected areas to diversify oil spill refugia.
Mistiming of dredging can impact herring spawning period.	• Work with CDFW and Long Term Management Strategy Managers to assess dredging windows. • Coordinate monitoring with the Middle Harbor Enhancement Area Project Beneficial Reuse Demonstration Project.
Food competition with invasive species, clams and phytoplankton alter Bay food supply and may affect juvenile herring.	• Track phytoplankton data to understand risk to herring. • Track juvenile fish condition based on ongoing monitoring.
Habitat	
Localized eelgrass decline (habitat loss) has been observed at high priority spawning sites (e.g., Richardson Bay).	• Conserve a range of eelgrass and spawning sites to reduce effects of loss. • Conduct research and monitoring to determine causes of eelgrass decline.
Relationship between eelgrass habitat and herring spawning is not well defined.	• Conduct a formal valuation of eelgrass value as essential fish habitat. • Build a formal conceptual model of the food web, including how species have interacting ecosystem services. • Evaluate factors influencing herring spawn in Richardson Bay (second largest eelgrass bed) versus Point Pinole (largest bed with little herring spawn).
High site-fidelity for spawning populations enhances vulnerability.	• Identify the diversity of sites to protect multiple spawning areas. • Manage fishing pressure in line with the Pacific Herring Fishery Management Plan (in development).

Threat	Opportunity
Fishing	
Herring stocks have highly variable recruitment rates.	• Build recruitment into stock assessment model to improve understanding of sources of variability.
Altered upwelling and ocean temperature affects adults and juvenile condition and growth rates.	• Include oceanography in stock assessment models.
Relationship between effects of fishing and effects of climate are not well understood in San Francisco Bay.	• Build a road map for scientists and managers that develops understanding of cross-system linkages.

4. Waterbirds

San Francisco Bay is the largest estuary on the Pacific Flyway and provides critical wintering habitat for birds. The greater San Francisco Bay provides habitat for hundreds of thousands of waterbirds each winter and Richardson Bay alone provides habitat to tens of thousands. One reason the Bay is so important to waterbirds in the winter is due to herring spawning events, which attract tens of thousands of diving ducks, gulls, pelicans, scaup and scoters each year. Within San Francisco Bay, Important Bird Areas, designated by the National Audubon Society, provide critical winter habitat, and one of these, in Richardson Bay, is managed by Audubon California.

Few studies feature the explicit relationship between waterbirds, herring spawn, and eelgrass. Here we summarize relevant information to guide an understanding of threats and opportunities for waterbird conservation in the Bay.

4.1 Waterbird Ecology and Biological Interactions between Waterbirds and Co-Occurring Species

In this review, we prioritized studies that address eelgrass and herring components of the waterbird food web with relevance to the Pacific Flyway and San Francisco Bay system. Bird species associated with eelgrass and herring are listed in Table 3.

Eelgrass Associations

Eelgrass supports certain species of waterbird directly and other species indirectly via herring spawn. Black Brant (*Branta bernicla*), for example, are herbivorous grazers on eelgrass and their winter and spring distribution is closely related to eelgrass distribution. One study at Crown Beach in San Francisco Bay showed that migratory geese remove eelgrass plants each fall, and may contribute to seed-based sexual regeneration of eelgrass beds at this site, whereas the rest of San Francisco Bay eelgrass is primarily sustained by rhizomatous spreading of mature plants. (S. Kiriakopolos. unpubl. data).

Eelgrass cover is positively associated with fish abundance and richness (Altstatt et al. 2014) and is an important spawn substrate for herring. In this way, eelgrass supports the wintering waterbird food chain and Richardson Bay supports the second largest eelgrass bed in the San Francisco Bay (Boyer and Wyllie-Echeverria 2010).

Herring Spawn

Pulsed prey, like herring and other forage fish, is a valuable resource for marine animals. Long-distance migratory birds can double their body weight by consuming pulsed prey such as herring (reviewed by Wilson and Womble 2006). In some regions, bird predation on pulsed prey is so intense that it

contributes to seasonal decline of prey species, and birds move on after depleting pulsed resources. In birds that have small winter home ranges, such dramatic relocations provide clear evidence of a seasonal habitat shift based on herring spawning. Aggregation of birds and duration of stay at spawning sites corresponds to spawn availability (Rodway et al. 2003, Lok et al. 2008).

Table 3. Birds in the San Francisco Bay Area Known to Associate with Herring (Bayer 1980, Bishop and Green 2001).

Group	Species
Gulls	• Glaucous-winged Gull (*Larus glaucescens*) • Western Gull (*Larus occidentalis*) • Ring-billed Gull (*Larus delawarensis*) • Mew Gull (*Larus canus*) • Bonaparte's Gull (*Chroicocephalus philadelphia*)
Geese	• Brant (*Branta bernicla*) • White-fronted Goose (*Anser albifrons*)
Dabbling Ducks	• American Wigeon (*Anas americana*)
Diving Ducks	• Redhead (*Aythya americana*) • Canvasback (*Aythya valisineria*) • Greater and Lesser Scaup • Bufflehead (*Bucephala albeola*) • Scoter
Sand Pipers	• Surfbird (*Aphriza virgate*) • Black Turnstone (*Arenaria melanocephala*)
Rails	• American Coot (*Fulica Americana*)
Other	• Common Murre (*Uria aalge*) • Pelagic Cormorant (*Phalacrocorax pelagicus*) • Common Loon (*Gavia immer*) • Grebe spp.

There are 17-22 species of birds associated with herring spawn (Bayer 1980, Weathers and Kelly 2007) and many are found in San Francisco Bay (Table 3). Some species feed on eggs exposed at low tide (e.g., gulls, shorebirds, geese, and crows), scoters and diving ducks feed subtidally, and some species eat both eggs and fish (e.g., murres, gulls, and mergansers; Wilson and Womble 2006).

Herring roe provide an energy-dense food source compared to other invertebrate prey such as clams, and egg predation can account for 39% of egg mortality

(Outram 1958, Lewis et al. 2007, Anderson et al. 2009). Herring consumption allows consumers to meet energetic requirements with reduced effort during springtime when energetic demands are increasing. There are reduced energy requirements for digestion of herring compared to hard-bodied prey, and birds can easily build lipid stores prior to and during spring migration (Bayer 1980, Bond and Esler 2006, Lewis et al. 2007).

Though data are lacking for San Francisco Bay, stomach content analyses in an Alaskan study revealed that herring spawn were found in 100% of all Glaucous-winged Gulls, Mew Gulls, and Surf Scoters sampled, and herring spawn accounted for 96-100% of gut food weight (Bishop and Green 2001). Up to 63,501 herring eggs were found in a single Glaucous-winged Gull (Bishop and Green 2001). On the central coast of Oregon, 83% of scoters in the lower Yaquina River estuary were observed feeding on herring roe (Bayer 1980). In the Baynes Sound, British Columbia, scoters forage exclusively on herring roe during the spawn and a 52% and 70% increase in dive duration was recorded for Surf Scoter and White-winged Scoter respectively (Lewis et al. 2007). Gut weight of Surf Scoters (n = 8) in Prince William Sound was comprised of 100% herring spawn, an indication that they foraged exclusively on spawn when eggs were available (Bishop and Green 2001). Herring mortality is largely a result of marine bird consumption (Bishop et al. 2015).

Juvenile and Adult Herring Consumption

Common Murres and Glaucous-winged Gulls consume large quantities of juvenile herring, while Pelagic Cormorants, grebes, and Common Loons consume

Gull with herring eggs attached to shafts of vegetation.
Photo: Richard Bangert

substantial amounts of adult herring (Shuford 2008, Bishop et al. 2015). Though data are not available for San Francisco Bay, in the Prince William Sound, Common Murre consume more herring than any other marine birds and were most abundant near historic spawning locations (Bishop et al. 2015).

4.2 Human-Related Impacts to Waterbirds in San Francisco Bay

Over the long-term, impacts to waterbirds in San Francisco Bay include pollution, development, bay filling, climate change, and impacts to breeding grounds. For the purposes of the report, we focused on two immediate concerns – boats and oil spills.

Boats

Human activities and disturbance cause birds to flush and increase their energy expenditure (Borgmann 2011). Millions of people seek recreation on or near the San Francisco Bay, which impacts wintering waterbirds. People in boats or walking on the beach can cause birds to flush, increase their energy expenditure, impede their food consumption, and potentially affect birds at the population-level (reviewed by Borgmann 2011). Large-scale events in San Francisco Bay, such as the 2014 America's Cup sailing competition, have the potential to harm waterbirds through vessel traffic, effluence, and damage to eelgrass beds (B. Langston, pers. comm). In addition, regular marine traffic including commuter ferries transit habitat areas on a regular basis, making those areas unavailable for foraging birds (J. Takekawa, unpubl. data). Helicopters and low-aircraft flyovers also contribute to waterbird disturbance in the Bay Area (Rojek et al. 2007).

Eighty-six percent of studies examining the effects of anthropogenic disturbance on waterfowl, diving ducks, shorebirds, and wading birds reported a disturbance to the study species (Borgmann 2011). Buffer zones and restricted areas can be particularly useful in limiting human disturbance (Rodgers and Schwikert 2003). Threats to waterbirds will rise as the increasing Bay Area population intensifies the demand for recreation, ferry routes, and shipping lanes across the Bay. Limiting recreational use and boat traffic in areas of concentrated waterbird use during the winter would help protect critical wintering habitat for millions of migratory birds that visit the Bay each year (Borgmann 2011).

Oil Spills

Birds are highly susceptible to unintentional oil spills and regular tank washings that release oil (Hampton et al. 2003). Oil is dangerous to birds because it seeps into their skin, preventing them from regulating their body temperature, which forces them to leave the water and risk starvation or predation on land. The estimated number of seabirds killed by oil pollution in central California during the 20th century ranges from hundreds of thousands to millions (Hampton et al. 2003).

The *Cosco Busan* oil spill of 2007 released about 53,000 gallons of bunker fuel into the San Francisco Bay, damaging or killing thousands of wintering waterbirds (https://baykeeper.org/news/column/cosco-busan-oil-spill-10-years-later-bay-safer-today). Scoters (White-winged and Black) had already arrived to the San Francisco Bay and suffered the most from the oil spill. Over 1,000 oiled scoters were treated after the spill (De La Cruz et al. 2013). Volunteers and staff of Audubon California monitored the beaches and waters of Richardson Bay following the spill for over 1,000 hours and took 2,635 birds to wildlife care facilities (B. Langston, pers. comm). On average, volunteers discovered 320 oiled birds per day in the Richardson Bay, the majority of which were scaup and scoters.

Thousands of scaup at Richardson Bay Audubon Sanctuary
Photo credit: Robert Hinz (2008)

San Francisco Bay has a large volume of container cargo and oil tanker traffic. The California Department of Transportation refers to the port of Oakland as a "megaport," the fifth busiest container port in the US

(www.dot.ca.gov). Oil spills have the potential to harm the most birds during the winter when species that winter in the Bay such as scaup, Buffleheads and Ruddy Ducks are present in the thousands (Hampton et al. 2003). The high volume of vessel and tanker traffic in the San Francisco Bay increases the potential for oil contamination and pollution, leaving critical waterbird habitat at risk.

4.3 Waterbirds in Richardson Bay

Much of our knowledge about wintering birds in Richardson Bay comes from the National Audubon Society's waterbird monitoring program (Audubon California, unpubl. data) and from research conducted by the U.S. Geological Survey (USGS)'s Western Ecological Research Center (De La Cruz et al., unpubl. data).

Richardson Bay Audubon Center & Sanctuary (RBACS) protects 900 acres of subtidal habitat and is the largest subtidal reserve in San Francisco Bay. Richardson Bay is located in southeastern Marin, just north of San Francisco. The surrounding land is highly urbanized, influencing critical wetland habitat and shoreline. Under Marin County ordinance (92-1), the Sanctuary's waters close to boats and other watercraft from October 1 to March 31 each winter, with the goal of preventing disturbance to the large numbers of overwintering waterbirds that use the Bay. As described previously, an extensive eelgrass exists within Richardson Bay that attracts large numbers of spawning herring. Thousands of waterfowl at high tide and shorebirds at low tide seek refuge in the Sanctuary, making it an important link of habitat in a highly urbanized region. The sanctuary supports a monthly average of 2,000-4,000 ducks including scaup, Ruddy Ducks, and Buffleheads and over 16,000 scaup have been recorded on a single day in the sanctuary alone (Audubon California, unpubl. data).

Richardson Bay Waterbird Trends: pre-2007

According to analysis of waterbird data within the Richardson Bay waterbird sanctuary from 1982 to 2007, herring spawn and fluctuations in eelgrass may be the most important factors influencing waterbird abundance (Shuford 2008). During this time, surveyors recorded a total of 62 species in Richardson Bay, the majority of which generally arrived between mid-November to mid-March. Bird abundance ranged from 2,137 – 14,658 individuals. Between 1982 and 2007, the most abundant waterbirds in Richardson Bay were Canvasbacks, American Wigeon, scaups, Surf Scoters, Buffleheads, American Coots, and gulls (Shuford 2008). These species are known to eat herring eggs (Shuford 2008). Other abundant groups were grebes and cormorants, which eat adult herring (Shuford 2008). American Wigeon and Canvasbacks were numerous in the late 1970s but became uncommon or rare in the early 2000s. It is unclear whether the declines were related to changing patterns of herring spawning, eelgrass and *Gracilaria spp.* abundance within Richardson Bay, or larger continental patterns. Individual species trends within Richardson Bay are compared to other areas in San Francisco Bay in Shuford (2008).

Richardson Bay Waterbird Trends: post-2007

Although various waterbird and shorebird surveys took place at RBACS over the years, pre-2007 protocols were infrequent and conducted at varying tidal stages (Shuford 2008). Working with staff from Point Blue Conservation Science and USGS during fall 2006, Audubon California initiated a new survey protocol with the goal of gathering long-term monitoring data on all waterbirds using the sanctuary.

Annual winter waterbird survey data collected since 2006 by Audubon California (Figure 3) reveal important winter foraging patterns in RBACS waters during the annual boat closure (October 1 to March 31). Preliminary analysis shows 53 species of waterbirds (duck, geese, grebe, coot, loon, cormorant, pelican, gull, tern, plus Osprey [*Pandion haliaetus*]) have been observed during the surveys. Two-thirds of observations were Greater/Lesser Scaup, Bufflehead and Ruddy Duck, with Western and Clark's Grebe and American Coot making up another 15% combined. The average number of birds per survey from 2006-16 peaks in January at about 7,500 birds. Bird numbers are dominated by scaup, with the most occurring in the northeast portion of Richardson Bay. Observations of behavior indicate 29% of the birds foraging, 23% swimming, and 48% resting. A survey on December 23, 2013 documented 21,000

birds on the sanctuary waters, of which 75% were diving ducks (Audubon California, unpubl data).

4.4 Waterbird Existing Data and Data Gaps

Research Recommendations
Compare RBACS bird count with CDFW spawning data.
Use existing waterbird data to explore relationships with spawning events.
Identify water quality data (such as wastewater outfalls) to describe environmental conditions for SAV communities.

San Francisco Bay research on waterbirds is summarized in Shuford (2008) and includes RBACS census data from 1982-1983, 1985, 1987-88, 1988-89, 1989-90, 1992, 1995-96, 1996-97, 1997-98, 1998-99, 2006-07, and 2006-present. Analyses indicate declines in scaup, Ruddy Duck, grebes, Surf Scoter, Bufflehead, Double-crested Cormorant, American Wigeon, Canvasback, American Coot, and gulls compared to the late 1970s (Shuford 2008). Additional data may exist in the Pacific Flyway Shorebird censuses, which includes 10 censuses in RBACS from 1988-1993, but only one is during early winter.

Accurso (1992) documented wintering waterbirds using all of San Francisco Bay during twice-monthly aerial surveys from 1988-1990. These bay-wide transects are used for the annual U.S. Fish & Wildlife Service Midwinter Waterfowl surveys (Richmond et al. 2014). The USGS also conducted within-season aerial surveys using these transects from 2003-2007 (Takekawa et al., unpubl. data).

Ongoing RBACS bird counts are conducted semi-monthly from October-March at five viewing locations using the same methods since 2006. These data could be compared with Richardson Bay spawning dates from CDFW to investigate the potential for a response to herring spawn. Although the bi-monthly waterbird surveys are not timed with herring spawn events, the dataset should be evaluated for patterns. Because surveys do not address bird use of herring spawns, it is difficult to estimate the value of the local herring spawn resources for waterbirds in San Francisco Bay. However, Audubon California is currently devising a plan to study pulsed spawning events in Richardson Bay and Pt. Richmond in partnership with CDFW. In addition, identification of existing sources of water quality data (such as wastewater outfalls) is needed to describe environmental conditions for SAV communities.
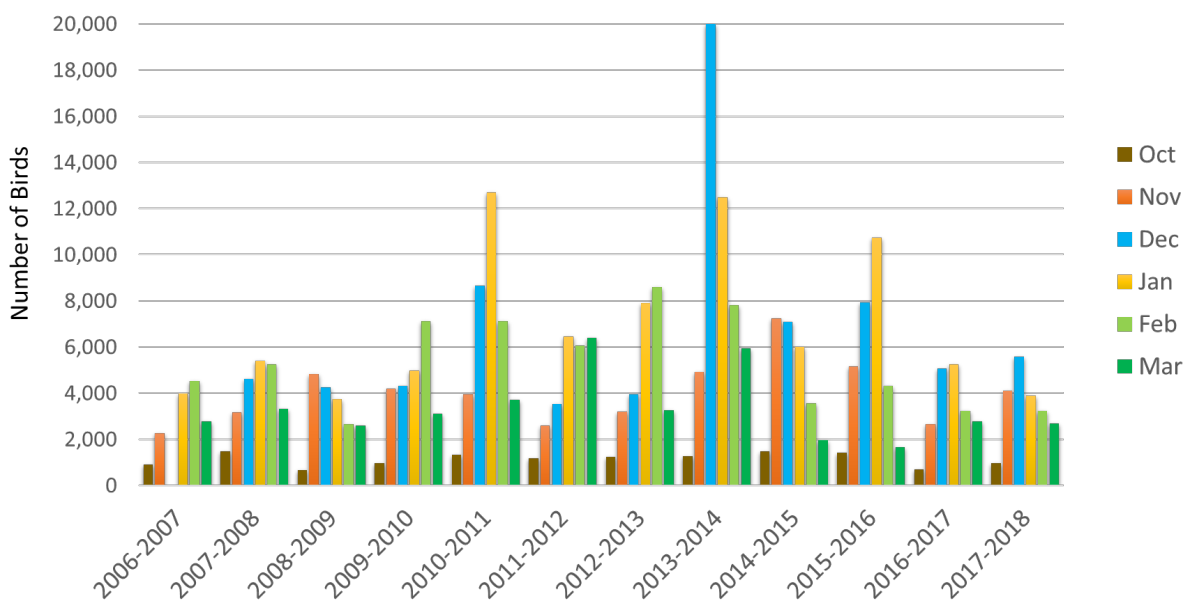
Figure 3: Average number of birds counted during bi-monthly surveys within Richardson Bay Sanctuary boundaries, 2006-Present.

4.5 Recommendations for Waterbird Monitoring

Additional research is needed to better understand the importance of the San Francisco Bay for wintering waterbirds. In general, there is limited knowledge of resource selection by sea ducks in the Bay, which constrains management and restoration plans (De La Cruz et al. 2014). Research that quantifies direct use of herring, eelgrass and other SAV by waterbirds would be valuable, particularly in Richardson Bay and Pt. Richmond. Methodology for waterbird and vegetation surveys should span the season of herring spawning to capture the arrival and departure of herring-associated waterbirds. SAV surveys should be integrated with existing research in San Francisco Bay and should document key aspects of SAV persistence including aerial coverage, shoot density, and change in lower depth distribution.

Monitoring Recommendations
Quantify direct use of herring, eelgrass and other SAV by waterbirds.
Capture arrival and departure of herring-associated waterbirds.
Collect behavioral data during spawning events, during egg development period, and following hatching as well as shifts from resting to foraging.

Behavior

Researchers in Canada have documented patterns in Surf Scoter foraging behavior associated with the appearance of herring spawn (Lewis et al. 2007). Such monitoring would be valuable within San Francisco Bay. Methods could be adapted to accommodate shore-based observations of individual birds. Behavioral data should be collected at the time of spawning, during the egg development period, and following hatching. Based on existing spawning data, Richardson Bay experiences the highest frequency of spawning events in all of San Francisco Bay (40% of total, average of 6/season), so during each season there would be multiple opportunities to monitor bird behavior at this site. In contrast, Pt. Richmond has only one to two events/season since herring started spawning there again in 2009. This approach will require communication with CDFW to accommodate the short-term notice of herring spawn activity.

Waterbird Distribution within Richardson Bay

Research elsewhere has indicated spatial shifts in waterbird habitat use associated with the arrival of herring spawn (Rodway et al. 2003, Lok et al. 2008), but these studies occur in regions where birds are overwintering rather than migrating so the pattern may be easier to detect. We recommend reviewing Audubon's existing waterbird dataset for evidence that waterbird numbers increase following the season's first spawn in Richardson Bay. Subsequent spawning dates may or may not show a similar response. The existing behavioral data should be explored to assess shifts from resting to foraging associated with spawning events. Data will need to be filtered to focus on bird count data that coincides with spawning events, and biomass of event must be considered since early spawns in November/December (400-2,300 tons) tend to be smaller compared to January/February spawn biomass (3,500-5,000 tons). Because the waterbird count and behavioral data are collected within four different regions in Richardson Bay, a spatial analysis of habitat use during years with fall/winter eelgrass area data (2006, 2007, 2008, 2009, 2010, 2011, 2013, and 2014) may be possible utilizing the location of eelgrass based on maps and the timing of spawning events.

Monitoring Herring Spawn Events

Richardson Bay may provide further insight to how birds respond to the pulsed herring resource, especially during the anomalous conditions present in El Niño years. Limited telemetry research on tagged Surf Scoters in San Francisco Bay from 2003-04 and 2004-05 indicates birds are elsewhere in San Francisco Bay during December but arrived in Richardson Bay by January during these two winters (De La Cruz et al. 2014). As noted above, peak spawning in Richardson Bay occurs during January and February. Detecting the arrival of these birds in Richardson Bay using existing semi-monthly Audubon surveys may be difficult because spawning occurs on a shorter timescale than the bird surveys. To adequately capture patterns of

waterbirds responding to herring spawning events using count-based methods (as opposed to telemetry) requires time-intensive continuous monitoring of known herring spawning sites. Since Richardson Bay contains the most frequent and largest spawning events, it provides a good site to explore the reaction of birds to this pulsed resource.

4.5 Threats to Waterbirds and Opportunities for Conservation

Based on material reviewed in preceding sections, we identified key threats to waterbirds in San Francisco Bay, as well as opportunities to conserve waterbird resources (Table 4). In some cases, opportunities are for specific conservation actions, and in other cases, the opportunities are focused on research and monitoring needs that will inform future conservation and restoration.

Table 4. Waterbird Threats and Opportunities

Threat	Opportunity
Food Availability	
Potential mismatch between timing of spawning herring and waterbird migration.	• Evaluate long-term changes to timing of spawning and compare to waterbird count data, as well as within-season movement and habitat use by waterbirds. • Assess how timing of spawning relates to age structure of herring population. • Ensure fishing regulations support a robust herring age structure, which affects timing of herring spawn.
Decline and lack of long-term recovery of herring following the 2007 *Cosco Busan* oil spill.	• Identify and conserve multiple herring spawning sites within San Francisco Bay to safeguard against future oil spills. • Designate herring spawning grounds as MPAs under Executive Order 13158, which promotes a science-based system of MPAs to enhance ecological and economic sustainability of marine environments.
Decrease in eelgrass beds may lead to reduced foraging habitat, substrate for roe, and fish nurseries.	• Protect and enhance existing eelgrass beds and future potential sites for eelgrass. • Better define ecological linkages between eelgrass, herring, and waterbirds. • Partner with local agencies (e.g. Richardson's Bay Regional Agency) to mitigate for damage within eelgrass bed boundaries. • Create signage to show locations of eelgrass and inform boaters of the extent, promoting less disturbance of eelgrass plants.
Disturbance	
Human interference can prevent large groups of waterbirds from assembling at spawning sites.	• Moderate recreational access to well-established spawning sites during spawning season. • Develop signage to educate and inform public about spawning importance and problems of bird disturbance at major spawning sites.
The number of anchored vessels in Richardson Bay threaten eelgrass communities.	• Partner with SFSU's Sustainable Communities and Local Environments Program to better understand anchor-out community and evaluate potential solutions for better vessel management. • Conduct weekly anchor-out surveys (e.g., location, registration) and share with marine patrols to identify and discourage new boats from mooring within eelgrass areas. • Meet with partners and stakeholders to develop eelgrass conservation initiatives. • Develop short and long-term action plans to remove anchor-out boats from eelgrass beds.

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