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Spatiotemporal occurrence of green sturgeon at dredging and placement sites in the San Francisco estuary

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Abstract We used acoustic telemetry to determine the spatial and temporal overlap between adult Green Sturgeon movements and areas affected by dredging within the San Francisco Estuary. Autonomous receivers were deployed for 3 years within the lower Estuary at priority locations to assess the potential for adverse effects on Green Sturgeon. Green Sturgeon were present at the designated placement sites during all months of the year but more were detected during two time periods (February–March and June–September). Of the 134 tagged fish detected in the estuary, 109 (81%) were detected at one or more dredged or dredged material placement sites. The median duration of residence at dredged material placement sites was 72.5 min near the Carquinez Strait, 141.1 min in San Pablo Bay, and 37.1 min near Alcatraz Island in San Francisco Bay. The median duration of residence at the dredged San Pablo Channel was 77.5 min. Nine fish were detected with depth sensing transmitters. The majority of detections (95.2%) from these fish were at depths greater than five meters. Combined with information regarding the specific impacts of dredging on Green Sturgeon (e.g., suspended sediments, toxicity, entrainment, and behavior changes), these spatiotemporal data could be used to make recommendations for reassessing best management practices.

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Introduction

Exposure to adverse impacts of dredging is one of the many threats facing fishes inhabiting anthropogenically-altered estuarine environments. These impacts include changes in habitat physical structure, temporary loss of food, direct entrainment in the dredge, and exposure to suspended sediment (SS) plumes. During dredging or placement of dredged material, sediment may be resuspended and embedded toxins become available for uptake by fish exposed to the SS plumes. Highly concentrated plumes, (1100 mg/L), may extend along the bottom more than a thousand meters (LaSalle et al. 1991). According to the Mobile District of the U.S. Army Corps of Engineers, SS plumes in the San Francisco Estuary (SFE) may take 2.3–3.5 d to pass a stationary point (Wilber and Clarke 2001) or remain in the confines of the channel for a few weeks after termination of the dredging project (Wakeman et al. 1975). Although the SS decreases in concentration as it moves

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away from the dredging or dredged material placement site (hereafter referred to as placement), there may be effects on fish encountering the plume relatively far from the site. These effects fall into three categories: lethal, sublethal, and behavioral (Newcombe and MacDonald 1991). Lethal effects include direct mortality and sublethal effects are those that that result in primary, secondary or tertiary stress responses (Rich 2010). Behavioral effects are changes or alterations to activities or activity patterns typically associated with an organism in an unperturbed environment (Newcombe and MacDonald 1991). The effects may be different based on taxonomic group, species of fish, natural history, life history phase, and the size of sediment particles (Newcombe and Jensen 1996).

The SFE is the largest estuary on the west coast of North America. Federal navigation channels and non-federal marinas and ports are dredged throughout the SFE to maintain deep and shallow water navigation channels. In the 1800s, sedimentation from mining practices in upstream rivers began to accumulate in the SFE. Dredging for navigational purposes began later that century and has continued on a yearly basis or more, except for a brief interruption in the late 1980s (Dwinnell et al. 2003). In 1982, it was discovered that a mound of dredged material was accumulating at the Alcatraz placement site (SF-11). This accumulation, and environmental concerns, prompted the creation of the Long-Term Management Strategy (LTMS) for the placement of dredged material in the San Francisco Bay Region. The LTMS (2004) has limited the amount of dredged material that can be placed at designated sites, with the goal of decreasing the widespread placement of these materials within the SFE and increasing the beneficial upland/wetland reuse of dredged material. The dredged material is currently placed in the lower SFE at designated open-water sites, the ocean, and beneficial reuse sites (e.g. tidal wetland restoration). The LTMS has also established Environmental Work Windows with the intent of limiting dredging and placement at locations during times of the year when sensitive species may be present. Environmental work windows are periods during which dredging may take place without additional consultation under Section 7 of the federal Endangered Species Act and have been established for many species potentially at risk of adverse effects from dredging operations. Currently, the environmental work windows in the SFE for all aquatic species, including Green Sturgeon, are June 1 – Nov 30. There are four designated open-water placement sites (Fig. 1) within the SFE: 1) SF-09 near Carquinez Strait; 2) SF-10 in San Pablo Bay; 3) SF-11 in San Francisco Bay; and 4) SF-16 in Suisun Bay (not shown on map). The first three open-water placement sites and many dredged sites throughout the SFE were the focus of this study.

The Green Sturgeon (*Acipenser medirostris)* is a species that is likely to encounter the footprint of dredging or placement effects. These effects include elevated levels of suspended sediments in placement areas and entrainment at the site of dredging operations as they migrate to and from the ocean. Green Sturgeon are an anadromous and iteroparous species found along the Pacific Coast of North America. They may live up to 70 years, reach maturity around 15 years of age (Moyle 2002), and spawn every 2–5 years (Moyle et al. 1995). There are two genetically distinct populations, the southern (sDPS) and northern Distinct Population Segments (nDPS). The sDPS fish spawn in the Sacramento River, whereas the nDPS fish reproduce in the Rogue, Klamath and Eel Rivers (NMFS 2005). The spawning areas for the sDPS are located in the upper reaches of the lower Sacramento River below Redding, California, where Keswick Dam impedes further upstream migration. Adult sDPS Green Sturgeon must traverse the SFE while moving upstream to spawning grounds, and again during migration back to the Pacific Ocean. Green Sturgeon are protected under the federal Endangered Species Act (ESA). In 2006 the sDPS was federally listed under the ESA as threatened, while the nDPS is considered a species of concern. Therefore, dredging in the SFE is subject to Section 7 federal Endangered Species Consultation.

Wilber and Clarke (2001) identified three knowledge gaps in the assessment of SS concentrations on estuarine fish: 1) the characteristics typical of both ambient and dredging-induced conditions, 2) the biological responses of aquatic organisms to these dosages, and 3) the likelihood that organisms of interest will encounter plumes. By providing the spatiotemporal use of dredged and placement sites in the SFE, this paper helps fill in the third data gap for adult Green Sturgeon. Telemetric studies have been conducted on both the nDPS and sDPS of Green Sturgeon that describe estuary use (Erickson et al. 2002; Benson et al. 2007; Erickson and Webb 2007; Kelly et al. 2007; Moser and Lindley 2007; Heublein et al. 2009; Lindley et al. 2011), without specific regard for potential encounters with dredging activity. Here we describe the locations and duration that

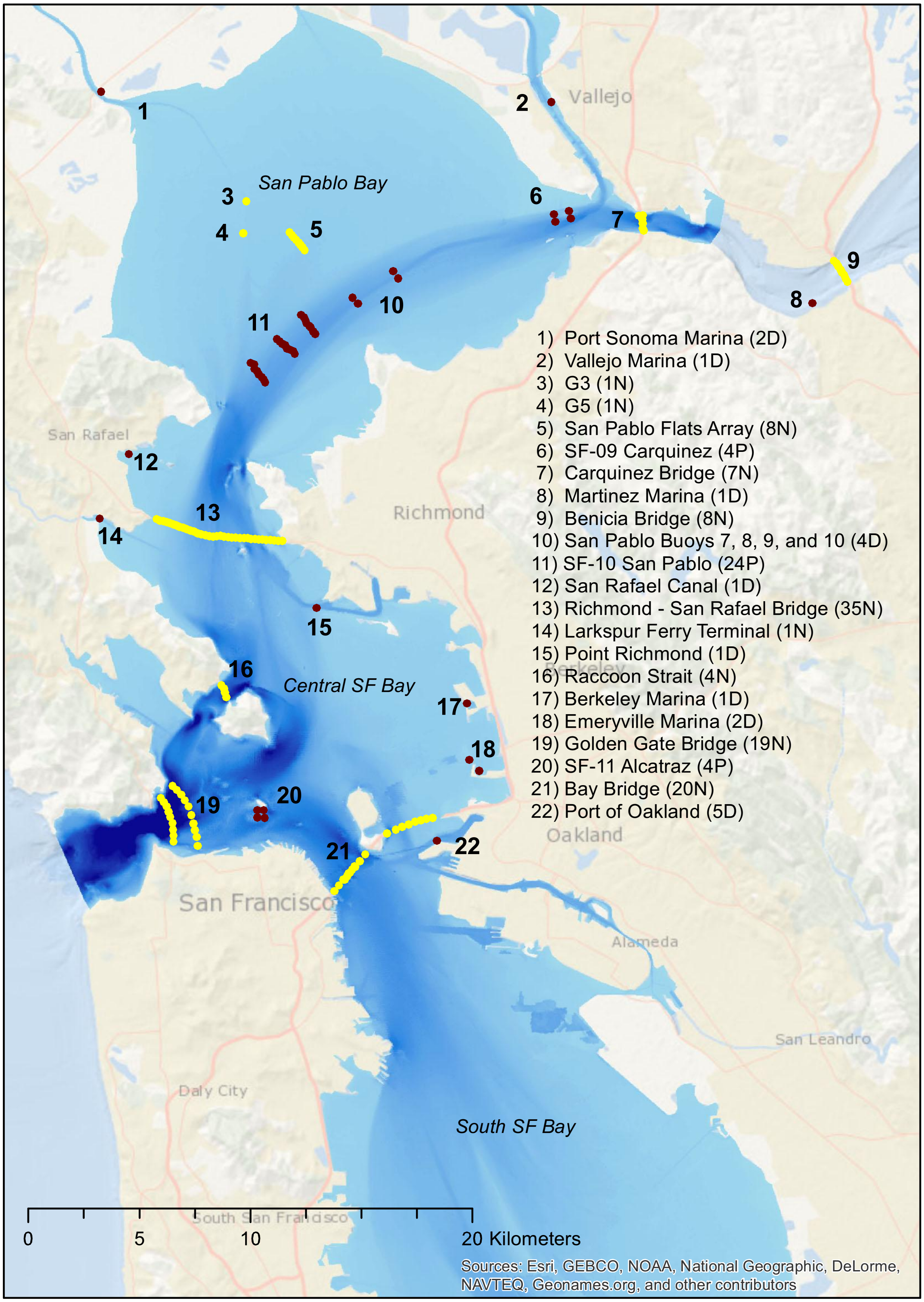


Fig. 1 Receiver locations with site type and number of receivers in parentheses: D = dredged site, P = placement site, and N = no dredging operations conducted. Red dots are either dredged or placement sites, yellow dots are receiver locations where no dredging or placement occurred

adult Green Sturgeon may be potentially exposed to dredging impacts at numerous sites within the SFE.

Methods

Study site

This study was conducted in the lower portion of the SFE from Benicia Bridge to the Golden Gate Bridge in San Francisco, California (Fig. 1). We deployed 106 autonomous acoustic receivers (69 kHz - VR2W, Vemco, Ltd.) at dredged sites and at placement sites. Many receivers in open water were deployed with one of two models of acoustic release (AR-50-AA and AR-60-AA, Sub Sea Sonics, LLC) which, upon command, free themselves from the mooring and float to the surface. A range test was conducted in San Pablo Bay at the SF-10 receiver location. Receivers were deployed in a line extending horizontally across the channel. A mooring was deployed with a float line that had two V7 and two V9 (Vemco, Ltd.) transmitters attached and was left for 1 month to cover a large range of tidal cycles. Based on the results of this month-long range test, receivers were placed 75 m apart. Seventy five percent of transmissions were detected at 75 m. V16 transmitters (Vemco, Ltd.) are stronger and therefore detected over a greater distance. However, we did not conduct range tests with V16 transmitters because this array was designed to simultaneously detect juvenile salmonids tagged with V7 and V9 transmitters.

A total of 19 receivers in two arcs (0.9 km apart) were deployed at the Golden Gate Bridge. Three of the open water placement sites (SF-09, SF-10, and SF-11) are considered to be unconfined and dispersive (United States Army Corps of Engineers, EA/EIR 2014). A brief explanation of each of these three in-Bay placement sites as outlined in the EA/EIR (2014) is as follows:

1) SF-09 Carquinez is a 300 m by 600 m rectangular site, approximately 3 to 17 m deep, located 1.4 km west of the entrance to Mare Island Strait in eastern San Pablo Bay in Solano County. Placement is limited to 765,000 m^3 of dredged material per month and a maximum of 1.5 million m^3 per year during wet years; and 765,000 m^3 per year during dry years.
2) SF-10 San Pablo is a 460 m by 915 m rectangular site, approximately 9 to 15 m deep, located 4.8 km northeast of Point San Pedro in southern San Pablo Bay in Marin County. Placement is limited to 380 m^3 of dredged material per year.
3) SF-11 Alcatraz is a circular placement site with a 300 m radius, approximately 12 to 21 m deep, located 0.5 km south of Alcatraz Island. Placement is currently regulated at a maximum of 300,000 m^3 per month from October to April and 230,000 m^3 per month from May to September. Since at least 1972, SF-11 has been the most heavily used placement site in the SFE.

Transmitter implantation

Adult Green Sturgeon [defined as those having a length greater that 130 cm TL (Moyle 2002)] were tagged over 10 years from 2004 to 2013. The fish used for these analyses were tagged by members of the Biotelemetry Laboratory at the University of California Davis and other researchers throughout the Pacific Northwest of the United States. The mean length of the fish used in analyses was 171.7 ± 19.8 cm SD total length (TL). The vast majority of Green Sturgeon were captured by gill net, while others were captured with hook and line. Transmitter implantation was conducted in the field with fish placed in a V-shaped sling. The fish were placed into the sling ventral side up to induce tonic immobility. Ambient water was continuously pumped into the anterior portion of the sling, which contained a large pocket to provide oxygenated water throughout the surgery. Each fish had a V16-6 L acoustic transmitter surgically implanted into its coelomic cavity, and we anticipated high detection probabilities as a result of our conservative spacing of acoustic receivers. The V16 transmitters weigh 34 g in air and 17.3 g in water, are 16.0 mm in diameter × 98 mm in length, and have an output of 150–162. These transmitters were configured with a 60 s nominal delay, and have a 10 y lifespan. Ten of the Sacramento River fish were implanted with a pressure/depth sensing transmitter (V16P ±1.7 m accuracy, Vemco Ltd.) which transmits a measurement of the depth of the fish to the receiver. The fish were immediately released upon completion of surgical implantation. Typical surgeries involved a 17–20 mm incision made on the ventral side of the fish placed between the third and fourth ventral scute, anterior to the pelvic girdle, parallel to the linea alba, and halfway between the linea alba and ventral scutes. Green Sturgeon were tagged in the Sacramento River in Red Bluff, California, the SFE, and in rivers of Washington and Oregon. Green Sturgeon from the nDPS are not known to migrate south to the SFE (Lindley et al. 2011; Schreier et al. 2016). As such, it is assumed that fish detected in the SFE are from the sDPS.

Data analysis

Green Sturgeon presence at each site is presented by month for descriptive purposes. Due to relatively small sample sizes Green Sturgeon detections at each site were also pooled by season: Winter (Dec, Jan, Feb), Spring (Mar, Apr, May), Summer (Jun, Jul, Aug), and Fall (Sep, Oct, Nov) for calculating duration of residence. Duration of residence (hereafter referred to as residence) was calculated using the V-Track package in R (Campbell et al. 2012). Residence was defined as the duration of time each individual Green Sturgeon was at a particular site. Green Sturgeon residence events at each site were totaled for the 3 years of the study across months. Green Sturgeon individuals that had residence events in multiple years were treated as distinct residence events. A residence event began at the first detection of an individual on any of the receivers within a site. Residence was judged to end if the fish was detected on a receiver at a different site, or if the gap in detections of the fish at the site was over 12 h. To define what constituted the end of one residence event and the beginning of another, we set a detection gap threshold (the length of time a fish must go undetected for the residence event to be considered terminated). The length of this gap affected the average duration of residence events, with longer gaps leading to increased residency duration. We increased the threshold until it no longer affected the average duration as seen in the asymptote here. The average residence reached an asymptote (Fig. 2) at 720 min (12 h) indicating that at this point, increasing the residence threshold no longer affected the residence results. The median and standard deviation was calculated for each of the three placement sites and for all receivers in the entire SFE from the Golden Gate Bridge to Benicia Bridge. Circular statistics and plots were performed using the number of detections at each of the placement sites (Kovach Computing Services, Oriana 3.21). The mean vector and vector length "r" were calculated and provide the mean time of detection and distribution throughout the 24 h day. An r value of 1 indicates all fish are detected at the same time of day, a value of zero indicates uniform distribution of detections over a 24 h period. A statistically significant threshold of $P < 0.05$ was used for all analyses.

Results

Presence

From 2009 to 2012, 134 tagged adult Green Sturgeon were detected in the SFE. One hundred and ten of these were tagged in the Sacramento River watershed, while 24 were tagged in Oregon/Washington. Of those fish, 81% (109) were detected at least one of the placement sites, the dredged channel, or one of the dredged marinas and all of these 109 fish were detected at two or more sites. Of the 134 fish, 74% (99) were detected at one or more of the three placement sites. During that time, 66% of all the individuals detected in the SFE (89) were detected at SF-10 San Pablo, 41% (55) at SF-09 Carquinez, 16% (21) at SF-11 Alcatraz, and 58% (78) at the dredged channel array in San Pablo (buoys 7, 8, 9, and 10).

Green Sturgeon were detected at SF-09, SF-10, and SF-11 throughout the year with few gaps in detections (Fig. 3). The detections of Green Sturgeon on all receivers throughout the SFE were bimodally distributed with the fewest fish detected in April/May and November/December. The two peaks in Green Sturgeon presence were observed in February/March and June through September. The work window from June 1 through November 30 covers the first peak in the distribution but the second peak occurs when many adult Green Sturgeon are present.

We also examined the occurrence of Green Sturgeon at sites where sediments were dredged. Of the 134 adult Green Sturgeon detected in the SFE, 57% (76 individuals) were detected at one of the dredged marinas (Fig. 4). We detected no Green Sturgeon at Berkeley Marina, <1% at Emeryville, Larkspur Ferry Terminal and Port of Oakland (1 adult Green Sturgeon at each site), 5% (7 adults) at Point Richmond, 19% (26 adults) at Vallejo Marina, 22% (29 adults) at Port Sonoma/Petaluma River mouth, and 43% (58 adults) at Martinez Marina.

Residency

From 2009 to 2012, the 89 individuals detected at the SF-10 San Pablo array each spent a median duration of

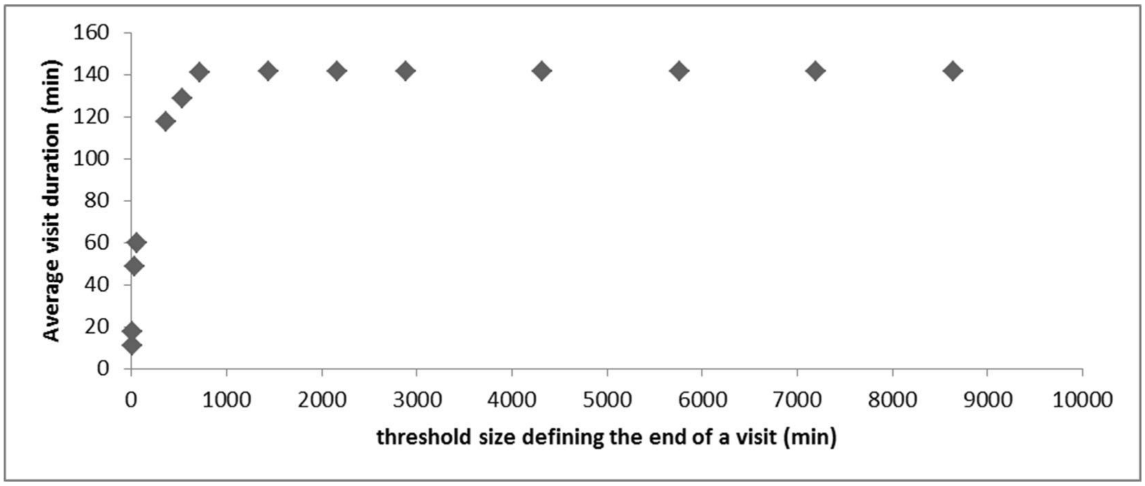


Fig. 2 The effect of the threshold size of detection gaps in defining the end of a residence event on the average residency duration of sturgeon at the site. To define what constituted the end of one residence event and the beginning of another, we set a detection gap threshold (the length of time a fish must go undetected for the residence event to be considered terminated). The length of this gap affected the average duration of residence events, with longer gaps leading to increased residency duration. We increased the threshold until it no longer affected the average duration as seen in the asymptote here. Data shown are from the SF-10 San Pablo array

141.1 ± 618.8 min SD at the site (Fig. 5). Adult Green Sturgeon spent a median duration of 72.5 min ± 263.0 per residence event at SF-09 Carquinez ($n = 55$) and 37.1 min ± 33.2 per residence event at SF-11 Alcatraz ($n = 21$). The 78 individuals detected at the dredged channel array spent a median duration of 77.5 min ± 231.0 per residence event at the site. A Kruskal Wallis test revealed a significant effect of receiver array site on duration of residence ($\chi^2(3) = 32.3$, $P < 0.01$). A Mann-Whitney post-hoc test with Bonferroni correction showed significant differences between all pairs of sites ($P < 0.05$) except for the dredged channel and Carquinez array.

At the dredged marina sites, adult Green Sturgeon spent a median ± SD duration of 23.5 ± 31.2 min at Point Richmond, 48.0 ± 249.3 min at Port Sonoma/ Petaluma River mouth, 155.7 ± 1021.0 min at Vallejo Marina, 6.7 ± 74.1 min at Martinez Marina, 60.6 min at

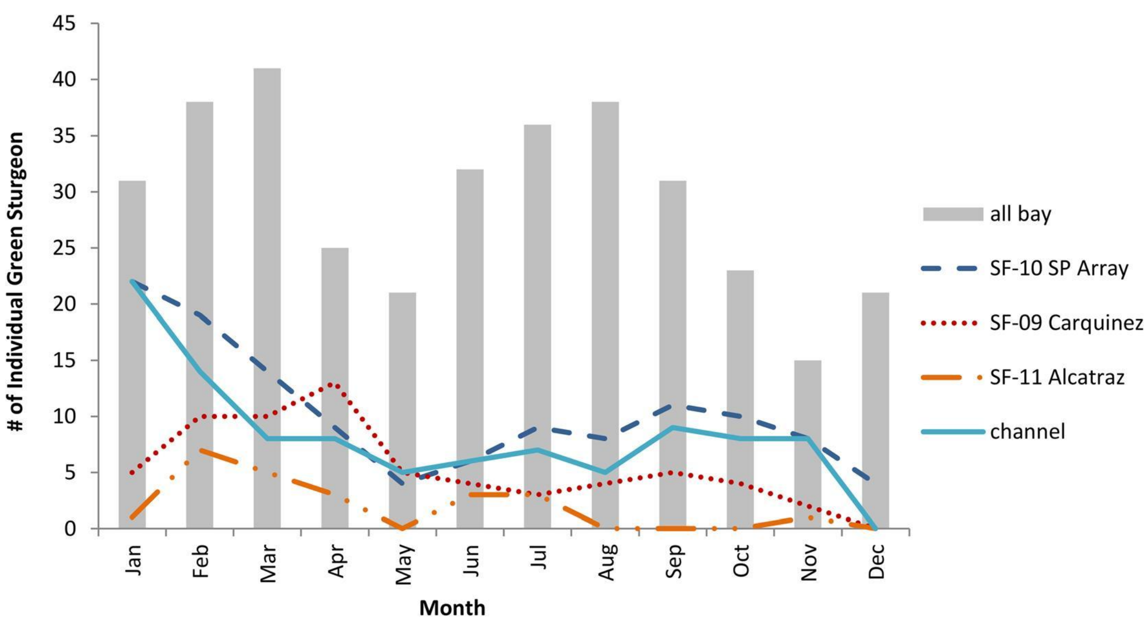


Fig. 3 Individual Green Sturgeon detected by month and over 3 years at all locations throughout the San Francisco Estuary (gray histograms), the three placement sites (dashed lines), and the dredged Pinole Shoal channel (solid blue line). Note that the same individual may be detected in different months

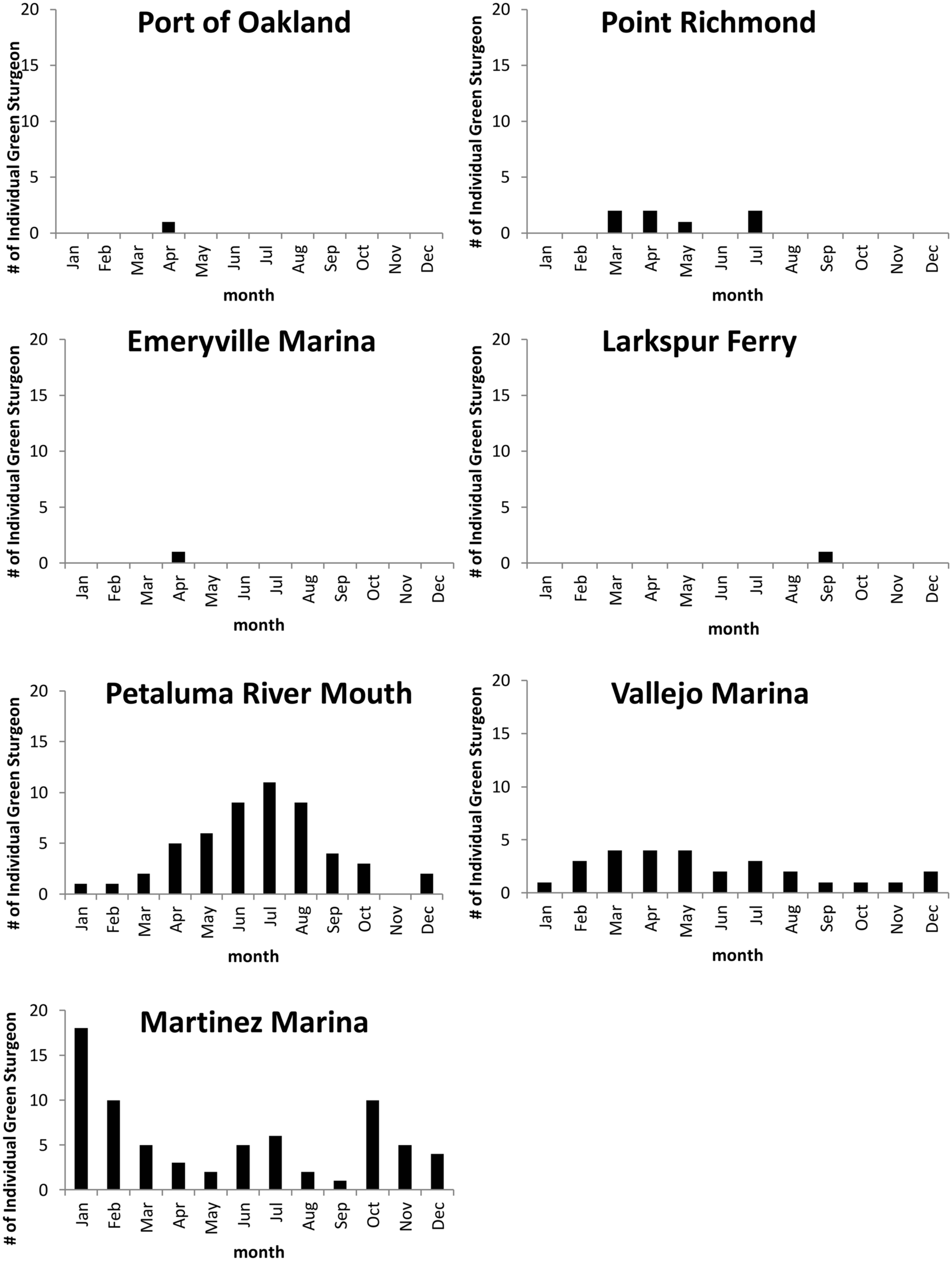


Fig. 4 Individual Green Sturgeon at dredged marina sites by month over 3 years

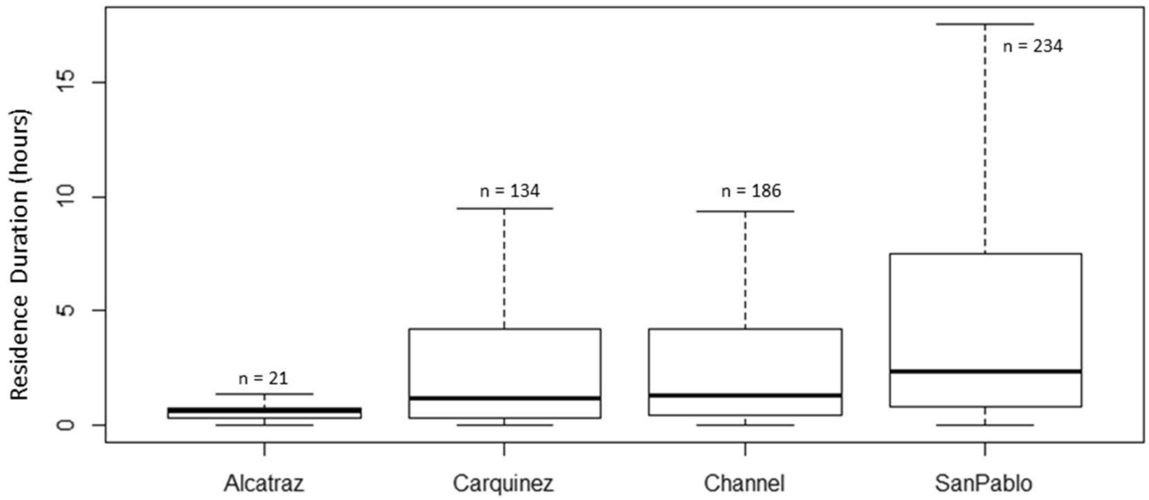


Fig. 5 Median duration of each residence event of individual Green Sturgeon is plotted for each of the three placement sites and the dredged channel. Boxplots indicate 25th and 75th quantile and whisker bars show 95% confidence intervals. Outlying points are not shown. The number of residence events per site is listed above each boxplot

Larkspur Ferry Terminal (only one visit), and 64.6 ± 88.9 min at Port of Oakland per visit. There was a single detection at Emeryville Marina and no detections at Berkeley Marina.

Seasonal residency

Green Sturgeon median residency did not differ by season for the SF-11 Alcatraz, SF-09 Carquinez, or dredged channel site arrays ($P > 0.05$, Kruskal-Wallace tests; Fig. 6). SF-11 Alcatraz array only detected one individual in the fall months. The duration of residence did, however, differ seasonally at the SF10-San Pablo array ($\chi^2(3) = 8.13$, $P = 0.043$, Kruskal-Wallis test). A Mann-Whitney post-hoc test with Bonferroni correction showed that at the SF-10 San Pablo array, adult Green Sturgeon spent a significantly longer duration at the site in summer months than in the spring winter or fall ($P < 0.05$).

Diel pattern

Although Green Sturgeon were clearly detected at all hours of the day (Fig. 7) the distribution of their detections was not uniform (Rayleigh test <0.01, Watson's U^2 test <0.01, and Kiuper's test <0.01) indicating a tendency to move at a certain time of day. The mean time/vector of detection was 23:47 h at SF-09, 00:57 h at SF-10, and 00:11 h at SF-11. The mean vector lengths (r) were small for SF-09 and SF-10 but longer for SF-11 indicating that fish were more likely to be detected at night at SF-11.

Depth use

Of the nine fish we detected with depth sensors, 95.2% of the detections at all receivers were in depths greater than 5 m and 77.0% were detected at depths greater than 10 m. The average depth of the water at all receivers was 17.9 m. The average depths of the fish were 8.2 m at SF-09 where the water depth averaged 14.1 m, and 9.3 m at SF-10 where the water depth averaged 12.1 m. Green Sturgeon were detected in greater numbers at the receivers in the deepest part of the channel in San Pablo Bay and averaged a depth of 11.8 m; the water depth averaged 10.4 m.

Discussion

The question of when and where to dredge must take into account a wide range of factors, among which are the life histories of threatened species that may be impacted by these activities. Here, we show that adult Green Sturgeon are detected at both dredged and placement sites throughout the year. However, due to acoustic releases needing to be periodically removed, there were few detections at the placement sites and channel receivers in December. The receivers deployed across the entire channel at bridges in the SFE detected many fish in December which may explain the relatively few

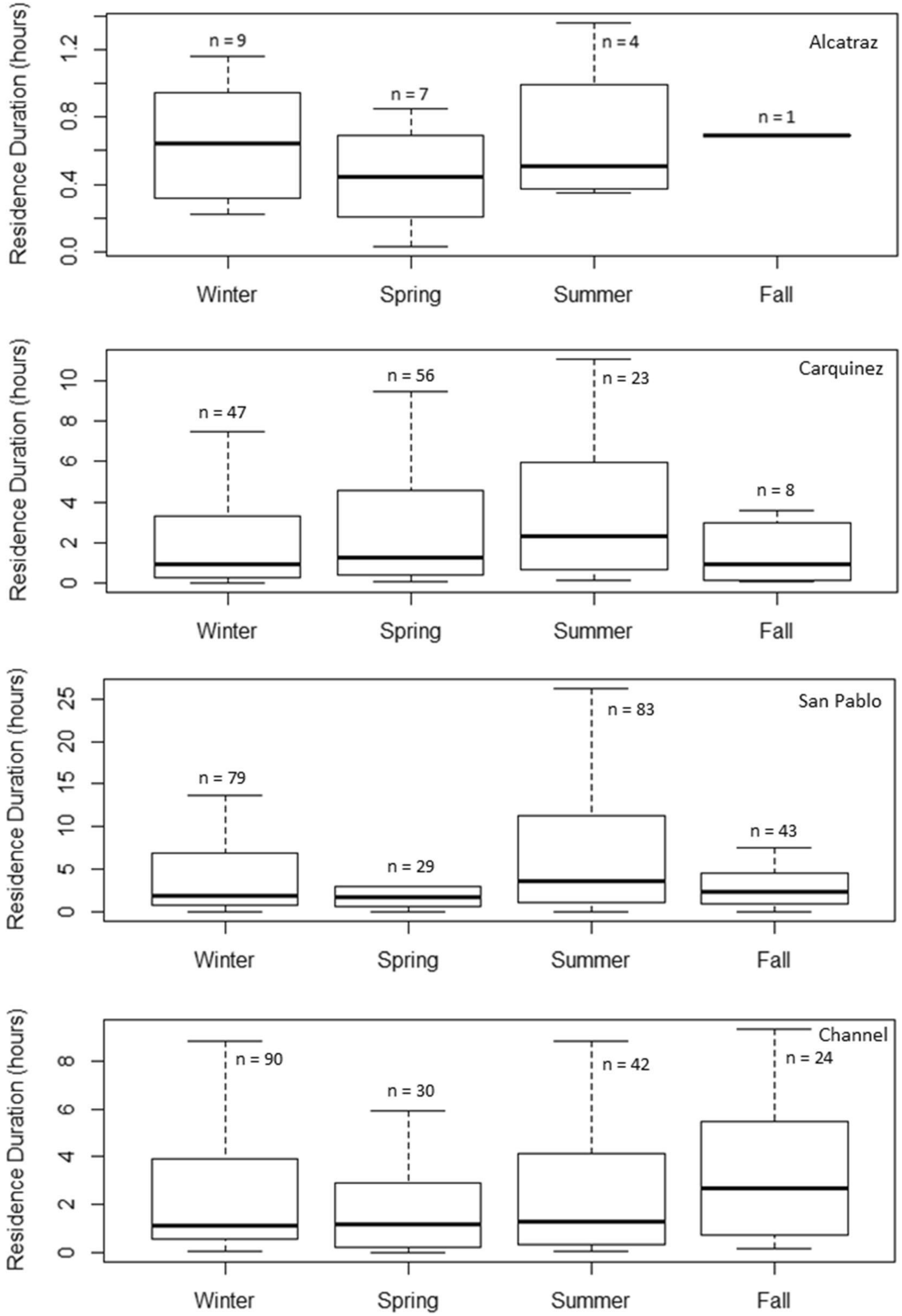
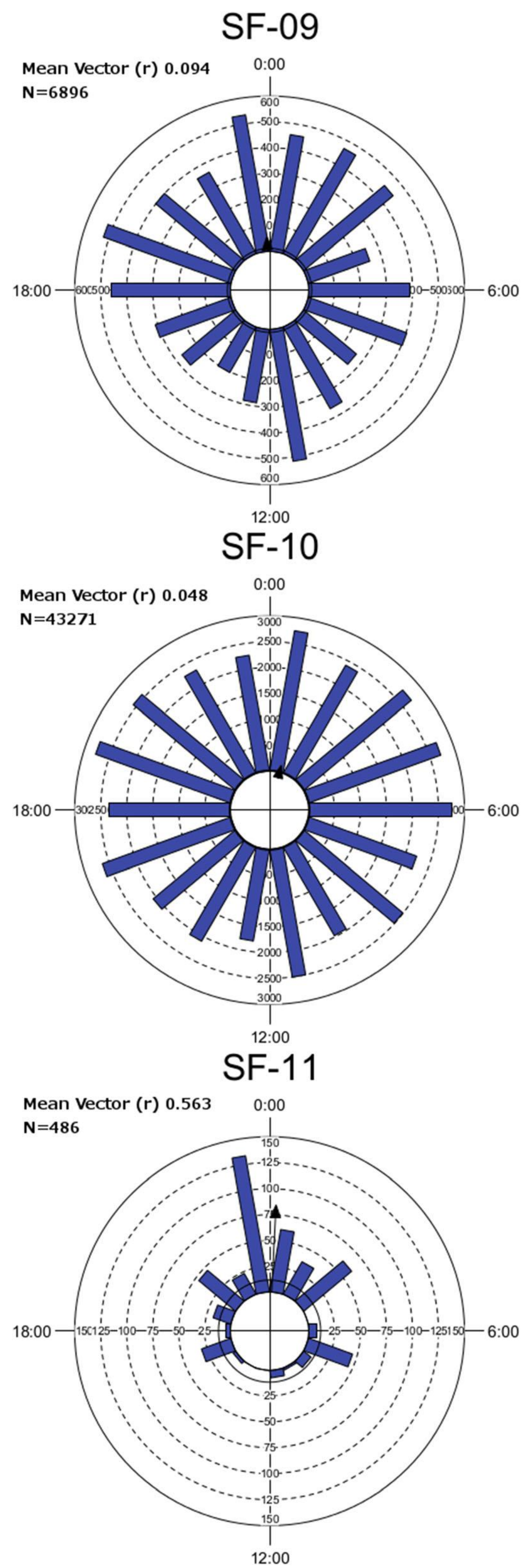


Fig. 6 Seasonal duration of residence at the three placement sites in the SFE from top to bottom: SF-11 Alcatraz, SF-09 Carquinez, SF-10 San Pablo, and the dredged channel. Boxplots indicate 25th and 75th quantile and whisker bars show 95% CI for each box. Outlying points are not shown. The number of residence events per site is listed above each boxplot



◀ **Fig. 7** Circular histograms for all detections at each of the three placement sites. The longer the mean vector and resulting r value, the more likely the fish are not detected uniformly throughout the day. An r vector of 1 would indicate all fish were detected at the same time of day. The smaller the r vector the less likely all fish were detected at the same time of day. Sample sizes represents the number of detections

detections at the placement and channel sites. If Green Sturgeon are present at these sites during active dredging or placement, the risk of entrainment in the dredge (United States Army Corps of Engineers, EA/EIR 2014) and exposure to SS plumes increases.

Many studies have examined the effects of suspended sediment (SS) on fishes (e.g. Berg and Northcote 1985; Barrett et al. 1992; Servizi and Martens 1992; Hess et al. 2015). However, very few studies examined the effects of SS on sturgeon behavior or physiology. One field study in the lower Columbia River, WA found that six of seven sub-adult White Sturgeon (*A. transmontanus)* moved towards the disposal area during disposal operations (Parsley et al. 2011). They found no change in rate of movement, a slight increase in core area, and no change in depth use. These results suggested that sturgeon may not have an aversion to dredging operations, rather they may be stimulated by them, possibly feeding on disturbed prey organisms. One concern in the SFE is that toxins are re-suspended and become available for uptake by fish, either through feeding or via gill filaments. Some fish maternally transfer pollutants to fish eggs and likely contribute to adverse effects on the developing embryos and larvae (Sundberg et al. 2007). The majority of tagged Green Sturgeon (81%) were detected at a dredged or placement site and all of those were detected at multiple sites. The population of adult Green Sturgeon in the Sacramento/San Joaquin watershed is estimated to be 17,548 fish (Mora et al. 2018). When extrapolating to the population level, an estimated 14,214 adult Green Sturgeon may have encountered more than one dredging or placement site.

The majority of fish with depth sensors were detected at greater than five meters and more than 75% were at depths greater than 10 m. At the channel receivers in San Pablo Bay the average depth of the fish was greater than the average depth of the water at the receivers. This was likely due to the fish being detected more often at the two receivers in deeper water (10.9 and 11.9 m), the error in the pressure sensor in the transmitter and tidal fluctuations (up to 2.5 m). Even though this is a limited dataset, Green Sturgeon appear to be benthically oriented while in the SFE. This is consistent with the findings of a manual tracking study that six Green Sturgeon tracked for periods up to nine days spent much of their time swimming near the bottom in a non-directional manner and at times swam into the flow (Kelly et al. 2007; Kelly and Klimley 2012). Kelly et al. (2012) found that Green Sturgeon were more likely to be near the surface during directional movements. In a combined active tracking and autonomous receiver study, Atlantic Sturgeon moved upstream during flood tides and downstream with ebb tides (Reine et al. 2014). The fish appeared to be using mid-water depths during directional movements and were observed using deeper water at night than during the day. The dearth of detections at the surface in our study indicates that these fish only periodically utilize the upper portion of the water column, and are benthically oriented where they might be exposed to the highest SS concentrations. Saucier et al. (1978) concluded that if dredged material were going to have an environmental impact, it would be upon the benthic community. However, some species of fish that may be found near the sediment-water interface may be more tolerant to suspended sediments (Sherk et al. 1974, 1975).

Depending on species-specific behavior, residence durations may be prolonged in areas where osmoregulatory adjustments are made (Wilber and Clarke 2001). It is likely that adult Green Sturgeon make some physiological modifications before transition between freshwater and saltwater, but as yet, this has not been documented. However, it has been documented in juvenile Green Sturgeon that endogenous influences as well as exposure to hyperosmotic environments trigger saltwater adaptation (Allen et al. 2009; Poletto et al. 2013). It is likely that Green Sturgeon do not expend unnecessary energy swimming against the strongest flood tides in an attempt to exit the SFE as quickly as possible. This assertion is supported by the residence observed in the SFE, which may be higher than if they were to expend time and energy swimming against the tidal currents.

The average speed over ground of Green Sturgeon of 101–153 cm TL has been recorded in the SFE as 0.5 $m \cdot s^{-1}$ at the bottom and 0.9 $m \cdot s^{-1}$ at the top of the water column (Kelly and Klimley 2012). A swimming speed of 0.5 $m \cdot s^{-1}$ across an assumed detection range of 250 m would be completed in roughly 16 min. The median residence duration at the three placement sites (37–141 min) suggests that Green Sturgeon do not migrate directly through the SFE. A greater number of adult Green Sturgeon were detected in winter and early spring and again in July, August, and September. During the summer, Green Sturgeon resided longer, indicating there may be foraging opportunities in San Pablo Bay by migratory and non-migratory adults. There were inter-annual differences in presence at the placement sites. For example, in the final year of this study there were more fish present during the spawning season (April through June) than in previous years. Many detections of Green Sturgeon at these study sites occurred during February and March when dredging and placement was not occurring. However, many sturgeon were present during the summer when work windows permit dredging and placement. We know from the detection records on receivers above our study site that some adult Green Sturgeon move up through the SFE and return without reaching the spawning grounds. Whether they are feeding in the SFE, re-acclimating to salt water, or carrying out some other life history event, it is apparent that adult Green Sturgeon utilize the SFE beyond a corridor to migrate through.

Green Sturgeon are present in SFE during the entire year, and thus subject to potentially high SS plumes from dredging operations. In using data from this study to examine current windows, additional consideration could focus on the differential uses of SFE by the various life stages and activities; Green Sturgeon use the SFE as a thoroughfare for spawning migrations, and for feeding during juvenile life stages (Moyle 2002). The stomach contents of green sturgeon collected from San Pablo Bay included bay shrimp, crab, amphipods, isopods, clams, and fish in San Pablo Bay (Ganssle 1966). Though potential prey abundance and distribution throughout the dredged areas are unknown, these taxa are known to occur throughout the San Francisco Bay. Possible refinements to be considered during future consultations might include not only temporal restrictions throughout the entire SFE, but also spatial ones. For example, our data suggest a consideration of separate work windows for some specific locations. The Martinez Marina receiver detected the most fish and exhibited a similar bi-modal distribution as the overall detections at all the receivers in the SFE. This Marina is situated on the outside bend of the narrow Carquinez Strait (from

Benicia Bridge to Carquinez Bridge) where many fish transit during spawning migrations. Conversely the Petaluma River Mouth and Vallejo Marina, did not present this bimodal distribution. The Vallejo Marina, which detected fish throughout the year, recorded the most fish in May, June, and July. This was different than all other sites we studied, except for the Petaluma River Mouth where there was an increase in detections from January through July when the most fish were detected, then a decrease through late summer and fall. The other dredged marina sites we monitored detected very few or no adult Green Sturgeon during the study.

The magnitude of the effects depends on many variables, including project site-specific environmental conditions, as well as the type of dredging operation (Rich 2010). Further research should focus on the effects of contaminated sediment plumes compared to ambient levels. Laboratory studies should be designed using suspended sediments from the SFE, as dredged material is readily available for use in these studies. The product of concentration and duration of exposure, together with behavioral responses of avoidance or attraction, should be included in the design, as it is a better indicator of effects than concentration alone (Newcombe and MacDonald 1991). Entrainment risk, particularly of hopper dredges, and the effects of reduced benthic forage in recently dredged areas should also be considered. Concurrent studies should include White Sturgeon, the other acipenserid in the SFE, and both the juvenile and sub-adult life stages of both species.

These and previous data on our acoustic telemetry receivers deployed at sites of dredging and placement provide information that could be used by managers to refine best management practices for Green Sturgeon and two salmonids (Chapman et al. 2009, 2015, 2017; Hearn et al. 2010, 2014; Singer et al. 2013). Currently, the environmental work windows for all aquatic species, including Green Sturgeon, are June 1 – Nov 30. For proposed dredging projects outside of these periods, formal consultation or other arrangements must take place. Additionally, no dredging is permitted from December 1 through May 31 upstream or within 1000 ft bayward of the mouths of Larkspur/Corte Madera Creek, Napa River Channel/Mare Island Strait (including Vallejo), Petaluma River, and Novato Creek without individual consultation. Our data indicate these dates include one of the two peaks in detections, from June through September, when adult Green Sturgeon are likely to be present in the SFE. Coincidently, at SF-10 San Pablo, summer is the time of year when adult Green Sturgeon exhibit significantly longer residence durations. Note that dredging operations do not take place continuously over the duration of the work window and vary greatly (a few days to a few months) depending on the volume of material dredged and the type of equipment used at a particular site.

There are many critical data gaps remaining in considering the possibility of adverse effects of dredging operations on Green Sturgeon or a consideration of the effectiveness of the current windows in conferring adequate protection. It is possible that work windows, either as they exist or with potential modifications, may not provide any or sufficient protection to Green Sturgeon. Additional precautions might be necessary to protect against potential adverse effects from dredging. All species of sturgeon can be considered as endangered (Rochard et al. 1990). The International Union for Conservation of Nature (IUCN) considers 85% of sturgeon in the world to be at risk of extinction and the most threatened group of animals on their Red List (IUCN 2010). Environmental managers and regulators need to ensure that encounters with dredging activities in the SFE, particularly the physiological effects of suspended sediments, are not adversely affecting Green Sturgeon. Importantly, the relative role of dredging impacts in the broader scope of potential risks to sturgeon also needs to be examined.

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