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RESEARCH

# Evaluating the Role of Boat Electrofishing in Fish Monitoring of the Sacramento–San Joaquin Delta

Ryan McKenzie*[1] and Brian Mahardja[1]

## ABSTRACT

The San Francisco Estuary is an incredibly diverse ecosystem with a mosaic of aquatic habitats inhabited by a number of economically, culturally, and ecologically important fish species. To monitor the temporal and spatial trends of this rich fish community, long-term fish monitoring programs within the estuary use a variety of gear types to capture fish species across life stages and habitats. However, concerns have been raised that current sampling gears may fail to detect certain species—or life stages—that inhabit areas that are not accessible by current gear types (e.g., riprap banks, shallow vegetated areas). Boat electrofishing is one sampling method that has been proposed to supplement current long-term fish monitoring in the upper estuary. In this study, we used fish catch data from past boat electrofishing studies, a long-term beach seine survey, and a couple of long-running trawl surveys to compare the relative probability of detecting various fishes across these sampling gears. Overall, we found that boat electrofishing led to notable improvements in the detection rates for many native and non-native fishes we examined. Boat electrofishing gear was better at detecting the majority of species in the spring (20 out of 38 species, 53%) and fall-winter (24 out of 34 species, 70%) sampling periods. Based on these findings, we recommend that resource managers consider the implementation of a long-term boat electrofishing survey to help them in their long-term conservation planning for fishes within the upper estuary.

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## KEY WORDS

electrofishing, gear comparison, fisheries, long-term monitoring, San Francisco Estuary, Delta, fish communities

## INTRODUCTION

Aquatic ecosystems worldwide have been rapidly degraded as a result of anthropogenic effects, leading to the development of ecological monitoring programs in order to understand and manage these changes (Radinger et al. 2019). This is especially true for the San Francisco Estuary (estuary) and its watershed, where a variety of monitoring programs are in place that extend back multiple decades (Honey et al. 2004; Baerwald et al. 2020). A considerable number of these monitoring programs in the estuary target either a particular fish species of concern or are meant to survey the fish community in a particular region (Honey et al. 2004).

Fish communities are important environmental indicators that often require a combination of sampling gears to adequately monitor across the variety of habitats and species found within estuarine environments (Casselman et al. 1990; Whitfield and Elliot 2002; Baker et al. 2016). In the estuary, fish monitoring programs currently use a combination of trawls and beach seines to sample pelagic (mid-channel) and littoral (nearshore) habitats for fishes across multiple life stages. Sampling gears for these programs were selected based on their ability to capture select fishes of concern to management at the time programs were started (Honey et al. 2004). However, the value of an ecosystem-based management approach has become more apparent over time, and data collected from single-species-focused monitoring programs have been increasingly used to assess the condition of the estuary's fish community (Brown and May 2006; Feyrer et al. 2007; Herrgesell 2012; Mahardja et al. 2017). Currently, net-based monitoring gears are not able to sample structured habitats that now dominate large portions of the estuary—e.g., riprap banks and shallow vegetated areas. This gear limitation has raised concerns that some fish species and ecological interactions may not be adequately captured by fish monitoring efforts, limiting the effectiveness of resource management and conservation plans for the estuary (Hart and Hunter 2004; IEP 2013; Hestir et al. 2016).

Boat electrofishing has often been suggested as a method to improve the scope of fish monitoring in the estuary because it is very effective and efficient at sampling within highly structured habitats of river and estuarine systems (Casselman et al. 1990; Mercado-Silva and Escandon-Sandoval 2008; Warry et al. 2013; IEP 2013; Stompe et al. 2020). Unlike net-based monitoring gears, boat electrofishing can "pull" fish out of structure by attracting them to an electrical field applied to the water, otherwise known as galvanotaxis (Sharber and Black 1999). Yet despite claims that boat electrofishing can better monitor species in the nearshore habitat—especially those associated with vegetation (IEP 2013; Stompe et al. 2020)—few studies have tested this assumption quantitatively (Feyrer and Healey 2002). Within the estuary, several ephemeral boat-electrofishing surveys have been conducted over the years, which have documented nearshore habitat use by a variety of fishes, and shifts in the nearshore fish community (Brown and Michniuk 2007; McLain and Castillo 2009; Young et al. 2018). Although these discrete studies varied in methods and scope, these boat electrofishing data sets, when used in combination with data from long-term monitoring programs, can be leveraged to evaluate the relative probability of detecting species across gears. As the management agencies of the estuary continue to review and adjust their long-term monitoring programs, it is important to consider how boat electrofishing may improve their scope of fish monitoring.

To date, no studies have compared the rate at which boat electrofishing detects species to the rate of long-term net-based monitoring gears across the full suite of fishes found in the upper estuary. In this study, we evaluated the relative differences in the probability of species being detected among boat electrofishing, beach seine, mid-water trawl, and Kodiak trawl fishing gears deployed within the Sacramento-San Joaquin River Delta (Delta). Using an occupancy modeling framework, we set out to answer two questions: (1) How does the probability of species detection compare across boat electrofishing and long-term net-based monitoring gears? (2) Would we see a significant improvement in species detection with the use of boat electrofishing, and if so, which species? Our goal was to highlight the strengths and weaknesses of long-term fish monitoring gears, and to provide information on how boat electrofishing may improve the monitoring of fish communities within the estuary. Note that this study is not meant to serve as a comprehensive assessment of gear efficiencies for fish monitoring surveys. Such an evaluation would likely require an understanding of how gears are linked to specific habitats (i.e., not all gears can be deployed in every habitat type) and how each species distributes themselves across habitats.

Rather, this study provides general information on the relative efficiency of gear types for fishes of the Delta with a focus on boat electrofishing, an oft-recommended sampling method for the Delta (IEP 2013; Stompe et al. 2020) that has yet to be implemented as a long-term monitoring program.

## METHODS

### Study Area

Within the estuary, boat electrofishing has been limited to freshwater habitats because the equipment used in surveys has not been capable of generating enough power to effectively sample in brackish waters (Conductivity > 3,000 µS/cm). Therefore, our study focused on the Delta, which comprises the upper freshwater portion of the estuary. The Delta has been heavily modified since the mid-19th century. The once-tidal marsh system has now been converted to a patchwork of levee-lined agricultural islands, interlaced with a network of canals, sloughs, and flooded islands (Whipple et al. 2012). Although many changes have occurred over time, the Delta still supports a rich fish community with over 23 native fishes—five of which are listed as threatened or endangered—and over 30 introduced species—14 of which support recreational fisheries.

### Data Sources

We used fish data collected from four different ecological monitoring programs and one collaborative study conducted within the Delta. To compare fish data across these efforts, we restricted our analysis to samples collected during daylight hours (6:00 am to 6:00 pm) and aggregated our data into two distinct seasonal and temporal data sets: (1) fall/winter data set–samples collected during September through December from 2001 to 2010; and (2) spring data set–samples collected in Januar through May from 2002 to 2010. We limited our data analysis to these periods to ensure there was adequate overlap between electrofishing, seine, and trawl gear types. We did not include certain fish surveys conducted during late-spring and summer months because trawl gear types used during these times were mainly designed to capture larval-sized fishes, and our gear comparison focused on juvenile and adult size classes. We also did not include fish survey data conducted in other regions within the estuary such as Yolo Bypass, Suisun Marsh, and San Pablo and San Francisco bays because they had minimal geographical overlap with past electrofishing surveys.

### CDFW Fall Midwater and Spring Kodiak Trawl Surveys

The California Department of Fish and Wildlife (CDFW) Fall Midwater Trawl (FMWT) survey has monitored juvenile fishes in the open-water habitat of the estuary since 1967 (Stevens and Miller 1983). The original goal of the FMWT was to monitor the annual relative abundance of young-of-year Striped Bass (*Morone saxatilis*); however, over the years it has provided valuable information on the endangered Delta Smelt (*Hypomesus transpacificus*) and other species of interest to management (Moyle et al. 1992; Feyrer et al. 2007, 2009; Rosenfield and Baxter 2007; Sommer et al. 2007; Mac Nally et al. 2010; Bever et al. 2016; Nobriga and Rosenfield 2016). The FWMT has sampled roughly 100 stations between the San Pablo Bay and the Delta once per month from September through December since 1967, and it has sampled an additional 22 stations per month since 2010. The midwater trawl is towed obliquely, sampling water from bottom to surface. Data from the FMWT was used as a part of the fall/winter data set.

The CDFW established the Spring Kodiak Trawl (SKT) survey in 2002 to collect information on the distribution and relative abundance of spawning Delta Smelt in the estuary (Polansky et al. 2018). The SKT has conducted sampling at 40 fixed stations that cover the range of adult Delta Smelt from Carquinez Strait to the Delta every month from January through May. Although Delta Smelt is the target species for the SKT, this survey has caught a number of other species over the years (Castillo et al. 2018). For the Kodiak trawl, the net is towed at the surface of the water by two vessels, with the bottom of the net mouth extending roughly 3.5 meters deep. Data from the SKT was used as a part of the spring data set.

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## USFWS Beach Seine Survey

The US Fish and Wildlife Service (USFWS) Delta Juvenile Fish Monitoring Program (DJFMP) has conducted beach seine surveys since 1976 to evaluate the abundance and distribution of juvenile Chinook Salmon (*Oncorhynchus tshawytscha*) and various resident fish species within the estuary (IEP et al. 2020). The DJFMP beach seine survey has been the primary monitoring program in the region that evaluates fish community changes in the nearshore, littoral habitat (Brown and May 2006; Mahardja et al. 2017). Although the DJFMP began in 1976, sampling in the late-spring and summer months (when non-salmonid juvenile fishes typically recruit into the gear) did not become part of standard protocol until 1995. Since 1995, the DJFMP has sampled 44 sites within the Sacramento-San Joaquin Delta and the lower Central Valley of California consistently, year-round. Beach seine sampling at each site is conducted either weekly or bi-weekly depending on the region and logistical constraints (IEP et al. 2020). Because the DJFMP beach seine survey has been conducted year-round since 1995, data from this survey was included in both the fall/winter and spring data sets.

## CDFW and CDWR–UC Davis Electrofishing Data Sets

The CDFW Delta Resident Shoreline Fish Monitoring Project has conducted boat electrofishing surveys sporadically since 1980 to estimate the relative abundance and distribution of resident fishes within the Delta, and to provide estimates of growth and mortality for Largemouth Bass via mark-and-recapture efforts (Schaffter 1998, 2000; Brown and Michniuk 2007). The project conducted monthly boat electrofishing surveys over three different time-periods: 1980–1984 (1980s); 1995, 1997, and 1999 (1990s); and 2001–2004 (2000s). Surveys were conducted using a stratified, random-sampling design between 1980 and 1983, and from 2001–2004 (Figure 1). From 1984 to 1999, surveys were conducted using fixed stations. In the 1980s and 1990s, fish sampling was conducted using a Smith and Root (Vancouver, WA) electrofishing boat with a VI-A shocking unit. In the 2000s, fish sampling was conducted using a Smith and Root electrofishing boat with a 5.0 gas-powered pulsator (GPP) shocking unit (GPP settings: 60 pulses per second, 50- to 500-Voltage range). During all sampling periods, sampling was standardized by adjusting the shocking unit voltage to maintain an output of 6 ± 1 average amperes.

The University of California-Davis conducted boat electrofishing surveys from 2008 to 2010 to explore the habitat associations of Largemouth Bass in the estuary (Conrad et al. 2016). Bimonthly boat electrofishing surveys were conducted at 33 fixed stations randomly selected within areas that had a water depth of < 3 meters, and where submerged aquatic vegetation (SAV) was known to previously occur (Figure 1). The majority of sites were adjacent to shorelines, with a few sites located in the open shallow waters of previously reclaimed wetland areas. Fish sampling was conducted using a Smith and Root electrofishing vessel equipped with a 5.0 GPP shocking unit (GPP Settings: 60 pulses per second, 50- to 500-V Range). To standardize sampling, the shocking unit voltage was adjusted to maintain an output of 6 to 10 average amperes.

## Data Analysis

We used occupancy models (Mackenzie et al. 2006) within the fall/winter and spring sampling periods for each fish species to estimate the mean site-level detection probabilities using each available gear type. Occupancy models require that data is collected with repeat sampling within a defined spatial and temporal scale. The models assume “closure, meaning that the status (presence or absence) of a given species does not change between replicate samples taken at the defined spatial and temporal scale. For our models, we used sampling regions derived from the CDFW Delta Resident Shoreline Fish Monitoring Project (Figure 1) and month (within years) as our spatial and temporal scale for a site. Therefore, we assumed the status of a given species would not change within a region over the course of a month, and samples taken within the same region and month were treated as our replicate sampling events used to calculate the probability of detection. Sampling frequency

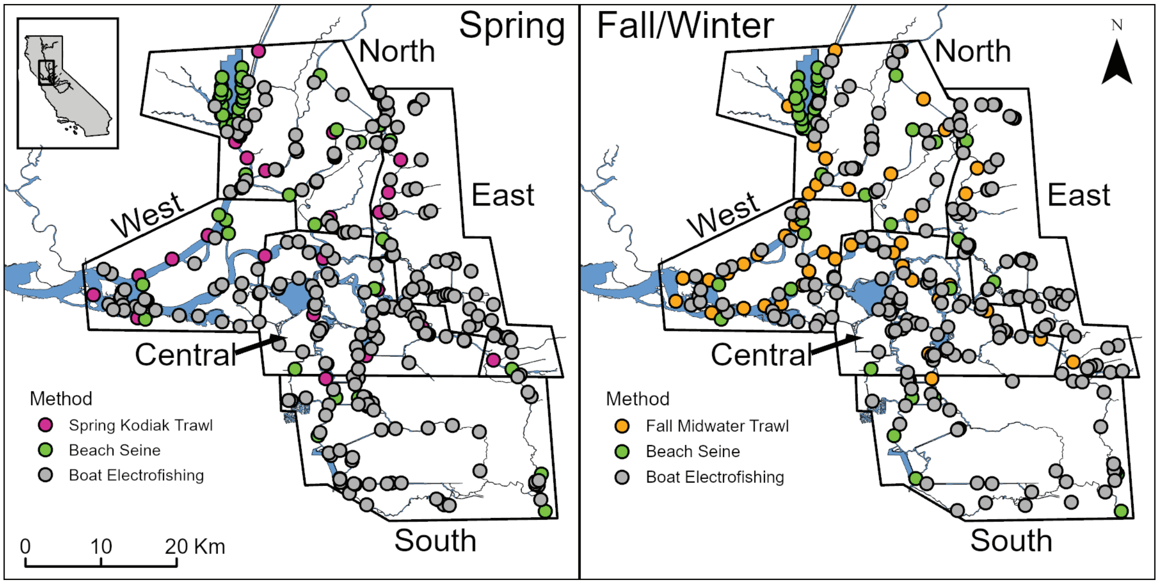

**Figure 1** Map of sampling distribution by each gear type within spring (Jan–May) and fall/winter (Sept–Dec) sampling periods. Spring Kodiak trawls, fall midwater trawls, and beach seines were conducted by repeat sampling at fixed stations. Boat electrofishing was conducted with both repeat sampling at fixed stations and a stratified random sampling. Sampling regions are indicated by *polygons*.

and spatial extent of sampling differed between gear types—i.e., not all regions were sampled by each gear type over a given month. To reduce any confounding effects of spatial and temporal variation in gear deployments on estimates of the probability of detection, we limited our analysis to include only region and month combinations where all available gear types had been deployed at least once. We also ensured that environmental conditions varied more between "sites" than *within* them by visually inspecting the water-quality data parameters that the monitoring programs collect (see Appendix A, Figure A1). Before constructing our occupancy models, we removed rarely detected species—species detected at < five sites—to ensure sufficient power to estimate detection probabilities.

Occupancy models were run using "occu" function in the unmarked package (Fiske 2011) for R (R Core Team 2021). Since probability of detection among gear types was our only interest, the occupancy parameter ($\psi$) was modeled as a constant, and the detection efficiency parameter ($p$) was modeled as a constant across space and time, with gear type as a categorical variable. Using this framework, our models were effectively logistic regression models that compared the overall detection rates between gear types when the species was present—i.e., detected at least once by any of the gear types. After an initial run, we ran each model a second time using the gear type that we estimated had the highest probability of detection as the reference level, to determine if the gear type were significantly ($p < 0.05$) better at detecting a given species than the other two available gear types. For comparisons between gear types where detection probability could not be estimated for one gear type because it failed to detect the species, we considered the gear type that did detect the species to be "significantly" better. To organize our model outputs, we grouped species based on a combination of their residency status and origin (e.g., resident native, non-resident native, resident-introduced, non-resident introduced). We did not explicitly address species-specific size-selectivity differences within or between gears in the occupancy model, because that is beyond the scope of our study. However, we constructed a series of histograms showing size-frequency distributions of each species by season to better understand the size ranges observed by each gear and how they affect our model interpretations.

## RESULTS

In the spring sampling period (Jan–May), 70 "sites" had all three gears deployed and gear detection probability compared (Figures 2 through 5). Within these sites, a combination of 1,411 beach seine, 329 boat electrofishing, and 347 Kodiak trawl samples detected 48 fish species (Appendix B, Table B1 and B3). Ten species were excluded from our analysis because of a low site detection, or observation rates which resulted in the failure of models to converge. For the spring sampling period, Mississippi Silversides (*Menidia audens*) were the most detected species, occurring at 69 sites, followed by Largemouth Bass (*Micropterus salmoides*; 67 sites), Redear Sunfish (*Lepomis microlophus*; 66 sites) and Golden Shiner (*Notemigonus crysoleucas*; 66 sites). Chinook Salmon were the most detected native species (63 sites) in the spring sampling period.

In the fall/winter sampling period (September through December), 63 sites were used in our analysis (Figures 2 through 5) where a combination of 1,332 beach seine, 252 boat electrofishing, and 450 midwater trawl samples detected 48 species (Appendix B, Table B2 and B3). Eleven species were excluded from the analysis as a result of low site detection or observation rates. Mississippi Silverside and Threadfin Shad (*Dorosoma petenense*) were the two most detected species in the fall/winter period;both species occurred at all 63 sites. Sacramento Pikeminnow (*Ptychocheilus grandis*) were the most detected native species (38 sites) in the fall/winter period.

Overall, our occupancy modeling results indicated that boat electrofishing gear was significantly better at detecting the majority of species in the spring (20 out of 38 species, 53%) and fall/winter (24 out of 34 species, 70%) sampling periods (Figures 2 through 5). Species size distributions varied across gear types and sampling periods; however, boat electrofishing generally captured a broader size range of individuals than long-term gears (Appendix C, Figures C1 and C2).

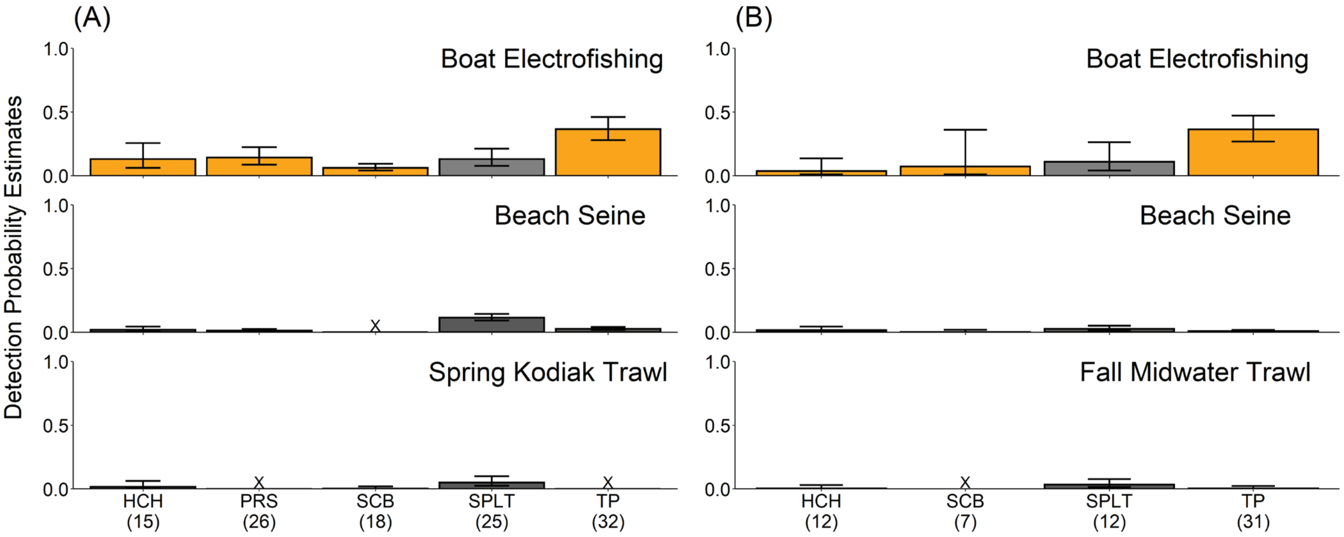

**Figure 2** Mean detection probability estimates for native resident fishes during (**A**) spring (Jan–May) and (**B**) fall /winter (Sept–Dec) sampling periods. Gears that were significantly better ($p < 0.05$) than both other gear types are indicated with *orange*. Error bars indicate 95% confidence intervals, (#) indicates number of sites used in occupancy models, and X indicates that a species was not detected by the gear type.

Table 1 Species code and figure references

| Species Code | Common name (scientific name) | Grouping (figure number) |
|---|---|---|
| HCH | Hitch (*Lavinia exilicauda*) | Native resident (2) |
| PRS | Prickly Sculpin (*Cottus asper*) | Native resident (2) |
| SCB | Sacramento Blackfish (*Orthodon microlepidotus*) | Native resident (2) |
| SPLT | Splittail (*Pogonichthys macrolepidotus*) | Native resident (2) |
| TP | Tule Perch (*Hysterocarpus traskii*) | Native resident (2) |
| BGS | Bluegill Sunfish (*Lepomis macrochirus*) | Introduced resident (3) |
| BKB | Black Bullhead (*Ameiurus melas*) | Introduced resident (3) |
| BKS | Black Crappie (*Pomoxis nigromaculatus*) | Introduced resident (3) |
| BRB | Brown Bullhead (*Ameiurus nebulosus*) | Introduced resident (3) |
| C | Common Carp (*Cyprinus carpio*) | Introduced resident (3) |
| CHC | Channel Catfish (*Ictalurus punctatus*) | Introduced resident (3) |
| GF | Goldfish (*Carassius auratus*) | Introduced resident (3) |
| GSF | Green Sunfish (*Lepomis cyanellus*) | Introduced resident (3) |
| GSN | Golden Shiner (*Notemigonus crysoleucas*) | Introduced resident (3) |
| LMB | Largemouth Bass (*Micropterus salmoides*) | Introduced resident (3) |
| LP | Bigscale Logperch (*Percina macrolepida*) | Introduced resident (3) |
| MQF | Western Mosquitofish (*Gambusia affinis*) | Introduced resident (3) |
| MSS | Mississippi Silverside (*Menidia audens*) | Introduced resident (3) |
| RES | Redear Sunfish (*Lepomis microlophus*) | Introduced resident (3) |
| RSN | Red Shiner (*Cyprinella lutrensis*) | Introduced resident (3) |
| SHM | Shimofuri Goby (*Tridentiger bifasciatus*) | Introduced resident (3) |
| SMB | Smallmouth Bass (*Micropterus dolomieu*) | Introduced resident (3) |
| SPB | Spotted Bass (*Micropterus punctulatus*) | Introduced resident (3) |
| W | Warmouth (*Lepomis gulosus*) | Introduced resident (3) |
| WHC | White Catfish (*Ameiurus catus*) | Introduced resident (3) |
| CHN | Chinook Salmon (*Oncorhynchus tshawytscha*) | Other natives (4) |
| DSM | Delta Smelt (*Hypomesus transpacificus*) | Other natives (4) |
| LAM | Lamprey (*Lampetra spp.*) | Other natives (4) |
| LFS | Longfin Smelt (*Spirinchus thaleichthys*) | Other natives (4) |
| PSS | Pacific Staghorn Sculpin (*Leptocottus armatus*) | Other natives (4) |
| RBT | Rainbow Trout/Steelhead (*Oncorhynchus mykiss*) | Other natives (4) |
| SAPM | Sacramento Pikeminnow (*Ptychocheilus grandis*) | Other natives (4) |
| SASU | Sacramento Sucker (*Catostomus occidentalis*) | Other natives (4) |
| TSS | Threespine Stickleback (*Gasterosteus aculeatus*) | Other natives (4) |
| AMS | American Shad (*Alosa sapidissima*) | Other introduced (5) |
| FHM | Fat Head Minnow (*Pimephales promelas*) | Other introduced (5) |
| RFK | Rainwater Killifish (*Lucania parva*) | Other introduced (5) |
| STB | Striped Bass (*Morone saxatilis*) | Other introduced (5) |
| TFS | Threadfin Shad (*Dorosoma petenense*) | Other introduced (5) |
| YFG | Yellowfin Goby (*Acanthogobius flavimanus*) | Other introduced (5) |

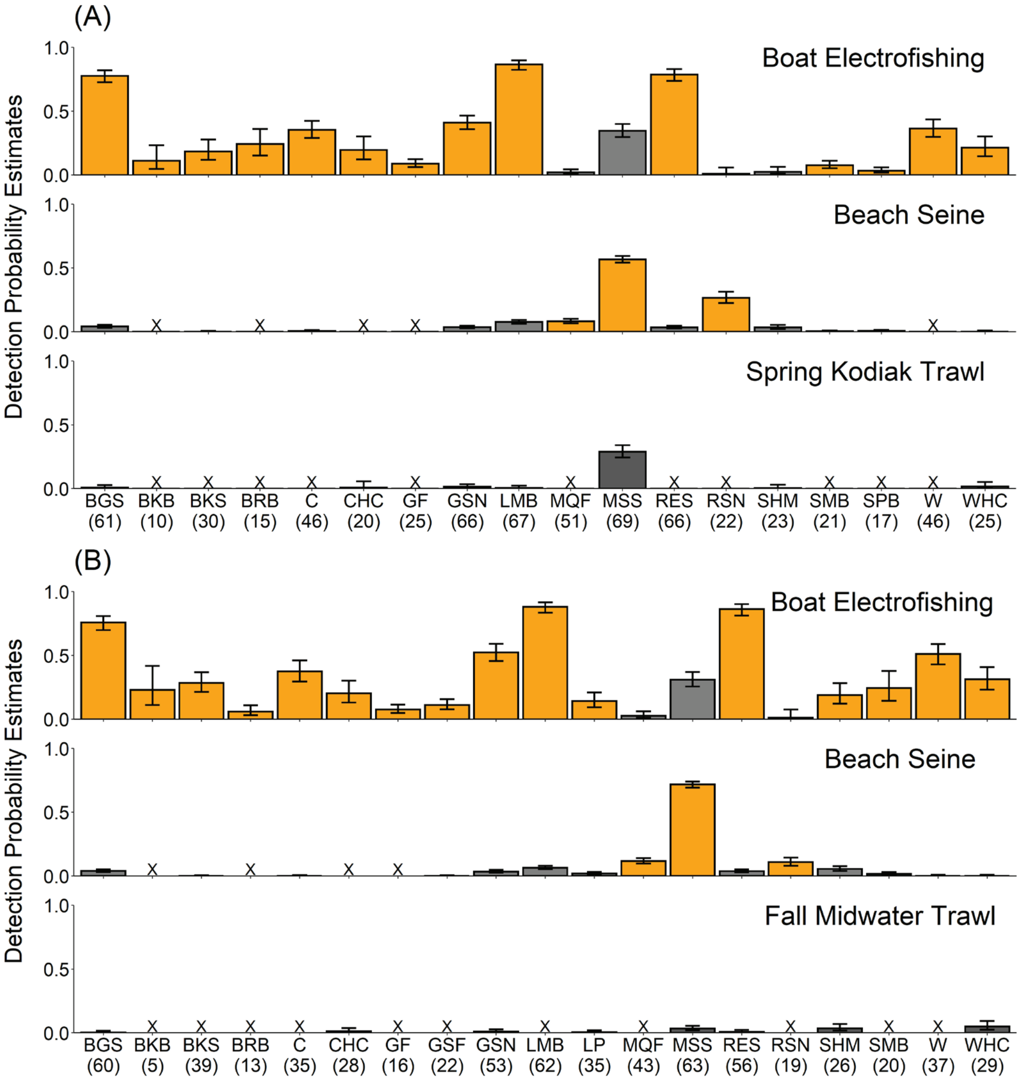

**Figure 3** Mean detection probability estimates for introduced resident fishes during (**A**) spring (Jan–May) and (**B**) fall/winter (Sept–Dec) sampling periods. Gears that were significantly better ($p < 0.05$) than both other gear types are indicated with *orange*. Error bars indicate 95% confidence intervals, (#) indicates the number of sites used in occupancy models, and X indicates that a species was not detected by the gear type.

## DISCUSSION

Based on our findings, it is clear that the Delta supports a wide variety of fish species, which require a diversity of gears to adequately monitor. Each monitoring gear significantly improved the probability of detection for one or more species, and no single gear was effective for detecting every species. In all but one case, long-term monitoring gears proved to be the most effective gear for the species they were initially designed to target. Beach seine was the most effective gear for Chinook Salmon, and Kodiak trawl was the most effective for Delta Smelt. However, midwater trawl had a lower probability of detecting Striped Bass than boat electrofishing. The difference in detection probability of these two gears may have resulted from differences in size selectivity, because boat electrofishing sampled a larger size range of individuals (i.e., more individuals were available to capture) than the midwater trawl (Appendix C, Figure C2). This result is not surprising, given that the FMWT survey was originally designed to target smaller age-0 Striped Bass.

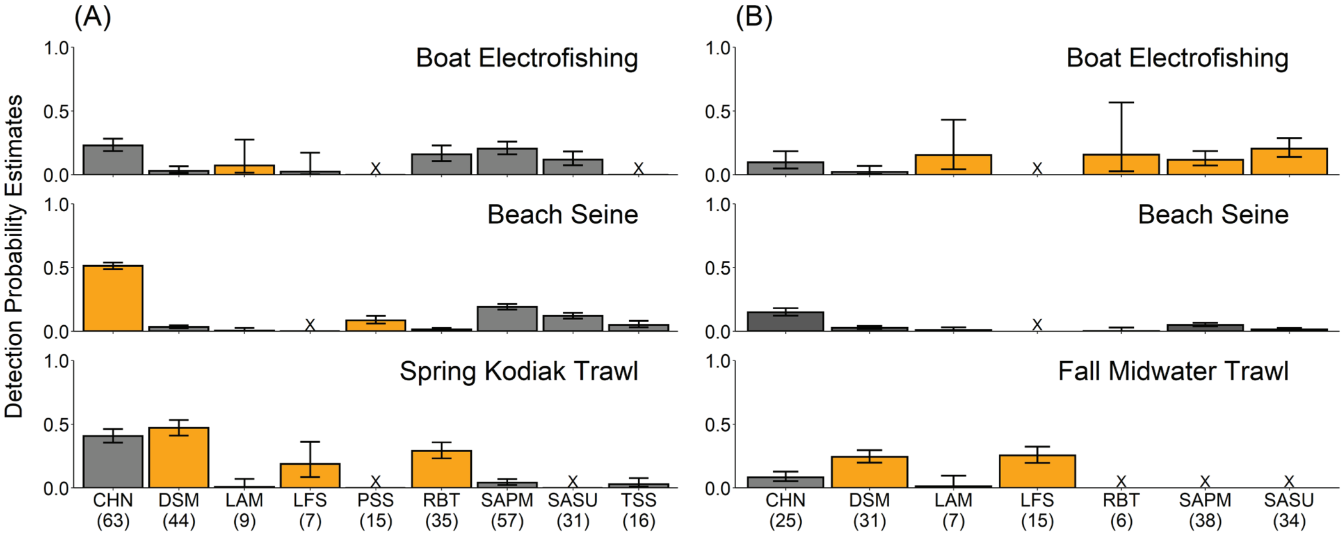

**Figure 4** Mean detection probability estimates for other native fishes during (**A**) spring (Jan–May]) and (**B**) fall/winter (Sept–Dec) sampling periods. Gears that were significantly better ($p < 0.05$) than both other gear types are indicated with *orange*. Error bars indicate 95% confidence intervals, (#) indicates the number of sites used in occupancy models, and X indicates that a species was not detected by the gear type.

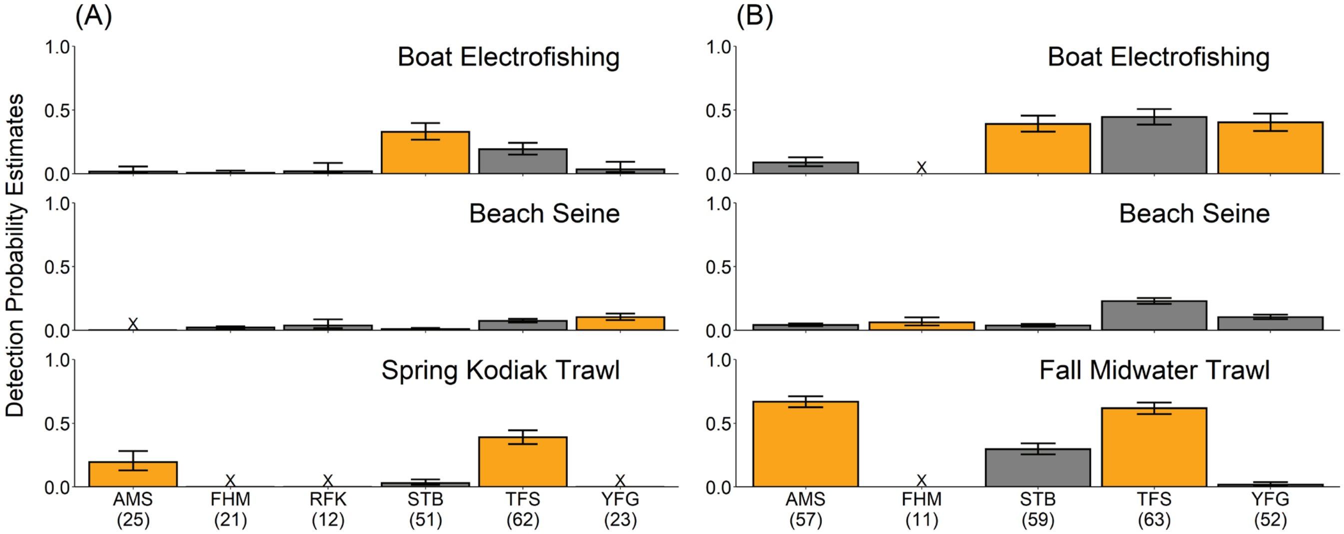

**Figure 5** Mean detection probability estimates for other introduced fishes during (**A**) spring (Jan–May) and (**B**) fall/winter (Sept–Dec) sampling periods. Gears that were significantly better ($p < 0.05$) than both other gear types are indicated with *orange*. Error bars indicate 95% confidence intervals, (#) indicate the number of sites used in occupancy models, and X indicates that a species was not detected by the gear type

## Caveats and Assumptions

In addition to size-selectivity differences that were not incorporated into our models, a couple of additional factors should be considered when interpreting results from our study. First, given our definition of a site (any sampling that occurred within a region in the same month), our models assumed that a single detection of a species at a region meant that the species was present in the region for the rest of the month. Estimates for more sedentary or resident species (e.g., Largemouth Bass) would likely be less affected by this assumption, while detection-probability estimates for more mobile or migratory species (e.g., Chinook Salmon) may be biased low to some extent. Although not ideal, the relatively large spatial and temporal scales used in our analysis were chosen to ensure adequate overlap between gear types, and reflect the challenges of integrating data sets across the estuary's suite of fish monitoring programs, which differ in their spatial and temporal scales. Second, it is important to note that our estimates of the probability of each gear type not exclusive measures of how efficient the gear is at capturing fishes but rather a combination of that and the relative abundance of individuals within the habitats the gear samples. In our analysis, the habitats sampled by gear types did differ: i.e., beach seines were deployed in shallow-water sandy beaches and boat ramps; trawls were conducted in mid-channel, deep-water habitats; and boat electrofishing surveys were conducted in shallow-water-structured habitats. Therefore, our estimates of the probability of gear detection reflect the true relative performance of monitoring gears as they have been used by monitoring programs in the estuary—including their sampling methods and the habitats sampled. In the future, the detection probabilities we report here for long-term monitoring gears could change if sampling methods and/or the habitats sampled are modified, and future analyses will be needed to account for these modifications.

Along these lines, it is important to consider the environmental constraints and sampling biases of boat electrofishing when thinking about its application. For example, net-based gears can sample in all areas of the estuary, whereas boat electrofishing typically has been limited to sampling freshwater areas, because power generators cannot produce enough power to effectively shock in highly conductive brackish and saline water (conductivity $> 5{,}000\,\mu S\,cm^{-1}$). To date, most commercially available boat electrofishing equipment is still constrained to these conductivity limits; however, boat electrofishing technology has been developed that may enable sampling to be extended into brackish water in the future (conductivity $> 20{,}000\,\mu S\,cm^{-1}$ citation; Warry et al. 2013). In addition, conditions that reduce the ability of crew to spot and retrieve fish when boat electrofishing—e.g., waves, high winds, and high turbidity—can decrease sampling efficiency (Lyon et al. 2014). Boat electrofishing can also be size-selective because the power transferred to individuals increases with body size; therefore, larger individuals become immobilized sooner than smaller individuals under the same electrical field applied to the water (Dolan and Miranda 2003). Species that lack a swim bladder may also be less susceptible to capture by electrofishing in some cases, because they sink after becoming immobilized and are inaccessible to netters (Polačik et al. 2008). These factors are not unique to boat electrofishing; however, because all monitoring gears have their limitations: e.g., high flows can limit the deployment and sampling efficiency of beach seines, and trawl mesh sizes and fishing methods (e.g., tow speed, fishing depth) can select for specific body sizes and/or species. Therefore, accounting for the environmental constraints and sampling biases of monitoring gear is an essential component of the logistical planning and statistical design of any monitoring program (Yoccoz et al. 2001).

## Boat Electrofishing and Species Diversity

Boat electrofishing was the most effective monitoring gear for the majority of species we examined. Our findings are supported by other studies that have found higher species diversity for boat electrofishing than beach seines and other net-based monitoring gears (Feyrer and Healy 2002; Neebling and Quist 2011; Smith et al. 2015). One factor that may contribute to the wider variety of species detected by boat electrofishing is the diversity of habitats the gear can sample. In our study, net-based monitoring gears are often deployed in relatively simple "open-water" habitats free of structure to allow the successful deployment and retrieval of the gear. Boat electrofishing, on the other hand, was conducted across a variety of habitats that included natural structure such as SAV, woody debris, emergent vegetation, and artificial structures such as rock revetment and docks. Structure adds to the complexity of habitats and can serve in a combination of ecological functions such as predation, reproduction, and foraging (Nash et al. 1999; Alexander et al. 2015). Habitat complexity is a driver of biodiversity in aquatic ecosystems (reviewed in Kovalenko et al. 2012). Therefore, the more complex habitats sampled by boat electrofishing in our study likely had a higher species diversity than the relatively simple habitats sampled by net-based gears, which contributed to the larger number of species detected.

## Management Implications

As climate change effects intensify and human development in California continues to expand, more native species in the estuary will likely become imperiled (Moyle et al. 1992; Moyle et al. 2011). This prediction is supported by similar declines in native freshwater and estuarine fishes throughout the world (Reinthal and Stiassny 1991; Jelks et al. 2008; Ferguson et al. 2013). The endangered Delta Smelt has taken the spotlight in the estuary since this endemic species was listed under the federal and California Endangered Species Acts. Yet, the decline of Delta Smelt might have gone undetected if the long-term monitoring programs meant to monitor juvenile Striped Bass (a non-native species) had not been in place several decades ago. Given these trends and the fact that the estuary has already seen the extinction and extirpation of two endemic fish species (e.g., Thicktail Chub [*Gila crassicauda*] and Sacramento Perch [*Archoplites interruptus*]) before any conservation actions could occur (Moyle 2002), it is clear that long-term monitoring has—and will continue to be—essential to conserve the viability of native fishes in the estuary.

We found that boat electrofishing had notable improvements in detection rates for many native species within the upper estuary, including the less-studied Tule Perch (*Hysterocarpus traskii*), Hitch (*Lavinia exilicauda*), Sacramento Blackfish (*Orthodon microlepidotus*), Sacramento Pikeminnow (*Ptychocheilus grandis*), and Sacramento Sucker (*Catostomus occidentalis*; Figures 2 and 4). By implementing a long-term boat electrofishing survey, data collected on the spatio-temporal distribution and habitat associations of species would provide valuable insights into conservation planning. Boat electrofishing surveys can provide data on preferred environmental parameters (e.g., shoreline composition, woody debris, in-water vegetation) to inform habitat-restoration projects. For example, boat electrofishing surveys in the past have been used to quantify the use of shoreline habitat by juvenile Chinook Salmon, and to inform levee improvements in the Sacramento River (reviewed in USFWS 2000) and the Delta (McLain and Castillo 2009). Similar surveys expanded to entire littoral fish assemblages would improve our understanding of how habitat characteristics affect species distribution, and inform our efforts to optimize environmental parameters for native species throughout the estuary.

Boat electrofishing surveys also can indirectly benefit native species by providing additional data on the spatial and temporal distribution of piscivorous fishes for population modeling. In the Pacific Northwest, spatial and temporal variability in predator density are known to be a significant factor in the survival rates of juvenile salmonids (Petersen 1994). Within the estuary, predators are believed to contribute a significant amount to the population dynamics of native species (Nobriga and Feyrer 2007; Cavallo et al. 2013; Buchanan et al. 2018). However, limited data on the distribution of predators have made it difficult to disentangle the effects of predation from other environmental factors (Hankin et al. 2010; Buchanan et al. 2018). Our results suggest that boat electrofishing surveys would significantly improve the monitoring of known piscivorous fishes within the estuary, including Largemouth Bass, Smallmouth Bass (*Micropterus dolomieu*), Brown Bullhead (*Ameiurus nebulosus*), Black Bullhead (*Ameiurus melas*), Channel Catfish (*Ictalurus punctatus*), Striped Bass, and Sacramento Pikeminnow. Improved monitoring of these predator populations would aid in the management and conservation of imperiled native species (e.g., Chinook Salmon, Delta Smelt, and Longfin Smelt [*Spirinchus thaleichthys*]) by providing a better understanding of how predator density, and thus predation risk, changes over time and space, and via management actions within the estuary.

A 2013 review of the DJMFP, the estuary's primary juvenile salmon monitoring program, recommended the use of boat electrofishing to provide a more accurate assessment of juvenile Chinook Salmon numbers in nearshore habitat (IEP 2013). A boat electrofishing study to identify the drivers of occupancy and estimate the catch probability of the Delta's littoral fishes is currently being undertaken by the USFWS' DJFMP and the United States Geological Survey. This new boat electrofishing sampling effort began in 2018, and involves segmented transects that act as spatial replicates. Sites for transects were chosen based on stratified random design, and crucial habitat parameters for the nearshore habitat—such as edge habitat type and relative density of SAV—were collected. Results from this work will be used to design a long-term boat electrofishing survey with a more robust statistical framework to monitor juvenile Chinook Salmon, as well as other fish species found within the littoral habitat of the Delta.

## CONCLUSIONS

Our study demonstrates that long-term monitoring gears are currently limited in their ability to monitor the full suite of species that make up the estuary's rich fish community. One major factor that contributes to this problem is an inability of current gears to survey shallow-water structured habitats that are prevalent throughout the estuary. Currently, efforts are being undertaken to address these concerns by further developing methods to estimate the occupancy and abundance of near-shore fishes throughout these habitats using boat electrofishing. Based on our findings, we recommend that resource managers consider the implementation of a long-term boat electrofishing survey to help them in their long-term conservation planning for fishes within the estuary. In the future, as technology and sampling environments evolve, it will be critical that ecological monitoring programs continue to re-evaluate sampling methods and gears to advance the understanding, management, and conservation of our vital natural resources.

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