

RESEARCH

Examining Retention-at-Length of Pelagic Fishes Caught in the Fall Midwater Trawl Survey

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ABSTRACT

The Fall Midwater Trawl Survey has provided data on aquatic organisms in the San Francisco Estuary for over 5 decades. In 2014–2015, a study was conducted to investigate and quantify the efficiency of this trawl for catching the endangered fish species Delta Smelt (*Hypomesus transpacificus*). In an analysis based on that study, we calculated retention probability—the probability that a Delta Smelt is retained in the cod end of the trawl—as a function of fish length, and fit a selectivity curve that reflected the relationship between size and retention. Here, we return to the same gear efficiency study and further utilize the data set by (1) fitting selectivity curves for three additional pelagic fish species: Threadfin Shad (*Dorosoma petenense*), American Shad (*Alosa sapidissima*), and Mississippi Silverside (*Menidia beryllina*); (2) refitting the selectivity curve for Delta Smelt

to incorporate between-haul variability; and (3) calculating the lengths of 50% and 95% retention in order to characterize and compare the resulting selectivity curves. We also present retention data on age-0 Striped Bass (*Morone saxatilis*), all of which were retained in the cod end. We found that Threadfin Shad, American Shad, and Delta Smelt are 95% retained at 45-, 49-, and 61-mm fork length, respectively. Because data were limited for Mississippi Silverside, American Shad, and age-0 Striped Bass, we used body shape—in conjunction with retention data—to develop hypotheses about selectivity based on whether each species' body shape resembles that of Threadfin Shad, which are more deep-bodied and laterally compressed, or Delta Smelt, which are more fusiform. We also found that retention-at-length was more variable for Delta Smelt than for Threadfin Shad, potentially because length is a good predictor of retention in deep-bodied, laterally compressed fish, whereas maximum girth is a better predictor of retention in fusiform fish.

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KEY WORDS

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INTRODUCTION

Trawl gear efficiency can affect status and trends reporting as well as management decisions related to fish species (Arreguín-Sánchez 1996; Trenkel and Skaug 2005; Miller 2013). If we can quantify this efficiency, we can improve estimates of vital metrics such as abundance and survival, which are important for effective population management (Newman 2008). Gear efficiency is a broad concept that includes all aspects of how well a sampling gear samples an organism of interest. For trawl nets and fishes, the focus is often on gear avoidance (i.e., the ability of a fish to avoid entering the trawl) and gear selectivity (i.e., the ability of the trawl's mesh to retain fish that enter the trawl), both of which can depend on fish size. Gear selectivity is quantified in terms of retention probability, which is defined as the probability of a fish of a given size being retained in the net, conditional on the fish having entered the net (Millar and Fryer 1999). A gear selectivity curve is a function that describes the relationship between retention probability and fish size. Trawl selectivity curves are often fit using data from a covered cod-end study or paired-trawl study, in which case either the trawl cover or one of the paired trawls is assumed to have a retention probability of one (Millar 1992; Millar and Fryer 1999). Newman (2008), for example, fit a gear selectivity curve using data from a covered cod-end study, and demonstrated how the resulting retention probability estimates could be used to improve estimates of fish abundance.

In the San Francisco Estuary, a variety of trawls are used to collect data on many species of management interest, including Chinook Salmon (*Oncorhynchus tshawytscha*) and four fish species that experienced decreases in population size during the Pelagic Organism Decline (POD; Baxter et al. 2007; Sommer et al. 2007), Delta Smelt (*Hypomesus transpacificus*), Longfin Smelt (*Spirinchus thaleichthys*), Threadfin Shad (*Dorosoma petenense*), and Striped Bass (*Morone saxatilis*). However, despite the importance of these trawls in the estuary's monitoring network—and how their efficiencies potentially affect the resulting data sets—local published gear

efficiency evaluations are few (e.g., Newman 2008; Mitchell et al. 2017, 2019).

The Fall Midwater Trawl (FMWT) Survey is a fish monitoring survey that the California Department of Fish and Wildlife has conducted since 1967. Once a month, from September through December, it currently samples 122 stations that extend from San Pablo Bay to the upper estuary (see <https://wildlife.ca.gov/Conservation/Delta/Fall-Midwater-Trawl> for details). The resulting catch data are used to calculate abundance indices, which in turn have provided population trend information used for management purposes (Sommer et al. 2007; USFWS 2008). In the San Francisco Estuary, selectivity analyses have focused largely on Delta Smelt and the open water trawling of the FMWT Survey (Newman 2008; Mitchell et al. 2017), though other trawl nets have also been studied (Mahardja et al. 2017; Mitchell et al. 2019). This is because the FMWT Survey has provided valuable trend data on the endangered Delta Smelt (Sommer et al. 2007; USFWS 2008; Latour 2016) despite the fact that the survey was originally designed to monitor age-0 Striped Bass (Stevens 1977; Stevens and Miller 1983). In particular, a FMWT covered cod-end study was conducted in 2014–2015 to improve our understanding of the trawl's ability to catch Delta Smelt, and to help separate gear selectivity effects from underlying population trends in the data (Mitchell et al. 2017).

Here, we revisit the 2014–2015 FMWT covered cod-end study, and use the data to examine retention-at-length for four additional fish species with the highest total catches: Threadfin Shad, age-0 Striped Bass, American Shad (*Alosa sapidissima*), and Mississippi Silverside (*Menidia beryllina*). We fit selectivity curves for these species (excluding age-0 Striped Bass, all of which were retained in the cod end) and refit the selectivity curve for Delta Smelt (Mitchell et al. 2017) to provide improved estimates of uncertainty, using bootstrapping (Millar and Fryer 1999). Because data were limited for some species as a result of low overall catches, limited length ranges, or both, we used comparative body shape to develop hypotheses about selectivity

that could be tested and refined through future gear-efficiency studies. Our objective for this analysis was to improve our understanding of the efficiency of the FMWT gear, and consequently inform future analyses based on FMWT Survey data. Just as the FMWT Survey has provided critical data on species that extend beyond its original focal species of Striped Bass, we are leveraging data from the FMWT covered cod-end study to provide selectivity results for species that extend beyond Delta Smelt.

MATERIALS AND METHODS

Data Collection

Complete details on the data collection methods for the FMWT covered cod-end gear selectivity study have been published by Mitchell et al. (2017). Here, we give an overview of the methods.

We collected data at two locations in the estuary, one in the lower Sacramento River near Sherman Island and one in the Sacramento Deepwater Ship Channel, in an effort to increase catch numbers and size variation in the species encountered (Figure 2 in Mitchell et al. [2017]). We sampled a total of 5 days between August 2014 and January 2015 (August 21, September 25, October 21, December 2, and January 27) using the trawl from the FMWT Survey and two towing methods: oblique and surface. During an oblique tow, the trawl was deployed to a depth close to the river or channel bottom, using a single boat, and retrieved such that the trawl sampled throughout the water column. During a surface tow, the trawl was deployed behind and between two boats, each of which pulled one of the two bridles attached to the trawl mouth, and towed such that the trawl sampled only the uppermost portion of the water column; a constraining line linked the distal ends of the two bridles, and limited lateral strain on the net mouth, maintaining a normal net-mouth shape (Figure 1 in Mitchell et al. [2017]).

The FMWT Survey uses single-boat oblique tows for routine sampling, but both towing methods were used in this study to compare differences in catch densities of Delta Smelt between the methods, based on the hypothesis that Delta

Smelt are surface-oriented during the fall and winter, and that single boat sampling disturbed the surface strata before the net passed through, potentially reducing catches of surface-oriented species. We attached a 0.25-cm mesh cover to the outside of the 1.3-cm mesh cod end of the trawl (Figure 1 in Mitchell et al. [2017]) to catch fish that passed through the cod-end mesh and that would not be retained under normal sampling conditions.

Variable numbers of replicate tows were conducted by date and location (Table 1). We identified and enumerated all fish caught in the cod end and cover, and measured all fish in the cover (i.e., those that slipped through) and most fish in the cod end for fork length to the nearest millimeter. Periodically, large catches of Threadfin Shad in the cod end required that sub-samples of 50 to 200 individuals be measured, and the remainder counted.

Retention Analysis

Following the general methods described by Millar and Fryer (1999), we used logistic regression models to fit selectivity curves for Threadfin Shad, American Shad, and Mississippi Silverside. For a given species, let $y_{i,j,codend}$ be the number of length- L_j fish of that species caught in the cod end during tow i , and let $y_{i,j,cover}$ be the number of length- L_j fish of that species caught in the cover during tow i . We defined the proportion of length- L_j fish caught in the cod end during tow i as $p_{i,j} = y_{i,j,codend} / (y_{i,j,codend} + y_{i,j,cover})$, and used a logit link function to model this proportion as a function of fork length. We considered the full model:

$$\text{logit}(p_{i,j}) = \log_e \left(\frac{p_{i,j}}{1 - p_{i,j}} \right) = \beta_0 + (\beta_1 + u_{1,i})L_{i,j} + \text{offset}(\log_e(q_i)), \quad (1)$$

where β_0 and β_1 are fixed-effect parameters, and $u_{1,i} \sim N(0, \sigma^2)$ are random effects that account for between-tow variability in slope. Additionally, we incorporated sub-sampling fraction, q_i , as an offset when not all individuals of the species of interest were measured for length. We calculated

Table 1 Summary of effort and catch of Threadfin Shad (TFS), American Shad (AMS), Delta Smelt (DSM), Mississippi Silverside (MSS), and age-0 Striped Bass (SB0) from the covered cod-end study by date, location (LSR= Lower Sacramento River; SDWSC= Sacramento Deep Water Ship Channel), tow method, and gear type (cod end or cover)

Date	Location	Tow method	Total tows	Total volume (m ³)	Gear type	Total catch				
						TFS	AMS	DSM	MSS	SB0
Aug 21, 2014	LSR	Oblique	3	16,620	Cod end	2	31	3	0	0
					Cover	0	2	18	0	0
Aug 21, 2014	LSR	Surface	3	28,738	Cod end	205	109	20	0	0
					Cover	20	0	55	0	0
Aug 21, 2014	SDWSC	Oblique	1	4,959	Cod end	1	2	0	0	1
					Cover	3	0	1	0	0
Aug 21, 2014	SDWSC	Surface	1	7,614	Cod end	18	19	4	0	0
					Cover	24	0	116	5	0
Sep 25, 2014	LSR	Oblique	3	14,576	Cod end	5	4	0	0	0
					Cover	0	0	13	0	0
Sep 25, 2014	LSR	Surface	2	7,678	Cod end	56	31	5	0	0
					Cover	0	0	27	0	0
Sep 25, 2014	SDWSC	Oblique	3	13,620	Cod end	96	3	0	2	0
					Cover	16	0	0	12	0
Sep 25, 2014	SDWSC	Surface	3	11,232	Cod end	70	18	0	3	0
					Cover	56	1	1	6	0
Oct 21, 2014	LSR	Oblique	2	8,326	Cod end	14	2	0	0	0
					Cover	0	0	1	0	0
Oct 21, 2014	LSR	Surface	4	14,862	Cod end	95	49	0	0	2
					Cover	0	0	5	0	0
Oct 21, 2014	SDWSC	Oblique	3	12,440	Cod end	40	8	0	0	0
					Cover	2	0	0	1	0
Oct 21, 2014	SDWSC	Surface	3	6,473	Cod end	248	52	0	0	0
					Cover	6	0	0	2	0
Dec, 2 2014	LSR	Surface	6	35,083	Cod end	2,063	55	4	0	3
					Cover	3	0	8	0	0
Dec, 2 2014	SDWSC	Surface	2	11,694	Cod end	493	39	3	2	2
					Cover	15	0	0	1	0
Jan 27, 2015	LSR	Surface	20	116,947	Cod end	100	6	7	0	13
					Cover	0	0	1	0	0
Total						3,651	431	292	34	21

q_i as the ratio of the proportion of fish from the cod end that were measured to the proportion of fish from the cover that were measured. We excluded the random effects term, $u_{1,i}$, if catches were prohibitively low. We investigated the possibility of including random effects in the intercept, as well as the possibility of including tow method (as a categorical variable), to test for differences in retention between surface and oblique tows, but found that we did not have sufficient data.

We fit all models using the *selfisher* package (Brooks 2019) in R (R Core Team 2020). We used the double-binomial bootstrap method available in *selfisher* to calculate 95% pointwise confidence bands for the mean selectivity curves. This method incorporates between-tow variability by first resampling tows with replacement, then, for each length class, using a binomial distribution to simulate the number of fish caught in the cod end (using the total number of observed fish in that haul as the total, and the observed proportion of fish in the cod end in the original data as the probability of success).

In addition to fitting models for Threadfin Shad, American Shad, and Mississippi Silverside, we re-fit the Delta Smelt model presented by Mitchell et al. (2017),

$$\text{logit}(p_{i,j}) = \gamma_0 + \gamma_1 L_{i,j} + \gamma_2 L_{i,j}^2 + \gamma_3 L_{i,j}^3 + \text{offset}(\log_e(q_i)), \quad (2)$$

with *selfisher*, keeping the individual tow structure of the data rather than pooling across tows. As with the other species, we calculated 95% pointwise confidence bands for the mean selectivity curve using the double-binomial bootstrap approach.

To characterize and compare selectivity curves for the different species, we calculated the length of 50% retention, l_{50} , and the length of 95% retention, l_{95} , for each fitted curve. We calculated corresponding standard errors using the same bootstrap approach described above.

To demonstrate the effects of selectivity on historical data, we calculated estimates of the number of Threadfin Shad that escaped the cod end during the FMWT Survey between 1995 and 2015. We first calculated the total number of Threadfin Shad caught by length and month, adjusting length frequencies to account for unmeasured fish as described in Appendix A. We then divided each total by the corresponding model-predicted retention probability to produce an estimate of the total number of fish-at-length that entered the trawl. We estimated losses by subtracting observed catch totals from estimated totals that entered the trawl. We restricted this analysis to the range of lengths used to fit the selectivity model.

RESULTS

Threadfin Shad had the most complete retention data set, with a total catch of 3,651 (Table 1) and a pattern of increasing retention-at-length between roughly 24 and 50 mm (Figure 1C). Though some data fall outside of this pattern (e.g., see points below 40 mm in Figure 1C with observed retention equal to one), these points are based on sample sizes of one or two individuals at length. All Threadfin Shad with lengths greater than or equal to 46 mm were retained in the cod end. Delta Smelt also show an increase in retention-at-length between 33 and 65 mm, with high variability between roughly 40 and 60 mm (Figure 1B). Although total catch of Mississippi Silverside (34 individuals) was low, the data suggest that retention increases over the length range 42 to 72 mm (Figure 1A). Over 99% percent of American Shad (428 out of 431 total) were retained in the cod end, including all individuals with lengths greater than or equal to 51 mm. The data indicate that retention may drop below one in the lower end of the observed length range (Figure 1D), though as with Mississippi Silverside, limited catches inhibit our ability to determine the shape of the retention curve. All age-0 Striped Bass (21 total between 73 and 160 mm) were retained in the cod end (Figure 1E).

We fit the full model (Equation 1) for Threadfin Shad, and the model without random effects for

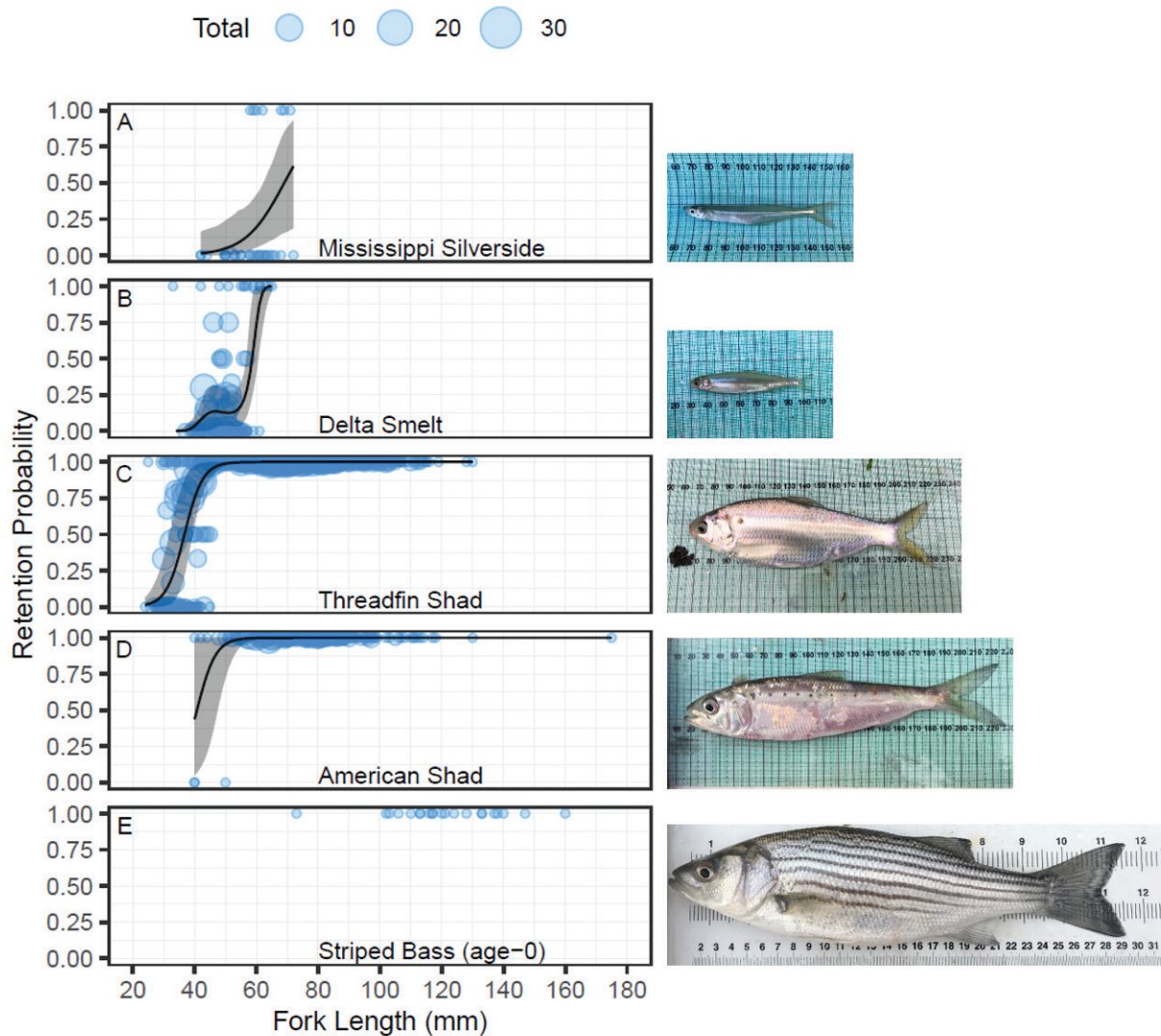


Figure 1 Results from gear selectivity analysis (*left*) and photos comparing body shapes and sizes (*right*) for (A) Mississippi Silverside, (B) Delta Smelt, (C) Threadfin Shad, (D) American Shad, and (E) age-0 Striped Bass. Graphs show observed retention rates calculated by tow and fork length (*circles*), fitted selectivity curves (*lines*), and 95% pointwise confidence bands (*gray shading*). Circle size reflects total number of fish-at-length caught in the cod end and cover combined. Photos are scaled to reflect relative fork lengths. Actual fork lengths are (A) 87 mm, (B) 72 mm, (C) 136 mm, (D) 175 mm, and (E) 270 mm. Photo credits: Jacob Stagg, US Fish and Wildlife Service.

American Shad, which had limited catches in the lower length range where observed retention was less than one, and for Mississippi Silverside, which had limited catches overall. Sub-sampling fractions (q_i) for Threadfin Shad ranged from 0.628 to 1. Sub-sampling fractions for Delta Smelt were all one, with the exception of a single tow in which one of the two individuals caught in the cod end was not able to be measured. We were

unable to fit a selectivity curve for age-0 Striped Bass because retention was uniformly one.

Selectivity model parameter estimates and estimated lengths of 50% and 95% retention are summarized in [Table 2](#).

Estimated losses of Threadfin Shad as a result of size selectivity decrease from September

Table 2 Estimates of selectivity model parameters and lengths of 50% and 95% retention for (A) Threadfin Shad, American Shad, Mississippi Silverside, and (B) Delta Smelt. Bootstrap standard errors are shown in parentheses. The estimated length of 95% retention for Mississippi Silverside falls outside of the range of observed lengths and is therefore not shown.

A. Parameter estimates for Threadfin Shad, American Shad, and Mississippi Silverside					
Species	β_0	β_1	σ	l_{50}	l_{95}
Threadfin Shad	-12.434 (27.3115)	0.338 (0.6748)	0.044 (0.2890)	36.738 (1.9500)	45.437 (2.4544)
American Shad	-13.491 (12.8478)	0.331 (0.4586)	—	40.765 (9.1341)	49.662 (11.5032)
Mississippi Silverside	-10.917 (5.2657)	0.158 (0.1099)	—	69.040 (79.8612)	—

B. Parameter estimates for Delta Smelt						
Species	γ_0	γ_1	γ_2	γ_3	l_{50}	l_{95}
Delta Smelt	-1.923 (0.6367)	-0.282 (1.2075)	0.367 (3.2045)	1.898 (3.5381)	58.645 (1.4322)	61.893 (1.6000)

to December as fish grow out of the range of imperfect retention (Figure 2). Estimated losses are effectively zero for lengths greater than or equal to 58 mm, regardless of the original number of individuals caught, which ranged from 1 to 1,157.

DISCUSSION

The ability of a fish to escape through the mesh of a trawl, either actively or passively, is largely a function of fish body depth or girth, but fish length is commonly used in size selectivity analyses because (1) it is positively correlated with height and girth, (2) it is easier to measure than height or girth, and (3) it is often the only measurement taken other than count. Although we were not able to determine the complete shape of the selectivity curve for Mississippi Silverside as a result of the lack of larger fish, or for American Shad and age-0 Striped Bass as a result of the lack of smaller fish, patterns emerge when we examine all five species together and take body shape into consideration along with fork length.

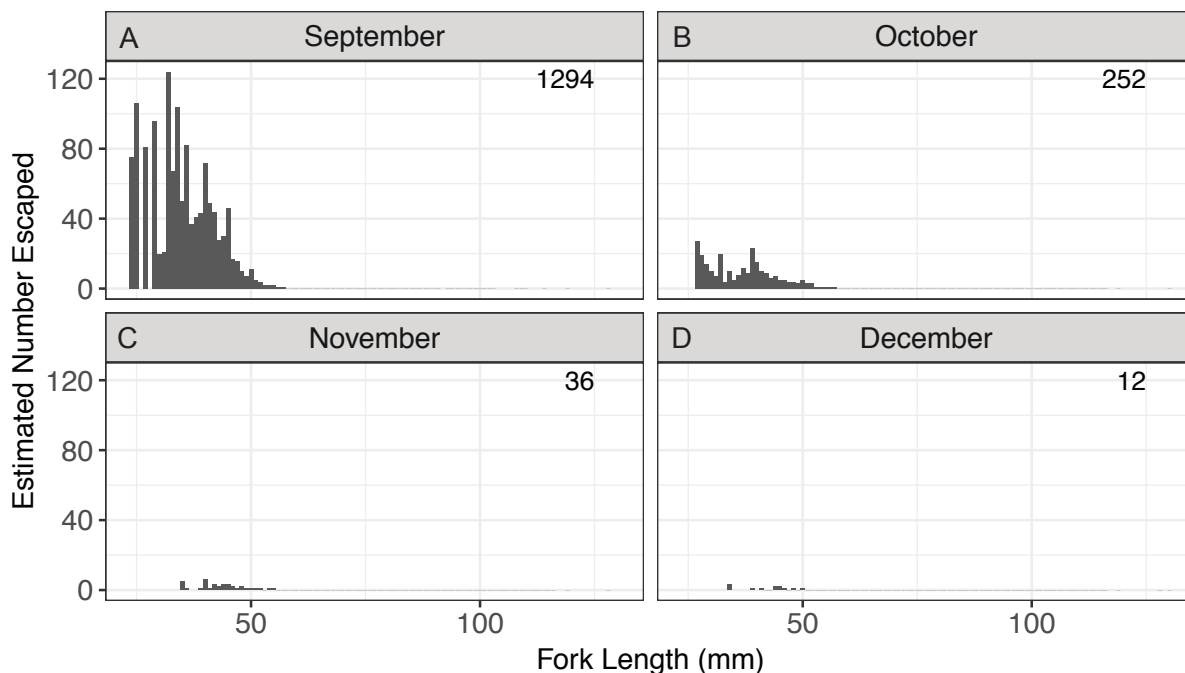


Figure 2 Estimated losses of Threadfin Shad in the Fall Midwater Trawl Survey (1995–2015), by length and month, based on model-predicted retention. Totals by month are shown in the upper right corner of each panel.

Predicted retention at a given fork length is lower for Delta Smelt than for Threadfin Shad, and both l_{50} and l_{95} for Delta Smelt are over 1.3 times that of Threadfin Shad. This is likely because Delta Smelt are generally more fusiform while Threadfin Shad are more deep-bodied. Delta Smelt also exhibit a high level of variability in retention compared to Threadfin Shad, particularly in the 40- to 60-mm range. While this could be because catches were low or between-tow variability in selectivity was high for Delta Smelt compared to Threadfin Shad, we postulate that these differences in retention are also attributable, in part, to differences in body shape. Because Threadfin Shad are considerably more deep-bodied than Delta Smelt, a Threadfin Shad between 40 and 60 mm is less likely to fit through the 1.3-cm cod-end mesh of the FMWT trawl than a Delta Smelt of the same length. This could be because body depth-at-length (or girth-at-length) is less variable in Threadfin Shad than in Delta Smelt, though we were not able to formally investigate this hypothesis with data from our study.

Based on similarities in overall size and body shape, we hypothesize that the true selectivity curves for Mississippi Silverside and Delta Smelt are similar, and that the relatively gentle slope of the fitted curve in [Figure 1A](#) (compared to both the Threadfin Shad and Delta Smelt curves) is the result of very low catches of Mississippi Silverside. Because they are particularly streamlined compared to Delta Smelt ([Figure 1](#)), we hypothesize that the true values of l_{50} and l_{95} for Mississippi Silverside are indeed greater than those of Delta Smelt, as predicted by our analysis.

American Shad and Threadfin Shad exhibit similar patterns in empirical retention ([Figure 1](#)), and the two species appear similar in body depth at length; thus, we hypothesize that the complete selectivity curve for American Shad is similar to that of Threadfin Shad but with slightly higher values of l_{50} and l_{95} (i.e., the American Shad curve would sit to the right of the Threadfin Shad curve). Since age-0 Striped Bass appear more deep-bodied at length than Delta Smelt, we hypothesize that the age-0 Striped Bass

selectivity curve falls between those of Delta Smelt and Threadfin Shad.

Based on FMWT Survey data from 1995–2015 ([Appendix A](#)), Threadfin Shad and Delta Smelt with lengths that fall below the point of 95% retention have historically been present in the estuary during part or all of the FMWT Survey (September–December; [Tables A1–A2](#)). This is certainly true for Mississippi Silverside as well ([Table A3](#)), though we were not able to present an estimate of l_{95} this species. The presence of American Shad or age-0 Striped Bass with lengths below l_{95} was limited overall in our samples in 2014–2015, but from year to year likely depends on spawning timing, survival, and growth rates. For example, American Shad and age-0 Striped Bass < 50 mm were not common in the estuary in fall 2014, but such small American Shad and Striped Bass (to a lesser degree) have been common in the fall of other years ([Tables A4–A5](#)), particularly years with high spring flow with protracted spawning and good summer survival of fish hatched late in the season (e.g., 2011; see http://www.dfg.ca.gov/delta/data/townet/Length_Frequency.asp). The presence of fish below l_{95} in FMWT catch, given that those fish are present in the population, likely results from a combination of how fish contact the cod end (i.e., those contacting at increasing angles from head-on stand an increasing probability of being pressed laterally on the mesh and retained) and how many other fish and how much debris were present that blocked mesh openings ([Mitchell et al. 2017](#)).

Many of the catches used in our selectivity analysis came from surface tows rather than oblique tows. The question of why surface tows tend to produce higher catch densities of these species than oblique tows remains somewhat open ([Mitchell et al. 2017, 2019](#)). However, the answer appears to involve systematic differences in catchability between surface and oblique tows, consistent patterns in the vertical distribution of fish across species, or a combination of the two. In particular, the presence of the boat may cause fish that are located near the water surface to move out of the path of the trawl during a

single-boat oblique tow. If this is the case, then boat-avoidance behavior may be less problematic during a two-boat surface tow, when the trawl is not directly behind either boat (Mitchell et al. 2017). These kinds of questions about where fish are located, how best to sample in the future, or how to adjust results from current sampling so we can calculate minimally biased estimates of fish densities are important, since these densities are often used to gain insight on population status and trends, which in turn influence Endangered Species Listing decisions and water management in the Sacramento–San Joaquin Delta (e.g., USFWS 2008).

CONCLUSIONS

Here, we extended an existing gear selectivity study on Delta Smelt to include four other pelagic fishes, including two additional POD species (Threadfin Shad and Striped Bass). We found that 95% retention of Threadfin Shad, American Shad, and Delta Smelt in the FMWT cod end occurs around 45-, 49-, and 61-mm fork length, respectively. Although sample sizes and length ranges were limited for Mississippi Silverside, American Shad, and age-0 Striped Bass, we developed informed hypotheses about their selectivity curves by classifying each species as either more Threadfin Shad-like or Delta Smelt-like according to body size and shape.

Our selectivity analyses could be improved by increasing the number of fish in length classes that currently have small sample sizes, including a sample size of zero, so that we can fit complete and accurate selectivity curves. For American Shad and Striped Bass, this would involve initiating sampling in summer, when smaller individuals make up the majority of the populations, and for Mississippi Silversides it would likely involve sampling later in winter and into the following spring when adults approach maximum size. Sampling close to the shoreline and within the channel margin habitat would also improve results, since Mississippi Silversides are common along the shoreline (Brown and May 2006; Brown and Michniuk 2007).

The results from these selectivity analyses can be applied to catch-at-length data to provide improved population abundance indices or absolute abundance estimates (Newman 2008; Mitchell et al. 2017; Polansky et al. 2019). As suggested by our comparison of oblique and surface tows, a better understanding of vertical and lateral fish distribution would also aid in constructing population metrics for these pelagic species, though see Bennett et al. (2002) and Sommer et al. (2011). Projects like Smelt Cam, acknowledging potential boat effects, can help answer questions about fish distribution and fish behavior that will inform our understanding of other gears such as FMWT, and lead to improved data analyses, and, consequently, better fisheries management.

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