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RESEARCH

A Covered Cod-End and Tow-Path Evaluation of Midwater Trawl Gear Efficiency for Catching Delta Smelt (*Hypomesus transpacificus*)

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ABSTRACT

For nearly 50 years, the California Department of Fish and Wildlife has used a midwater trawl to intensively monitor fish populations in the San Francisco Estuary during the fall, sampling over 100 locations each month. The data collected have been useful for calculating indices of fish abundance, and for detecting and documenting the decline of the endangered fish species Delta Smelt (*Hypomesus transpacificus*). However, efforts to calculate estimates of absolute abundance have been hampered by the lack of information on gear efficiency, in particular, questions about contact selectivity and the effect of tow method on catches. To answer these questions, we conducted a study that used a covered cod end on a net towed either near the surface, referred to as a surface tow, or throughout the water column, referred to as an oblique tow. We fit a contact selectivity model to estimate the probability that a Delta Smelt that has come into contact with the net is retained in the cod end of the net conditional on its body length. We found that full retention of Delta Smelt occurred at around 60-mm fork length. Delta Smelt catch densities for the surface tows were an order of magnitude greater than densities in the oblique tows, suggesting a surface orientation at the sub-adult life stage. These results represent an important step in being able to calculate absolute abundance estimates of the Delta Smelt population size using decades' worth of monitoring data.

KEY WORDS

Contact selectivity, retention, fish availability, abundance estimation, *Hypomesus transpacificus*

INTRODUCTION

Long-term fish monitoring surveys such as the Fall Midwater Trawl (FMWT) Survey provide information on temporal changes in the relative abundance and spatial distribution of many fish species in the San Francisco Estuary (Feyrer et al. 2007; Sommer et al. 2007a; Sommer and Mejia 2013). The data collected by these surveys are used extensively for research and management purposes, with particular attention being given to species-specific indices of abundance that reflect significant decreases in the population size of several pelagic fish species in recent decades (Sommer et al. 2007b). Among these species, the collapse of the Delta Smelt (*Hypomesus transpacificus*) has been of especially high concern (Bennett 2005).

Though indices of abundance are informative and relatively simple to calculate, being able to generate estimates of absolute abundance for fish species of interest in the estuary is desirable. Absolute abundance estimates from different surveys at different times of year, targeting different life stages, could be integrated into analyses designed to assess the effects of management actions and environmental conditions on population dynamics, and, in the case of endangered or threatened species, to assess population recovery (Somerton et al. 1999; Methot and Wetzel 2013). In the case of Delta Smelt, our underlying goal is to use abundance-based models to help answer increasingly important management questions about the current population size and the proportion of the population that is killed by water export operations in the estuary (Newman 2008).

Naïve estimates of abundance can be calculated by multiplying average catch densities from one or more surveys by estimates of the volume of water occupied by fish. However, such estimates ignore differences in the ability of each survey to catch different species and sizes of fishes, and it is important for an analysis of population dynamics to account for such differences (Pollock et al. 2002). The number of fish caught by a particular fishing gear is affected by two factors (Crone et al. 2013): (1) fish availability, i.e., the presence or absence of fish in the water volume sampled, and (2) contact selectivity, the probability that the gear will catch a fish of a particular size conditional on it being available to the gear, i.e., conditional on it being present in the sampled volume. Fish availability is affected by the horizontal and vertical distribution of the fish, and how and where the gear is deployed (e.g., tow depth). Contact selectivity is affected by fish behavior (e.g., net avoidance), fish size, and the physical characteristics of the sampling gear (e.g., net mesh size).

In this paper, we present an analysis of data from a covered cod-end study designed to provide information on the efficiency of the gear used in the FMWT to catch Delta Smelt. Our objectives for this study were to (1) directly estimate contact selectivity of the FMWT cod end for Delta Smelt over a range of fish lengths, and (2) investigate the effect of tow method on the resulting catches. We address objective (1) by fitting logistic contact-selectivity models describing the probability that a Delta Smelt is retained in the trawl cod end as a function of its fork length. We also fit selectivity models that include total organism (fish and invertebrate) biomass in the cod end as a predictor variable, because a large biomass may result in Delta Smelt being trapped and retained when they otherwise could have escaped through the cod-end mesh. We compare our selectivity results to those from an earlier FMWT covered cod-end study to borrow strength from the two studies which were similar but not identical. We discuss examples of how selectivity estimates can be applied to catch models of varying complexity. We address objective (2) by comparing Delta Smelt catch densities from surface tows, where the net is towed in the upper portion of the water column, and oblique tows, where the net is dropped near the bottom and brought up to the surface along an inclined path, and by discussing potential causes for observed differences in density that relate to fish behavior and sampling procedures. We also look for systematic differences in fork-length distributions between surface and oblique tows that could indicate age- or size-dependent depth preferences in Delta Smelt.

MATERIALS AND METHODS

Field Data Collection

We sampled with the midwater trawl net used in the FMWT Survey (*https://www.wildlife.ca.gov/Conservation/Delta/Fall-Midwater-Trawl*), which has mouth dimensions of 3.7 m by 3.7 m, and consists of nine sections of decreasing mesh size from 20-cm stretch mesh near the mouth to 1.3-cm stretch mesh at the cod end (Figure 1). We placed a cover with 0.25-cm woven mesh, similar to that of the Summer Townet (TNS) cod end (*https://www.wildlife.ca.gov/Conservation/Delta/Townet-Survey*), on the outside of the 1.3-cm cod-end mesh. The cover material attached at the junction of the 1.3-cm and 2.5-cm meshes and its design provided a >5-cm gap between itself and the cod-end material, as well as doubling the pore space relative to the cod-end material. Thus, the cover design allowed unimpeded passage from the cod end to the cover for fish that fit through the

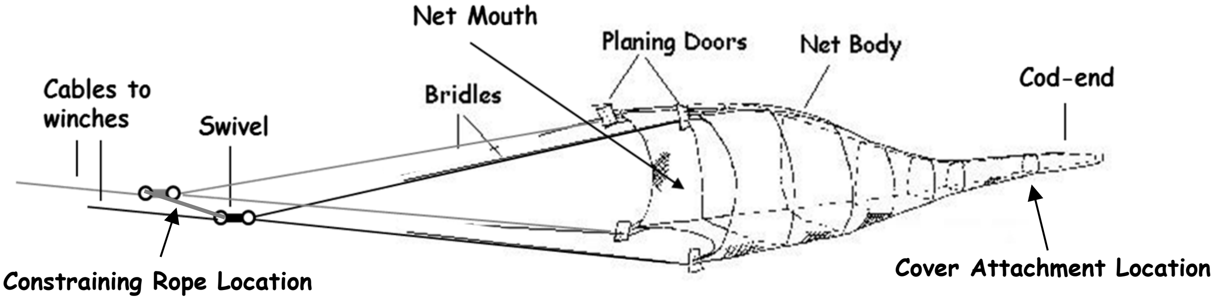

Figure 1 Diagram of the FMWT gear and cover used in the 2014–2015 covered cod-end study

cod end, and minimized any additional back pressure (i.e., beyond any from the cod-end mesh itself) that might help fishes to swim forward in the net and move through larger meshes. We used the cover throughout the study.

We sampled on five dates between August 2014 and January 2015, and at two sites in the Sacramento River system expected to have relatively high Delta Smelt densities (Table 1). The first sampling site was located on the lower Sacramento River downstream of Decker Island (Figure 2), where the channel is wide (800 to 900 m) and relatively straight, flowing northeast to southwest. Water depth varies across the channel, dropping rapidly with distance off the northwest bank and into a >9 meters deep by 60+ meters wide shipping channel that runs the mid-line of the northwestern half of the channel. Outside the shipping channel to the southeast, the depth remains in the 7- to 9-m range before sloping up sharply approaching the bank. Tidal flow during fall low-outflow conditions measured 10 km upstream at Rio Vista ranged from just less than 2,832 $m^3 \cdot s^{-1}$ (100,000 $ft^3 \cdot s^{-1}$) to slightly more than 3,540 $m^3 \cdot s^{-1}$ (125,000 $ft^3 \cdot s^{-1}$) across the spring-neap cycle (California Data Exchange, Sacramento River at Rio Vista station, SRV). The TNS Survey caught Delta Smelt near this location throughout the summer (June to August) 2014, and in August it was the only location at which more than one Delta Smelt was caught. The second site was in the Sacramento Deepwater Ship Channel (SDWSC), about 30 km upstream of Rio Vista. The SDWSC measures about 200 m across, and possesses the same relatively straight channel and 60-m-wide dredged channel running its mid-line as the lower Sacramento River, but this channel is oriented close to north–south, and the bottom outside the shipping channel varies between 5 to 7 m deep before sloping up sharply at each bank. Tidal flow during fall months measured at the lower end of the SDWSC ranges from about 354 $m^3 \cdot s^{-1}$ (12,500 $ft^3 \cdot s^{-1}$) on a neap flood tide to over 878 $m^3 \cdot s^{-1}$ (31,000 $ft^3 \cdot s^{-1}$) on a spring ebb (California Data Exchange, SDWSC station, DWS). Like the first sampling site, this site was chosen because it produced relatively high Delta Smelt

Table 1 2014–2015 FMWT covered cod end study sampling design. *Lower Sac* and *SDWSC* are used to represent the sampling areas in the lower Sacramento River and Sacramento Deep Water Ship Channel, respectively.

(A) Sets of paired oblique and surface tows

Date	Location	No. of sets
Aug 21, 2014	Lower Sac	3
Aug 21, 2014	SDWSC	1
Sep 25, 2014	Lower Sac	2
Sep 25, 2014	SDWSC	3
Oct 21, 2014	Lower Sac	2
Oct 21, 2014	SDWSC	3

(B) Individual oblique tows

Date	Location	No. of tows
Sep 25, 2014	Lower Sac	1

C) Individual surface tows

Date	Location	No. of tows
Oct 21, 2014	Lower Sac	2
Dec 2, 2014	Lower Sac	6
Dec 2, 2014	SDWSC	2
Jan 27, 2015	Lower Sac	20

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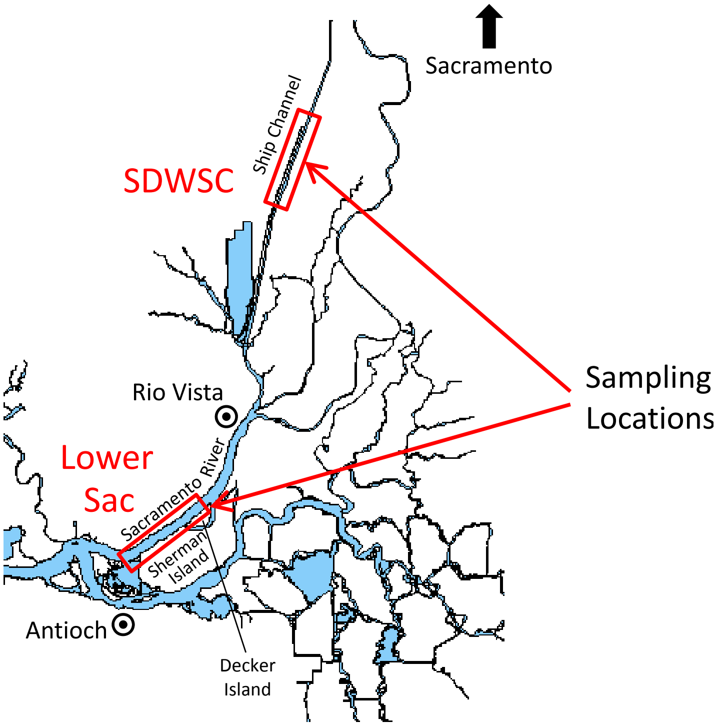

Figure 2 Sampling areas (rectangles) in the lower Sacramento River (Lower Sac) and the Sacramento Deep Water Ship Channel (SDWSC) for the 2014–2015 covered cod end study.

catches during the TNS Survey in summer 2014. Additionally, increased Delta Smelt densities are associated with increased turbidity levels (Feyrer et al. 2007), and this site had higher turbidity levels than other sites within the shipping channel. We chose two widely separated sampling locations, hoping to encounter a larger range of Delta Smelt sizes. Within a sampling site, we chose tow locations to target local areas of increased salinity (0.4 ppt) and high turbidity, as determined by the tide stage (spring or neap) at the time of sampling.

Two methods of towing were used: oblique and surface. Oblique tows followed the standard FMWT Survey protocol of dropping the net so that it was close to but not contacting the river bottom, and retrieving it back up through the water column at an oblique angle relative to the water surface, using a single boat. We conducted surface tows by mimicking the Spring Kodiak Trawl (SKT) Survey to potentially increase Delta Smelt catches; we towed the trawl between two boats using a relatively short length of tow cable to keep the net in the uppermost section of the water column for the duration of the tow. During surface tows, we affixed a constraining rope at the ends of the 30.5-m (100-ft) bridle to maintain net-mouth shape and bridle separation equivalent to deployment from a single boat (see Figure 1). This also ensured that the force of the two boats towing slightly away from one another did not change mouth dimensions or collapse the net. We did not add additional floatation to the nets on surface tows, so the net typically dropped briefly in the water column as we transferred lines from the tow-boat to the chase-boat, but the net returned rapidly to the surface when towing began.

In August and September, we paired every oblique tow with a surface tow except for one (see Table 1). We conducted paired tows close together in time and in space, after randomly determining the order of the two tows for each pair. The average amount of time between the end of the first tow and the start of the second was 14.6 minutes. We conducted paired tows between one and three times per sampling date and location. We changed the tow location within a sampling site between pairs to cover a wider area and increase the probability of catching Delta Smelt. In October, we conducted two sets of paired tows along with two additional surface tows. In December and January, we conducted only surface tows because of low Delta Smelt catches by oblique tows in the previous months, as well as low overall catches by the regular FMWT Survey in fall 2014. We needed sufficient catches of Delta Smelt in the length range above 55 mm to model retention in the upper length range, and by this point surface tows appeared much more likely to result in Delta Smelt catches than oblique tows.

After we completed each tow, we placed the contents of the cod-end cover in one water-filled tub and the contents of the standard cod end in another. We processed fish from the cover first. We identified, enumerated, and measured all fish species for fork length to the nearest millimeter. We recorded the following covariates immediately before each tow: Secchi depth (cm), surface specific conductance ($\mu S \cdot cm^{-1}$ corrected to 25 °C), surface water temperature (°C), surface water turbidity (ntus), water depth (ft), tide code (high slack, ebb, low slack, or flood), and tow direction (with current, against current, neither/indeterminate). We recorded specific conductance and water temperature at the bottom of the water column before oblique tows only.

We conducted a total of 43 tows in the lower Sacramento River and a total of 16 tows in the SDWSC. Of the 59 total tows, 44 were surface tows and 15 were oblique. Tows were made during daylight hours and lasted an average of 9.6 minutes. Sampling was scheduled to occur predominantly during flood tides, but generally extended into the ebb tide as well. We made the majority of tows against the prevailing current on ebb or flood tides.

Contact Selectivity Analysis

Length-Only Model

The contact selectivity or retention, p, of a fishing gear represents the probability that a fish of a specific size is retained by the gear, given that the fish made contact with the gear, i.e., the fish was in a portion of the water that the gear swept through. Observed retention of the FMWT cod end for Delta Smelt with fork length was calculated as:

$$\hat{p}(L) = \frac{y_{codend}(L)}{y_{codend}(L) + y_{cover}(L)}, \qquad (1)$$

where $y_{codend}(L)$ and $y_{cover}(L)$ are the total numbers of length L Delta Smelt caught in the cod end and cover, respectively, across all tows.

Using methodology developed by Millar (1992), we modeled contact selectivity of the cod end as a function of fork length. An assumption of the method is that selectivity of the cover mesh is one for all Delta Smelt in the population at the time of sampling so that no individuals are able to escape through the cover. This assumption is reasonable because Delta Smelt are too big to go through the cover mesh during late summer/early fall (Bennett 2005). Because catches were low, we pooled data across dates, locations, and replicate tows. We treated each Delta Smelt caught in the study as a Bernoulli trial, defined retention in the cod end to be a successful outcome, and modeled the logit of the retention probability as a cubic function of fork length. We fit the maximal model, $\text{logit}(p(L)) = \beta_0 + \beta_1 L + \beta_2 L^2 + \beta_3 L^3$, and all hierarchical nested models (Peixoto 1990) using the GLM function in the R programming environment (R Core Team 2015), and compared the models using AIC (Burnham and Anderson 2002). We used the ANOVA function in R to compare competing models. To reduce multicollinearity, we centered and scaled fork lengths (by subtracting the mean, and by dividing by the standard deviation, respectively), before we fit the model.

Length–Biomass Model

We also fit a second set of models that included both Delta Smelt fork length and total organism (fish and invertebrate) biomass in the cod end as predictors for retention. We refer to these as length–biomass models to distinguish them from the length-only models that regress against length but not biomass. We defined total organism biomass as the mass (g) of all organisms retained in the cod end of the trawl during a tow. We hypothesized that increased amounts of biomass would lead to higher observed retention probabilities because organisms would block the cod end and prevent Delta Smelt from escaping. By using organism mass, we were able to account for both the number and size of organisms caught in the cod end. For example, a large number of relatively large organisms could potentially block a greater area of mesh and affect retention more than the same number of relatively small organisms. We estimated individual fish masses from measured fork lengths using species-specific length–mass relationships developed through a combination of original work conducted by CDFW and existing literature (Gartz 2004; Kimmerer et al. 2005). All fish length–mass relationships were based on wet mass except those for Shimofuri Goby (*Tridentiger bifasciatus*) and Mississippi Silverside (*Menidia audens*), which were based on formalin-preserved specimens. A length–mass relationship was not available for Wakasagi (*Hypomesus nipponensis*), so we substituted the relationship for Longfin Smelt (*Spirinchus thaleichthys*). Unidentified fish larvae were assumed to be *Tridentiger* gobies. When individual fish were not measured for size, we substituted the mean length of all other individuals of that species in the same tow. We calculated shrimp and jellyfish masses using historical data because we counted invertebrates during this study but did not measure them for size. Details on these calculations are available in Appendix A.

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Let B represent the total organism biomass in the tow during which a given Delta Smelt was caught. The maximal length–biomass model contained polynomial length terms, a linear biomass term, and interactions between length and biomass: $\mathrm{logit}(p(L,B)) = \alpha_0 + \alpha_1 L + \alpha_2 L^2 + \alpha_3 L^3 + \alpha_4 B + \alpha_5 LB + \alpha_6 L^2 \mathrm{B} + \alpha_7 L^3 B$. We fit the maximal model and all hierarchical nested models using the same procedure described for the length-only models. We centered and scaled length and biomass before we fit the model.

Comparison of 1991 and 2014–2015 FMWT Selectivity Studies

In 1991, the CDFW conducted a selectivity study in which a cover was placed around the 1.3-cm mesh section and the 2.5-cm mesh section of the FMWT net (Sweetnam and Stevens 1993). Newman (2008) used data from the 1991 study to model the combined selectivity of the two sections using a linear logit selectivity curve. We noticed that although the resulting curve captures the pattern of increased retention with increased length, it does not fit the data as well as might be expected. In particular, the curve under-predicts retention in the range above 70 mm (see Figure 5 in Newman [2008]). We investigated whether the flexibility of a higher-order polynomial logit model would provide a better fit to the 1991 data by fitting length-only selectivity curves using the same set of candidate models and model-fitting procedure described for the 2014–2015 study. Length–biomass models were not able to be fit for the 1991 study because total catch data were not available.

There was one additional difference between the model fit by Newman and the models we fit as part of this analysis. Newman used length frequencies calculated from a histogram published by Sweetnam and Stevens (1993) because raw length data from the 1991 study were not available. We recently discovered an unpublished memorandum by Sweetnam that contained the same length–frequency data except with a different length-binning scheme than the one used by Newman (1991 memorandum by D. Sweetnam, unreferenced, see “Notes”). We chose to fit length-only selectivity models using the binning scheme reflected in the memo, because it is presumably more likely to reflect the true distribution of the raw length data. For a comparison of the two binning schemes, see Table 4 in this document and Table 1 in Newman (2008).

Tow Method Analysis

We investigated the effect of tow method on Delta Smelt catches in two ways. First, we modeled catch as a function of tow method, as well as date and sampling location, using a generalized linear model. Both oblique and surface tows sample near the water surface, but oblique tows also sample deeper in the water column. Any Delta Smelt located deeper in the water column are therefore available to oblique tows, but not to surface tows. Boat avoidance behavior - and the use of one boat versus two boats - may also impact the ability of each tow method to catch Delta Smelt. As a simple example, suppose the net is being towed behind one boat, and fish move laterally out of the path of the approaching boat; then these fish, which would have been available to the net without the effects of the boat, are no longer available to be caught. If the net is being towed between tow boats and fish move laterally out of path of the boat and into the path of the net, then some fish which were initially unavailable to the net will now be available.

Second, we calculated the empirical density of fork lengths for Delta Smelt caught in oblique tows, and compared it to the empirical density of fork lengths for Delta Smelt caught in surface tows. Our goal was to look for systematic differences in fish size that might indicate if surface and oblique tows have access to different size classes. For example, if larger individuals were spending time near the surface and smaller individuals were spending time deeper in the water column, then oblique tows would have access to smaller individuals that surface tows would not.

Oblique vs. Surface Catch Density Comparison

We modeled the total number of Delta Smelt caught in the i^{th} tow (summing up the number caught in the cod end and the number caught in the cover), using a negative binomial distribution $y_i \sim \mathrm{NegBin}(\mu_i, \theta)$ with expected value μ_i and variance $\mu_i + \mu_i^2/\theta$, where θ is a dispersion parameter. The expected number of Delta Smelt caught in the i^{th} tow was modeled as

$$\mu_i = \exp\left(\gamma_0 + \gamma_1 Date_i + \gamma_2 Location_i + \gamma_3 TowMethod_i\right) Volume_i, \tag{2}$$

where $Volume_i$ is the volume of water sampled during the tow, and the exponential component represents the local density of Delta Smelt. We used three covariates to model the local density:

Date. A numeric variable representing the sampling date as the number of days since January 1, 2014. The overall population size is expected to decrease as a function of time between August and January because spawning and hatching events are typically finished by late June (Bennett 2005), leaving mortality and movement as the primary drivers of the population dynamics during this period. We did not have adequate data to attempt to separately estimate mortality and movement.

Location. A categorical variable representing sampling location (lower Sacramento River or SDWSC). We used treatment contrasts with lower Sacramento River as the reference level.

Tow Method. A categorical variable representing tow method (oblique or surface). We used treatment contrasts with oblique tow as the reference level.

We fit the model shown in Equation 2 and all nested subsets containing an intercept using data from all 59 tows. We chose a negative binomial model because the data contained a large number of zero catches (33 of the 59 tows caught zero Delta Smelt) and a small number of large catches (the two highest catches were 69 and 120). We also fit zero-inflated negative binomial models to the data for comparison. We treated the probability of a structural zero as a constant parameter in each zero-inflated model. We fit all models using the glmmadmb function in the glmmADMB package within R. We generated model predictions with the predict function. This analysis allowed us to investigate the significance of tow method in predicting total catch while accounting for temporal and spatial effects at a coarse level. We considered environmental covariates such as tide, turbidity, and specific conductance for inclusion in the model, because these affect local Delta Smelt distributions (Feyrer et al. 2007), but we ultimately excluded them to avoid over-fitting.

Oblique vs. Surface Length Distribution Comparison

We compared the distributions of Delta Smelt lengths from paired oblique and surface tows for systematic differences that could result from, for example, size-dependent depth preferences. We calculated empirical length distributions for each tow method to allow visual comparison. We calculated the oblique tow length distribution using Delta Smelt lengths (from the cod end and cover) pooled across all paired oblique tows, and similarly for the surface-tow length distribution. We performed a two-sided bootstrap Kolmogorov–Smirnov test using the ks.boot function in the Matching package in R to test whether the two sets of lengths come from the same underlying distribution.

RESULTS

Catch Summary

During the study, a total of 291 Delta Smelt were caught. Of these, 45 were retrieved from the cod end and 246 were retrieved from the cover (Table 2). The single largest catch occurred during a surface tow on August 21 at SDWSC, when four Delta Smelt were caught in the cod end and 116 were caught in the cover. Average Delta Smelt catch densities (including individuals retrieved from the cod end and cover) were consistently higher for surface tows than for oblique tows, and were generally higher in the Lower Sacramento River than in the SDWSC (Table 2). Across the study, the mean volume of water sampled per tow was 5,269 ± 1,614 (SD) m^3. Variability in sample volume was higher for surface tows than for oblique tows (Figure 3). This likely results from the brief increases in boat speed needed to bring the net back to the surface after deployment, as well as slight increases in speed caused by the use of two boats operated at the same throttle setting used for a single-boat oblique tow.

Contact Selectivity

Length-Only Model

Delta Smelt fork lengths ranged from 33 to 65 mm, and observed retention rates for fork lengths in this interval ranged from zero to one (Table 3). When fitting length-only selectivity models with all of the

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Table 2 Delta Smelt catch summaries by date, location, and tow method. Lower Sac and SDWSC are used to represent the sampling areas in the lower Sacramento River and Sacramento Deep Water Ship Channel, respectively. Densities are based on total catch in the cod end and cover. Standard error for the mean density is shown in parentheses.

				Delta Smelt Summary (across tows)				
				Catch				
Date / Location	**Tow method**	**# of tows**	**Total volume (m^3)**	**Cod end**	**Cover**	**Total**	**Fork length range (mm)**	**Mean density (per 10,000 m^3)**
Aug 21, 2014								
Lower Sac	Oblique	3	16,620	3	18	21	41 to 55	12.6 (8.6)
Lower Sac	Surface	3	28,738	20	55	75	33 to 57	26.1 (23.1)
SDWSC	Oblique	1	4,959	0	1	1	50	2.0 (–)
SDWSC	Surface	1	7,614	4	116	120	39 to 56	157.6 (–)
Sep 25, 2014								
Lower Sac	Oblique	3	14,576	0	13	13	48 to 55	8.9 (6.3)
Lower Sac	Surface	2	7,678	5	27	32	46 to 61	41.7 (25.0)
SDWSC	Oblique	3	13,620	0	0	0	NA	0 (0.0)
SDWSC	Surface	3	11,232	0	1	1	55	0.9 (0.9)
Oct 21, 2014								
Lower Sac	Oblique	2	8,326	0	1	1	56	1.2 (1.2)
Lower Sac	Surface	4	14,862	0	5	5	51 to 55	3.4 (2.6)
SDWSC	Oblique	3	12,440	0	0	0	NA	0 (0.0)
SDWSC	Surface	3	6,473	0	0	0	NA	0 (0.0)
Dec 2, 2014								
Lower Sac	Surface	6	35,083	4	8	12	48 to 59	3.4 (1.2)
SDWSC	Surface	2	11,694	2	0	2	56 to 59	1.7 (0.0)
Jan 27, 2015								
Lower Sac	Surface	20	116,947	7	1	8	55 to 65	0.7 (0.3)

data, we found that a single 33-mm Delta Smelt caught in the cod end of the trawl had a noticeable effect on the fitted curves. In the model containing all four terms, this point had a Cook's distance of 2.47 while the next largest Cook's distance value in that model was 0.09. This 27-fold increase supported the conclusion that the observation at 33 mm was influential. As a result, we removed this point, and fit selectivity models with the resulting reduced data set. For the reduced data, the length-only selectivity model that contained all four terms had the lowest Akaike Information Criterion (AIC) value by a margin of 3.7 units (see Appendix B). Table 5 shows parameter estimates for this model, and the resulting curve is shown in Figure 4. The standard errors are likely under-estimates, however, because the between-tow variability within a given day–location has not been accounted for because the data were pooled (Millar and Fryer 1999).

Length–Biomass Model

Fish species other than Delta Smelt caught during the study included Shimofuri Goby, Mississippi Silverside, Wakasagi, Longfin Smelt, American Shad (*Alosa sapidissima*), Threadfin Shad (*Dorosoma petenense*), Striped Bass (*Morone saxatilis*), White Catfish (*Ameiurus catus*), Yellowfin Goby (*Acanthogobius flavimanus*), Shokihaze Goby (*Tridentiger barbatus*), Chinook Salmon (*Oncorhynchus tshawytscha*), Splittail (*Pogonichthys macrolepidotus*), and Threespine Stickleback (*Gasterosteus aculeatus*).

Table 3 Delta Smelt length frequencies by catch type, cod end, or cover, from the 2014–2015 covered cod end study. $\hat{p}(L)$ is the fraction of Delta Smelt retained in the cod end.

Fork length (mm)	Cod end	Cover	$\hat{p}(L)$
33	1	0	1.00
37	0	2	0.00
39	0	1	0.00
40	0	6	0.00
41	0	7	0.00
42	1	5	0.17
43	3	15	0.17
44	2	12	0.14
45	0	20	0.00
46	3	10	0.23
47	2	24	0.08
48	5	24	0.17
49	3	14	0.18
50	3	31	0.09
51	5	23	0.18
52	3	15	0.17
53	0	9	0.00
54	0	8	0.00
55	1	10	0.09
56	3	4	0.43
57	2	4	0.33
59	1	1	0.50
60	2	0	1.00
61	2	1	0.67
63	1	0	1.00
64	1	0	1.00
65	1	0	1.00
Total	45	246	

Four invertebrate species were caught during the study: California bay shrimp (*Crangon franciscorum*), Siberian prawn (*Exopalaemon modestus*), oriental shrimp (*Palaemon macrodactylus*), and Black Sea jellyfish (*Maeotias marginata*). Total tow-level biomass values ranged from 0 to 6,757 g, with a median of 273 g and an interquartile range of 541 g.

Using the reduced data set described in the previous section, we found that the length–biomass model with the lowest AIC contained the same four terms

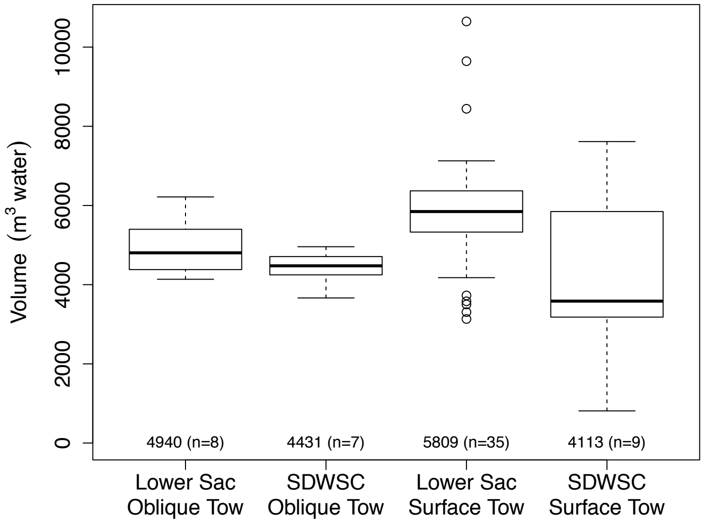

Figure 3 Tow volume variability across sampling sites and tow methods. Mean values (and sample sizes) are shown below each box plot.

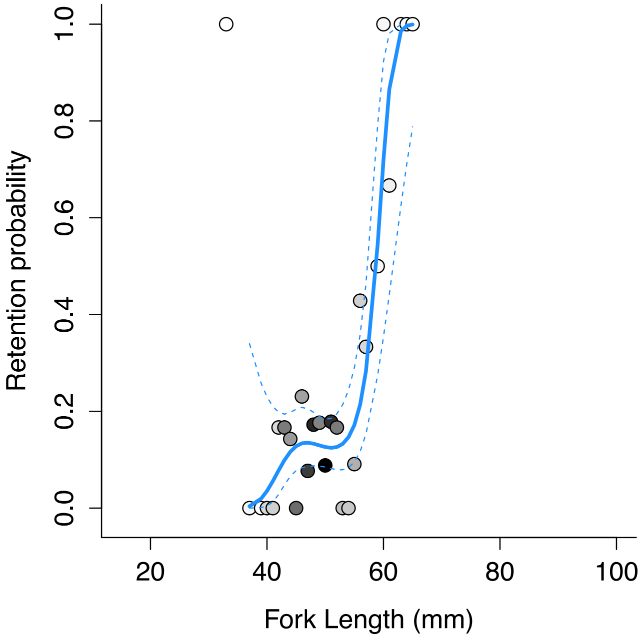

Figure 4 Observed Delta Smelt retention (circles) and fitted length-only selectivity curve (solid line) based on the 2014–2015 FMWT covered cod end study. Dashed lines show a 95% confidence interval. Darker circle shading indicates a larger number of fish-at-length. The point at (33, 1) was not used in model fitting.

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Table 4 Delta Smelt length frequencies by catch type, net, or cover, from the 1991 selectivity study (see text for information on the data source). $\hat{p}(L)$ is the fraction of Delta Smelt retained in the net (either in the cod end or the 2.5-cm mesh section).

Fork length group	Midpoint (mm)	Net	Cover	$\hat{p}(L)$
1	22.5	1	0	1.00
2	25.0	1	0	1.00
3	27.5	0	2	0.00
4	30.0	0	2	0.00
5	32.5	0	1	0.00
6	35.0	2	6	0.25
7	37.5	3	7	0.30
8	40.0	6	20	0.23
9	42.5	6	33	0.15
10	45.0	26	92	0.22
11	47.5	28	77	0.27
12	50.0	52	155	0.25
13	52.5	32	77	0.29
14	55.0	25	63	0.28
15	57.5	8	19	0.30
16	60.0	5	10	0.33
17	62.5	2	2	0.50
18	65.0	2	2	0.50
19	67.5	1	1	0.50
20	70.0	2	0	1.00
21	72.5	2	0	1.00
22	75.0	4	0	1.00
23	77.5	7	0	1.00
24	80.0	8	0	1.00
25	82.5	11	0	1.00
26	85.0	6	0	1.00
27	87.5	1	0	1.00
28	90.0	2	0	1.00
	Total	243	569	

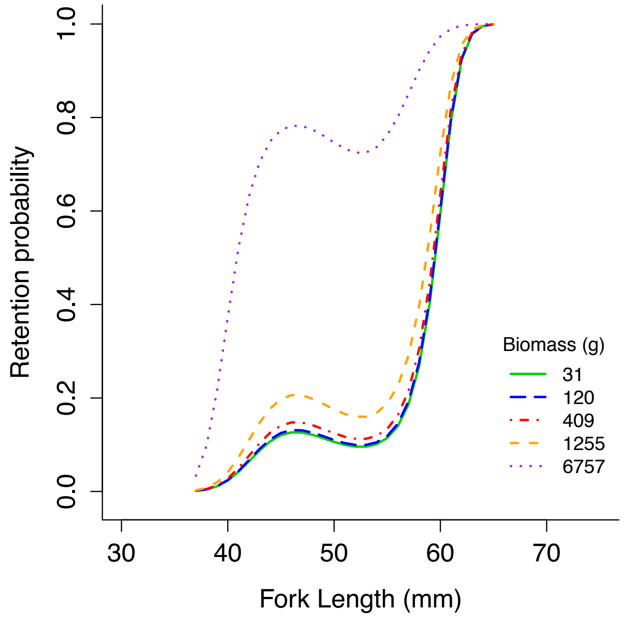

Figure 5 Fitted length-biomass model selectivity curves based on the 2014–2015 FMWT covered cod end study.

as the length-only model plus a linear biomass term (Table 5). Six other models had AIC values that were within three units of the lowest value (see Appendix B for all the AIC values), but generalized likelihood ratio tests did not support the inclusion of any of the additional terms in the alternative models ($P > 0.16$ in each test). The AIC for the length–biomass model shown in Table 5 was 6.0 units less than the AIC for the length-only model. Figure 5 shows model-predicted retention curves for a subset of biomass values.

Comparison of 1991 and 2014–2015 FMWT Selectivity Studies

The 1991 length–frequency data used for fitting length-only selectivity models are shown in Table 4. Visual inspection of the fitted models suggested that two Delta Smelt caught in the trawl, one at 22.5 mm and the other at 25 mm, represented influential points. In the model with all four terms, these observations had Cook's distances of 0.27 and 0.11, both of which were more than four times greater than the remaining values. We removed these two points and fit selectivity models with the resulting reduced data set. With the reduced data, the length-

Table 5 Selectivity model parameter estimates and standard errors for the 2014–2015 and 1991 selectivity studies. Values shown are based on standardized data. Mean fork length (and SD) used for standardization of the 2014–2015 data was 48.8000 (4.7419) mm, and mean biomass used for standardization was 389.1360 (820.1554) g. Mean fork length (and SD) used for standardization of the 1991 data was 50.9383 (8.7251) mm.

Model	Parameter	Estimate (SE)	Two-sided *p* value
2014–2015 length-only model	β_0	–1.898 (0.231)	< 0.001
$\text{logit}(p) = \beta_0 + \beta_1 L + \beta_2 L^2 + \beta_3 L^3$	β_1	–0.155 (0.329)	0.639
	β_2	–0.023 (0.212)	0.912
	β_3	0.253 (0.129)	0.050
2014–2015 length-biomass model	α_0	–1.867 (0.237)	< 0.001
$\text{logit}(p) = \alpha_0 + \alpha_1 L + \alpha_2 L^2 + \alpha_3 L^3 + \alpha_4 B$	α_1	–0.357 (0.345)	0.301
	α_2	–0.126 (0.231)	0.585
	α_3	0.301 (0.133)	0.024
	α_4	0.392 (0.156)	0.012
1991 length-only model	β_0	–1.063 (0.096)	< 0.001
$\text{logit}(p) = \beta_0 + \beta_1 L + \beta_2 L^2 + \beta_3 L^3$	β_1	0.189 (0.193)	0.329
	β_2	0.186 (0.121)	0.125
	β_3	0.151 (0.080)	0.059

only selectivity model that contained all four terms had the lowest AIC value by a margin of 4.2 units (see Appendix B for AIC values from all of the fitted models). Table 5 shows parameter estimates for the lowest-AIC model, and Figure 6 shows the fitted curve. The fitted 2014–2015 length-only selectivity curve is also shown in Figure 6 for comparison.

Out of concerns about over-dispersion, we re-fit all of the selectivity models (from both studies and for both length-only and length–biomass models) using a quasi-binomial error structure. The resulting over-dispersion parameters ranged from 0.95 to 1.07, suggesting that the data were not over-dispersed.

Oblique vs. Surface Catch Density Comparison

We found date, location, and tow method to be important predictors of Delta Smelt catch. Of the competing negative binomial models, the one containing all four terms had the lowest AIC value by a margin of 2.6 units (Table 4 in Appendix B) and the most encouraging residual diagnostics. The zero-inflated models were qualitatively and quantitatively similar to their non-zero-inflated counterparts. Appendix B shows AIC values for all of the fitted models, and Table 6 shows the parameter estimates from the lowest-AIC model without zero-inflation. According to this model, expected catch increases by a factor of 7.33 when tow method switches from oblique to surface, and expected catch decreases by a factor of 0.25 when location switches from the Lower Sacramento River to the SDWSC. Despite the significance of the covariates in this model, much of the variability in catch remained unaccounted for.

Oblique vs. Surface Length-Distribution Comparison

Across the set of paired oblique and surface tows, the oblique tows caught a total of 26 Delta Smelt with fork lengths that ranged from 41 to 56 mm, and the surface tows caught a total of 233 Delta Smelt with lengths that ranged from 33 to 61 mm. Empirical length distributions for the two tow methods are visually similar (Figure 7), and results from a two-sided Kolmogorov–Smirnov test strongly suggested that the samples come from the same underlying length distribution ($P = 0.68$).

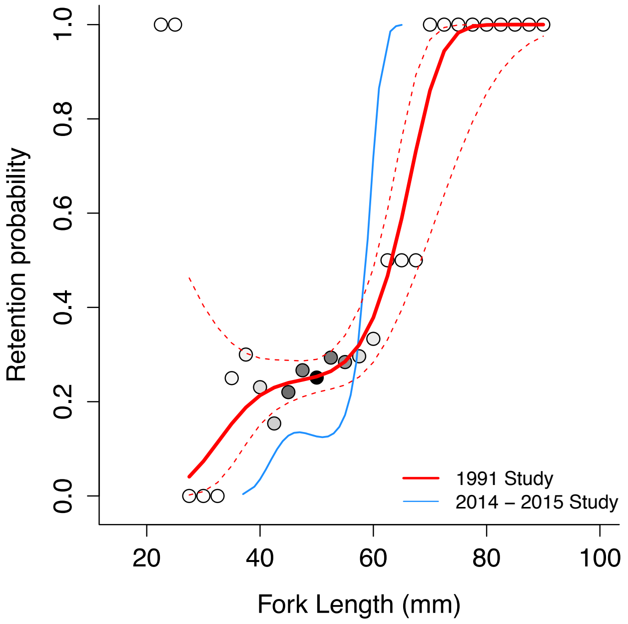

Figure 6 Observed Delta Smelt retention (circles) and a fitted cubic polynomial selectivity curve (thick solid line) based on the 1991 FMWT selectivity study. Dashed lines show a 95% confidence interval. Darker circle shading indicates a larger number of fish-at-length. The points at (22.5, 1) and (25, 1) were not used in model fitting. The selectivity curve from Figure 4 is reproduced here using a thin solid line.

Table 6 Parameter estimates from the lowest-AIC negative binomial catch model (no zero-inflation). The Location parameter is for SDWSC (relative to Lower Sac) and the TowMethod parameter is for surface tow (relative to oblique tow).

Covariate	**Estimate (SE)**	**Two-sided *p* value**
Intercept	514.67 (84.63)	< 0.001
Date	-0.032 (5.2e-3)	< 0.001
Location	-1.37 (0.64)	0.03
Tow method	1.99 (0.64)	< 0.01
Dispersion parameter	0.47 (0.14)	

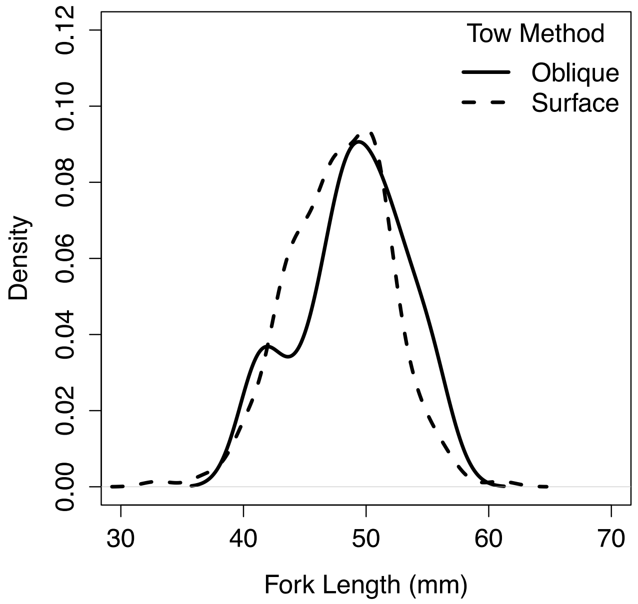

Figure 7 Empirical (non-parametric fit) densities of Delta Smelt lengths from paired oblique and surface tows

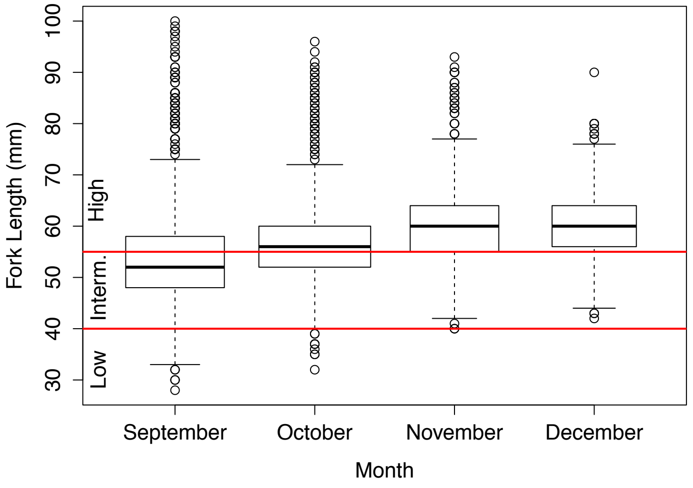

Figure 8 Box plots of Delta Smelt lengths from the FMWT Survey, by month, from the years 1985 to 2015. Individuals with lengths greater than 100 mm were excluded because of potential misidentification. Box width is proportion to sample size. Approximate ranges of high (>55 mm), intermediate (40 to 55 mm), and low (<40 mm) retention are indicated.

DISCUSSION

Conceptual Model of Selectivity

As the FMWT net moves through the water, Delta Smelt that occupy the water mass in its path respond. Some individuals that possess sufficient swimming capability and are located toward the margins of the mouth area are able to avoid the net. For those not able to avoid the net, four primary mechanisms affect the ability of the FMWT net to catch Delta Smelt. The first mechanism relates to the guidance of fish toward the cod end by the front panels of the net. Relatively small, poor-swimming individuals may pass through large meshes with exiting water or may contact the mesh, unable to avoid it, and slip out. Those able to avoid the meshes but too small to out-swim the net will eventually contact the cod-end mesh where they are vulnerable to the three remaining mechanisms: wedging, pinning, and trapping. Wedging occurs when an individual within a particular size range contacts the net "head-on," slips partially through the mesh, wedges into the mesh, and becomes stuck (we have not observed "tail-first" wedging). Pinning occurs when fish contact the mesh laterally but are too large and rigid to be pushed through by water pressure and hence become pinned against the mesh. Trapping involves individuals becoming trapped by debris or other organisms that end up blocking or clogging the mesh. This may result in the retention of both smaller fish that normally would have escaped through the mesh and of larger fish that normally would have been retained by one of the previous two mechanisms had they made direct contact with the mesh. Below a hypothetical lower size threshold, Delta Smelt are too small to be affected by any of these mechanisms (except in the case of complete blockage or clogging of all meshes) and retention is essentially zero. Above an upper threshold, Delta Smelt are affected by all four mechanisms and retention probability is expected to be one (assuming no gear avoidance). In between these thresholds, retention is dominated by net guidance and trapping by debris or organisms, and theoretical retention rates are expected to be intermediate.

The observed and modeled retention probabilities from the 2014–2015 study show a lower threshold around 40 mm, below which Delta Smelt are largely unaffected by the previously mentioned retention mechanisms, and an upper threshold around 55 mm, above which all four mechanisms have an effect (Figure 4). We emphasize, however, that only four Delta Smelt smaller than 40 mm were collected, so there is still considerable uncertainty about retention in the lower length range. Based on the model, full retention of Delta Smelt in the 1.3-cm mesh section of the trawl appears to occur around 60 mm. During this study, we observed two Delta Smelt wedged into the 1.3-cm mesh; these fish had fork lengths of 61 mm and 63 mm. During a different gear efficiency study conducted in October 2012, we observed 20 of the 23 Delta Smelt with lengths greater than 60 mm wedged into the 1.3-cm mesh of the FMWT gear, further supporting the conclusion that full retention occurs around 60 mm. Conversely, fish somewhat smaller than 60 mm would have passed through the 1.3-cm mesh unless another mechanism took effect. Our ability to document pinning was limited because Delta Smelt were typically caught among numerous other fish and invertebrates. In such cases, Delta Smelt as small as 33 mm (but mostly in the 42- to 55-mm range) were retained by the 1.3-cm mesh. Although trapping seems the most likely mechanism for many individuals, pinning is conceivable if some of the Delta Smelt ≤ 55 mm were assumed to be among the first organisms to contact the cod-end mesh. During this study, trapping rather than pinning appeared to be the main retention mechanism for sub-60-mm Delta Smelt. During the FMWT Survey itself, there have been thirty instances when ≤ 55-mm Delta Smelt were retained either alone ($n = 4$) or among small catches of five fewer total organisms (1967–2016 CDFW FMWT data, unreferenced, see "Notes"). Thus, pinning occurs and may be partially responsible for retention of some ≤ 55-mm Delta Smelt in tows that include many other organisms.

Observed retention rates from the 1991 selectivity study also agree with our conceptual model. In this case, the lower and upper thresholds occur around 34 mm and 65 mm (Figure 6). Use of a cubic polynomial logit model allowed for flexibility in capturing the thresholds in both studies, but may have led to over-fitting. For example, the 2014–2015 fitted curve shows a decrease in retention between 40 and 55 mm. Such a decrease is unlikely in reality, and is probably a result of small sample sizes, high variability in retention in this length range, and the

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ability of the cubic polynomial to fit random error rather than the underlying relationship between size and retention. Data points that correspond to the smallest retained Delta Smelt were removed from both data sets because they unduly influenced the models, and we think they do not represent retention in the lower length range. More data would be needed to resolve the selectivity of the net for smaller Delta Smelt.

Direct comparison of retention rates from the two studies is confounded by differences in the placement of the cover, but the two fitted curves in Figure 6 show some qualitative agreement. In a scenario where Delta Smelt are slipping through the 2.5-cm mesh section, we would expect observed retention to be lower when the 2.5- and 1.3-cm mesh sections are covered relative to when only the 1.3-cm section is covered. This is because in the former case the escaping fish that pass through the 2.5-cm mesh are accounted for whereas in the latter case they are not. This is the pattern seen in Figure 6 for lengths above roughly 55 mm, where 1991 retention rates are lower than 2014–2015 rates. The relatively higher retention below about 55 mm in 1991 likely reflects another mechanism. If overall catches (all species) were higher in 1991, then the 1991 data may reflect a total catch biomass effect.

We found some evidence that retention of Delta Smelt increases with the total biomass of organisms in the cod end of the trawl. We are probably not able to quantify the relationship between biomass and retention accurately because the data do not span the full joint fork length and biomass ranges. In other words, we have relatively few observations at any given combination of length and biomass, so it becomes difficult to resolve what the selectivity curves should look like across the observed length and biomass ranges. Additionally, there is a temporal component to this process since an individual Delta Smelt is more likely to be trapped by organisms that encounter the net before it than by organisms that encounter the net after it. We did not have information on encounter times that could be included in the model.

Applications of Selectivity

Selectivity bias can lead to biased abundance estimates and inflated variances, and can affect interpretation of trends in measures of relative abundance (Pollock et al. 2002). For example, FMWT-based estimates of Delta Smelt abundance for the month of September may be large in years of rapid growth relative to years of slow growth because larger fish are more likely to be caught and not because the population size is substantially different between years. To get a feel for when and to what extent Delta Smelt catches in the FMWT Survey are affected by size selectivity of the gear, we plotted the distribution of Delta Smelt lengths, by month, from 1985 to 2015 (Figure 8). The horizontal lines in Figure 8 identify ranges of relatively high, intermediate, and low retention based on the 2014–2015 length-only selectivity model. Based on our analysis, Delta Smelt in the high retention range should be well-represented in the historical catch data relative to the population at the time of sampling while those in the two remaining ranges are under-represented. In Figure 8, the percentage of fish in the high retention range increases over time and reaches 75% in November; this suggests that data from November and December are affected by size selectivity to a lesser extent than data from September and October. Interpretation of abundance estimates can also be influenced by the effect of total catch biomass on retention. In particular, the effect of catch biomass on Delta Smelt retention may have been larger in years before the Pelagic Organism Decline (Sommer et al. 2007b) when there were more organisms to block the trawl mesh than in years after the decline.

Newman (2008) provides details on how estimates of size selectivity can be used in a design-based abundance estimation method to account for fish that escaped from the net. The general idea is that the number of length L fish caught in the cod end, y_L, is divided by the selectivity for that length, $p(L)$, to give an estimate of the total number of length L fish that were in the volume of water sampled. An alternative application would be include the selectivity estimates in a parametric model. For example, Equation 3 shows a catch density model where y_L represents the number of length L fish caught in the cod end, and f represents a probability distribution with expected value μ, where μ is the product of the density-at-length, N_L/V, the water volume sampled, v, and the gear selectivity, $p(L)$:

$$y_L \sim f\left(\mu = \frac{N_L}{V} \times v \times p(L)\right) \tag{3}$$

The gear selectivity factor shrinks the expected catch to account for the fact that catches will be smaller when fish in the sample have fork lengths for which selectivity is less than one. This could be fit as a stand-alone model for directly estimating the abundance-at-length, N_L, or it could be used in the observation component of a state–space model (Newman et al. 2014) where N_L is defined in the state component. Length–biomass selectivity estimates, $p(L,B)$, could be applied in a similar manner as length-only selectivity estimates, $p(L)$.

There are some practical issues to consider when applying selectivity estimates. First, the selectivities of different parts of a trawl may differ, especially if the mesh sizes differ, as they do in the FMWT. If non-negligible numbers of fish escaped from each section, then a measure of overall net selectivity would be needed to account for escaped fish. Second, inaccurate estimates of selectivity can lead to biased abundance estimates. In particular, model-predicted probabilities that are close to zero can lead to unrealistically large adjusted catch values for small fish. Finally, the data requirements for both fitting and applying a length–biomass model are greater than those of a length-only model because length measurements and length–mass relationships must be available for all organisms caught.

Here, we have presented two separate Delta Smelt length-only selectivity models for the FMWT gear based on different studies. In situations where selectivity of the 1.3-cm mesh section of the net is of interest, the 2014–2015 model would be the better choice. In situations where the overall selectivity of the net is of interest, the 1991 model may give a better approximation because the cod-end cover was larger and the overall probability of retention might be estimated more accurately. Because the length–biomass model was fit to a relatively small number of length and biomass combinations, it is not suitable for practical application. If selectivity of the gear truly is a function of both fish length and total catch biomass, then there is a trade-off between loss of accuracy and ease of applicability upon excluding biomass from the model.

Investigation of Tow Method

During our study, we found that surface tows resulted in higher Delta Smelt catch densities than oblique tows. This could be because of a strong surface orientation in visually feeding sub-adult Delta Smelt (Slater and Baxter 2014). Feyrer et al. (2013) observed Delta Smelt throughout the water column on flood tides and only in the lower portion of the water column on ebb tides. During this study, we targeted flood tides to maximize catch. This means that the results of our tow method analysis apply primarily to flood-tide sampling and that further research is needed to determine if similar catch patterns occur during ebb tides. If Delta Smelt are positioned lower in the water column during ebb tides, oblique tows may then produce higher catch densities than surface tows.

Patterns in vertical distribution may also differ for different life stages (Rockriver 2004) or across the diel cycle (Bennett et al. 2002). Vertical distribution also may vary by the necessity to maintain position or migrate in the estuary (Bennett and Burau 2015) or to follow food (Hobbs et al. 2006). Nonetheless, the substantially higher surface densities of Delta Smelt compared to subsurface tows detected in previous side-by-side gear evaluations (CDFW 1994, unpublished data, see “Notes”) subsequently led to a change in 2002 from monitoring the distribution of Delta Smelt in the winter and spring with a midwater trawl to a surface-oriented Kodiak trawl (Honey et al. 2004).

Another partial explanation for the observed differences in surface and oblique tow densities relates to how the tows are carried out, as well as the vertical distribution of fish. It is possible that surface-oriented Delta Smelt may be driven from the path of an oblique tow by the preceding boat and herded between the two boats used to pull the trawl in a surface-oriented tow. We suspect that herding had little effect during this study because boat separation during surface tows typically averaged 18.2 ± 0.5 (SD) m ($n = 29$) based on laser range-finder measures during sampling (CDFW 2014, unpublished data, see “Notes”), whereas net width had previously been estimated to range from 3 to 3.5 m. Thus, Delta Smelt would have had to swim 7+ m from the edge of either boat to begin to reach the area swept by the net. Herding between two boats, if it occurs, is more likely to inflate densities in the SKT Survey, where the edge of the net appears to more closely follow the edge of the boats.

The high degree of similarity in the distribution of fish lengths in the oblique and surface tows is consistent with a hypothesis that fish of different lengths (at least within the range examined) do not occupy different vertical strata. For example, there was no evidence that shorter fish tended to be more surface oriented than longer fish or vice versa. Our results were particular to the sub-adult and adult life stages, however, and are not necessarily what might be observed for larval or juvenile fish. For example, the degree of swim bladder development affects the ability of larvae to control vertical distribution. Larvae with more developed swim bladders are going to be larger and may be more surface-oriented than larvae with undeveloped swim bladders (Wang 1991).

CONCLUSIONS

Several other types of fishing gear (e.g., egg and larval fixed-frame trawls and Kodiak trawls), are used to catch Delta Smelt at other life stages. Replicating the covered cod end and oblique and surface-tow studies with these other gear types would allow us to make improved abundance estimation for other life stages using historical survey data. Side-by-side covered cod end studies with multiple gear types would also provide a means of comparing relative efficiencies.

The gear selectivity analyses discussed here are conditional on fish being available to the gear, but there are still questions about the availability of Delta Smelt to the FMWT Survey gear during regular sampling. While our analysis of surface and oblique tows gives some insight into the issue of availability, further investigation is needed to quantify the effect of availability bias on abundance estimates.

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