UC Davis
San Francisco Estuary and Watershed Science

Title
Estimating the Size Selectivity of Fishing Trawls for a Short-Lived Fish Species

Permalink
https://escholarship.org/uc/item/0hh7n9x2

Journal
San Francisco Estuary and Watershed Science, 17(1)

Authors
Mitchell, Lara
Newman, Ken
Baxter, Randall

Publication Date
2019

DOI
10.15447/sfews.2019v17iss1art5

Supplemental Material
https://escholarship.org/uc/item/0hh7n9x2#supplemental

Peer reviewed

RESEARCH

Estimating the Size Selectivity of Fishing Trawls for a Short-Lived Fish Species

Lara Mitchell*[1], Ken Newman[1,2], and Randall Baxter[3]

ABSTRACT

Long-term fish survey monitoring programs use a variety of fishing gears to catch fish, and the resulting catches are the basis for status and trends reports on the condition of different fish stocks. These catches can also be part of the data used to set stock assessment models, which establish harvest regulations, and to fit population dynamics models, which are used to analyze population viability. However, most fishing gears are size-selective, and fish size—among other possible covariates, such as environmental conditions—affects the probability that a fish will be caught in the path the gear sweeps. Failing to properly account for selectivity can adversely affect the ability to interpret and use status and trends measures, stock-assessment models, and population-dynamics models. Our side-by-side gear comparison study evaluated the selectivity of multiple open-water trawl surveys that have provided decades worth of information on the imperiled fish species Delta Smelt (*Hypomesus transpacificus*). We used data from the study to estimate gear selectivity curves for multiple trawls using two methods. The first method examines the total number of fish-at-length caught across all gears, and does not directly use or estimate fish length distribution in the population. The second method examines the total number of fish caught by each gear separately, and explicitly estimates fish length distribution in the population. The results from the two methods were similar, and we found that one trawl was highly efficient at catching larger Delta Smelt. This is the first formal multi-gear evaluation of how well survey gear used to monitor Delta Smelt in the San Francisco Estuary selects fish by size, and we plan to incorporate the results into Delta Smelt population models.

KEY WORDS

gear selectivity, fishing gear, Delta Smelt, long-term monitoring, status and trends

INTRODUCTION

Fishing gear selectivity is defined as the probability that a fish will be captured by a particular fishing gear, assuming the fish is located where the gear is deployed, or, more generally, assuming the fish is available to the gear. Selectivity is used synonymously with retention rate or retention probability, because it represents the probability that the gear will retain a fish. This probability typically depends on fish size. For example, smaller fish can escape through large-sized mesh in gears such as trawls, seines, and gill nets; larger fish may be able to swim out of the path of a towed gear (gear avoidance behavior). The physical characteristics that make fish susceptible to capture vary by gear type. For example, the ability of a fish to escape a trawl cod end—either by swimming through the mesh volitionally or by being pushed through via water pressure—depends on the fish's girth and length (MacLennan 1992; Wileman et al. 1996; Herrmann et al. 2009). In practice, selectivity is often described as a function of fish length since length is an easy-to-measure proxy for overall size (Millar and Fryer 1999).

Understanding gear selectivity is important in commercial fisheries management as well as in scientific investigations that depend on fishing gears. In commercial fisheries, the size range of harvested individuals affects the reproductive success and long-term stability of commercial fish populations (Wileman et al. 1996). Hence, there is an incentive to develop and use gears likely to retain fish in a target size range but not other fish. In surveys of population status and trends, or abundance and survival quantity estimates, an ideal gear would generally be non-selective for the target population, meaning that it captures and retains all individuals in that population with a probability of one.

In reality, survey gears are not perfectly non-selective, and inherent selectivity can cause bias in catch data (Somerton et al. 1999; Williams et al. 2013) and increased uncertainty in abundance estimates (Newman 2008). Selectivity bias in catch data is confounded with the true underlying dynamics of the population, and hence can affect interpretation of patterns in data collected by a single gear (Maunder and Punt 2004). In some cases, multiple gears may be used simultaneously or in succession as one gear replaces another that targets successive size (or age) groups, and differences in gears' selectivities should be addressed when data is combined or compared across gears (Bishop 2006; Miller 2013). Retention probabilities for a given gear and species, if known, can be used to correct bias in catch data (Trenkel and Skaug 2005), account for uncertainty associated with variable capture probability (Newman 2008), and standardize data across multiple gears (Bishop 2006; Miller 2013). Making such adjustments using estimated retention probabilities, however, is more complex because the uncertainty in the estimates needs to be accounted for.

The process of estimating selectivity generally involves fitting a selectivity function—also commonly referred to as a selectivity curve—that gives the probability of retaining the species of interest as a function of length. Estimating selectivity is difficult because the length frequency distribution of observed fish is the product of the length frequency distribution of the population and gear selectivity (Millar 1995). To isolate and estimate the latter quantity, the former quantity must be known, but the former quantity is difficult to estimate because most gears are selective for at least some lengths.

Side-by-side gear comparison studies are often used to collect data that can be used to investigate the overall efficiency of gear and estimate its selectivity. A side-by-side gear comparison study involves sampling with two or more gears at the same place and time so gear performances can be compared (Wileman et al. 1996; Millar and Fryer 1999). If one gear is non-selective, the absolute selectivity of the other gears can be estimated (Somerton et al. 2013). Absolute selectivity is simply selectivity as we have defined it here. Relative selectivity, in contrast, is one gear's selectivity in relation to another's. If all the gears in an experiment are selective, then only relative selectivity can be estimated (Millar 1995; Kotwicki et al. 2017). A potential further complication in side-by-side studies is that even for two different gears with identical selectivity, overall gear efficiency can differ if the gears are deployed in such a way that the distributions of available fish differ in terms of density or length.

Various approaches have been developed to estimate absolute or relative selectivity using experimental data, including: catch comparison models (Krag et al. 2014), selectivity ratios (Kotwicki et al. 2017), the SELECT method (Millar 1992; Millar and Fryer 1999), log-linear models (Millar and Holst 1997), and a length frequency method described by Quang and Geiger (2002). If data from a gear-comparison study are not available, selectivity can be estimated as part of a stock assessment model; this approach requires making assumptions about the selectivity curve, and investigating how sensitive the model is to the assumptions (Punt et al. 2014).

Here we report on a side-by-side gear comparison study that involved six open-water trawls used in long-term monitoring surveys in the San Francisco Estuary (the estuary). Details on the surveys and trawls are given in the section "Background on Monitoring Surveys and Gears." The study focused on the small, endangered pelagic fish species Delta Smelt (*Hypomesus transpacificus*), which is found only in the estuary, and which has significantly declined in abundance in recent decades (Sommer et al. 2007; Moyle et al. 2016).

Our goal was to fit selectivity curves for the trawls that could be used to correct selectivity-related bias in historical survey data as described by Newman (2008). These surveys are an important source of data to monitor and model changes in the Delta Smelt population for management purposes (Kimmerer 2008; Maunder and Deriso 2011; Rose et al. 2013; IEP MAST 2015), but how efficiently the surveys catch Delta Smelt has not been studied comprehensively. Gear selectivity estimates can help improve efforts to manage the population by providing more accurate estimates of abundance and their corresponding uncertainties.

We applied two methods of estimating selectivity: (1) the SELECT method (Millar 1992) and (2) a method presented by Quang and Geiger (2002). The SELECT method (Millar 1992) reflects the common approach of conditioning on the total number of fish caught by all gears (Millar and Fryer 1999; Fryer et al. 2003; Browne et al. 2017). The second method evaluates the total number of fish of a particular length caught by each gear separately—and explicitly models the population length distribution, which

is more feasible for Delta Smelt than some species because Delta Smelt are short-lived (most live 1 to 2 years), and overlap between year-classes is minimal. Applying both methods enabled the resulting selectivity estimates—qualitatively similar between the methods—to be compared, and further supported our findings. We also calculated pointwise confidence intervals for each selectivity curve using a bootstrap procedure.

MATERIALS AND METHODS

Background on Monitoring Surveys and Gears

The Fall Midwater Trawl Survey (FMWT), Spring Kodiak Trawl Survey (SKT), 20-mm Survey (20-mm), Summer Townet Survey (STN), and Smelt Larva Survey (SLS) are operated by the California Department of Fish and Wildlife, and the Chipps Island Midwater Trawl Survey (CMWT) is operated by the U.S. Fish and Wildlife Service. We use shortened survey names here (e.g., FMWT) to refer to the monitoring surveys themselves or to refer to the trawls used in the surveys, depending on the context. The FMWT, SKT, 20-mm, STN, and SLS surveys each operate for between 3 and 5 consecutive months annually, and cover broad spatial ranges in the estuary; the CMWT samples year-round at a single location near the confluence of the Sacramento River and the San Joaquin River. Table 1 shows the year each survey started, along with the current months of operation, current number of sample locations, and the life stages of Delta Smelt that dominate at that time of year. Table 1 also indicates the target species the surveys were originally designed to monitor, which include Striped Bass (*Morone saxatilis*), Longfin Smelt (*Spirinchus thaleichthys*), and Chinook Salmon (*Oncorhynchus tshawytscha*).

Descriptions of the trawls and tow methods used in the FMWT, SKT, 20-mm, STN, SLS, and CMWT surveys are shown in Table 2. The FMWT, 20-mm, STN, and SLS surveys use oblique towing methods; the SKT and CMWT use surface towing methods. During an oblique tow, the net is dropped down near the bottom of the river channel or embayment being sampled and retrieved at an angle over a predetermined amount of time (typically 10 to 12 min). Typically, one to three stepped-oblique tows are conducted at each sampling location. Stepped-

Table 1 Summary of the six monitoring surveys, including start year, current sampling details, original target species, and dominant Delta Smelt life stages targeted or caught.

Survey name	Start year	Sampling period	Sampling frequency	Number of locations	Original target species	Delta Smelt life stage(s)
FMWT	1967	September–December	Monthly	100+	Striped Bass	Sub-adults, adults
SKT	2002	January–May	Monthly	40	Delta Smelt	Adults
20-mm	1995	March–July	Biweekly	50+	Delta Smelt	Larvae, juveniles
STN	1959	June–August	Biweekly	32+	Striped Bass	Larvae, juveniles
SLS	2009	January–March	Biweekly	35	Longfin Smelt	Larvae, juveniles
CMWT	1976	Year-round	3 to 7 days per week	1	Chinook Salmon	All

Table 2 Descriptions of trawls and tow methods from the Fall Midwater Trawl Survey (FMWT), Spring Kodiak Trawl Survey (SKT), 20-mm Survey (20mm), Summer Townet Survey (STN), Smelt Larva Survey (SLS), and Chipps Island Midwater Trawl Survey (CMWT). Mesh characteristics reflect the trawls currently used and may differ from trawls used in the past.

Survey name	Maximum mouth area (m^2)	Maximum mouth height (m)	Mesh size and composition	Tow method
FMWT	13.4	3.7	Nine panels of stretch mesh starting at 20.3-cm near net mouth and decreasing to 1.3 cm at cod end	Stepped-oblique
SKT	13.95	1.8	Five panels of stretch mesh starting at 5.08-cm near net mouth and decreasing to 0.64 cm at cod end	Surface, 2 boats
20-mm	1.51	1.18	1,600-µm Nitex or nylon mesh	Stepped-oblique
STN	1.51	1.2	1.3-cm nylon mesh section near net mouth; 2,500-µm nylon mesh section at cod end	Stepped-oblique
SLS	0.37	0.62	500-µm Nitex mesh	Stepped-oblique
CMWT	58.65	6.9	Seven panels starting with 10.2-cm stretch mesh near net mouth and decreasing to 0.8-cm knotless material at cod end	Surface, 1 boat

oblique tows are conducted when minimum retrieval speed is faster than that needed to complete the tow in the proper time. In such a situation, the net is rapidly retrieved for a consistent, short distance and then paused for a consistent amount of time; this process is repeated so the net rises in the water column in a stepped fashion throughout the tow, and retrieval is complete at the end of the predetermined amount of time. The CMWT and SKT trawls are each towed parallel to the water surface with the net near the surface but fully submerged. The CMWT trawl is towed by a single boat while the SKT trawl is towed behind two boats that keep the mouth net open.

Gear dimensions and materials vary among nets, depending on the size range of the target fish. Single tows are conducted for larvae (SLS), sub-adults (FMWT), and adults (SKT) with appropriately scaled net mouth area and mesh size. Fish densities typically decline sharply as fish transition from larvae to juveniles, so as fish grow to juveniles three tows are used to filter additional water and improve detection (20-mm and STN). Further information on the FMWT, SKT, 20-mm, STN, and SLS surveys is available at *https://www.wildlife.ca.gov/Regions/3* (see "Surveys, Studies, Programs" and click on the survey name), and further information on the CMWT survey is available at *https://www.fws.gov/lodi/juvenile_fish_monitoring_program/jfmp_index.htm*.

Data Collection

We deployed subsets of the SLS, 20-mm, STN, FMWT, SKT, and CMWT survey trawls side-by-side over 12 days between September 2012 and July 2015 (Table A1 in Appendix A). We chose a side-by-side experimental design because it could accommodate multiple gears without the need for additional equipment such as cod-end covers. Generally, we

used trawls when the range of fish lengths in the Delta Smelt population was similar to the range of lengths the surveys would normally encounter, e.g., we used the SLS, 20-mm, and STN trawls when fish were smaller, and the FMWT and SKT trawls when fish were larger. In some cases, we used trawls to sample time-periods not ordinarily sampled by the trawls—when the fish are smaller or larger than would be seen during the standard survey period—to provide additional data and to better understand the overall shape of the selectivity curves. Although the CMWT survey samples year-round, we restricted our use of the CMWT trawl to when fish were larger, because the size of this gear and its target species (Chinook Salmon smolts) categorize it as a "larger fish" trawl in relation to Delta Smelt.

We sampled in the lower San Joaquin River near Jersey Point, in the lower Sacramento River adjacent to and just downstream of Decker Island, and in the Sacramento Deep Water Ship Channel (Figure 1), where routine monitoring surveys detected concentrations of Delta Smelt immediately before we sampled. To target areas with turbidity and salinity conditions thought favorable for Delta Smelt, we chose exact sampling locations on a per-date

basis. For all sampling, we tried to find turbidity >10 NTU (typically 12 to 30 NTU) and surface electro-conductivity (EC) >500 micro Siemens. Because turbidity and EC were less consequential for locating larvae, we identified sampling locations for them based on successful catches in long-term monitoring surveys. To account for depth bias, we defined three or four towing lanes that ranged from near shore to mid-channel (Figure 1). Trawls would start in a randomly assigned lane and sequentially move to the next lane after completing one tow (e.g., SKT) or a set of replicate tows (e.g., 20-mm, STN) in each lane. Once every gear had sampled in every lane, we randomly re-assigned the gears to new lanes, and the process would repeat. Larger trawls (FMWT, SKT, CMWT) typically completed one tow in a set; smaller trawls (SLS, 20-mm, STN) completed two to three replicate tows to increase the volume sampled and maximize the likelihood of encountering Delta Smelt. We chose dates so sampling would generally start on a morning flood tide and extend into the subsequent ebb tide. We targeted flood tides to increase the chance of encountering Delta Smelt (Feyrer et al. 2013), and, once we mobilized crews, continued to sample the ebb tide to use field time effectively. We
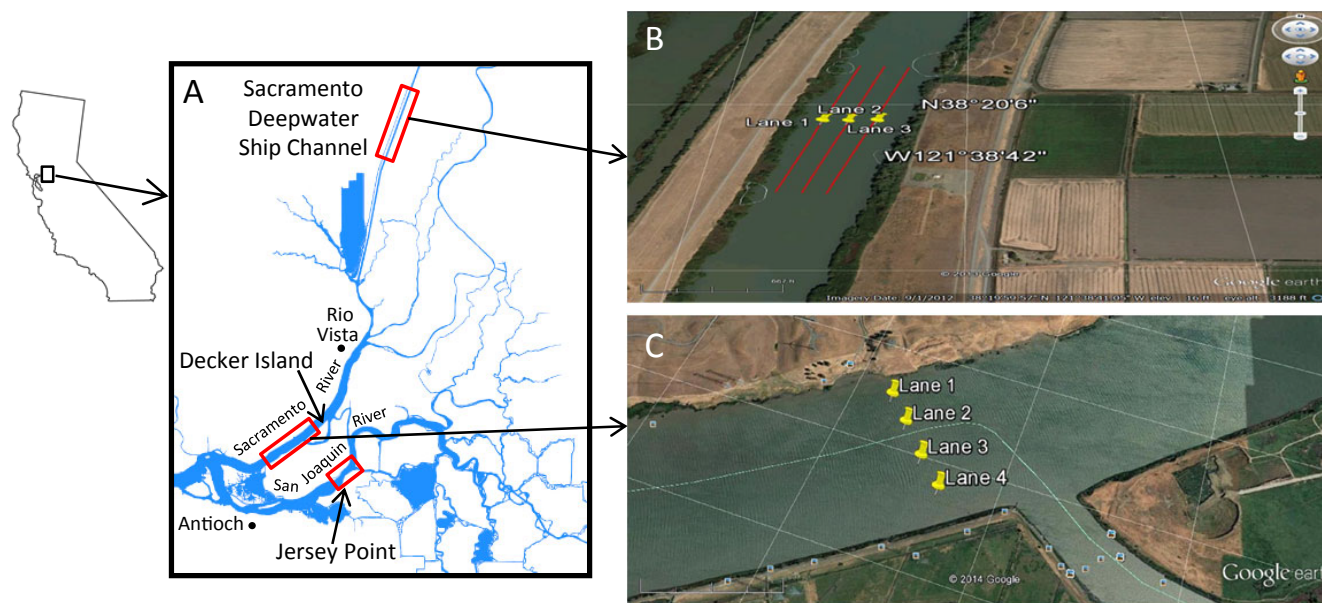

Figure 1   (**A**) Partial map of the San Francisco Estuary, California. Sampling for this study occurred in the San Joaquin River near Jersey Point, in the Sacramento River near Decker Island, and in the Sacramento Deep Water Ship Channel. The general sampling areas are indicated with *red boxes*. The cities of Antioch and Rio Vista are shown for reference. (**B**, **C**) Example tow lanes are shown in the sub-panels on the right for two of the three sample locations.

sampled only one of the three sampling locations (Jersey Point, Decker Island, or Sacramento Deep Water Ship Channel) on each date.

We individually enumerated, and measured to the nearest millimeter fork length, fish that could be identified in the field, unless the catch for a given species was particularly large, in which case we measured the first couple of hundred individuals and plus-counted the rest, except for Delta Smelt, which were all enumerated and measured. We wrapped identifiable Delta Smelt in aluminum foil and preserved them in liquid nitrogen; we preserved any non-identifiable larvae in a sample jar with a 10% formalin solution. The 10% formalin solution was buffered, and Rose Bengal was added to "color" translucent or white-ish larvae pink, making them easier to separate from debris and vegetation in the sample. Except for a few cases where we caught over 100 identifiable Delta Smelt and released some, we preserved all remaining Delta Smelt in liquid nitrogen or ethanol for additional studies, and to verify their identity when they arrived at the lab. We released all other identifiable fish species. We recorded flowmeter readings for every tow so we could estimate sample volume.

Gear Selectivity Estimation Methods

Catch Equation

Let $y_{d,j,l,i}$ be the number of length-l fish caught by gear j in replicate sample i on day d. A general equation for the expected number of fish caught (Millar and Fryer 1999) can be written as:

$$\mathrm{E}\big(y_{d,j,l,i}\big) = \delta_d \lambda_d(l) e_{d,j,i} r_j(l) \qquad (1)$$

where δ_d is the density of fish in the population being sampled, $\lambda_d(l)$ is the relative frequency of length-l fish in the population being sampled, $e_{d,j,i}$ is a measure of sampling effort in replicate sample i, and $r_j(l)$ is the gear selectivity function.

For the trawls in our study, this equation can be modified to:

$$\mathrm{E}\big(y_{d,j,l,i}\big) = \delta_d \lambda_d(l) v_{d,j,i} t_j r_j(l) \qquad (2)$$

where δ_d is the density of fish (i.e., the number of fish per unit volume of water) and sampling effort is given by the product of $v_{d,j,i}$, which is the volume of water sampled during the tow, and t_j, which is a constant representing other factors that may influence catch, such as the method used to deploy and tow the trawl (e.g., one vs. two boats, sampling at the surface vs. deeper in the water column). Our data, as well as other studies, suggest that tow method may affect catch densities of Delta Smelt (Anonymous 1994; Souza 2002; Mitchell et al. 2017). However, such an effect has not been well quantified for the gears in this study, which means that sampling effort may not be well defined despite the availability of tow volume estimates.

Overview of Catch Comparison Methods

Selectivity estimation methods for multiple gears often involve modeling proportional catch-at-length or catch per unit effort (CPUE)-at-length as a function of length (Millar and Fryer 1999; Browne et al. 2017; Kotwicki et al. 2017). Here, we describe two of these methods within a unifying framework.

Dropping date and tow subscripts for simplicity, let $\phi_{j,l}$ be the proportion of length-l fish caught by gear j relative to the total catch by all gears:

$$\phi_{j,i} = \frac{y_{j,l}}{\Sigma_k y_{k,l}} \qquad (3)$$

The denominator in this equation, subscripted by k, runs across all the gears. Then, using Equation 1, the expected value of $\phi_{j,l}$ (Millar and Fryer 1999) can be written as:

$$E\big(\phi_{j,i}\big) = E\!\left(\frac{y_{j,l}}{\Sigma_k y_{k,l}}\right) \approx \frac{\delta\lambda(l) r_j(l) e_j}{\Sigma_k \delta\lambda(l) r_k(l) e_k} = \frac{r_j(l) e_j}{\Sigma_k r_k(l) e_k} \qquad (4)$$

where the last term, $r_j(l)e_j / \Sigma_k r_k(l)e_k$, is proportional relative efficiency. From this point, one approach is to fit a model that describes the proportional catch data (Equation 3) as a function of gear and length (and possibly other covariates), denoted $g(j,l)$. Then, this function can be used to approximate proportional relative efficiency:

$$\frac{r_j(l) e_j}{\Sigma_k r_k(l) e_k} = g(j,l) = \hat{\phi}_{j,l}. \qquad (5)$$

For example, the logit of proportional catch may be modeled as a polynomial:

$$\text{logit}(\phi_{j,l}) = \beta_{0,j} + \beta_{1,j}l + \beta_{2,j}l^2 + \beta_{3,j}l^3$$

(Krag et al. 2014; Kotwicki et al. 2017). Rearranging Equation 5 leads to the relationship:

$$\frac{r_j(l)e_j}{\Sigma_{k \neq j}r_k(l)e_k} \approx \left(\frac{\hat{\phi}_{j,l}}{1 - \hat{\phi}_{j,l}}\right), \quad (6)$$

which in the case of two gears and known effort can be further simplified to give the ratio of the two selectivities (Kotwicki et al. 2017). In the special case where there are two gears, effort is known, and one gear is non-selective, the absolute selectivity of the other gear can be determined (Somerton et al. 2013).

The SELECT (share each length's catch total) method (Millar 1992) offers an alternative approach in which gear selectivity, $r_j(l)$, and gear-specific measures of *relative* sampling effort—referred to as "relative fishing intensities"—are estimated separately (in contrast to Equation 5). Relative fishing intensity, denoted here by p_j rather than e_j, is interpreted as the probability of a fish being caught by gear j given that it was available to the set of gears that sampled together (Millar 1992). The relative fishing intensities, therefore, sum to one across gears ($\Sigma_k p_k = 1$). See Millar and Fryer (1999) for a comprehensive overview of the SELECT method and further discussion of relative fishing intensity.

Under the SELECT method, catch by gear and length class is multinomially distributed:

$$y_{1,1}, y_{1,2}, \ldots, y_{1,L}, y_{2,1}, \ldots, y_{J,L} \sim Multinomial\left(n, E\left(\varphi_{j,l}\right)\right), \quad (7)$$
$$j = 1, \ldots, J, l = 1, \ldots L,$$

where n is the total catch over all gears and lengths, and the cell probabilities are given by:

$$\varphi_{j,l} = \frac{r_j(l)\,p_j}{\Sigma_k r_k(l)\,p_k} \cdot$$

The log-likelihood for the SELECT model can then be written as:

$$\ell = \sum_j \sum_l y_{j,l} \log_e\left(\frac{r_j(l)\,p_j}{\Sigma_k r_k(l)\,p_k}\right) \quad (8)$$

where a functional form is assumed for $r_j(l)$. The values of p_k can be fixed or estimated (Millar 1992; Fujimori and Tokai 2001), depending on the assumptions made about the availability of fish to each gear; for example, if there are two gears and it is reasonable to assume they sampled with equal intensity, then both p_1 and p_2 can be set equal to 0.5.

Alternative Method Based on Estimating Length Distribution

Quang and Geiger (2002) described a method to estimate selectivity that is based on the total number of fish caught by an individual gear, and uses a multinomial model to describe the number of length-l fish caught. The method requires assumptions about the functional forms of the population-length distribution and the selectivity curves. We overview the method here.

The probability density function (PDF) for the lengths of fish caught by gear j can be written as:

$$f_j(l) = \frac{\psi(l)r_j(l)}{\int_0^\infty \psi(x)r_j(x)dx} \quad (9)$$

where $\psi(l)$ is the PDF of lengths in the population. Note that the integral of $\psi(l)$ over an interval around l yields $\lambda(l)$ in Equation 1. Integrating $f_j(l)$ over a small interval of width Δ centered around length l gives the probability that a fish caught by gear j will have length l:

$$q_{j,l} = \int_{l-\Delta/2}^{l+\Delta/2} f_j(x)dx \quad (10)$$

The catches by length class for gear j ($y_{j,1}, y_{j,2}, y_{j,3}, \ldots$) are multinomially distributed with total $n_j = \Sigma_l y_{j,l}$ and cell probabilities ($q_{j,1}, q_{j,2}, q_{j,3}, \ldots$). The log-likelihood for the multinomial model can be written as:

$$\ell = \sum_j \sum_l y_{j,l} \log_e\left(q_{j,l}\right) \quad (11)$$

and maximum likelihood can be used to estimate the parameters that define the selectivity curves and the population length densities. Note that if Δ is small, $f_j(l)$ can be used in place of $q_{j,l}$:

$$\ell = \sum_j \sum_l y_{j,l} \log_e\left(f_j(l)\right) \quad (12)$$

For convenience, we refer to this as the SELF (share each length frequency) method because the population length frequencies used in Equation 9 are the same for each gear. One fundamental difference between the SELECT and SELF methods is that SELECT involves fitting a single multinomial distribution for *all* the gears; SELF involves fitting a separate multinomial distribution for *each* gear.

Applying Selectivity-Estimation Methods to Delta Smelt

We used both the SELECT and the SELF methods to estimate selectivity curves for the SLS, 20-mm, STN, and SKT gears. Given that we co-deployed different subsets of trawls on different days, and the range of observed lengths on any given day was limited because of minimal overlap between year-classes of Delta Smelt, we wanted to integrate data from multiple days of sampling into a single analysis. We therefore extended the SELECT and SELF methods (as described in the next two sections) to incorporate multiple days of sampling, and let the parameters of the selectivity curves be shared across days. We applied both methods because they both appeared to be viable options to estimate selectivity for Delta Smelt, and we chose the SELECT method over other catch comparison-based approaches because our goal was to fit trawl-specific selectivity curves (i.e., to isolate the $r_j(l)$ functions).

We fit models that included data from the SLS, 20-mm, STN, and SKT gears but not FMWT or CMWT. We excluded FMWT and CMWT because they had consistently low catches and did not provide length information outside of the ranges caught by the other gears used in the fall. Although SLS and STN also often had low catches, SLS provided data on the smallest fish, and STN was the one gear deployed on every sample date.

Method One: SELECT

Extending Equation 8, the log-likelihood for the multi-day SELECT model can be written as:

$$\ell = \sum_d \sum_{j \in \mathcal{J}_d} \sum_l y_{d,j,l} \log_e \left(\frac{r_j(l) \, p_{d,j}}{\sum_{k \in \mathcal{J}_d} r_k(l) \, p_{d,k}} \right) \quad (13)$$

where the relative fishing intensities are date-specific, and $\mathcal{J}_d$ represents the set of gears that sampled on day d. To ensure the relative fishing intensities were each between zero and one and that they summed to one on a given date, we re-expressed $p_{d,j}$ as:

$$p_{d,j} = \frac{\exp(\alpha_{d,j})}{\sum_{j=1}^{J_d} \exp(\alpha_{d,j})} \quad (14)$$

where $\alpha_{d,j}$ is a real number and J_d is the number of gears that sampled on day d. Because of the summation constraint, only $J_d - 1$ of the parameters $\alpha_{d,j}$ need to be estimated, so we fixed one $\alpha_{d,j}$ at zero and estimated the remaining values as model parameters.

We used a three-parameter exponential–logistic function (Thompson 1994) for the SLS, 20-mm, and STN selectivity functions:

$$r_j(l) = \left(\frac{1}{1 - \beta_{0,j}} \right) \left(\frac{1 - \beta_{0,j}}{\beta_{0,j}} \right)^{\beta_{0,j}} \left(\frac{\exp\left(\beta_{1,j} \beta_{0,j} \left(\beta_{2,j} - l \right) \right)}{1 + \exp\left(\beta_{1,j} \left(\beta_{2,j} - 1 \right) \right)} \right), \quad (15)$$

$$j = \text{SLS, 20mm, STN}.$$

The exponential–logistic function is dome-shaped when $\beta_{0,j}$ is positive and logistic when $\beta_{0,j}$ is zero, so it allows for some flexibility in curve shape. The maximum value of this function is 1 when the function is dome-shaped, and approaches 1 when the function is logistic. We determined each function $r_j(l)$ up to an unknown constant scaling factor that is confounded with $p_{d,j}$ (Millar 1992).

We first used an exponential–logistic function for SKT, too, but found that $\beta_{0,\text{SKT}}$ was zero, which suggests that the SKT curve is logistic. To reduce fitting time going forward, we modeled SKT selectivity with a logistic function directly:

$$r_{\text{SKT}}(l) = \frac{1}{1 + \exp\left(\gamma_{1,j} \left(l - \gamma_{2,j} \right) \right)} \quad (16)$$

Note that this equation has a different parameterization but is equivalent to Equation 15 with $\beta_{0,j} = 0$.

We used maximum likelihood to estimate the selectivity-function parameters and relative fishing intensities. Optimization was carried out in R (R Core Team 2018) using the optim function. We excluded data from May 17, 2013, and November 21, 2013

because of low catches by all of the gears and zero catches by STN on these dates, respectively. For a given date and trawl, we pooled data from replicate tows because catches in individual tows were generally low. We used 1-mm length classes, and for a given day only included length classes for which there was at least one Delta Smelt catch across all gears; this means that the denominator inside the log term in Equation 13 included only length classes with at least one fish. We started with generic initial values and iteratively fit the model to find initial values that corresponded to progressively smaller values of the negative log-likelihood. We used bounds to constrain the model parameters (Table 3).

Method Two: SELF

We extended the general SELF model to incorporate multiple days of sampling by defining date-specific, population-length probability density functions, represented by $\psi_d(l)$. The likelihood for this modified model can be written as:

$$\ell = \sum_d \sum_{j \in \mathcal{J}_d} \sum_l y_{d,j,l} \log_e\left(f_{d,j}(l)\right) \qquad (17)$$

where

$$f_{d,j}(l) = \frac{\psi_d(l) r_j(l)}{\int_0^\infty \psi_d(x) r_j(x) dx} \qquad (18)$$

We used a log-normal random-variable PDF with log-scale mean μ_d and log-scale standard deviation σ_d to describe the population length density curve:

$$\psi_d(l) = \frac{1}{\sqrt{2\pi}\sigma_d l} \exp\left(-\frac{\left(\log_e(l) - \mu_d\right)^2}{2\sigma_d^2}\right) \qquad (19)$$

For ease of interpretation when applying Equation 19, we specified the mean on the natural (non-log) scale, m_d, and the coefficient of variation on the natural scale, cv_d. These are related to μ_d and σ_d as follows:

$$\mu_d = \log_e\left(m_d / \sqrt{1 + cv_d^2}\right) \text{ and } \sigma_d^2 = \log_e\left(1 + cv_d^2\right).$$

The lengths of Delta Smelt caught by a given gear on a given date were pooled, meaning we did not distinguish between replicate tows.

As in the SELECT model, we used exponential–logistic functions for SLS, 20-mm, and STN, and a logistic function for SKT. We again determined each function $r_j(l)$ up to an unknown constant scaling factor that cancels from Equation 18.

We used maximum likelihood to estimate the selectivity-function parameters and length-distribution parameters. As before, we optimized in R using optim, and we excluded data from May 17, 2013, and November 21, 2013. We also excluded age-1 Delta Smelt (see next paragraph). In Equation 18, we numerically calculated the integral from 1 to 90. To reduce the number of parameters, we shared σ_d parameters across dates that we expected to have similar coefficients of variation based on the time of year. We used one parameter, σ_{AprMay}, for all dates in the months of April or May, σ_{Jun} for June, σ_{JulAug} for July and August, and σ_{SepOct} for September and October. We iteratively investigated initial values; for the final set of initial values, we used the same selectivity parameters as in the SELECT model.

Delta Smelt are commonly grouped into two age categories: age 0, meaning the individual hatched in the same calendar year in which it was caught, and age 1+, meaning the individual hatched in a year before the year in which it was caught. Based on the life history of Delta Smelt, we expected most of the individuals we caught during this study to be age 0 because sampling avoided the January through March period when most individuals are age 1. We used an age-length key to assign age categories to individual fish based on length and month of catch. The age-length key (Table A1 in Appendix A) was provided by S. Slater (2013 email from S. Slater, CDFW, to L. Mitchell, unreferenced, see "Notes"), and is based on an age-length key published in Baxter (1999). We estimated that nine Delta Smelt caught by SKT and three caught by STN were age 1+. Because age-1+ fish will have a different length distribution than age-0 fish, and because it was not realistic to

Table 3 Bounds, estimates, and coefficients of variation (absolute value) from the SELECT model. To facilitate interpretation, calculated relative fishing intensities are shown on the right.

Parameter	Lower bound	Upper bound	Estimate	CV	Quantity	Value	CV
$\alpha_{2013\text{-}04\text{-}18,SLS}$	$-\infty$	∞	−0.439	4.274	$p_{2013\text{-}04\text{-}18,SLS}$	0.162	0.673
$\alpha_{2013\text{-}04\text{-}18,20mm}$	$-\infty$	∞	0.844	2.224	$p_{2013\text{-}04\text{-}18,20mm}$	0.586	0.352
$\alpha_{2014\text{-}04\text{-}24,SLS}$	$-\infty$	∞	−0.929	1.447	$p_{2013\text{-}04\text{-}18,STN}$	0.252	0.938
$\alpha_{2014\text{-}04\text{-}24,20mm}$	$-\infty$	∞	0.899	1.424	$p_{2014\text{-}04\text{-}24,SLS}$	0.103	0.869
$\alpha_{2014\text{-}05\text{-}22,SLS}$	$-\infty$	∞	−0.847	1.527	$p_{2014\text{-}04\text{-}24,20mm}$	0.638	0.279
$\alpha_{2014\text{-}05\text{-}22,20mm}$	$-\infty$	∞	0.794	1.400	$p_{2014\text{-}04\text{-}24,STN}$	0.260	0.729
$\alpha_{2013\text{-}06\text{-}13,20mm}$	$-\infty$	∞	1.438	0.797	$p_{2014\text{-}05\text{-}22,SLS}$	0.118	0.966
$\alpha_{2014\text{-}06\text{-}19,20mm}$	$-\infty$	∞	−0.212	5.842	$p_{2014\text{-}05\text{-}22,20mm}$	0.608	0.278
$\alpha_{2015\text{-}07\text{-}02,20mm}$	$-\infty$	∞	0.667	2.201	$p_{2014\text{-}05\text{-}22,STN}$	0.275	0.660
$\alpha_{2015\text{-}07\text{-}02,STN}$	$-\infty$	∞	−3.711	0.233	$p_{2013\text{-}06\text{-}13,20mm}$	0.808	0.217
$\alpha_{2014\text{-}08\text{-}19,20mm}$	$-\infty$	∞	−0.516	3.979	$p_{2013\text{-}06\text{-}13,STN}$	0.192	0.915
$\alpha_{2014\text{-}08\text{-}19,STN}$	$-\infty$	∞	−4.034	0.331	$p_{2014\text{-}06\text{-}19,20mm}$	0.447	0.485
$\alpha_{2012\text{-}09\text{-}27,STN}$	$-\infty$	∞	−2.240	0.472	$p_{2014\text{-}06\text{-}19,STN}$	0.553	0.392
$\alpha_{2013\text{-}09\text{-}26,STN}$	$-\infty$	∞	−2.936	0.416	$p_{2015\text{-}07\text{-}02,20mm}$	0.655	0.366
$\alpha_{2012\text{-}10\text{-}25,STN}$	$-\infty$	∞	−2.127	0.697	$p_{2015\text{-}07\text{-}02,STN}$	0.008	1.689
$\beta_{0,SLS}$	0	0.99	0.989	0.340	$p_{2015\text{-}07\text{-}02,SKT}$	0.336	0.700
$\beta_{1,SLS}$	0.0001	5	0.216	7.246	$p_{2014\text{-}08\text{-}19,20mm}$	0.370	0.756
$\beta_{2,SLS}$	−20	50	18.999	0.209	$p_{2014\text{-}08\text{-}19,STN}$	0.011	2.834
$\beta_{0,20mm}$	0	0.99	0.088	1.091	$p_{2014\text{-}08\text{-}19,SKT}$	0.619	0.450
$\beta_{1,20mm}$	0.0001	5	1.121	0.965	$p_{2012\text{-}09\text{-}27,STN}$	0.096	1.725
$\beta_{2,20mm}$	−20	50	13.315	0.202	$p_{2012\text{-}09\text{-}27,SKT}$	0.904	0.184
$\beta_{0,STN}$	0	0.99	0.079	1.406	$p_{2013\text{-}09\text{-}26,STN}$	0.050	3.236
$\beta_{1,STN}$	0.0001	5	0.479	1.984	$p_{2013\text{-}09\text{-}26,SKT}$	0.950	0.172
$\beta_{2,STN}$	−20	50	24.172	0.208	$p_{2012\text{-}10\text{-}25,STN}$	0.107	2.289
$\gamma_{1,SKT}$	0	3	1.621	0.028	$p_{2012\text{-}10\text{-}25,SKT}$	0.893	0.273
$\gamma_{2,SKT}$	0	80	29.970	0.0006			

estimate additional length distributions based on sporadic age-1+ catches, we removed the age-1+ fish from the SELF model. Age-1+ fish were not removed from the SELECT model because the SELECT method does not distinguish between year-classes.

Confidence Interval Calculations and Diagnostics

To account for extra variability (namely, between-date and between-tow variability), we calculated standard errors and confidence intervals using a bootstrap procedure (Fryer 1991; Millar and Fryer 1999). For the SELECT method, we generated 1,000 replicate data sets by first resampling dates; for

each gear-date combination, we resampled from the replicate tows that had positive Delta Smelt catch, and for each of these tows we resampled Delta Smelt fork lengths. We carried out all bootstrap resampling with replacement. We restricted resampling of tows to those with positive catch because many tows had zero catch. We re-fit the SELECT model with each replicate data set using the parameter estimates from the original model as initial values. We calculated a standard error for each model parameter estimate using the resulting sets of parameter estimates. We also calculated a 95% pointwise confidence interval for each predicted probability-at-length value, $r_j(l)$. For a particular gear and length class, we did this by

calculating 2.5th and 97.5th percentiles from the set of bootstrap-predicted values of $r_j(l)$. We repeated the entire procedure for the SELF method.

We evaluated goodness-of-fit of the SELECT and SELF models by plotting standardized catch-at-length residuals against fish length. We calculated standardized residuals as the difference between observed and expected catch, divided by an estimate of the standard error of the catch:

$$e_{d,j,l} = \frac{y_{d,j,l} - \mathrm{E}(y_{d,j,l})}{\mathrm{SE}(y_{d,j,l})} \tag{20}$$

For the SELECT method, the expected catch of length-l fish on date d by gear j was calculated as:

$$\mathrm{E}(y_{d,j,l}) = n_{d,\cdot,l}\hat{\phi}_{d,j,l} = \left(\sum_j y_{d,j,l}\right)\hat{\phi}_{d,j,l} \tag{21}$$

and the standard error was calculated as:

$$\mathrm{SE}(y_{d,j,l}) = \sqrt{n_{d,\cdot,l}\hat{\phi}_{d,j,l}\left(1 - \hat{\phi}_{d,j,l}\right)} \tag{22}$$

using formulas for a multinomial distribution. For the SELF method, we first grouped fish into 18 5-mm-length bins that covered the range from 1 to 91 mm. Let Δl_i represent the ith bin and let $y_{d,j,\Delta l_i}$ be the number of fish caught on date d by gear j that belong in bin i. We calculated expected catch as:

$$\mathrm{E}(y_{d,j,\Delta l_i}) = n_{d,j,\cdot}\int_{\Delta l_i}\hat{f}_j(x)dx = \left(\sum_l y_{d,j,l}\right)\int_{\Delta l_i}\hat{f}_j(x)dx \tag{23}$$

and standard error as:

$$\mathrm{SE}(y_{d,j,\Delta l_i}) = \sqrt{n_{d,j,\cdot}\int_{\Delta l_i}\hat{f}_j(x)dx\left(1 - \int_{\Delta l_i}\hat{f}_j(x)dx\right)} \tag{24}$$

We used 5-mm bins to increase the number of non-zero expected catches. Expected catches between zero and one were rounded to the nearest integer, and plots were restricted to lengths for which expected catch was greater than zero.

RESULTS

Delta Smelt Catch Summary

We caught 2,371 Delta Smelt during the gear comparison study. Figures 2 through 4 summarize catches by date, gear, and fork length. These figures also show the total volume of water each gear sampled on each date. Figure 5 summarizes catch densities of Delta Smelt, calculated at the individual tow level. Although FMWT and CMWT had the highest levels of sampling effort in terms of volume of water sampled, they produced low catches compared to SKT. The trawls commonly had a high number of low or zero catches mixed with occasional very large catches (e.g., SLS on April 18, 2013, and SKT on August 19, 2014), likely as a result of patchiness in the distribution of Delta Smelt as well as net evasion.

Box plots of Delta Smelt fork lengths pooled over select sampling dates indicate that below roughly 40 mm, size selectivity of the SLS, 20-mm, and STN gears follows an increasing pattern with increasing mesh size (panels A and B on Figure 6). Between roughly 40 and 60 mm, the observed length distributions for the 20-mm, STN, and SKT gears appear to be similar, though low catches by 20-mm and STN in July and August make comparison difficult (panel C in Figure 6). In the 40 to 80+ mm range, the FMWT and CMWT gears appear to have caught the larger fish and missed some of the smaller fish that STN and SKT were able to catch (panel D in Figure 6). Based on these data, a general ranking of size selectivity from smallest to largest would be: SLS, 20-mm, STN, SKT, FMWT, CMWT, which — with the exception of the ordering of FMWT and CMWT — follows the order of increasing cod-end mesh size (Table 2).

Selectivity Estimates

The SELECT and SELF models produced selectivity curves that are qualitatively similar (Figure 7). Note that while the vertical axes in Figure 7 range from zero to one, the predicted retention probabilities are relative, since the scaling of the curves is undetermined. In both models, SLS retention decreases with increasing fish size, the STN and 20-mm curves are dome-shaped, and the relative selectivity of SKT is one over the range of lengths it caught. According to these models, SLS is most efficient at catching the smallest fish, 20-mm is most efficient around roughly 20 mm, STN is most efficient around roughly 30 mm, and SKT is
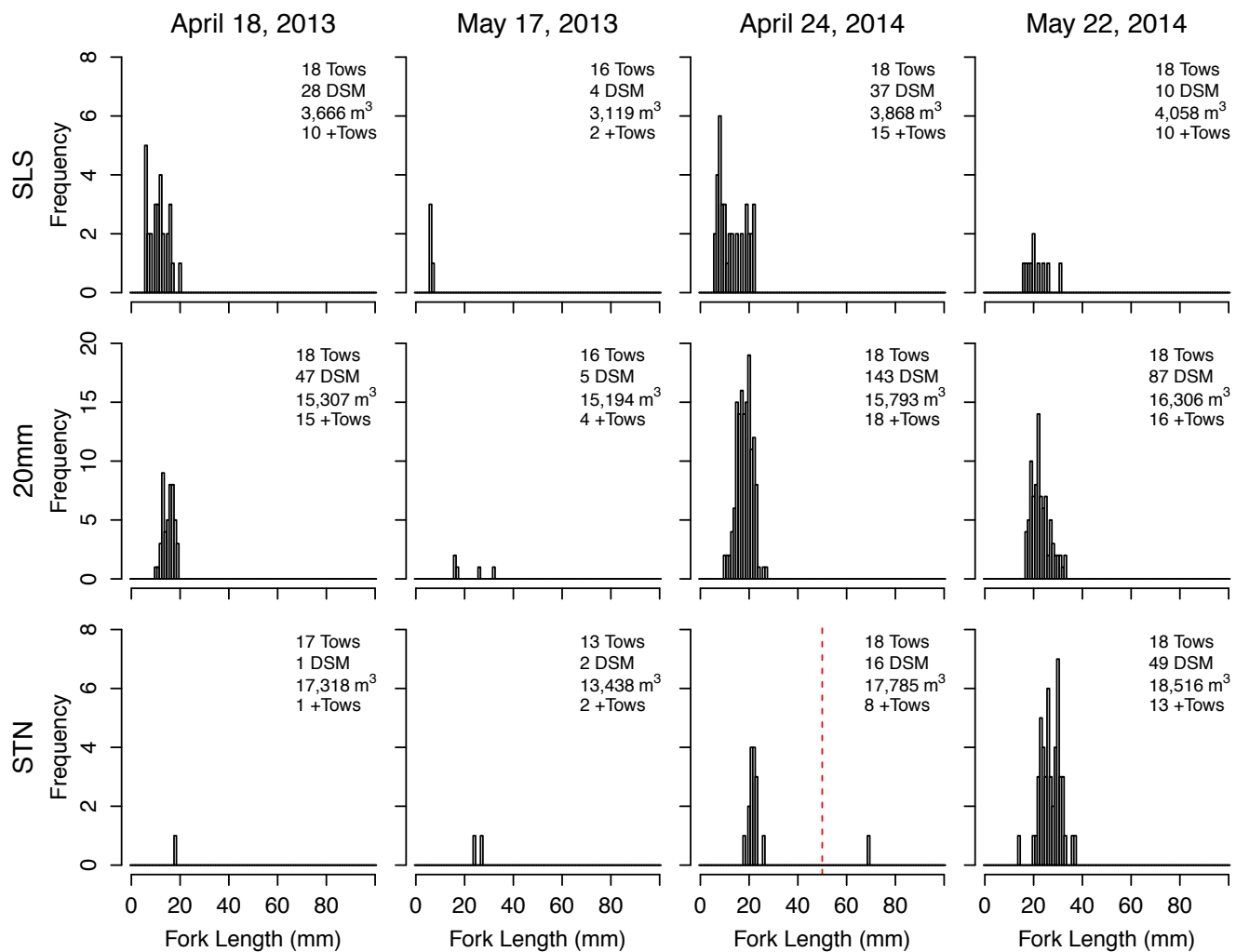
Figure 2 Delta Smelt length–frequency distributions during spring sampling dates, arranged by gear and date. The total number of tows, total number of Delta Smelt caught (DSM), total volume of water sampled (in cubic meters, m³), and number of tows with positive Delta Smelt catch (+Tows) is indicated in the *top right corner* of each panel. A *dashed vertical line* is shown in cases where at least one fish was determined to be age 1+; the length(s) of the age 1+ fish occur on or to the right of the dashed line.

relatively efficient above 35 mm. We observed that SLS catches of multiple fish species, including Delta Smelt, dropped off for fish larger than approximately 10 mm. The peak in the 20-mm SELF curve occurs at 20.5 mm, and the peak in the SELECT curve occurs at 15.4 mm. The peak in the STN SELF curve occurs at 26.5 mm, and in the SELECT curve at 29.3 mm. The parameter $\mu_{2014\text{-}06\text{-}19}$ in the SELF model hit the upper bound, and increasing the bound resulted in the model's non-convergence.

The parameter estimates and the predicted selectivity values show a high level of uncertainty (Tables 3

and 4; Figure 7). We had difficulty resolving the shape of the SLS selectivity curve as well as the right tails of the STN and 20-mm curves, which have some pointwise confidence intervals that range from 0 to 1. The SKT curves have confidence intervals that range from 0.99 to 1 over the range of lengths that SKT caught. The models were sensitive to initial values, and SLS selectivity was particularly unstable, as reflected in its wide confidence intervals. Furthermore, the SELF model had high correlation (> 0.9) between the 20-mm and SLS selectivity curve parameters, and frequently between gear-selectivity parameters and the length-distribution parameters.
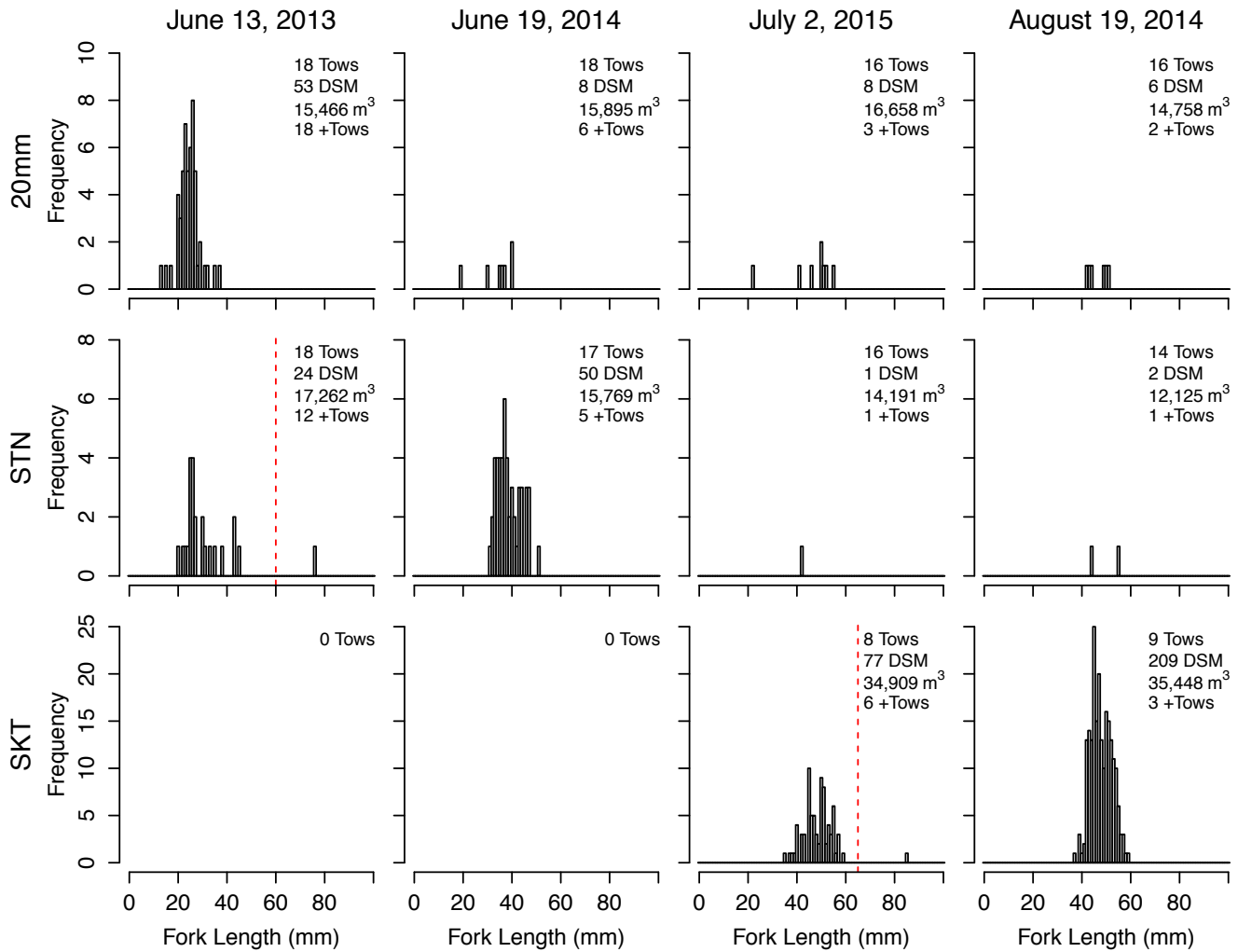
Figure 3 Delta Smelt length–frequency distributions during summer sampling dates, arranged by gear and date. The total number of tows, total number of Delta Smelt caught (DSM), total volume of water sampled (in cubic meters, m³), and number of tows with positive Delta Smelt catch (+Tows) is indicated in the *top right corner* of each panel. A *dashed vertical line* is shown in cases where at least one fish was determined to be age 1+; the length(s) of the age 1+ fish occur on or to the right of the dashed line. One of the eight Delta Smelt caught on June 19, 2014, in the 20-mm trawl did not have its length recorded.

The SELF residual patterns (Figure 8) for all four gears and the SELECT residual patterns for SLS, 20-mm, and STN do not indicate systematic misfit of the selectivity models. The SELECT model has some large negative SKT residuals. The differences between observed and predicted SKT catches corresponding to the ten largest negative residuals ranged from 0.9 to 3.5, with most differences being less than 2.

The estimated relative fishing intensities for SELECT (Table 3) generally do not reflect the level of relative sampling effort that the total daily sample volumes predict. For example, on June 13, 2013, 20-mm and STN sampled 47.2% and 52.7% of the total volume for that day (see volume information in Figure 3), while the relative fishing intensities are 80.8% and 19.2% (Table 3). The fitted population length density curves (from SELF) show average length increasing over time from spring to fall as fish grow, and the coefficient of variation decreasing over time, presumably as fish approach an asymptotic upper size limit (Table 4 and Figure 9).
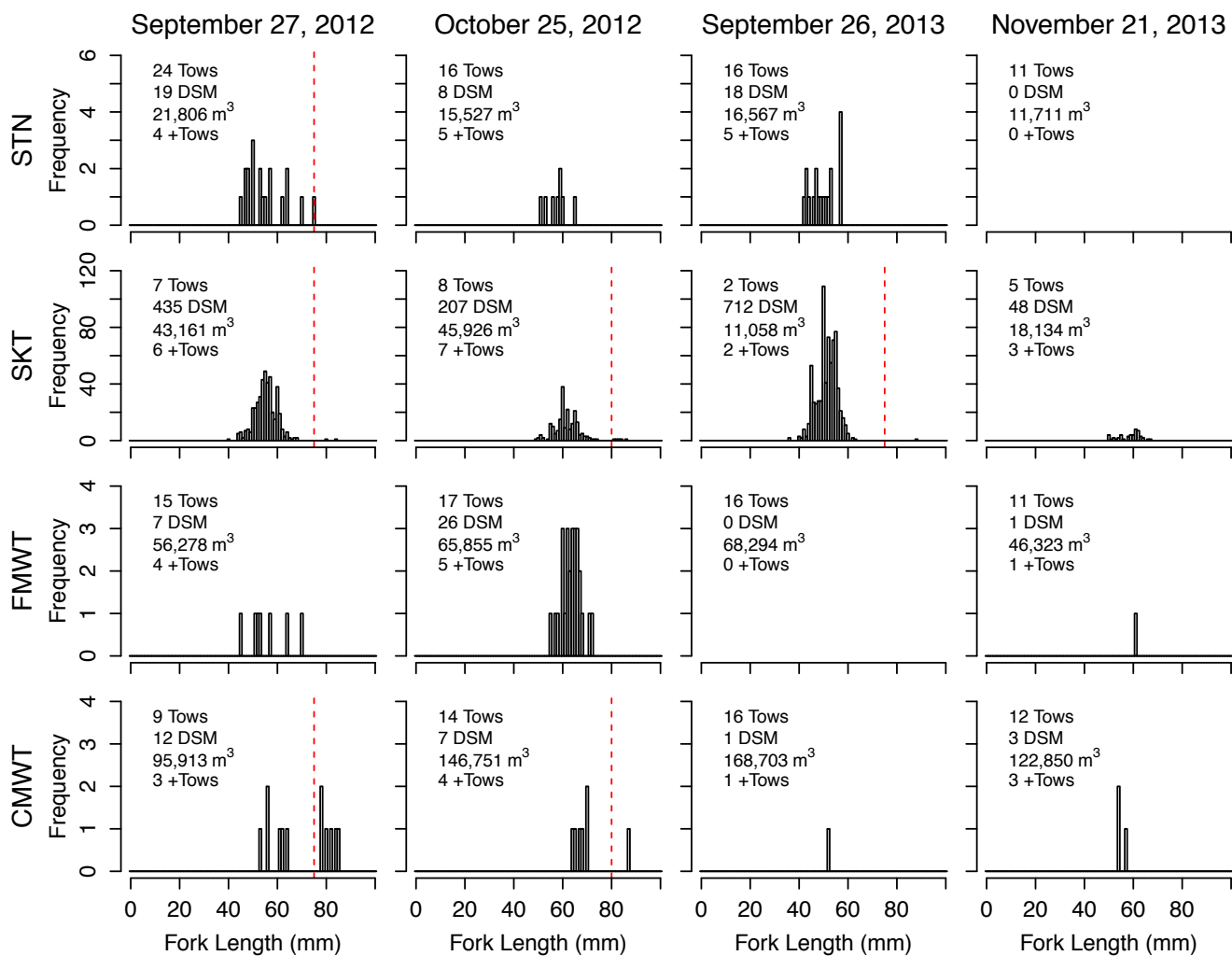
Figure 4 Delta Smelt length–frequency distributions during fall sampling dates, arranged by gear and date caught. The total number of tows, total number of Delta Smelt caught (DSM), total volume of water sampled (in cubic meters, m³), and number of tows with positive Delta Smelt catch (+Tows) is indicated in the *top left corner* of each panel. A *dashed vertical line* is shown in cases where at least one fish was determined to be age 1+; the length(s) of the age 1+ fish occur on or to the right of the dashed line.

DISCUSSION

Application of Delta Smelt Selectivity

Survey gear efficiency has been evaluated in the estuary for several decades (Miller 1977; Fujimura 1989; McLain 1998; Gartz et al. 1999). Such gear evaluations can inform management decisions in direct ways (e.g., through the replacement of one survey gear with a more efficient gear [Souza 2002]) — as well as indirect ways (e.g., through scaling historical catch densities with measures of gear efficiency to standardize data; Newman 2008; Kotwicki et al. 2017). Previous studies have examined the selectivity of the FMWT gear alone (Newman 2008; Mitchell et al. 2017), but this study constitutes the first formal evaluation of multiple gears used to monitor Delta Smelt. We are currently using these selectivity results to calculate Delta Smelt abundance indices that incorporate multiple sources of uncertainty, including uncertainty in the gear selectivity curves themselves. One way to accomplish this is to use a Horvitz–Thompson estimator (Horvitz and Thompson 1952), in which the number of fish caught is upwardly adjusted to account for fish *that would have been caught if the gear were non-selective* (Newman 2008). For example, suppose a
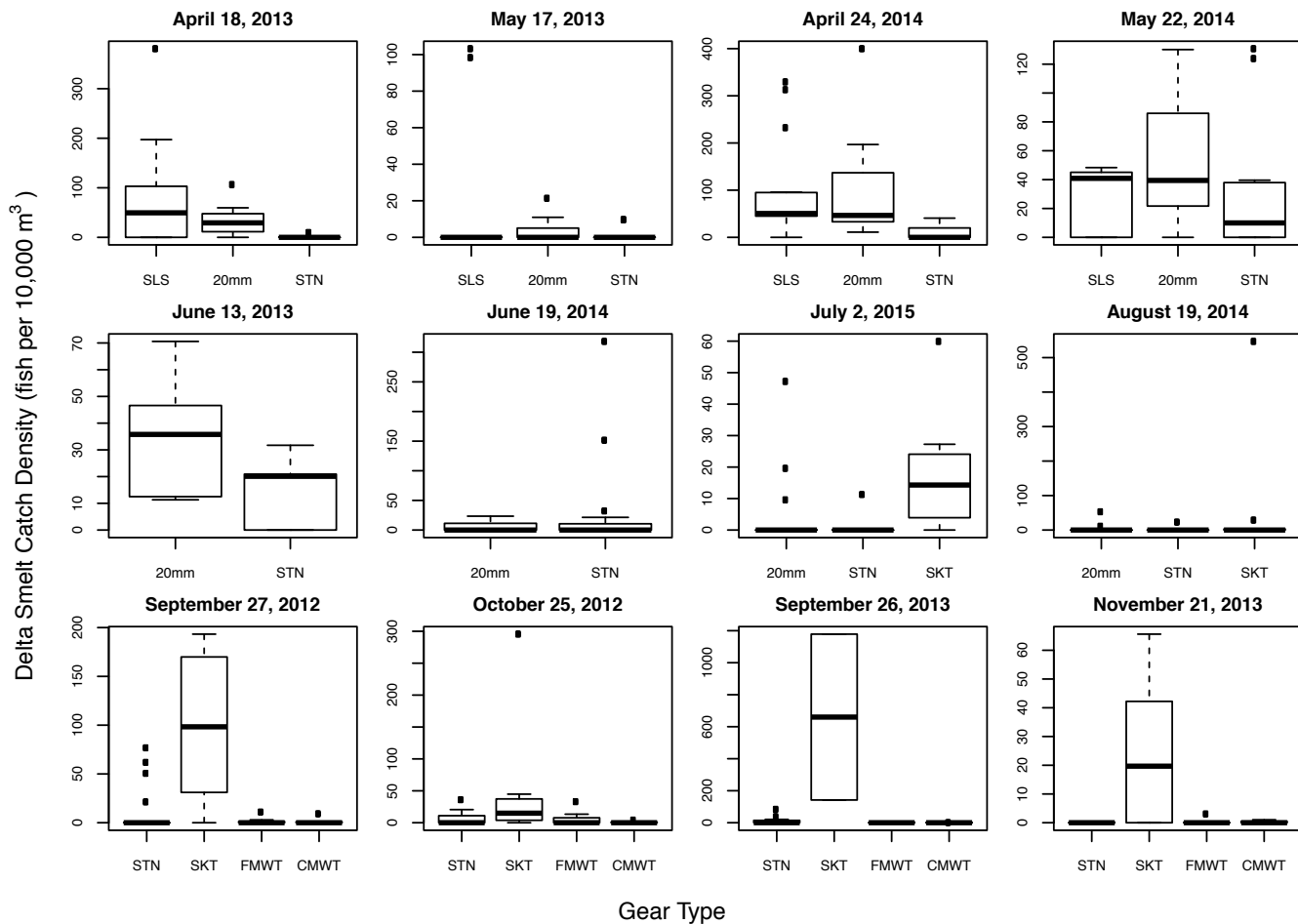
Figure 5 Box plots of tow-level catch densities of Delta Smelt by gear type and date caught. Densities are calculated as the number of fish per 10,000 m³ of water sampled.

survey catches n fish in a tow, let L_i be the length of the ith fish, and let $r(L)$ be the selectivity function for the survey. Then, the adjusted catch is given by:

$$n^* = \sum_{i=1}^{n} \frac{1}{r(L_i)}.$$

Suppose the n fish are caught in sample volume v; then an estimate of the abundance of fish can be calculated as:

$$\widehat{N} = \frac{n^*}{v} \times V,$$

where V is the total volume of water occupied by fish. A multi-stage variance formula can then be used to estimate the variance of $\widehat{N}$ (Newman 2008). Alternatively, data from the side-by-side study and data from the fish surveys could be incorporated into an integrated population model that simultaneously

estimates gear selectivity and abundance (Schaub and Abadi 2011). This approach would then automatically account for uncertainty in the gear-selectivity parameters.

Discussion of Overall Relative Efficiency

The SKT gear was more efficient overall for catching Delta Smelt between roughly 40 and 80 mm than the other gears with which it was co-deployed. For adult Delta Smelt, these results are consistent with previous studies in which a surface-oriented Kodiak trawl produced substantially higher catch densities of adults than a traditional midwater trawl (Anonymous 1994; Souza 2002). Our results also suggest that the SKT gear has a higher probability of catching Delta Smelt than the other gears as early in the year as
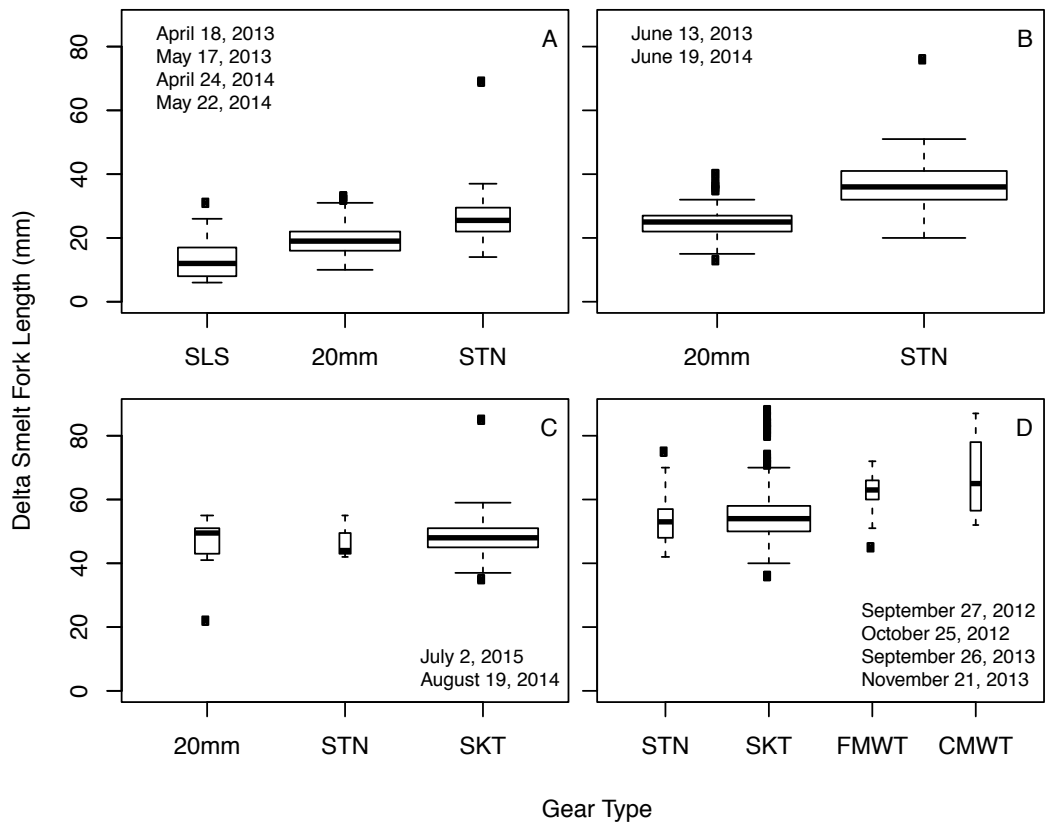
Figure 6 Box plots of Delta Smelt fork lengths by gear type and date-group. Each panel represents a group of dates when the gears shown sampled together; the dates that make up each group are shown in the t*op left* or *bottom right corner* of the panels. Box plot width is proportional to the square-root of the number of observations.
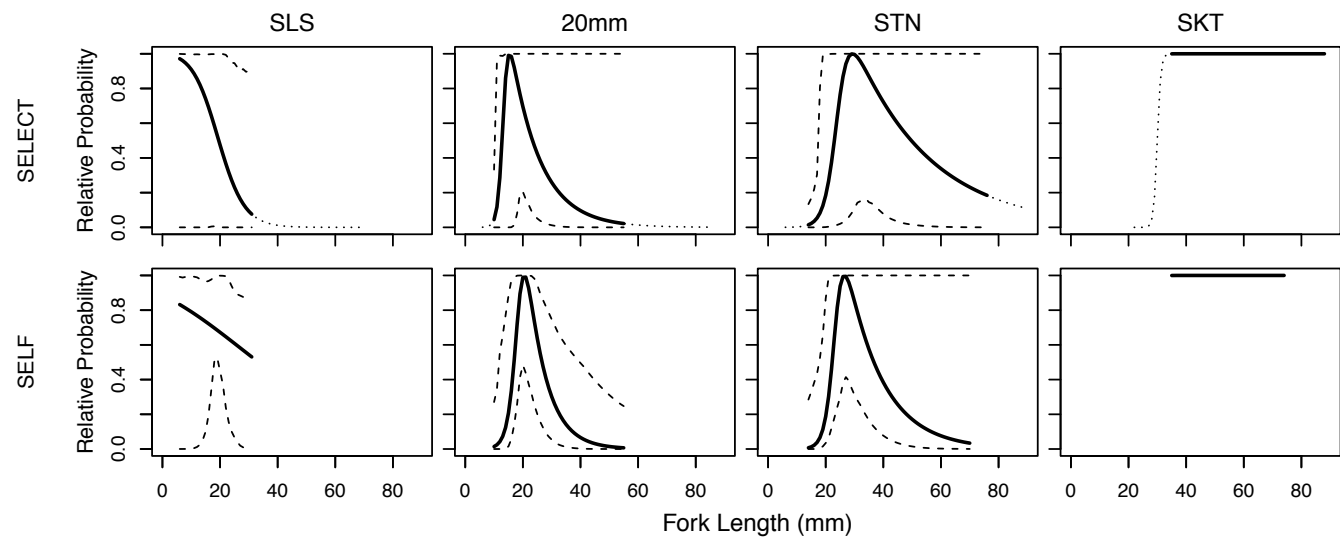

Figure 7 Fitted selectivity curves (solid and dotted lines) and 95% confidence intervals (dashed lines) for Delta Smelt by estimation method (row) and gear type (column). Thick lines reflect the range of lengths caught by the gear and used in the model. Dotted lines reflect the length range over which the function was evaluated in the model (Equation 13); note that this range can extend beyond the range of lengths caught by that gear.
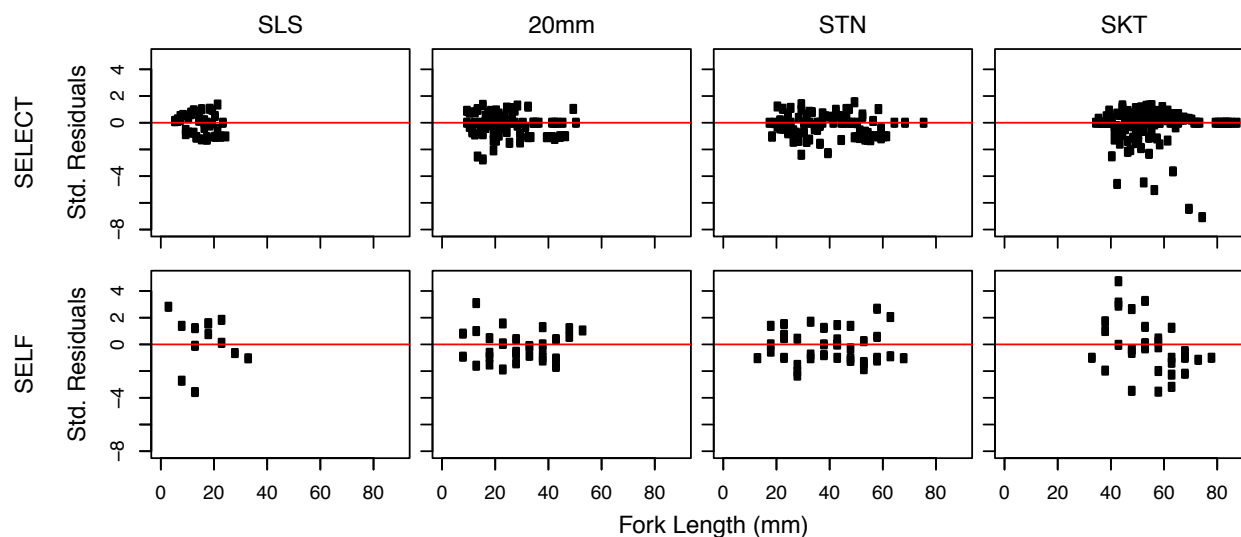
Figure 8 Standardized catch residuals vs. fish length organized by estimation method (*row*) and gear type (*column*). Residuals are shown only if expected catch was greater than zero. A *horizontal line* is shown at zero.

July and August, when most individuals are in the juvenile life stage (Bennett 2005).

The SKT gear may have been more effective than the obliquely towed gears (20-mm, STN, FMWT, CMWT) for several reasons, including (1) individuals in the juvenile, sub-adult, and adult life-stages were surface-oriented when sampling took place (in which case SKT spent more time sampling where fish were present than the others gears did), (2) fish avoiding the boat move out of the net's path when one boat is used (Noel et al. 1980, see Figure on p. 4), (3) the two-boat method also likely results in fish avoiding the boats, but in this case some fish avoiding the boats reposition in front of the net being towed between the boats (i.e., a herding effect), or (4) some combination of these reasons. These remain hypothetical explanations for the observed differences in gear efficiency because we did not formally investigate the mechanisms that lead to these differences as part of this study. However, a study described by Mitchell et al. (2017) found that surface tows with the FMWT net produced higher catch densities of sub-adult and adult Delta Smelt than oblique tows, further supporting the idea that tow method and surface-orientation of individuals in these life stages affect gear efficiency.

The SLS, 20-mm, and STN selectivity curves indicated that these gears are more likely to catch smaller

fish than larger fish. The selectivity curves for SLS indicate highest retention of the smallest (6 mm during this study) newly-hatched larvae and a rapid decline for increasing fork lengths. The mesh of the 20-mm net was selected to fully retain Delta Smelt with fork lengths greater than or equal to 20 mm (ignoring the issue of gear avoidance and focusing on whether fish can physically fit through the mesh), and both models did predict high relative selectivity around 20 mm. In an analysis of historical 20-mm Survey data, Mahardja et al. (2017) found that the survey's Delta Smelt detectability is a dome-shaped function of fork length, with a peak detection probability of roughly 0.75 around 25 mm. Because their detection probability curve reflects both the length–frequency distribution of the population and the selectivity of the gear, their results neither support nor refute our results regarding the selectivity of the 20-mm gear. The STN selectivity curves are similar to the 20-mm but less sharp and shifted to larger fork lengths. Together, SLS, 20-mm, and STN provide sequentially effective gears to capture Delta Smelt from hatch to the juvenile stage (ca. 35 mm).

The decreased efficiency of the SLS, 20-mm, and STN trawls to catch larger fish may relate to these fish detecting and moving out of the path of the trawl (i.e., gear avoidance). In particular, the back pressure generated by these finer-meshed trawls may be more

Table 4 Bounds, estimates, and coefficients of variation (absolute value) from the SELF model. To facilitate interpretation, calculated natural-scale length–distribution parameters are shown on the right.

Parameter	Lower bound	Upper bound	Estimate	CV	Quantity	Value	CV
$\mu_{2013\text{-}04\text{-}18}$	1.607	2.842	2.283	0.066	$m_{2013\text{-}04\text{-}18}$	10.272	0.134
$\mu_{2014\text{-}04\text{-}24}$	1.607	2.842	2.524	0.051	$m_{2014\text{-}04\text{-}24}$	13.064	0.109
$\mu_{2014\text{-}05\text{-}22}$	2.300	3.247	3.168	0.024	$m_{2014\text{-}05\text{-}22}$	24.880	0.073
$\mu_{2013\text{-}06\text{-}13}$	2.993	3.758	3.300	0.032	$m_{2013\text{-}06\text{-}13}$	27.704	0.131
$\mu_{2014\text{-}06\text{-}19}$	2.993	3.758	3.758	0.012	$m_{2014\text{-}06\text{-}19}$	43.821	0.053
$\mu_{2015\text{-}07\text{-}02}$	3.688	4.020	3.870	0.005	$m_{2015\text{-}07\text{-}02}$	48.223	0.019
$\mu_{2014\text{-}08\text{-}19}$	3.688	4.020	3.867	0.004	$m_{2014\text{-}08\text{-}19}$	48.076	0.017
$\mu_{2012\text{-}09\text{-}27}$	3.805	4.100	4.008	0.001	$m_{2012\text{-}09\text{-}27}$	55.204	0.004
$\mu_{2013\text{-}09\text{-}26}$	3.805	4.100	3.935	0.002	$m_{2013\text{-}09\text{-}26}$	51.310	0.009
$\mu_{20123\text{-}10\text{-}25}$	4.006	4.243	4.112	0.004	$m_{20123\text{-}10\text{-}25}$	61.254	0.014
σ_{AprMay}	0.07	0.555	0.303	0.157	cv_{AprMay}	0.311	0.165
σ_{Jun}	0.07	0.555	0.209	0.375	cv_{Jun}	0.211	0.397
σ_{JulAug}	0.05	0.385	0.105	0.206	cv_{JulAug}	0.105	0.208
σ_{SepOct}	0.05	0.385	0.081	0.054	cv_{SepOct}	0.082	0.054
$\beta_{0,SLS}$	0	0.99	0.906	0.272			
$\beta_{1,SLS}$	0.0001	5	0.045	9.958			
$\beta_{2,SLS}$	-20	50	19.115	0.057			
$\beta_{0,20mm}$	0	0.99	0.216	0.653			
$\beta_{1,20mm}$	0.0001	5	0.703	0.769			
$\beta_{2,20mm}$	-20	50	18.666	0.107			
$\beta_{0,STN}$	0	0.99	0.126	0.848			
$\beta_{1,STN}$	0.0001	5	0.641	0.745			
$\beta_{2,STN}$	-20	50	23.483	0.124			
$\gamma_{1,SKT}$	0	3	1.619	0.062			
$\gamma_{2,SKT}$	0	80	29.972	0.028			

easily detected than that generated by larger-meshed trawls. It may also be easier for fish to move out of the path of these trawls because they have relatively small net mouth areas (Table 1). In particular, July and August catch densities by 20-mm and STN may have been lower than those of SKT because 20-mm and STN have smaller net mouths that are easier for fish — especially larger fish — to evade.

Although the CMWT trawl samples in the upper portion of the water column like the SKT, catch densities of sub-adults and adults were lower in the CMWT compared with the SKT. There may be a herding effect by SKT's two-boat deployment method, and, in a similar fashion, boat operation may chase surface-oriented fishes out of the path of the CMWT net. Another possible explanation is that Delta Smelt tend to occupy a limited portion of the water column closest to the surface, so the CMWT — which has a larger net mouth height — more often may sample water that does not contain Delta Smelt. Isolating the factors that affect the relative efficiencies of the SLS,
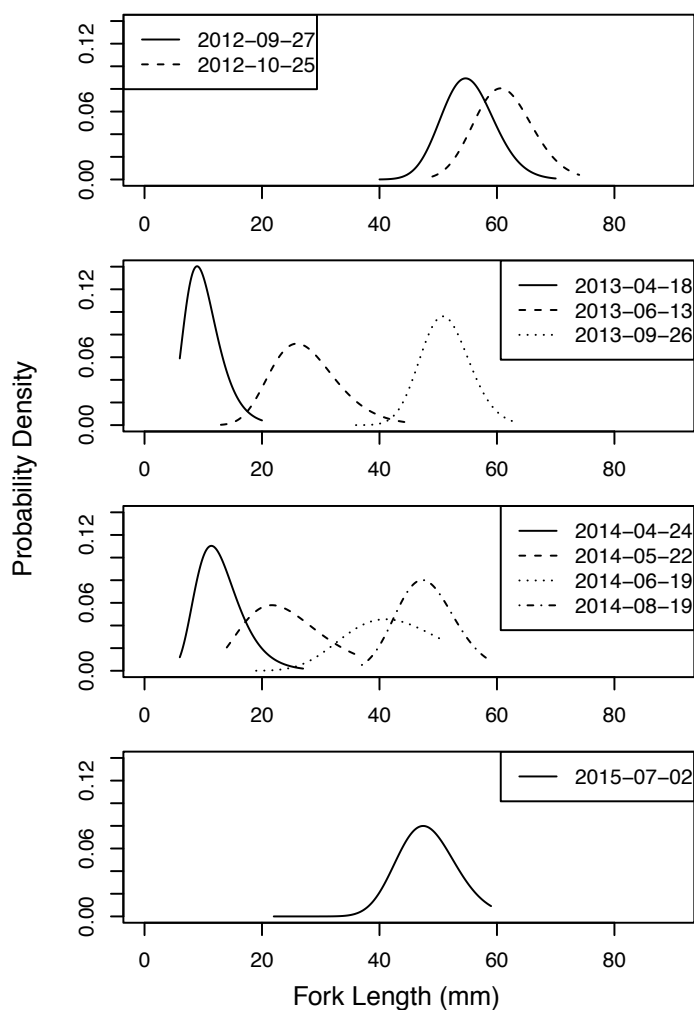
Figure 9 Fitted population length densities from the SELF model

20-mm, STN, SKT, FMWT, and CMWT remains a challenge because each gear is unique. A partial list of the gear-related features that can affect relative efficiency includes overall net size and porosity, cod-end mesh size, numbers and sizes of panels other than the cod end, size of mesh on panels other than the cod end, surface deployment vs. oblique deployment, and the use of two boats compared with only one.

Discussion of Model Assumptions

The choice of functional form for a modeled selectivity curve is important because the wrong functional form can lead to incorrect conclusions about selectivity — and, consequently, incorrect

conclusions about population dynamics (Punt et al. 2014). We used an exponential–logistic function to allow for flexibility between logistic and dome-shaped curves in this analysis. Using this function allowed us to show high volatility in the shapes of the bootstrapped curves, which reflects high uncertainty that likely results from small sample sizes. Further work includes investigation of other functional forms (e.g., gamma or log-normal probability density functions, logit polynomials) and formal model selection using Akaike's Information Criterion (AIC).

In the SELF model, we assumed that length could range from 1 to 90 mm. We used this interval because it encompassed the range of Delta Smelt lengths observed during the study (6 to 88 mm) and because it encompassed the theoretical range of sizes in the population on a given date (including both age classes). At hatching, Delta Smelt are roughly 5 mm (Bennett 2005), so an alternative approach would be to use a length distribution truncated so the smallest possible size is 5 mm. Monitoring surveys in the estuary have historically caught Delta Smelt that were larger than 90 mm, so the upper bound could potentially be increased, though few individuals larger than 90 mm have been caught in recent years. Nor are any of these larger individuals likely to be caught in the future, unless we can strongly change the system's productivity and allow the pelagic portion of the food web a greater share (Kimmerer et al. 1994; Merz et al. 2016).

The assumption that population length variability, σ_d, is the same across sets of months is an important one, particularly in spring when April-hatched fish, combined with May-hatched fish, will lead to greater variability in May than in April. The SELF model results, especially the SLS curve, were sensitive to whether a separate σ_d was used for April and May, indicating that we had trouble estimating length distributions and selectivity curves simultaneously.

General Remarks on the Selectivity Estimation Methods

We applied both the SELECT and SELF models because we weren't certain how either model would perform, given certain aspects of our study design, some of which are specific to an annual and rare

species. First, sampling took place over multiple days throughout the year to target Delta Smelt throughout their full size range. However, it was not logistically feasible to sample with all six gears simultaneously on every sample date. Despite high levels of sampling effort, some of the catch-at-length sample sizes in the Delta Smelt data set are smaller than would likely be recommended (Herrmann et al. 2016), even after aggregating over replicate tows.

It was unclear at the beginning of the analysis whether we would be able to estimate the relative fishing-intensity parameters in the SELECT method, or the length-distribution parameters in the SELF method, or both, given our study design and sample sizes. As discussed by Millar and Fryer (1999), the advantage of the SELECT method is that the relative fishing intensities are not treated as functions of length, and hence are not confounded with the selectivity curves. We found that the SELECT method did perform better, based on it having lower parameter correlations than SELF, and based on the general sensitivity of the SELF results to assumptions about length-distribution parameters. An additional advantage of the SELECT method is that we did not need to remove age-1+ fish from the model. Despite the differences between the two methods, that the SELECT and SELF fitted curves agree qualitatively helps supports our general findings about selectivity, and both models reflected high levels of uncertainty.

CONCLUSIONS

This study estimated length-dependent selectivity curves for trawls used to monitor Delta Smelt, but further investigation is needed into other factors that affect gear efficiency such as tow method. This is important because biologically implausible patterns in catch densities can occur between surveys, even after accounting for gear selectivity. For example, catch densities in the SKT Survey in the spring can still be higher than FMWT Survey catch densities in the fall, even though recruitment has ceased, and mortality and movement are the main drivers of population dynamics between fall and spring.

Although this study focused on Delta Smelt, the data could be used to investigate trawl selectivity for other fish species caught in abundance such as Threadfin Shad (*Dorosoma petenense*). Based on

the Delta Smelt analysis, we recommend using the SELECT method for any further selectivity analyses. The selectivity results for other species could be used to standardize historical catch data as described here for Delta Smelt.

ACKNOWLEDGEMENTS

REFERENCES

Anonymous. 1994. Net comparison studies. Interagency Ecological Program for the Sacramento–San Joaquin Estuary Newsletter [Internet]. [accessed 2018 April 18];7(16). Available from: *http://wdl.water.ca.gov/iep/newsletters/1994/IEPNewsletterAutumn1994.pdf*

Baxter R. 1999. Osmeridae. In: Orsi J, editor. 1999. Report on the 1980-1995 fish, shrimp, and crab sampling in the San Francisco Estuary, California. Technical report 63. [Internet]. [accessed 2019 February 28]. [Sacramento (CA)]: Interagency Ecological Program for the Sacramento-San Joaquin Estuary. p. 179-216. Available from: *http://downloads.ice.ucdavis.edu/sfestuary/ orsi_1999/archive1049.PDF*

Bennett WA. 2005. Critical assessment of the Delta Smelt population in the San Francisco Estuary, California. San Franc Estuary Watershed Sci [Internet]; [accessed 2018 April 18];3(2). Available from: *https://doi.org/10.15447/sfews.2005v3iss2art1*

Bishop J. 2006. Standardizing fishery-dependent catch and effort data in complex fisheries with technology change. Rev Fish Biol Fisheries [Internet]. [accessed 2018 May 4];16(21). *https://doi.org/10.1007/s11160-006-0004-9*

Browne D, Minto C, Cosgrove R, Burke B, McDonald D, Officer R, Keatinge M. 2017. A general catch comparison method for multi-gear trials: application to a quad-rig trawling fishery for Nephrops. ICES J Mar Sci [Internet]. [accessed 2018 May 4];74(5):1458–1468. *https://doi.org/10.1093/icesjms/fsw236*

Feyrer F, Portz D, Odum D, Newman KB, Sommer T, Contreras D, Baxter R, Slater SB, Sereno D, Van Nieuwenhuyse E. 2013. SmeltCam: underwater video codend for trawled nets with an application to the distribution of the imperiled delta smelt. PLoS ONE [Internet]. [accessed 2016 Apr 2];8(7):e67829. *https://doi.org/10.1371/journal.pone.0067829*

Fryer RJ. 1991. A model of between-haul variation in selectivity. ICES J Mar Sci [Internet]. [accessed 2018 April 18]; 48(3):281–290. *https://doi.org/10.1093/icesjms/48.3.281*

Fryer RJ, Zuur AF, Graham N. 2003. Using mixed models to combine smooth size-selection and catch-comparison curves over hauls. Can J Fish Aquat Sci [Internet]. [accessed 2018 May 4];60(4):448–459. *https://doi.org/10.1139/f03-029*

Fujimori Y, Tokai T. 2001. Estimation of gillnet selectivity curve by maximum likelihood method. Fisheries Sci [Internet]. [accessed 2018 April 18];67(4):644–654. *https://onlinelibrary.wiley.com/doi/ abs/10.1046/j.1444-2906.2001.00301.x*

Fujimura RW. 1989. Tests on the effect of mesh size on the capture of striped bass larvae in the Sacramento-San Joaquin Estuary. [Sacramento (CA)]: Interagency Ecological Program for the Sacramento-San Joaquin Estuary. Technical report 21. [Internet]. [accessed 2018 April 18]. Available from: *https://www.water.ca.gov*

Gartz RG, Miller LW, Fujimura RW, Smith PE. 1999. Measurement of larval striped bass (*Morone saxatilis*) net avoidance using evasion radius estimation to improve estimates of abundance and mortality. J Plankt Res [Internet]. [accessed 2018 April 18];21(3):561–580. *https://doi.org/10.1093/plankt/21.3.561*

Herrmann B, Krag LA, Frandsen RP, Madsen N, Lundgren B, Staehr K. 2009. Prediction of selectivity from morphological conditions: Methodology and a case study on cod (*Gadus morhua*). Fish Res [Internet]. [accessed 2018 December 4];97:59–71. *https://doi.org/10.1016/j.fishres.2009.01.002*

Herrmann B, Sistiaga M, Santos J, Sala A. 2016. How many fish need to be measured to effectively evaluate trawl selectivity? PLoS One [Internet]. [accessed 2018 December 5];11(8). *https://doi.org/10.1371/journal.pone.0161512*

Horvitz DG, Thompson DJ. 1952. A generalization of sampling without replacement from a finite universe. J Am Statl Assoc [Internet]. [accessed 2018 December 7];47:663–685. *https://doi.org/10.1080/01621459.1952.10483446*

IEP MAST: Interagency Ecological Program, Management Analysis and Synthesis Team. 2015. An updated conceptual model of Delta Smelt biology: our evolving understanding of an estuarine fish. Technical report 90. [Sacramento (CA)]: Interagency Ecological Program for the Sacramento-San Joaquin Estuary [Internet]. [accessed 2018 August 7]. Available from: *https://pubs.er.usgs.gov/publication/70141018*

Kimmerer WJ. 2008. Losses of Sacramento River Chinook Salmon and Delta Smelt to entrainment in water diversions in the Sacramento-San Joaquin Delta. San Franc Estuary Watershed Sci [Internet]. [accessed 2018 April 18];6(2). Available from: *https://doi.org/10.15447/sfews.2008v6iss2art2*

Kimmerer WJ, Gartside E, Orsi JJ. 1994. Predation by an introduced clam as the likely cause of substantial declines in zooplankton of San Francisco Bay. Mar Ecol Prog Ser [Internet]. [accessed 2018 December 10];113:81–93. Available from: https://www.int-res.com/articles/meps/113/m113p081.pdf

Kotwicki S, Lauth RR, Williams K, Goodman SE. 2017. Selectivity ratio: a useful tool for comparing size selectivity of multiple survey gears. Fish Res [Internet]. [accessed 2018 July 9];191:76–86. https://doi.org/10.1016/j.fishres.2017.02.012

Krag LA, Herrmann B, Karlsen JD. 2014. Inferring fish escape behaviour in trawls based on catch comparison data: Model development and evaluation based on data from Skagerrak, Denmark. PLoS ONE [Internet]. [accessed 2018 July 27];9(2). https://doi.org/10.1371/journal.pone.0088819

MacLennan D. 1992. Fishing gear selectivity: an overview. Fish Res [Internet]. [accessed 2018 December 4];13(3):201–204. https://doi.org/10.1016/0165-7836(92)90076-6

Mahardja B, Young MJ, Schreier B, Sommer T. 2017. Understanding imperfect detection in a San Francisco Estuary long-term larval and juvenile fish monitoring programme. Fish Manage Ecol [Internet]. [accessed 2018 July 27];24(6):488–503. https://doi.org/10.1111/fme.12257

Maunder MN, Deriso RB. 2011. A state-space multistage life cycle model to evaluate population impacts in the presence of density dependence: illustrated with application to delta smelt (*Hypomesus transpacificus*). Can J Fish Aquat Sci [Internet]. [accessed 2018 April 18];68(7):1285–1306. https://doi.org/10.1139/f2011-071

Maunder MN, Punt AE. 2004. Standardizing catch and effort data: a review of recent approaches. Fisheries Research [Internet]. [accessed 2018 May 7];70:141–159. https://doi.org/10.1016/j.fishres.2004.08.002

McLain J. 1998. Relative efficiency of the midwater and Kodiak trawl at capturing juvenile Chinook Salmon in the Sacramento River. Interagency Ecological Program for the Sacramento-San Joaquin Estuary Newsletter [Internet]. [accessed 2018 April 18];11(4):26–29. Available from: http://wdl.water.ca.gov/iep/newsletters/1998/IEP-fall-1998.cfm

Merz JE, Bergman PS, Simonis JL, Delaney D, Pierson J, Anders P. 2016. Long-term seasonal trends in the prey community of Delta Smelt (*Hypomesus transpacific*) within the Sacramento-San Joaquin Delta, California. Estuaries and Coasts [Internet]. [accessed 2018 December 10];39:1526–1536. Available from: https://link.springer.com/content/pdf/10.1007%2Fs12237-016-0097-x.pdf

Millar RB. 1992. Estimating the size-selectivity of fishing gear by conditioning on the total catch. J Am Stat Assoc [Internet]. [accessed 2018 April 18];87(420):962–968. Available from: http://www.jstor.org/stable/2290632

Millar RB. 1995. The functional form of hook and gillnet selection curves cannot be determined from comparative catch data alone. Can J Fish Aquat Sci [Internet]. [accessed 2018 April 18];52(5):883–891. https://doi.org/10.1139/f95-088

Millar RB, Fryer RJ. 1999. Estimating the size-selection curves of towed gears, traps, nets, and hooks. Rev Fish Biol Fisheries [Internet]. [accessed 2018 April 18];9(1):89–116. https://doi.org/10.1023/A:1008838220001

Millar RB, Holst R. 1997. Estimation of gillnet and hook selectivity using log-linear models. ICES J Mar Sci [Internet]. [accessed 2018 July 24]; 54:471–477. https://doi.org/10.1006/jmsc.1996.0196

Miller LW. 1977. An evaluation of sampling nets used for striped bass and *Neomysis* in the Sacramento-San Joaquin Estuary. Technical report 3. [Sacramento (CA)]: California Department of Fish and Game, Anadromous Fisheries Branch.

Miller TJ. 2013. A comparison of hierarchical models for relative catch efficiency based on paired-gear data for U.S. Northwest Atlantic fish stocks. Can J Fish Aquat Sci [Internet]. [accessed 2018 May 4]; 70(9):1306–1316. https://doi.org/10.1139/cjfas-2013-0136

Mitchell L, Newman K, Baxter R. 2017. A covered cod-end and tow-path evaluation of midwater trawl gear efficiency for catching Delta Smelt (*Hypomesus transpacificus*). San Franc Estuary Watershed Sci [Internet]. [accessed 2018 April 18];15(4). https://doi.org/10.15447/sfews.2017v15iss4art3

Moyle PB, Brown LR, Durand JR, Hobbs JA. 2016. Delta Smelt: life history and decline of a once-abundant species in the San Francisco Estuary. San Franc Estuary Watershed Sci [Internet]. [accessed 2018 April 23];14(2). https://doi.org/10.15447/sfews.2016v14iss2art6

Newman KB. 2008. Sample design-based methodology for estimating delta smelt abundance. San Franc Estuary Watershed Sci [Internet]. [accessed 2018 April 18];6(3). https://doi.org/10.15447/sfews.2008v6iss3art3

Noel HS, Ben-Yami M, Maugeri S, Carlesi M, Barcali A. 1980. Pair trawling with small boats. Technical report, Food and Agriculture Organization of the United Nations [Internet]. [accessed 2018 April 18]. Available from: https://ia801406.us.archive.org/23/items/pairtrawlingwith034684mbp/pairtrawlingwith034684mbp.pdf

Punt AE, Hurtado-Ferro F, Whitten AR. 2014. Model selection for selectivity in fisheries stock assessments. Fish Res [Internet]. [accessed 2018 July 27];158:124–134. Available from: http://www.sciencedirect.com/science/article/pii/S0165783613001550

Quang PX, Geiger HJ. 2002. A review of the net selectivity problem and a model for apportioning species based on size-selective sampling. Alaska Fishery Res Bull [Internet]. [accessed 2018 April 18];9(1):16–26. Available from: http://www.adfg.alaska.gov/static/home/library/PDFs/afrb/2quanv9n1.pdf

R Core Team. 2018. R: A Language and Environment for Statistical Computing. [Vienna, Austria]: R Foundation for Statistical Computing. Available from: http://www.R-project.org/

Rose KA, Kimmerer WJ, Edwards KP, Bennett WA. 2013. Individual-based modeling of Delta Smelt population dynamics in the upper San Francisco Estuary: 1. Model description and baseline results. Trans Am Fish Soc [Internet]. [accessed 2018 April 18]; 142(5):1238–1259. https://doi.org/10.1080/00028487.2013.799518

Schaub M, Abadi F. 2011. Integrated population models: a novel analysis framework for deeper insights into population dynamics. J Ornithol [Internet]. [accessed 2018 December 11]; 152(Suppl 1):S227–S237.

Somerton D, Ianelli J, Walsh S, Smith S, Godo OR, Ramm D. 1999. Incorporating experimentally derived estimates of survey trawl efficiency into the stock assessment process: a discussion. ICES J Mar Sci [Internet]. [accessed 2018 July 19];56:299–302. https://doi.org/10.1006/jmsc.1999.0443

Somerton DA, Weinberg KL, Goodman SE. 2013. Catchability of snow crab (*Chionoecetes opilio*) by the eastern Bering Sea bottom trawl survey estimated using a catch comparison experiment. Can J Fish Aquat Sci [Internet]. [accessed 2018 July 20];70(12):1699–1708. https://doi.org/10.1139/cjfas-2013-0100

Sommer T, Armor C, Baxter R, Breuer R, Brown L, Chotkowski M, Culberson S, Feyrer F, Gingras M, Herbold B, Kimmerer W, Mueller-Solger A, Nobriga M, Souza K. 2007. The collapse of pelagic fishes in the upper San Francisco Estuary. Fisheries [Internet]. [accessed 2018 April 18];32(6):270–277. https://doi.org/10.1577/1548-8446(2007)32[270:TCOPFI]2.0.CO;2

Souza K. 2002. Revision of California Department of Fish and Game's spring midwater trawl and results of the 2002 spring Kodiak trawl. Interagency Ecological Program for the Sacramento-San Joaquin Estuary Newsletter [Internet]. [accessed 2018 April 18];15(3):44–47. Available from: http://wdl.water.ca.gov/iep/newsletters/2002/IEPNewslettersummer2002.pdf

Thompson GG. 1994. Confounding of gear selectivity and the natural mortality rate in cases where the former is a nonmonotone function of age. Can J Fish Aquat Sci [Internet]. [accessed 2018 April 18];51(12):2654–2664. https://doi.org/10.1139/f94-265

Trenkel VM, Skaug HJ. 2005. Disentangling the effects of capture efficiency and population abundance on catch data using random effects models. ICES J Mar Sci [Internet]. [accessed 2018 May 4];62(8):1543–1555. https://doi.org/10.1016/j.icesjms.2005.05.010

Wileman DA, Ferro RST, Fonteyne R, Millar RB. 1996. Manual of methods of measuring the selectivity of towed fishing gears. Technical report 215. [Internet]. [accessed 2019 February 28]. [Copenhagen, Denmark]: International Council for the Exploration of the Sea. Available from: https://doi.org/10.17895/ices.pub.4628

Williams K, Wilson CD, Horne JK. 2013. Walleye pollock (*Theragra chalcogramma*) behavior in midwater trawls. Fisheries Research [Internet]. [accessed 2018 July 23];143:109–118. https://doi.org/10.1016/j.fishres.2013.01.016

NOTES

S. Slater. 2013. Email communication to Lara Mitchell regarding Delta Smelt age-length key.