ARTICLE

A novel method for modeling age and length selectivity of sockeye salmon as applied to the Bristol Bay Port Moller test fishery

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Abstract: This paper presents a novel approach for assessing sources selectivity in test fisheries using the Port Moller test fishery (PMTF) as a case study. The PMTF intercepts sockeye salmon (*Oncorhynchus nerka*) migrating to Bristol Bay, Alaska, to estimate run strength and timing. In 2011, the mesh size of gillnets used in the test fishery was decreased for half of the net panels to generate more accurate run estimates by correcting for greater selectivity of larger 3-ocean fish (fish that have spent 3 years in the ocean) relative to smaller 2-ocean fish (fish that have spent 2 years in the ocean). Here, we quantify two sources of age selectivity in the PMTF program, length selectivity parameterized by mean fish length (which should be corrected by the net mesh change) and length-independent selectivity, which we refer to as residual program selectivity (which would not be impacted by the net mesh change), both before and after the net change. Model parameters of selectivity show strong support length selectivity was eliminated, but residual program selectivity still existed after the reduction in net mesh size. Our results demonstrate the necessity of considering both vulnerability and accessibility to fishing gear when assessing selectivity in test fisheries.

Résumé : L'article présente une approche novatrice pour évaluer les sources de sélectivité dans des pêches expérimentales en utilisant la pêche expérimentale de Port Moller (PMTF) comme étude de cas. La PMTF intercepte des saumons rouges (*Oncorhynchus nerka*) migrant vers la baie de Bristol (Alaska) afin d'estimer la force et le moment de migrations. En 2011, la taille des mailles des filets utilisés dans la pêche expérimentale a été réduite pour la moitié des panneaux de filet afin de produire des estimations plus exactes des migrations en corrigeant pour la plus grande sélectivité de grands poissons ayant passés 3 années en mer par rapport à celle de poissons plus petits ayant passé 2 années en mer. Nous quantifions deux sources de sélectivité selon l'âge dans le programme PMTF, la sélectivité selon la longueur mesurée par la longueur moyenne des poissons (que le changement de taille des mailles devrait corriger) et la sélectivité indépendante de la longueur, ou sélectivité résiduelle du programme (sur laquelle la modification des filets ne devrait pas avoir d'incidence) avant et après le changement de filets. Les paramètres de sélectivité modélisés appuient fortement l'élimination de la sélectivité selon la longueur, alors que la sélectivité résiduelle du programme demeure après la réduction de la taille des mailles des filets. Nos résultats démontrent la nécessité de tenir compte de la vulnérabilité et de l'accès des poissons aux engins de pêche dans l'évaluation de la sélectivité dans les pêches expérimentales. [Traduit par la Rédaction]

Introduction

In-season management is an important tool for preventing overexploitation of commercially harvested species. Test fisheries are commonly used to aid active management by assisting managers in meeting escapement goals, providing inputs to stock assessment models, and assessing exploitation rates of newly introduced gear types for a variety of species (Melvin et al. 1999; Haist 2012; Priest et al. 2016). In the Pacific Northwest, Alaska, and British Columbia, test fisheries are frequently used for commercial salmon management, as they can provide information to managers on run timing, daily fish abundance, and size of Pacific salmon stocks. As of 2017, there were at least 13 Pacific salmon test fisheries in operation in the region, with additional test fisheries for herring and crab species (Table S1[1]). The primary output of most test fisheries is an index or indicator of overall daily run strength. Ultimately, these data are used to actively manage fish-

ing effort to meet in-season escapement goals (Clark et al. 2006; Priest et al. 2016).

Test fishery data are a valuable indicator of in-season run size and timing, but variations in run characteristics can present problems for index accuracy. For example, a test fishery index does not directly reflect the abundance of fish, but instead represents the number of fish that are susceptible to being caught by the gear in use (Cox-Rogers and Jantz 1993; Link and Peterman 1998). Susceptibility of fish to the gear is a result of accessibility (i.e., whether the fish are passing through the area being fished) and vulnerability (i.e., whether the fish can be caught by the gear being used). Ideally, a stock will be uniformly susceptible to the gear, such that all fish are equally as likely to be accessible and vulnerable to the gear. However, target stocks are often not equally susceptible to test fisheries owing to logistical constraints such as gear restrictions, limited time and capacity, or variability in migration route or timing. This differential susceptibility results in program selec-

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tivity, or the systematic oversampling of some portion of the population relative to another portion of the population. Thus, program selectivity results from a difference in fish accessibility, vulnerability, or both. More specifically, contact selectivity (also called length, net, or gear selectivity) refers to the chance that a fish in contact with the gear will be caught. Contact selectivity reflects fish vulnerability to the gear only and contributes to the fishery's overall program selectivity. However, residual program selectivity that is not accounted for by contact selectivity can still exist because of differential accessibility, and thus contact selectivity may not reflect all program selectivity.

Selectivity in test fisheries is problematic, as it can lead to an inconsistent relationship between the test fishery index and the number of fish that arrive in commercial fishing districts, measured as run per index (RPI). RPI is calculated as total run size (R) divided by the index or catch per unit effort (CPUE). When a test fishery index includes a sampling bias due to program selectivity, the calculated RPI may reflect an incorrect relationship between index and run size. For example, when the test fishery index is low relative to return, then RPI would be overestimated, signifying the increased potential for escapement to exceed the escapement goal. Alternatively, when a test fishery index is high relative to return, RPI would be underestimated, and the risk of failing to meet the lower bound escapement goal increases.

Program selectivity has been shown to occur in several salmon gillnet fisheries (Ricker 1981; Westrheim 1998), including test fisheries and the Bristol Bay salmon fishery (Fried et al. 1984; Kendall et al. 2009). Contact selectivity typically results from size-selective mesh, but can also be caused by the material of the net and method of fishing (Hamley 1975). In addition to contact selectivity, program selectivity is affected by the age and sex composition of the stock, daily abundance, run size, and environmental conditions (Hyatt et al. 2003; Kendall et al. 2009; Dann et al. 2013).

In 2011, the PMTF net mesh size was changed to mitigate contact selectivity between age classes and improve index calculations. The change in mesh size is thought to have successfully removed contact selectivity. However, there is a need to understand how much program selectivity remains in the test fishery and to quantify the reduction or removal of contact selectivity. Here, we parameterize contact selectivity using mean length of each age class as a proxy for vulnerability to gear. Because the mechanism for fish capture and retention in gillnets is directly related to fish girth rather than length (Hamon et al. 2003), for accurate representation we reference this parameter as "length selectivity" and define it as an estimate of contact selectivity parameterized by fish length. We also parameterize length-independent selectivity in the program and refer to it as residual program selectivity.

In this paper, we present a novel approach for assessing both length and residual program selectivity in a long-term test fishery. We achieved this aim by (*i*) quantifying the annual total program selectivity of the PMTF since 1990, (*ii*) quantifying the interannual variability of total program selectivity, and (*iii*) determining whether there is a difference in program selectivity between the periods before (1990–2010) and after (2011–2016) the change in mesh size. We also test the extent to which length selectivity explains any changes in program selectivity and consider its potential to explain contact selectivity. When a long time series is available, this modeling framework can assess contributing factors to overall program selectivity and thereby uncover mechanisms driving different sources of selectivity. This can be achieved by parameterizing additional system components, which is demonstrated in this study by parameterizing both length selectivity and residual program selectivity. Here, we present a proof of concept.

Methods

General model description

Our purpose in this study was to create a model that could assess multiple sources of program selectivity in test fisheries using the PMTF as a case study. First, we estimated total program selectivity as the selectivity of 2-ocean fish relative to 3-ocean fish. Then, our model parameterizes the portion of program selectivity that is (*i*) dependent on length and (*ii*) additional program selectivity that is length independent or not explained by the length parameter. Sockeye salmon (*Oncorhynchus nerka*) age composition is reported in the European notation (e.g., 2.3), where the first digit represents the number of years spent in fresh water and the second represents the number of years spent in the ocean. Program selectivity is represented as age selectivity, or the selectivity of 2-ocean fish (fish that have spent 2 years in the ocean) relative to 3-ocean fish (fish that have spent 3 years in the ocean); see the Selectivity model section. This approach differs from other selectivity assessments, which use mean length distribution curves or ratio of length to mesh size curves to quantify size selectivity, but do not quantify length-independent program selectivity (Hamley 1975; Tanaka 2002; Bromaghin 2005).

The Port Moller test fishery

The Bristol Bay commercial sockeye salmon fishery is temporally compressed and takes place between mid-June and late July as fish return to the rivers of Bristol Bay to spawn. Established in 1967, the Port Moller test fishery (PMTF) provides indices of abundance, stock size, run timing, and migration patterns of the terminal Bristol Bay sockeye salmon fishery (Randall 1977; Raborn et al. 2017). Currently operated by the Bristol Bay Science and Research Institute (BBSRI), the PMTF vessel samples daily during the run, typically with five sampling stations located 10 miles apart along a 50-mile transect (1 mile = 1.609 km) between Port Moller and Cape Newenham (Fig. 1). Along the transect, the vessel fishes for a definite period (this varies among years and weather conditions) using a 200 fathom (1 fathom = 1.8288 m) drift gillnet to intercept Bristol Bay sockeye salmon runs along their migration route. While the test fishery has undergone several changes over the years, from 1987 to 2015, five even-numbered stations (2–10) have typically been fished each day during both outbound and return trips. Station 12 was fished sporadically from 1999 to 2010 and consistently in 2016, while station 14 was also fished occasionally (Raborn et al. 2017; Fig. 1).

CPUE is calculated and standardized for each station and across all stations to create the cumulative CPUE, or Port Moller index (PMI), an indicator of overall daily run strength. When combined with known travel times to fishing districts in Bristol Bay, the PMI allows fishers, processors, and managers to anticipate when salmon will arrive to fishing districts and the approximate expected run strength, or number of fish. Sex and length are recorded for each fish caught, and a random sample of fish is selected for age and genetic analysis using tissue and scale samples (Nemeth et al. 2016). Genetic estimates of stock composition are returned within 3–5 days of collection and are reported as the percentage of the PMTF catch attributed to each of the 12 reporting groups, that is, the large river systems associated with Bristol Bay fishing districts (Habicht et al. 2012; Nemeth et al. 2016). Variation in CPUE at each of the stations can also indicate anticipated strength of runs bound for specific fishing districts due to spatially differentiated migration patterns (Dann et al. 2013; Nemeth et al. 2016; Raborn et al. 2017). Age composition provides an estimate of the size and age of fish that are expected to arrive in the fishing districts, as well as information on run timing (Nemeth et al. 2016).

The in-season run information provided by the PMTF aids Bristol Bay fishing district managers in determining daily fishery openings and closures based on anticipated run strength and timing

Fig. 1. Map of the five Bristol Bay fishing districts and Port Moller test fishery stations (reproduced from Raborn et al. 2017).
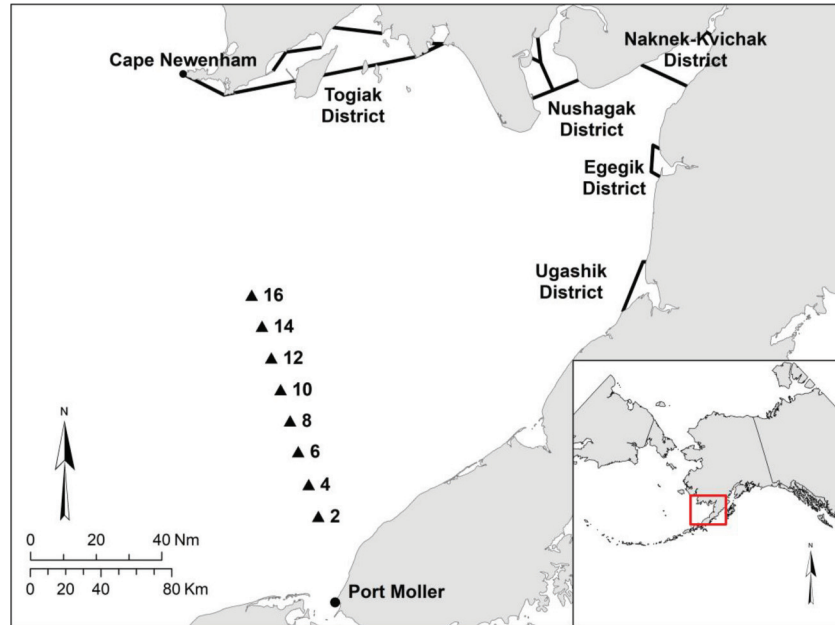
(T. Sands and T. Elison, personal communication, 2017). Controlling daily fishing effort is the managers' primary method of ensuring that escapement goals are met and the fishery achieves maximum sustainable yield. The PMTF run updates also help fishers and processors plan informed harvest and processing strategies, guiding decisions such as in which district to place their effort.

Program selectivity has been identified in the PMTF. A study from Flynn and Hilborn (2004) described several sources of variability in the PMI, with contact selectivity of different ages having the largest effect. In the PMTF, the smaller size of 2-ocean fish makes them less susceptible than 3-ocean fish to being caught in the traditionally used 5 1/8 inch mesh (1 inch = 2.54 cm). This variable susceptibility of age classes to the PMTF gear creates uncertainty in PMI estimation. Disparate contact selectivity between age classes combined with variability in relative proportion of the two age classes per annual return (Fig. 2) can make correcting for contact selectivity problematic.

In 2011, the mesh size used in the PMTF was decreased for half of the gillnet set to mitigate for contact selectivity. BBSRI replaced two of the four 5 1/8 inch mesh size 50-fathom panels with two 50-fathom panels of 4 1/2 inch mesh, such that the two mesh sizes alternate. The selectivity of the smaller mesh size panels for 2-ocean fish was considered sufficient to offset the selectivity of the larger mesh size panels for 3-ocean fish, and therefore no additional corrections were made for program selectivity in the index calculation (Priest et al. 2016). However, a change in mesh size would not alleviate additional program selectivity that could exist owing to run size and environmental conditions (Hyatt et al. 2003; Kendall et al. 2009; Dann et al. 2013). A complimentary index that corrects for residual program selectivity is calculated by the University of Washington Fishery Research Institute (UWFRI) using the Flynn index as described by Flynn and Hilborn (2004). Analysis of the residual program selectivity that remains in the PMTF will assist in future index calculations.

Selectivity model

To calculate program selectivity, we first summarized Bristol Bay brood table data (Cunningham et al. 2018) from 1990 to 2016 for all districts; we chose this year range because it coincided with consistent and reliable PMTF sampling (Priest et al. 2016). We

Fig. 2. Proportion of 2-ocean fish and 3-ocean fish in total runs from 1990 to 2016.
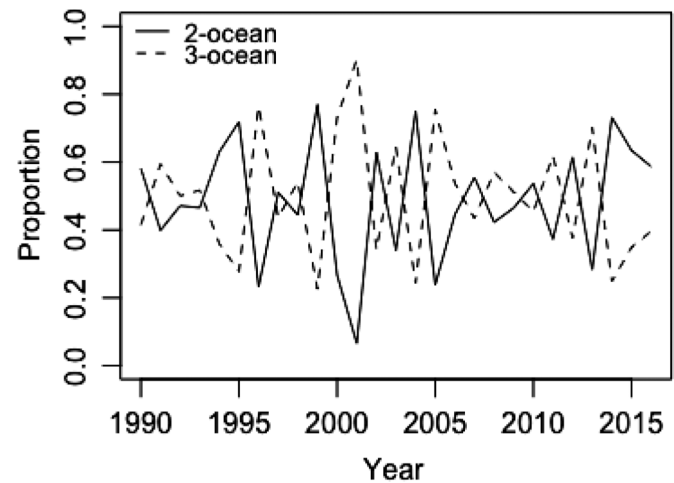
calculated the total return each year by summing the return by ocean age class for both catch and escapement for all of Bristol Bay. We then calculated the proportion of the total return for 2-ocean fish and 3-ocean fish by dividing the age-class return by the total return (eq. 1):

$$(1) \qquad P_{a,y} = \frac{N_{a,y}}{\Sigma_a N_{a,y}}$$

where $P_{a,y}$ is the proportion of the total return of age a in year y and $N_{a,y}$ is the number of individuals of age a in year y. Only 2-ocean fish and 3-ocean fish were used for simplification, because the 1-ocean, 4-ocean, and 5-ocean fish made up less than 1% of the remaining catch.

Using the Port Moller daily data set summarized and provided by Alaska Department of Fish and Game (ADF&G); (C. Cunningham, personal communication, 2017), we calculated the number of 2-ocean fish and 3-ocean fish caught by the test fishery by multi-

plying the PMI by the proportion of 2-ocean fish or 3-ocean fish caught that day and summing across all days in a year (eq. 2):

$$(2) \qquad M_{a,y} = \Sigma_d Q_{a,d,y} \cdot I_{d,y}$$

where $M_{a,y}$ is the number of individuals of age a caught in the test fishery in year y, $Q_{a,d,y}$ is the proportion of the total Port Moller catch of age a caught on day d in year y, and $I_{d,y}$ is the PMI on day d in year y. We then calculated the yearly proportion of 2-ocean fish and 3-ocean fish caught in the test fishery (eq. 3):

$$(3) \qquad Q_{a,y} = \frac{M_{a,y}}{\Sigma_a M_{a,y}}$$

where $Q_{a,y}$ is the proportion of the total return of age a in year y and $M_{a,y}$ is the number of Port Moller individuals of age a in year y.

To calculate the selectivity of 2-ocean fish and 3-ocean fish for each year and age, we divided the number of fish of each age class caught by the PMTF by the number of fish of each class in the total return to Bristol Bay, both catch and escapement (eqs. 4 and 5):

$$(4) \qquad S_{2,y} = \frac{M_{2,y}}{N_{2,y}}$$

$$(5) \qquad S_{3,y} = \frac{M_{3,y}}{N_{3,y}}$$

where $S_{2,y}$ is the selectivity of 2-ocean fish in year y and $S_{3,y}$ is the selectivity of 3-ocean fish in year y. We adjusted the selectivity of 2-ocean fish to be relative to 3-ocean fish by dividing the selectivity of 2-ocean fish by the selectivity of 3-ocean fish (eq. 6):

$$(6) \qquad S_{R,y} = \frac{S_{2,y}}{S_{3,y}}$$

where $S_{R,y}$ is the relative selectivity of 2-ocean fish to 3-ocean fish and represents the total program selectivity. We report the mean and standard deviation of the relative selectivity comparison with the selectivity of 3-ocean fish relative to themselves, a constant value of 1.

Mean length of 2-ocean fish and 3-ocean fish was calculated as the weighted mean length of each age class (e.g., 1.2 and 2.2 fish and 1.3 and 2.3 fish, respectively) for each year, using mean length of catch and escapement combined and age-class proportions from ADF&G (eqs. 7 and 8):

$$(7) \qquad L_{2,y} = P_{1.2,y} \cdot \bar{L}_{1.2,y} + P_{2.2,y} \cdot \bar{L}_{2.2,y}$$

$$(8) \qquad L_{3,y} = P_{1.3,y} \cdot \bar{L}_{1.3,y} + P_{2.3,y} \cdot \bar{L}_{2.3,y}$$

where $L_{2,y}$ is the mean length of 2-ocean fish in year y, $L_{3,y}$ is the mean length of 3-ocean fish in year y, $P_{1.2,y}$ is the proportion of age 1.2 fish in year y, and $\bar{L}_{1.2,y}$ is the mean length of age 1.2 fish in year y.

Yearly means were standardized about the mean length for all years by applying eq. 9 to calculate the length deviation from the long-term mean of 2-ocean fish relative to 3-ocean fish.

$$(9) \qquad H_y = \frac{L_{2,y}}{L_{3,y}} - \frac{\bar{L}_2}{\bar{L}_3}$$

where H_y is the standardized deviation proportion of 2-ocean to 3-ocean fish length in year y, $\bar{L}_2$ is the mean length of 2-ocean fish across all years, and $\bar{L}_3$ is the mean length of 3-ocean fish across all years.

To test whether there is differential program selectivity among fish ages and lengths and between net mesh sizes, we ran 12 candidate models predicting the selectivity of 2-ocean fish relative to 3-ocean fish for a given year based on the selectivity of 3-ocean fish for that same year. We included the following parameters: Δ_y, representing the length-independent difference in selectivity of 2-ocean fish relative to 3-ocean fish — i.e., the residual program selectivity that is not explained by length — and l_y, representing the length-dependent difference in selectivity of 2-ocean fish relative to 3-ocean fish (eq. 10):

$$
\begin{aligned}
(10) \qquad & S_{2,y} = S_{3,y}(\Delta_y + H_y \cdot l_y) + \epsilon_y \\
& \text{where } \Delta_y = \begin{cases} \Delta_A \text{ if } y \text{ is } 2011 - 2016 \\ \Delta_B \text{ if } y \text{ is } 1990 - 2010 \\ \Delta \text{ if } \Delta_A = \Delta_B \end{cases} \\
& \text{where } l_y = \begin{cases} l_A \text{ if } y \text{ is } 2011 - 2016 \\ l_B \text{ if } y \text{ is } 1990 - 2010 \\ l \text{ if } l_A = l_B \end{cases}
\end{aligned}
$$

where the error, ϵ_y, is normally distributed with a mean of zero and a standard deviation of σ_ϵ. Two different Δ variables were used for the different times periods (with Δ_A indicating the period after the net mesh size was changed and Δ_B indicating the period before the mesh size was changed) in models that represent the influence of change in mesh size on net selectivity due to fish age. The same approach was taken to model simulations in which the change in mesh size affected net selectivity to fish size by using l_B and l_A. Models representing no effect of age on selectivity will have a Δ of one, while those representing no effect of length on selectivity will have an l of zero. When the change in mesh size has no effect, Δ and l will remain the same both before and after, and thus there will be only one Δ and one l (assuming each type of selectivity is parameterized in the given model). We chose to include additive error after testing for normality of the error distribution using a Q–Q plot and a Shapiro–Wilk test.

We used a nonlinear minimization package to minimize the negative log likelihood of the models by changing the parameter values of Δ_y and l_y. The candidate model set included the 12 models listed in Table 1. We used Akaike's information criterion corrected for small sample sizes (AIC$_c$) (Akaike 1974; Anderson 2008) to compare the candidate model set, and we report the AIC$_c$ value, ΔAIC$_c$ value, and relative weight assigned to each model (Table 2).

Parameter weights were calculated for Δ_B, Δ_A, l_B, and l_A by summing AIC$_c$ weights across all models that include the given parameter. An estimate of each of the four parameters was calculated using a weighted mean, where the parameter estimate for each model was multiplied by the respective model's AIC$_c$ weight and summed across all models. Parameter estimates were used to calculate an effect size for 2-ocean fish and 3-ocean fish for each parameter. The effect size represents the predicted proportion of 2-ocean fish and 3-ocean fish caught by PMTF given the selectivity represented by an individual parameter, assuming the true proportion is 50% 2-ocean fish and 50% 3-ocean fish. A combined effect size was also calculated to represent total program selectivity before and after the change in mesh size. The parameters Δ_A and l_A were combined for the "after" effect size, and Δ_B and l_B were combined for the "before" effective size.

Results

Variability in age-class proportion and relative selectivity over time

The mean proportion of each class in the total run from 1990 to 2016 is 0.487 ± 0.177 for 2-ocean fish and 0.497 ± 0.176 for 3-ocean

Table 1. The candidate model set, model numbers, model names, and number of parameters (including σ_ϵ) used in AIC$_c$ analysis grouped by model outcomes, where models containing time-specific terms are represented with separate equations for each time period.

Model No.	Model name	Model B: 1990–2010	A: 2011–2016	No. of parameters
No selectivity				
1	No residual program selectivity or length selectivity	$S_{2,y} = S_{3,y} + \epsilon_y$		1
No change in selectivity with new panels				
2	No residual program selectivity, same length selectivity before and after	$S_{2,y} = S_{3,y} (H_y{\cdot}l) + \epsilon_y$		2
3	Same residual program selectivity before and after, no length selectivity	$S_{2,y} = S_{3,y} (\Delta) + \epsilon_y$		2
4	Same residual program and length selectivity before and after	$S_{2,y} = S_{3,y} (\Delta + H_y{\cdot}l) + \epsilon_y$		3
Change in residual program selectivity with new panels				
5	Change in residual program selectivity, no length selectivity	$S_{2,y} = S_{3,y} (\Delta_B) + \epsilon_y$	$S_{2,y} = S_{3,y} (\Delta_A) + \epsilon_y$	3
6	Change in residual program selectivity, same length selectivity before and after	$S_{2,y} = S_{3,y} (\Delta_B + H_y{\cdot}l) + \epsilon_y$	$S_{2,y} = S_{3,y} (\Delta_A + H_y{\cdot}l) + \epsilon_y$	4
7	Change in residual program selectivity and length selectivity before but not after	$S_{2,y} = S_{3,y} (\Delta_B + H_y{\cdot}l) + \epsilon_y$	$S_{2,y} = S_{3,y} (\Delta_A) + \epsilon_y$	4
8	Change in both residual program and length selectivity	$S_{2,y} = S_{3,y} (\Delta_B + H_y{\cdot}l_B) + \epsilon_y$	$S_{2,y} = S_{3,y} (\Delta_A + H_y{\cdot}l_A) + \epsilon_y$	5
All change in program selectivity accounted for by change in length selectivity				
9	No residual program selectivity, change in length selectivity	$S_{2,y} = S_{3,y} (H_y{\cdot}l_B) + \epsilon_y$	$S_{2,y} = S_{3,y} (H_y{\cdot}l_A) + \epsilon_y$	3
10	No change in residual program selectivity, all length selectivity removed	$S_{2,y} = S_{3,y} (\Delta + H_y{\cdot}l_B) + \epsilon_y$	$S_{2,y} = S_{3,y} (\Delta) + \epsilon_y$	3
11	No change in residual program selectivity, change in length selectivity	$S_{2,y} = S_{3,y} (\Delta + H_y{\cdot}l_B) + \epsilon_y$	$S_{2,y} = S_{3,y} (\Delta + H_y{\cdot}l_A) + \epsilon_y$	4
All selectivity removed with new panels				
12	Residual program and length selectivity before but not after	$S_{2,y} = S_{3,y} (\Delta_B + H_y{\cdot}l_B) + \epsilon_y$	$S_{2,y} = S_{3,y} + \epsilon_y$	3

Note: AIC$_c$, Akaike information criterion corrected for small sample sizes.

Table 2. AIC$_c$ analysis for the 12 candidate models predicting net selectivity of 2-ocean fish (salmon that have spent 2 years at sea) in the Port Moller test fishery from 1990 to 2016.

Model No.	Model name	AIC$_c$	ΔAIC$_c$	Weight
No selectivity				
1	No residual program selectivity or length selectivity	328.55	45.82	0.00
No change in selectivity with new panels				
2	No residual program selectivity, same length selectivity before and after	328.70	45.97	0.00
3	*Same residual program selectivity before and after, no length selectivity*	*282.72*	*0.00*	*0.31*
4	Same residual program and length selectivity before and after	285.27	2.54	0.09
Change in residual program selectivity with new panels				
5	*Change in residual program selectivity, no length selectivity*	*282.96*	*0.23*	*0.28*
6	Change in residual program selectivity, same length selectivity before and after	285.73	3.01	0.07
7	Change in residual program selectivity and length selectivity before but not after	285.72	3.00	0.07
8	Change in both residual program and length selectivity	287.05	4.33	0.04
All change in program selectivity accounted for by change in length selectivity				
9	No residual program selectivity, change in length selectivity	329.81	47.09	0.00
10	No change in residual program selectivity, all length selectivity removed	285.24	2.51	0.09
11	No change in residual program selectivity, change in length selectivity	288.01	5.29	0.02
All selectivity removed with new panels				
12	Residual program and length selectivity before but not after	286.65	3.92	0.04

Note: Models with relative support (under 2 units ΔAIC$_c$) are italicized. AIC$_c$, Akaike information criterion corrected for small sample sizes.

fish. The relative abundance of these two age classes is inversely proportional and highly variable over time (Fig. 2). The program selectivity of 2-ocean fish relative to 3-ocean fish, $S_{R,y}$, was also variable over time from 1990 to 2016 (mean = 0.737, SD = 0.21). On average, $S_{R,y}$ was 26.3% less than the relative selectivity of 3-ocean fish (Fig. 3). Additive error did not significantly deviate from normality based on a Shapiro–Wilk test ($w = 0.96$; $p = 0.28$), which was confirmed by the distribution of the Q–Q plot.

Program and length selectivity before and after change in mesh size

In the two models with substantial support (models 3 and 5), length selectivity is not parameterized. In model 3, residual program selectivity is the same before and after the change in net panels and there is no length selectivity, while in model 5 residual program selectivity is reduced with the change in net panels and,

again, there is no length selectivity. Together, these two models account for the majority of model weight (59%), with respective weights of 0.31 and 0.28. Model 4, in which the net panels had no effect on either residual program or length selectivity, and model 10, in which the net panels resulted in removal of all length selectivity, and all change in program selectivity was accounted for by the change in length selectivity, each had a weight of 0.09. Models 6 and 7 each had a weight of 0.07, indicating that there was a reduction in residual program selectivity, with length selectivity being reduced and completely removed, respectively. The remaining models had weights of 0.04 (models 8 and 12), 0.02 (model 11), and 0 (models 1, 2, and 9) (Fig. 4; Table 2, Table S2[1]). Given this degree of model uncertainty, parameter estimates and effect sizes are more useful for understanding the effect of the change in mesh size than individual model support. For clarity, models 7

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Fig. 3. Relative selectivity of 2-ocean fish to 3-ocean fish over time (S_{2RY}; circles connected with solid lines) contrasted with mean relative selectivity of 2-ocean fish (mean S_{2RY}; dashed line) and relative selectivity of 3-ocean fish to themselves (S_{3RY}; dotted line = 1).
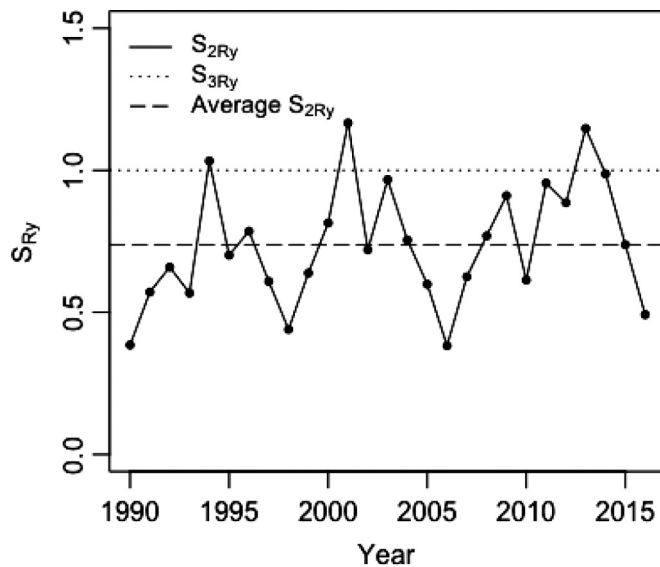
and 8 each had an l_B estimate of 0.35, and models 9 and 10 each had an l_B estimate of 0.75. This is difficult to interpret in Fig. 1 given the substantially larger l_B estimates for models with only length selectivity (models 2 and 11).

Based on overall parameter weights calculated across all models, both length selectivity (l_y) and residual program selectivity (Δ_y) declined after the change in net mesh size (Table 3). A Δ estimate of one would indicate no residual program selectivity, while an l estimate of zero would indicate no length selectivity. The presence of both residual program and length selectivity prior to the change in mesh size had substantial support based on overall l_B and Δ_B parameter weights of 0.90 and 0.91, respectively, and parameter estimates of 0.68 and 0.14, respectively. Both length selectivity and residual program selectivity decreased with the reduction in net mesh size; length selectivity decreased by 0.14 and was zero after the net change, while residual program selectivity was reduced by 0.08, becoming 0.76 after the net change. This demonstrates that length selectivity was eliminated with the implementation of smaller mesh size, and residual program selectivity was also reduced.

Residual program selectivity still existed after the reduction in net mesh size. This is supported by the overall parameter estimate for Δ_A of 0.76 (Table 3). Based on combined residual program and length selectivity effect size estimates, if age-class proportions were 50% 2-ocean fish and 50% 3-ocean fish, after the change in mesh size the proportion of 2-ocean fish would be underestimated to be 43% and the proportion of 3-ocean fish would be overestimated to be 57%; however, prior to the net change, 2-ocean fish would be underestimated to be 35% and 3-ocean fish would be overestimated to be 65% (Table 3). This demonstrates that selectivity of 2-ocean fish relative to 3-ocean fish still exists within the test fishery. Nevertheless, these results support the presence of a substantial reduction in selectivity after the net change and show that the effect size of overall program selectivity has been reduced by half since 2011.

Discussion

Our analysis demonstrates that the change in net mesh size reduced program selectivity in the PMTF but did not eliminate it, while it did eliminate length selectivity. Given that multiple models had subs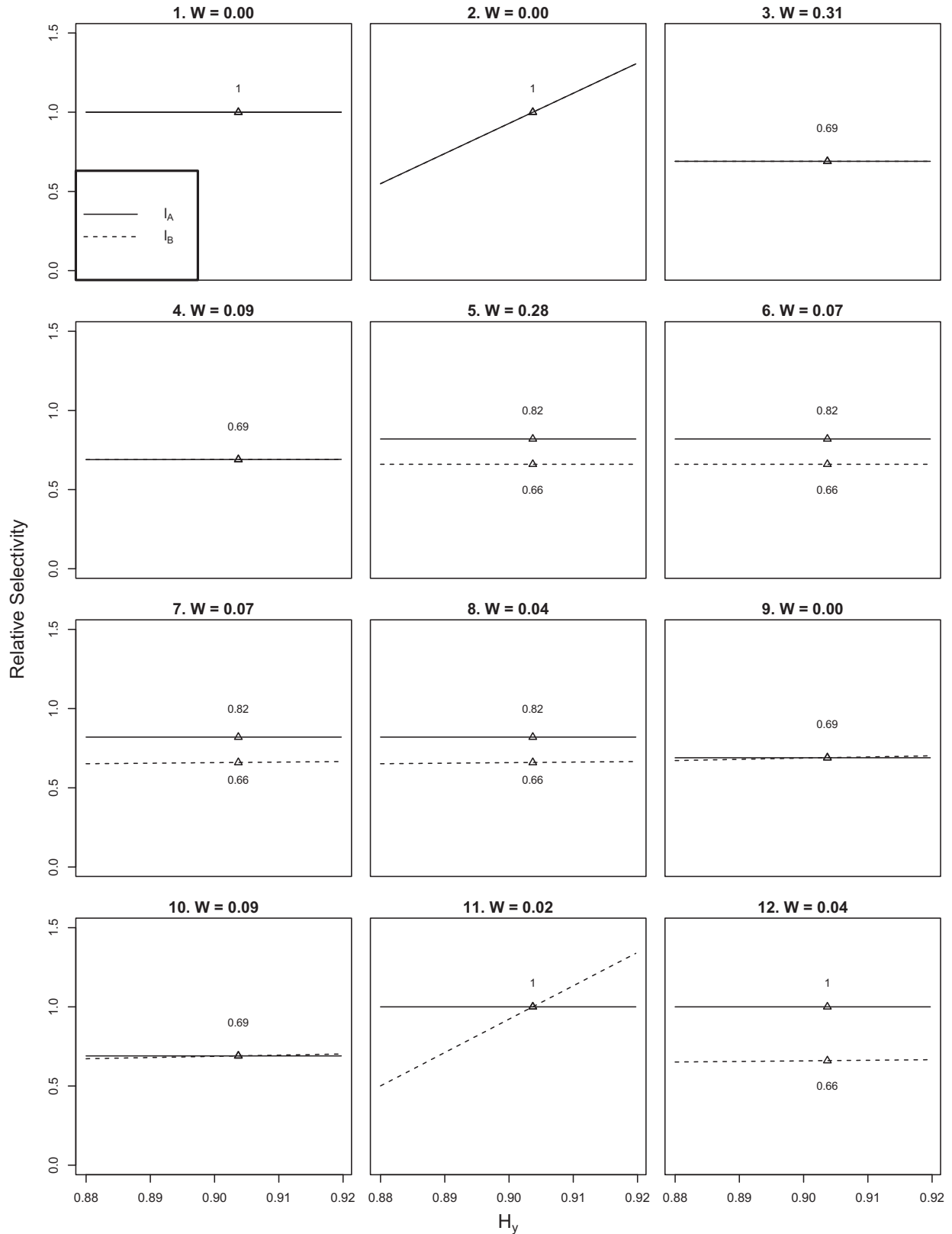tantial support based on AIC_c weights, assessing cumulative parameter estimates and overall effect size is necessary to draw conclusions about the test fishery's program selectivity. Although the individual models that received the most weight reflect that length selectivity was either unimportant in the system or unchanged by the net mesh size change, overall parameter estimates suggest that length selectivity existed prior to the net mesh size change and was eliminated after (Table 3). Because we are testing selectivity before and after a change in net mesh size, we would expect the majority, if not all, of the change in program selectivity to be accounted for by a change in contact selectivity (i.e., the change in net mesh size should only affect fish vulnerability to the fishery, not accessibility). However, our results indicate that changes in contact selectivity parameterized by length did not account for all changes in program selectivity, as indicated by the increase in the cumulative Δ after the net change. The reduction in length-independent program selectivity suggests three possibilities: (1) length is not a sufficient proxy for fish vulnerability and additional contact selectivity was not captured by the length parameter; (2) other changes in the system that were not parameterized in our model have resulted in reduced program selectivity, independent of the change in net mesh size; or (3) a combination of both options 1 and 2. While length selectivity was eliminated, we cannot verify whether it is analogous to contact selectivity and thus cannot conclude that all contact selectivity has been eliminated, although we can conclude that it has been reduced.

Both explanations of why length selectivity did not fully account for the entire change in overall program selectivity could be due to variable ocean environmental conditions. First, fish vulnerability to the net is a factor of fish girth, which we represented in our model as length, based on the assumption that the relationship between fish length and girth is consistent over time and age class. Girth data are not available for most fisheries or cannot be calculated from readily available data, and unless girth measurements are taken at the mesh mark, length is the most useful proxy for assessing vulnerability (Regier 1969; Kendall et al. 2009). Regardless, this assumption is limiting, as body condition is highly dependent on ocean environmental factors and can vary over years and between age classes for some salmonids (Pyper et al. 1999; Bacon et al. 2009). Since girth data are not available for the Bristol Bay sockeye run, we were unable to assess the role of body condition in contact selectivity in this study. In future studies, it may be possible to account for differential girth-to-length relationships by parameterizing trends in condition by ocean age and site.

Second, it is possible that the reduction in length-independent program selectivity is a result of altered accessibility of the run. One mechanism driving change in accessibility could be changes in environmental conditions that have altered migration patterns (Blackbourn 1987; Welch et al. 1995; Crozier et al. 2008; Martins et al. 2012). Studies have shown that the migration patterns of Fraser River sockeye salmon have changed as a result of climate-related environmental changes (Hinch et al. 1995; Hodgson et al. 2006). In addition, Groot and Quinn (1987) found that the migratory route of sockeye salmon was correlated with Gulf of Alaska sea surface temperature, likely affecting the coastal migratory route of the population by altering open ocean distribution. Furthermore, sockeye salmon tend to avoid warm ocean water during coastal migration, migrating at depth when in stratified water and at the surface in cooler, well-mixed water (Quinn et al. 1989).

Changing environmental conditions, such as water temperature and flow, could affect the migratory route and timing of Bristol Bay sockeye and alter accessibility of the stocks to the PMTF sets. Within the PMTF, migratory trends vary both among stocks and among years for a given stock, likely because of environmental conditions (Flynn and Hilborn 2004; Dann et al. 2013). Some fish have been observed to migrate beyond the northwest end of the test fishery transect, but distribution of fish migration

Fig. 4. Twelve candidate models depicted as length deviation from long-term mean (H_y) versus relative selectivity, with values for program selectivity minus length selectivity (Δ) and length selectivity (slope) calculated from maximum likelihood estimates, for 1990–2010 (broken line) and 2011–2016 (solid line). Associated AIC_c weights are shown above. A more positive slope indicates greater length selectivity over that time period; a larger difference between Δ values indicates a greater change in overall program selectivity between the two time periods. A smaller Δ parameter estimate indicates higher program selectivity, while a Δ of one indicates no program selectivity. A larger l parameter (slope) estimate indicates higher length selectivity, while an l of zero indicates no length selectivity. AIC_c, Akaike information criterion corrected for small sample sizes.

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Table 3. Weight, estimate, and effect size for each of the four estimated parameters, where effect size assumes the true population proportion of 2-ocean fish (2 years at sea) is 50% and 3-ocean fish (3 years at sea) is 50%.

Parameter	Parameter weight	Parameter estimate	Effect size	
			2-Ocean	3-Ocean
Δ_B	0.91	0.68	40%	60%
Δ_A	0.84	0.76	43%	57%
l_B	0.90	0.14	46%	54%
l_A	0.47	0.00	50%	50%
Combined before	—	—	35%	65%
Combined after	—	—	43%	57%

Note: Combined effect size represents overall program selectivity, including both length selectivity and Δ.

across Bristol Bay has not been characterized beyond test fishery data. In 2015 and 2016, researchers noted that a large portion of the stock seemed to have migrated beyond station 10, resulting in the consistent implementation of additional sampling stations (12 and 14) in 2016 and 2017 (Raborn et al. 2017). These potential sources of altered accessibility could contribute to the change in program selectivity quantified here if (*i*) a substantially larger portion of the run passed beyond the transect prior to 2011 and (*ii*) the missed portion of the run was dominated by 2-ocean fish. Regardless, it is likely that differential accessibility still exists in the system given the substantial program selectivity still observed after the net change.

Research examining additional sources of selectivity would be useful for understanding residual program selectivity in this system. BBSRI researchers have identified several potential factors that could contribute to the PMTF's remaining program selectivity as a result of differential accessibility between sampling stations. Specifically, time-of-day effects and inclement weather can impact the strength of the run at and the ability of the vessel to access different stations. Runs during the middle of the day demonstrate the most consistent movement (M. Link and S. Raborn, personal communication, 2017). Since mid-transect stations are typically fished at midday, and stations at the ends of transects are fished either early or late in the day, effects of time of day could result in reduced run accessibility due to daily temporal migration variability. Similarly, stations at the ends of transects might not be sampled owing to weather and time constraints. These sources of differential accessibility would only contribute to the residual program selectivity identified in our model if 2-ocean fish were more likely to pass through sampling stations on the ends of the transect, such as station 12 or 14, which may be plausible. The Nushagak–Wood stock tends to be dominated by 2-ocean fish and has been more represented with the implementation of >10 sampling stations (Raborn et al. 2017). Therefore, these stocks are more likely to be fished late or early in the day when there is less run movement or missed altogether by the transect, thus resulting in reduced accessibility relative to the overall run (Kendall and Quinn 2009; Dann et al. 2013; Kendall et al. 2014; Raborn et al. 2017). While these factors have not been included in our study, they could potentially be parameterized in future iterations of the model to elucidate underlying mechanisms driving the additional program selectivity observed. For example, deviation of annual migration patterns from the center of the transect and mean ocean age of stocks that dominate the northwest stations (10–14) could be used to understand residual program selectivity caused by variation in migration patterns; however, the data necessary for this parameterization were not available for this analysis. An understanding of the drivers of residual program selectivity would continue contributing to the development of appropriate sampling strategies to mitigate selectivity.

Correcting for the residual selectivity that was identified in this analysis would assist managers in generating a more accurate RPI, but would be difficult given interannual variability of the proportion of returning age classes. If the proportion of ocean age classes were constant over time, the residual effect size after the net change could be used to adjust PMI for selectivity. However, there is large interannual variation in the proportion of returning 2-ocean and 3-ocean age classes, where the proportion of 3-ocean fish was as high as 93% in 2011 and as low as 23% in 1999 (Fig. 2). This means the effect size of the PMTF's selectivity each year is difficult to assess without an accurate estimate of the proportion of each age class within that year's run. Regardless, these results support estimation of RPI separately by age class for in-season forecast models, with the assumption that selectivity has changed since 2011.

The utility of this method extends beyond salmon test fisheries. It can be applied to a variety of test fisheries in which assessing sources of program selectivity is useful. For example, in the British Columbia herring fishery, test fishery age and length data are combined with data from the seine row fishery to generate stock assessments. However, the British Columbia herring test fishery is selective for younger fish relative to the seine roe fishery, creating challenges for incorporating both data sets into stock assessment models (Haist 2012). Investigation of the assumptions concerning differential selectivity of these two data sets has been suggested (Haist 2012), thus providing an example of a situation in which this framework could be a useful tool beyond the scope of the PMTF case study.

The model presented here is well suited to analyzing and quantifying the selectivity of seasonal test fisheries that have long time series, but it can also be used to better understand selectivity in different fishing systems. Another application of the model is assessing the selectivity of new fishing gear types prior to adoption into a fishery. For example, test fisheries have been used to assess effectiveness of fish aggregation devices (FADs) in American Samoa, catchability of new crab pots in Bristol Bay, and reduction of seabird bycatch in Puget Sound (Buckley et al. 1989; Byersdorfer 1996; Melvin et al. 1999). New gear has the potential to introduce new sources of both contact selectivity and residual program selectivity, which can have negative effects on the target stock. In addition, this modelling framework is not limited to assessing age selection, as it could also be used to assess sex selectivity in fisheries. Sex selectivity could be parameterized within an age selectivity model or could be assessed independently of age.

While we see a broad range of applications for the modeling framework we have presented, it has limitations. The primary limitation is that extensive data of the true population age and size composition are necessary for robust model outputs. Accuracy of modeling outputs is limited by the quality of age and size composition data, which can be challenging to acquire in many cases. Nonetheless, we've identified several applications to fishery systems that have the necessary input data, some of which are included in this discussion.

This study demonstrates the utility of accounting for multiple sources of program selectivity in test fisheries and shows the potential to both quantify program selectivity and identify mechanisms of different types of selectivity. In the PMTF case study presented, we have demonstrated that the introduction of the smaller mesh size reduced contact selectivity of 3-ocean fish relative to 2-ocean fish, but did not eliminate all program selectivity. Thus, we have identified that contact selectivity is not the only source of program selectivity occurring in the PMTF. Given the remaining age selectivity in the system, our results support the estimation of RPI separately by age class, confirms that selectivity has changed since 2011, and highlights the need to examine additional sources of program selectivity in the PMTF. This novel approach for assessing program selectivity in test fisheries has the

potential to identify sources of selectivity and inform meaningful programmatic change to support improved management of fishery stocks.

Acknowledgements

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