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Size-selectivity and capture efficiency of sablefish (*Anoplopoma fimbria*) using pot escape rings in Southeast, Alaska

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Abstract will go here. It will be written once authors have reviewed the manuscript and agree on methods and interpretation of results.

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1 | INTRODUCTION

Selectivity, or the probability of capture as a function of age or length, is a crucial fisheries stock assessment quantity that scales the observed population to the total population (Quinn and Deriso, 1999; Beverton and Holt, 1957). It is notoriously challenging to estimate, and a mis-specified selectivity curve can produce unreliable estimates of MSY-based biological reference points (Butterworth et al., 2014; Crone and Valero, 2014) or lead to biased projections of fish abundance (e.g. Stewart and Martell, 2014; Walters and Maguire, 1996).

Numerous intrinsic and extrinsic factors influence gear selectivity. For example, changes in fishing gear, regulations, or fisher behavior can shift selectivity (Graham et al., 2007; Valdemarsen and Suuronen, 2003). These changes can be motivated by shifting markets or processor preference, for example, if the development of a live market fishery increases the desirability of smaller or medium-sized fish (Reddy et al., 2013; Kindsvater et al., 2017). Modification of fishing gear or regulations can also be motivated by conservation efforts to protect a segment of a fish population, reduce bycatch, or avoid interaction with habitat or protected species (Kennelly and Broadhurst, 2002). Environmental factors like water temperature can influence selectivity on a seasonal basis due to spawning period and body condi-

Abbreviations: MSY, maximum sustainable yield; ADFG, Alaska Department of Fish and Game.

tion (e.g. Özbilgin et al., 2007) or swim speed (e.g. Yanase et al., 2007). Additionally, fish behavior or availability can change selectivity, for example, if fish occupy deeper waters as thermal refuge during periods of warm sea surface temperatures. This has been observed in Pacific cod in the Gulf of Alaska (*Gadus macrocephalus*), with fish greater than 34 cm moving to deeper water in years with warmer shelf temperatures (Barbeaux et al., 2019; Li et al., 2019).

For the case of sablefish in Alaska, several recent changes in fishery dynamics and regulations have created the potential for changing fishery selectivity. Two commercial sablefish fisheries occur in Alaskan waters. The primary is the federal fishery prosecuted in the United State's exclusive economic zone (EEZ, 3-200 nm), which has been regulated under an Individual Fishing Quota (IFQ) program since 1995 (Hanselman et al., 2019). The IFQ sablefish fishery can be characterized as a low volume, high profit fishery, averaging a first wholesale volume 7,185 mt worth $107.90 million US dollars between 2008-2017 (Fissel et al., 2020). This fishery is primarily a longline fishery; however, sablefish catch by pots has increased dramatically since 2000 in the Bering Sea and Aleutian Islands from 0.5-0.7% in 1991-1999 to 45% in 2017/2018 (Hanselman et al., 2020). This increase is attributed to killer whale depredation on longline gear, which can remove 54-74% of sablefish from longline gear and affect upwards of 21% of sets in the Bering Sea (Peterson et al., 2013, 2014). A regulation to allow pot fishing in the Gulf of Alaska went into effect in 2017, and subsequent landings from pot gear in this area have increased to 13% of the total catch in 2019 (Hanselman et al., 2020). Length compositions suggest pot gear selects for smaller-sized individuals than longline gear, and resultant changes in selectivity will be addressed if catch continues to increase for pot gear (Hanselman et al., 2020).

A smaller sablefish fishery exists in Alaskan state waters up to 3 nm, which has been regulated by the Alaska Department of Fish and Game (ADFG) under a limited entry program since 1995 (Dressel, 2009). The majority of sablefish catch in state waters occurs in Chatham Strait and Clarence Strait in Southeast Alaska; however, smaller fisheries also occur in Prince William Sound and Cook Inlet (FIGURE MAP). Many vessels participate in both IFQ and state water sablefish fisheries. A fundamental difference between the two fisheries is full retention is mandated in federal waters, while the release of healthy sablefish in allowed in state waters (Olson and Sullivan, 2019; Sullivan et al., 2019). The seasons for the fisheries differ slightly; the IFQ sablefish fishery is 8 months long (March to November), while seasons in Chatham Strait and Clarence Strait are considerably shorter and occur September to November and July, respectively. Pot fishing is permitted under regulation in Clarence Strait but not currently in Chatham Strait.

In 2018 a live market pot fishery for sablefish was proposed in Clarence Strait. The primary concern among management biologists was the harvest of immature individuals, which comprise the "plate size" target generally seen in live fish markets (McGilvray and Chan, 2003). A pot fishery for sablefish exists in British Columbia (BC), Canada, where a minimum size limit of 55 cm and the use of 8.9 cm escape rings for sablefish was implemented based on the length at 50% maturity (L_{50}) for sablefish in BC (Haist et al., 2000; Haist and Hilborn, 2000). Studies have shown large variability in growth and maturity between Alaska, BC, and the United States west coast (e.g. Head et al., 2014; Kapur et al., 2020). Additionally, because sablefish spawn in the winter months, classification of maturity status during summer annual surveys can be difficult (Rodgveller, 2018). A comparison of macroscopic and histological maturity samples collected across the Gulf of Alaska showed that L_{50} ranged between 58 and 64 cm (Rodgveller, 2018). These findings are consistent with macroscopic maturity data collected in annual surveys conducted by ADFG in Southeast Alaska (L_{50}=63 cm for females; Dressel, 2009). In order to account for the higher L_{50} while reducing catch rates of immature sablefish, 10.2 cm (4 in) escape rings were adopted in the Clarence Sound sablefish pot fishery in 2018 (Olson and Sullivan, 2019).

An escape ring experiment was conducted in May 2019 to analyze the impact of escape rings on capture efficiency and gear selectivity. An optimal escape ring size provides the best compromise between low catches of immature sablefish while maintaining high CPUE of mature sablefish. Three alternative escape ring sizes, 8.9 cm (3.5 in), 9.5 cm (3.75 in), and 10.2 cm (4 in), were evaluated during the ADFG sablefish tagging survey in May 2019 in Chatham

Strait (Green et al., 2016). A combination of techniques were employed to evaluate the impact of escape rings on pot selectivity. Given that girth, or the circumference of a fish at its widest point, determines whether a sablefish can pass through an escape ring, the girth-length relationship was used to develop theoretical selectivity curves. Additionally, selectivity was estimated directly using the SELECT (Share Each LEngth's Catch Total) method (Millar, 1992). The SELECT method has a long history in fisheries literature for gear selectivity experiments and has been applied to a variety of trawl and pot gear experiments (e.g. Xu and Millar, 1993; Millar and Walsh, 1992). Although sablefish maturity estimates are variable, an L_{50} of 63 cm was selected as a reference length for evaluating alternative selectivity curves and escape ring sizes (Dressel, 2009).

2 | METHODS

2.1 | Capture efficiency

A longline of 40 conical pots with 5.08 x 5.08 cm mesh (Figure 1) was set for 24-hr soaks at 17 randomly selected stations in Chatham Strait during the 2019 ADFG sablefish tagging survey on the R/V *Medeia* (Green et al., 2016). Each set was comprised of 4 treatments with 10 pots per treatment in a fixed alternating design. The study included four different escape ring scenarios: a control with no escape rings, and three treatments with internal ring diameters of 8.9, 9.5, and 10.2 cm. Each experimental pot included two escape rings installed on opposing vertical or sloping walls of the pot (Figure 1).

Differences in catch rates of sablefish between control and escape ring pots (CPUE) were evaluated using the non-parametric Kruskal-Wallis test, which evaluates the null hypothesis that mean CPUE between groups is the same (Neter et al., 1974). Post hoc multiple comparisons Dunn tests were conducted using a Bonferroni adjustment (Zar, 2010). Statistical analyses were conducted in the statistical software R (R Core Team 2019) and the R library FSA (Ogle et al., 2019). Comparisons of CPUE were conducted with all fish combined and by size groups. Catches of different sized fish were defined using length at 50% maturity L_{50}=63 cm (Dressel 2009). Catch of $\geq$ 63 cm was compared to catch $<$ 63 cm.

2.2 | Theoretical size-selectivity curves

Sablefish fork length and girth data were used to develop theoretical size-selectivity curves for escape ring sizes examined in this study. A similar approach was developed for Southern rock lobsters (*Jasus edwardsii*) in Australia using carapace depth and length (Treble et al., 1998). Girth data were not normally distributed, so a generalized linear model was developed using log-transformed girth (G) and length (L), such that $\log(G) = a + b\log(L)$.

Seasonal changes in the girth-length relationship between the timing of the survey (May) and fishery (Sep-Nov) were evaluated by comparing a regression with a single slope and intercept with progressively more complicated models, including one with separate intercepts and a second with separate intercepts and slopes for each time period. Candidate models were compared using the Akaike Information Criterion (AIC) (Burnham and Anderson, 1992). A total of 153 girths were collected from control pots during the survey, and 411 girths were collected during the fishery.

All sablefish with an approximate diameter (G/π) greater than the escape ring diameter were assumed to be retained in the pot, while sablefish less than or equal to the escape ring diameter were assumed to escape. Using the residual standard deviation from the generalized linear regression, sablefish girths were simulated across a range of lengths using a lognormal distribution. The proportion of sablefish at a given length that had a diameter greater than the escape ring were plotted as probabilities of retention or theoretical size-selectivity curves. These theoretical selectivity curves were used to develop priors for the SELECT analyses.

2.3 | SELECT models of experimental escape ring data

A Bayesian SELECT model was developed using the R package Template Model Builder (TMB), which allows fast implementation of nonlinear random effects models by estimating the marginal likelihood of the fixed effects via the Laplace approximation and estimating the random effects using empirical Bayes methods (Kristensen et al., 2016). The SELECT method estimates selectivity parameters of experimental gear fished in tandem with control gear assumed to retain all length classes of fish encountered by the gear (Millar, 1992). Control pots were assumed fully selected at 50 cm, and length frequencies were binned into 1 cm increments. Length frequencies obtained with each escape ring treatment were compared with those observed in the control pots. Given that a fish in length bin i is caught and retained in a pot in set j, the probability that it is captured in escape ring treatment k (ϕ_{ijk}) is

$$\phi_{ijk} = \frac{P_{ijk}}{P_{ijk} + \delta r_j} \tag{1}$$

where P_{ijk} in the probability that a fish is retained in an escape ring treatment (i.e. selectivity), δ is the relative probability of entering a control pot (i.e. the probability of entering a control pot / the probability of entering an escape ring pot), and r_j is the ratio of control pots sampled to escape ring pots sampled in set j. The inclusion of r_j permitted unequal sampling of pots across sets (Haist et al., 2000).

Relative gear selectivity (P_{ijk}) is modeled as a logistic function. A random effect is included at the set level (η_j) to account for variability in length frequencies that may be explained within a set. The probability of retaining a fish of length i in set j and treatment k is

$$P_{ijk} = \frac{1}{1 + \exp(-\kappa(i - s_{50}) + \eta_j)}, \tag{2}$$

where s_{50} is the length at which 50% of sablefish are selected to the gear and κ is the slope of the logistic curve at s_{50}. The SELECT log-likelihood is

$$\log(L) = \sum_{k=1}^{K} \sum_{j=1}^{J} \sum_{i=1}^{I} T_{ijk} \cdot \log(\phi_{ijk}) + C_{ij} \cdot \log(1 - \phi_{ijk}), \tag{3}$$

where T_{ijk} and C_{ij} are numbers observed in each length bin and set for each treatment and control pots, respectively.

Normal priors on length at 0 and 100% retention probabilities were developed using results from the theoretical selectivity curves for each escape ring. Mean lengths at 0% retention in the theoretical curves were 51.1, 54.7, and 58.1 cm for 8.9, 9.5, and 10.2 cm escape rings, respectively. A weakly informative prior variance (σ=0.35) was assumed for the length at 0% retention to account for factors like fish availability and soak time that could influence the lower arm of the selectivity curve. Mean lengths at 100% retention were 67.6, 72.2, and 77.4 cm for 8.9, 9.5, and 10.2 cm escape rings, respectively. An informed prior variance (σ=0.05) was applied to the length at 100% retention, which loosely constrains the upper arm of the logistic curve to asymptote according to the girth-length relationship. Broad uniform priors were used for all other parameters (Table 3).

Markov chain Monte Carlo (MCMC) sampling was implemented in the tmbstan R library using the no-U-turn sampler (NUTS), a self-tuning MCMC algorithm popularized by the Bayesian software Stan (Monnahan and Kristensen, 2018; Carpenter et al., 2017; Hoffman and Gelman, 2014; Stan Development, 2018). Seven chains were run with 2,000 iterations each, including 1,000 samples for burn-in. Convergence diagnostics included a visual examination of trace plots and pairwise correlation plots for fixed effects. The tmbstan package produces convergence diagnostics, including the bulk and tail effective sample size (ESS) for each chain and parameter, which measures sampling efficiency in the bulk (95%) and tails (outer 5% and 95%) of the posterior distributions. The ESS statistics corrects for autocorrelation within chains, and both the bulk and tail ESS should be >100 per chain (Stan Development, 2018). Additionally, tmbstan calculates an $\widehat{R}$ convergence diagnostic, which measures the agreement or mixing between chains (Vehtari et al., 2019). An $\widehat{R} \leq 1.05$ is considered fully mixed or converged.

The relationship between estimated selectivity parameters for each treatment was used to develop a generalized function that defines the size-selectivity of a pot with any escape ring size (Arana and Ziller, 1994; Arana et al., 2011):

$$P = \frac{1}{1 + \exp(-(a_1 + b_1 \cdot E) \cdot (i - (a_2 + b_2 \cdot E)))}, \tag{4}$$

where E is the escape ring size and a_1, a_2, b_1, and b_2 are coefficients from the following linear relationships: $\kappa = a_1 + b_1 E_k$ and $S_{50} = a_2 + b_2 E_k$.

3 | RESULTS

3.1 | Capture efficiency

A total of 17 sets with 40 pots per set (680 pots total) were fished over a 17 day period. A total of 14,234 sablefish were caught during the survey, of which 11,107 were measured to fork length (Figure 2, Table 1). All data, code, and output files for this study can be found at `https://github.com/commfish/great_escape`.

Results of the non-parametric Kruskal-Wallis test showed that CPUE of sablefish (all sizes combined) declined significantly with increasing escape ring size (Figure 3, Table 2, $\chi^2 = 77.2$, $p < 0.001$). However, when sablefish were split into groups based on size at 50% maturity (< 63 cm and ≥ 63 cm), the difference between treatments was only significant for smaller sized sablefish (Figure 3, Table 2; < 63 cm: $\chi^2 = 46.9$, $p < 0.001$; ≥ 63 cm: $\chi^2 = 5.3$, $p = 0.151$). For all sizes combined, post hoc multiple comparison Dunn tests showed that all groups were significantly different ($\alpha = 0.05$) from each other except the 10.2 cm - 9.5 cm ring combination (Table 2). For CPUE of sablefish < 63 cm, all treatments were significantly different from each other except the 8.9 cm - Control ($p_{adj} = 0.139$) and 10.2 cm - 9.5 cm ($p_{adj} = 1.00$) combinations (Table 2). In contrast, no CPUE comparisons of sablefish ≥ 63 cm were significantly different. In summary, although CPUE declined with increasing escape ring diameter, this change is best explained by a decrease in CPUE for small sablefish. CPUE of large sablefish remained relatively constant between Control and escape ring pots, although the distribution of CPUE for Control pots was most closely matched by the 8.9 cm escape rings (Figure 3).

3.2 | Theoretical selectivity curves

The girth-length relationship for sablefish was best characterized by a generalized linear model with a single intercept and separate slopes for data collected in May and Sep/Oct (Figure 4A). Theoretical selectivity curves show that as girth-at-length increases throughout the growing season, the proportion retained at length increases for a given escape ring size (Figure 4B). In other words, as fish get fatter over the growing season, they have a harder time escaping from a pot and are retained at a higher rate for a given length.

Results suggest large changes in selectivity with relatively small increases in escape ring size (Figure 4B). For the 8.9 cm escape ring, sablefish are fully selected by 65 cm in the fishery, meaning that by the time 50% of sablefish are mature at 63 cm, they will be 99% selected to the gear. In contrast, results from the 9.5 cm and 10.2 cm escape rings show that only 89% and 50% of 63 cm fish are selected during Sep/Oct, respectively. Theoretical selectivity curves for Sep/Oct suggest that sablefish are not fully selected to the gear until 69 cm and 74 cm for 9.5 and 10.2 cm rings, respectively. If the management goal is to protect immature sablefish while maximizing proportion retained above L_{50}, an escape ring as small as 8.9 cm may be appropriate.

3.3 | SELECT modelling

A total of 24 parameters were estimated, including 7 fixed effects and 17 random effects for set using the SELECT approach (Table 3). Residual plots show the model fit the data well, with the exception of residual patterns in the larger length bins for the 8.9 cm escape ring and in the smaller length bins for the 10.2 cm escape ring (Figure 5). The relative probability of entering a control pot (δ) was estimated to be 0.95, suggesting there is a slightly higher probability of entering a pot with escape rings than not. This may be a spurious result as the 95% credible interval contained $\delta = 1$ (Table 3).

Posterior distributions and correlation plots for the model's fixed effects show that parameters are well-estimated (Figure 6). As expected, a positive linear correlation was observed between the s_{50} parameters and escape ring size (Figure 6). Trace plots for the six chains indicated the model were well mixed (figure omitted for brevity). This interpretation was corroborated by an $\widehat{R}$ statistic = 1.00, well below the maximum convergence threshold of 1.05. Similarly, the minimum bulk and tail ESS were 1,972 and 2,824, respectively, well above the recommended minimum of 100.

SELECT logistic selectivity curves with 95% credible intervals are shown in Figure 7. A comparison of theoretical and SELECT curves show that theoretical curves are far steeper than the SELECT curves, resulting in a much narrower selection range (Figure 7). At L_{50}=63 cm, sablefish are 89% (95% credible interval: 85-93%), 75% (70-80%), and 65% (59-70%) selected for the 8.9 cm, 9.5 cm, and 10.2 cm escape rings, respectively. These percentages are lower at L_{50} than they are for the theoretical curves, resulting in different management implications. However, based on seasonal changes in the theoretical selectivity curves, one would expect the SELECT curves to be shifted to the left later in the year when the fishery occurs, resulting in an increased retention percentage at L_{50} for all escape rings. The SELECT curves retain a much higher proportion of smaller-sized sablefish than what would be suggested by the theoretical selectivity curves. The SELECT curves indicate that sablefish are not fully selected until they are at least 80 cm for the 8.9 cm escape ring and even greater for the 9.5 cm and 10.2 cm escape rings.

Linear regressions of SELECT model's estimates of selectivity slope (κ) and length-at-50% selectivity (s_{50}) parameters yielded the following results: $\kappa = 0.53 - 0.037 \cdot E$ ($R^2 = 0.94$) and $s_{50} = 6.28 + 5.22 \cdot E$ ($R^2 = 0.97$), where E is internal escape ring diameter. These regression coefficients were used to develop a generalized equation that can be used to calculate the size-selectivity for any escape ring size:

$$P = \frac{1}{1 + \exp(-(0.53 - 0.037 \cdot E) * (i - (6.28 + 5.22 \cdot E)))}. \quad (5)$$

4 | DISCUSSION

There is a long history of modifying fishing gear to alter selectivity and reduce incidental catch of smaller size or age classes or bycatch of non-target species (Kennelly and Broadhurst, 2002; Broadhurst et al., 2007). Our experiment demonstrated that escape rings significantly reduced catch of small, immature sablefish, while maintaining average catch rates of larger individuals (Table 2, Figure 3). There was no additional decrease in CPUE of small sablefish between the 9.5 and 10.2 cm escape rings, suggesting there is no added benefit of an escape ring > 9.5 cm. Theoretical and SELECT-estimated size-selectivity curves suggest that the 8.9 cm escape ring will maximize catch of sablefish ≥ 63 cm, with the trade off that it will also result in the highest catches of sablefish < 63 cm. This trade off was realized in the capture efficiency analysis; the 8.9 cm escape ring had intermediate CPUE for small fish, but its distribution of CPUE of large sablefish was most similar to the control pot CPUE (Figure 3).

Several factors contribute to the apparent differences in the theoretical and SELECT estimated selectivity curves (Figure 7). One hypothesis is that the current study's relatively short soak time (24 hr) was insufficient to observe the full effects of the escape rings on size-selectivity. The theoretical curves assume all fish smaller than the escape ring will escape, which may be unrealistic given search time and crowding in the pots. Further experimentation is needed to assess the effects of soak time on escape ring size-selectivity and capture efficiency. Another factor to consider is the availability of small sablefish in the population during the time of the study. Record year-classes in 2014 and 2016 have been observed for sablefish throughout the North Pacific Ocean, which were observed as peaks in the length frequencies around 48 cm and 53 cm (Figure 2). Finally, residual patterns in the model fits to the proportion retained in the escape ring pots could potentially be remedied with alternative selectivity curves. Other studies have suggested that pot gear for sablefish may follow a dome-shaped selectivity (Assonitis, 2008), and others have used an asymmetric logistic curve (Haist and Hilborn, 2000; Haist et al., 2000). Residual patterns were not consistent across escape rings, however, and therefore did not warrant further exploration. Additional research would be needed to develop methods to generalize these alternative selectivity parameterizations as a function of escape ring size as has been done in this study.

The present study's results differed from previous escape ring studies conducted in British Columbia for sablefish. Haist et al. (2000) found that the length at which 50% of sablefish are retained (s_{50}) was 60-64 cm for a 9.8 cm escape ring, while s_{50} was 52-59 cm in the present study for the escape ring sizes examined. This difference may be attributed to the parameterizations of the logistic curve, which varied between the two studies. However, it is likely due to the differences in the data collected in the two studies. For example, the proportion in treatment pots (ϕ) showed significantly more contrast in Haist et al. (2000), with observations of ϕ ranging between 0 and 1, while the ϕ in this study ranged between 0.2 and 0.6. These differences are likely explained by variation in fish availability between areas and years.

A fundamental tension exists in modern fisheries management between the traditional guidance to reduce incidental catch of small, immature fish and an alternative strategy of "balanced harvesting" or spreading fishing mortality more evenly across size or age classes (Zhou et al., 2010). While most harvest strategies rely on a reference point based on a fishing mortality rate (F) averaged across all ages (e.g. F_{35}; Clark, 1991), the realized resultant age-specific Fs may be much higher if mortality is concentrated on large fish in a population (Garcia et al., 2012; Breen et al., 2016).

The debate between selective and balanced harvesting remains highly relevant among fisheries managers and biologists regulating fisheries with limited resources and shrinking budgets. This study demonstrates that larger escape rings select for larger individuals, while smaller escape rings may offer a compromise that results in a slightly more balanced harvest across size classes.

These results should be interpreted in the current management framework, which varies between the IFQ and state sablefish fisheries. In particular, because releasing small fish is legal in state water fisheries, there is a large incentive to discard small fish because the price per pound can be more than double for larger grade sablefish (Fissel et al., 2020; Sullivan et al., 2019). In response, managers in state waters may prefer the medium-sized escape ring (9.5 cm) because it effectively minimizes CPUE for small sablefish. In contrast, the smaller escape ring (9.5 cm) may be preferable for the IFQ fishery where full retention is mandatory in order to promote balanced harvest of sablefish across a wider spectrum of size and age classes. Interestingly, the development of a live market sablefish fishery in Clarence Strait stalled due to a steep increase in tariffs of U.S. seafood products going to China from 10% to 25-30% (J. Scoblic, personal communication, January 3, 2020). Although an optimal fish size has not been determined, fishery managers navigating a developing live market sablefish fishery that targets small fish may favor the 8.9 cm escape ring, which has a higher CPUE for small sablefish than the 9.5 or 10.2 cm rings. Alternatively, if exclusively small fish are desirable for a live market fishery, a separate management strategy with a reduced harvest rate and no escape rings may be needed in order to manage this fishery in tandem with the traditional sablefish fishery.

In summary, the addition of escape rings to a sablefish pot fishery has numerous benefits. Minimizing catch of small, immature fish can be helpful for reducing discards and handling mortality of released fish. Escape rings may also offer a solution to the current "small fish problem" in the IFQ sablefish fishery. Record year classes were observed in 2014 and 2016, which resulted in an influx of small fish into the commercial fishery (Hanselman et al., 2020). Because these fish are of low economic value, the IFQ fleet proposed a change in federal regulation to allow discarding of small sablefish in the IFQ fishery (Armstrong and Cunningham, 2018). Escape rings provide a simple and cost effective way to reduce catch rates of small sablefish, while maintaining catch rates of larger sablefish.

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Conflict of interest

The authors have no conflict of interest to disclose.

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5 | TABLES

TABLE 1 Number of sablefish caught, fork lengths sampled, and mean fork length with standard error (SE) by escape ring treatment during the May 2019 survey. Control = no escape ring.

Treatment	Total catch	Fork lengths	Mean fork length (SE)
Control	5,216	4,059	56.7 (0.13)
8.9 cm	3,604	2,827	58.0 (0.15)
9.5 cm	2,918	2,244	58.2 (0.18)
10.2 cm	2,495	1,977	58.2 (0.21)
Total	**14,233**	**11,107**	**57.6 (0.08)**

TABLE 2 Results for non-parametric Kruskal-Wallis and post hoc multiple comparison Dunn tests for CPUE of all sizes of sablefish combined, sablefish < 63 cm, and sablefish ≥ 63 cm. Statistically significant results (α = 0.05) for Dunn tests are highlighted in bold and p-values have been adjusted using the Bonferroni correction.

Comparison	Z-statistic	p_{adj}
All sizes combined: χ^2-statistic = 77.2, $p < 0.001$		
10.2 cm - Control	-8.20	< **0.001**
9.5 cm - Control	-6.63	< **0.001**
10.2 cm - 8.9 cm	-4.23	< **0.001**
8.9 cm - Control	-3.98	< **0.001**
8.9 cm - 9.5 cm	2.66	**0.047**
10.2 cm - 9.5 cm	-1.57	0.702
Sablefish < 63 cm: χ^2-statistic = 46.9, $p < 0.001$		
10.2 cm - Control	-6.17	< **0.001**
9.5 cm - Control	-5.12	< **0.001**
10.2 cm - 8.9 cm	-3.85	**0.001**
8.9 cm - 9.5 cm	2.80	**0.030**
8.9 cm - Control	-2.27	0.139
10.2 cm - 9.5 cm	-1.06	1.000
Sablefish ≥ 63 cm: χ^2-statistic = 5.3, p = 0.151		
9.5 cm - Control	-2.15	0.187
10.2 cm - Control	-1.74	0.490
10.2 cm - 8.9 cm	-0.51	1.000
10.2 cm - 9.5 cm	0.36	1.000
8.9 cm - 9.5 cm	0.89	1.000
8.9 cm - Control	-1.25	1.000

TABLE 3 SELECT model parameters estimates (medians and 95% credible intervals, CI) with priors used for Bayesian analysis. For brevity, only median values are reported for random effects. Parameters are indexed by escape ring treatment, such that 1 = 8.9 cm, 2 = 9.5 cm, and 3 = 10.2 cm. The relative probability of entering a control pot δ was estimated using a log-link and is reported on the natural scale for clarity.

Parameter	Symbol	Median	95% credible interval	Prior
Length at 50% selectivity, 8.9 cm	$s_{50,1}$	52.5	(50.9, 53.9)	$U \sim (0, 100)$
Length at 50% selectivity, 9.5 cm	$s_{50,2}$	56.5	(54.8, 58.0)	$U \sim (0, 100)$
Length at 50% selectivity, 10.2 cm	$s_{50,3}$	59.1	(57.4, 60.6)	$U \sim (0, 100)$
Slope at 50% selectivity, 8.9 cm	κ_1	0.20	(0.17, 0.25)	$U \sim (0, 0.9)$
Slope at 50% selectivity, 9.5 cm	κ_2	0.17	(0.15, 0.20)	$U \sim (0, 0.9)$
Slope at 50% selectivity, 10.2 cm	κ_3	0.15	(0.14, 0.17)	$U \sim (0, 0.9)$
Relative probability of entering a control pot	δ	0.95	(0.90, 1.01)	$U \sim (0.1, 2)$

380 ## 6 | FIGURES

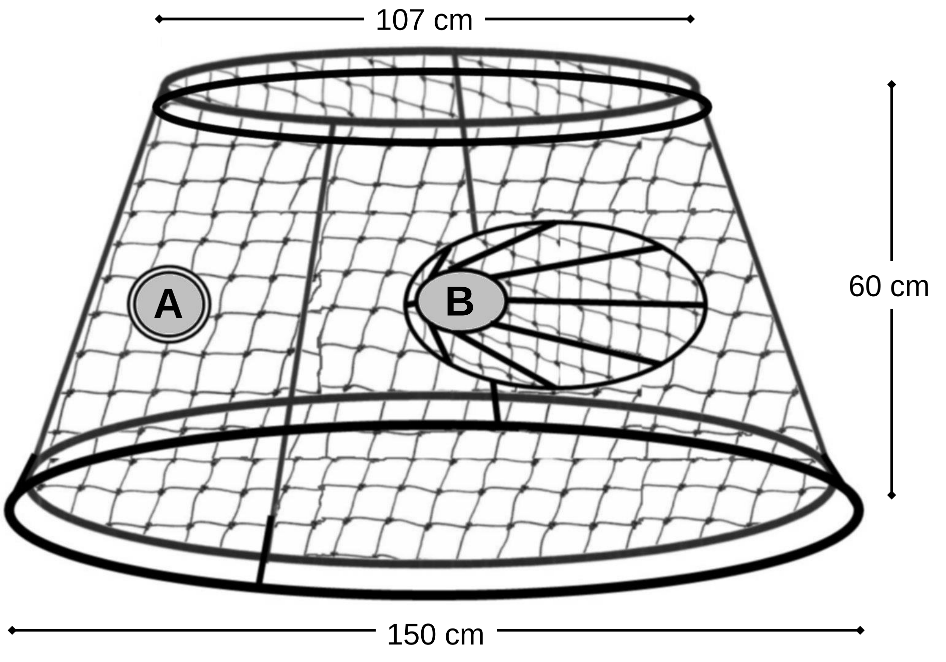

FIGURE 1 Diagram of the conical pot used during the survey, including the placement of the escape ring (A), the soft-sided entrance tunnel (B), the top diameter (107 cm), bottom diameter (150 cm), and height (60 cm). Both the entrance tunnel and escape ring are mirrored on the opposite quandrants of the pot (not shown in this diagram).

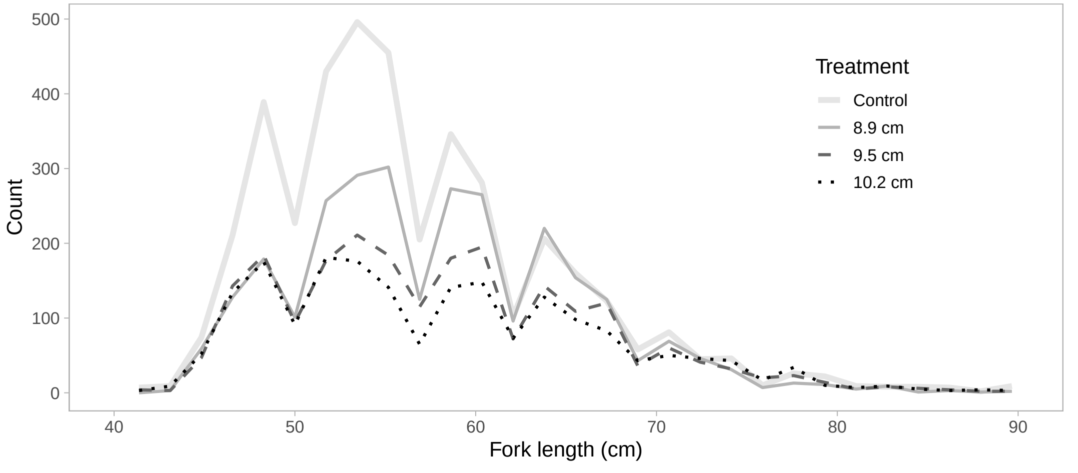

FIGURE 2 Length frequency distributions obtained using different sizes of escape rings (Control = no escape ring).

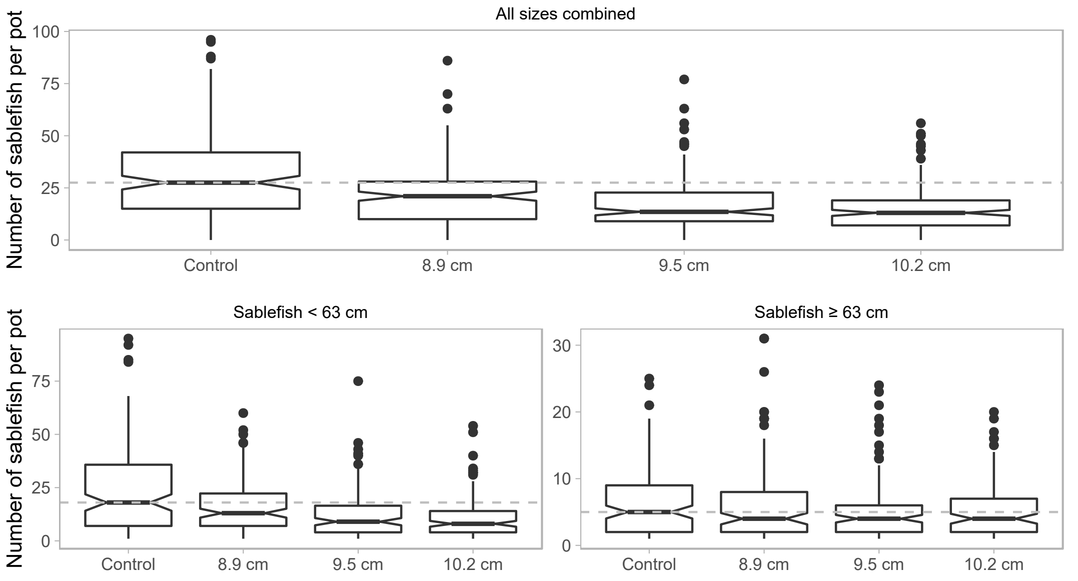

FIGURE 3 Number of sablefish caught per pot (CPUE) by escape ring treatment shown as notched box plots for all sized fish combined, sablefish < 63 cm and sablefish ≥ 63 cm. Each box shows the median (line), interquartile range (IQR, the box), 1.5 times the IQR (the whiskers), and the notches show roughly 95% confidence intervals around the median. The median CPUE for control pots are shown as reference in each panel.

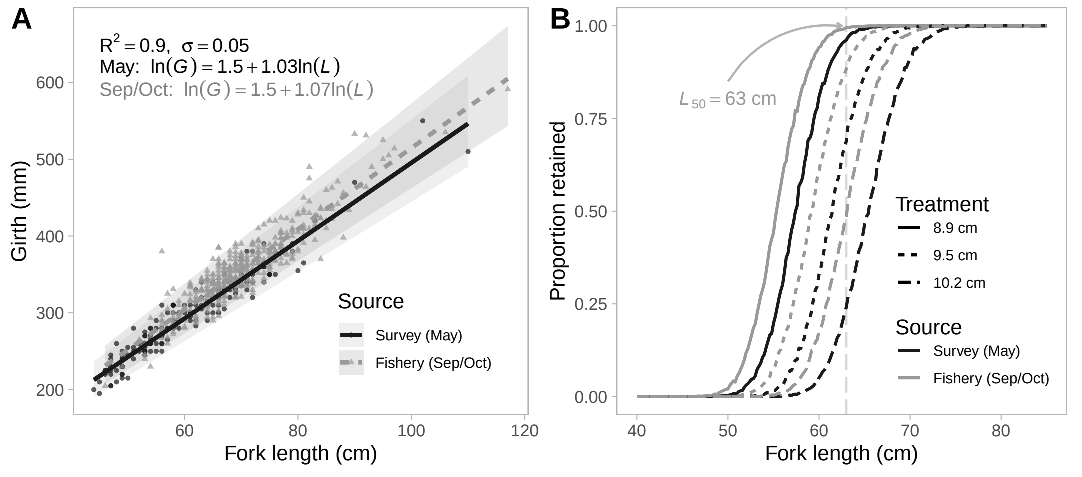

FIGURE 4 A) Fitted values and prediction intervals for the regression of girth on length for data collected during the survey in May (black circles, solid line) and fishery in September and October (grey triangles, dashed line). The coefficient of variation (R^2), residual standard deviation (σ), and model equations are shown in the upper left. B) Theoretical curves developed using the girth-length regression and (σ) for each treatment (line style) and season (colour). The length-at-50% maturity (L_{50}) for sablefish is shown for reference.

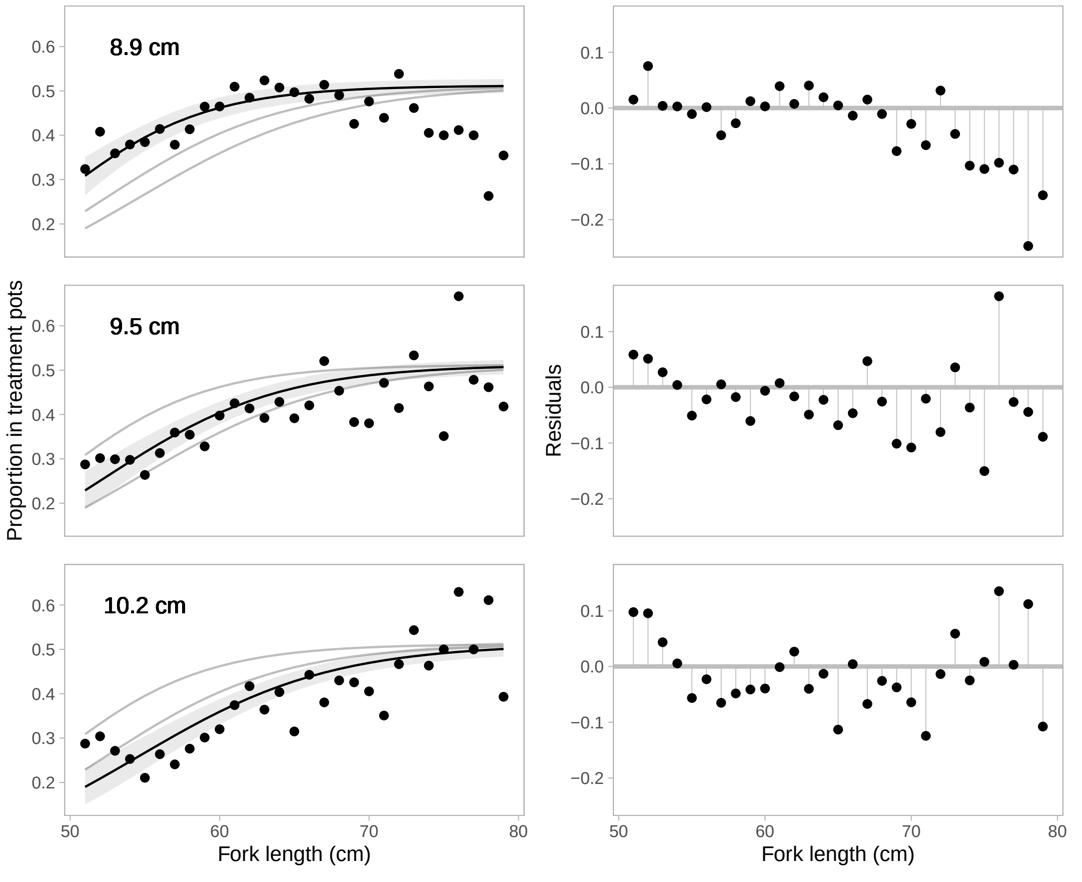

FIGURE 5 Model fits to proportion of fish in each treatment with 95% credible intervals (left) with associated residuals by length bin (right). Fits for the other treatments are shown in grey for comparison.

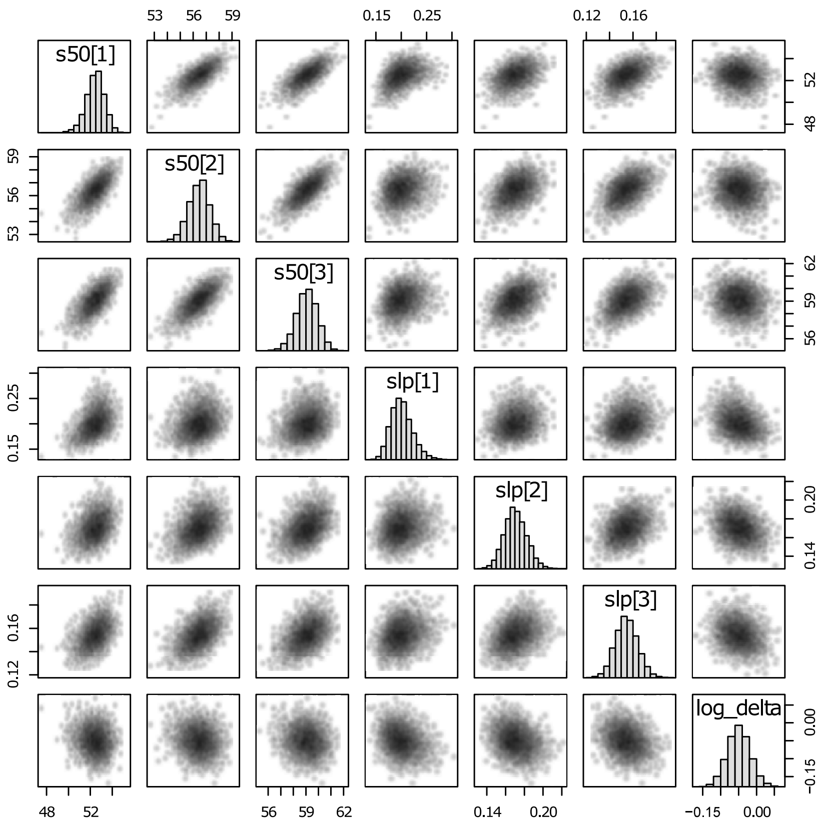

FIGURE 6 Marginal posterior distributions for SELECT model fixed effects (diagonal) with pairwise correlation plots. Parameters are indexed by escape ring treatment, such that 1 = 8.9 cm, 2 = 9.5 cm, and 3 = 10.2 cm.

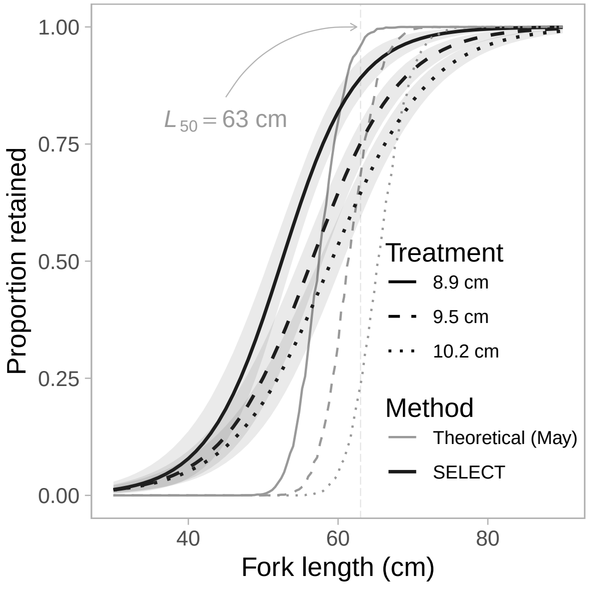

FIGURE 7 Theoretical selectivity curves calculated using girth data collected in May (grey) are compared with SELECT model estimated curves with 95% credible intervals for each treatment (line type). The length-at-50% maturity (L_{50}) for sablefish is shown for reference.