

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

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**KEY WORDS**

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**1 | INTRODUCTION**

8 Fishing gear selectivity is a critical fisheries stock assessment quantity for scaling an observed population to total  
9 population abundance (Quinn and Deriso, 1999; Beverton and Holt, 1957). Selectivity can be estimated in numerous  
10 forms, though it is most often incorporated into assessments as the probability of capture by length or age. Misspec-  
11 ified selectivity estimates can produce unreliable estimates of maximum sustainable yield-based biological reference  
12 points (Butterworth et al., 2014; Crone and Valero, 2014) or lead to biased projections of fish abundance (e.g. Stewart  
13 and Martell, 2014; Walters and Maguire, 1996).

14 Numerous intrinsic and extrinsic factors influence gear selectivity. For example, changes in fishing gear, regula-  
15 tions, or fisher behavior can shift selectivity (Graham et al., 2007; Valdemarsen and Suuronen, 2003). These changes  
16 can be motivated by shifting markets or processor preference, for example, if the development of a live market fishery  
17 increases the desirability of smaller or medium-sized fish (Reddy et al., 2013; Kindsvater et al., 2017). Modification  
18 of fishing gear or regulations can also be motivated by conservation efforts to protect a segment of a fish population,  
19 reduce bycatch, or avoid interaction with habitat or protected species (Kennelly and Broadhurst, 2002). Environmen-

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

tal factors (e.g. water temperature) can influence selectivity on a seasonal basis due to spawning period and body condition (e.g. Özbilgin et al., 2007) or swim speed (e.g. Yanase et al., 2007). Additionally, fish behavior or availability can change selectivity if, for example, fish occupy deeper waters as thermal refuge during periods of warm sea surface temperatures (e.g. Barbeaux et al., 2019; Li et al., 2019).

Several recent changes in sablefish (*Anoplopoma fimbria*) fishery dynamics and regulations in Alaska have created the potential for changing fishery selectivity. Two commercial sablefish fisheries occur in Alaskan waters. A federal fishery prosecuted in the United State's exclusive economic zone (EEZ, 3-200 nm; Figure 1) has been regulated under an Individual Fishing Quota (IFQ) program since 1995 (Hanselman et al., 2019). This fishery is predominately a longline fishery; however, sablefish catch by pot gear in the Bering Sea and Aleutian Islands has increased dramatically since 2000 from 0.5-0.7% in 1991-1999 to 45% in 2017-2018 (Hanselman et al., 2020) due to killer whale (*Orcinus orca*) depredation on longline gear (Peterson et al., 2013, 2014). Regulatory changes implemented in 2017 permit pot gear to be fished in federal waters in the Gulf of Alaska (GOA). Subsequent landings from pot gear in the GOA have increased to 13% of the total catch in 2019 (Hanselman et al., 2020). Sablefish length composition data suggest that pot gear selects for smaller-sized individuals than longline gear, and resultant changes in selectivity will be addressed if catch in pot gear continues to increase (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 1985 (Dressel, 2009; Olson et al., 2017). The majority of sablefish catch in state waters occurs in Chatham Strait and Clarence Strait in Southeast Alaska; however, directed fisheries also occur in Prince William Sound and Cook Inlet (Figure 1). Many vessels participate in both IFQ and state water sablefish fisheries (Hanselman et al., 2019). A fundamental difference between the two fisheries is that full retention of all sablefish caught is mandated in federal waters, while the release of healthy sablefish is allowed in state waters (Olson and Sullivan, 2019; Sullivan et al., 2019). The seasons for the fisheries differ slightly; the IFQ sablefish fishery is eight months long (March-November), while seasons in Clarence Strait and Chatham Strait occur in June-November and August-November, respectively (Hanselman et al., 2019; Olson et al., 2017). Directed sablefish pot fishing has been permitted under regulation since 1970 in Clarence Strait but is not currently permitted in Chatham Strait (Olson et al., 2017).

Record year classes of sablefish were observed in 2014 and 2016 in the North Pacific Ocean, leading to an influx of small fish into commercial sablefish fisheries (Hanselman et al., 2020). This rapid population increase has resulted in poor model fits to population abundance indices and increased uncertainty in fishery and survey selectivity estimates (Hanselman et al., 2020). Conservation concerns over suppressed spawning stock biomass and lack of diversity in the population's age structure, coupled with high uncertainty in large recruitment events, have prompted cautionary harvest policies for sablefish in IFQ and state fisheries (Hanselman et al., 2019, 2020; Sullivan et al., 2019). Despite these measures, fishery performance in the IFQ fishery is at a historic low, in part due to high catch rates of small fish (Hanselman et al., 2020). There is a considerable economic incentive to target large sablefish; they can be worth more than seven times the price per kg compared to the smallest-sized sablefish caught in the fishery (Sullivan et al., 2019). Consequently, the IFQ fleet has pushed to change federal regulations to allow discarding of small sablefish in the IFQ fishery (Armstrong and Cunningham, 2018).

In 2018 a live market pot fishery for sablefish was proposed for Clarence Strait (Figure 1). A primary concern for this type of fishery among management biologists is growth overfishing (Diekert, 2012), and the harvest of immature sablefish 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

63 west coast of the United States (e.g. Head et al., 2014; Kapur et al., 2020). Additionally, because sablefish spawn in  
64 the winter months, classification of maturity status during summer annual surveys can be difficult (Rodgveller, 2018).  
65 A comparison of macroscopic and histological maturity samples collected across the Gulf of Alaska produced an  $L_{50}$   
66 between 58–64 cm (Rodgveller, 2018). These findings are consistent with macroscopic maturity data collected in  
67 annual surveys conducted by ADFG in Southeast Alaska ( $L_{50}=63$  cm for females; Dressel, 2009). To account for the  
68 relatively high  $L_{50}$  while reducing catch rates of immature sablefish, 10.2 cm (4 in) escape rings were required in the  
69 Clarence Sound sablefish pot fishery beginning in 2018 (Olson and Sullivan, 2019).

70 An escape ring experiment was conducted in May 2019 to analyze the impact of escape rings on capture efficiency  
71 and gear selectivity of sablefish. An optimal escape ring size provides the best compromise between low catches of  
72 immature sablefish while maintaining high CPUE of mature sablefish. Three alternative escape ring sizes, 8.9 cm (3.5  
73 in), 9.5 cm (3.75 in), and 10.2 cm (4 in), were evaluated during the ADFG sablefish tagging survey in May and June  
74 2019 in Chatham Strait (Green et al., 2016). A combination of techniques were employed to evaluate the impact of  
75 escape rings on pot selectivity. Given that girth, or the circumference of a fish at its widest point, determines whether  
76 a sablefish can pass through an escape ring, a girth-length relationship was used to develop theoretical selectivity  
77 curves. Additionally, selectivity was estimated directly using the SELECT (Share Each LEngth's Catch Total) method  
78 (Millar, 1992), which has been applied to a variety of trawl and pot gear experiments (e.g. Xu and Millar, 1993; Millar  
79 and Walsh, 1992).

## 80 2 | METHODS

81 A longline of 40 conical pots with 5.08 x 5.08 cm mesh spaced 50 m apart was set for approximately 24-hr soaks at 17  
82 stations in Chatham Strait in May 14–Jun 3 during the 2019 ADFG sablefish tagging survey on the R/V *Medeia* (Figure  
83 1; Green et al., 2016). Each set was comprised of four treatments with 10 pots per treatment in a fixed alternating  
84 design. The study included four different escape ring scenarios: a control with no escape rings, and three treatments  
85 with internal ring diameters of 8.9, 9.5, and 10.2 cm. Each treatment pot included two escape rings installed on  
86 opposing vertical or sloping walls of the pot (Figure 2). An  $L_{50}$  of 63 cm was selected as a reference length for  
87 evaluating capture efficiency and size-selectivity among escape rings treatments.

### 88 2.1 | Capture efficiency

89 Differences in catch rates of sablefish between control and treatments pots (CPUE) were evaluated using the non-  
90 parametric Kruskal-Wallis test to evaluate the null hypothesis that mean CPUE between escape ring scenarios is the  
91 same (Neter et al., 1974). Statistical comparisons of CPUE between escape ring scenarios were conducted for all  
92 sablefish combined, sablefish greater than or equal to 63 cm, and sablefish less than 63 cm. Post hoc multiple com-  
93 parisons Dunn tests were conducted using a Bonferroni adjustment (Zar, 1999). Statistical analyses were conducted  
94 using the statistical software R (R Core Team 2019) and the R library FSA (Ogle et al., 2019).

### 95 2.2 | Theoretical size-selectivity curves

96 Sablefish fork length and girth data were collected to develop theoretical size-selectivity curves for the different es-  
97 cape ring treatments following an approach developed for Southern rock lobsters (*Jasus edwardsii*) in Australia (Treble  
98 et al., 1998). Sablefish girths ( $\hat{G}$ ) were estimated using a linear regression model with log-transformed data to deter-

99 mine the allometric relationship with length ( $L$ ):

$$\hat{G} = aL^b. \quad (1)$$

100 Seasonal changes in the girth-length relationship were evaluated by comparing a single slope and intercept regression  
 101 with regressions that provided for separate intercepts or separate intercepts and slopes between the survey (May-  
 102 Jun) and fishery (Sep-Nov). Candidate models were compared using the Akaike Information Criterion (AIC; Burnham  
 103 and Anderson, 1992). Using the residual standard deviation from the best-fitting regression model, sablefish girths  
 104 were simulated across a range of lengths using a lognormal distribution for the survey and fishery time periods. All  
 105 sablefish with an approximate diameter ( $\hat{G}/\pi$ ) greater than the escape ring diameter were assumed to be retained in  
 106 the pot and those less than or equal to the escape ring diameter were assumed to escape. The proportions of sablefish  
 107 by length with a  $\hat{G}$  greater than the escape ring were plotted as probabilities of retention or theoretical size-selectivity  
 108 curves. Theoretical selectivity curves for the control pots were developed in the same way using an assumed mesh  
 109 diameter of 70 mm. Resultant theoretical selectivity curves were used to develop priors for the SELECT analyses.

### 110 2.3 | SELECT models of experimental escape ring data

111 A Bayesian SELECT model was developed using the R package Template Model Builder (TMB; Kristensen et al., 2016).  
 112 The SELECT method estimates selectivity parameters of experimental gear fished in tandem with control gear as-  
 113 sumed to retain all length classes of fish encountered by the gear (Millar, 1992). Control pots were assumed fully  
 114 selected at 50 cm based on results from the theoretical selectivity curves, and length frequencies were binned into 1  
 115 cm increments. Length frequencies obtained with each escape ring treatment were compared with those observed in  
 116 the control pots. Given that a fish in length bin  $i$  was caught and retained in a pot in set  $j$ , the probability that it was  
 117 captured in escape ring treatment  $k$  ( $\phi_{ijk}$ ) was modeled as

$$\phi_{ijk} = \frac{P_{ijk}}{P_{ijk} + \delta r_j} \quad (2)$$

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

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

$$P_{ijk} = \frac{1}{1 + \exp(-\kappa_k(i - s_{50,k}) + \eta_j)}, \quad (3)$$

125 where  $s_{50}$  is the length at which 50% of sablefish are selected to the gear, and  $\kappa$  is the slope of the logistic curve  
 126 at  $s_{50}$ . The SELECT log-likelihood is

$$\log(L) = \sum_{k=1}^K \sum_{j=1}^J \sum_{i=1}^I T_{ijk} \cdot \log(\phi_{ijk}) + C_{ij} \cdot \log(1 - \phi_{ijk}), \quad (4)$$

127 where  $T_{ijk}$  and  $C_{ij}$  are numbers observed in each length bin and set for each treatment and control pots, respec-  
128 tively.

129 Normal priors on length at 0 and 100% retention probabilities were developed using results from the theoretical  
130 selectivity curves for each escape ring. Mean length at 0% retention in the theoretical curves was 51, 55, and 58 cm  
131 for 8.9, 9.5, and 10.2 cm escape rings, respectively. A weakly informative prior variance ( $\sigma=0.35$ ) was assumed for  
132 the length at 0% retention to account for factors that could influence the lower arm of the logistic selectivity curve  
133 (e.g. fish availability and soak time). Mean length at 100% retention was 68, 72, and 77 cm for 8.9, 9.5, and 10.2 cm  
134 escape rings, respectively. An informed prior variance ( $\sigma=0.05$ ) was applied to the length at 100% retention to loosely  
135 constrain the upper arm of the logistic curve to asymptote according to the girth-length relationship. Broad uniform  
136 priors were used for all other parameters (Table 3).

137 Markov chain Monte Carlo (MCMC) sampling was implemented in the *tmbstan* R package using the no-U-turn  
138 sampler (NUTS), a self-tuning MCMC algorithm (Monnahan and Kristensen, 2018; Carpenter et al., 2017; Hoffman and  
139 Gelman, 2014; Stan Development, 2018). Seven chains were run with 2,000 iterations each, including 1,000 samples  
140 for burn-in. Convergence diagnostics included a visual examination of trace plots and pairwise correlation plots for  
141 fixed effects. The sampling efficiency in the bulk (95%) and tails (outer 5% and 95%) of the posterior distributions was  
142 evaluated using the effective sample size (ESS) for each chain and parameter calculated by the *tmbstan* package. The  
143 ESS statistics corrects for autocorrelation within chains, and both the bulk and tail ESS should be greater than 100 per  
144 chain (Stan Development, 2018). The agreement or mixing between chains was evaluated using an  $\hat{R}$  convergence  
145 diagnostic produced by *tmbstan*; an  $\hat{R}$  less than or equal to 1.05 was considered fully mixed or converged (Vehtari  
146 et al., 2019).

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

$$P = \frac{1}{1 + \exp(-(a_1 + b_1 \cdot E) \cdot (i - (a_2 + b_2 \cdot E)))}, \quad (5)$$

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

## 151 3 | RESULTS

### 152 3.1 | Capture efficiency

153 A total of 14,234 sablefish were caught in 17 longline sets over a 17 day period in May and June of 2019. Fork lengths  
154 were recorded for 11,107 sablefish (Figure 3, Table 1). All data, code, and output files for this study can be found at  
155 [https://github.com/commfish/great\\_escape](https://github.com/commfish/great_escape).

156 CPUE of sablefish (all sizes combined) declined significantly with increasing escape ring size (Figure 4, Table 2;  $\chi^2$   
157 = 77.2,  $p < 0.001$ ). However, when sablefish were grouped by  $L_{50}$  ( $< 63$  cm and  $\geq 63$  cm), the difference between

treatments was no longer significant for the larger sized group (Figure 4, Table 2; < 63 cm:  $\chi^2 = 46.9, p < 0.001$ ;  $\geq 63$  cm:  $\chi^2 = 5.3, p = 0.151$ ). For all sizes combined, post hoc multiple comparison Dunn tests showed that all treatments were significantly different ( $\alpha = 0.05$ ) from each other except the 10.2 cm - 9.5 cm ring combination (Table 2). The CPUE of sablefish less than 63 cm was significantly different between escape ring scenarios except for 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 greater than or equal to 63 cm were significantly different. In summary, CPUE declined with increasing escape ring diameter due to decreases in CPUE of small sablefish. CPUE of large sablefish remained relatively constant between control and treatment pots, although the distribution of CPUE in control pots was most closely matched by the 8.9 cm escape ring treatment (Figure 4).

### 3.2 | Theoretical selectivity curves

Girth and length measurements were collected from 153 sablefish captured in control pots during the survey, and an additional 411 samples were collected during the fishery in Sep and Oct 2019. The girth-length relationship for sablefish was best characterized by a linear model with a single intercept and separate slopes for data collected in May and Sep/Oct (Figure 5A). Theoretical selectivity curves showed that as girth-at-length increases throughout the growing season, the proportion retained at length increases for a given escape ring size (Figure 5B). 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 showed large changes in selectivity with relatively small increases in escape ring size (Figure 5B). For the 8.9 cm escape ring, sablefish were fully selected by 64 cm in the fishery, meaning that by the time 50% of sablefish are mature at 63 cm, they are 99% selected to the gear. In contrast, results from the 9.5 cm and 10.2 cm escape rings showed that 89% and 50% of 63 cm fish are selected during Sep/Oct, respectively. Theoretical selectivity curves for Sep/Oct showed that sablefish are not fully selected to the gear until 69 cm and 73 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

The Bayesian SELECT model was applied to length frequency data from the escape ring experiment, resulting in selectivity estimates for the three escape ring treatments (Table 3). Residual plots suggested 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 6). The relative probability of entering a control pot ( $\delta$ ) was estimated to be 0.95, indicating 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). Alternative hypotheses include attraction to the metal escape rings or habituation to the control pots, which are used annually on the survey.

Posterior distributions and correlation plots for the model's fixed effects showed that parameters are well-estimated (Figure 7). As expected, a positive linear correlation was observed between the  $s_{50}$  parameters and escape ring size (Figure 7). Trace plots for the seven chains indicated the model was well mixed (figure omitted for brevity). This interpretation was corroborated by an  $\hat{R}$  statistic of 1.00, below the maximum convergence threshold of 1.05, and a minimum bulk and tail ESS well above the recommended minimum of 100.

A comparison of theoretical and SELECT curves showed that theoretical curves are far steeper than the SELECT curves, resulting in a much narrower selection range (Figure 8). At  $L_{50}=63$  cm, sablefish were 89% (95% credible

197 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,  
 198 respectively. These retention probabilities were lower at  $L_{50}$  than they were for the theoretical curves, resulting in  
 199 different management implications. However, based on seasonal changes in the theoretical selectivity curves, one  
 200 may expect the SELECT curves to be shifted to the left later in the year when the fishery occurs, resulting in an  
 201 increased retention probability at  $L_{50}$  for all escape rings. The SELECT curves retained a much higher proportion of  
 202 smaller-sized sablefish than would be suggested by the theoretical selectivity curves. The SELECT curves indicated  
 203 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  
 204 9.5 cm and 10.2 cm escape rings.

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

$$P = \frac{1}{1 + \exp(-(0.53 - 0.037 \cdot E) * (i - (6.28 + 5.22 \cdot E)))}. \quad (6)$$

## 209 4 | DISCUSSION

210 There is a long history of modifying fishing gear to alter selectivity and reduce incidental catch of non-target species or  
 211 size classes (Kennelly and Broadhurst, 2002; Broadhurst et al., 2007). Our experiment demonstrates that escape rings  
 212 significantly reduce catch of small, immature sablefish ( $L_{50}=63$  cm), while maintaining average catch rates of larger,  
 213 mature individuals (Table 2, Figure 4). Theoretical and SELECT-estimated size-selectivity curves suggest that the 8.9  
 214 cm escape ring will maximize catch of sablefish greater than or equal to 63 cm, with the trade off that it will also  
 215 result in the highest catches of sablefish less than 63 cm. This trade off was realized in the capture efficiency analysis;  
 216 the 8.9 cm escape ring had intermediate CPUE for small fish, but its distribution of CPUE of large sablefish was most  
 217 similar to the control pot CPUE (Figure 4). There was no additional decrease in CPUE of small sablefish between the  
 218 9.5 and 10.2 cm escape rings. If the management goal is to provide the best compromise between decreasing catches  
 219 of small fish while maximizing catches of large fish, these results indicate that an escape ring size greater than 9.5 cm  
 220 may not be preferred.

221 Several factors contribute to the apparent differences in the theoretical and SELECT estimated selectivity curves  
 222 (Figure 8). One hypothesis is that the current study's relatively short soak time (24 hr) was insufficient to observe the  
 223 full effects of the escape rings on size-selectivity. Theoretical curves assume all fish smaller than the escape ring will  
 224 escape, which may be unrealistic given search time and crowding in the pots. Further experimentation is needed to  
 225 assess the effects of soak time on escape ring size-selectivity and capture efficiency. Another factor to consider is  
 226 the availability of small sablefish in the population during the time of the study. Large recruitment events of sablefish  
 227 from 2014 and 2016 were observed as peaks in the length frequencies around 48 cm and 53 cm (Figure 3). The high  
 228 abundance of small fish may have caused crowding in the pots, making it difficult for fish to escape, and thus biasing  
 229 selectivity estimates. Finally, residual patterns in the model fits to the data (Figure 6) could potentially be remedied  
 230 with alternative selectivity curves. Other studies have suggested that pot gear for sablefish may follow a dome-shaped  
 231 selectivity (Assonitis, 2008), and others have used an asymmetric logistic curve (Haist and Hilborn, 2000; Haist et al.,  
 232 2000). Residual patterns were not consistent across escape ring treatments, however. Further research would be  
 233 needed to develop methods to generalize these alternative selectivity parameterizations as a function of escape ring

size as has been done in this study (Equation 6). Finally, the SELECT model relies on the assumption that all size classes included in the analysis are fully selected to the control gear (Millar, 1992). If this assumption is violated, selectivity estimates from this method may be unreliable.

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 ( $\phi$ ) showed significantly more contrast in Haist et al. (2000), with observations of  $\phi$  ranging between 0 and 1, while the  $\phi$  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  $F$ s 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 more balanced harvest across size classes.

Management recommendations from this study vary between 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 large sablefish can be worth more than seven times per kg than smaller fish (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 of small sablefish (Figure 4). 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 over 40% (J. Scoblic, personal communication, January 10, 2020). Although an optimal fish size in a live market has not been determined, fishery managers navigating developing live markets for sablefish that target 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 (Figure 4). 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 is beneficial in that it minimizes catch of small, immature fish, and reduces discarding and handling mortality of released fish. Escape rings may also offer a solution to the current small fish problem in the IFQ sablefish fishery in Alaska. Though transitioning from longline to pot gear is expensive, pot gear has the advantage of reducing negative interactions with marine mammals (Peterson et al., 2014), while providing flexible gear size-selectivity. 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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**275 Conflict of interest**

276 The authors have no conflict of interest to disclose.

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390 *National Academy of Sciences*, **107**, 9485–9489.

**391 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 2019 pot survey in May and June. 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)
<b>Total</b>	<b>14,233</b>	<b>11,107</b>	<b>57.6 (0.08)</b>

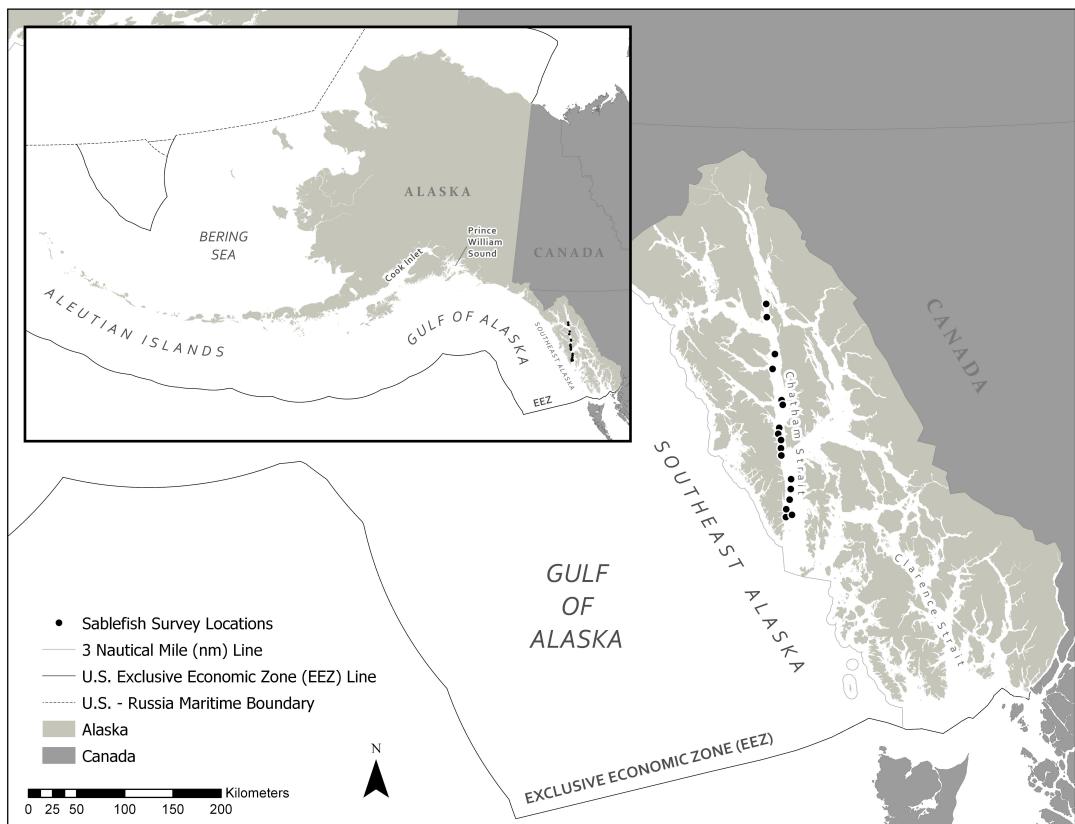
**TABLE 2** Results for non-parametric Kruskal-Wallis and post hoc multiple comparison Dunn tests for CPUE of all sizes of sablefish combined, sablefish < 63 cm, and sablefish  $\geq$  63 cm. Statistically significant results ( $\alpha = 0.05$ ) for Dunn tests are highlighted in bold and p-values have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

Comparison	Z-statistic	p <sub>adj</sub>
<b><u>All sizes combined:</u></b> $\chi^2$ -statistic = 77.2, $p < 0.001$		
10.2 cm - Control	-8.20	< <b>0.001</b>
9.5 cm - Control	-6.63	< <b>0.001</b>
10.2 cm - 8.9 cm	-4.23	< <b>0.001</b>
8.9 cm - Control	-3.98	< <b>0.001</b>
8.9 cm - 9.5 cm	2.66	<b>0.047</b>
10.2 cm - 9.5 cm	-1.57	0.702
<b><u>Sablefish &lt; 63 cm:</u></b> $\chi^2$ -statistic = 46.9, $p < 0.001$		
10.2 cm - Control	-6.17	< <b>0.001</b>
9.5 cm - Control	-5.12	< <b>0.001</b>
10.2 cm - 8.9 cm	-3.85	<b>0.001</b>
8.9 cm - 9.5 cm	2.80	<b>0.030</b>
8.9 cm - Control	-2.27	0.139
10.2 cm - 9.5 cm	-1.06	1.000
<b><u>Sablefish <math>\geq</math> 63 cm:</u></b> $\chi^2$ -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

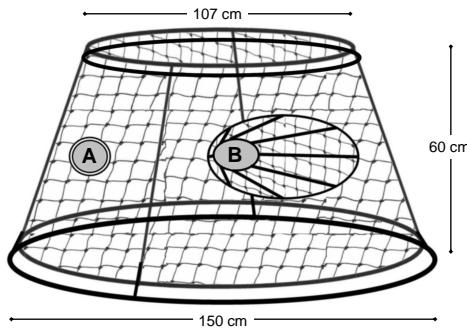
**TABLE 3** SELECT model parameters estimates (medians and 95% credible intervals, CI) with priors used for Bayesian analysis. For brevity, only median values are reported for random effects. Parameters are indexed by escape ring treatment, such that 1 = 8.9 cm, 2 = 9.5 cm, and 3 = 10.2 cm. The relative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

Parameter	Symbol	Median	95% CI	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	$\kappa_1$	0.20	(0.17, 0.25)	$U \sim (0, 0.9)$
Slope at 50% selectivity, 9.5 cm	$\kappa_2$	0.17	(0.15, 0.20)	$U \sim (0, 0.9)$
Slope at 50% selectivity, 10.2 cm	$\kappa_3$	0.15	(0.14, 0.17)	$U \sim (0, 0.9)$
Relative probability of entering a control pot	$\delta$	0.95	(0.90, 1.01)	$U \sim (0.1, 2)$

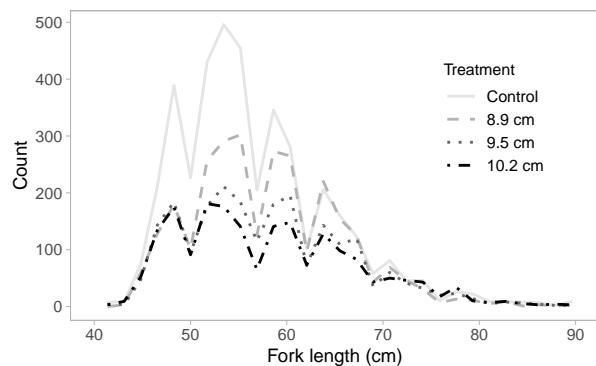
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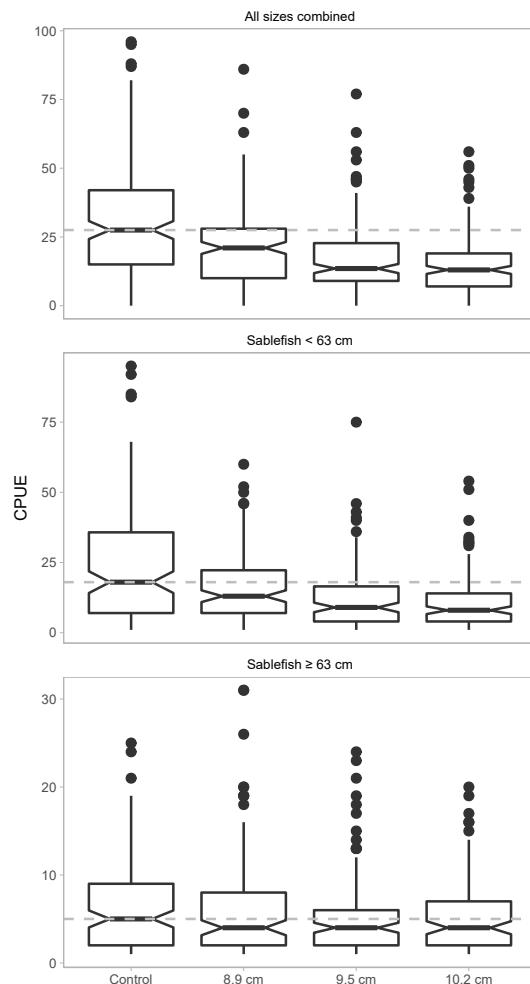
**FIGURE 1** Map of study area and survey locations in Southeast Alaska.



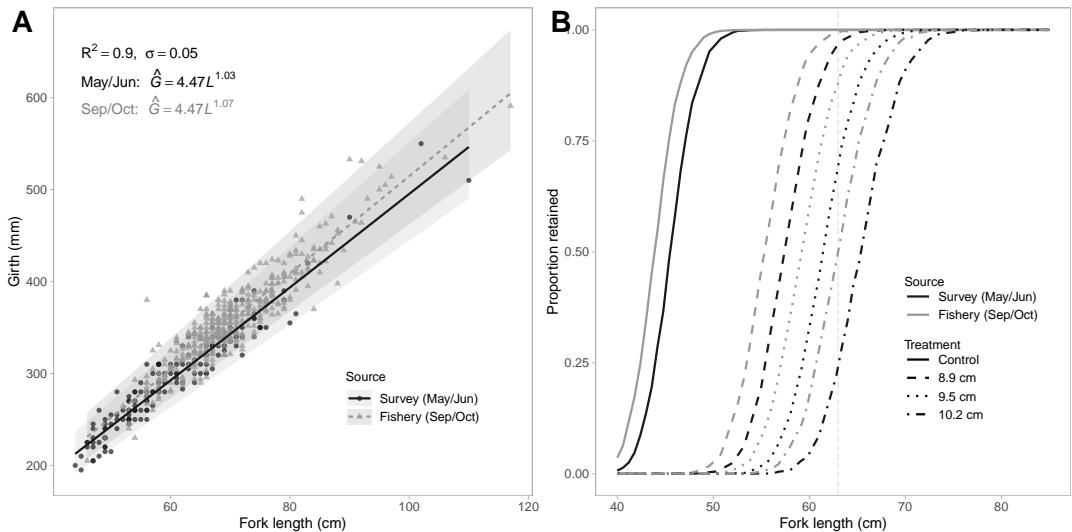
**FIGURE 2** Diagram of the conical pot used during the survey, including the placement of the escape ring (A), the soft-sided entrance tunnel (B), the top diameter (107 cm), bottom diameter (150 cm), and height (60 cm). Both the entrance tunnel and escape ring are mirrored on the opposite quadrants of the pot (not shown in this diagram).



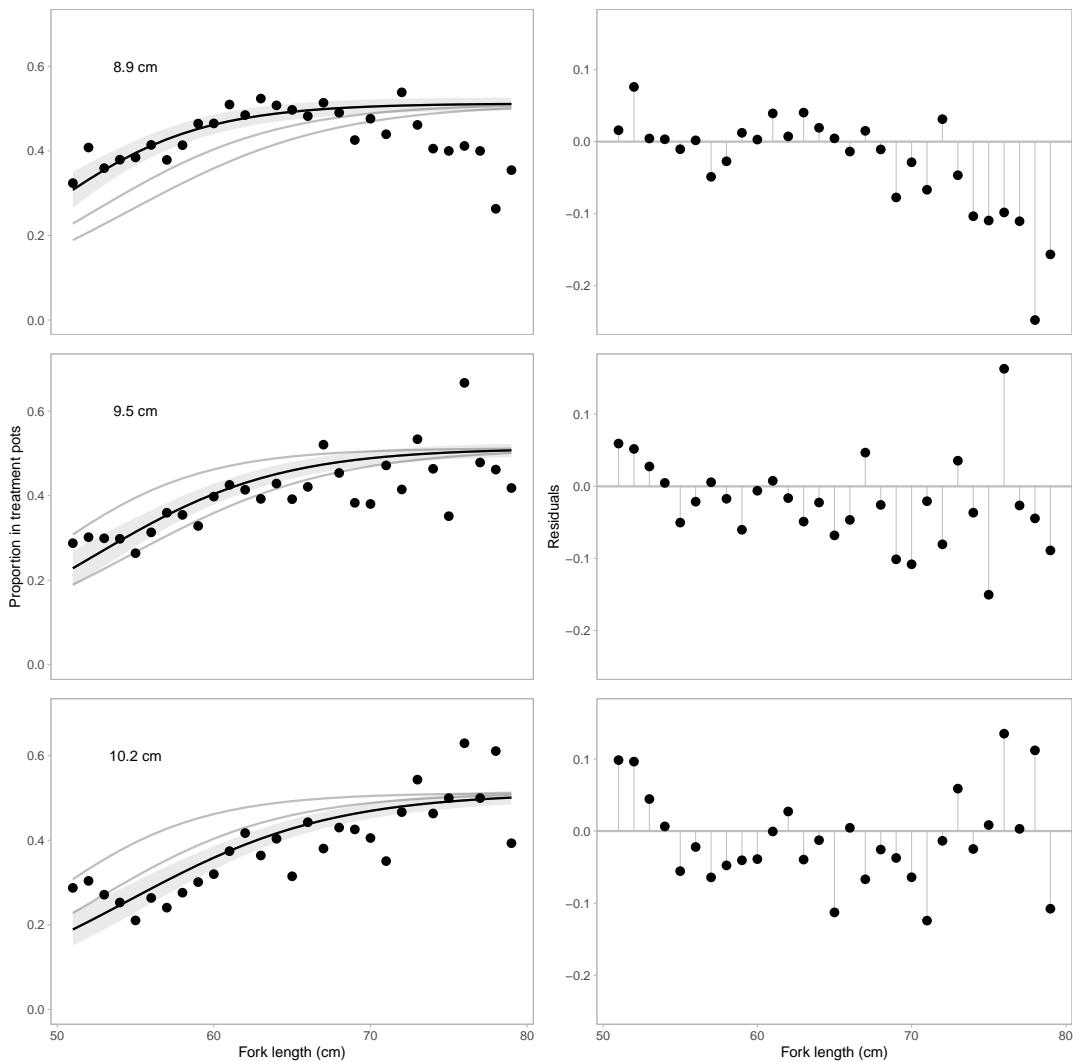
**FIGURE 3** Length frequency distributions obtained using different sizes of escape rings (Control = no escape ring).



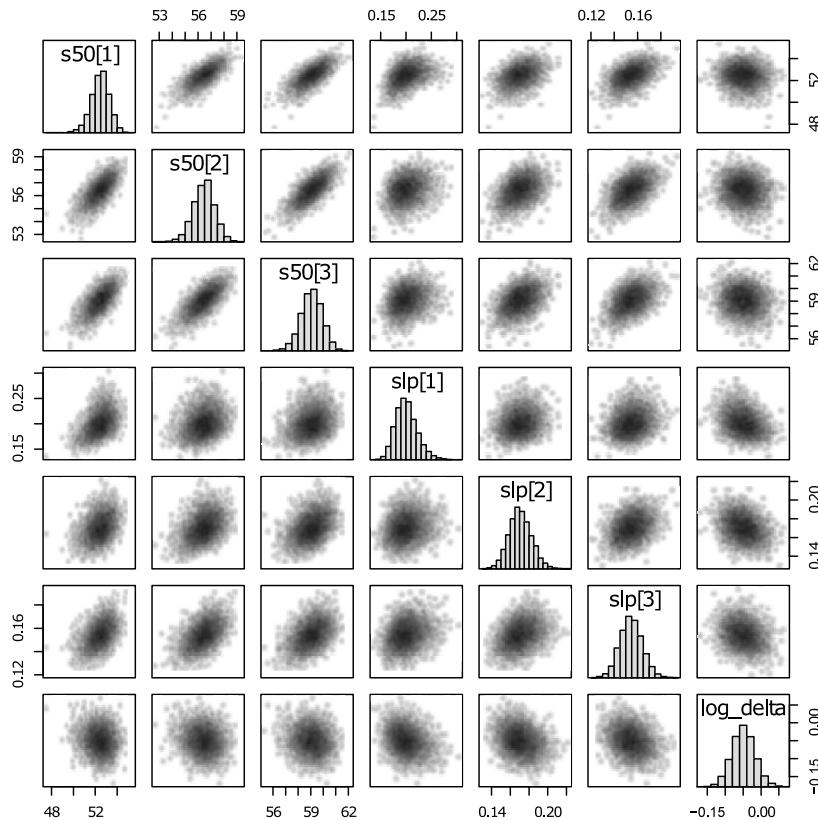
**FIGURE 4** Number of sablefish caught per pot (CPUE) by escape ring treatment shown as notched box plots for all sized fish combined, sablefish  $< 63$  cm and sablefish  $\geq 63$  cm. Each box shows the median (line), interquartile range (IQR, the box), 1.5 times the IQR (the whiskers), and the notches show roughly 95% confidence intervals around the median. The median CPUE for control pots is shown as reference in each panel as a grey dashed horizontal line.



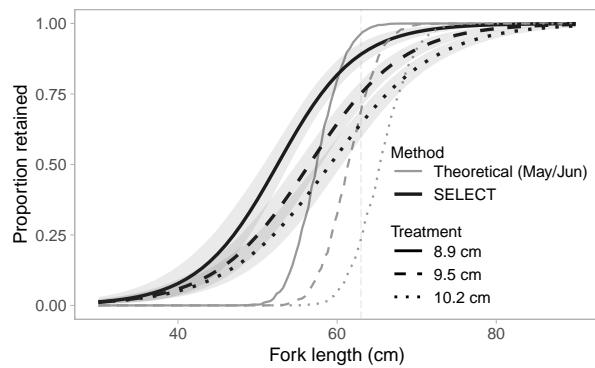
**FIGURE 5** A) Fitted values and prediction intervals for the regression of girth on length for data collected during the survey in May and June (black circles, solid line) and fishery in September and October (grey triangles, dashed line). The coefficient of variation ( $R^2$ ), residual standard deviation ( $\sigma$ ), and model equations are shown in the upper left. B) Theoretical curves developed using the girth-length regression and  $\sigma$  for each treatment and season. The length-at-50% maturity ( $L_{50}$ ) for sablefish is shown as a grey dashed vertical line for reference.



**FIGURE 6** 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 7** Marginal posterior distributions for SELECT model fixed effects (diagonal) with pairwise correlation plots. Parameters include the  $s_{50}$  ( $slp$ ) and  $k$  for each treatment, which were indexed as 1 = 8.9 cm, 2 = 9.5 cm, and 3 = 10.2 cm. The relative probability of entering a control pot  $\delta$  ( $\log_{\delta}$ ) was estimated using a log-link.



**FIGURE 8** Theoretical selectivity curves calculated using girth data collected during the survey in May and June (grey) are compared with SELECT model estimated curves with 95% credible intervals for each treatment. The length-at-50% maturity ( $L_{50}$ ) for sablefish is shown as a grey vertical line for reference.