**ORIGINAL ARTICLE**

**Journal Section**

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

**Jane Y. Sullivan[1] | Andrew P. Olson[2] | Aaron P. Baldwin[2] | Benjamin C. Williams[1] | Kellii L. Wood[3]**

[1]Alaska Department of Fish and Game, 1255 W. 8th Street, Juneau, Alaska, 99801, U.S.A.

[2]Alaska Department of Fish and Game, 802 3rd Street, Douglas, Alaska, 99824, U.S.A.

[3]Alaska Department of Fish and Game, 16 Sing Lee Alley, Petersburg, Alaska, 99833, U.S.A.

**Correspondence**
Email: jane.sullivan1@alaska.gov

**Funding information**

An experiment was conducted in Chatham Strait in Southeast Alaska to estimate size-selectivity and capture efficiency of sablefish (*Anoplopoma fimbria*) using pot gear with escape rings. Four escape rings scenarios were considered: control pots with no escape rings, and three treatment pots with internal diameters of 8.9, 9.5, and 10.2 cm. Theoretical size-selectivity curves developed using the sablefish girth-length relationship were compared to selectivity curves estimated using a Bayesian SELECT (Share Each LEngth's Catch Total) model. Relatively small increases in escape ring size caused large shifts in selectivity. Results suggest that 9.5 cm escape rings provide the best compromise between reducing catch rates of small, immature sablefish, while maximizing selectivity and capture efficiency of large, mature sablefish. Further experimentation is needed to determine if discrepancies between theoretical and SELECT selectivity curves can be explained by the current study's relatively short soak time.

**KEYWORDS**

size-selectivity, escape ring, *Anoplopoma fimbria*, sablefish, CPUE, SELECT model, pot fishing

# 1 | INTRODUCTION

Fishing gear selectivity is a critical fisheries stock assessment quantity for scaling an observed population to total population abundance (Quinn and Deriso, 1999; Beverton and Holt, 1957). Selectivity can be estimated in numerous forms, though it is most often incorporated into assessments as the probability of capture by length or age. Misspecified selectivity estimates can produce unreliable estimates of maximum sustainable yield-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 (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. 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). Similar regulatory changes were implemented in the Gulf of Alaska (GOA) in 2017 to allow pot fishing in federal waters to mitigate increasing sperm whale (*Physeter macrocephalus*) depredation on longline gear (Hanselman et al., 2020). 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).

Commercial harvest of sablefish in Alaskan state waters up to 3 nm is regulated by the Alaska Department of Fish and Game (ADFG) in the Bering Sea and Aleutian Islands, Cook Inlet, Prince William Sound, and Southeast Alaska management areas (Figure 1; Russ et al., 2013; Rumble et al., 2017; Olson et al., 2017; Beder and Shaishnikoff, 2018). The majority of sablefish harvest in state waters occurs in Southeast Alaska in Chatham Strait and Clarence Strait (Figure 1), which have been regulated under an Equal Quota Share (EQS) program since 1994 and 1996, respectively (Olson et al., 2017). Many vessels participate in both federal IFQ and state sablefish fisheries (Hanselman et al., 2019). However, a fundamental difference between the IFQ and EQS fisheries is that full retention of all sablefish caught is mandated in the IFQ fishery, while the release of healthy sablefish is allowed in EQS fisheries (Olson and Sullivan, 2019; Sullivan et al., 2019). The seasons for the fisheries also differ slightly; the IFQ sablefish fishery is eight months long (March-November) to align with the Pacific halibut (*Hippoglossus stenolepis*) IFQ fishery, 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 EQS 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 among sablefish in Alaska, BC, and the west coast of the United States (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 produced an $L_{50}$ between 58-64 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). To account for the relatively high $L_{50}$ while reducing catch rates of immature sablefish, 10.2 cm (4 in) escape rings were required in the Clarence Sound sablefish pot fishery beginning 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 size-selectivity of sablefish. 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 marking survey in May and June 2019 in Chatham Strait (Green et al., 2016). A combination of techniques were employed to evaluate the impact of escape rings on pot size-selectivity. Given that girth, or the circumference of a fish at its widest point, determines whether a sablefish can pass through an escape ring, a 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), which has been applied to a variety of trawl and pot gear experiments (e.g. Xu and Millar, 1993; Millar and Walsh, 1992).

## 2 | METHODS

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 stations in Chatham Strait in May 14–Jun 3 during the 2019 ADFG sablefish marking survey on the R/V *Medeia* (Figure 1; Green et al., 2016). Each set was comprised of four treatments with ten 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 treatment pot included two escape rings installed on opposing vertical or sloping walls of the pot (Figure 2). An $L_{50}$ of 63 cm was selected as a reference length for evaluating capture efficiency and size-selectivity among escape rings treatments.

## 2.1 | Capture efficiency

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

## 2.2 | Theoretical size-selectivity curves

Sablefish fork length and girth data were collected to develop theoretical size-selectivity curves for the escape ring scenarios following an approach developed for Southern rock lobsters (*Jasus edwardsii*) in Australia (Treble et al., 1998). Sablefish girths ($\hat{G}$) were estimated using a linear regression model with log-transformed data to determine the allometric relationship with length ($L$):

$$\hat{G} = aL^{b}. \tag{1}$$

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

## 2.3 | SELECT modelling of experimental escape ring data

A Bayesian SELECT model was developed using the R library Template Model Builder (TMB; 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 based on results from the theoretical selectivity curves, 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 $i$ was caught and retained in a pot in set $j$, the probability that it was captured in escape ring treatment $k$ ($\phi_{ijk}$) was modelled as

$$\phi_{ijk} = \frac{P_{ijk}}{P_{ijk} + \delta r_j} \tag{2}$$

where $P_{ijk}$ is the probability that a fish was retained in an escape ring treatment (i.e. selectivity), $\delta$ 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 ($P_{ijk}$) was modelled as a logistic function. A random effect was included at the set level ($\eta_j$) 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 $k$ was defined as

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

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 at $s_{50}$. The SELECT log-likelihood is

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

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 size-selectivity curves for each escape ring. Mean length at 0% retention in the theoretical curves was 51, 55, and 58 cm for 8.9, 9.5, and 10.2 cm escape rings, respectively. A weakly informative prior variance ($\sigma$=0.35) was assumed for the length at 0% retention to account for factors that could influence the lower arm of the logistic selectivity curve (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 escape rings, respectively. An informed prior variance ($\sigma$=0.05) was applied to the length at 100% retention to loosely constrain 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 (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 sampling efficiency in the bulk (95%) and tails (outer 5% and 95%) of the posterior distributions was evaluated using the effective sample size (ESS) for each chain and parameter calculated by the tmbstan library. The ESS statistics corrects for autocorrelation within chains, and both the bulk and tail ESS should be greater than 100 per chain (Stan Development, 2018). The agreement or mixing between chains was evaluated using an $\widehat{R}$ convergence diagnostic produced by tmbstan; an $\widehat{R}$ less than or equal to 1.05 was considered fully mixed or converged (Vehtari et al., 2019).

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

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

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

CPUE of sablefish (all sizes combined) declined significantly with increasing escape ring size (Figure 4, Table 2; $\chi^2$ = 77.2, $p < 0.001$). However, when sablefish were grouped by $L_{50}$ (< 63 cm and ≥ 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; ≥ 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 $L_{50}$, theoretical size-selectivity curves suggest that 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 $\widehat{R}$ 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 interval: 85-93%), 75% (70-80%), and 65% (59-70%) selected for the 8.9, 9.5, and 10.2 cm escape rings, respectively. These retention probabilities were lower at $L_{50}$ than they were for the theoretical curves, resulting in different management implications. However, based on seasonal changes in the theoretical selectivity curves, one may expect the SELECT curves to be shifted to the left later in the year when the fishery occurs, resulting in an increased retention probability at $L_{50}$ for all escape rings. The SELECT curves retained a much higher proportion of smaller-sized sablefish than would be suggested by the theoretical size-selectivity curves. The SELECT curves indicated 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 parameter estimates $\kappa$ and $s_{50}$ 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 $E$ was the 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:

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

## 4 | DISCUSSION

There is a long history of modifying fishing gear to alter selectivity and reduce incidental catch of non-target species or size classes (Kennelly and Broadhurst, 2002; Broadhurst et al., 2007). Our experiment demonstrates that escape rings significantly reduce catch of small, immature sablefish ($L_{50}$=63 cm), while maintaining average catch rates of larger, mature individuals (Table 2, Figure 4). Theoretical and SELECT-estimated size-selectivity curves suggest that the 8.9 cm escape ring will maximize catch of sablefish greater than or equal to 63 cm, with the trade off that it will also result in the highest catches of sablefish less than 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 4). There was no additional decrease in CPUE of small sablefish between the 9.5 and 10.2 cm escape rings. If the management goal is to provide the best compromise between minimizing catches of small fish to reduce discard mortality, while maximizing catches of large fish, these results indicate that an escape ring size greater than 9.5 cm may not be preferred.

Several factors contribute to the apparent differences in the theoretical and SELECT estimated selectivity curves (Figure 8). 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. 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. Large recruitment events of sablefish from 2014 and 2016 were observed as peaks in the length frequencies around 48 cm and 53 cm (Figure 3). The high abundance of small fish may have caused crowding in the pots, making it difficult for fish to escape, and thus biasing selectivity estimates. Finally, residual patterns in the model fits to the data (Figure 6) could potentially be remedied with alternative selectivity curves. Other studies have suggested that pot gear for sablefish may follow a dome-shaped selectivity curve (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 ring treatments, however. Further 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 (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 federal IFQ and state EQS sablefish fisheries. In particular, because releasing small fish is legal in EQS state 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 particular, managers in state waters may prefer the medium-sized escape ring (9.5 cm) because it effectively minimizes CPUE of small sablefish, thus reducing discarding mortality (Figure 4). In contrast, the smaller escape ring (8.9 cm) may be preferable for the IFQ fishery where full retention is mandatory to promote balanced harvest of sablefish across a wider spectrum of size and age classes. Escape rings may also offer a solution to fishermen trying to avoid small sablefish in the IFQ sablefish fishery in Alaska (Hanselman et al., 2020). 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). The use of 9.5 cm escape rings will sufficiently protect immature sablefish from discard mortality, while allowing for the development of a live market sablefish fishery in the future.

## Acknowledgements

We acknowledge the crew of the R/V *Medeia* and Alaska Department of Fish and Game biologists for assisting in data collection and review.

## Conflict of interest

The authors have no conflict of interest to disclose.

## References

Arana, P. and Ziller, S. (1994) Modelación de la selectividad de trampas para la captura de langosta (*Jasus frontalis*) en el archipiélago de Juan Fernández (Chile). *Investigación Pesquera*, **38**.

Arana, P. M., Orellana, J. C. and De Caso, Á. (2011) Escape vents and trap selectivity in the fishery for the Juan Fernández rock lobster (*Jasus frontalis*), Chile. *Fisheries Research*, **110**, 1–9.

Armstrong, J. and Cunningham, S. (2018) Sablefish discard allowance. *North Pacific Fishery Management Council, Discussion Paper*, 1–32. URL: `http://meetings.npfmc.org/CommentReview/DownloadFile?p=b6b509dd-a14c-442b-867b-3f88fa9f8d98.pdf&fileName=D2%20Sablefish%20Discard%20Allowance.pdf`.

Assonitis, K. (2008) *Size-selectivity of British Columbia's sablefish (Anoplopoma fimbria) fisheries and implications for the economic losses associated with discarding*. Ph.D. thesis, School of Resource and Environmental Management-Simon Fraser University.

Barbeaux, S., Aydin, K., Fissel, B., Holsman, K., Laurel, B., Palsson, W., Shotwell, K., Yang, Q. and Zador, S. (2019) Assessment of the Pacific cod stock in the Gulf of Alaska. *Stock Assessment and Fishery Evaluation Report for the Groundfish Resources of the GOA and BS/AI*.

Beder, A. and Shaishnikoff, J. (2018) Annual management report for groundfish fisheries in the Bering Sea–Aleutian Islands management area, 2017. *Alaska Department of Fish and Game Fishery Management Report*, **No. 18-18**, 1–42.

Beverton, R. J. and Holt, S. J. (1957) *On the dynamics of exploited fish populations*. Chapman and Hall, London. Facsimile reprint, 2012.

Breen, M., Graham, N., Pol, M., He, P., Reid, D. and Suuronen, P. (2016) Selective fishing and balanced harvesting. *Fisheries Research*, **184**, 2–8.

Broadhurst, M. K., Kennelly, S. J. and Gray, C. (2007) Strategies for improving the selectivity of fishing gears. In *By-catch Reduction in the World's Fisheries*, 1–21. Springer.

Burnham, K. P. and Anderson, D. R. (1992) Data-based selection of an appropriate biological model: the key to modern data analysis. In *Wildlife 2001: populations*, 16–30. Springer.

Butterworth, D. S., Rademeyer, R. A., Brandão, A., Geromont, H. F. and Johnston, S. J. (2014) Does selectivity matter? A fisheries management perspective. *Fisheries research*, **158**, 194–204.

Carpenter, B., Gelman, A., Hoffman, M. D., Lee, D., Goodrich, B., Betancourt, M., Brubaker, M., Guo, J., Li, P. and Riddell, A. (2017) Stan: A probabilistic programming language. *Journal of statistical software*, **76**.

Clark, W. G. (1991) Groundfish exploitation rates based on life history parameters. *Canadian Journal of Fisheries and Aquatic Sciences*, **48**, 734–750.

Crone, P. R. and Valero, J. L. (2014) Evaluation of length-vs. age-composition data and associated selectivity assumptions used in stock assessments based on robustness of derived management quantities. *Fisheries research*, **158**, 165–171.

Diekert, F. K. (2012) Growth overfishing: the race to fish extends to the dimension of size. *Environmental and Resource Economics*, **52**, 549–572.

Dressel, S. C. (2009) 2006 Northern Southeast Inside sablefish stock assessment and 2007 forecast and quota. *Alaska Department of Fish and Game Fishery Data Series*, **No. 09-50**, 1–78.

Garcia, S., Kolding, J., Rice, J., Rochet, M.-J., Zhou, S., Arimoto, T., Beyer, J., Borges, L., Bundy, A., Dunn, D. et al. (2012) Reconsidering the consequences of selective fisheries. *Science*, **335**, 1045–1047.

Graham, N., Ferro, R. S., Karp, W. A. and MacMullen, P. (2007) Fishing practice, gear design, and the ecosystem approach—three case studies demonstrating the effect of management strategy on gear selectivity and discards. *ICES Journal of Marine Science*, **64**, 744–750.

Green, K., Baldwin, A. and Stahl, J. (2016) Northern Southeast Inside (Chatham Strait) sablefish marking survey. *Alaska Department of Fish and Game Regional Operation Plan*, **CF.1J.2015.06**, 1–24.

Haist, V. and Hilborn, R. (2000) Sablefish stock assessment for 2000 and recommended yield options for 2001. *Fisheries and Oceans Canada, Research Document*, **2000/157**, 1–74.

Haist, V., Kronlund, A. and Wyeth, M. (2000) Sablefish (*Anoplopoma fimbria*) in British Columbia, Canada: Stock assessment for 2003 and advice to managers for 2004. *Fisheries and Oceans Canada, Research Document*, **2004/055**, 1–74.

Hanselman, D. H., Rodgveller, C. J., Fenske, K. H., Shotwell, S. K., Echave, K. B., Malecha, P. W. and Lunsford, C. R. (2019) Assessment of the sablefish stock in Alaska. *Stock Assessment and Fishery Evaluation Report for the Groundfish Resources of the GOA and BS/AI*.

— (2020) Assessment of the sablefish stock in Alaska. *Stock Assessment and Fishery Evaluation Report for the Groundfish Resources of the GOA and BS/AI*.

Head, M. A., Keller, A. A. and Bradburn, M. (2014) Maturity and growth of sablefish, *Anoplopoma fimbria*, along the US West Coast. *Fisheries research*, **159**, 56–67.

Hoffman, M. D. and Gelman, A. (2014) The No-U-Turn sampler: adaptively setting path lengths in Hamiltonian Monte Carlo. *Journal of Machine Learning Research*, **15**, 1593–1623.

Kapur, M., Haltuch, M., Connors, B., Rogers, L., Berger, A., Koontz, E., Cope, J., Echave, K., Fenske, K., Hanselman, D. and Punt, A. (2020) Oceanographic features delineate growth zonation in Northeast Pacific sablefish. *Fisheries Research*, **222**, 105414.

Kennelly, S. J. and Broadhurst, M. K. (2002) By-catch begone: changes in the philosophy of fishing technology. *Fish and Fisheries*, **3**, 340–355.

Kindsvater, H. K., Reynolds, J. D., Sadovy de Mitcheson, Y. and Mangel, M. (2017) Selectivity matters: rules of thumb for management of plate-sized, sex-changing fish in the live reef food fish trade. *Fish and fisheries*, **18**, 821–836.

Kristensen, K., Nielsen, A., Berg, C. W., Skaug, H. and Bell, B. M. (2016) TMB: Automatic differentiation and Laplace approximation. *Journal of Statistical Software*, **70**, 1–21.

Li, L., Hollowed, A. B., Cokelet, E. D., Barbeaux, S. J., Bond, N. A., Keller, A. A., King, J. R., McClure, M. M., Palsson, W. A., Stabeno, P. J. et al. (2019) Subregional differences in groundfish distributional responses to anomalous ocean bottom temperatures in the northeast Pacific. *Global change biology*.

McGilvray, F. and Chan, T. (2003) Market and industry demand issues in the live reef food fish trade. *SPC Live Reef Fish Information Bulletin*, **11**, 36–39.

Millar, R. and Walsh, S. (1992) Analysis of trawl selectivity studies with an application to trouser trawls. *Fisheries Research*, **13**, 205–220.

Millar, R. B. (1992) Estimating the size-selectivity of fishing gear by conditioning on the total catch. *Journal of the American Statistical Association*, **87**, 962–968.

Monnahan, C. C. and Kristensen, K. (2018) No-U-turn sampling for fast Bayesian inference in ADMB and TMB: Introducing the adnuts and tmbstan R packages. *PloS one*, **13**, e0197954.

Neter, J., Wasserman, W. and Kutner, M. H. (1974) *Applied linear statistical models*. Richard D. Irwin, Inc.

Ogle, D. H., Wheeler, P. and Dinno, A. (2019) *FSA: Fisheries Stock Analysis*. URL: `https://github.com/droglenc/FSA`. R package version 0.8.25.

Olson, A., Stahl, J., Vaughn, M., Carroll, K. and Baldwin, A. (2017) Annual management report for the Southeast and Yakutat commercial groundfish fisheries, 2017. *Alaska Department of Fish and Game Fishery Management Report*, **No. 17-54**, 1–47.

Olson, A. and Sullivan, J. (2019) 2019 Southern Southeast Inside subdistrict sablefish Fishery Management Plan. *Alaska Department of Fish and Game Regional Information Report*, **No. 1J19-06**, 1–17.

Özbilgin, H., Tosunoğlu, Z., Tokaç, A. and Metin, G. (2007) Seasonal variation in the trawl codend selectivity of picarel (*Spicare smaris*). *ICES Journal of Marine Science*, **64**, 1569–1572.

Peterson, M. J., Mueter, F., Criddle, K. and Haynie, A. C. (2014) Killer whale depredation and associated costs to Alaskan sablefish, Pacific halibut and Greenland turbot longliners. *PLoS One*, **9**, e88906.

Peterson, M. J., Mueter, F., Hanselman, D., Lunsford, C., Matkin, C. and Fearnbach, H. (2013) Killer whale (*Orcinus orca*) depredation effects on catch rates of six groundfish species: implications for commercial longline fisheries in Alaska. *ICES Journal of Marine Science*, **70**, 1220–1232.

Quinn, T. J. and Deriso, R. B. (1999) *Quantitative fish dynamics*. Oxford University Press.

Reddy, S. M., Wentz, A., Aburto-Oropeza, O., Maxey, M., Nagavarapu, S. and Leslie, H. M. (2013) Evidence of market-driven size-selective fishing and the mediating effects of biological and institutional factors. *Ecological Applications*, **23**, 726–741.

Rodgveller, C. J. (2018) A comparison of methods for classifying female sablefish maturity and skip spawning outside the spawning season. *Marine and Coastal Fisheries*, **10**, 563–576.

Rumble, J., Russ, E., Russ, C. and Byerly, M. (2017) Prince William Sound Registration Area E groundfish fisheries management report, 2014–2017. *Alaska Department of Fish and Game Fishery Management Report*, **No. 17-40**, 1–67.

Russ, E., Trowbridge, C. E. and Russ, C. (2013) Cook Inlet area groundfish management report, 2005–2011. *Alaska Department of Fish and Game Fishery Management Report*, **No. 03-04**, 1–64.

Stan Development, T. (2018) Stan modeling language users guide and reference manual, version 2.18.0.

Stewart, I. J. and Martell, S. J. (2014) A historical review of selectivity approaches and retrospective patterns in the Pacific halibut stock assessment. *Fisheries Research*, **158**, 40–49.

Sullivan, J., Olson, A. and Williams, B. (2019) 2018 Northern Southeast Inside subdistrict sablefish fishery stock assessment and 2019 management plan. *Alaska Department of Fish and Game Regional Information Report*, **No. 5J19-03**, 1–81.

Treble, R. J., Millar, R. B. and Walker, T. I. (1998) Size-selectivity of lobster pots with escape-gaps: application of the SELECT method to the southern rock lobster (*Jasus edwardsii*) fishery in Victoria, Australia. *Fisheries Research*, **34**, 289–305.

Valdemarsen, J. W. and Suuronen, P. (2003) Modifying fishing gear to achieve ecosystem objectives. *Reykjavik Conference on Responsible Fisheries in the Marine Ecosystem*, 3–21.

Vehtari, A., Gelman, A., Simpson, D., Carpenter, B. and Bürkner, P.-C. (2019) Rank-normalization, folding, and localization: An improved $\widehat{R}$ for assessing convergence of mcmc. *arXiv preprint arXiv:1903.08008*.

Walters, C. and Maguire, J.-J. (1996) Lessons for stock assessment from the northern cod collapse. *Reviews in fish biology and fisheries*, **6**, 125–137.

Xu, X. and Millar, R. B. (1993) Estimation of trap selectivity for male snow crab (*Chionoecetes opilio*) using the SELECT modeling approach with unequal sampling effort. *Canadian Journal of Fisheries and Aquatic Sciences*, **50**, 2485–2490.

Yanase, K., Eayrs, S. and Arimoto, T. (2007) Influence of water temperature and fish length on the maximum swimming speed of sand flathead, Platycephalus bassensis: implications for trawl selectivity. *Fisheries Research*, **84**, 180–188.

Zar, J. H. (1999) *Biostatistical analysis*. Pearson Education India.

Zhou, S., Smith, A. D., Punt, A. E., Richardson, A. J., Gibbs, M., Fulton, E. A., Pascoe, S., Bulman, C., Bayliss, P. and Sainsbury, K. (2010) Ecosystem-based fisheries management requires a change to the selective fishing philosophy. *Proceedings of the National Academy of Sciences*, **107**, 9485–9489.

# 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) |
| **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 $\geq$ 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 | $p_{adj}$ |
|---|---|---|
| ***All sizes combined***: $\chi^2$-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***: $\chi^2$-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***: $\chi^2$-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) | $U \sim (0.1, 2)$ |

# 6 | FIGURES

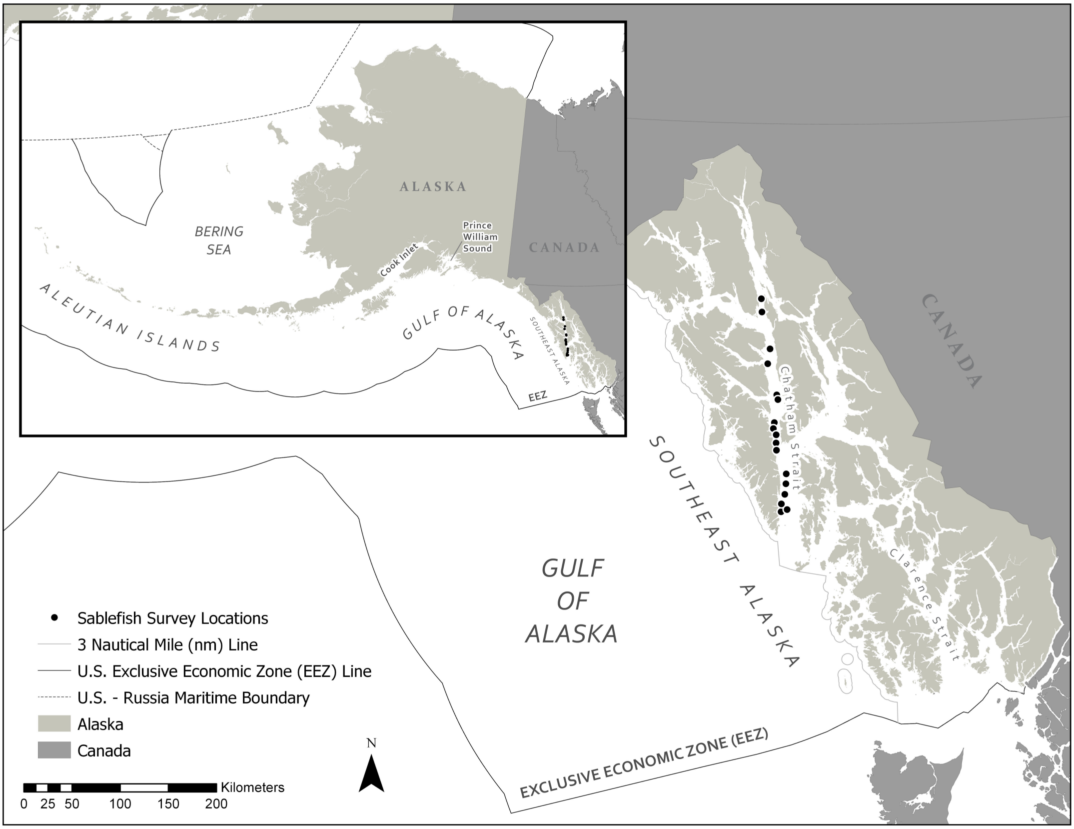


**FIGURE 1** Map of study area and survey locations in Southeast Alaska.

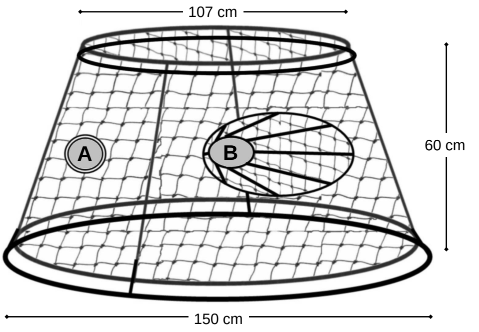


**FIGURE 2** Diagram of the conical pot used during the survey, including the placement of the escape ring (A), the soft-sided entrance tunnel (B), the top diameter (107 cm), bottom diameter (150 cm), and height (60 cm). Both the entrance tunnel and escape ring are mirrored on the opposite quandrants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

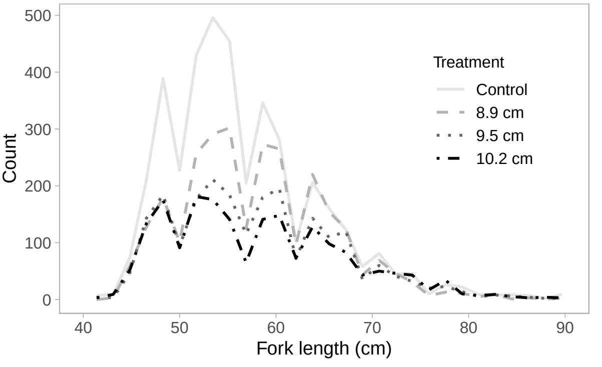


**FIGURE 3** Length frequency distributions obtained using different sizes of escape rings (Control = no escape ring).

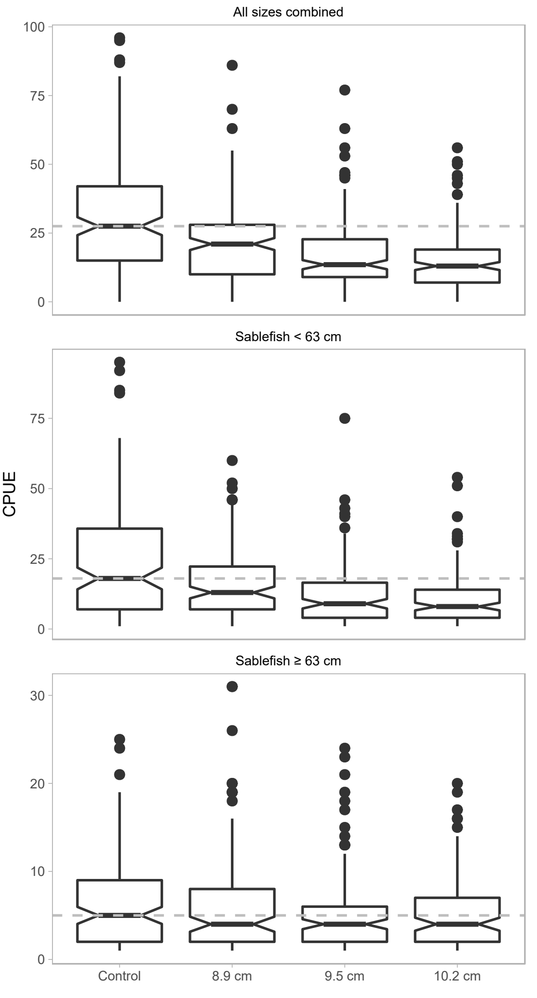


**FIGURE 4** Number of sablefish caught per pot (CPUE) by escape ring treatment shown as notched box plots for all sized fish combined, sablefish < 63 cm and sablefish ≥ 63 cm. Each box shows the median (line), interquartile range (IQR, the box), 1.5 times the IQR (the whiskers), and the notches show 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.

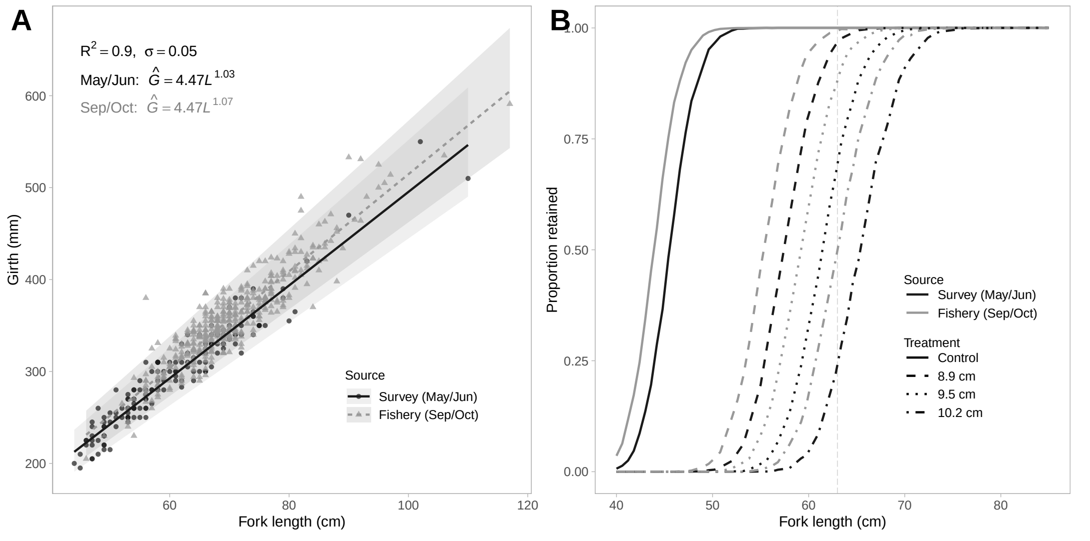


**FIGURE 5** A) Fitted values and prediction intervals for the regression of girth on length for data collected during the survey in May and June (black circles, solid line) and fishery in September and October (grey triangles, dashed line). The coefficient of variation ($R^2$), residual standard deviation ($\sigma$), 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.

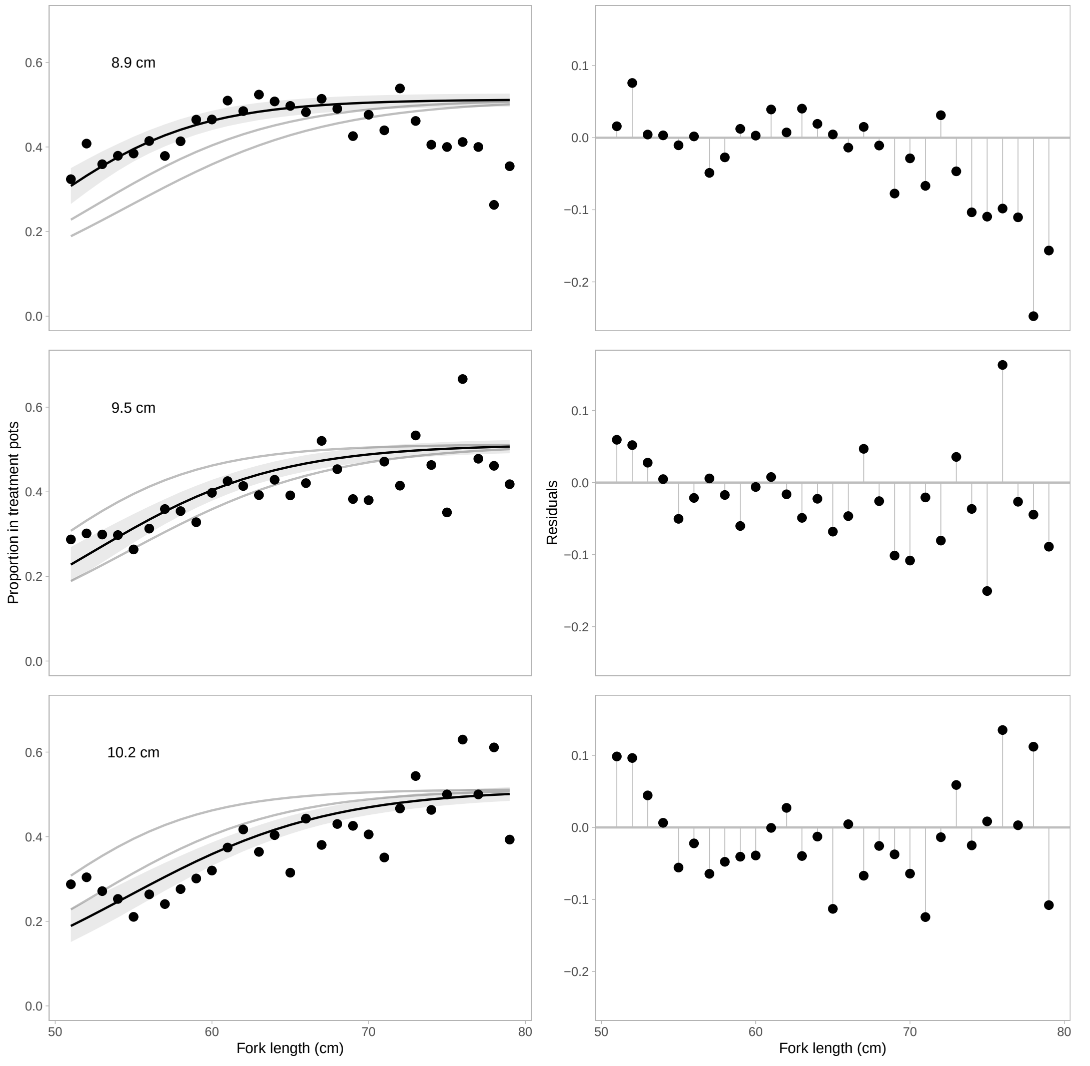


**FIGURE 6** Model fits to proportion of fish in each treatment with 95% credible intervals (left) with associated residuals by length bin (right). Fits for the other treatments are shown in grey for comparison.

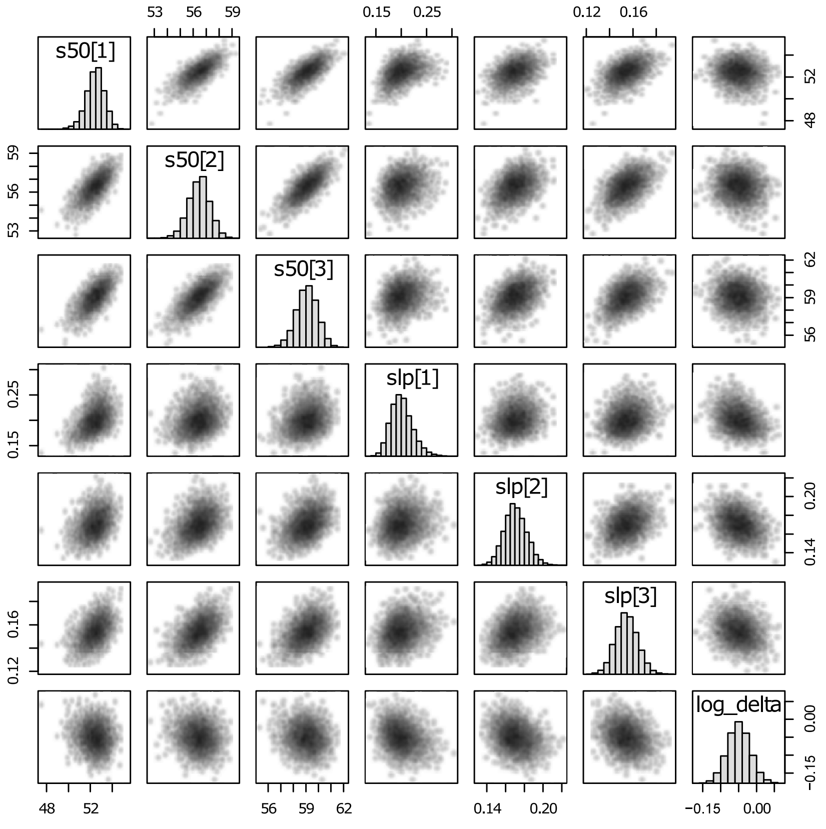


**FIGURE 7** Marginal posterior distributions for SELECT model fixed effects (diagonal) with pairwise correlation plots. Parameters include the $s_{50}$ (s50) and $k$ (slp) for each treatment, which were indexed as 1 = 8.9 cm, 2 = 9.5 cm, and 3 = 10.2 cm. The relative probability of entering a control pot $\delta$ (log_delta) was estimated using a log-link.

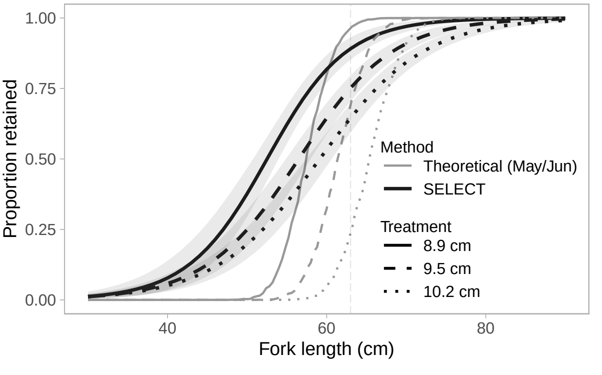


**FIGURE 8** Theoretical selectivity curves calculated using girth data collected during the survey in May and June (grey) are compared with SELECT model estimated curves with 95% credible intervals for each treatment. The length-at-50% maturity ($L_{50}$) for sablefish is shown as a grey vertical line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