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ARTICLE

Improving Catch Utilization in the U.S. West Coast Groundfish Bottom Trawl Fishery: an Evaluation of T90-Mesh and Diamond-Mesh Cod Ends

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Abstract
The limited-entry bottom trawl fishery for groundfish along the U.S. West Coast operates under a catch share program, which is implemented with the intention of improving the economic efficiency of the fishery, maximizing fishing opportunities, and minimizing bycatch. However, stocks with low harvest guidelines have limited the ability of fishermen to maximize their catch of more abundant stocks. Size-selection characteristics of 114-mm and 140-mm T90-mesh cod ends and the traditional 114-mm diamond-mesh cod end were examined by using the covered cod end method. Selection curves and mean L_{50} values (length at which fish had a 50% probability of being retained) were estimated for two flatfish species (Rex Sole *Glyptocephalus zachirus* and Dover Sole *Microstomus pacificus*) and two roundfish species (Shortspine Thornyhead *Sebastolobus alascanus* and Sablefish *Anoplopoma fimbria*). Mean L_{50} values were smaller for flatfishes but larger for roundfishes in the 114-mm T90 cod end compared to the diamond-mesh cod end. For Rex Sole, Dover Sole, and Shortspine Thornyheads, selectivities of the 140-mm T90 cod end were significantly different from those of the other cod ends; the 140-mm T90 cod end was most effective at reducing the catch of smaller-sized fishes but with a considerable loss of larger-sized marketable fishes. Findings suggest that T90 cod ends have potential to improve catch utilization in this multispecies fishery.

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The limited-entry (LE) bottom trawl fishery for groundfish along the U.S. West Coast operates under a catch share program that allocates individual fishing quotas (IFQs) and establishes annual catch limits (ACLs) for over 30 managed groundfish units (PFMC and NMFS 2011, 2015). In this program, fishermen are allocated a proportion of the fishery ACL, are subject to full at-sea observer coverage, and are held fully accountable for all IFQ species' catches, whether discarded or retained.

Over the continental shelf break and upper slope of the U.S. West Coast, fishermen target Dover Sole *Microstomus pacificus*, Shortspine Thornyhead *Sebastolobus alascanus*, Longspine Thornyhead *S. altivelis*, Sablefish *Anoplopoma fimbria*, and (to a lesser extent) Rex Sole *Glyptocephalus zachirus*. In this LE trawl fishery, commonly referred to as the Dover Sole/Thornyhead/Sablefish (DTS) fishery, Sablefish are the most economically important species harvested. Ex-vessel prices for Sablefish can range from US$1.10 to $9.35 per kilogram, with the price increasing with fish weight. However, Sablefish has become a constraining species in the DTS fishery, as their 2015 shoreside trawl allocation (6,028 metric tons) is relatively low in comparison with the Dover Sole allocation (45,986 metric tons; NMFS 2015). Recent catches of Dover Sole have been approximately 6,251 metric tons (PacFIN 2015), which represents only 13% attainment of the shoreside trawl allocation. This low attainment of the Dover Sole ACL is partly due to the attainment of constraining IFQ species, such as Sablefish. Minimizing the catches of smaller-sized Shortspine Thornyheads could also benefit fishermen, as prices for Shortspine Thornyheads can range from US$0.88 to $2.42 per centimeter, with larger-sized individuals receiving the highest price. Dover Sole, on the other hand, are priced at $0.99 per kilogram regardless of length (minimum market size = 33 cm). Hence, reducing the catch rate of smaller-sized Sablefish and Shortspine Thornyheads relative to Dover Sole would allow fishermen more opportunities to capitalize on their Dover Sole IFQ and increase their net economic benefits while still attaining their quota shares of Sablefish and Shortspine Thornyheads.

A simple technique that has been shown to improve trawl selectivity is modifying the size and configuration of the cod end mesh (Perez-Comas et al. 1998; He 2007; Madsen and Valentinsson 2010). Recent studies have focused on the development and use of T90-mesh cod ends (Digre et al. 2010; Wienbeck et al. 2011, 2014; Madsen et al. 2012; Herrmann et al. 2013, 2015; Bayse et al. 2016). The T90 mesh is conventional diamond mesh that has been turned 90° in orientation; this configuration allows the meshes over the entire cod end to remain more open than those of diamond-mesh cod ends, thereby improving size-selection characteristics (Herrmann et al. 2007). Research has demonstrated that diamond-mesh cod ends become distorted into a bulbous shape as catch accumulates and as tension on the netting increases (Stewart and Robertson 1985; Wileman et al. 1996). The majority of escapement occurs just ahead of the accumulating catch bulge, where a few rows of meshes are more open and unblocked by fish. The T90 cod end's simple construction, ease of repair when damaged, and potential to improve size selection provide some advantages over other mesh orientations (e.g., knotless square mesh) that have been used to enhance cod end selectivity (Perez-Comas et al. 1998; He 2007). This T90 mesh configuration, which was originally designed for use in Atlantic Cod *Gadus morhua* fisheries, has gained increased interest from other fisheries, such as the otter trawl fishery for Norway lobster *Nephrops norvegicus* in the Kattegat–Skagerrak area (Madsen et al. 2012) and the multispecies demersal trawl fishery in the Mediterranean Sea (Tokaç et al. 2014). Compared to diamond-mesh cod ends with similar mesh sizes, T90-mesh cod ends have demonstrated the ability to reduce catches of smaller-sized roundfishes (Wienbeck et al. 2011; Herrmann et al. 2013; Tokaç et al. 2014).

The objective of this study was to compare the size-selection characteristics of 114-mm and 140-mm T90-mesh cod ends and the traditional 114-mm diamond-mesh cod end and evaluate whether T90-mesh cod ends can improve groundfish catch utilization in the West Coast LE bottom trawl fishery.

METHODS

Trawl design.—The chartered F/V *Last Straw*, a 23.2-m-long, 540-hp trawler, provided its two-seam trawl for sea trials of the three cod end types. The headrope was 24.1 m in length and utilized sixteen 28.0-cm-diameter deepwater floats for lift. The footrope was 24.7 m in length and incorporated 20.3-cm-diameter rubber disks, with 45.7-cm rockhopper discs placed approximately every 73.7 cm across the length of the footrope. The trawl sweeps were 91.4 m in length and incorporated with 8.9-cm-diameter rubber discs. Thyborøn type-11 standard trawl doors were used.

Cod ends tested.—The cod ends we evaluated were nominal 114-mm T90 mesh (mean mesh size ± SE = 118.5 ± 0.33 mm), 140-mm T90 mesh (139.4 ± 0.37 mm), and 114-mm diamond mesh (119.6 ± 0.46 mm). Mesh sizes were measured using an OMEGA gauge with a 125-Newton stretching force (Fonteyne et al. 2007) following the International Council for the Exploration of the Sea protocol for measuring cod end meshes (Wileman et al. 1996). Each cod end was constructed within a four-seam tube of 6.0-mm, double-twine polyethylene netting with chafing gear protecting the aft-most 50 meshes of the bottom seam. A 50-mesh-length, two-seam to four-seam transitional tube of netting was used to attach each cod end to the trawl when tested. Specifications of the three cod end types are shown in Figure 1.

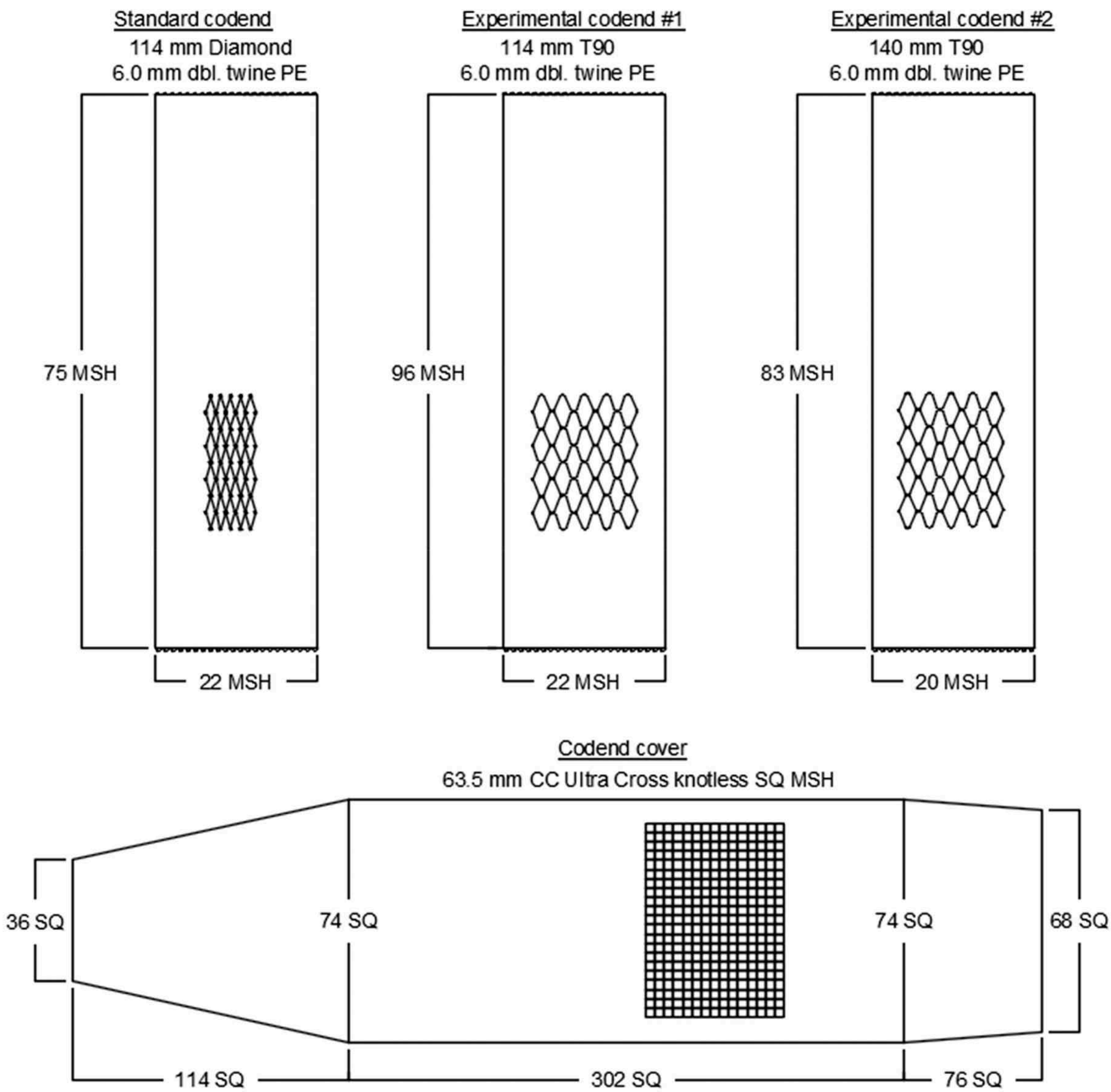

FIGURE 1. Schematic diagram depicting a top-panel view of the cod ends and the cod end cover used in evaluating the cod end types for the West Coast groundfish bottom trawl fishery. Diamond mesh (DM) and T90 mesh sizes are nominal stretched measurements between knots (MSH = mesh; dbl. = double twine; PE = polyethylene; CC = center-to-center mesh measurement; SQ = square). Diagram is not drawn to scale.

Cod end selectivity was measured by using the covered cod end method (Wileman et al. 1996). The cover was a four-seam net constructed of Ultra Cross Dyneema knotless square-mesh netting (63.5-mm center-to-center, 20-ply twine). The cover was attached to the intermediate section of the trawl 30 meshes forward of where the cod end connected to the trawl. At this attachment point, the circumference of the cover was 144 squares, excluding squares in each selvedge. Moving aft, the cover then gradually angled outward over the length of 114 squares to become 296 squares in circumference and 302 squares in length before tapering to 68 squares per panel over the distance of 76 squares (Figure 1). Where the cover encompassed the cod end, the dimensions were approximately 1.5 times the extended width and approximately 1.3 times the extended length of the cod end. Chafing material (102-mm diamond mesh, 5.0-mm single twine) along the bottom seam of the cover was used to protect the aft-most 227 squares from abrasion and net tearing. To keep the cover from masking the cod end, a combination of trapezoidal-shaped kites (0.95-cm-thick conveyor belt material; dimensions = 61 × 31 × 31 cm) and 20.3-cm-diameter floats were used. The kites were positioned along the outer and lower sides of the cover (two sets of four kites on each side) in relation to the fore and aft ends of the cod end, whereas the floats were positioned along the top

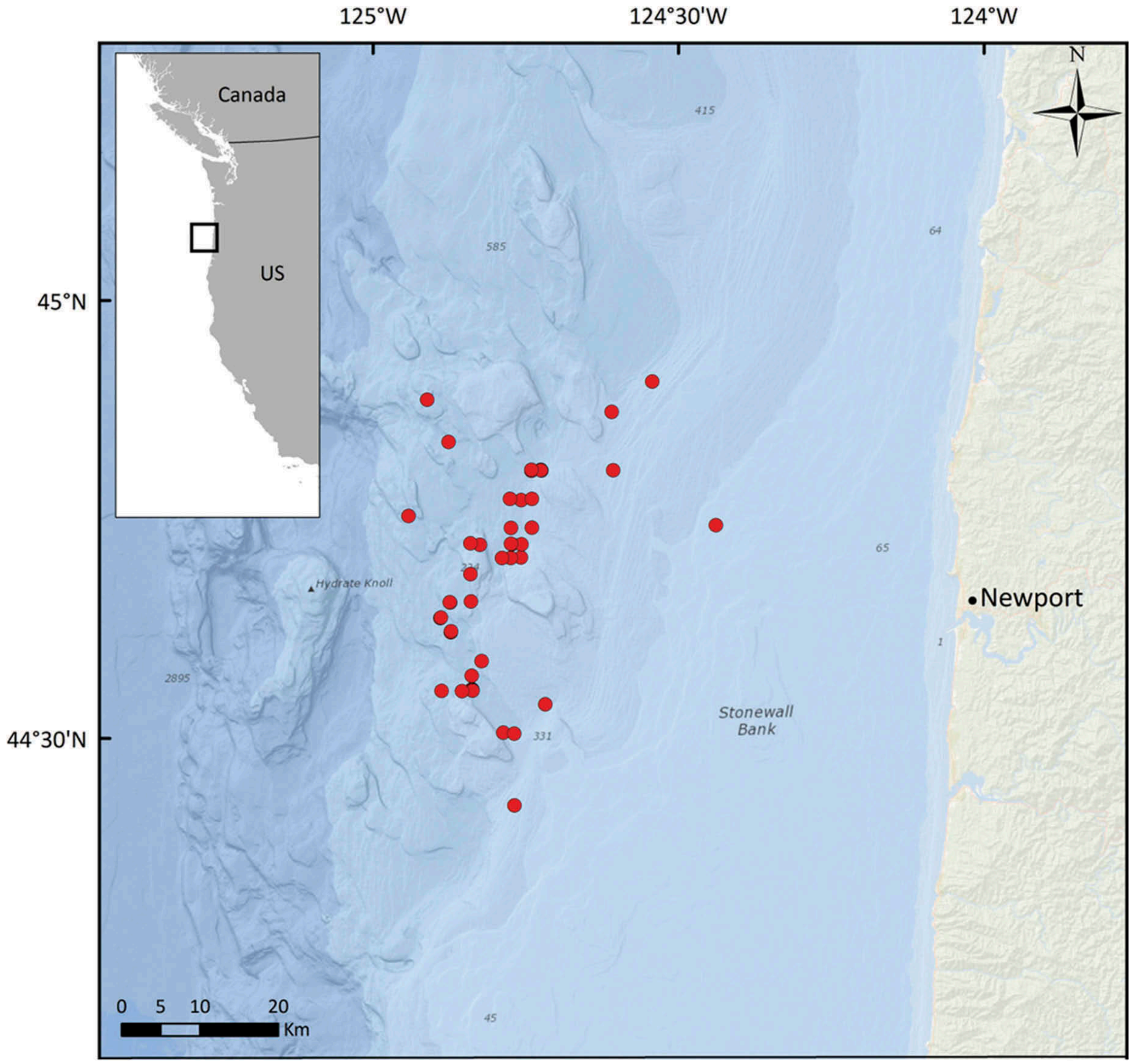

FIGURE 2. Map of the area off the Oregon coast where sea trials were conducted to compare size selectivity of T90-mesh and diamond-mesh cod ends. Bottom trawl tow locations are depicted by the red circles.

riblines (five on each ribline) of the cover. A video camera system was used before data were collected to confirm that the cover was not masking the cod end.

Sea trials.—Tests occurred off the coast of Oregon between 44°25′N and 44°55′N and between 124°27′W and 124°58′W during August 2015 (Figure 2). Towing occurred in the vicinity of the continental shelf break and upper slope during daylight hours (between 0600 and 2000 hours Pacific daylight time) at bottom depths from 311 to 622 m. Towing speed over ground ranged from 4.07 to 4.82 km/h (2.2–2.6 knots). Tow durations were set to 105 min so that all catches could be completely weighed and sampled.

A randomized block design was used to determine the order in which each cod end was tested (Table 1). Overall, 45 tows were completed: 14 tows were made with the 114-mm diamond cod end, 15 tows were made with the 114-mm T90 cod end, and 16 tows were made with the 140-mm T90 cod end. After each tow, all fish that were caught in the cover and in the cod end were identified to species and weighed by using a motion-compensated platform scale. Rex Sole, Dover Sole, and Shortspine Thornyheads from the cover and from the cod end were randomly selected per tow and measured to the nearest centimeter TL, while Sablefish were measured to the nearest centimeter FL. Subsampling was avoided when possible; however, time constraints and relatively large catches often required subsampling for length measurements. Table 2 presents the length data that were used to obtain the selectivity results. During this study, the minimum market size was

TABLE 1. Summary data for the 45 bottom trawl tows completed with three cod end types (114-mm T90 mesh; 140-mm T90 mesh; and 114-mm diamond mesh [DM]) off the Oregon coast in 2015; total catch values were rounded for inclusion in the table ("block" refers to the randomized block design).

Block	Date	Cod end type	Number of tows	Bottom depth range (m)	Total catch range (kg)
1	Aug 2	114 T90	3	366–402	937–3,630
	Aug 3	114 DM	4	380 421	779–1,399
	Aug 5	140 T90	4	397–439	543–1,235
2	Aug 6	140 T90	4	384–622	635–1,091
	Aug 7	114 T90	4	329–393	1,099–1,385
	Aug 10	114 DM	3	311–421	2,051–6,263
3	Aug 11	114 T90	4	395–604	661–3,362
	Aug 12	140 T90	4	512–549	635–1,397
	Aug 15	114 DM	4	487–549	1,110–2,134
4	Aug 16	114 T90	4	402–430	843–1,166
	Aug 17	140 T90	4	386–417	767–1,274
	Aug 18	114 DM	3	494–536	1,300–3,127

31.8 cm for Rex Sole, 33 cm for Dover Sole, and 21.6 cm for Shortspine Thornyheads. There was no minimum market size for Sablefish.

Selectivity analysis.—The statistical analysis software SELNET (SELection in trawl NETting) was used to analyze the data (Sistiaga et al. 2010; Herrmann et al. 2012). Average size-selection curves were estimated by pooling length (l) data across tows for each cod end, $r_{av}(l)$. As various parametric models were evaluated, a vector (v) was included to incorporate the parameters of the model and expressed as $r_{av}(l,\ v)$. All tows and all length-classes caught were used in the analysis. Five models (logit, probit, Gompertz, Richard, and double logistic [DLogit]) were considered for estimating the average size-selection properties for each species and each type of cod end. The logit, probit, and Gompertz models were described by the L_{50} (length at which fish had a 50% probability of being retained) and selection range (SR; the length difference between L_{25} and L_{75}) parameters. The Richard model was described by the L_{50}, SR, and 1/δ (δ = Delta) selection parameters. The logit, probit, Gompertz, and Richard models assumed that all fish are subjected to the same size-selection process. For the DLogit model (Herrmann et al. 2016), a primary assumption was that a fraction of the fish encountering the cod end (C_1) will be exposed to one size-selection process (i.e., towing process) and is described by parameters $L_{50,1}$ and SR_1, while the remaining fraction ($1 - C_1$) will be exposed to another size-selection process (i.e., haulback) and is described by parameters $L_{50,2}$ and SR_2. The overall L_{50} and SR parameters for the DLogit model considered both the C_1 value and the $1 - C_1$ value and were estimated by using a statistical method implemented in SELNET. The five model functions evaluated were

$$r_{av}(l,\ v) = \begin{cases} \text{logit}(l, L_{50}, \text{SR}) \\ \text{probit}(l, L_{50}, \text{SR}) \\ \text{Gompertz}(l, L_{50}, \text{SR}) \\ \text{Richard}(l, L_{50}, \text{SR}, 1/\delta) \\ \text{DLogit}\left(l, C_1, L_{50,1}, \text{SR}_1, L_{50,2}, \text{SR}_2\right) \\ \quad = C_1 \times \text{logit}\left(l, L_{50,1}, \text{SR}_1\right) + (1 - C_1) \\ \quad \times \text{logit}\left(l, L_{50,2}, \text{SR}_2\right). \end{cases}$$

For complete model details, see Wileman et al. (1996), Wienbeck et al. (2014), and Herrmann et al. (2016).

To determine which model best described the data, we evaluated fit statistics for each model. Fit statistics indicating that a model could adequately describe the data included P-values greater than 0.05 and a deviance value no greater

TABLE 2. Length data that were used to model size selectivity for each cod end type evaluated (114-mm T90 mesh; 140-mm T90 mesh; and 114-mm diamond mesh [DM]) in the West Coast groundfish bottom trawl fishery. Lengths are reported as FL for Sablefish and TL for all other species.

	Rex Sole			Dover Sole			Shortspine Thornyhead			Sablefish		
Variable	114 DM	114 T90	140 T90	114 DM	114 T90	140 T90	114 DM	114 T90	140 T90	114 DM	114 T90	140 T90
Number of tows	13	14	15	14	15	16	14	14	16	14	15	16
Number of fish in cod end (measured)	566	1,040	397	1,090	1,579	974	1,050	1,351	629	1.150	934	844
Number of fish in cod end (raised)	2,073	2,746	503	8,064	7,674	2,657	2,190	2,732	745	5,439	1,893	1,743
Number of fish in cover (measured)	986	1,486	1,196	1,541	1,593	1,754	1,419	1,821	2,010	208	83	290
Number of fish in cover (raised)	3,053	3,975	3,114	7,228	5,194	6,268	4,948	5,794	5,248	208	83	290
Length range (cm)	21–42	19–42	22–42	25–60	24–58	23–60	16–74	16–63	16–74	40–88	43–90	39–92

than approximately 2 times the degrees of freedom. Among the models with acceptable fit statistics, the model with the lowest value of Akaike's information criterion (Akaike 1974) was selected as the best model. After model selection, we estimated Efron bootstrap 95% confidence intervals (CIs; Efron 1982) for L_{50} and SR based on 1,000 bootstrap repetitions using a double-bootstrapping method implemented in SELNET to account for both within-tow and between-tow variation. This is the same approach that was used by Sistiaga et al. (2010) and Herrmann et al. (2012) to avoid underestimating confidence limits for selectivity curves when pooling tow data. To determine whether the selectivity curves for a given species differed significantly between any two of the three cod end types, the *P*-value was calculated as the number of times out of the 1 million pairs of bootstrap L_{50} values that the L_{50} for net A was less than the L_{50} for net B. For a two-sided test (with $\alpha = 0.05$), if this value was less than 25,000 (2.5%), then the difference was deemed significant.

RESULTS

Total catch per tow (cover plus cod end) ranged from 543 to 6,263 kg (Table 1). Rex Sole comprised 5.7% of the total catch by weight, Dover Sole made up 28.9%, Shortspine Thornyheads constituted 9.1%, and Sablefish comprised 31.7%. The remaining catch consisted of 46 species and included Longspine Thornyheads, secondary target species (i.e., skates [Rajidae] and rockfishes *Sebastes* spp.), unmarketable-sized groundfishes, noncommercial species, and Pacific Halibut *Hippoglossus stenolepis*.

Rex Sole

The mean L_{50} value of Rex Sole caught in the 140-mm T90 cod end was significantly larger than the mean L_{50} values for the 114-mm diamond cod end and 114-mm T90 cod end (Table 3). The mean L_{50} value of the 114-mm diamond cod end was also significantly larger than that of the 114-mm T90 cod end. Mean selectivity curves for Rex Sole showed that selectivity 95% CIs overlapped between the 114-mm diamond cod end and the 114-mm T90 cod end around L_{25} and for all three cod ends well above L_{75}; however, there was a clear separation of the selectivities for the three cod end types at L_{50} (Figure 3). The 114-mm T90 cod end exhibited the narrowest SR and thus the steepest selectivity curve (Table 3). Acceptable fit statistics were observed for the 114-mm diamond cod end and the 140-mm T90 cod end. However, a *P*-value less than 0.05 for the 114-mm T90 cod end required further assessment to determine whether the model was adequately describing the data for Rex Sole. The assessment indicated that the *P*-value less than 0.05 was due to overdispersion of the data rather than the inability of the model to adequately describe the data.

Dover Sole

The mean L_{50} value for Dover Sole caught in the 140-mm T90 cod end was significantly larger than the mean L_{50} values for the 114-mm diamond cod end and 114-mm T90 cod end; the mean L_{50} value for the 114-mm diamond cod end was also significantly larger than that for the 114-mm T90 cod end (Table 3). Mean selectivity curves for Dover Sole illustrated the closer similarities in selectivity between the 114-mm diamond and 114-mm T90 cod ends and their greater differences from the 140-mm T90 cod end (Figure 4). As was observed for Rex Sole, the mean L_{50} value for Dover Sole was smallest with the 114-mm T90 cod end. For both flatfish species, the 114-mm and 140-mm T90 cod ends showed narrower SRs and steeper selectivity curves than the 114-mm diamond cod end.

TABLE 3. Mean selection results for models describing the size selectivity of the three cod end types evaluated (114-mm T90 mesh; 140-mm T90 mesh; and 114-mm diamond mesh [DM]) for the West Coast groundfish bottom trawl fishery (Efron bootstrap 95% confidence intervals are shown in parentheses; SSTH = Shortspine Thornyhead; L_{50} = length at which 50% of fish have the probability of being retained; SR = selection range; SF = selection factor). For a given species, lowercase letters (z, y, x) indicate whether the L_{50} is significantly different among cod end types (at the $\alpha = 0.05$ level); the magnitude of the L_{50} value increases from z to x. The model that best described the data is presented (DLogit = double logistic).

Species	Cod end type	L_{50}	SR	SF	Model	*P*-value	Deviance	df
Rex Sole	114 DM	33.1 (32.3–34.9) y	6.5 (5.0–8.7)	0.28	Logit	0.4338	20.4	20
	114 T90	31.8 (31.2–32.4) z	3.8 (3.1–4.8)	0.27	DLogit	0.0051	38.5	19
	140 T90	36.4 (35.8–37.4) x	4.7 (3.8–5.8)	0.26	Logit	0.1827	24.4	19
Dover Sole	114 DM	34.9 (33.9–35.9) y	4.5 (3.0–7.8)	0.29	DLogit	0.1125	40.8	31
	114 T90	33.6 (33.0–34.2) z	3.5 (3.2–4.0)	0.28	Probit	0.9959	15.5	33
	140 T90	39.2 (38.3–40.2) x	3.6 (3.0–4.2)	0.28	Probit	0.9780	21.0	36
SSTH	114 DM	28.4 (27.6–30.5) z	8.0 (5.9–11.7)	0.24	DLogit	0.9521	28.8	43
	114 T90	30.0 (28.8–31.8) z	6.4 (5.1–8.2)	0.25	DLogit	0.1317	50.1	40
	140 T90	36.3 (34.9–37.4) y	6.7 (5.4–7.9)	0.26	Richard	0.9563	36.8	53
Sablefish	114 DM	42.2 (31.9–44.9) z	2.6 (0.1–14.5)	0.35	DLogit	0.9815	23.6	40
	114 T90	43.9 (42.3–45.4) zy	5.1 (4.1–6.5)	0.37	Gompertz	0.8082	34.8	43
	140 T90	46.5 (42.9–48.5) y	7.8 (4.4–51.5)	0.33	DLogit	0.9998	17.9	44

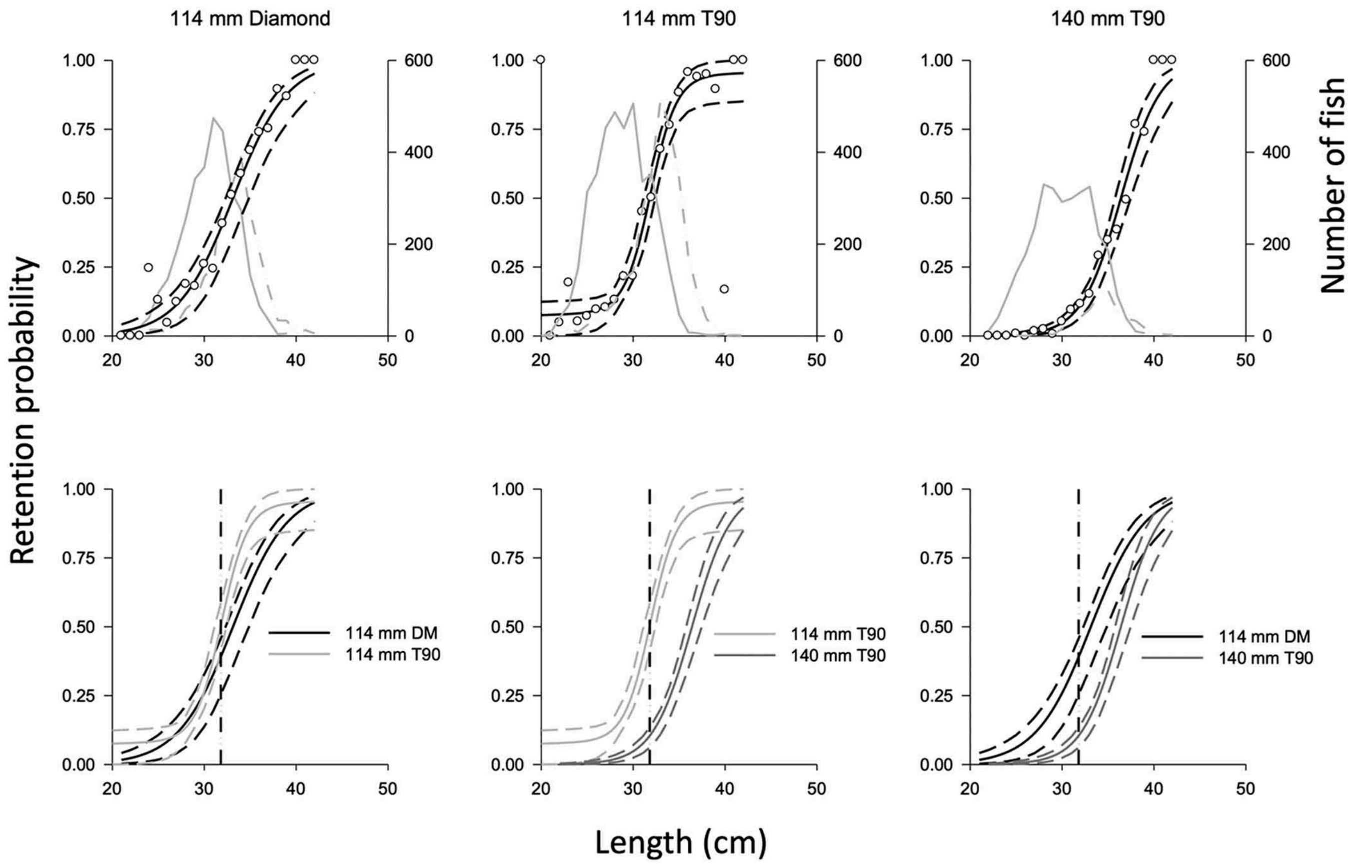

FIGURE 3. Mean selectivity curves (upper panels) modeled for Rex Sole in each cod end type examined (DM = diamond mesh; black solid line = the modeled value; black dashed lines = 95% confidence interval; open circles = experimental data; gray solid line = number of fish caught in the cod end cover; gray dashed line = number of fish caught in the cod end). Lower panels present comparisons of mean selectivity curves for the three cod end types (solid line = the modeled value; dashed lines = 95% confidence interval; vertical black dashed line = minimum market size).

Shortspine Thornyhead

The mean L_{50} for Shortspine Thornyheads caught in the 140-mm T90 cod end was significantly larger than the mean L_{50} values for the 114-mm diamond and 114-mm T90 cod ends (Table 3). Although the mean L_{50} value for the 114-mm T90 cod end was larger than that for the 114-mm diamond cod end, the two means did not differ statistically, as suggested by their substantially overlapping 95% CIs at L_{50} (Table 3; Figure 5). Mean selectivity curves for Shortspine Thornyheads illustrated the similarity in selectivity between the 114-mm diamond and 114-mm T90 cod ends and their differences in selectivity relative to the 140-mm T90 cod end (Figure 5). The 114-mm and 140-mm T90 cod ends exhibited narrower SRs and steeper selectivity curves than the 114-mm diamond cod end.

Sablefish

The mean L_{50} value for Sablefish that were caught in the 140-mm T90 cod end was significantly larger than the mean L_{50} for those caught in the 114-mm diamond cod end (Table 3). For Sablefish, mean L_{50} values did not differ significantly between the two 114-mm cod ends tested or between the two T90 cod ends tested, as too few fish were caught in the cover for the models to detect any significant differences (Figure 6). Overall, the 114-mm T90 cod end had a greater mean L_{50} value and a narrower SR 95% CI than the 114-mm diamond cod end. The 140-mm T90 cod end had a larger mean L_{50} and a wider SR 95% CI than the 114-mm T90 cod end (Table 3). As occurred in Shortspine Thornyheads, the mean L_{50} value for Sablefish was smallest with the 114-mm diamond cod end. Mean selectivity curves for Sablefish captured in the three cod ends are presented in Figure 6.

DISCUSSION

Turning diamond mesh 90° in orientation (i.e., T90 mesh) can affect the selection properties of a cod end. In this study, mean L_{50} values for Rex Sole and Dover Sole were significantly smaller in the 114-mm T90 cod end than in the 114-mm diamond cod end.

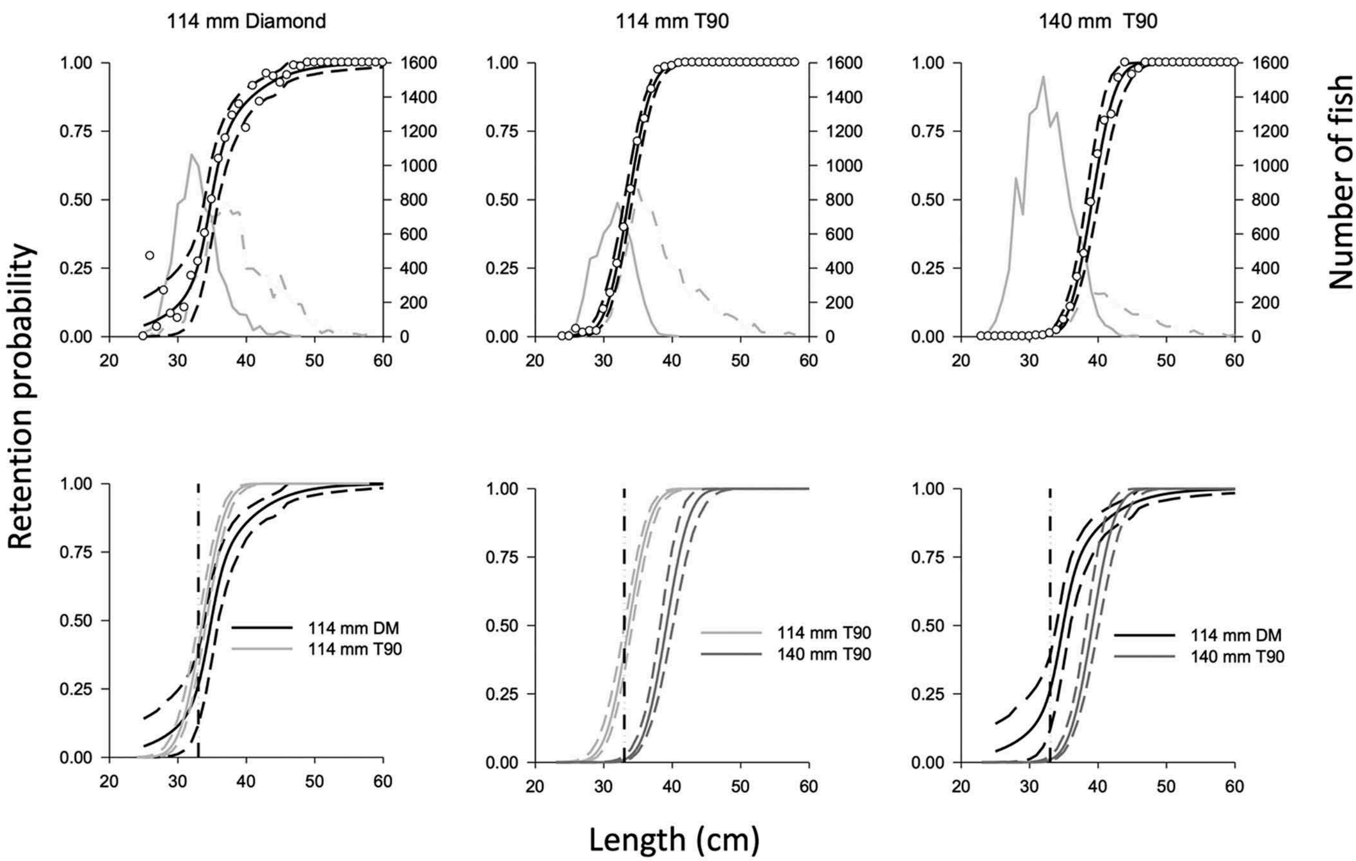

FIGURE 4. Mean selectivity curves (upper panels) modeled for Dover Sole in each cod end type examined (DM = diamond mesh; black solid line = the modeled value; black dashed lines = 95% confidence interval; open circles = experimental data; gray solid line = number of fish caught in the cod end cover; gray dashed line = number of fish caught in the cod end). Lower panels present comparisons of mean selectivity curves for the three cod end types (solid line = the modeled value; dashed lines = 95% confidence interval; vertical black dashed line = minimum market size).

For Shortspine Thornyheads and Sablefish, the opposite trend was consistently seen (Table 3), with larger mean L_{50} values occurring in the 114-mm T90 cod end than in the 114-mm diamond cod end. In our analyses of Rex Sole, Dover Sole, and Shortspine Thornyheads, selectivity values for the 140-mm T90 cod end were significantly different from those of the other two cod end types. The mean L_{50} value for Sablefish was largest in the 140-mm T90 cod end, and that mean was significantly different from the mean L_{50} associated with the 114-mm diamond cod end but not from the mean obtained with the 114-mm T90 cod end. However, the small number of Sablefish in the cover reduced the power of comparison tests for Sablefish relative to those conducted for the other three species. Our general findings of smaller mean L_{50} values for flatfishes but larger means for roundfishes occurring in the 114-mm T90 cod end relative to those in the 114-mm diamond cod end are similar to previous studies that have compared diamond cod ends to T90 cod ends (Wienbeck et al. 2011; Herrmann et al. 2013; Tokaç et al. 2014; Bayse et al. 2016) and square-mesh cod ends (Wallace et al. 1996; Perez-Comas et al. 1998; He 2007) with similar mesh sizes.

The selection factor (SF) parameter represents the ratio between L_{50} and mean mesh size. This parameter can be used to estimate L_{50} values (SF value × mesh size = L_{50}) for a species across different mesh sizes and is useful for comparing results within and/or between studies in which slightly different mesh sizes are used (Herrmann et al. 2016). In the present study, there was a slight difference in the mean mesh size between the nominal 114-mm cod ends (118.5 mm versus 119.6 mm). Therefore, SF values were calculated (Table 3) and examined to determine whether the difference in mesh size affected the L_{50}. Inspection of the SFs showed that the difference in mean mesh size between the 114-mm cod ends had a minimal effect, as the results still showed smaller mean L_{50} values for flatfishes but larger mean L_{50} values for roundfishes in the nominal 114-mm T90 cod end than in the 114-mm diamond cod end.

Prior to this study, cod end selectivity research off the U. S. West Coast had focused on diamond-mesh and square-mesh cod ends. Wallace et al. (1996) and Perez-Comas et al. (1998) examined the selection properties of 114-, 127-, and

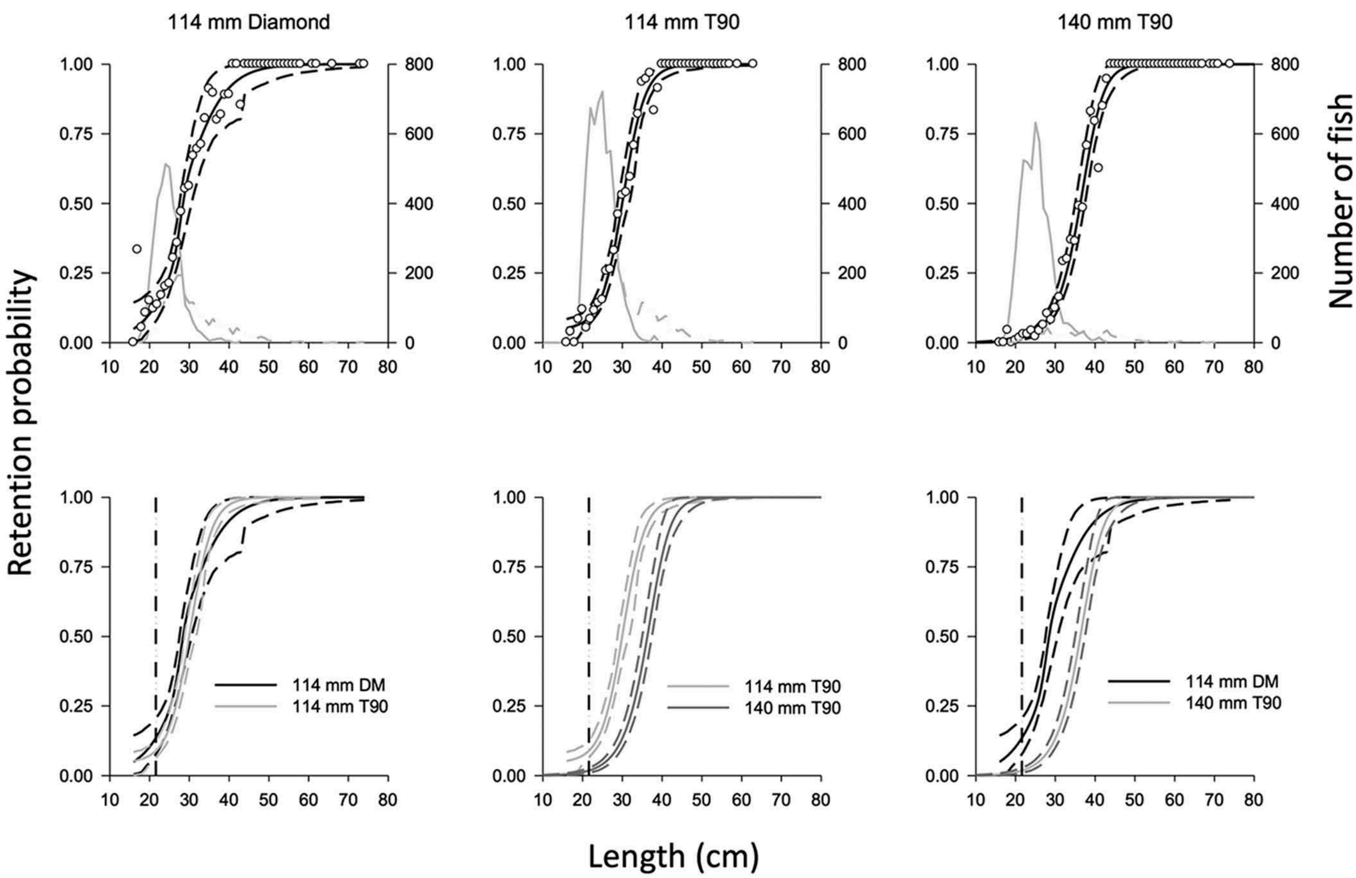

FIGURE 5. Mean selectivity curves (upper panels) modeled for Shortspine Thornyheads in each cod end type examined (DM = diamond mesh; black solid line = the modeled value; black dashed lines = 95% confidence interval; open circles = experimental data; gray solid line = number of fish caught in the cod end cover; gray dashed line = number of fish caught in the cod end). Lower panels present comparisons of mean selectivity curves for the three cod end types (solid line = the modeled value; dashed lines = 95% confidence interval; vertical black dashed line = minimum market size).

140-mm diamond-mesh cod ends and 114- and 127-mm square-mesh cod ends. In general, their results indicated that total discard rates decreased with increasing mesh sizes for both diamond and square-mesh cod ends. A decline in catch utilization also corresponded to increasing mesh size, with the highest loss occurring in the 140-mm diamond cod end. In the present study, where the size-selection properties of 114-mm T90, 140-mm T90, and 114-mm diamond-mesh cod ends were evaluated, the 114-mm T90 cod end showed a consistent trend of increasing the retention of flatfishes while lowering the catches of smaller-sized Shortspine Thornyheads and Sablefish relative to the 114-mm diamond and 140-mm T90 cod ends. Perez-Comas et al. (1998) observed a similar result when comparing a 114-mm square-mesh cod end to a 114-mm diamond cod end, with more immature and unmarketable-sized flatfishes (e.g., Rex Sole and Dover Sole) retained in the square-mesh cod end. They observed the opposite for roundfishes. Wallace et al. (1996) presented similar findings in the outer nearshore fishery (91–183-m depth), where the percentage of roundfishes is typically higher; the 114-mm square-mesh cod end performed better than the 114-mm diamond cod end at reducing roundfish discards. In the inner nearshore fishery (0–91-m depth), where the proportion of flatfishes is generally higher, Wallace et al. (1996) found that the 114-mm diamond cod end performed better at limiting discards. Results from the current study indicate that the 114-mm T90 cod end may perform better at reducing catches of smaller-sized roundfishes than the similar-sized diamond cod end. For the DTS fishery, in which the Sablefish has become a constraining species, the 114-mm T90 cod end could potentially benefit fishermen by reducing their catch rate of smaller-sized Sablefish and Shortspine Thornyheads while allowing them more opportunities to catch their Dover Sole IFQs. Although the 140-mm T90 cod end was effective at reducing catches of smaller-sized flatfishes and roundfishes (as indicated by the mean L_{50} values), this cod end would be economically unfeasible for use under current management regulations and market fish sizes because it exhibited a considerable loss of the catch of marketable-sized fishes.

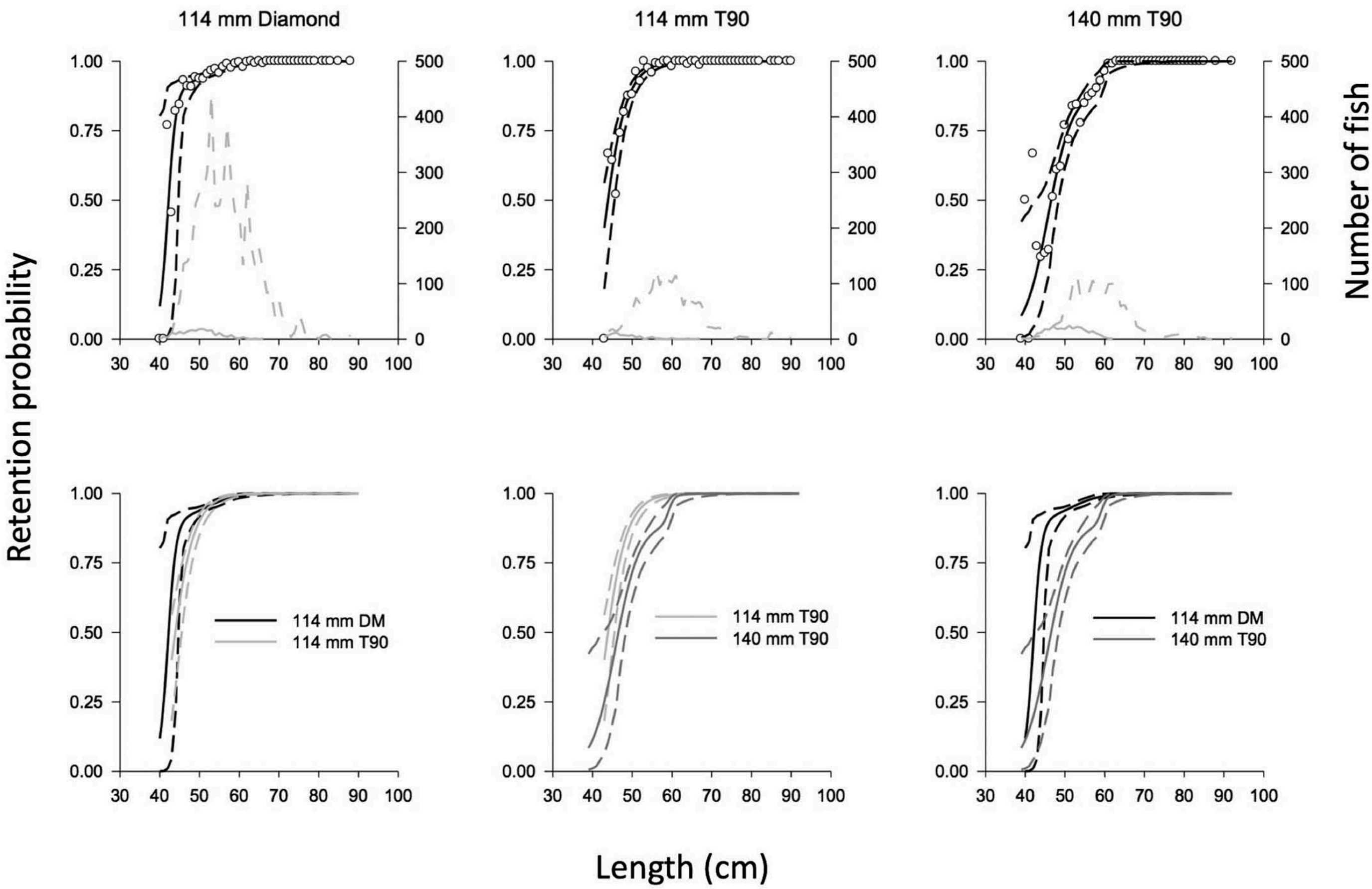

FIGURE 6. Mean selectivity curves (upper panels) modeled for Sablefish in each cod end type examined (DM = diamond mesh; black solid line = the modeled value; black dashed lines = 95% confidence interval; open circles = experimental data; gray solid line = number of fish caught in the cod end cover; gray dashed line = number of fish caught in the cod end). Lower panels present comparisons of mean selectivity curves for the three cod end types (solid line = the modeled value; dashed lines = 95% confidence interval).

Although there may be clear benefits to using T90 cod ends in the LE groundfish bottom trawl fishery, the use of cod end circumferences, twine thicknesses, and twine numbers (e.g., single or double) other than those employed in this study may improve results for trawl fishermen. In a simulated study on Haddock *Melanogrammus aeglefinus* (Herrmann et al. 2007) and a field study of Atlantic Cod in the Baltic trawl fishery (Wienbeck et al. 2011), reducing the number of meshes in the circumference of T90 and diamond-mesh cod ends improved size-selection characteristics (i.e., increased the mean L_{50} values). Both studies demonstrated that T90 and diamond cod ends with reduced circumferences improved selectivity, but the best selection results were achieved by using the T90 cod ends with reduced circumferences. Herrmann et al. (2013) examined the effects of twine characteristics (e.g., thickness, number, and orientation [T90 versus diamond]) on size selectivity for Atlantic Cod and Plaice *Pleuronectes platessa* in the Baltic trawl fishery. For the same mesh size, results showed that T90 cod ends increased the mean L_{50} values for Atlantic Cod. However, as twine thickness in the double-twine T90 cod ends increased, the mean L_{50} values for Atlantic Cod decreased. Increasing the twine thickness, increasing the twine number, and turning the diamond mesh 90° in orientation had a negative effect on Plaice size selectivity. Improvements in size selection of Atlantic Cod from reducing the cod end circumference and twine thickness and turning the diamond mesh 90° in orientation have also been demonstrated (Herrmann et al. 2016).

Identifying a particular cod end mesh size and mesh configuration that can effectively reduce discards while limiting catch losses in multispecies groundfish bottom trawl fisheries has been a challenge for researchers (Wallace et al. 1996; Perez-Comas et al. 1998; He 2007; Herrmann et al. 2013). In several cases, the selectivity for some species has improved, whereas the selectivity for other species has decreased. In these fisheries, where the composition of flatfishes and roundfishes can change spatially and temporally, the use of different cod end mesh sizes and mesh configurations as fishing operations change would most likely improve the ability of fishermen to enhance trawl selectivity relative to use of a single cod end mesh size and a single configuration across the whole fishery. Wallace et al. (1996) provided a good example of how the use of different cod end mesh sizes and configurations could improve trawl selectivity in the nearshore bottom trawl fishery for groundfish along the U.S. West Coast. In their study, square-mesh cod ends were found to perform best at reducing total discard rates in the outer nearshore fishery (91–183-m depth), where assemblages of Arrowtooth Flounder *Atheresthes stomias*, Pacific Cod *Gadus macrocephalus*, Sablefish, Lingcod *Ophiodon elongatus*, and Dover Sole were targeted, whereas diamond-mesh cod ends with a mesh size of at least 114 mm performed better in the inner nearshore fishery (0–91-m depth), where Pacific Sanddab *Citharichthys sordidus*, English Sole *Parophrys vetulus*, Rex Sole, and rockfishes were the main targeted species. Helping fishermen to identify more selective trawl gear that can reduce the retention of unmarketable-sized fishes as well as species with relatively low ACLs or allocations will allow the fishermen to more effectively utilize their IFQs and increase their economic benefits; furthermore, benefits will accrue to coastal communities, management, and the resource.

In conclusion, the size-selection characteristics of 114-mm T90, 140-mm T90, and 114-mm diamond-mesh cod ends were evaluated for two flatfish species and two roundfish species that are commonly caught over the continental shelf break and upper slope of the U.S. West Coast. Although there may be clear benefits to using T90 cod ends in this mixed-stock groundfish fishery, mesh sizes, cod end circumferences, twine thicknesses, and twine numbers other than those used here may improve results for trawl fishermen. Further evaluation of T90 cod ends over a range of mesh sizes and circumferences and under various fishing conditions would provide important information to better determine their potential efficacy in this fishery.

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