Size-selectivity of T90 mesh and diamond mesh codends on five groundfish species commonly caught over the upper continental slope of the U.S. west coast

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Abstract

The U.S. west coast groundfish bottom trawl fishery operates under a catch share program, 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 fishermen's ability to maximize catch of more abundant stocks. Size-selection characteristics of 114 mm and 140 mm T90 mesh, and traditional 114 mm diamond mesh codends were examined using the covered codend method. Selection curves and mean L_{50} values for two flatfish species (rex sole *Glyptocephalus zachirus*, and Dover sole *Microstomus pacificus*), and three roundfish species (shortspine thornyhead *Sebastolobus alascanus*, longspine thornyhead *S. altivelis*, and sablefish *Anoplopoma fimbria*) were estimated. Mean L_{50} values were smaller for flatfishes, but larger for roundfishes in the 114 mm T90 codend compared to the diamond codend. The 140 mm T90 codend showed significantly different selectivities from the others, being most effective at reducing the catch of unmarketable-sized fishes, however with a considerable loss of marketable-sized fishes. Findings suggest T90 codends have potential to improve catch utilization in this multispecies fishery.

Introduction

The U.S. West Coast limited entry (LE) groundfish bottom trawl fishery operates under a catch share program that allocates individual fishing quotas (IFQ) and establishes annual catch limits (ACLs) for over 30 groundfish managed units (PFMC and NMFS 2010, 2012). 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 upper continental slope of 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 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/kg and are dependent on weight, with fish 5.4 kg and larger exhibiting the highest price/kg. However, sablefish have become a constraining species in the DTS fishery as their shorebased trawl allocation (2,641 mt) is relatively low when compared to the Dover sole allocation (22,234 mt) (NMFS 2014). Recent catches of Dover sole have been approximately 6,378 mt (PacFIN 2014) with constraining species, such as sablefish, as the primary cause. Minimizing catches of smaller-sized shortspine and longspine thornyheads could also benefit fishermen as prices for thornyheads are dependent on length (ranging from $0.88 to $2.42/cm), with larger individuals receiving the highest price/cm. Dover sole, on the other hand, are priced at $0.99/kg regardless of length. Hence, reducing the catch rate of smaller-sized sablefish and 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 thornyheads.

A simple technique shown to improve trawl selectivity is modifying the size and configuration of the codend mesh (Perez-Comas et al. 1998; He 2007; Madsen and Valentinsson 2010). Recently, research has focused on the development and use of T90 mesh codends (Digre et al. 2010; Wienbeck et al. 2011, 2014; Madsen et al. 2012; Herrmann et al. 2013). T90 mesh is conventional diamond mesh that has been turned 90^{o} in orientation. This configuration allows the meshes over the entire codend to remain more open than those of diamond mesh codends, improving size-selection characteristics. For diamond mesh codends, research has demonstrated that they become distorted into a bulbous shape as tension on the netting increases and catch levels accumulate (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 fishes. The simple construction of a T90 codend, ease of repair when damaged, and its potential to improve size-selection provides some advantages over other mesh orientations used to enhance codend selectivity, such as knotless square mesh (Perez-comas et al. 1998; He 2007). This T90 mesh configuration, originally designed for use in cod *Gadus morhua* fisheries, has gained increased interest in other fisheries such as the Norway lobster *Nephrops norvegicus* otter trawl fishery in the Kattegat–Skagerrak area (Madsen et al. 2012) and in the Mediterranean Sea multispecies demersal trawl fishery (Tokaç et al. 2014). Compared to diamond mesh codends with similar mesh sizes, T90 mesh codends 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 between 114 mm and 140 mm T90 mesh codends, and the traditional 114 mm diamond mesh codend and evaluate if T90 mesh codends can improve catch utilization in the LE groundfish bottom trawl fishery.

Materials and Methods

Trawl Design

The chartered F/V *Last Straw*, a 23.2 m long 540 horsepower trawler, provided its two-seam trawl for sea trials. The headrope was 24.1 m in length and utilized sixteen 28.0 cm diameter deep-water floats for lift. The footrope was 24.7 m in length and covered with rubber disks 20.3

cm in diameter with 45.7 cm rockhopper discs placed approximately every 73.7 cm over the length of the footrope. The trawl sweeps were 91.4 m in length and covered with rubber discs 8.9 cm in diameter. Thyborøn type 11 standard trawl doors were used.

Codends Tested and Experimental Design

The codends tested were 114 mm and 140 mm T90 mesh, and 114 mm diamond mesh (nominal stretched measurements between-knots). Each codend 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. The same netting material was used to construct each codend. The 114 mm T90 and 114 mm diamond codends were 75 meshes in length and 88 meshes in circumference, excluding meshes in each selvedge. The 140 mm T90 codend was 65 meshes in length and 72 meshes in circumference, excluding meshes in each selvedge (Fig. 1.). A 50 mesh length two-seam to four-seam transitional tube of netting was used to attach each codend to the trawl when tested.

At completion of the study 100 meshes across each codend were measured using an ICES mesh gauge of 4 kg spring force. Mesh measurements showed the nominal 114 mm diamond, and 114 mm and 140 mm T90 codends had actual mesh sizes of 112.0 mm, 104.4 mm, and 127.2 mm, respectively. The disparity among the nominal and actual mesh sizes in the T90 codends is likely from the mesh gauge inability to exert enough longitudinal force to fully stretch the meshes to obtain accurate measurements (Fonteyne et al. 2007). Therefore, the actual mesh sizes of the T90 codends evaluated are believed to be larger than the values observed.

Codend selectivity was measured using the covered codend 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 codend connects 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 (Fig. 1.). Where the cover encompasses the codend, the dimensions are approximately 1.5 times the extended width and approximately 1.3 times the extended length of the codend. 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 codend, a combination of trapezoidal shaped rubber-coated canvas waterborne kites and 20.3 cm diameter floats were used. The kites were positioned along the outer and lower sides of the cover (two sets of 6 on each side) in relation to the fore and aft end of the codend, whereas the floats were positioned along the top riblines (five on each ribline) of the cover. A video camera system was used, before data was collected, to confirm that the cover was not masking the codends.

Sea Trials

Tests were conducted off Oregon between 43°56′ and 45°05′N and between 124°28′ and 125°01′W during September 2012. Towing occurred at bottom depths between 376 to 664 m. Towing speed over ground ranged from 2.2 to 2.6 knots. Tow durations were set to 45 minutes so that all catches could be completely weighed.

Each codend was fished 15 times. A randomized block design (i.e., ABC, BCA, ACB, etc.), consisting of 15 blocks, was used solely to determine the order in which each codend was tested. After each tow, all fishes caught in the cover and codend were identified to species and weighed using a motion compensating platform scale. To examine size-selectivity, up to 50 individuals of each species from the cover and codend separately were randomly selected per tow and measured to the nearest cm fork length. Percent retention by weight (codend / (codend + cover)) was calculated per tow. During this study, the minimum market size was 31.8 cm for rex sole, 33 cm for Dover sole, and 21.6 cm for shortspine thornyhead and longspine thornyhead. Sablefish did not have a minimum market size.

Selectivity Analysis

A certain amount of data manipulation was required before selectivity functions could be estimated. A maximum of 50 individuals per species were sampled from each of the codend and cover in any tow, and the raw data did not include the total weights or counts nor individual weights of the sampled fish of each species in either codend or cover. Therefore, to estimate to total number of individuals of each species caught in the codend and cover in any given tow, it was necessary to first estimate the weight of the sampled individuals using a length-to-weight relationship. This length-weight relationship was calculated using length and weight data for each species from the NOAA Northwest Fisheries Science Center trawl survey (Bradburn et al. 2011). The equations describing the length-weight relationship are provided in Appendix A. Using these relationships, the average individual weight of each sampled species in each net and tow was able to be estimated. The total number of individuals of a species for the codend and cover for each tow was then estimated by dividing the total weight of the species for that tow and net by that average weight for that tow and net. The length data were then re-scaled (or weighted) to reflect the total estimated number caught for each species, tow and net, before use in those analyses described below which estimate selectivity from combined tows. While this often (but not always) increased the purported number of fish sampled as input to the analysis, for most tows and species it increased the number in only one of the codend or cover (as usually at most only one of these had more than 50 individuals of a species). Since the uncertainty in a logistic regression analysis is most highly influenced by the less populous of the zeros and ones in the data (and certainly given the patterns in this data when the more populous of the two had more than 50 individuals), this had little influence on the estimates of uncertainty, while providing the proper information for weighting among tows for each species, where needed.

To model selectivity, a logistic curve was assumed, which is the generally accepted model (Stiratelli et al. 1984; Fryer 1991; He 2007; Wienbeck et al. 2011), while approaching the overall analysis in a number of different ways. The form of the logistic is:

$$P(L) = \frac{e^{(\alpha+\beta L)}}{1 + e^{(\alpha+\beta L)}}$$

where the length of 50% selection is:

$L_{50} = -\frac{\alpha}{\beta}$,

and the selection range (SR = the difference between the lengths of 25% and75% selection) is:

$$SR = \frac{ln9}{\beta}$$

The model was implemented in the R programming language (R Development Core Team, 2012).

For each species, the selectivity parameters for individual tows were calculated from the re-scaled (weighted) data. Because some tows had very few fish of a particular species in the codend or cover (or both), the resultant estimates for those tows could be quite uncertain, and the associated curves counterintuitive. After examining the data, a general rule was applied that a minimum of 8 fish of a species sampled in each codend and cover was required for a tow to be used for that species in the analysis described below, with the exception of the estimates based upon pooled data across all tows for each codend tested. This minimum sampling requirement balanced the need for adequate sample size, in terms of number of tows included in the analysis, and the need to avoid including tows that provided individually estimated curves that did not reflect the overall selectivity of the codend for a given species.

Two statistical approaches were applied to the data. First, analysis of variance (ANOVA) was used to compare the L_{50} values for each codend from the individual tows included in the analysis for each species. This approach does not give more weight to those tows that caught more individuals of a species (beyond the exclusion of those tows not meeting the minimum sampling requirement above). Second, using the same set of tows, a non-linear mixed-effects (NLME) model, similar to the formation of Stiratelli et al. (1984) was used to estimate a single selectivity curve for each species and codend. The NLME model also calculated the between-tow variation in selectivity for each codend, thus allowing it to estimate the uncertainty in the mean selectivity parameters separately from the between-tow variability. This provides an improved estimate of the mean selectivity curve and the uncertainty in the estimated selectivity parameters for each codend, while limiting the influence of any one tow. For comparison, logistic selectivity curves were also calculated for pooled data across all tows for each species and net.

Results

Mean percent retention of all fishes combined for the 114 mm diamond mesh, and 114 mm and 140 mm T90 mesh codends were 71.3%, 86.3%, and 44.0%, respectively (Table 1). Catch per tow ranged from 49.5 to 1,915.1 kg for the codend and 38.3 to 734.0 kg for the cover. Rex sole, Dover sole, shortspine thornyhead, longspine thornyhead, and sablefish comprised 83% of the total catch by weight. The remaining 17% of the catch consisted of 42 species and included secondary target species, unmarketable-sized groundfishes, non-commercial species, and Pacific halibut. Total catch and retention rates from the 45 tows conducted are summarized in Table 1.

Length frequency distributions of the five groundfish species analyzed in this paper are depicted in Figure 2. The size range of the population fished, by species, was similar among the codends. Total catches from tows used to run each NLME model for the five groundfish species analyzed are presented in Table 2.

Rex sole

Mean L_{50} values for rex sole differed significantly among the codends (Table 3, $p<0.00001$), with a much smaller L_{50} value occurring in the 114 mm T90 codend than the 114 mm diamond and 140 mm T90 codends (Table 4). This result is also reflected in the observed percent retention of marketable- and unmarketable-sized rex sole, with the 114 mm T90 codend exhibiting a much higher percent retention of marketable- and unmarketable-sized rex sole than the other two codends. The 140 mm T90 codend had the largest L_{50} value and retained the lowest percent of unmarketable-sized rex sole. However, the retention of marketable-sized rex sole was only 19.4% for this codend (Table 5). The probability of retaining a rex sole of minimum marketable-size was 22.6%, 48.1%, and 5.2% for the 114 mm diamond, 114 mm T90, and 140 mm T90 codend, respectively. The 114 mm T90 codend exhibited the narrowest selection range and steepest selectivity curve (Table 4, Figs. 3 and 4). While the selectivity of the 114 mm diamond and 140 mm T90 codends differed significantly ($p<0.001$), their selection ranges were more similar.

Dover sole

Dover sole mean L_{50} values differed significantly among the codends (Table 3, $p<0.00001$), with a much smaller L_{50} value occurring in the 114 mm T90 codend than the 114 mm diamond and 140 mm T90 codends (Table 4). This result is also reflected in the observed percent retention of marketable- and unmarketable-sized Dover sole, with the 114 mm T90 codend exhibiting a much higher percent retention of marketable- and unmarketable-sized Dover sole than the other two codends. The 140 mm T90 codend had the largest L_{50} value and retained the lowest percent of unmarketable-sized Dover sole. However, the retention of marketable-sized Dover sole was only 41.3% for this codend (Table 5). The probability of retaining a Dover sole that is of minimum marketable-size was 30.0%, 62.9%, and 1.9% for the 114 mm diamond, 114 mm T90, and 140 mm T90 codend, respectively. Selectivity curves of individual tows and mean curves for Dover sole show smaller selection ranges and steeper selectivity curves occurring in the T90 codends than the diamond codend (Figs. 3 and 4). As occurred in rex sole, the mean L_{50} value for Dover sole was smallest in the 114 mm T90 codend.

Shortspine thornyhead

The mean L_{50} value of shortspine thornyhead caught in the 140 mm T90 codend was significantly larger than the mean L_{50} value of the 114 mm diamond and 114 mm T90 codends (Table 3). Mean L_{50} values for shortspine thornyhead did not differ statistically between the 114 mm diamond and 114 mm T90 codends. Selectivity curves of individual tows and mean curves for shortspine thornyhead illustrate the selectivity similarities between the 114 mm diamond and 114 mm T90 codend and their selectivity differences from the 140 mm T90 codend (Figs. 3 and 4). The percent retention of marketable-sized shortspine thornyhead was highest for the 114 mm T90 codend followed second by the 114 mm diamond codend. The 140 mm T90 codend was the most effective at reducing the catch of unmarketable-sized shortspine thornyhead. However, its retention of marketable-sized fish was only 61.4% (Table 5). The probability of retaining a shortspine thornyhead that is of minimum marketable-size was 6.7%, 3.6%, and 1.7% for the 114 mm diamond, 114 mm T90, and 140 mm T90 codend, respectively.

Longspine thornyhead

For each codend, too few tows occurred where adequate numbers of longspine thornyhead were retained in the codend to provide adequate statistical power to discern differences among the codends for this species. However, the estimated L_{50} values from the NLME model show the same overall pattern as for shortspine thornyhead, though with less difference between the treatments (Table 4, Fig. 4). In all three codends, retention of longspine thornyhead was extremely low. The probability of retaining a longspine thornyhead that is of minimum marketable-size was 2.7%, 3.9%, and 1.2% for the 114 mm diamond, 114 mm T90, and 140 mm T90 codend, respectively.

Sablefish

The mean L_{50} value of sablefish caught in the 140 mm T90 codend was significantly larger than the mean L_{50} value of the 114 mm diamond and 114 mm T90 codends (Table 3). Mean L_{50} values for sablefish did not differ statistically between the 114 mm diamond and 114 mm T90 codends, however a relatively low sample size resulted in somewhat low power to detect a difference between those two codends. Selectivity curves of individual tows and mean curves for sablefish show the selectivity similarities between the 114 mm diamond and 114 mm T90 codend and their selectivity differences from the 140 mm T90 codend (Figs. 3 and 4). The 140 mm T90 codend was the most effective at reducing the catch of smaller-sized sablefish, however, this codend only retain 77.0% of the marketable-sized sablefish (Table 5). As was found in shortspine thornyhead, and longspine thornyhead, the mean L_{50} value for sablefish was smallest in the 114 mm diamond codend.

Discussion

Rotating diamond mesh 90^{o} in orientation can significantly affect the selection properties of a codend. In this study, mean L_{50} values for flatfishes were significantly smaller in the 114 mm T90 codend than the 114 mm diamond codend, resulting in more smaller-sized flatfishes retained in the 114 mm T90 codend than the 114 mm diamond codend. For roundfishes, while there was no significant difference between the two 114 mm codends (Table 3), the opposite trend was consistently seen (Table 4), with larger mean L_{50} values occurring in the 114 mm T90 codend than the 114 mm diamond codend. These general results were the same for the NLME and pooled data models (Table 4) with the exception of longspine thornyhead, where the lack of data (minimal amount retained in the codend; Table 2) resulted in inconsistent results. General findings from this study noting smaller mean L_{50} values for flatfishes, but larger mean L_{50} values for roundfishes occurring in the 114 mm T90 codend than the 114 mm diamond codend are similar to previous studies comparing diamond codends to T90 codends (Wienbeck et al. 2011; Herrmann et al. 2013; Tokaç et al. 2014), and square mesh codends (Perez-Comas et al. 1998; Wallace et al. 1996; He 2007) with similar mesh size.

Prior to this study, codend selectivity research off the U.S. west coast has focused on diamond mesh and square mesh codends. Wallace et al. (1996) and Perez-Comas et al. (1998) examined the selection properties of 114 mm, 127 mm, and 140 mm diamond, and 114 mm, and 127 mm square mesh codends. In general, their results showed total discard rates decreased with increasing mesh sizes for both diamond and square mesh codends. A drop in catch utilization also corresponded with increasing mesh size, with the highest loss occurring in the 140 mm diamond codend. In the present study, where the size-selection properties of 114 mm and 140 mm T90 mesh, and 114 mm diamond mesh codends were evaluated, the 114 mm T90 codend retained a higher percentage of marketable-sized flatfishes and roundfishes than the 114 mm diamond and 140 mm T90 codends. However, it was less effective at reducing the retention of unmarketable-sized rex sole and Dover sole as mean L_{50} values for these flatfishes decreased in this codend. Perez-Comas et al. (1998) observed a similar result when comparing a 114 mm square mesh codend to a 114 mm diamond codend, with more immature and unmarketable-sized flatfishes, such as rex sole and Dover sole, retained in the square mesh codend. 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, with the 114 mm square mesh codend performing better than the 114 mm diamond codend at reducing roundfish discards. In the inner nearshore fishery (0-91 m depth), where the proportion of flatfishes is generally higher, they found the 114 mm diamond codend performed better at limiting discards. Results from the current study, indicate that the 114 mm T90 codend may perform better at reducing catches of smaller-sized roundfishes than the similar size diamond codend. In the DTS fishery, where sablefish have become a constraining species, this codend could potentially benefit fishermen by reducing their catch rate of smaller-sized sablefish, and thornyheads, while allowing them more opportunities to catch their Dover sole IFQs. Use of the 114 mm T90 codend, however, would create tradeoffs between economic yields and discards that individual fishermen would have to assess relative to their bycatch reduction needs, quota mix, and operating costs. On the other hand, the 140 mm T90 codend was highly effective at reducing discards. This codend, however, would be economically unfeasible for use (under current management regulations and market fish sizes) as it exhibited a considerable catch loss of marketable-sized fishes (e.g., 58.7% catch loss of Dover sole, and 23% catch loss of sablefish).

Although there may be clear benefits for using T90 codends in the LE groundfish bottom trawl fishery, codend circumferences other than those used in this study may improve results for trawl fishermen. In a simulated study on haddock *Melanogrammus aeglefinus* (Herrmann et al. 2007), and in a field study in the Baltic cod trawl fishery (Wienbeck et al. 2011), reducing the number of meshes in the circumference of T90 and diamond mesh codends improved size-selection characteristics (i.e., increase mean L_{50} values). While both studies demonstrated that T90 and diamond codends with reduced circumferences improved selectivity, best selection results were achieved in the T90 codends evaluated with reduced circumferences.

Identifying a particular codend mesh size and mesh configuration that can effectively reduce discards, while limiting catch loss, in multispecies groundfish bottom trawl fisheries has challenged researchers (Perez-Comas et al. 1998; Wallace et al. 1996; He 2007; Herrmann et al. 2013). In several cases, the selectivity for some species improves whereas the selectivity of other species decreases. In these fisheries, where the composition of flatfishes and roundfishes can change spatially and temporally, the use of different codend mesh sizes and mesh configurations as fishing operations change would most likely improve fishermen's ability to enhance trawl selectivity, relative to using a single codend mesh size and configuration across the whole fishery. Wallace et al. (1996) illustrated a good example of how the use of different codend mesh sizes and configurations could improve trawl selectivity in the U.S. West Coast groundfish bottom trawl nearshore fishery. In their study, square mesh codends 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 are targeted, whereas diamond codends of at least 114 mm did better in the inner nearshore fishery (0-91 m depth) where Pacific sanddab *Citharichthys sordidus*, English sole *Parophrys vetulus*, rex sole, and rockfishes *Sebastes* spp. are the main targeted species. Helping fishermen identify more selective trawl gear that can reduce retention of unmarketable-sized fishes, as well as species with relative low ACLs or allocations, will allow them to more effectively utilize their IFQs and increase their economic benefits, and be beneficial to fishermen, coastal communities, management, and the resource.

In conclusion, the size-selection characteristics of 114 mm and 140 mm T90 mesh, and diamond mesh codends were evaluated for two flatfish species and three roundfish species commonly caught over the upper continental slope of the U.S. west coast. While there may be clear benefits for using T90 codends in this mixed-stock groundfish fishery, other mesh sizes and/or codend circumferences other than those used in this study may improve results for trawl fishermen. Further evaluation of T90 codends over a range of mesh sizes, circumferences, and under various fishing conditions would provide important information to better determine their potential efficacy in this fishery.

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Table 1. Catch summaries for each codend tested. DM = diamond mesh.

Block #	Tow #	Start time (PDT)	Duration (min)	Depth (m)	Sea state (m)	Total catch Cover (kg)	Total catch Codend (kg)	Retention (%)
114 mm DM								
1	2	6:46	45	435	2.13	108.2	310.0	74.1
2	5	14:52	46	555	1.55	141.3	372.5	72.5
3	8	9:39	45	475	1.96	389.4	450.2	53.6
4	10	19:18	42	439	1.99	627.8	409.1	39.5
5	13	12:38	45	599	1.34	139.7	502.1	78.2
6	17	12:15	45	615	1.05	149.9	600.4	80.0
7	21	12:04	45	149	1.69	209.5	1,395.0	86.9
8	24	6:55	45	532	0.94	81.6	215.6	72.5
9	25	9:07	46	654	1.02	80.8	301.2	78.8
10	28	7:01	45	533	1.78	130.9	469.3	78.2
11	31	15:02	45	650	1.95	98.3	182.5	65.0
12	35	17:22	45	613	1.11	90.6	218.1	70.7
13	38	9:31	45	552	0.90	186.5	311.3	62.5
14	42	6:54	45	568	1.07	40.7	187.1	82.1
15	43	8:50	46	584	1.25	147.2	577.5	79.7
Mean	-	-	45	531	1.44	174.8	433.5	71.3
SE	-	-	0.3	32.3	0.11	38.5	77.1	-
114 mm T90								
1	1	16:03	45	436	2.48	52.1	858.1	94.3
2	4	12:12	45	504	1.78	56.8	477.7	89.4
3	9	16:03	45	376	2.27	289.8	611.9	67.9
4	12	9:44	45	581	1.35	144.5	500.0	77.6
5	14	15:47	44	664	1.37	116.5	385.0	76.8
6	18	15:20	45	524	1.27	74.6	533.5	87.7
7	19	17:41	45	510	1.4	142.9	806.7	85.0
8	22	15:43	34	148	1.45	170.9	1,206.7	87.6
9	26	11:51	45	640	1.06	96.2	1,915.1	95.2
10	30	12:21	45	635	2.09	93.9	649.0	87.4
11	33	6:49	45	505	1.57	97.6	241.3	71.2
12	36	7:03	45	521	1.10	76.0	217.2	74.1
13	37	7:02	45	487	0.85	134.2	797.3	85.6
14	40	14:30	47	512	0.81	156.4	601.1	79.4
15	45	13:52	45	574	1.28	42.5	1,193.2	96.6
Mean	-	-	44	508	1.48	116.3	732.9	86.3
SE	-	-	0.8	32.4	0.13	16.1	113.1	-

Table 1. Continued.

Block #	Tow #	Start time (PDT)	Duration (min)	Depth (m)	Sea state (m)	Total catch Cover (kg)	Codend (kg)	Retention (%)
				140 mm T90				
1	3	9:29	45	427	2.02	247.5	275.5	52.7
2	6	17:47	45	519	1.63	206.8	139.4	40.3
3	7	6:47	45	487	1.93	447.0	424.9	48.7
4	11	6:55	45	437	1.66	653.2	118.1	15.3
5	15	6:51	45	648	0.97	476.4	167.3	26.0
6	16	9:12	45	649	0.98	303.3	209.9	40.9
7	20	6:44	45	104	1.82	306.6	49.5	13.9
8	23	19:08	45	380	1.33	355.1	124.0	25.9
9	27	18:09	45	707	1.50	132.8	114.9	46.4
10	29	9:41	45	548	2.01	177.4	239.4	57.4
11	32	18:33	45	608	1.61	38.3	65.8	63.2
12	34	9:54	45	630	1.42	118.5	119.1	50.1
13	39	11:52	45	601	0.95	144.2	642.4	81.7
14	41	17:06	48	599	0.86	154.8	535.2	77.6
15	44	11:18	45	448	1.20	734.0	307.9	29.6
Mean	-	-	45	520	1.46	299.7	235.6	44.0
SE	-	-	0.2	38.9	0.10	52.1	45.3	-

Table 2. Total catch by weight (kg) of rex sole, Dover sole, shortspine thornyhead, longspine thornyhead, and sablefish from tows used to run each non-linear mixed-effects (NLME) model for non-pooled and pooled data. # of tows = numbers of tows used in each NLME model. For the NLME model using non-pooled data, a minimum of 8 individuals of the species in each codend cover and codend was required for inclusion of the tow in the analysis. Total catch values were rounded for inclusion in the table.

Species and nominal codend (mm)	Total catch from non-pooled data			Total catch from pooled data		
	cover	codend	# of tows	cover	codend	# of tows
Rex sole						
114 DM	436	221	13	437	222	15
114 T90	334	389	10	336	393	15
140 T90	468	65	8	488	67	13
Dover sole						
114 DM	1,358	2,184	15	1,358	2,184	15
114 T90	479	3,684	13	485	3,864	15
140 T90	2,482	1,286	11	2,485	1,323	15
Shortspine thornyhead						
114 DM	93	296	12	109	322	14
114 T90	111	514	11	129	563	14
140 T90	121	209	10	157	213	14
Longspine thornyhead						
114 DM	79	3	6	339	26	12
114 T90	97	5	4	361	37	11
140 T90	208	2	3	414	13	11
Sablefish						
114 DM	64	582	6	106	2,027	15
114 T90	89	2,398	7	123	4,285	15
140 T90	445	1,479	13	446	1,494	14

Table 3. ANOVA comparison of the 50% retention length (L_{50}) for rex sole, Dover sole, shortspine thornyhead, longspine thornyhead, and sablefish for each codend tested. For this test each tow included for each species is treated as a data point, rather than the more complex GLMM used for determining L_{50s} and SEs. Tows with at least 8 individuals in each codend cover and codend were included in this analysis. The value beside each species represents the p-value for the ANOVA as a whole, while p-values for each pair of nets represents the result of the Tukey multiple comparison test. NS = not significant (p>0.05); NT = not tested since ANOVA not significant.

Species and nominal codend (mm)	114 mm T90	140 mm T90
Rex sole	p<0.00001	
114 DM	p<0.01	p<0.001
114 T90		p<0.00001
Dover sole	p<0.00001	
114 DM	p<0.0001	p<0.00001
114 T90		p<0.00001
Shortspine thornyhead	p<.00001	
114 DM	NS	p<0.0001
114 T90		p<0.01
Longspine thornyhead	NS	
114 DM	NT	NT
114 T90		NT
Sablefish	p<0.0001	
114 DM	NS	p<0.0001
114 T90		P<0.05

Table 4. The 25, 50, and 75% retention length (L_{25}, L_{50}, L_{75}), and selection range for rex sole, Dover sole, shortspine thornyhead, longspine thornyhead, and sablefish for each codend tested. SR = selection range (L_{75} - L_{25}); # of tows = numbers of tows used in each non-linear mixed-effects (NLME) model for non-pooled data, and for the model using pooled data. For the NLME model using non-pooled data, a minimum of 8 individuals of the species in each codend cover and codend was required for inclusion of the tow in the analysis.

Species and nominal codend (mm)	NLME model using non-pooled data					Model using pooled data		
	L_{25}	L_{50} (SE)	L_{75}	SR (SE)	# of tows	L_{50}	SR	# of tows
Rex sole								
114 DM	32.04	34.36 (0.38)	36.69	4.65 (0.49)	13	34.07	4.58	15
114 T90	30.06	31.86 (0.21)	33.66	3.60 (0.47)	10	31.77	4.22	15
140 T90	36.00	38.63 (0.40)	41.26	5.26 (0.64)	8	38.41	4.90	13
Dover sole								
114 DM	32.21	35.53 (0.31)	38.84	6.64 (0.94)	15	35.96	6.26	15
114 T90	30.34	32.15 (0.21)	33.96	3.63 (0.26)	13	32.26	3.87	15
140 T90	37.32	38.97 (0.31)	40.61	3.29 (0.10)	11	39.09	3.37	15
Shortspine thornyhead								
114 DM	25.74	28.77 (0.37)	31.80	6.06 (0.74)	12	29.07	5.94	14
114 T90	27.16	29.97 (0.45)	32.78	5.62 (0.45)	11	30.34	5.88	14
140 T90	31.37	35.06 (0.75)	38.75	7.38 (0.67)	10	35.58	7.57	14
Longspine thornyhead								
114 DM	27.67	30.42 (0.90)	33.18	5.51 (0.97)	6	31.91	6.55	12
114 T90	29.13	32.11 (1.99)	37.07	7.94 (1.14)	4	32.83	7.83	11
140 T90	30.14	33.01 (1.45)	35.90	5.75 (1.06)	3	31.93	4.48	11
Sablefish								
114 DM	31.18	37.93 (4.94)	44.67	13.49 (5.46)	6	37.14	12.10	15
114 T90	42.09	44.80 (2.27)	47.52	5.43 (1.73)	7	43.65	5.66	15
140 T90	44.90	49.93 (0.84)	54.98	10.08 (1.47)	13	49.60	9.33	14

Table 5. Percent retention by weight of marketable- and unmarketable-sized rex sole, Dover sole, shortspine thornyhead (SSTH), longspine thornyhead (LSTH), and sablefish by each codend tested. The minimum market size when this study was conducted was 31.8 cm for rex sole, 33 cm for Dover sole, and 21.6 cm for SSTH and LSTH. n/a = sablefish did not have a minimum market size; DM = diamond mesh. Total catch values were rounded for inclusion in the table.

	Total catch (kg)			% Retained in the codend that encountered the trawl	
Species and nominal codend (mm)	cover	codend	% retention	marketable-sized fish	unmarketable-sized fish
Rex sole					
114 DM	437	222	33.7	50.7	12.8
114 T90	336	393	53.9	77.4	22.6
140 T90	488	67	12.1	19.4	3.2
Dover sole					
114 DM	1,358	2,184	61.7	66.7	18.0
114 T90	485	3,864	88.8	92.8	43.7
140 T90	2,485	1,323	34.7	41.3	2.1
Shortspine thornyhead					
114 DM	109	322	74.7	77.1	18.6
114 T90	129	563	81.4	83.2	46.5
140 T90	157	213	57.6	61.4	0.0
Longspine thornyhead					
114 DM	339	26	7.1	9.1	3.1
114 T90	361	37	9.3	10.6	5.6
140 T90	414	13	3.0	3.2	1.6
Sablefish					
114 DM	106	2,027	95.0	95.0	n/a
114 T90	123	4,285	97.2	97.2	n/a
140 T90	446	1,494	77.0	77.0	n/a

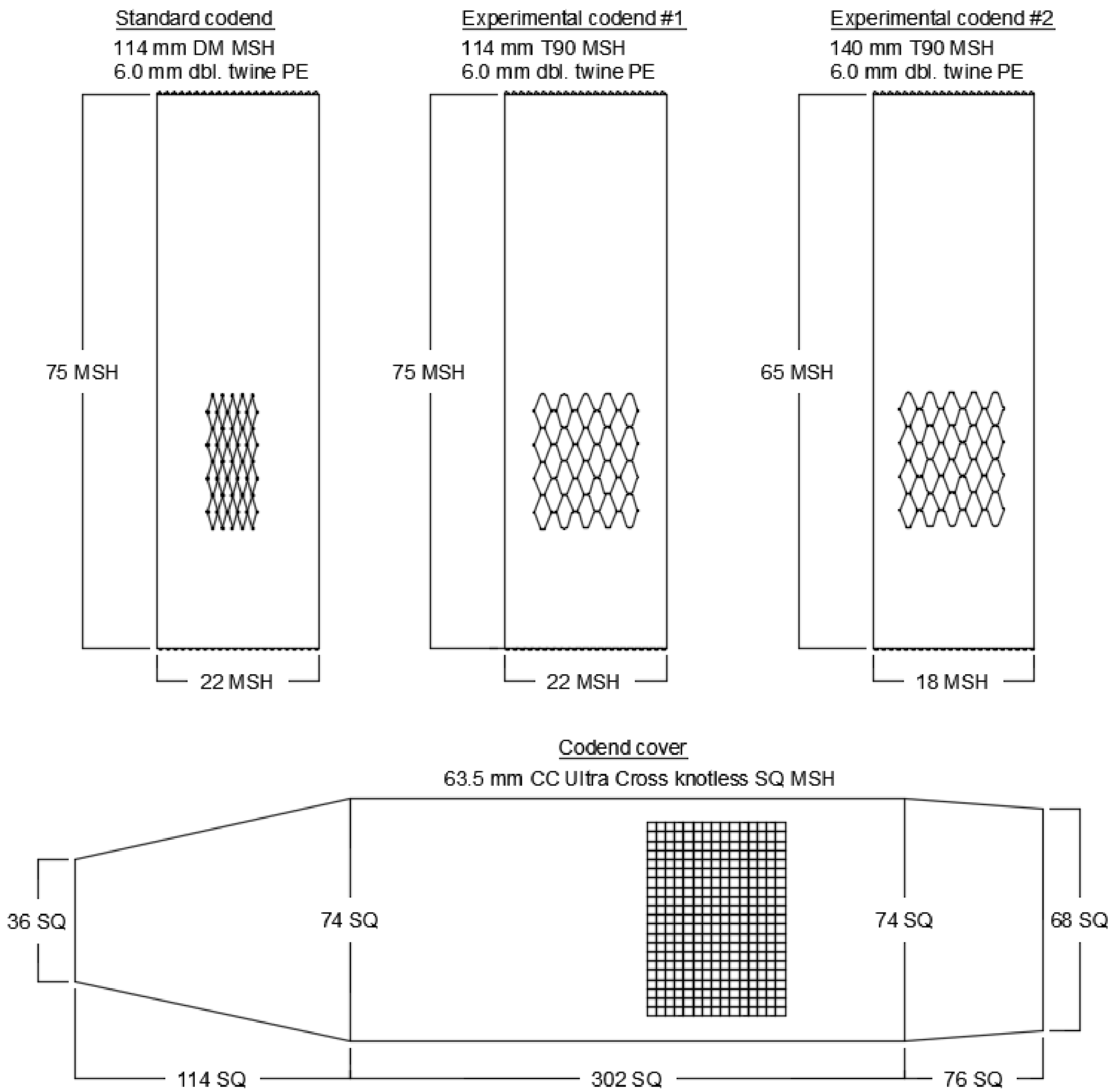

Figure 1. Schematic diagram depicting a top panel view of the codends tested and codend cover. Diamond and T90 mesh sizes are nominal stretched measurements between-knots. DM = diamond mesh; MSH = mesh; dbl. = double twine; PE = polyethylene; CC = center-to-center mesh measurement; SQ = square. Note: diagram is not drawn to scale.

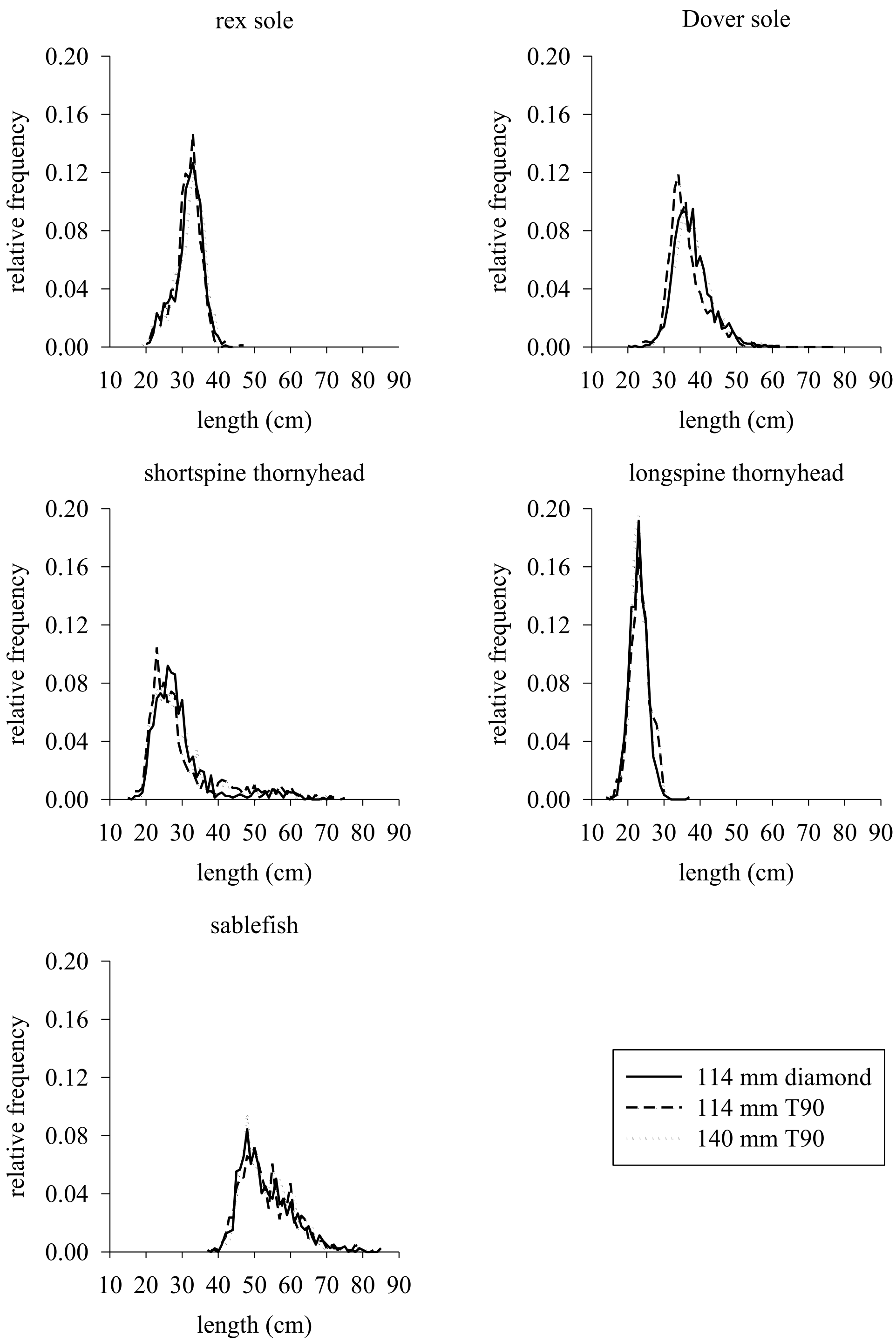

Figure 2. Length frequency distribution of rex sole, Dover sole, shortspine thornyhead, longspine thornyhead, and sablefish that encountered the codends tested (i.e., lengths from fish in the codend cover and the codend combined)

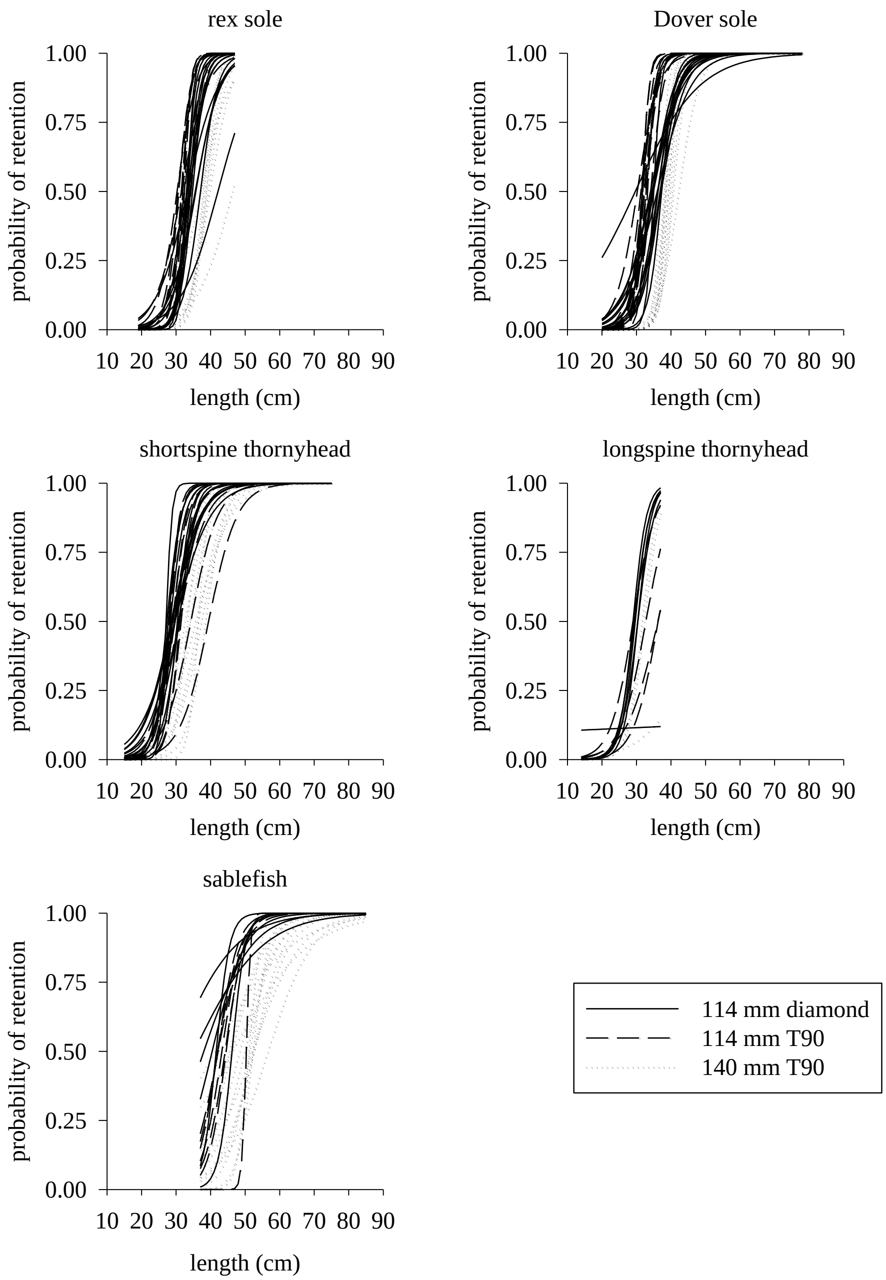

Figure 3. Selectivity curves for the three codends tested for the five groundfish species analyzed. Only tows with at least 8 individuals in each codend cover and codend were included to produce these selectivity curves.

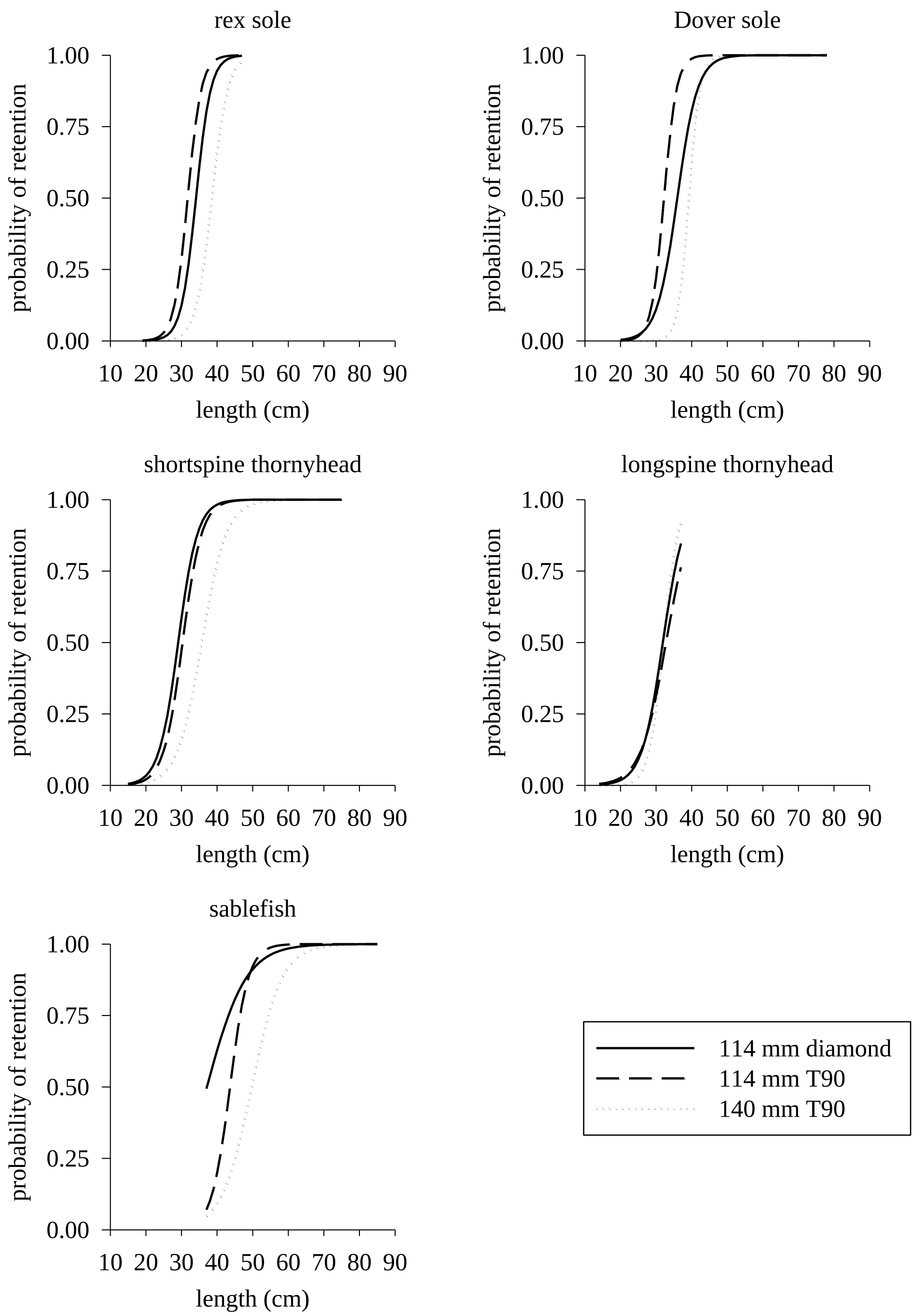

Figure 4. Fishery selectivity curves for the three codends tested for the five groundfish species analyzed (based on the pooled data analyses in Table 4).

Appendix A

The length-to-weight relationships used for all species in this study were based upon data collected in 2012 on the Northwest Fisheries Science Center's West Coast Bottom Trawl Survey of groundfish resources. The survey and associated data collection protocols are described in Bradburn et al. (2011). The length-weight relationships are all of the form:

$$W = aL^b$$

where W is weight in kg and L is length in cm. Males and females were combined for this analysis, and there was little difference in the length-weight relationship between the sexes for any of the species considered here when they were estimated independently. The parameters a and b are estimated via linear regression in log space, and are reported in Table A-1.

Table A-1. Estimated length-to-weight conversion parameters from data collected in the West Coast Bottom Trawl Survey of groundfish resources. The R-squared column reports those of the regressions in log-space.

Species	a	b	R-squared	Sample size
Rex sole	3.080 E-06	3.206	0.953	833
Dover sole	3.138 E-06	3.316	0.981	1,097
Shortspine thornyhead	5.038 E-06	3.251	0.992	1,159
Longspine thornyhead	8.199 E-06	3.120	0.943	910
Sablefish	3.193 E-06	3.279	0.985	2,308