Modifying a pelagic trawl to better retain small Arctic fishes

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ABSTRACT

Pelagic trawls are one of the primary methods of sampling midwater fishes. However, these trawls are species- and size-selective, and small fish can escape through trawl meshes. This can introduce uncertainty and bias into survey abundance estimates if not accounted for. The small, abundant pelagic fishes of the Alaska Arctic are challenging to sample with trawls as they are sufficiently motile to avoid small fine-mesh trawls but are also small enough to escape through the meshes of trawls designed to capture larger fishes. A pelagic herring trawl equipped with a fine-mesh codend liner was used to quantify the size and species composition of pelagic fishes during a baseline acoustic-trawl survey of the Chukchi Shelf. Subsequent experiments with recapture nets attached to the outside of the trawl netting suggested that escapement of small fishes was substantial, particularly in the aft net section. Thus, the trawl was further modified by reducing the taper in the aft net section and adding a small-mesh section in front of the codend to potentially reduce escapement. Further use of recapture nets during two subsequent acoustic-trawl surveys confirmed that this trawl modification substantially increased retention of small fishes and resulted in less size selectivity. These improvements will reduce biases in estimates of abundance, size, and species composition of pelagic Arctic fishes. This work highlights the importance of quantifying escapement from survey trawls and demonstrates that escapement estimates can guide successful trawl modifications.

1. Introduction

Pelagic trawls derived from designs used in commercial fishing are widely used to sample midwater fishes in pelagic and acoustic-trawl surveys. These trawls rely on fish reactions to the netting to capture fishes, as most meshes are much larger than the fish. Pelagic trawls typically gradually decrease in diameter and mesh size from the trawl mouth, leading to a long intermediate section followed by a small-mesh codend. Most meshes in the forward and intermediate sections of a trawl are large enough to allow fish to escape. However, fish are reluctant to pass through these larger meshes, and instead orient themselves parallel to the netting (referred to as 'herding', see Glass et al., 1993). The herded fish swim parallel to the direction the trawl is towed and become increasingly concentrated as they tire and fall back towards the smaller diameter codend where they are retained in smaller meshes (Olla et al., 1997; Kennelly and Broadhurst, 2021). The graduated mesh and gradual narrowing (taper) of this trawl design reduces drag so larger nets can be towed on a given vessel, increasing catch rates. However, if behavioral reactions to the trawl or swimming abilities are species- and size-specific (He, 1993), the catch composition will not be representative of the fish entering the trawl. Fish behaviors have been extensively exploited to reduce commercial catches of unwanted species and/or size classes (Kennelly and Broadhurst, 2002). Overall, trawl gear for commercial fishing is designed to maximize the catch rates of target species while reducing the proportion of unwanted species and/or size classes in the catch.

The requirements for research survey trawls differ from those of commercial fish trawls. Ideally, a survey trawl should be unselective, capturing all species and size classes with equal efficiency. Unfortunately, this rarely if ever, occurs in practice, so a more attainable aim is to design trawls that capture all species and sizes of interest at relatively high and constant efficiencies. Trawl catches can then be corrected for species/size selectivity if these average size- and species-dependent probabilities of capture (i.e. selectivity) are known (Bethke et al., 1999; Kotwicki et al., 2017). If species and size selectivity are known without error, these corrections would fully account for trawl selectivity. In practice, selectivity corrections are uncertain (Williams et al., 2011; De Robertis et al., 2017a). Thus, designing survey trawl gear with high catch rates is important: when the probability of retention is high, the absolute correction for selectivity will be smaller, and uncertainties in the correction will result in smaller biases in the catch estimates.

While there has been substantial effort to increase the selectivity of trawls to reduce unwanted bycatch (Kennelly and Broadhurst, 2021), comparatively little work has been conducted to design less selective pelagic trawls for research surveys or to quantify the selectivity of these survey trawls. Pelagic trawls designed for commercial fishing are regularly used as survey trawls (Bethke et al., 1999; Williams et al., 2011). Fishes that escape from pelagic trawls are generally smaller than those retained (Matsushita et al., 1993; Suuronen et al., 1997) and a small-mesh liner is often added to the codend of survey trawls to improve retention of smaller fishes (Simmonds et al., 1992). This is a pragmatic first step as selection in the codend is often high (Matsushita et al., 1993; Wileman et al., 1996; Kennelly and Broadhurst, 2021). However, this does not address escapement from the meshes forward of the codend, which can be substantial, particularly for smaller organisms large enough to be retained in the codend but not the rest of the trawl (Williams et al., 2011; Herrmann et al., 2018).

Although trawl selectivity can be investigated via gear comparisons (Kotwicki et al., 2017), acoustic and optical imaging (Williams et al., 2013; Underwood et al., 2020), or small-mesh recapture nets to capture fishes escaping through the trawl meshes (Matsushita et al., 1993; Skúvadal et al., 2011), the selectivity of most survey trawls is unknown. In many applications, it is implicitly assumed that all species and size classes are equally likely to be retained by the survey trawl (Simmonds et al., 1992). While this assumption is sometimes acceptable, it is tenuous in other situations, such as in areas of mixed species and size aggregations. Quantifying trawl selectivity allows selectivity corrections to be incorporated into abundance estimates, thereby reducing a major source of uncertainty (Williams et al., 2013, Kotwicki et al., 2017).

Selectivity corrections are particularly desirable in the context of acoustic-trawl surveys as species and size compositions derived from trawl sampling are used in combination with scattering models to convert acoustic backscatter into animal densities (Simmonds and MacLennan, 2005). In acoustic surveys, trawl sampling is used to estimate the proportion of acoustic backscatter attributable to a given species and size class. In this application, the abundance of all species and size classes are inter-related. For example, if the proportion of one species or size class is under-estimated relative to other organisms, its abundance will be under-estimated. This will lead to an over-estimate of all other species and size classes present as they now represent a higher proportion of the observed backscatter (McClatchie and Coombs, 2005; De Robertis et al., 2017b). Therefore, selectivity corrections are desirable for acoustic-trawl surveys as errors in species or size composition introduced by trawl selectivity influence the abundance estimates of all organisms.

The Pacific Arctic, which was sampled as part of the Arctic Integrated Ecosystem Research Program (AIERP, Baker et al., 2020; in review), presents a challenging case in terms of the potential for biases to be introduced by trawl selectivity. The dominant pelagic fishes are small (~5 cm), and it is highly probable that they will be poorly retained in large-mesh trawls. However, they are also sufficiently mobile to avoid smaller fine-mesh nets designed for larval fishes and invertebrates (Kwong et al., 2018). Acoustic-trawl surveys of the Chukchi Sea required the ability to sample both large and small fishes, and a large Cantrawl pelagic trawl was used in an initial baseline survey (De Robertis et al., 2017b). A smaller Marinovich herring trawl was introduced in a subsequent survey after it became clear that small fishes likely to escape from the Cantrawl trawl dominated this Arctic pelagic fish community. The Marinovich trawl was equipped with a small-mesh codend liner in an effort to better retain small fishes (De Robertis et al., 2017a; 2021. Although the Marinovich trawl captured pelagic fishes in the Chukchi Sea more efficiently than the larger Cantrawl trawl, experiments with recapture nets indicated that escapement and size-selectivity remained high, particularly in the aft area of the trawl (De Robertis et al., 2017a; see De Robertis et al., 2021for a corrigendum). Specifically, the Marinovich trawl was selective in the size range of most pelagic fishes in this Arctic region. For example, only ~23% of 4 cm Arctic cod (*Boreogadus saida*), the most common species and size class in this environment, were retained. Retention of Arctic cod was highly size-dependent: ~10% at 3 cm and

~45% at 5 cm. Given the relatively low catch efficiency and substantial size selectivity of the trawl, the aft section of the trawl where escapement was highest was lengthened and smaller meshes were added forward of the codend for use during the AIERP program in an effort to improve retention of all small fish species and to reduce the trawl size-selectivity. This study thus has two aims: 1) establish size-dependent selectivity curves for abundant fish species to correct the retained catch for escapement to reduce uncertainty in fish abundance estimates (Baker et al., 2022; Levine et al., in review), and 2) evaluate whether the Marinovich trawl modifications increased the catch rates of small fishes present in this Arctic region.

2. Materials and methods

2.1. Trawl modification

The trawl used in previous surveys of the Chukchi Shelf in 2013 (De Robertis et al., 2017b) is a symmetrical 4-seam Marinovich herring box trawl constructed of diamond (T0) meshes (Fig. 1a). This trawl (hereafter referred to as the mod-1 trawl) was modified from the original design by fitting the codend with a 2 by 3 mm oval mesh liner to improve retention of small organisms and enlarging the wings to allow it to be fished with oversized doors as this project required fishing both this trawl and a larger pelagic trawl without swapping trawl doors (De Robertis et al., 2017b).

The trawl was further modified (Fig. 1b) to better retain the small fishes abundant in the study area (this version of the trawl is hereafter referred to as the mod-2 trawl). The aim was to increase capture rates of small fishes to reduce the uncertainties in estimates of the abundance, size, and species composition of pelagic fishes. Given that escapement was substantially higher in the aft area of the net, we focused on this part of the trawl.

The modifications consisted of replacing the 3.8 cm mesh panel immediately forward of the codend with two new panels after reviewing the recapture net results and consulting with trawl manufacturers and commercial fishers. One panel was redesigned with the same mesh (3.8 cm T0 meshes) but with a more gradual taper (Fig. 1b). A second panel of 1.9 cm T0 meshes was added immediately aft of the first new section, increasing the overall length of the mod-2 trawl by 249 1.9 cm meshes (Fig. 1b). The codend and 26.5 of the 1.9 cm meshes of the second new panel were lined with 2 by 3 mm oval mesh placed inside the netting (see grey shading forward of the codend in Fig. 1b). These modifications resulted in a more gradual taper towards the rear of the net and reduced the mesh size in the area immediately forward of the lined codend where escapement was greatest (De Robertis et al., 2021). Hereafter, the two forward panels of the mod-2 trawl are referred to jointly as the forward section, the two middle panels are referred to as the middle section, and the new small-mesh panel as the aft section (Fig. 1b).

2.2. Recapture nets

The mod-1 and mod-2 trawls were fitted with small-mesh recapture nets designed to quantify the degree to which fish escape through the mesh panels of the trawl (Nakashima, 1990; Williams et al., 2011). The recapture nets were constructed with the same 2 by 3 mm oval mesh material as the codend liner. They were designed with a diamond-shaped mouth equivalent to a 2.4 m stretched diamond mesh, a 2.6 m long tapered body, and codend (see De Robertis et al., 2021, their Fig. S1.2 for details). The recapture nets were dyed black to reduce visibility and permanently attached to the trawl netting on the outside of the trawl.

The mod-1 trawl was fitted with eight recapture nets: one in the forward section and one in the aft section on each of the four sides of the trawl (i.e. top, bottom, port and starboard). The recapture nets were placed at the center of each section (i.e. same number of meshes in front of and behind the recapture net, Fig. 1a). The number of meshes covered by the recapture nets was counted, and the proportion of the area covered by the recapture net was computed (see De Robertis et al., 2021, their section

S2). The recapture nets covered 6.5% of the area in the front section and 13.2% of the area in the aft section.

The mod-2 trawl was fitted with nine recapture nets in the center of the forward, middle, and aft sections of the net (Fig. 1). Recapture nets were mounted on the top, bottom, and starboard sides. To reduce the effort required to process the catch, we did not mount nets on the port side and assumed equal escapement from the port and starboard sides of the net. The recapture nets covered 6.5% of mesh area in the front section, 12.7% of mesh area in the middle section, and 30.5% of the unlined mesh area in the aft section.

2.3. Field sampling

The mod-1 trawl equipped with recapture nets was used in 30 hauls as part of a daytime acoustic-trawl survey of the continental shelf of the U.S. Chukchi Sea in summer (August-September) of 2013. These deployments are described elsewhere (De Robertis et al., 2017a), but results are included here as a reference to judge the effectiveness of the subsequent modifications made to the mod-2 trawl.

The mod-2 trawl equipped with recapture nets was used in summer (August-September) acoustic-trawl surveys in 2017 and 2019, which sampled the same area as the previous survey with the mod-1 trawl (Fig. 2). The mod-2 trawl was fished with Nor'Eastern Trawl Systems 3 m^2 Series 2000 doors, synthetic rigging with 55 m long bridles, and 170 kg weights on each wingtip. A Simrad FS70 3rd wire trawl sonar was mounted on the headrope to monitor trawl geometry and fish entering the net. A total of 75 hauls with the mod-2 trawl (Fig. 2, n = 32 in 2017, n = 43 in 2019) were conducted during daytime as part of an acoustic-trawl survey (Levine et al., in review). Most trawls were shallow (average depth of 31.7 ± 32.3 m (mean ± SD), range 11.6 - 228.8 m), with 95% of hauls < 40.2 m. The trawl was fished at 1.2 ± 0.2 m s^{-1}, and exhibited a vertical mouth opening of 7.8 ± 0.9 m and a horizontal opening of 7.5 ± 0.6 m while fishing.

2.4. Biological sampling

Catches in the codend and the recapture nets were weighed, subsampled if large, sorted to species, and enumerated. The lengths of individuals in the codend (up to 60 for gadids and 20 for other species) and in each recapture net (up to 20) were measured to the nearest millimeter using an electronic measuring board (Towler and Williams, 2010). Fork length was measured for all species other than gadids and Arctic sand lance (*Ammodytes hexapterus*). Gadid lengths were not measured consistently across years: in 2013, fork length was measured, in 2017, total length was measured, and in 2019, standard length was measured. These measurements were converted to standard length using species-specific linear regressions (see Levine et al., in review, their appendix A) for further analysis. Sand lance were measured as standard length in 2013 and fork length in 2017 and 2019. Sand lance standard lengths were converted to fork length by multiplying by 1.065 (Frose and Pauly, 2021).

Small gadids [particularly age-0 Arctic cod, and walleye pollock (*Gadus chalcogrammus*)] could not be reliably distinguished at sea based on external morphology (Wildes et al., 2022). Thus, species for juvenile gadids in 2017/2019 were assigned probabilistically based on size-dependent genetic sampling of the catch (see Levine et al., in review, their appendix B). In 2013, pollock were almost absent, and saffron cod (*Eleginus gracilis*), which are easier to distinguish at this size, were spatially distinct from Arctic cod (De Robertis et al., 2017b). The identifications of juvenile gadids in the 2013 survey are thus believed to be generally reliable (Wildes et al.,2022; Levine et al., in review).

2.5. Estimation of trawl selectivity

The most abundant fishes in the catch, Arctic cod, saffron cod, walleye pollock, capelin (*Mallotus catervarius*), Arctic sand lance, (see Levine et al., in review, their figure 2a-b), were aggregated by species for analysis. In addition, a grouping for ‘other fishes’ (i.e. all other fishes pooled) was defined. In the mod-1 trawl hauls catches of ‘other fishes’ were dominated by pricklebacks (*Stichaeidae*, 40%), sculpins (*Cottidae*, 33.3%), and snailfishes (*Liparidae*, 13.5%). In the mod-2 trawl hauls, catches of ‘other fishes’ were dominated by pricklebacks (41.9%), sculpins (16.3%), and Pacific herring (16.2%). A selectivity relationship was fitted to the ‘other fishes’ complex as an approximate selectivity relationship is required to correct the size and species composition of low-abundance species encountered in the acoustic-trawl survey (Levine et al., in review). However, given the differences in species and size composition, the selectivity of the ‘other fishes’ group should not be compared directly between the mod-1 and mod-2 trawl designs. For each species grouping listed above, hauls in which >10 individuals were measured were used for further analyses.

Each specimen (i.e. a measured fish) was associated with a scaling factor indicating the total number of individuals that fish represents in the total catch if in the codend, or the total number of fish escaping from the trawl meshes if in the recapture nets. The scaling factor *W* for each measured individual *i* in the catch is defined as

$$W_{i,s,j} = \frac{1}{p_{i,j,s}} \cdot \frac{1}{c_j}, \quad (1)$$

where $p_{i,j,s}$ is the proportion of individuals of species *s* in captured in trawl location *j* (referring to the codend or recapture net location) that were measured, and c_j is the proportion of the area in location *j* covered by the recapture nets or codend liner. In the case of the mod-1 trawl, c_j = 0.065 for the front recapture nets and 0.132 for the aft recapture nets. In the case of the mod-2 trawl, in the top and bottom sides of the trawl, c_j was 0.065 for the front recapture nets, 0.127 for the middle recapture nets, and 0.305 for the aft recapture nets. Given that only the starboard side of the net was fitted with recapture nets, escapement was assumed to be equivalent from both sides. Escapement from both the port and starboard sides was approximated from the catch on the starboard side by fixing c_j to account for the fraction of meshes on both sides of the trawl covered by the starboard recapture nets (front = 0.033, middle = 0.064, aft = 0.152). The codend was fully covered by the 2 by 3 mm oval mesh, thus c_j = 1 for both trawls.

The total number of fish of species *s* escaping from the trawl (E_s) can be determined by summing the scaling factors for all fish measured from the recapture nets

$$E_s = \sum_i \left(W_{i,s,j=recapture\ net}\right). \quad (2)$$

Likewise, the total number of fish retained in the codend (R_s) is estimated as

$$R_s = \sum_i \left(W_{i,s,j=codend}\right). \quad (3)$$

2.6. Selectivity estimates

Selectivity was treated as a binomial process, where a fish entering the net is either retained in the codend or escapes through the meshes. A logistic curve was used to model this as a length-dependent process. To estimate the parameters of the logistic curve, a generalized linear model was fitted (Millar and Fryer, 1999) where the dependent binomial data are logit transformed into a linear variable and two linear coefficients are estimated (i.e. the slope *a* and intercept *b*).

The selectivity, as a function of length, *l,* is described as

$$S(l) = \frac{\exp(a+bl)}{1+\exp(a+bl)}, \quad (4)$$

where *S(l)* represents the length-dependent probability of being caught in the codend.

These coefficients can be re-defined (Williams et al., 2011) in terms of the length at which 50% of the fish are retained (L_{50} = -(*a*/*b*)), and the selection range (*SR* = (2 $\log_e$(3))/*b* which represents the length range between 25% and 75% retention). A length-dependent logistic function was parametrized from L_{50} and *SR* as

$$S(l) = (1 + \exp^{(\frac{k(L_{50}-l)}{SR})})^{-1}, \quad (5)$$

where *l* is length in cm and *k* = 2 $\log_e$(3) (Millar, 1993).

2.7. Bootstrap estimates of confidence intervals

Uncertainty in the fitted selectivity relationships was estimated using a 2-stage bootstrap approach (Millar, 1993; Kotwicki et al., 2017). The approach considered uncertainty in both the haul catches (between-haul variation) and fish specimen lengths (within-haul variation). Between-haul variation was simulated by selecting *n* hauls with replacement from the *n* hauls used to fit equation 4 for each species. Within-haul variation was simulated by randomly selecting (with replacement) the same number of fish measured in the codend and the recapture nets as in the original haul from the measured individuals. The approach mimics the sampling of individual fishes in the catch by separately sampling the escapees captured in the resample nets and the retained fish in the codend. The probability of selecting a given measured specimen, *i* was equivalent to its contribution to the proportion of the fish retained in or escaping from the net (i.e., W_i). Given that the total number of escaped fish depends on the expansion factors of randomly drawn fish, which differ among the recapture nets, the total number of escapees varies between bootstrap replicates in a haul.

Selectivity curves for each of 5000 bootstrap replicates were computed following equations 1-4. The approximate 95% confidence intervals were computed for each size class were estimated by computing the 2.5% and 97.5% percentiles of the selectivity curves at that length. Confidence intervals for other descriptive parameters of interest (e.g. the proportion of fish or sizes of fish escaping from a given area of the net) were computed in an analogous fashion from the bootstrapped data sets.

3. Results

Similar species were captured in the mod-1 and mod-2 trawl deployments. However, pollock were much more abundant in the mod-2 trawl catches, and Arctic sand lance and saffron cod represented a larger proportion of the catch in the mod-1 trawl hauls (Fig. 3). Given the time differences (≥ 4 years) between sampling, the differences in species composition between trawls primarily reflect temporal changes in species composition in the study area (Baker et al., 2022, Levine et al., in review). Small fishes continued to be abundant in the study area, and large numbers were captured in the codend and recapture nets during the mod-2 trawl deployments (Table 1). For example, 355,390 Arctic cod were captured in the codend, 7596 in the recapture nets, and 6386 Arctic cod were measured.

The recapture net catches indicated that a consistently higher proportion of fishes entering the trawl mouth were retained in the codend of the mod-2 trawl than previously observed with the mod-1 trawl (Fig. 4a). Escapees tended to be smaller than retained fish for both trawls (Table1, Fig. 4b), and the ratios of mean size for retained and escaped fish were similar for the mod-1 and mod-2 trawls (Fig. 4b). The mod-2 trawl exhibited lower and more uniform escapement from the top, side, and bottom of the trawl, and forward, middle, and aft sections of the trawl than the mod-1 trawl (Fig. 5). The mod-2 trawl exhibited less escapement from the aft section of the trawl than the mod-1 trawl, (Fig. 5, right panels). As the aft section of the mod-1 trawl was converted into the middle and aft sections of the mod-2 trawl (Fig. 1), it is informative to note that the combined escapement in the middle and aft sections of the mod-2 trawl was less than the escapement in the equivalent aft section of the mod-1 trawl (Fig. 5, panels on right side). Escapement was highest in the middle section of the mod-2 trawl, and escapement was low in the new aft section of the mod-2 trawl (Fig. 5), likely due to the gradual taper and small meshes (Fig. 1). Although the retained fish tended to be larger than the escapees, escapees in the top/side/bottom and the forward/middle/aft areas of the trawl were generally of consistent size (Fig. 6). Taken together, this indicates that the modification to the aft section of the mod-2 trawl reduced escapement, and that escapement no longer disproportionately occurred in a particular area of the mod-2 trawl.

For all species and length classes, a higher proportion of fish were retained in the mod-2 trawl than the mod-1 trawl (Fig. 7, compare the proportion of bars that are light grey in the histograms). The fitted selectivity curves demonstrate that the estimated probability of retention increased with length for all species, particularly for the smallest size classes (Fig. 7). Retention of Arctic cod, capelin, and Arctic sand lance was substantially higher for mod-2 than mod-1 for all size classes (Fig. 7, Table 2). The modifications also reduced size selectivity: this can be visualized by comparing the probability of capturing a large and small individual of each species. For example, the fitted selectivity curves in Fig. 7a indicate that a 5 cm Arctic cod was 5.2 times more likely to be retained than a 3 cm Arctic cod in the mod-1 trawl (i.e. a selectivity ratio of 0.47/0.09), but only 1.3 times more likely to be retained (0.91/0.71) in the mod-2 trawl. This indicates that the mod-2 trawl exhibited both higher capture rates and lower size selectivity. Uncertainty in the fitted selectivity relationships was lowest for more abundant species and size classes (Fig. 7). For example, the bootstrapped 95% confidence estimates of the selectivity curve for saffron cod for the mod-2 trawl were broad (Fig. 7b) as only six hauls with sufficient catch were available for analysis (Table 2). Similarly, few capelin were captured in the mod-2 recapture nets, and some bootstrap realizations led to predictions that larger fish were less likely to be retained than smaller ones (Fig. 7d). Overall, the differences in selectivity across species for mod-2 trawl were similar to those for the mod-1 trawl. Arctic sand lance were less likely to be retained than other species at a given size (likely due to their elongated morphology), as were saffron cod.

4. Discussion

A higher proportion of fish entering the trawl were retained in the codend of the mod-2 trawl compared to previous sampling with the mod-1 trawl. This indicates that, as intended, the modification of the aft section of the mod-2 trawl substantially decreased escapement of small Arctic fishes. Escapement observed in the recapture nets was lower and no longer occurred disproportionately in a single area of the mod-2 trawl, indicating that further alteration of a limited area of the mod-2 trawl is unlikely to produce a substantial benefit. The mod-2 trawl also exhibited less size selectivity over the size range of fishes encountered. The increased capture rates and lower size selectivity of the mod-2 trawl will reduce biases in estimates of abundance, size and species composition (Williams et al., 2011). The selectivity relationships derived from these data were applied to trawl catches of Arctic sand lance (Baker et al., 2022) and used to correct an acoustic-trawl survey for the size- and species-specific probability of escapement from the trawl (Levine et al., in review). Applying these selectivity relationships avoids the assumption that all organisms and size classes are captured with equal efficiency, reducing biases in the abundance estimates (Williams et al., 2011; De Robertis et al., 2017b).

The mod-2 trawl was modified to exhibit a more gradual taper in the aft areas of the net and a small-mesh panel was added in front of the codend (Fig. 1). The changes were motivated by previous work with recapture nets indicating that escapement in the aft part of the mod-1 trawl was high (De Robertis et al., 2017a; 2022). The additional modifications successfully decreased escapement in the aft area of the net compared to the mod-1 trawl (Fig. 5). Escapement of small fishes often increases in the aft trawl sections (Matsushita et al., 1993; Williams et al., 2011; Kennelly and Broadhurst, 2021), likely due to increased interaction with the netting due to increased concentration of organisms as the net reduces in diameter and decreased flow rates near the codend.

Commercial pelagic trawls have generally been designed to exploit the behaviors of large fishes and are unlikely to be optimized to capture smaller individuals. Small fishes have limited swimming abilities and are likely to exhibit different behavioral responses during the capture process (He, 1993; Kwong et al., 2018). For example, a 5 cm fish would have to swim at 24 body lengths s^{-1} to keep pace with the forward progress of the trawl, which is well above its burst swimming capability (He, 1993). In this context, one should recognize that the modifications to the mod-2 trawl share common elements with commercial krill trawls, which are designed to capture small animals with relatively limited swimming capabilities. Krill trawls are long, comprised of small meshes, and have small mouth openings compared to pelagic trawls designed to capture large fishes (Herrmann et al., 2018). In addition, the gradual reduction in diameter (i.e. low taper) results in krill encountering meshes with a relatively low angle of attack, reducing escapement when they encounter the meshes (Krag et al., 2014). We did not directly observe the interaction of fish with the mod-1 and mod-2 trawl during the hauls. However we surmise that this may be an analogous situation as the reduced swimming speed and endurance of small fishes means that they are more likely to contact the netting than larger fishes as the speed of the net through the water may exceed their capability to maintain position and orientation relative to the netting (He, 1993, Olla et al., 1997). The combined effects of encountering trawl meshes at lower angles due to the more gradual taper and the presence of smaller meshes in the aft portion of the net where the small fishes are more likely to encounter the netting likely contributed to the higher catch rates of the mod-2 trawl.

The selectivity of the pelagic trawls used in many survey applications is unknown. One reason for this is that field experiments to estimate selectivity are time consuming and expensive (Kotwicki et al., 2017). A practical advantage of the recapture net approach (Matsushita et al., 1993; Williams et al., 2011) employed here is that the trawling was conducted during a survey (De Robertis et al., 2017b; Levine et al., in review) and thus did not require dedicated vessel time. This approach allowed a relatively large sample size (number of hauls and individuals captured) to be collected at minimal cost. Another benefit of conducting the recapture net study during a survey is that the trawls were conducted at the size and species compositions relevant to that survey. Furthermore, environmental conditions potentially influencing the capture process (e.g. temperature and light level: He, 1993; Ryer and Olla, 2000) will also be representative of those encountered during a survey.

It is also important to recognize the limitations of the recapture net method. The recapture net method allows one to quantify the probability that a fish entering the trawl will be retained in the codend (i.e. mesh selection). Although selection within the body of the trawl is an important source of trawl selectivity (Nakashima, 1990; Williams et al., 2011), recapture nets do not address the probability that a fish within the trawl path will enter the trawl opening. In other words, the approach does not account for reactions to the vessel or the trawl gear affecting the probability that the fish will enter the trawl (Handegard and Tjøstheim, 2005; Kaartvedt et al., 2012). The magnitude of these reactions can be established by comparing trawl catches to other measurements of abundance such as acoustic observations (Handegard and Tjøstheim, 2005; Somerton et al., 2011; Underwood et al., 2020). While these factors have not been characterized for Arctic fishes, small fishes may be less likely to avoid the net or be herded into the net due to their limited swimming ability (He, 1993).

When selectivity is quantified using modified gear such as the recapture nets, the resulting selectivity may not be representative of the unmodified gear (Kotwicki et al., 2017). This is less of a concern in our case, as the recapture nets are permanently mounted for the duration of the survey and are considered integral to the trawl (i.e. the recapture nets will be used on future surveys). However, the recapture nets were mounted in the center of trawl sections, and the observed escapement in the recapture nets was assumed to be representative of escapement in the other uncovered meshes. The presence of recapture nets on the exterior of the trawl may affect flow patterns near covered meshes that may influence the rate of escapement. Although we did not evaluate whether the recapture nets affected the capture process, previous observations with cameras have indicated that recapture nets of similar design do not appreciably distort the shape of pelagic trawls or alter fish behavior compared to uncovered meshes (Matsushita et al., 1993; Williams et al., 2011). Methods to better characterize escape reactions occurring before fish enter the trawl mouth and potential biases related to sampling with recapture nets (e.g. whether fish behavior or flow patterns differing in meshes covered by recapture nets) remain important areas for further work. While these potential biases are certainly important limitations, our view is that they should not deter future use of recapture nets for survey applications until better or more comprehensive methods to characterize trawl selectivity become available. There are few viable alternatives to the use of recapture nets which provide a practical approach to better understand mesh selection during the trawl capture process, which is too-often ignored in abundance surveys.

One benefit of a using a moderately large pelagic trawl to sample small fishes is that the gear can also capture large fishes if they are present. During initial testing of the mod-2 trawl in the eastern Bering Sea, adult pollock up to 61 cm in length were captured (Honkalehto and McCarthy, 2015). The ability to detect the presence of large fish is important in rapidly changing environments such as the Alaska Arctic. For example, there is potential for adult gadids to colonize the Chukchi Sea from the south as the environment warms, as has happened in the Northern Bering Sea (Stevenson and Lauth, 2019). The lack of adult gadids in the mod-2 trawl catches described here provides evidence that pelagic adult gadids were not abundant during the 2017 and 2019 AIERP program surveys (Levine et al., in review).

Trawls with both known and high capture probabilities are desirable as these characteristics lead to more accurate estimates of species composition, organism abundance, and size distribution. In the application of Arctic acoustic-trawl surveys examined here, size and species selectivity have been reduced relative to the mod-1 trawl, and the probability of capture as a function of species and size has been established. This reduces uncertainty (as selectivity has been quantified), and biases (as small fishes are more likely to be retained) in future analyses of the catch data, including acoustic-trawl surveys (Levine et al., in review), and analyses of trawl catches (Baker, 2022). Although the probability of retaining small fishes has been improved, as with all trawls, the trawl remains species- and size-selective. Thus, best practice is to correct the observed trawl catch ($catch_{obs}$) of a given species with the fitted selectivity relationships (i.e. $Catch_{corr,l} = \frac{Catch_{obs,l}}{S_l}$, where S is the probability of retention in the trawl codend, and l is length) rather than assuming that the trawl catch is unbiased.

Characterizing selectivity for different trawl gears can be advantageous as it allows for improved trawl gear to be introduced as surveys evolve. The use of trawls with characterized selectivity allows the requirement for methodological consistency to maintain a consistent sampling bias to be relaxed in a survey time series. If selectivity has been quantified, corrections for selectivity can be implemented, and catches from different sampling gears can be combined. This was the case for development of acoustic-trawl surveys of the Chukchi Sea. A large pelagic trawl was replaced with the mod-1 trawl after it became clear that fishes were small (De Robertis et al., 2017b). Then, the mod-2 trawl was developed after it became clear that there was substantial escapement in the aft area of the mod-1 trawl (De Robertis et al., 2017a; 2022). Gear with known selectivity would also improve confidence in conclusions drawn from the comparison of sampling with different gears (e.g., Logerwell et al., 2015; Deary et al., 2021, Baker et al., 2022). This is particularly relevant to environments such as the

Alaska Arctic where monitoring programs are not well-established, sampling methods are not well standardized, and data are scarce.

Although this study focused on a particular application and ocean region, the principles are transferable to a broad range of applications with pelagic trawls. Understanding trawl selectivity is most important when estimates of absolute abundance are desired (as escapees will not be enumerated), or in cases where size and species composition are required but there are large differences in the probability of capture. In the case of acoustic surveys, the effect of trawl selectivity depends on several interacting factors: the size and species present, the target strengths of the species, and the degree to which species spatially overlap spatially (Williams et al., 2011, De Robertis et al., 2017b). In general, mixed aggregations of fish species spanning a large size range will be most impacted by trawl selectivity (Williams et al., 2011; Davison et al., 2015). Likewise, acoustic trawl-survey estimates in areas with mixed-species aggregations of strong and weak acoustic scatters (e.g. fishes with and without gas-filled swimbladders) are highly sensitive to selectivity-induced biases in trawl species composition (McClatchie and Coombs, 2005; Davison et al., 2015). Recapture nets may prove useful in constraining uncertainties in global abundance estimates of mesopelagic fishes, which remain poorly quantified. Both trawl and acoustic-trawl abundance estimates of mesopelagic fishes are highly dependent on trawl selectivity (Koslow et al., 1997; Davison et al., 2015; Kwong et al., 2018), and characterizing trawl selectivity will reduce the uncertainty in these estimates.

This work highlights the utility of quantifying the size and species selectivity of pelagic survey trawls. The use of recapture nets allowed the primary area of escapement from within a survey trawl to be identified. This allowed the trawl to be re-designed to reduce escapement, and the improved trawl performance could be quantified. Estimates of trawl selectivity were used to reduce biases in both the abundance and size composition of acoustic-trawl abundance estimates of small Arctic fishes (De Robertis et al., 2017b; Levine et al., in review). The trawl gear was improved to reduce selectivity during these surveys and catches from the three different trawls used in this survey could be integrated into a consistent abundance survey time series by estimating and then accounting for the impact of selectivity on abundance estimates.

This work demonstrates that recapture nets can improve abundance estimates derived from sampling with midwater trawls, and that survey trawls can, and should, be modified to improve performance for specific applications.

CRediT author statement

Alex De Robertis: Conceptualization, Methodology, Investigation, Formal Analysis, Writing- original draft. Robert Levine: Investigation, Data curation. Kresimir Williams: Methodology. Chris Wilson: Methodology, Investigation.

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Table 1. Summary of the most abundant fishes captured in mod-2 trawl hauls equipped with recapture nets. The number of hauls in which >10 fish were measured is given, and the total numbers of individuals captured in the codend and all recapture nets combined are listed. The mean and standard error of the standard length of the specimens and the number of specimens measured also given. See De Robertis et al., 2017a, their Table 1 for an equivalent summary of catches for the mod-1 trawl hauls.

Species	# hauls	Total # captured	# in codend	# in recapture nets	Length (cm) in codend $\bar{x}$ ± SE, (n)	Length (cm) in recapture nets $\bar{x}$ ± SE, (n)
Arctic cod	51	362986	355390	7596	4.5 ± 0.0 (4094)	4.0 ± 0.0 (2292)
Saffron cod	6	1206	1137	68	7.9 ± 0.2 (291)	4.9 ± 0.3 (38)
Pollock	57	116885	114501	2384	5.7 ± 0.1 (3197)	3.9 ± 0.0 (997)
Capelin	19	6967	6944	23	9.5 ± 0.1 (495)	8.7 ± 0.3 (23)
Arctic sand lance	34	27442	26125	1317	7.9 ± 0.1 (1899)	6.3 ± 0.1 (618)
Other fishes	57	29914	28456	1458	7.1 ± 0.1 (1823)	4.9 ± 0.0 (1047)

Table 2. Parameters of logistic selectivity curves fitted to catch data from the mod-1 and mod-2 trawls. *L50* represents the length in cm at which 50% of individuals are retained, the selection range (*SR*) is the length range in cm between 25 and 75% retention. Bootstrap estimates of the 95% confidence intervals of *L50* and *SR* are given in parentheses. A negative *SR* indicates a prediction that small fish are more likely to be retained than larger fish. A negative *L50* indicates that the length at 50% retention is poorly constrained, which occurs when capture probabilities are high for all sizes encountered). Insufficient pollock were captured during mod-1 trawl hauls to compute a selectivity curve. Other fishes refers to the grouping of all fishes other than those specifically listed below. These relationships should not be applied uncritically outside of the size ranges used to fit the relationships (see Fig. 7).

Species	**mod-1 trawl**		**mod-2 trawl**	
	L50	*SR*	*L50*	*SR*
Arctic cod	5.1 (4.6, 5.9)	2.0 (1.3, 3.0)	1.8 (-0.3, 2.6)	3.1 (2.1, 6.2)
Saffron cod	8.8 (6.6, 30.7)	4.6 (2.5, 23.6)	3.5 (-6.1, 45.1)	5.0 (-30.7, 24.9)
Pollock	n/a	n/a	2.1 (-0.2, 2.9)	2.7 (1.7, 5.4)
Capelin	10.2 (-14.5, 34.2)	6.0 (-40.4, 49.4)	-19.0 (-156.7, 125.6)	17.4 (-72.0, 95.4)
Arctic sand lance	12.0 (7.4, 27.2)	6.5 (2.5, 25.8)	5.2 (3.2, 5.8)	3.7 (2.5, 6.7)
Other fishes	3.8 (3.6, 5.2)	0.7 (0.5, 2.0)	5.0 (4.0, 6.0)	2.9 (1.7, 4.3)

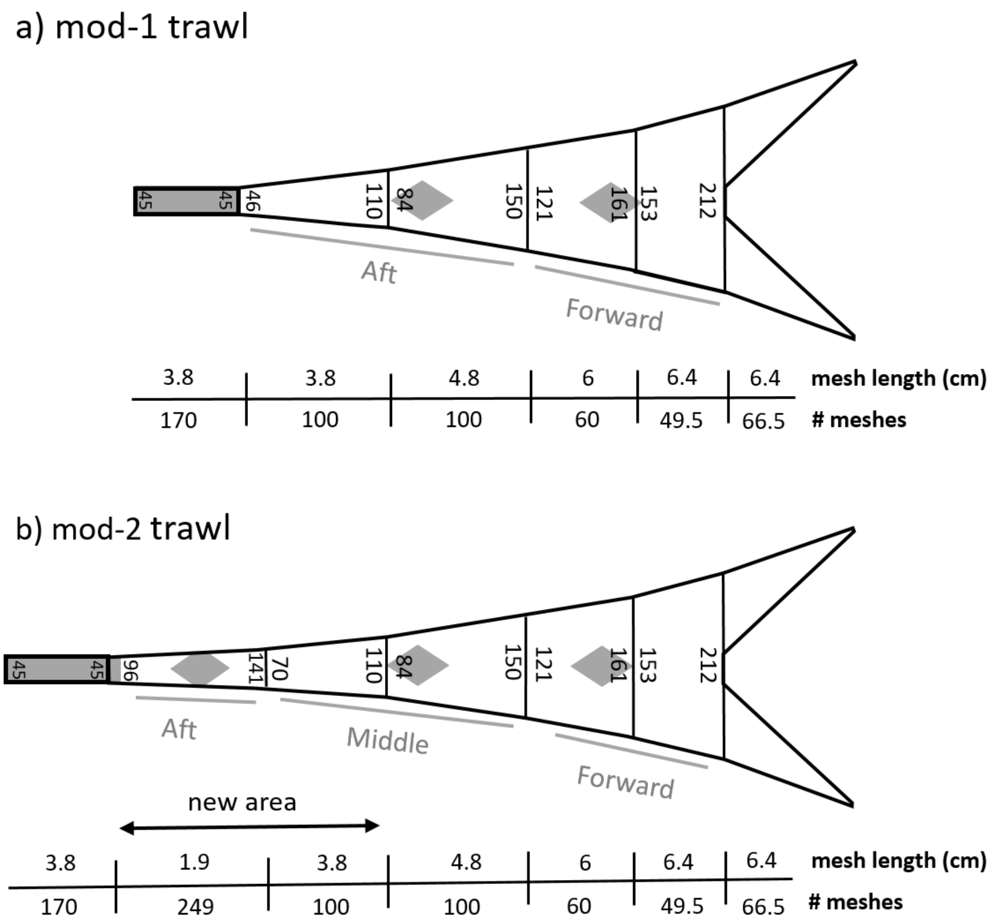

Fig. 1. Diagrams of the a) mod-1 and b) mod-2 trawls. The mod-2 trawl is the result of replacing the aft-most 3.8 cm mesh panel of the mod-1 trawl forward of the codend with a new 3.8 cm mesh panel with more gradual taper, and adding a smaller mesh section forward of the codend (the modified sections are annotated as “new area”). The size and number of meshes of each panel are annotated (mesh lengths are the distance between the centers of two opposite knots of a stretched mesh) This box trawl is symmetrical with an equivalent top, sides and bottom. Therefore, only one side is depicted. For the purposes of analysis, the trawl body was divided into forward, middle, and aft sections of similar mesh size. The approximate location of the recapture nets in the center of each section is given by the grey diamonds. The 2 by 3 mm liner is indicated by grey shading.

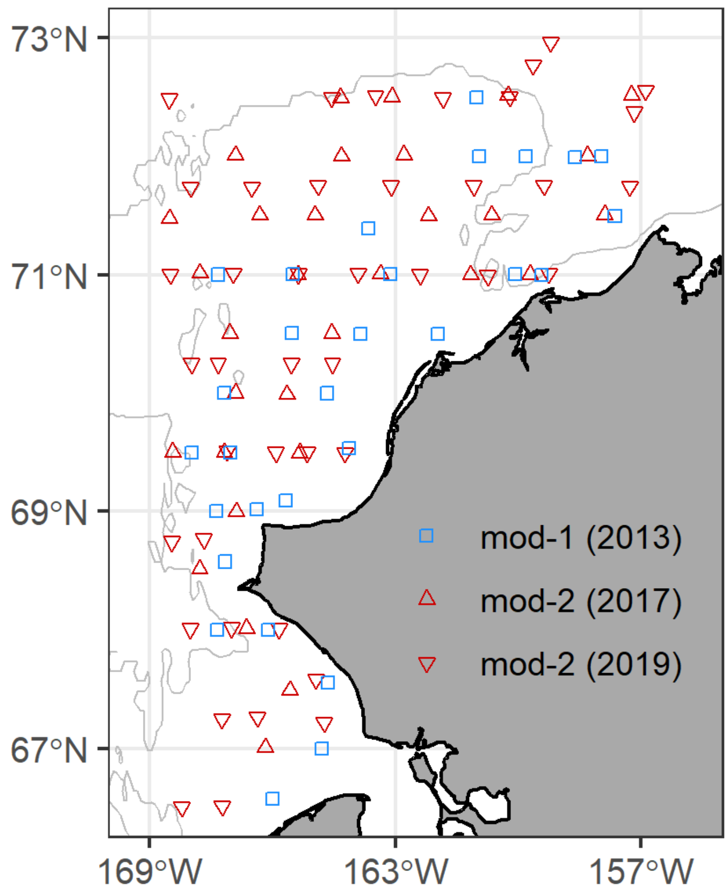

Fig. 2. Map of the study area indicating locations where the mod-1 and mod-2 trawls were fished during acoustic-trawl surveys of the Chukchi Sea The 50 m depth contour is shown as a grey line.

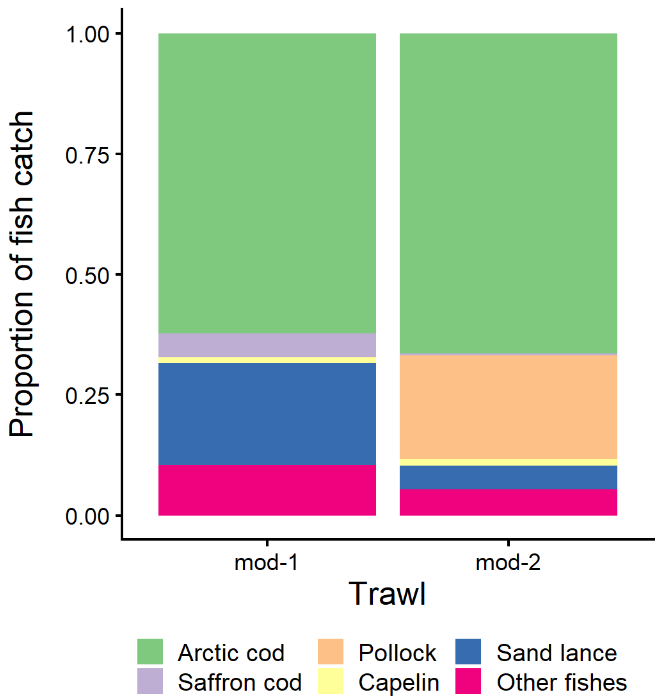

Fig. 3. Fish species composition based on codend catches of trawl hauls conducted with the mod-1 and mod-2 trawls.

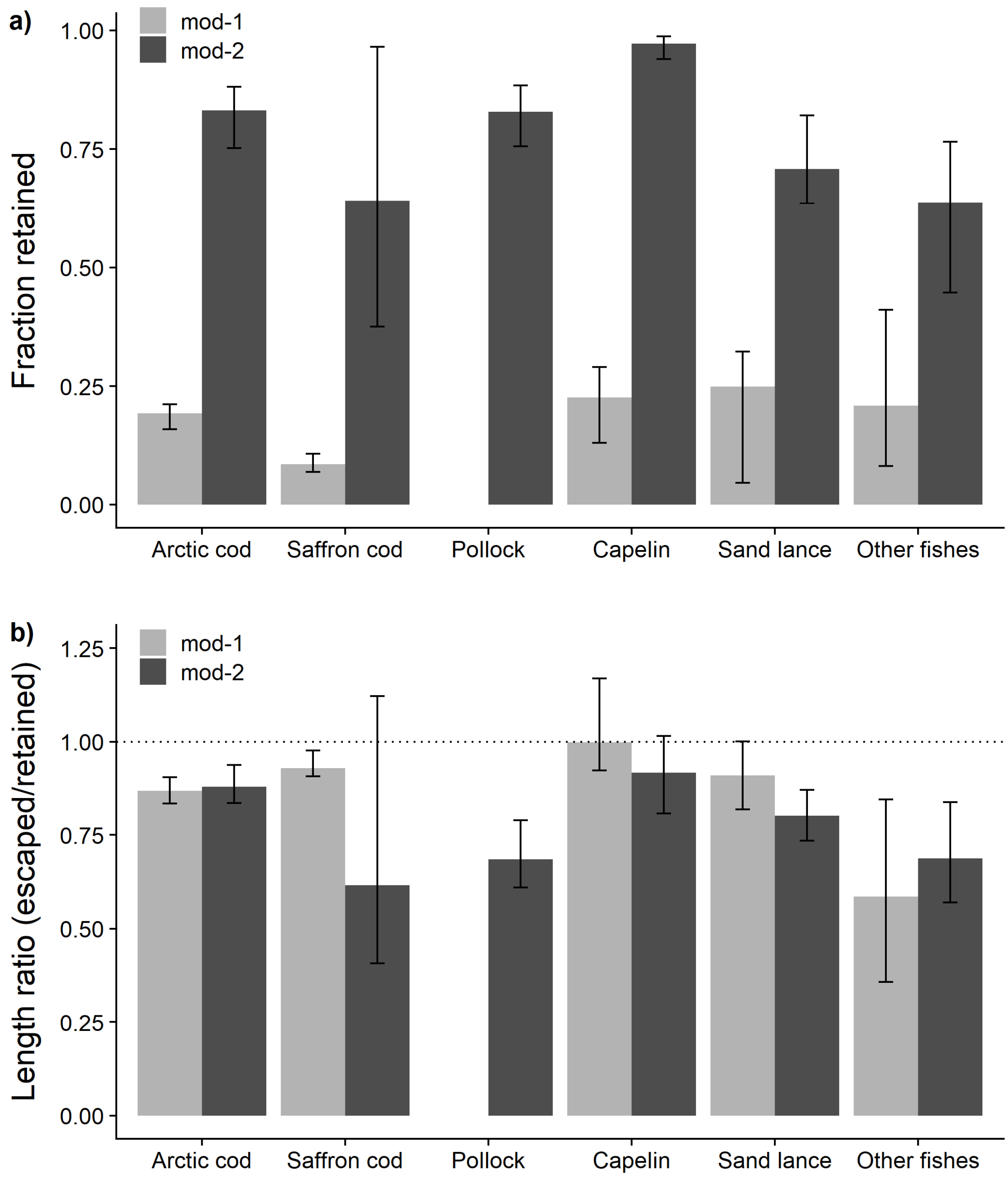

Fig. 4. Summary of a) proportion of fish entering the trawl retained in the codend and b) ratio in the mean length of the escaped/retained fish for the mod-1 and mod-2 trawls. The error bars show the observed values (all hauls pooled) and the error bars are 95% confidence intervals computed via bootstrapping of the haul catches and measured fish specimen lengths. The dotted line in b) indicates the expectation if the escaped and retained fish are of equivalent size.

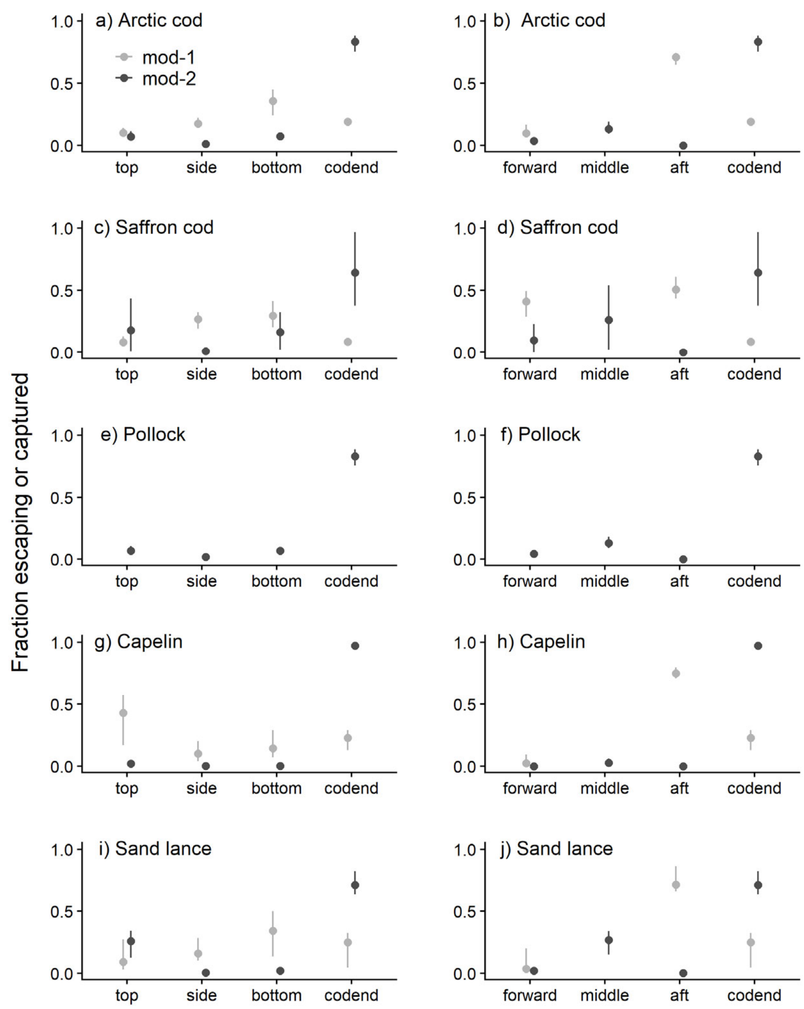

Fig. 5. Escapement pattern in mod-1 and mod-2 trawls derived from recapture net and codend catches. a,b) Arctic cod, c,d) saffron cod, e,f) pollock, g,h) capelin, and i,j) Arctic sand lance. Panels on the left depict the estimated proportion of individuals escaping through the meshes in the top, each side, or bottom of the trawl, or retained in the codend. The mod-1 trawl lacks a middle section (see Fig. 1). Panels on the right indicate the estimated proportion of fish entering the trawl mouth escaping through the forward, middle, or aft net sections or retained in the codend. The points represent the observed means, and error bars represent 95% bootstrap confidence intervals. In some cases, error bars are small and obscured by the symbols.

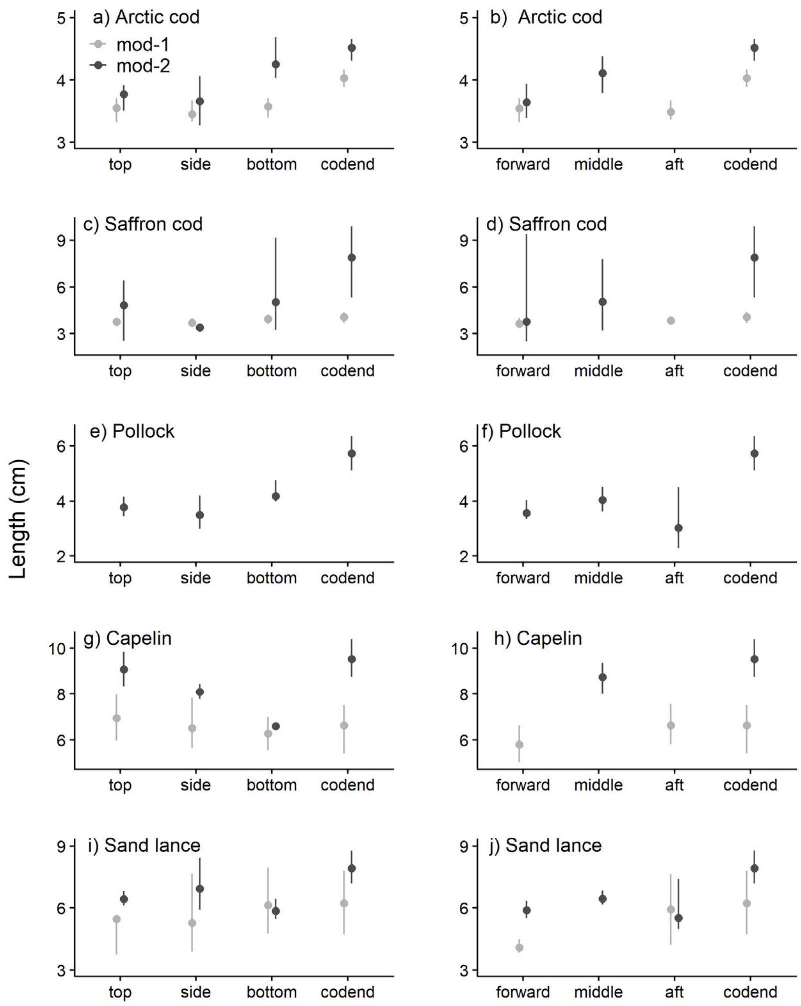

Fig. 6. Length of fishes caught in recapture nets and codend of mod-1 and mod-2 trawls. a,b) Arctic cod, c,d) saffron cod, e,f) pollock, g,h) capelin, and i,j) Arctic sand lance. Panels on the left depict the lengths of fish caught in recapture nets on the top, side, bottom, or codend of the trawls. Panels on the right indicate the size of fish caught in the forward, middle, or aft net sections or the codend. The mod-1 trawl lacked a middle section (see Fig. 1). The points represent the observed means, and error bars represent 95% bootstrap confidence intervals. Note that no capelin were captured in the forward and aft recapture nets of the mod-2 trawl and few were captured in the side (n = 3) and bottom (n = 2) recapture nets.

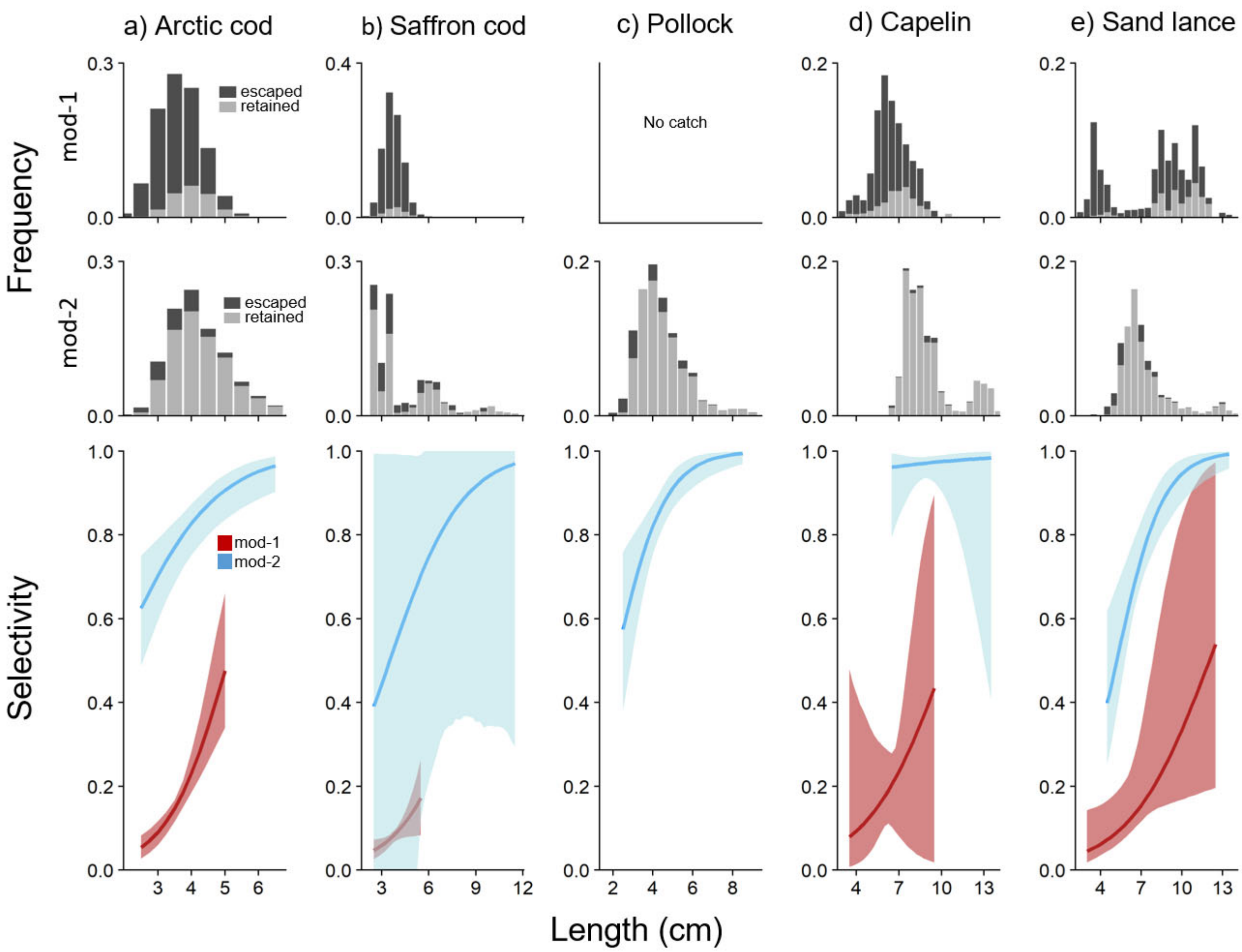

Fig. 7. Summary of escapement and fitted selectivity curves for a) Arctic cod, b) saffron cod, c) walleye pollock, d) capelin, and e) Arctic sand lance. The top panel shows a size histogram with color shading representing the proportion of fish escaping through the meshes (dark grey) or captured in the codend (light grey) of the mod-1 trawl. The middle panel shows an equivalent histogram for the mod-2 trawl. The bottom panels compare the fitted selectivity curve and bootstrapped 95% confidence intervals for the mod-1 and mod-2 trawls. Pollock were effectively absent in the mod-1 data set.

References

Baker, M.R., Farley, E.V., Danielson, S.L., Mordy, C., Stafford, K.M., Dickson, D.M.S., in review. Integrated Research in the Arctic – ecosystem linkages and shifts in the northern Bering Sea and eastern and western Chukchi Sea. Deep Sea Res. Part II

Baker, M.R., Farley, E.V., Ladd, C., Danielson, S.L., Stafford, K.M., Huntington, H.P., Dickson, D.M.S., 2020. Integrated ecosystem research in the Pacific Arctic – understanding ecosystem processes, timing and change. Deep Sea Res. Part II 177, 104850. https://doi.org/10.1016/j.dsr2.2020.104850

Baker, M.R, De Robertis, A., Levine, R. M., Cooper, D., Farley, E. V., 2022 Spatial distribution of Arctic sand lance in the Chukchi Sea related to the physical environment. Deep Sea Res. Part II, 206, 105213. https://doi.org/10.1016/j.dsr2.2022.105213

Bethke, E., Arrhenius, F., Cardinale, M., and Håkansson, N. 1999. Comparison of the selectivity of three pelagic sampling trawls in a hydroacoustic survey. Fish. Res. 44, 15-23. doi: 10.1111/j.1439-0426.2010.01446.x

Davison, P., Lara-Lopez, A., and Koslow, J. A. 2015. Mesopelagic fish biomass in the southern California current ecosystem. Deep Sea Res. Part II 112, 129-142. http://dx.doi.org/10.1016/j.dsr2.2014.10.007

De Robertis, A., Taylor, K., Williams, K., and Wilson, C. D. 2017a. Species and size selectivity of two midwater trawls used in an acoustic survey of the Alaska Arctic. Deep Sea Res. Part II 135, 40-50. http://dx.doi.org/10.1016/j.dsr2.2015.11.014

De Robertis, A., Taylor, K., Wilson, C., and Farley, E. 2017b. Abundance and distribution of Arctic cod (*Boreogadus saida*) and other pelagic fishes over the U.S. continental shelf of the northern Bering and Chukchi seas Deep Sea Res. Part II 135, 51-65. http://dx.doi.org/10.1016/j.dsr2.2016.03.002

De Robertis, A., Taylor, K., Wilson, C., and Williams, K. 2021. Corrigendum to: "Species and size selectivity of two midwater trawls used in an acoustic survey of the Alaska Arctic" (Deep-Sea Res. II 135 (2017) 40-50). Deep Sea Res. Part II 194, 104997. https://doi.org/10.1016/j.dsr2.2021.104997

Deary, A. L., Vestfals, C. D., Mueter, F. J., Logerwell, E. A., Goldstein, E. D., Stabeno, P. J., Danielson, S. L., et al. 2021. Seasonal abundance, distribution, and growth of the early life stages of polar cod *(Boreogadus saida*) and saffron cod (*Eleginus gracilis*) in the US Arctic. Polar Biol. https://doi.org/10.1007/s00300-021-02940-2

Frose, R., and Pauly, D. 2021. FishBase. World Wide Web electronic publication. www.fishbase.org (Accessed 10/12/21)

Glass, C. W., Wardle, C. S., and Gosden, S. J. 1993. Behavioral studies of the principles of mesh penetration by fish. ICES Mar. Sci. Symp. 196, 92-97.

Handegard, N. O., and Tjøstheim, D. 2005. When fish meet a trawling vessel: examining the behaviour of gadoids using a free-floating buoy and acoustic split-beam tracking. Can. J. Fish. Aquat. Sci. 62, 2409-2422. doi: 10.1139/F05-131

He, P. G. 1993. Swimming speeds of marine fish in relation to fishing gears. ICES Mar. Sci. Symp. 196, 183-189.

Herrmann, B., Krag, L. A., and Krafft, B. A. 2018. Size selection of Antarctic krill (*Euphausia superba*) in a commercial codend and trawl body. Fish. Res. 207, 49-54. https://doi.org/10.1016/j.fishres.2018.05.028

Honkalehto, T., and McCarthy, A. 2015. Results of the acoustic-trawl survey of walleye pollock (*Gadus chalcogrammus*) on the U.S. and Russian Bering Sea Shelf in June - August 2014 (DY1407). AFSC Processed Rep. 2015-07, 62 p. Alaska Fish. Sci. Cent., NOAA, Natl. Mar. Fish. Serv., 7600 Sand Point Way NE, Seattle WA 98115. http://www.afsc.noaa.gov/Publications/ProcRpt/PR2015-07.pdf.

Kaartvedt, S., Staby, A., and Aksnes, D. L. 2012. Efficient trawl avoidance by mesopelagic fishes causes large underestimation of their biomass. Mar. Ecol. Prog. Ser. 456, 1-6. doi: 10.3354/meps09785

Kennelly, S. J., and Broadhurst, M. K. 2002. By-catch begone: changes in the philosophy of fishing technology. Fish Fish. 3, 340-355. 10.1046/j.1467-2979.2002.00090.x

Kennelly, S. J., and Broadhurst, M. K. 2021. A review of bycatch reduction in demersal fish trawls. Rev. Fish Biol. Fish. 31, 289-318. https://doi.org/10.1007/s11160-021-09644-0

Koslow, J. A., Kloser, R. J., and Williams, A. 1997. Pelagic biomass and community structure over the mid-continental slope off southeastern Australia based on acoustic and midwater trawl sampling. Mar. Ecol. Prog. Ser. 149, 21-25.

Kotwicki, S., Lauth, R. R., Williams, K., and Goodman, S. E. 2017. Selectivity ratio: A useful tool for comparing size selectivity of multiple survey gears. Fish. Res. 191: 76-86. http://dx.doi.org/10.1016/j.fishres.2017.02.012

Krag, L. A., Herrmann, B., Iversen, S. A., Engås, A., Nordrum, S., and Krafft, B. A. 2014. Size selection of Antarctic krill (*Euphausia superba*) in trawls. Plos One 9, e102168.10.1371/journal.pone.0102168

Kwong, L. E., Pakhomov, E. A., Suntsov, A. V., Seki, M. P., Brodeur, R. D., Pakhomova, L. G., and Domokos, R. 2018. An intercomparison of the taxonomic and size composition of tropical macrozooplankton and micronekton collected using three sampling gears. Deep Sea Res. Part I 135, 34-45. https://doi.org/10.1016/j.dsr.2018.03.013

Levine, R., De Robertis, A., Grunbaum, D., Wildes, S., Farley, E., Stabeno, P. J., and Wilson, C. D. in review. Climate-driven shifts in the pelagic fish community of the Chukchi Sea. Deep Sea Res. Part II.

Logerwell, E. A., Busby, M., Carothers, C., Cotton, S., Duffy-Anderson, J., Farley, E., Goddard, P., et al. 2015. Fish communities across a spectrum of habitats in the western Beaufort Sea and Chukchi Sea. Prog. Oceanogr. 136, 115-132. http://dx.doi.org/10.1016/j.pocean.2015.05.013

Matsushita, Y., Inoue, Y., Shevchenko, A. I., and Norinov, Y. G. 1993. Selectivity in the codend and in the main body of the trawl. ICES Mar. Sci. Symp. 196, 170-177.

McClatchie, S., and Coombs, R. F. 2005. Low target strength fish in mixed species assemblages: the case of orange roughy. Fish. Res. 72, 185-192. doi:10.1016/j.fishres.2004.11.008

Millar, R. B. 1993. Analysis of trawl selectivity studies (addendum): implementation in SAS. Fish. Res. 17, 373-377. https://doi.org/10.1016/0165-7836(93)90137-V

Millar, R. B., and Fryer, R. J. 1999. Estimating the size-selection curves of towed gears, traps, nets and hooks. Rev. Fish Biol. Fish. 9, 89-116.

Nakashima, B. S. 1990. Escapement from a Diamond IX midwater trawl during acoustic surveys for capelin (*Mallotus villosus*) in the Northwest Atlantic. J. Cons. Int. Explor. Mer. 47, 76-82.

Olla, B. L., Davis, M. W., and Schreck, C. B. 1997. Effects of simulated trawling on sablefish and walleye pollock: the role of light intensity, net velocity and towing duration. J. Fish Biol., 50, 1181-1194. https://doi.org/10.1111/j.1095-8649.1997.tb01646.x

Ryer, C. H., and Olla, B. L. 2000. Avoidance of an approaching net by juvenile walleye pollock *Theragra chalcogramma* in the laboratory: the influence of light intensity. Fish. Res., 45, 195-199. https://doi.org/10.1016/S0165-7836(99)00113-7

Simmonds, E. J., and MacLennan, D. N. 2005. Fisheries Acoustics 2nd. Ed. Blackwell Science LTD, Oxford, UK.

Simmonds, E. J., Williamson, N. J., Gerlotto, R., and Aglen, A. 1992. Acoustic survey design and analysis procedure: a comprehensive review of current practice. ICES Coop. Res. Rep., 187, 127 pp.

Skúvadal, F. B., Thomen, B., and Jacobsen, J. A. 2011. Escape of blue whiting (*Micromesistius poutassou*) and herring (*Clupea harengus*) from a pelagic survey trawl. Fish. Res.111, 65-73. doi:10.1016/j.fishres.2011.06.012

Somerton, D. A., Williams, K., von Szalay, P. G., and Rose, C. S. 2011. Using acoustics to estimate the fish-length selectivity of trawl mesh. ICES J. Mar. Sci. 68, 1558-1565. doi:10.1093/icesjms/fsr083

Suuronen, P., Lehtonen, E., and Wallace, J. 1997. Avoidance and escape behavior by herring encountering midwater trawls. Fish. Res. 29, 13-24.

Stevenson, D. E., and Lauth, R. 2019. Bottom trawl surveys in the northern Bering Sea indicate recent shifts in the distribution of marine species. Polar Biol. 42, 407-421. https://doi.org/10.1007/s00300-018-2431-1

Towler, R., and Williams, K. 2010. An inexpensive millimeter-accuracy electronic length measuring board. Fish. Res. 106, 107-111. doi:10.1016/j.fishres.2010.06.012

Underwood, M. J., García-Seoane, E., Klevjer, T. A., Macaulay, G. J., and Melle, W. 2020. An acoustic method to observe the distribution and behaviour of mesopelagic organisms in front of a trawl. Deep Sea Res. Part II 180, 104873. https://doi.org/10.1016/j.dsr2.2020.104873

Wildes, S., Whittle, J., Nguyen, H., Marsh, M., Karpan, K., D'Amelio, K., Dimon, A., Cieciel, K., De Robertis, A., Levine, R., Larson, W. Guyon, J. 2022. Walleye Pollock breach the Bering Strait: A change of the cods in the Arctic. Deep Sea Res. Part II 204, 105165. https://doi.org/10.1016/j.dsr2.2022.105165

Wileman, D. A., Ferro, R. S. T., Fonteyen, R., and Millar, R. B., (Eds), 1996. Manual of methods of measuring the selectivity of towed fishing gears. ICES Coop. Res. Rep. 215, 126 pp.

Williams, K., Punt, A. E., Wilson, C. D., and Horne, J. K. 2011. Length-selective retention of walleye pollock, *Theragra chalcogramma*, by midwater trawls. ICES J. Mar. Sci. 68, 119-129. doi:10.1093/icesjms/fsq155

Williams, K., Wilson, C., and Horne, J. K. 2013. Walleye pollock (*Theragra chalcogramma*) behavior in midwater trawls. Fish. Res. 143, 109-118. doi:10.1093/icesjms/fsq155