Species and size selectivity of two midwater trawls used in an acoustic survey of the Alaska Arctic

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Abstract:

Acoustic-trawl (AT) survey methods are widely used to estimate the abundance and distribution of pelagic organisms. This technique relies on estimates of size and species composition from trawl catches along with estimates of the acoustic properties of these animals to convert measurements of acoustic backscatter into animal abundance. However, trawls are selective samplers, and if the catch does not represent the size and species composition of the animals in the acoustic beam the resulting abundance estimates will be biased. We conducted an experiment to quantify trawl selectivity for species encountered during an AT survey of the Alaska Arctic. The pelagic assemblage in this environment was dominated by small young-of-the-year (age-0) fishes and jellyfish, which may be poorly retained in trawls. A large midwater trawl (Cantrawl) and a smaller midwater trawl (modified Marinovich) were used during the survey. The Marinovich was equipped with 8 small-mesh recapture nets which were used to estimate the probability that an individual that enters the trawl is retained. In addition, paired hauls were made with the Cantrawl and Marinovich to estimate the difference in selectivity between the two trawls. A statistical model was developed to combine the catches of the recapture nets and the paired hauls to estimate the length-dependent selectivity of the trawls for the most abundant species (e.g., age-0 fishes and jellyfish). The analysis indicated that there was substantial size and species selectivity: although the modified Marinovich generally had a higher catch per unit effort, many of the animals encountered in this environment were poorly retained by both trawls. The observed size and species selectivity of the trawls can be used to select appropriate nets for sampling pelagic fishes, and correct survey estimates for the biases introduced in the trawl capture process.

Key words: Acoustic Surveys, Trawl Selectivity, Midwater Trawl, Chukchi Sea, Echo surveys, Arctic zone, Fish Trawling, Escapement, Recapture Net

1. Introduction

Acoustic-trawl (AT) survey methodology relies on trawl sampling to estimate the species and size composition of sound-scattering organisms. The catches from survey trawls are used to convert observations of volume backscattering into animal abundance (Simmonds and MacLennan, 2005). However, fishing gear is selective (i.e. there are size and species differences in the probability of capture), and the trawl catch is likely to have a different size and species composition than the population in the volume sampled (MacLennan, 1992, Wileman et al., 1996, Bethke et al., 1999). If the trawl gear is size or species selective this can cause substantial biases in AT abundance estimates (Nakashima 1990, Bethke et al., 1999, Williams, 2013). Biases in trawl-based species or size composition introduce errors in all size or species classes in AT surveys. This occurs because the acoustic measurement detects backscatter from all species (and sizes) present in the acoustic beam, and this echo energy is converted to species abundance based on the acoustic scattering expected from the animals retained in the trawl (Bethke et al., 2010). For example, in the case of a mixture of strong and weak sound scattering organisms, underestimates in the proportion of the strong scatterers due to net selectivity will result in comparatively large overestimates of the weakly scattering organisms, as a larger proportion of the observed backscatter is allocated to the weakly scattering organisms in the calculation of animal abundance from acoustic backscatter (e.g. McClatchie and Coombs, 2005).

Trawls used in commercial fishing are species and size selective, and there has been considerable interest in quantifying and altering the selectivity of trawls to reduce unwanted bycatch (reviewed in MacLennan 1992, Wileman et al., 1996). However, the size and species selectivity of survey trawls is commonly assumed to be negligible (i.e. catchability is constant across species and size classes), and trawl catches are often used to estimate fish abundance with no correction for trawl selectivity. Trawls capture fish primarily by exploiting herding behavior (Wardle, 1984, 1993), and the probability of retention in the trawl is often strongly size and species dependent (Nakashima, 1990, Wardle, 1993, Williams et al., 2011). When fish aggregations are dominated by a single species, and size classes are spatially segregated, trawl selectivity may have relatively minor impacts on acoustic estimates of abundance. However, in many environments, fish occur in aggregations of mixed species and sizes, and the species and size compositions of acoustic scatterers are inferred from trawl samples. The assumption of negligible selectivity is likely to be untenable in these mixed species or size class situations, and trawl selectivity is likely to introduce large biases into AT survey results. For example, Williams (2013) found that accounting for trawl selectivity in an area of mixed age aggregations of walleye pollock resulted in large underestimates of the poorly retained juvenile pollock and comparatively small changes in the biomass of adults.

This study was a part of a large-scale baseline survey of the Arctic Ecosystem integrated survey (Arctic Eis) of the eastern Alaska Chukchi Sea in 2012 and 2013. A large midwater trawl (Cantrawl) was used for the AT survey in 2012 to estimate the abundance and distribution of near-surface and midwater fishes. The trawl had been used in earlier surface trawl surveys and was used in the 2012 and 2013 surveys to continue that surface trawl survey time series (Farley et al., 2009, Eisner et al., 2013). During the 2012 AT survey, it became clear that the fish assemblage in the eastern Chukchi Sea was dominated by small and/or juvenile fishes which were likely to be poorly retained by the Cantrawl. During the 2013 survey, a smaller modified midwater herring trawl (hereafter mod-Marinovich) was used to target acoustically observed fish aggregations, as it was expected to be better at retaining the small size classes of fishes present in the survey area in 2012.

This work aims to quantify the size and species selectivity of the two trawls used in the Arctic Eis AT surveys. The information is necessary to correct the trawl-based estimates of species and size composition used to convert acoustic backscatter to species abundances so that accurate and comparable estimates of animal density are generated from the two surveys. A two-part experiment was conducted in 2013 in which 1) the mod-Marinovich was equipped with small-mesh recapture nets to capture fishes that escaped from the trawl, and 2) a series of paired trawls with the Cantrawl and mod-Marinovich were conducted during the survey. The results of these fishing trials are analyzed jointly in a model framework to estimate the size-dependent selectivity of the trawls for the abundant species.

2. Materials and Methods

2.1 Trawl sampling

A series of hauls with the mod-Marinovich trawl equipped with small-mesh recapture nets to capture fish exiting out the trawl meshes, as well as back-to-back trawl hauls with the mod-Marinovich and a large Cantrawl 400/601 rope trawl were conducted as part of an interdisciplinary survey of the Chukchi Sea. These midwater trawl hauls were conducted aboard the F/V *Bristol Explorer*, a chartered 55 m commercial stern trawler during an AT survey conducted between 7 August and 11 September 2013 (Fig. 1). Both nets were fished with 5 m^2 alloy doors at a vessel speed of ~ 2 m s^{-1} during daylight hours. The trawl opening during fishing (measured after the doors had spread the net and the net depth was stable) was observed with a Wesmar trawl sonar attached to the headrope, and the depth of the trawl was measured with Seabird SBE-39 temperature and pressure recorders attached to the headrope.

The Cantrawl is ~198 m long, has a 122 m headrope, and is constructed with ropes at the leading edge of the net followed by meshes reducing from 162 to 1.2 cm stretched length in the codend liner (Farley et al., 2009). The Cantrawl was equipped with floats to keep the headrope near the surface and towed for 30 min at predetermined locations. A trawl vertical opening of 19.7 ± 2.7 m (mean ± SD) and a horizontal opening of 45.8 ± 3.6 m was measured while surface trawling.

The mod-Marinovich herring trawl is ~31 m long, has a 12 m headrope, and is constructed as a symmetrical 4 seam box trawl with meshes reducing from 6.4 cm in the wings to 3.8 cm in the aft panel (Fig. 2). The body of the trawl is constructed from four panels. The aftmost panel was covered by 2 by a 3 mm knotless oval mesh liner. Hereafter, the two forward panels are referred to collectively as the forward section, the remaining unlined panel as the aft section, and the rear lined panel as the codend (Fig. 2). The trawl was modified from the original design to allow it to be fished effectively (i.e. with minimal overspreading of the net) with the same 5 m^2 trawl doors used for the Cantrawl by adding larger wings and fishing it with 55 m bridles. A trawl vertical opening of 5.7 ± 0.6 m (mean ± SD) and a horizontal opening of 8.3 ± 0.9 m was observed while fishing.

The mod-Marinovich was equipped with recapture nets designed to recapture organisms that escape from inside the trawl by exiting through the trawl meshes (e.g. Zijlsta, 1969, Nakashima, 1990, Matsushita et al., 1993, Williams et al., 2011). The trawl was divided into the codend and 8 additional partitions, defined by each trawl side (i.e. top, bottom, left, right), with each side divided into front and aft sections (Fig. 2). Recapture nets were attached to the outside of the trawl at the center of each of the 8 partitions (Fig. 2). The recapture nets were made of the same 2 by 3 mm oval mesh as the mod-Marinovich codend liner, and were constructed with a mouth opening as a rhombus with 1.2 m sides and a 2.6 m long body reducing into a codend. The recapture nets, which were dyed black to minimize their visibility, covered approximately 3.1 % of the trawl surface area: 2.2 % of the meshes in the forward section, and 5.5 % of the meshes in the aft section (Fig. 2).

The mod-Marinovich was fished in 30 hauls in which all 8 recapture nets and the codend were sampled. Although the recapture nets were permanently attached to the mod-Marinovich, they were not sampled on all trawl hauls due to the effort required to sample the catches. On several occasions, catch was lost from one or more nets from inadvertently opened codend(s). Data from these hauls were not used.

A total of 14 paired hauls were conducted when the mod-Marinovich and Cantrawl were fished over a similar trawl path near the surface (Fig. 1). These comparison hauls were conducted by first fishing the Cantrawl and then towing the mod-Marinovich over the reciprocal tow path. During these hauls, the Cantrawl headrope depth averaged 3.2 ± 2.8 m (mean ± SD) and the footrope depth averaged 22.7 ± 2.3 m. The mod-Marinovich, which could not be fished as close to the surface, had an average headrope depth of 15.0 ± 5.1 m and a footrope depth of 20.3 ± 4.9 m during the paired surface hauls. The catches in the recapture nets on the mod-Marinovich were sampled on 9 of the 14 paired hauls (i.e. 5 paired hauls in which the recapture nets were not sampled are included in the analysis).

Trawl catches were weighed, subsampled if large, and the catch was enumerated and identified to species where possible. Fork lengths of a subsample of up to 50 fishes and bell diameters of up to 50 undamaged jellyfishes were measured to the nearest 1.0 mm using an electronic measuring board (Towler and Williams, 2010). The volume (V) sampled by each net was computed by estimating the mouth opening as an ellipse based on the mean horizontal and vertical mouth opening (a, b) observed on each haul with the trawl sonar, and multiplying this by the distance fished (d; $V = \pi \cdot a/2 \cdot b/2 \cdot d$). The surface area of the mouth opening of the Cantrawl averaged (± SD) 708 ± 97 m^2, and the mouth opening of the mod-Marinovich was 36 ± 2 m^2, which means that the Cantrawl sampled ~20 times more volume per unit distance towed.

2.2 Description of mod-Marinovich escapement pattern

The catches in the recapture nets were used to describe the rate of escapement in different sections of the mod-Marinovich trawl. The proportion p of the individuals of a given species entering the trawl mouth that either escapes from a trawl partition or is captured in the codend was calculated as

$$p_i = \sum_s \left(c_{mar,s,i}/f_{mar,i}\right) / \sum_{s,i} \left(c_{mar,s,i}/f_{mar,i}\right), \quad (1)$$

where i represents the mod-Marinovich trawl partition (i.e. the 8 partitions covered by recapture nets and the codend), s represents the trawl station, $c_{mar,s,i}$ represents the number of individuals captured at station s in partition i, and $f_{mar,i}$ is the fraction of the meshes in trawl partition i covered by the 2 by 3 mm oval mesh in the recapture nets and the codend (Fig. 2).

Confidence intervals for p_i were estimated by drawing bootstrap samples with replacement from the recapture net trawl hauls in which the species of interest was captured. In a given realization, a bootstrap sample was assembled by randomly drawing a series of trawl stations s' with replacement from the subset of the original series of stations s in which the species was captured (i.e. randomly draw from the subset of hauls where the species was captured as many times as there are hauls where the species was captured). The proportion of fish retained in each trawl section was computed using *s'* and equation 1. Approximate 95% confidence intervals of p_i were estimated by finding the 2.5 and 97.5% percentiles from 10^5 bootstrap realizations.

We compared the size of fish escaping from different sections of the trawl with the length of those captured in the codend in an analogous manner. For each fish k captured in trawl partition i at station s, the length discrepancy from the mean length of fish in the codend catch was estimated as

$$\Delta l_{k,i,s} = l_{k,i,s} - \overline{l_{s,cod}}\ , \tag{2}$$

where $\overline{l_{h,cod}}$, is the mean length of the fish captured in the codend at station *s*. The mean difference in length for fish in partition *i* relative to the codend was computed as

$$\overline{\Delta l_i} = \textstyle\sum_{k,s} \Delta l_{k,i,s}/n_i\ , \tag{3}$$

where n_i is the total number of fish captured in partition *i* in all hauls. Approximate confidence intervals for Δl_i were estimated by drawing bootstrap samples with replacement from the recapture net trawl hauls as described above.

2.3 Estimation of trawl selectivity

A statistical analysis was undertaken to estimate the selectivity of the mod-Marinovich and the Cantrawl from the recapture nets and the paired hauls. An analysis framework was developed that allowed the catch data from both the paired trawls and the recapture nets on the mod-Marinovich to be considered simultaneously. The observed catch in the trawl partitions in the mod-Marinovich (codend, 4 aft recapture nets, 4 front recapture nets), and the catch in the Cantrawl codend was fit to a statistical model as follows:

The proportion of the total catch at a given station (i.e. a sampling location) of length class *l* expected in the mod-Marinovich codend can be expressed as

$$p_{mar,l} = r_{mar,l} \cdot \rho_{mar} \, , \tag{4}$$

where $r_{mar,l}$ is the probability that a fish of length *l* entering the mod-Marinovich is retained in the codend, and ρ_{mar} is the fraction of the total volume sampled at this station by the mod-Marinovich i.e. $\rho_{mar} = V_{mar}/(V_{mar}+V_{can})$, where V_{mar} is the volume sampled by the mod-Marinovich net and V_{can} is the volume sampled by the Cantrawl. $r_{mar,l}$ was modeled as a length-dependent logistic function parameterized in terms of the length at which 50% of fish are retained (L_{50}), and the selection range (*SR*; length in cm between 25% and 75% retention):

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

where *l* is length in cm and $k = 2 \log (3)$ (Millar, 1993). The corresponding probability of escapement at length *l* is 1- $r_{mar,l}$.

The proportions of the total catch of length *l* expected in the mod-Marinovich aft and forward recapture nets are:

$$p_{mar,aft,l} = \left(1 - r_{mar,l}\right) \cdot \rho_{mar} \cdot (1-e) \cdot f_{mar,aft} \, , \tag{6}$$

$$p_{mar,fwd,l} = \left(1 - r_{mar,l}\right) \cdot \rho_{mar} \cdot e \cdot f_{mar,fwd} \, , \tag{7}$$

Where e is a fitted parameter representing the fraction of the mod-Marinovich escapement occurring in the forward panel, and f_{aft} and f_{fwd} are the fractions of the aft and forward mod-Marinovich sections covered by recapture nets (0.055 and 0.022, respectively – see Fig. 2).

The proportion of the total catch of length class l expected in the Cantrawl codend is

$$p_{can,l} = r_{can,l} \cdot (1 - \rho_{mar}) \, , \tag{8}$$

where $r_{can,l}$ is the probability that a fish entering the Cantrawl mouth is retained in the codend, which has the same logistic form as $r_{mar,l}$.

The total number of fish (U) in the volume sampled by all trawls deployed at each trawl station s (i.e. $V_{mar,s}+V_{can,s}$) can be estimated by dividing the catch of that length class by the expected proportion of animals retained in the trawl partitions i and summing over length classes:

$$U_s = \sum_l \left(\sum_i c_{i,s,l} / \sum_i p_{i,s,l} \right) . \tag{9}$$

Note that this allows for cases where only some trawl partitions were sampled to be included in the analysis (e.g. stations where the Cantrawl was not deployed are handled by setting the volume sampled by the Cantrawl ($V_{can,s}$) and the Cantrawl codend catch ($c_{can,s}$) for that station to zero).

The predicted total catch y in each partition i at each station is estimated as

$$y_{i,s} = p_i \cdot U_s \, . \tag{10}$$

The size-dependent selectivity in the mod-Marinovich and Cantrawl (r_{mar} and r_{can}) and e, the proportion of the mod-Marinovich escapement in the forward panel were fit by maximizing agreement of the observed (*c*) and predicted (*y*) catches over all partitions *i* (i.e. mod-Marinovich codend, 8 partitions sampled by recapture nets, and the Cantrawl codend) and all stations *s* by maximizing the following log likelihood function:

$$LL = \sum_s \sum_i \left(c_{i,s} \cdot \ln(y_{i,s}) - y_{i,s}\right) , \qquad (11)$$

which assumes that the probability of capture follows a Poisson distribution, similar to the model described by Kirkwood and Walker (1986). Thus, fitting the model for a given species or species group produces maximum likelihood estimates for 5 parameters, two for the logistic function r_{mar}, two for the logistic function r_{can}, and *e*, the proportion of Marinovich escapement occurring in the front panel, which is not of immediate interest, but must be accounted for in the model.

Interpretation of the selectivity estimates derived by the model depends on the estimate of volumetric abundance of a given organism in the path of both trawls (i.e. U_s in equation 9). This is most easily understood when the volumetric density of the organism estimated from the mod-Marinovich (i.e. catch and escapement combined) exceeds the catch rate in the Cantrawl codend (as is generally the case – see section 3.4). In this situation, a selectivity of 1 corresponds to the case in which all the catch in the mod-Marinovich occurs in the codend (i.e. no catch of this species/size class in the recapture nets, indicating that all individuals entering the net are retained). If the volumetric density estimated from the Cantrawl codend exceeds the density estimated from the Marinovich (i.e. catch and escapement), the Cantrawl is assumed to be fully selective for this species/size class (i.e. selectivity =1). However, in either case, the results can be interpreted in terms of the ratio of the Cantrawl to mod-Marinovich selectivity.

The model was fit to catches of the following species groups: Arctic cod (*Boreogadus saida*), saffron cod (*Eleginus gracilis*), Pacific sand lance (*Ammodytes hexapterus*), capelin

(*Mallotus villosus*), all other fishes combined (various species pooled, ~ 23.2 % of catch was larvae), and jellyfishes (86.4% *Cyanea capillata* , 13.4 % *Chrysaora melanaster*). The results for Arctic cod are presented in detail, as this group was abundant and was consistently captured in the survey area. The results for other species groups are summarized.

A bootstrap resampling procedure was employed to evaluate the uncertainty in the parameters of the two logistic functions. For each species group, a bootstrap sample was assembled by establishing the number of cases in which the species was captured in 1) paired hauls 2) paired hauls with Marinovich recapture nets and 3) mod-Marinovich hauls with recapture nets. A bootstrap sample comprised of this number of trawls of each type (i.e. paired, paired with recapture nets, mod-Marinovich with recapture nets) was randomly drawn with replacement from the trawls in which at least 1 individual was caught. The parameters of the selectivity function were fit to the data with the model described above for 10^5 bootstrap samples.

The resulting L_{50} and *SR* parameters were often variable, and were particularly uncertain for species and size ranges where few individuals were captured, as there was little data to constrain the fit in these areas of the curves. We chose to use the 90% confidence intervals of the parameters to characterize variability of the parameter estimates, as in some bootstrapped samples the total catch was low and the tails of the bootstrap parameter estimates were highly skewed. To evaluate the relative performance of these two nets for the size distribution of animals encountered in the survey, the selectivity parameters were used to calculate the average probability (*pc*) that fishes with a size distribution corresponding to that in the environment are retained by the trawl, i.e.

$$\boldsymbol{pc} = \sum_l \boldsymbol{r_l} \cdot \boldsymbol{PL_l}\,, \tag{12}$$

where $r(l)$ is as in eq.5, PL_l is the proportion of the population in length class l in the environment. PL was estimated from the mod-Marinovich hauls equipped with recapture nets, as this accounts for the size distribution of fish that are not retained in the trawl as well as those that are captured,

$$\boldsymbol{PL_l} = \left(\sum_{s,i} \boldsymbol{c_{mar,i,l,s}} / \left(\boldsymbol{f_{mar,i}} \cdot \boldsymbol{v_{mar,s}}\right)\right) / \left(\sum_{s,i,l} \boldsymbol{c_{mar,i,l,s}} / \left(\boldsymbol{f_{mar,i}} \cdot \boldsymbol{v_{mar,s}}\right)\right), \tag{13}$$

where l represents length, i represents the mod-Marinovich trawl partition (codend, 4 aft recapture nets, 4 forward recapture nets), s represents station, $c_{mar,i}$ represents the number of individuals captured in mod-~~Marionvich~~Marinovich partition i, and $f_{mar,i}$ is the fraction of the meshes covered by the recapture nets or codend liner in partition i (e.g. Fig. 2), and $v_{mar,s}$ is the volume sampled by the mod-Marinovich in at station s. The quantity pc quantifies the probability that a fish of the size distribution estimated to occur in the environment (PL) was captured by the trawl, and is contingent on the assumption that the volumetric density of this organism is reflected by U_s. In addition, the selectivity at size of 4 cm (i.e. l = 4 cm) was computed to allow for comparisons of selectivity across species at common size. The bootstrap estimates of mean selectivity at the size distribution estimated to occur in the environment (PL), and the estimated selectivity at a common size of 4 cm are presented as boxplots.

3 Results

3.1 Trawl catches

The fishes captured in the trawl hauls were generally small. For example, in the 14 paired hauls, they were primarily < 12 cm in size (Fig. 3A). The mod-Marinovich captured ~

11.2 times more fishes in the codend per unit volume sampled than the Cantrawl in the paired hauls (Fig. 3A). The species composition of fishes (Fig. 3 B-C) in the trawl catch differed ($p < 0.001$; Chi-squared test on the aggregated trawl catch from the 14 paired trawl hauls), with Pacific sand lance, other fishes, and jellyfish comprising a higher proportion of the catch in the mod-Marinovich than in the Cantrawl. In contrast, capelin and Arctic cod made up a higher proportion of the Cantrawl catch than the mod-Marinovich catch.

A substantial number of individuals were caught in the recapture nets, indicating that there was high escapement from the mod-Marinovich (Table 1). In the 30 mod-Marinovich hauls with recapture nets, 36.8 % of all fishes captured were retained in the recapture nets, which covered only ~3.1 % of the unlined meshes in the trawl body, and 63.2 % of the total was captured in the codend. Depending on the species, between 28-52 % of the total catch was captured in the recapture nets (Table 1). The individuals captured in the codend were consistently larger than those in the recapture nets (Table 1), which indicates that larger specimens were preferentially retained in the mod-Marinovich codend.

When expressed as catch per unit volume sampled, catch rates tended to be higher for the mod-Marinovich than the Cantrawl. For example, in the 7 paired trawls with mod-Marinovich recapture nets where Arctic cod were caught, an average of 83.4 juvenile Arctic cod were calculated to enter the net (i.e. mod-Marinovich codend + escapees) for every 1000 m^3 of water sampled, with 6.9 fish (~ 8.3 %) retained in the mod-Marinovich codend, and 2.3 fish (~ 2.7 %) fish retained in the Cantrawl codend (Fig. 4 A). This indicates that the majority of small Arctic cod escaped the trawls, and that the probability of capture in the Cantrawl is lower than in the mod-Marinovich. On average, smaller individuals were caught in the recapture nets, intermediate sizes in the mod-Marinovich codend, and larger specimens in the Cantrawl (Fig.

4B). This indicates that there is a low probability that juvenile Arctic cod entering the nets will be retained in the codends, and that the probability of retention is size-dependent, with smaller individuals less likely to be retained.

3.2 Escapement pattern in the mod-Marinovich

Juvenile Arctic cod and Pacific sand lance exhibited similar escapement patterns (Fig. 5 A-D). The majority of individuals entering the trawl exited the net through the aft trawl meshes (Fig. 5 A, C), with only a small fraction of individuals retained in the trawl codend. There was higher escapement of Arctic cod in the bottom of the trawl compared to the sides and the top panel (Fig. 5 B), and Pacific sand lance escapement exhibited a similar pattern but with overlapping confidence intervals (Fig. 5D).

Juvenile saffron cod, which are similar in size (Table 1) and gross morphology to juvenile Arctic cod tended to exhibit a higher proportion of escapement in the forward meshes of the mod-Marinovich than the other species (Fig. 5 E), and higher escapement in the bottom and side panels than in the top trawl panel (Fig. 5 F). Saffron cod were relatively poorly retained in the codend compared to Arctic cod, with 3.3 % (95% CI: 2.7-4.5 %) of juvenile saffron cod and 8.7% (95% CI: 7.0-9.8 %) of juvenile Arctic cod retained in the codend (Fig 5 A, E). Capelin escapement occurred primarily in the aft part of the mod-Marinovich (Fig 5 G). The probability of capelin escapement in the top, sides and bottom of the trawl exhibited broadly overlapping confidence intervals. However, there is an indication that capelin escapement may be high in the top panel, which was not the case for the other species.

When interpreting these results, one should keep in mind that these estimates are for escapement out of the entire panel, and that the panels differ in size. For example, in the case of Arctic cod, 36.3 % of the total escapement was estimated to occur in the bottom aft panel, which represents 7.2 % of the unlined trawl meshes. Thus, escapement expressed per unit surface area would be much higher in the aft panel than depicted in Fig. 5. Additionally, the sample sizes differ substantially among species (Table 1), and the size of the confidence intervals reflects both the variability in behavior and the sample size.

Mean fish size tended to be slightly larger in the codend than in the recapture nets (Fig. 6), but there was substantial inter-haul variability in the mean size of fish capture in the various recapture nets, as shown by the overlap in the bootstrap confidence intervals. Arctic and saffron cod captured in the forward and aft recapture nets were consistently smaller than those captured in the codend (Fig. 6 A, E). Capelin captured in the forward recapture nets tended to be smaller than those in the aft recapture nets and codend (Fig. 6 G). Pacific sand lance captured in the different net partitions did not differ substantially in size. The catches of all species in the top, side and bottom recapture nets were similar in mean length (Fig. 6 B, D, E, F).

3.4 Estimates of trawl size and species selectivity

The numerical abundance and size distribution of fishes in the codends of both trawls and those calculated to escape from the meshes of the mod-Marinovich trawl (e.g. Fig. 4 A-B) were used to fit logistic size selection curves for each trawl. Overall, the estimates were highly size-dependent and for small size classes, relatively low for both trawls (Fig. 7). The mod-Marinovich retained a larger fraction of small organisms in the codend (i.e. compare Fig 7A and

B at < 5 cm). The Cantrawl selectivity for jellyfish and Pacific sand lance was particularly low. The size-selectivity of the Cantrawl was steeper than that of the mod-Marinovich, with very low selectivity for individuals < ~5 cm. On average, the mod-Marinovich had a higher probability of capturing the (relatively small) species and size classes present in this environment than the Cantrawl, with the exception of the larger size classes of capelin (see dotted line in Fig. 7).

The bootstrap analysis, which reflects between-haul variation in the number and size of fish captured in the trawl partitions, indicates that the L_{50} and SR parameters are often highly uncertain (Table 2). In some bootstrap realizations there was little size dependence, and the selectivity curve was relatively flat (high SR), or selectivity decreased with size (negative SR). In cases where size dependence was low (high absolute value of SR), L_{50} was often variable, which contributed to the broad confidence intervals for L_{50}. However, the logistic curves described by the combination of these parameters tended to be relatively constrained for the most abundant species and size classes in the catch (e.g. see < 5 cm Arctic cod in Fig. 8). The selectivity estimates tended to be less uncertain for the mod-Marinovich than the Cantrawl (e.g. compare Fig. 8 A-B), as the estimates for the mod-Marinovich are based on more hauls and do not depend solely on the paired trawl experiment, which has a limited sample size and is subject to uncertainty introduced by differences in fish abundance in each trawl path.

Despite the variability in the parameter estimates, the conclusions drawn from the analysis are relatively robust for the size ranges observed in the trawl catches. For example, when the selectivity of the gear for 4 cm individuals as well as the size distribution estimated to be in the environment is considered (Fig. 8), two main conclusions can be drawn: 1) there are strong species-specific differences in the probability of capture. For example, Arctic cod are substantially better retained than saffron cod of equivalent size (see Fig. 9 A-B, keeping in mind that axes differ among plots). 2) Overall, the mod-Marinovich tends to be less selective than the Cantrawl (i.e. Fig. 9, compare left and right box plots in a panel). There is a tendency in many bootstrap realizations for larger capelin to be better retained by the Cantrawl than by the mod-Marinovich (Fig. 9 D), but there is substantial overlap in the bootstrap estimates indicating that this is not consistent among hauls.

4. Discussion

The trawl experiment revealed that there was substantial escapement of small fishes from both the mod-Marinovich and Cantrawl midwater trawls. Escapement from the Cantrawl was higher than the mod-Marinovich for most size/species classes encountered. In general, there was less escapement from the mod-Marinovich, but even for this relatively small net, a surprisingly small fraction (< 10%) of the small fishes in this environment were retained in the codend. It is possible that many of the small fishes in this environment exhibit relatively weak herding responses to the meshes once they enter the trawl which results in a substantial fraction of individuals encountering and then exiting from the meshes. The fish encountered in this study were relatively small, and one should be careful not to extrapolate the resulting selectivity estimates to larger size classes rarely encountered in these catches. The logistic function used to describe size selectivity is constrained to be symmetric about a selectivity of 0.5 (Wileman et al., 1996). Thus the selectivity for size classes absent from the catch cannot be estimated with any confidence..

As documented in previous studies (Nakishima, 1990, Suuronen et al., 1997, Williams et al., 2011), escapement was strongly size and species specific. Although both nets were size selective, the Cantrawl exhibited very low retention of fishes < ~5 cm, which were abundant in this environment. The Cantrawl was not very effective at capturing jellyfish, likely due to negligible herding ability in response to the large meshes that comprise most of the trawl body. Although there was substantial uncertainty in the parameters of the logistic selectivity functions, there was less uncertainty in the selectivity of the mod-Marinovich for the most commonly encountered species and size classes. The observed trawl selectivity indicates that ignoring trawl selectivity and assuming that the trawl catch accurately represents species and size composition has the potential to introduce substantial biases into AT and other trawl-based survey estimates. Although the mod-Marinovich is a relatively small mesh trawl designed to capture small fishes, a surprisingly large fraction of fish entering the trawl are lost through the meshes. The biases introduced by this trawl selectivity, which will be more severe for the Cantrawl, will result in over-estimates of large and easily captured individuals, and underestimates of the less easily captured species and smaller size classes (Nakashima, 1990, Williams et al., 2011).

The catches in the recapture nets on the mod-Marinovich revealed that escapement differs among sections of the trawl. As observed in previous studies employing recapture nets on bottom (Zijlstra, 1969, Matsushita et al., 1993) and pelagic trawls (Nakashima, 1990, Suuronen et al., 1997, Williams et al., 2011, 2013), escapement was size-dependent and tended to be highest in the aft portion of the net. In the case of Arctic cod and Pacific sand lance, escapement was highest in the bottom aft part of the trawl, as has been observed with juvenile pollock (Williams et al., 2011). Escapement for saffron cod was more evenly distributed. It was high in the bottom and sides of both the forward and aft panel, but relatively low in the top panel. Escapement of capelin exhibited a different pattern, with higher escapement in the aft part of the trawl and a tendency towards more escapement in the top rather than bottom panel as observed for the other species. The behavior of capelin is consistent with the observations of Nakashima (1990), who found that capelin escapement in a pelagic trawl tended to be upwards towards the rear of the net.

The observed escapement pattern can be exploited to design more effective nets. For example, the surprisingly high escapement of small fishes observed in the aft section of the mod-Marinovich has motivated us to further modify this net by increasing the length of the aft section to produce weaker flow out of the meshes, and reducing the mesh size to reduce escapement. Smaller, fine-mesh trawls could potentially be used to more effectively sample small fishes such as those abundant in the Arctic Eis survey area. However, small trawls are likely subject to higher avoidance of species and size classes with well-developed swimming capabilities, and may exhibit strong size selectivity. These uncertainties highlight the importance of evaluating trawl selectivity to guide selection of appropriate trawl gear, and to correctly infer the size and species composition in the environment from trawl catches.

The conclusions drawn from this analysis rest on several assumptions. The calculations are based on the assumption that escapement from meshes covered by the recapture nets is representative of meshes without recapture nets, which was not tested. However, recapture nets of a similar design have not been reported to alter the behavior of fish relative to the surrounding uncovered meshes (Nakashima 1990, Matsushita et al., 1993, Williams et al., 2013). In addition, the escapement from the trawl is estimated based on the relatively small fraction of the net covered by the recapture nets. Although the number of meshes covered by the recapture nets is known, the relatively low coverage likely introduces substantial variability as the fraction of the net which is covered by recapture nets is not the same as the fraction of escapees that is recaptured in a given trawl haul, even if escapement from meshes covered by the recapture nets is representative of meshes without recapture nets. This will contribute to the uncertainty in the estimates of escapement, and larger or more recapture nets would reduce this uncertainty. We did not observe strong gradients in size composition of escapees across recapture nets, which indicates that the size distribution in the recapture net are a reasonable approximation of the size distribution of the escapees from the entire net partition.

Furthermore, the analysis of the paired trawls assumes that the average fish density encountered by the Cantrawl and the mod-Marinovich was equivalent. Although the depth range sampled in the paired trawls overlapped substantially, the average headrope depth of the Cantrawl, which was rigged as a surface trawl, was consistently shallower than the mod-Marinovich headrope, and this may introduce biases in the selectivity values estimated for species exhibiting strong near-surface vertical abundance gradients. In addition, it is likely that at a given location, one of the trawls will encounter higher densities or different size distributions due to small-scale patchiness. This will not result in a bias if the two nets encounter the same densities on average, but will increase the variance of the counts in the trawl partitions. This additional variance is captured as between-haul variation in the process of resampling the trawl hauls to generate bootstrap confidence intervals (Millar and Fryer, 1999), and likely contributed to the wide confidence intervals of the selectivity parameters.

We have estimated mesh selection (i.e. the probability that fish will be captured in the codend as opposed to escaping through the meshes), which is only one component of selectivity and does not include selection that takes place in front of the net itself (Wileman, 1996, Suuronen et al., 1997, Heino et al., 2011). The fish in this Arctic environment are small, and mesh selection is likely the primary cause of selectivity. While some species have been reported to lack a strong herding response to the vessel, doors, and bridles (e.g walleye pollock, Somerton, 2004, Williams et al., 2015), the processes occurring prior to the time the fish encounter the mouth of a pelagic trawl remain poorly understood. In most cases, the catch rate was substantially higher for the much smaller mod-Marinovich, which suggests that mesh selection is an important factor in determining selectivity. The larger size classes of capelin may be an exception as this was the only case where the Cantrawl captured more fish per unit volume than the Marinovich. This may suggest that processes occurring prior to when the capelin encountered the net, for example herding by the trawl wings, doors , or bridles, or escapement in front of the trawl (Heino et al., 2011), may have played an important role in the capture of this species. Alternately, because the Cantrawl headrope was fished near the ocean surface (~3 m depth), whereas the average mod-Marinovich headrope depths were ~12 m deeper in the paired comparisons, the increased Cantrawl catch rate may have occurred because greater densities of capelin occurred above the depth sampled by the mod-Marinovich.

The impacts of trawl selectivity on acoustic surveys can be difficult to predict, as errors in species composition that alter the relative abundance of one species or size class will affect the proportion of backscatter assigned to all other species (Simmonds and MacLennan, 2005). The impact of trawl selectivity depends on the species present, their degree of spatial overlap, their size distributions, and their acoustic scattering properties, all of which interact (Williams et al., 2011, De Robertis et al., this issue). A practical method to evaluate the impact of trawl selectivity is to compare abundance estimates with and without accounting for trawl selectivity on species and size composition. For example, in the Arctic Eis acoustic-trawl survey the impacts of trawl selectivity on abundance estimates depend on the trawl gear used and are highly species-dependent. In the case of the 2012 survey, the Cantrawl was used for midwater and surface trawl sampling (De Robertis et al., this volume). The AT survey estimates use the selectivity estimates derived in this study to allocate acoustic backscatter to species. However, if the effects of trawl selectivity are ignored (i.e. by assuming that selectivity = 1 for all species and sizes), the abundance estimate of capelin, which are well-retained and thus over-represented in the catch, increases by > 3 fold (De Robertis et al., this issue). This over-estimate of the abundance of capelin causes the abundance of other, more poorly retained species such as Arctic and saffron cod to decrease by up to ~30 % in this scenario (i.e. backscatter from these species is allocated to capelin). In 2013, the survey results are less sensitive to trawl selectivity estimates as the high-backscatter regions were sampled with the less selective mod-Marinovich and the corrected and uncorrected estimates are thus more similar (De Robertis et al., this issue).

In cases where selectivity is primarily attributable to processes occurring inside the net rather than in front of the net, recapture nets provide a viable method to estimate the selectivity of midwater trawls used in acoustic-trawl surveys, which has been proven difficult to quantify due to the large size of these nets. One practical advantage of the method employed here is that it can be conducted without disruption to survey operations by deploying recapture nets on the survey trawl during the survey. Trawl efficiency is influenced by conditions during capture such as water temperature and light levels (Zijistra 1969, Suuronen et al., 1997, Williams et al, 2011, 2015). By conducting the trawl selectivity work throughout the survey, the range of conditions, such as species and size distributions and environmental conditions (location, sea state, temperature, time of day, light level, etc.) during the trawl selectivity work will be representative of conditions during the survey as a whole, thus reducing the impact of these potential biases. Additionally, this sampling design will ensure that there will be greater sample sizes for many of the more common species, resulting in higher certainty in the selectivity estimates for the most important species. Despite the potential limitations of the methods used in this study, and the relatively large confidence intervals in the selectivity estimates for less abundant species and size classes, the recapture net technique provides a practical method for estimating the first-order effects of trawl selectivity on an acoustic-trawl survey and other studies relying on midwater trawl catches. This is preferable to making the common implicit assumption that the size and species composition of organisms retained in a pelagic trawl reflects the size and species distribution in the environment.

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Table 1: Summary of the most abundant fishes captured in mod-Marinovich hauls equipped with recapture nets. The number of hauls in which a given species was captured, and the total numbers of individuals captured, as well as the number captured in the codend and all recapture nets are listed. The mean and standard error of the fork length of the specimens and the number of specimens measured are also given.

Species	# hauls	Total # captured	# in codend	# in recapture nets	Length (cm) in codend $\bar{x} \pm$ SE, (n)	Length (cm) in recapture nets $\bar{x} \pm$ SE, (n)
all fishes	30	63826	40310	23516	4.6 ± 0.1 (2596)	3.7 ± 0.2 (5814)
Arctic cod	28	38172	25077	13095	4.0 ± 0.1 (941)	3.5 ± 0.2 (2337)
Pacific sand lance	28	11762	8468	3294	5.8 ± 0.1 (302)	5.3 ± 0.1 (473)
saffron cod	16	4319	2057	2262	4.0 ± 0.1 (371)	3.7 ± 0.1 (863)
capelin	20	701	482	219	6.4 ± 0.1 (169)	6.1 ± 0.1 (98)

Table 2. Description of data used to fit logistic size selection for the mod-Marinovich and Cantrawl trawls by species group, and the resulting parameter estimates. The number of individuals captured in the codend of each trawl, the number of hauls of each type where the species group was captured, and the parameters of the point estimates (i.e. estimated with all available data, see Fig. 6) of the logistic selection curves with bootstrap estimates of the 90% confidence intervals for these parameters are listed. L_{50} is the length in cm at 50% retention, and *SR* is the length in cm between 25 and 75% retention. In the case of the Cantrawl selectivity for Pacific sand lance, the point estimate of L_{50} and SR fall outside of the 90% bootstrap confidence interval.

Species Group	No. captured Marin. codend	No. captured Cantrawl codend	No. hauls paired only	No. hauls recapture only	No. hauls paired with recapture	Marin. L_{50} (cm) (90% CI)	Marin. *SR* (cm) (90% CI)	Can. L_{50} (cm) (90% CI)	Can. *SR* (cm) (90% CI)
Arctic cod	26550	23305	5	20	7	6.2 (5.4,7.2)	2.2 (1.6, 3.1)	5.6 (4.2, 6.1)	0.8, (0.1, 0.9)
saffron cod	2055	3406	0	8	5	13.0 (10.1, 26.1)	6.1 (4.2, 14.2)	6.8 (-11.3, 17.2)	1.1 (-0.9, 3.2)
Pacific sand lance	8672	532	4	11	8	13.6 (7.4, 25.4)	5.9 (2.1,15.5)	129.6 (-90.1, 87.0)	34.4 (-24.9,20.8)
capelin	496	13113	4	10	6	31.5 (-56.7, 73.7)	24.7 (-58.9, 63.7)	8.0 (-6.0, 25.8)	1.9 (-10.1, 15.5)
other fishes	5199	462	5	22	8	11.7 (10.1, 31.3)	5.3 (4.3, 15.7)	13.5 (9.7, 34.7)	2.7 (1.7, 8.2)
jellyfish	7598	1939	4	21	9	4.1 (2.0, 4.7)	1.8 (0.1, 2.1)	66.0 (-145.6, 397.1)	36.0 (-94.8, 236.8)

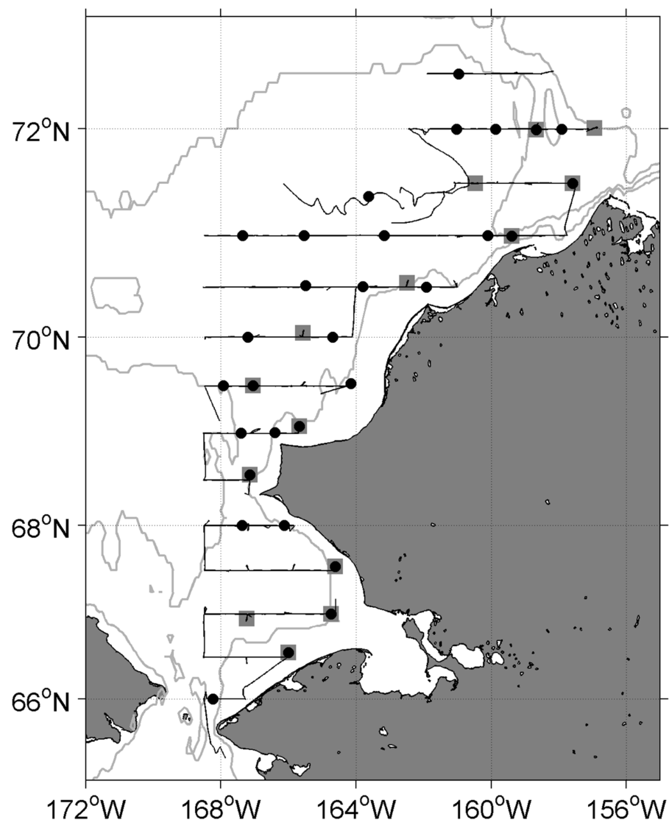
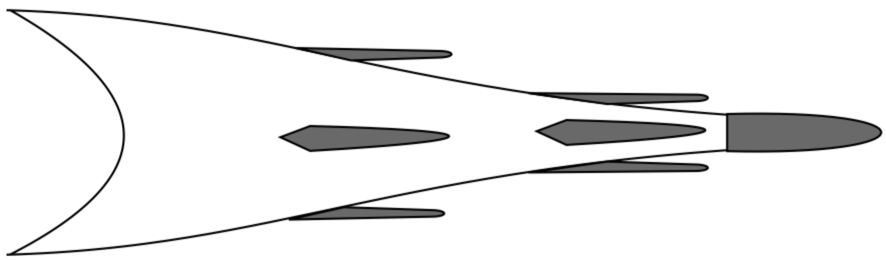


Figure 1. Map of the study area. The locations of paired Cantrawl and mod-Marinovich trawl stations are shown as grey squares, and stations where the mod-Marinovich was fished with 8 recapture nets are given as black circles. Locations with both a circle and a square indicate the trawl stations where paired trawls and resample nets were deployed. The vessel survey track is shown as a black line and the 25, 50 and 100 m depth contours are shown as grey lines.



Section	Forward	Aft	Codend
Stretched mesh size (cm)	6.4,6.0	4.8	3.8 cm with 0.3 cm liner
Approx. length (m)	2.9,3.2	4.3	3.3
Fraction sampled	0.022	0.055	1.0

Figure 2. Illustration of recapture nets used on mod-Marinovich fishing trials. The figure depicts the net viewed from the side with recapture nets on the forward and aft sections of the symmetrical top, side, and bottom panels visible. The two forward panels of different mesh sizes are designated as the forward section, the aft section as a single unlined panel, and the codend consists of the aft section lined with a fine-mesh liner (see section 2.1 for details). The sampling fraction represents the ratio of the number of meshes covered by the recapture net or the codend and the total number of unlined meshes in each section.

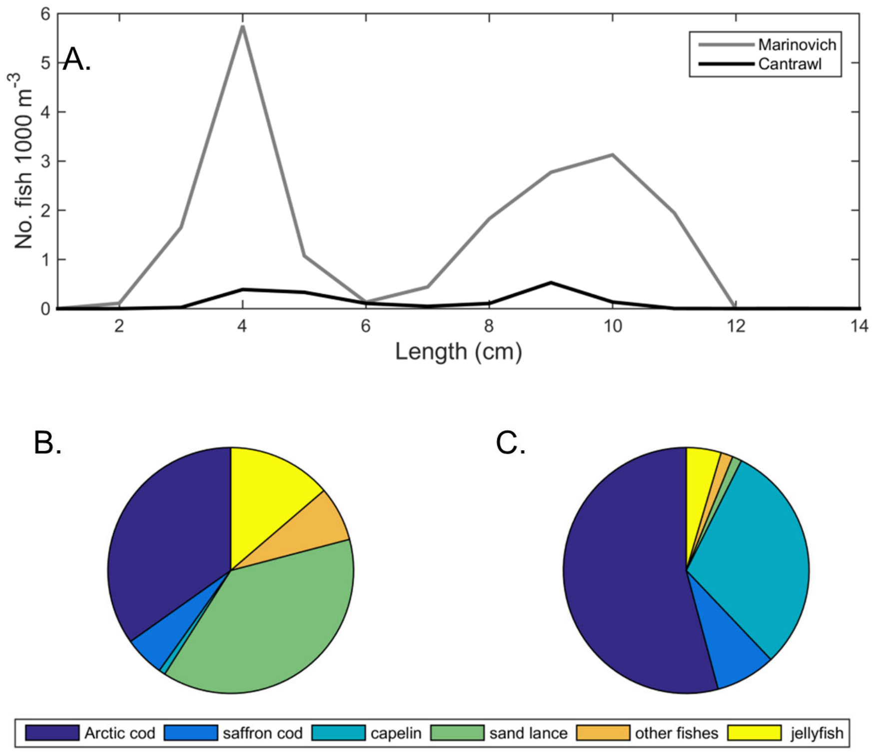


Figure 3. Summary of codend catch in the 14 locations where paired mod-Marinovich and Cantrawl hauls were conducted. A) Abundance of fishes by length captured by each trawl (all species combined). The pie graphs show the catch composition (by number) of B) the mod-Marinovich catch and C) the Cantrawl catch at these locations.

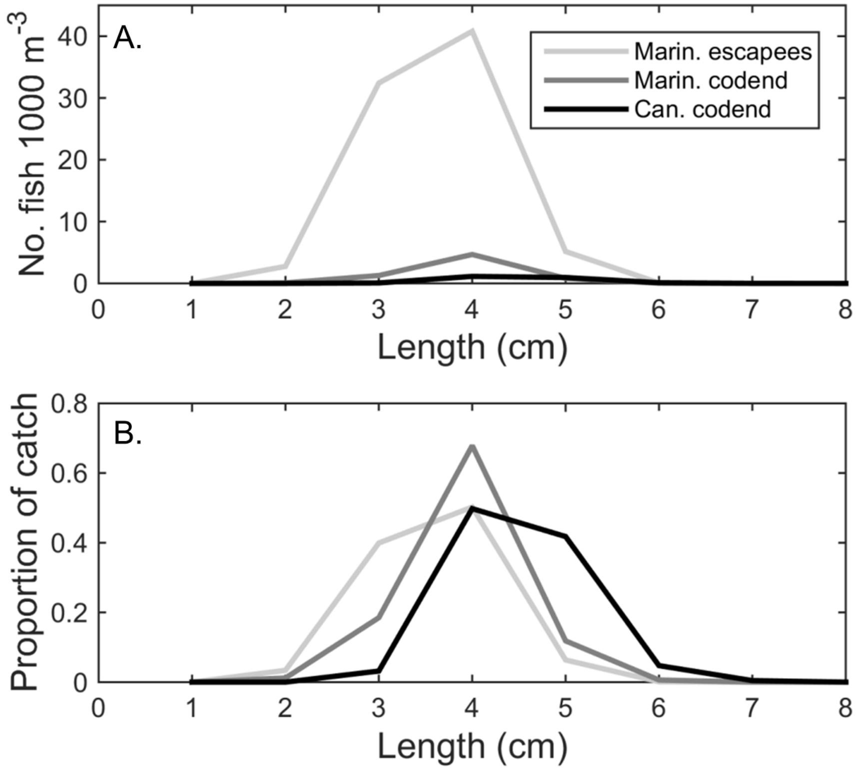


Figure 4. Abundance and size distribution of Arctic cod escaping from the mod-Marinovich trawl, and those captured in the mod-Marinovich and Cantrawl codends. The catches represent the catch in the 7 hauls where the mod-Marinovich with recapture nets and Cantrawl net were deployed and Arctic cod were caught. A) Abundance of fish as a function of length estimated to escape from the mod-Marinovich based on the recapture net catches and abundance of those captured in the codends of the mod-Marinovich and Cantrawl trawls. Abundances of escapees are computed by extrapolating the recapture net escapement over the body of the net. B) Size distribution of juvenile Arctic cod in recapture nets, and the codends of the mod-Marinovich and Cantrawl trawls.

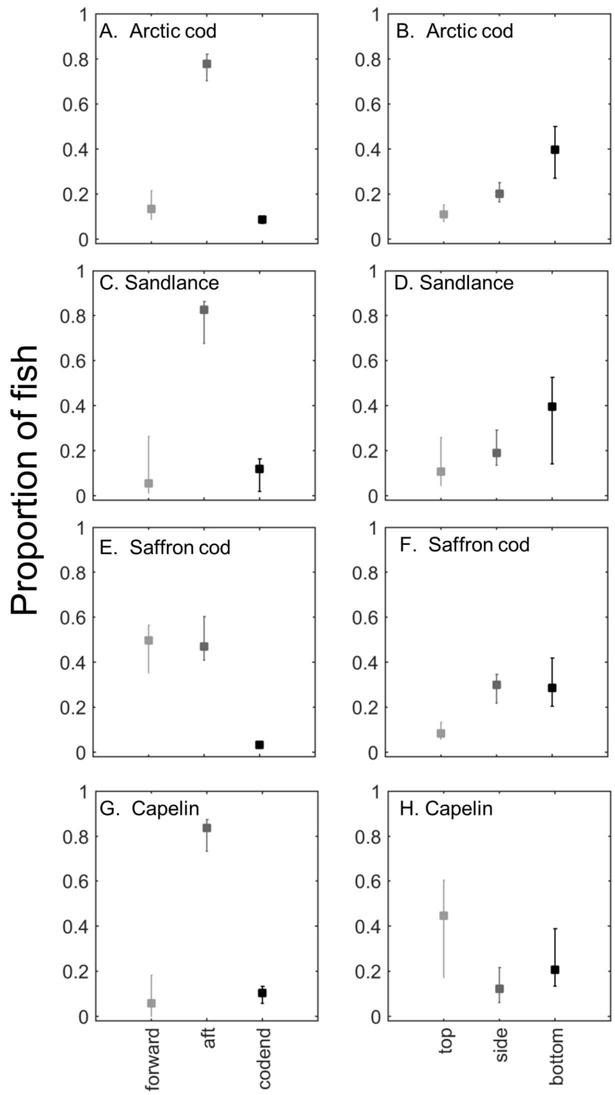


Figure 5. Escapement pattern in mod-Marinovich for abundant fish species derived from recapture net catches. A-B) Arctic cod, B-C) Pacific sand lance, E-F) saffron cod, G-H) capelin. Panels on the left indicate the proportion of fish entering the trawl mouth estimated to either escape through the forward or aft net sections or be retained in the codend. Panels to the right depict the proportion of individuals expected to exit the net through the meshes in the top, either side (i.e. total escapement from both sides divided by 2), and bottom of the trawl. The points represent the observed means, and error bars represent 95% bootstrap confidence intervals.

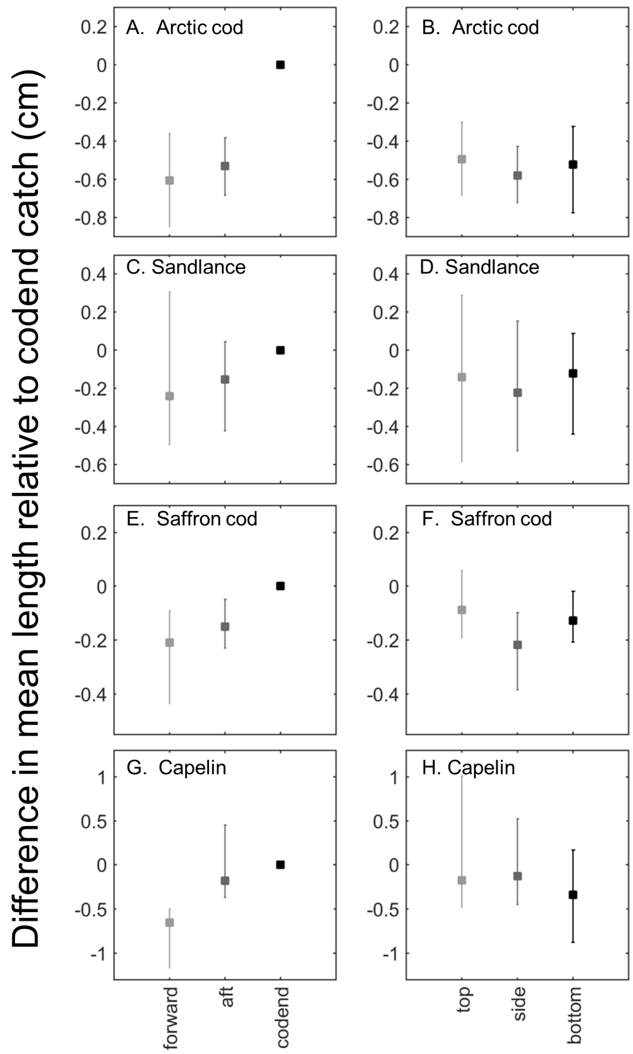


Figure 6. Size of fishes escaping from and retained in the mod-Marinovich based on catches in the codend and recapture nets. A-B) Arctic cod, B-C) Pacific sand lance, E-F) saffron cod, G-H) capelin. Panels on the left indicate the mean difference in length between fish captured in forward and aft recapture nets and those retained in the codend. Panels to the right depict the mean difference in length of fishes captured in the top, side and bottom recapture nets. The points represent the observed means, and error bars represent 95% bootstrap confidence intervals.

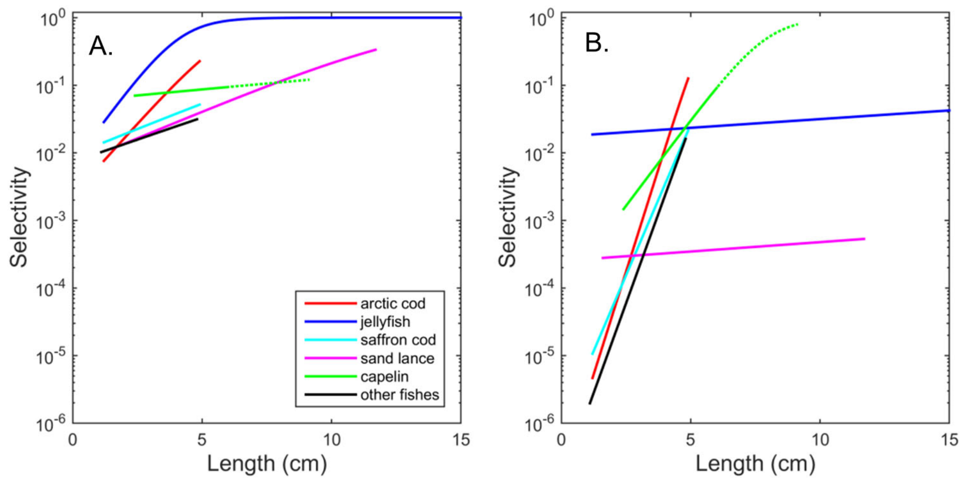


Figure 7. Estimates of size-specific selectivity by species group for A) mod-Marinovich and B) Cantrawl trawls derived from joint analysis of catches in the mod-Marinovich recapture nets and codend catches in both trawls. The logistic selectivity curves fitted in the model are depicted on semi-log plots as the probabilities of retention are low for small individuals. The predicted selectivity at a given size was higher for the mod-Marinovich than the Cantrawl except for the case of large capelin where the dotted green indicates that the calculated selectivity for capelin is higher for the Cantrawl. The curves extend over the size range encompassing 99% of the fish in the environment (as estimated by combining the mod-Marinovich codend catch with the recapture nets, equation 13). Note that the corresponding size range for jellyfish extends to 26 cm, but results are truncated to 15 cm to increase the visibility of the results for the other species.

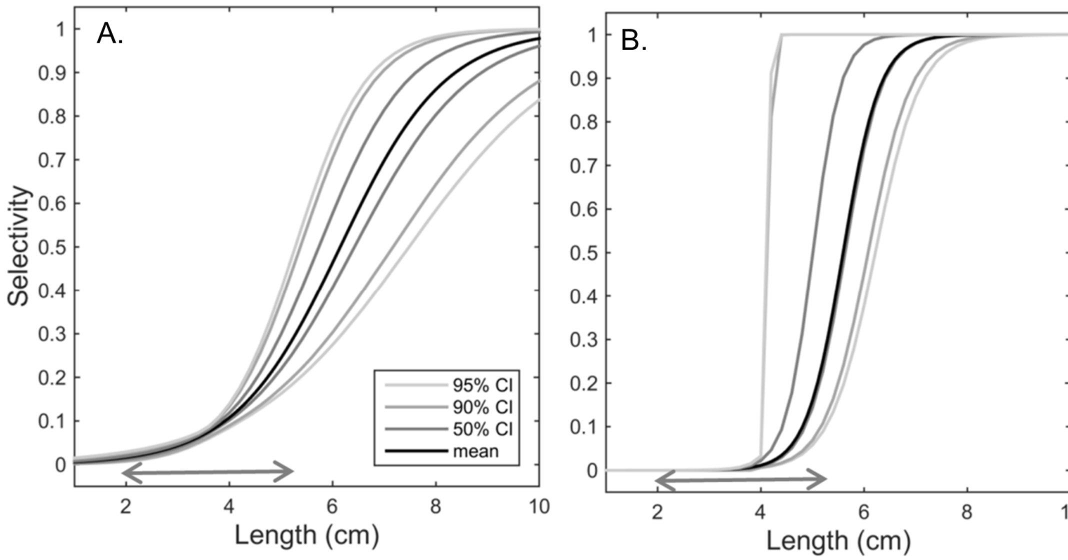


Figure 8. Confidence intervals (CI) of selectivity of A) mod-Marinovich and B) Cantrawl trawls on Arctic cod generated by taking the 95th, 90th and 50th percentiles of 10000 bootstrap estimates. The lower 50% CI in panel B is very close to the black line representing the mean value and is difficult to visualize. The arrows indicate the size range of 99 % of Arctic cod individuals as estimated from the mod-Marinovich catches.

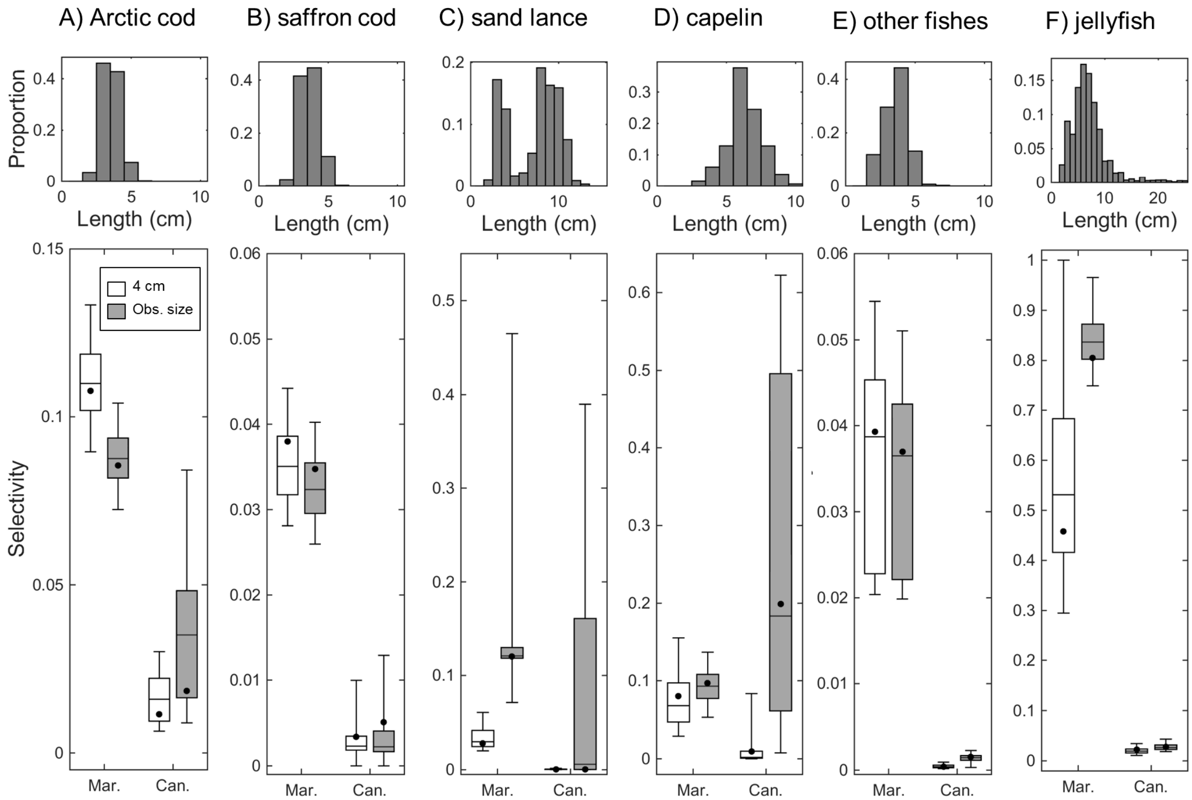


Figure 9. Bootstrap analysis of the variability in estimates of mod-Marinovich and Cantrawl selectivity for different species groups: A) Arctic cod, B) saffron cod, C) Pacific sand lance, D) capelin, E) other fishes, F) jellyfish. The top panel shows the size distribution estimated to be present in the environment based on 30 hauls with the mod-Marinovich equipped with recapture nets (eq. 13). The histograms extend over the size range encompassing at least 99% of the fish in the environment. The bottom panel shows box plots of bootstrapped probabilities of retention of a 4 cm individual (white boxes), and the probability of capturing animals with the size distribution in the upper plot. The boxplots represent the 5^{th}, 25^{th}, 50^{th}, 75^{th} and 95^{th} percentiles of the selectivity estimate for an organism of a given size. Estimates of selectivity using parameters derived from all available data (Table 2) are shown as a black dot.