**Escaping the net: Assessing midwater gear selectivity for the Joint United States and Canada Integrated Ecosystem and Pacific hake (*Merluccius productus*) Acoustic-Trawl survey**

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## Abstract

Acoustic-trawl surveys use trawl catches to validate the species and size composition of fish aggregations detected acoustically. However, certain sizes of fish may be more likely to escape some trawls, which can bias the size and age distribution of the catch used to estimate biomass. To quantify size-selectivity, we studied 3 midwater trawls used for the United States and Canada joint survey of Pacific hake (*Merluccius productus*). The survey most recently used an Aleutian Wing Trawl (AWT) with different codend liners until 2023, then switched to a Multi-Function Trawl (MFT) in 2025. To prepare for the switch, we assessed differences in escapement and catch rates using recapture nets, and in paired trawls of both net-types sampling the same aggregations. All nets retained greater than 85% of hake longer than 30-cm (age 2+). In general, the MFT was more efficient than the AWT, with near full retention of all sizes. A substantial fraction of small hake (age 0 to 1) escaped the AWT. A power analysis indicated a low probability of detecting differences in escapement from the AWT with different liners. Gear selectivity information is important to improve the accuracy of fishery survey data and account for changes in sampling gear.

## Introduction

Acoustic-Trawl Method (ATM) surveys are used to estimate the distribution and abundance of pelagic fish populations. These populations are often patchily distributed across vast ocean areas but relatively easy to detect with active acoustic sensors and to sample with midwater trawls (Everson et al., 1996; Horne, 2000; Simmonds and MacLennan, 2005). The ATM surveys of pelagic fish populations rely on active underwater acoustics to detect targets of interest and sampling by a trawl to identify the species, size, and age composition of the acoustically-detected aggregations. Trawling is an essential component of an ATM survey because the composition of an aggregation is often difficult or impossible to discern from the acoustics alone (Horne, 2000). The composition of the aggregation obtained by trawling is used to estimate fish numbers-at-length, the age distribution, and biomass by applying a species-specific, length-based acoustic target strength calculation to apportion the acoustic backscatter (Traynor, 1996; Simmonds and MacLennan, 2005). Thus, the trawl samples provide information on the composition of different fish aggregations and the acoustic backscatter informs the density. The acoustically derived biomass estimates observed along survey transects are interpolated within a geographic area to estimate total population biomass and distribution (NMFS, 2005; Simmonds and MacLennan, 2005).

The reliance on trawling to sample acoustically-detected fish aggregations depends on the assumption that trawl catches accurately represent the composition of a sampled aggregation. The ideal scientific trawl for an ATM survey would be one that captures all fish, and other organisms, that produce acoustic backscatter with equal probability. This presents several challenges from both the conceptual design and practical deployment of sampling gear. While the use of trawling to confirm species identification of midwater pelagic fishes is well established (Simmonds and MacLennan, 2005; Thomas et al., 2024), less is known about how variations between different trawl net designs may bias what sizes of fish are caught (Williams et al., 2011). Trawl nets used in ATM surveys are often modifications of nets used by the commercial fishing industry, which are typically larger in overall size and designed to capture certain sizes of fish. Size-selective nets benefit the fishing industry by minimizing the bycatch of unwanted species and/or certain sizes while maximizing the retention of fish that are most profitable. However, a size-selective net that is desirable for commercial fisheries can be problematic for fisheries surveys, particularly if any biases related to net selectivity are not accounted for. This includes the potential for greater escapement of small fish from the net relative to large fish.

The consequences of a size-selective net vary depending on the type of aggregations encountered. In aggregations composed of only small, or only large fish, there is little concern of biased sampling because any escapement from the net is expected to be proportional (Williams, 2013). In aggregations with mixed sizes of fish, a selective net could allow a greater escapement of small fish relative to large fish resulting in an underrepresentation of small fish and overrepresentation of large fish in that sample. Biased size-selection has the potential to introduce errors into the estimates of fish abundance-at-length, age distribution, and total biomass. For example, a 2018 survey of Walleye pollock (*Gadus chalcogrammus*) in the Gulf of Alaska found fish abundance (mainly of small fish) was underestimated by up to 20% and biomass (mainly of large fish) overestimated by up to 9% when not accounting for the size-selectivity of the trawl used to sample fish[1]. This was a year when the population was dominated by large adults with some mixing of small age 1 fish. A simulation of Walleye pollock survey data found that a greater mixing of juveniles and adults, which sometimes occurs, has the potential to overestimate biomass by up to 40% when net size-selectivity is not accounted for (Williams, 2013). These studies highlight the importance of quantifying the size-selectivity of sampling gear for ATM surveys to adjust for potential size bias in the estimate of fish biomass.

Various methods to measure the size-selectivity of different types of fishing and survey gear have been developed (Wileman et al., 1996). Trawl nets capitalize on aggregating fish

[1] National Marine Fisheries Service. 2019. NOAA processed report 2019-05, 101 p. [Available at https://doi.org/10.25923/rt3f-b427]

behavior by herding fish through a wide mouth into a tapering codend, where fish density increases and escapement from the net is most likely to occur (Williams et al., 2013). Size-dependent escapement has been measured for midwater trawls by attaching small recapture nets, also called pocket nets, to the outside of the main body of the trawl on panels of different mesh sizes and distance from the codend (Nakashima, 1990; Dremière et al., 1999; Williams et al., 2011). This method assumes that some fraction of fish that escape through a side panel before entering the codend are recaptured in a pocket net. By comparing the length distribution of fish retained in the codend to escaped fish recaptured in pocket nets, size-selectivity relationships can be developed to estimate the probability that a fish of a certain size entering the net will be retained in the codend (Williams et al., 2011). This length-based probability estimate can then be applied to correct for bias in the length-frequency distributions of trawl samples due to size-dependent escapement for more accurate estimates of fish numbers-at-length, at-age, and biomass[1].

Pacific hake (*Merluccius productus*), also called Pacific whiting (hereafter, hake), is one of the most abundant and productive fish species of the California Current Ecosystem in the Northeastern Pacific Ocean (Grandin et al., 2024). Hake are generally found along the west coast of North America from southern California, United States of America (U.S.) to British Columbia, Canada. Individuals can grow in length to greater than 75-cm and can live to 20 years (Ressler et al., 2007). Females mature at a relatively young age with 50% of females successfully producing eggs between 1.9 to 3.2-years of age, depending on region and environmental conditions (Head et al., 2025). Hake consume large amounts of krill, as well as fish, including myctophids, smelt, anchovies, herring, and even cannibalize younger hake (Ressler et al., 2007; Bizzarro et al., 2023; Wassermann et al., 2024). This large standing stock of biomass plays an important role in ecosystem dynamics since hake are both predators and prey, depending on life stage (Hicks et al., 2013). Hake migrate north along the continental shelf in the summer months to feed, typically forming large aggregations at midwater depths of 50 to 500-meters during day-light hours, making them accessible for commercial midwater trawls (Ressler et al., 2007; Hamel et al., 2015). The hake fishery is the largest by volume on the west coast, and is managed jointly by the U.S. and Canada (NMFS, 2025b).

The U.S. and Canada have used an ATM approach to survey hake in west coast waters of the U.S. and Canada jointly since 2001 in support of international fisheries management under the Pacific Hake/Whiting Treaty[2]. The Joint U.S.-Canada Integrated Ecosystem and Pacific hake Acoustic Trawl survey (hereafter, hake survey) is conducted by the National Oceanographic and Atmospheric Administration's (NOAA) Northwest Fisheries Science Center (NOAA) and Fisheries and Oceans Canada (DFO). The hake survey occurs biennially in the summer months (June to September) and generally surveys shelf and shelf break waters from Point Conception, California, U.S. to northern British Columbia, Canada (Ressler et al., 2007; Thomas et al., 2024). The survey is extended as far north as southeast Alaska, U.S. in some years if hake are encountered on the northernmost transects. Using active acoustics and midwater trawls, the joint survey for hake provides information on age, length, abundance, and distribution to inform a biennial index of age-1 abundance, and age-2+ biomass for stock assessment.

The U.S. and Canada both used a 24/20 Aleutian Wing Trawl (AWT) in recent years to validate the acoustic signal. The AWTs used by each country are the same size and configuration

[2] National Marine Fisheries Service. 2024. NOAA Processed Report NMFS-NWFSC-PR-2024-01, 43 p. [Available at https://doi.org/10.25923/j8qt-kx31]

but with different liners in each of the codends of 32-mm and 8-mm mesh size, respectively. The AWTs are assumed to effectively retain age 2+ hake, although this has not been quantified. In 2023, a new trawl net was developed to support the integration of the U.S. portion of the hake survey with the NOAA Southwest Fisheries Science Center's California Current Ecosystem survey of Coastal Pelagic Species (hereafter, CPS survey). The Multi-Function Trawl (MFT) design differs from the AWT in several ways, which allows the net to be fished at surface and midwater depths and to target a range of pelagic species of different sizes (NMFS, 2025a). Important design differences include 2 additional finer mesh panels adjacent to the codend, and an 8-mm mesh liner of the codend, similar to the DFO's AWT (Fig. 1). The lack of information about the size-selectivity of the 2 AWTs with the different liners, as well as design differences of the MFT relative to the AWT, limits our understanding of how a change in trawl nets may influence estimates of abundance and biomass that inform fishery management.

The aim of our study was to compare the 3 nets most recently used to survey hake (NOAA's AWT, DFO's AWT, and the MFT) to quantify species- and size- selectivity, and to assess differences in catch efficiency, which could also influence survey methods in the amount of time nets are towed and time to process the catch. We accomplished this by using a combination of recapture 'pocket' nets attached to each net, and a series of paired trawl trials of the MFT and DFO's AWT fishing on the same fish aggregations. We hypothesize that the MFT is less selective due to its design, meaning that it will retain a greater fraction of small hake and other small-sized organisms compared to the AWT, where a greater escapement of small hake is predicted. We also expect that the MFT will be more efficient at catching hake due to a larger mouth area relative to the AWT. These results are important for correcting potential sampling bias and to standardize survey data collected by different trawls.

## Materials and methods

### Trawl nets

The Aleutian Wing Trawl (AWT, [Net Systems[3], Bainbridge Island, WA]) was used in the U.S. portion of the hake survey from 2005 to 2023 and the Canadian portion from 2021 to 2023. The AWT is a 4-seamed net, meaning it has 4 side panels attached to 4 riblines, and was designed for commercial midwater fishing on pelagic, aggregating fishes. The 2 AWTs are the same design, but the codend mesh liner in NOAA's AWT is 32-mm mesh, whereas DFO's AWT has 8-mm mesh. The new Multi-Function Trawl (MFT, [Swan Nets[3], Seattle, WA]) is also a 4-seamed net; and was also a modification of commercial fishing nets but was designed as a scientific trawl to support NOAA's new Integrated West Coast Pelagics Survey in U.S. waters starting in 2025 (NMFS, 2025a). Important design differences among the 3 nets include an approximately 15% larger mouth opening of the MFT relative to the AWT, a more streamlined taper of the MFT, which has panels of increasingly smaller mesh that transition more quickly from large to small along the net from the mouth to the codend, culminating in 2 finer 50-mm mesh panels adjacent to the codend, and differences in the size of mesh lining each of the codends (Fig.1). The MFT has a similar 8-mm mesh liner to DFO's AWT, which is a finer mesh liner than NOAA's AWT. The trawl support systems also differ between the 2 net designs, which include the shape of the trawl doors, bridle configurations, and differences in the attachment points of the rigging to the doors (Table 1). Fishing performance is tracked in real-time with a net mensuration system that provides visualization of the position of the net while fishing, size and shape of the trawl

[3] Mention of trade names or commercial companies is for identification purposes only and does not imply endorsement by the National Marine Fisheries Service, NOAA.

opening, and the relative quantity of fish entering the mouth. This information is used to assess how well the net is fishing and to adjust the duration of the trawl to control the catch size.

**Recapture 'pocket' nets**

Recapture ('pocket') nets were designed at Net Systems based on previous work conducted by NOAA's Alaska Fisheries Science Center (Williams et al., 2011). The dimensions of each pocket net were the same for all 3 nets. The diamond-shaped mouth of each pocket net was 1.62-m by 1.62-m, which matched the diamond shaped meshes of the trawl. The flat length (mouth to tail) of each pocket net was 9.75-m in length, which was designed to minimize drag on the net by flying at 7.97-m in length and allowing the pocket net to shed water efficiently and not disturb the net while fishing (Tamura[4]). The mesh size of the pocket nets matched the mesh size of the codend liner for each respective net based on standard procedures for pocket net testing (Wileman et al., 1996). The pocket nets were sewn onto the outside of the main net and the tails folded inward and strapped closed with Velcro to create an effective codend for each pocket net.

The original experimental design called for each of the 3 trawls to be outfitted with 12 pocket nets to quantify the escapement of fish from different sections of the net (Williams et al., 2011). Pocket nets were attached to sections made of 100-mm, 200-mm, and 800-mm size mesh (Fig. 1). Each section had a pocket net set comprised of 4 pocket nets attached to the top, bottom, port, and starboard panels of the trawl. Both NOAA's AWT and the MFT had 3 sets of pocket nets, resulting in 12 total. Only 6 pocket nets were built for DFO's AWT due to supply chain issues in acquiring enough fine mesh material for all 12 pocket nets. Four of these 6 pocket nets were attached to the 100-mm mesh size section on the top, bottom, port, and starboard panels,

[4] Tamura, K. 2024. Personal commun. Net Systems, Bainbridge Island, Washington, USA.

and the remaining 2 pocket nets were attached on the top and bottom panels of the 200-mm mesh section. The DFO AWT did not have pocket nets on the 800-mm mesh section.

## Research design and paired trawling

Net testing occurred from July through August 2024 (Table 2). The objective was to build a database of species composition and size-selectivity for each of the 3 nets, and to directly compare the catch efficiency of the MFT with DFO's AWT. The NOAA AWT was deployed on Leg 1 (5 July 2024 to 25 July 2024) of the research survey from the NOAA Ship *Bell M. Shimada* (hereafter, the *Shimada*) in coastal waters off California (Table 2, Fig. 2). This was an area where previous surveys had found mixed size aggregations of age 1 and adult hake. Modified survey year protocols were used to scout for aggregations of hake in a zig-zag pattern from north to south. A trawl was deployed when an aggregation was observed acoustically. If the aggregation was hake, the ship continued to scout 5-nm north or south along the isobath to map the spatial extent of the aggregation while the catch was being processed. If the aggregation extended beyond 5-nm, a second trawl was set 2-nm north or south (depending on the direction of the scout) from the location of the first trawl. A third trawl was set another 2-nm away. The ship returned to scouting for a new aggregation after 2 to 3 successful trawls or after the first trawl if the aggregation was too small or did not catch hake.

During Leg 2 of the research survey, from 1 August 2024 to 21 August 2024, the *Shimada* switched to deploying the MFT and began conducting trawls in central California to assess species composition and size-selectivity as done for NOAA's AWT on Leg 1. The *Shimada* then moved north and was joined by the Canadian Coast Guard Ship *Sir John Franklin* (hereafter, the *Franklin*), from 10 August 2024 to 18 August 2024 fishing in coastal waters off northern California and Oregon. The 2 ships worked in coordination to conduct paired trawls of the MFT, deployed from the *Shimada*, and DFO's AWT, deployed from the *Franklin*, fishing on the same acoustically detected aggregations of hake.

The paired trawls followed the scouting protocols of Leg 1, and once hake were located, alternated fishing on the same aggregation. The paired trawls were either side-by-side at the same time, targeting a hake aggregation separated by 500-meters (m), or (more often) one-after-the-other depending on ocean conditions. All trawl operations occurred over a similar depth profile and towing orientation.  Both ships transited across the same trawl target point to confirm a similar acoustic sign was observed before conducting the trawl.

**Biological sampling**

For all trawls, both ships recorded the time that the net was deployed as when the trawl doors entered the water, the time at arrival of the net to the target fishing depth, the time at haul back, and the time when the trawl doors reached the surface. Trawl duration was calculated as the amount of time elapsed from reaching target depth to haul back, in minutes. Trawl duration was used as a measure of effort to compare catch efficiency between the DFO AWT and MFT nets for the paired trawls. The other time measurements were used to better understand potential differences in fishing styles between the 2 ships, such as deployment and retrieval rates of the trawls, which could influence the escapement of fish from the net.

The content from each partition, the trawl codend or individual pocket net, was sorted independently. Respective catches were placed in labeled baskets to measure the size and species composition of each partition. All fish were counted and identified to species or to the lowest taxonomic level possible. For each pocket net, all hake were measured for length and weight.

From the codend, a random subsample of approximately 400 hake were similarly sampled for length, and 50 of those randomly selected for enhanced sampling of individual weights.

A subsampling expansion factor was calculated for any subsampled catches in the codend as the ratio of the total weight of the catch to the subsample weight. The expansion factor was used to expand the subsample count to a total count for each species or used as a weighting factor in the size-selectivity analysis. Subsampling the codend was common, with 41 out of 51 hauls among all 3 nets that caught hake in the codend subsampled. Species composition was calculated as the proportion by weight of the total codend catch in kilograms (kg).

**Recapture 'pocket' net expansions**

The pocket net catches measure escapement from only a small area of the net and were thus expanded to a representative area of the trawl to estimate escapement from different sections of the net (Williams et al., 2011). For example, pocket nets on the 100-mm mesh section were expanded to the total area of 100-mm meshes of the trawl for each side panel. Since pocket nets were only attached to the 100-mm, 200-mm, and 800-mm mesh sections, we only considered escapement from these sections and did not consider escapement from sections of the net with mesh sizes greater than 800-mm or less than 100-mm. The MFT was the only net with mesh panels finer than 100-mm, which were the 50-mm mesh sections adjacent to the codend (Fig. 1).

The DFO AWT had 6 pocket nets compared to 12 on both the NOAA AWT and MFT, so we explored 2 methods to expand the pocket net catches to estimate escapement that would be comparable to the 2 other nets. The first method was a 'direct' expansion method. The direct method expanded each pocket net catch to its representative mesh size area using only the 100-mm and 200-mm pocket nets present on all 3 nets (Suppl. 1, Table SM1-1). This ensured that escapement estimates were comparable among all 3 nets but only estimated escapement from the 100-mm and 200-mm mesh sections of each net. Because DFO's AWT only had 2 pocket nets on the 200-mm section, catches from the 2 pocket nets in the 200-mm section were each doubled to estimate escapement from the 200-mm mesh size section. We used this 'direct' recapture expansion method for all subsequent analyses for a standardized comparison among nets.

In Supplemental Materials 1, we also explored a second, 'full' expansion method. The full expansion method included expansion of the 800-mm pocket net catches of NOAA's AWT and the MFT, which were not present on DFO's AWT (Suppl. 1, Table SM1-2). We used the full expansion of recaptures from NOAA's AWT and the MFT compared to the direct 100-mm and 200-mm pocket net expansion method to better understand how not including data from the 800-mm section would influence the estimates of the size-selectivity parameters.

**Species composition**

We assessed differences in species composition of codend catches by comparing the proportion of hake by weight in the codend among the 3 nets. Non-hake species that represented greater than 1% of the catch by weight, or were of special interest were separated into different taxonomic groups for comparisons. These included prey species of hake (e.g., myctophids), other important forage species (e.g., anchovy), and fish species with swim bladders that also scatter sound at 38-kHz (e.g., rockfish), which was the frequency used to identify hake.

**Catch efficiency**

Data from the sets of paired trawls on Leg 2 were used to assess differences in the catch efficiency between the MFT and DFO AWT nets. Both nets had an 8-mm mesh liner in the codend, which allowed for a direct comparison of catch rates. The general approach was to calculate the proportion of a paired trawl catch attributed to the focal net, which was the MFT in our study, for hake of different length (Kotwicki et al., 2017; NMFS, 2024). Proportions were calculated for different length classes to understand how differences in catch efficiency may vary by the size of the fish. The approach assumes that for each set of paired trawls, both nets sample the same aggregation, meaning that the same species, sizes, and numbers of fish are equally likely to be captured by both nets and that the same proportion of fish could escape either net. Deviations from these assumptions, especially for paired trawls on small and patchy aggregations, contribute to inherent variability in the paired trawl catches.

To compare catch rate efficiency for different lengths of hake, we first calculated the catch-per-unit-effort (CPUE) for each net in terms of the number of hake caught per trawl minute by length bin to compare a standardized number of fish entering the net and retained in the codend. To maximize the number of data points for the analysis, we binned fish into 5-cm length bins (NMFS, 2024). Next, we used the CPUE of each net to calculate the catch efficiency ratio ($p\_MFT$) for each set of paired trawls $s$ and each length bin $l$ in that set:

$$p_{MFT_{sl}} = \frac{CPUE_{MFT_{sl}}}{CPUE_{MFT_{sl}} + CPUE_{AWT_{sl}}} \;. \quad (1)$$

The catch efficiency ratio is thus the proportion of the catch rate in each length bin attributed to the MFT relative to the combined catch rate of both nets for each set of paired trawls (Kotwicki et al., 2017; NMFS, 2024). The catch efficiency ratio is a continuous variable of proportions and bounded by 0 and 1.

To understand how catch efficiency may differ between nets by fish size, we fit a beta regression to the catch efficiency ratios over the range in observed lengths. A beta regression is appropriate to model data that are proportions, but cannot accommodate exact 0s or 1s, so we first rescaled the data to slightly shift values away from 0 and 1 before fitting the beta regression (Douma and Weedon, 2019; NMFS, 2024):

$$p_{MFT_{sl}} * = \frac{p_{MFT_{sl}}(n-1) + 0.5}{n} . \quad (2)$$

In equation (2), $p\_MFT_{sl} *$ is the rescaled catch efficiency ratio, of which the data no longer contain exact 0s or 1s, and $n$ is the number of observations.

We modeled the rescaled catch efficiency ratios using a beta distribution with mean $\mu$ and precision $\phi$ (Ferrari and Cribari-Neto, 2004):

$$p\_MFT_{sl} * \sim Beta(\mu, \phi) . \quad (3)$$

The expected mean proportion of the catch rate attributed to the MFT was modeled as a linear function of fish length $L$ using a logit link function (Douma and Weedon, 2019):

$$E(p\_MFT_{sl} *) = \mu = \frac{1}{1 + e^{(\alpha_\mu + \beta_\mu L)}} . \quad (4)$$

The estimated parameters $\alpha_\mu$ and $\beta_\mu$ are the intercept and slope, respectively, for the effect of fish length on the mean proportion. Precision was estimated as a single value and not dependent on fish length (Douma and Weedon, 2019).

To account for vastly different catch rates among the different length bins, which ranged from less than 1 fish per minute as a combined CPUE to greater than 10,000 fish per minute for some length bins, the catch efficiency ratios were weighted by the combined catch rate for each length bin and each set of paired trawls (i.e., weighted by the denominator of equation 1, [Douma & Weedon, 2019]).

We compared differences in catch efficiency between the MFT and DFO's AWT for both the *codend* and the *total catch*. The codend catch represented only fish retained in the codend. The total catch was the sum of fish retained in the codend and the estimate of escapement from the net using the number of hake recaptured in pocket nets expanded to the representative area of the net. Thus, the total catch provided an estimate of the number of hake entering the net prior to escapement, and the codend catch reflected only retained hake. The total catch efficiency comparison was used to show potential differences in catch rates of fish entering the net, with an expected slope of 0 (i.e., $\beta_\mu = 0$) if both nets were equally likely to encounter fish of the same sizes. The codend catch efficiency comparison reflected potential differences in the retained catch, where some fish may have entered the net but then escaped through the sides. Because of this, the slope of the regression was expected to be different than 0 if one net selectively retained a greater fraction of a certain size class of fish, such as small fish, relative to the other net.

The 95% confidence intervals of the expected means for the beta regression were estimated by bootstrapping (NMFS, 2024). For bootstrapping procedures, catch efficiency ratios were simulated by randomly sampling the sets of paired trawls 1000 times, with replacement, and fitting a beta regression to each simulation. We then extracted the 2.5 and 97.5-percentiles of the predicted values for each length bin to obtain the 95% confidence intervals. Confidence intervals that did not overlap with 0.5 indicated a significant difference in the catch efficiency of the MFT relative to DFO's AWT.

**Size-selectivity**

To first understand which sizes of hake could physically fit through different size mesh, we developed a relationship of fish length and girth and compared this to the perimeter measurement of different mesh sizes of the nets. We measured fish length in centimeters (cm), head girth (cm), and maximum body girth (cm) for a subset of hake to develop a linear relationship of body length and girth (Mendes et al., 2006). We fit a simple linear least squares regression to the data of the form $y = mx+b$. This relationship was then compared to the perimeter measurement of different sized diamond shaped meshes, where the perimeter measurement was the sum of lengths (cm) from knot to knot around the 4-knot diamond mesh. Both the perimeter and body girth measurements clarified what sizes of hake could, or could not, physically escape from different mesh sizes not represented by pocket nets (i.e., finer than 100-mm). This allowed us to better understand the potential for escapement from the 2 50-mm mesh size panels on the MFT, which did not have pocket nets and were not present on the AWTs, and the potential for escapement from the different sized liners of each codend.

Next, we used pocket net data to fit length-based size-selectivity relationships for each net. This analysis used pocket net data from the 100-mm and 200-mm mesh sections of each net for both the paired and unpaired trawls. We estimated length-based size-selectivity for hake as the probability that a fish of a given length was retained in the codend when entering the net. The data were binomial, where fish retained in the codend were coded as '1' and fish escaping into a recapture net were coded as '0'. Lengths were rounded to the nearest 1-cm. For the size-selectivity model, we used the raw, subsampled data of measured fish weighted by the combined expansion factors for each partition of either the codend or a pocket net. The combined expansion factors were the subsampling expansion multiplied by the recapture expansion, where the recapture expansion was 1 for codend catches and expanded to the representative area of the net for each pocket net (see Recapture 'pocket' net expansions).

We fit a generalized linear mixed-effects model (GLMM) to the weighted data using a binomial distribution and logit link function. Trawl identity was modeled as a random effect to account for unexplained variability among trawls, including sampling different aggregation types, environmental conditions, and vessel effects. The probability of fish $i$ in trawl $j$ with length $L$ being retained in net $k$ was modeled as:

$$P[Retention_{ijk}] = \frac{1}{1 + e^{-[(\alpha_k + a_{jk}) + (\beta_k + b_{jk})L_{ijk}]}}. \quad (5)$$

The coefficients $\alpha_k$ and $\beta_k$ are the intercept and slope, respectively, for the fixed effect of net as a function of the continuous predictor of length. The correlated coefficient pairs $a_{jk}$ and $b_{jk}$ are the random effect of trawl identity for each net, which was modeled as a normal distribution centered on 0, with normal variances of $\sigma_a$ and $\sigma_b$, respectively, and correlation $\rho$. This full complexity model allowed for both the intercept and slope parameters to vary by net.

A simple logistic equation to model net selectivity can be reparametrized, where $-\frac{\alpha}{\beta}$ is the length at 50% retention, $L_{50\%}$, and $\frac{2log(3)}{\beta}$ is the selection range, $SR$. The $SR$ is the measure, in centimeters, between the length at 25% and 75% retention (Williams et al., 2011). This parametrization is helpful to compare differences more easily in $L_{50\%}$ and in the shape of the size-selectivity curves among nets. All analyses were conducted in R (version 4.3.3, R Core Team, 2024) using the ‘lmer4’, ‘glmmTMB’, and ‘ggeffects’ packages (Bates et al., 2015; Brooks et al., 2017; Lüdecke, 2018). Significance was assumed at $P < 0.05$.

**Power analysis**

Following the size-selectivity analysis, we used simulation methods to determine whether we had adequate statistical power to detect differences among nets based on the number of trawls conducted. Specifically, we assessed the statistical power to detect significant differences in the intercept parameter of the size-selectivity model among all 3 nets (i.e., contributing to differences in the length at 50% retention among the NOAA AWT, DFO AWT, and MFT) for which we were most interested in. To develop the power analysis, we used the data collected by this study to simulate new escapement datasets, which included total catch size (i.e., the estimated number of fish entering the net), the size distribution of the total catch, and whether fish were retained in the codend or escaped.

To simulate catch size, we fit a negative binomial distribution to the empirical distribution of catch sizes of hake from our collected dataset. We used the parameters of this fitted binomial distribution to simulate the number of fish caught for a new, simulated trawl. Catches were capped at 55,000 fish based on the maximum total catch size (codend plus estimated escapement) in the original dataset. Next, we simulated the size distribution of the total catch by sampling the bins of an empirical histogram of length frequency information for all hake caught, with replacement. From this simulated total catch, which now had associated length information, we simulated whether each of these fish was either retained in the codend or escaped the net. We did this by sampling from a binomial distribution with a size of 1 and a probability equal to the logistic size-dependent retention probability estimated by the data for each net (i.e., we applied the net-specific, size-selectivity curve from equation 5 to determine if a fish was retained or escaped in the simulated dataset). This probability included a random offset of both the intercept and slope parameters for each trawl by sampling a random variability offset from a normal distribution of mean 0 and standard deviation equal to the standard deviation of the random effect of trawl from the analysis. Thus, the simulated data included total catch size, fish length, whether each fish was retained or escaped the net, and included random variability by trawl.

We then fitted the same mixed effects logistic model in equation 5 to the simulated dataset to test for a significant difference in the intercept parameters of all 3 nets (i.e., whether the coefficient for the intercept parameter was statistically different than 0 for the comparison of all 3 nets). We did not consider the power to test for statistical differences in slope because the slope parameters for the 3 nets were ultimately similar and we were more interested in lateral shifts in the selectivity curves, shown mainly by differences in the estimated intercept parameter. For each simulation we recorded the result using $P < 0.05$ to indicate a significant difference among all 3 nets.

For different sets of trawl sample sizes, we ran 100 simulations to determine the power we had to detect a significant difference. Statistical power was defined as the fraction of positive detections out of the total number of simulations. We ran the 100 simulations for 8 different sets of trawl sample sizes by net. The first set of simulations used the actual sample size of the number of trawls conducted for each net in this study. This allowed us to first determine the statistical power we had to detect a significant difference in all 3 nets based on our study findings and trawl sample sizes. The subsequent sets of simulations incrementally added 15 additional trawls for each net more than the 2024 study trawl sample sizes. These simulations of additional trawls were used to inform future research decisions to determine how many trawls per net are likely needed to obtain adequate statistical power to detect significant differences among all 3 nets, if differences exist. Predictions from the power analysis assume that the nets will continue to encounter similar conditions in the future, such as similar catch sizes, length distributions of fish, and similar random variability among trawls. See Supplemental Materials 2 for more details on the power analysis.

## Results

### Summary of trawl operations

We successfully completed 22 trawls using NOAA's AWT during leg 1 of the research survey, and 21 trawls using the MFT during leg 2 of the research survey aboard the NOAA Ship *Shimada* (Table 2). The CCGS *Franklin* completed 13 trawls with DFO's AWT. Of the DFO AWT trawls, 12 were paired with the MFT fished by the *Shimada*, and both nets caught hake in 11 of those trawls. Sampled hake ranged in size from 3-cm to 82-cm (Table 3).

The 3 nets were fished at similar depths and tow speeds (Fig. 3, D and E). The MFT was intentionally deployed at a slightly slower rate than the AWTs because it was the first time the *Shimada's* crew deployed this net, but this rate did not differ from the mean rate of deployment of NOAA's AWT on Leg 1 (Fig. 3, A). Trawl duration was variable for each trawl because of differences in fish density detected by the trawl sonar and differences in the mouth size between the AWT and MFT but did not significantly differ among nets (Fig. 3, B). The DFO AWT and MFT were retrieved at similar rates for paired trawls on Leg 2, compared to a slightly faster mean retrieval rate of NOAA's AWT during Leg 1 (Fig. 3, C).

## Species composition

Hake composed the majority of the codend catch by weight for NOAA's AWT (Fig. 4). Although hake was the target species, it is not always clear that an acoustically detected aggregation would be hake. For example, one trawl on Leg 1 caught a large number of rockfish (*Sebastes* spp), which also have swim bladders that reflect sound similar to hake and can form the same type of aggregations. The larger 32-mm mesh liner of NOAA's AWT codend did not retain many small organisms as a proportion of total weight of the catch. On leg 2, the MFT and DFO's AWT also predominantly caught hake but the codend catches were more diverse. The finer 8-mm mesh liner in the codend of both the MFT and DFO's AWT retained greater numbers of small organisms, such as myctophids and euphausiids. Similar to Leg 1, a few trawls were composed of mostly rockfishes, and 2 MFT hauls were relatively empty, only catching cnidarians and other invertebrates.

## Catch efficiency of MFT relative to AWT from paired trawls

As expected, the MFT was more efficient, in general, at catching hake relative to DFO's AWT in the paired trawl comparisons (Fig. 5, A and B). Differences in the comparison of codend catches were significant for medium sized hake (fork length: 20 to 55-cm) but with large uncertainty intervals overlapping the equal efficiency value of 0.5 for smaller and larger fish. The slope of the beta regression for retained fish (codend catch) was negative (Table 4, Fig. 5, A), which suggested very high retention of small hake in the MFT relative to the AWT.

Results for the total catch (codend plus estimated escapement from the net) were different. The analysis of total catch showed a similar pattern of a greater catch efficiency of the

MFT for medium sized hake relative to the AWT with larger uncertainty intervals overlapping the equal efficiency value of 0.5 for small and large fish (Fig. 5, B). However, the slope of the beta regression for the total catch was positive (Table 4, Fig. 5, B).

**Comparison of size-selectivity among nets**

The body length and girth relationships for hake were compared to the perimeter measurements of different sizes of mesh to better understand which mesh sizes and areas of each net hake could physically fit through (Fig. 6). This was as an approximation for potential escapement since many other factors, such as fish behavior, angle of attack, and other unaccounted for fish anatomical features (i.e., fins and gills) and construction of meshes (i.e., knot size, flexibility of material, and mesh shape) can influence the ability of a fish to escape. The relationship showed that the 8-mm codend liners of DFO's AWT and the MFT were likely to retain almost all sizes of hake greater than 3.9-cm in length. The 32-mm mesh size codend liner of NOAA's AWT was likely to retain nearly all sizes of age 1 hake longer than 16-cm. The 50-mm mesh size panels closest to the codend on the MFT, which did not have pocket nets attached, were likely to retain all larger-sized age 1 and all age 2+ hake longer than 25-cm.

A total of 177 hake escaped from the NOAA AWT into recapture pocket nets (Table 3). Escaped fish ranged in length from 8-cm to 43-cm. The DFO AWT had a fewer number of trawls and fewer recapture nets, but a similar number of hake (n = 163) escaped into recapture nets with a range in lengths from 8-cm to 40-cm. Only 12 hake escaped from the MFT into recapture nets with a range in lengths from 3-cm to 28-cm. For NOAA's AWT, the escapement rate into pocket nets (i.e., the mean count of hake caught in a pocket net per trawl minute, [fish/min]) differed among the 100-mm, 200-mm, and 800-mm mesh sections of the net (ANOVA, $F_{2,261} = 18.6$, $P$ <

0.001). The greatest escapement rate into pocket nets occurred from the 100-mm mesh section, which was closest to the codend, with a mean escapement rate of 0.94 fish/min. In comparison, mean escapement into pocket nets on the 200-mm mesh section was of 0.06 fish/min, and 0.04 fish/min for the 800-mm section. For DFO's AWT, the mean escapement rate was 0.46 fish/min into pocket nets on the 100-mm mesh section, which did not differ from the mean escapement rate of 0.02 fish/min into pocket nets on the 200-mm mesh section (ANOVA, $F_{1,76}$ = 1.83, $P$ = 0.18). The mean escapement rates for the MFT also differed by section of the net (ANOVA, $F_{2,201}$ = 5.62, $P$ = 0.004), but were low, in general, with the greatest escapement rate into pockets nets on the 200-mm section of the net (0.04 fish/min) compared to pocket nets on the 100-mm (0.004 fish/min) and 800-mm sections (< 0.001 fish/min). Even with few recaptures for the MFT, each of the 100-mm, 200-mm, and 800-mm mesh sections had at least 1 hake recaptured in a pocket net.

All 3 nets encountered a broad size range of hake, which allowed us to assess size-selectivity over the full range of lengths (Fig. 7, A and B). This included juvenile hake less than 15-cm in length, which were assumed to be age 0 fish, as well as fish between 15-cm and 30-cm, which were assumed to be age 1, and longer than 30-cm, which were assumed to be age 2+ based on previous surveys' age and growth information (Thomas et al. in prep). The 3-net comparison of size-selectivity found a significant difference in the intercept parameter of the size-selectivity curve for the MFT relative to the AWTs (GLMM, $P$ = 0.001, Table 5). The MFT retained all sizes of hake, including small fish, with an estimated probability of relative retention near 1.0 for all sizes. This contrasted with the 2 AWTs, which successfully retained larger fish, but allowed a greater fraction of small fish to escape. The length at 50% retention was 11.2-cm for NOAA's AWT and 19.3-cm for DFO's AWT. The intercepts were not statistically different between the 2

AWTs with the different codend liners. Also, the slope parameters did not statistically differ among nets (Table 5). There was greater uncertainty in the size-selectivity parameter estimates for DFO's AWT, indicated by wide 95% confidence intervals, which likely were a result of the fewer number of trawls and fewer encounters of age 0 hake with that net.

The size-selectivity parameters of the 2 AWTs were not statistically different in the 3-net analysis so the data were pooled for the AWTs to compare with the MFT. The analysis of pooled AWT data compared to the MFT also showed a statistical difference in the intercept size-selectivity parameter of the MFT compared to the combined AWTs (GLMM, $P = 0.017$, [Table 5, Suppl. 1, Fig. SM1-3]) and, again, no difference in slope.

**Power analysis**

The size-selectivity analysis found that the MFT was less selective relative to the AWTs, but there was no difference in the size-selectivity parameters between the AWTs with the 2 different liners. However, given the number of trawls, the subsequent power analysis found that we only had a 15% chance of detecting a significant difference between the 2 AWTs, in addition to the already significant difference of the MFT (Suppl. 2, Fig. SM2-3) given the number of trawls. Simulating additional hauls in the power analysis indicated that 105 more trawls per net would be needed to approach an adequate power of 80% to detect statistical differences among all 3 nets, assuming that the underlying observed patterns in size-selectivity were true.

**Discussion**

The species composition, catch efficiency, and size-selectivity of the 2 Aleutian Wing Trawls (AWTs) used to survey hake differed from the new Multi-Function Trawl (MFT) and, in some cases, from each other due to differences in the size of the mesh lining in the codend, and possible differences in how the nets are fished from different ships. The DFO AWT encountered fewer age 0 hake compared to the other 2 nets, which could have influenced the comparison of size-selectivity and the intercept 'anchoring' of the selectivity curve. This was reflected in the greater uncertainty of the estimated size-selectivity parameters for DFO's AWT. These differences are important to consider in order to standardize data from different gear types, vessels, and when switching to a new survey trawl gear. Different gear types (or the same gear type fished in different ways) may sample different sizes of the same fish population, as well as different non-target species. Differences in catch introduced by a change in survey gear should be identified and corrected for (or back-corrected), if needed, to maintain consistency of survey data products over time and to better address uncertainty in biomass estimates.

**Improved information on species diversity**

The finer codend mesh liner of DFO's AWT and the MFT retained a greater number of small pelagic organisms and increased the diversity of the catch relative to the larger mesh size of the codend liner of NOAA's AWT. This was most likely due to differences in mesh size of the codend, although we could not entirely rule out spatial effects of sampling different regions and hake aggregations along the coast. The NOAA AWT was mostly deployed in central California, whereas DFO's AWT and the MFT were mostly deployed off northern California and Oregon, with the first 6 trawls of the MFT in central California. The early trawls of the MFT in central California, near where NOAA's AWT had been deployed, also showed a greater diversity of catch, which suggested differences were less likely due to geographic region and more likely due to differences in the mesh size of the codend liner.

The greater diversity of small organisms caught by DFO's AWT and the MFT probably represent a more accurate species composition of mixed aggregations and other organisms present in the water column. The finer codend mesh liner of these 2 nets retained more myctophids and krill, which are important prey of hake. Additional quantitative data on these taxa may be useful to improve information on predator-prey dynamics and other ecosystem food web interactions, which could better inform studies of growth and productivity of the commercially and ecologically important species such as hake (Iglesias et al., 2023; Phillips et al., 2023).

In addition, many of these small organisms also effectively reflect sound, such as small fishes with gas-bearing swim bladders and some invertebrates (Becker and Warren, 2015). The ability to more completely sample all organisms that are mixed within aggregations of hake can be used to improve the assignment and apportioning of backscatter to species within an acoustically detected aggregation. A more accurate accounting for these types of species mixed with hake has the potential to improve biomass estimates of hake and could reduce uncertainty of the estimate. One drawback of sampling smaller organisms with the finer mesh codend liner is an increase in the time to sort, identify, and measure small organisms in the catch, which could limit the overall number of trawls that can occur during an ATM fisheries survey.

**Greater catch efficiency**

The generally greater efficiency of the MFT to catch hake relative to the AWT is explained, in part, by its slightly larger size. The mouth opening of the MFT is 15.5% larger than the AWT. While a larger mouth means a larger area and volume of water sampled, this does not entirely explain the much greater catch efficiency of the MFT, which caught, on average, approximately

80% of the combined catch for each of the paired trawls. This greater than expected efficiency could be due to other differences in the design of the MFT trawl system, which may be more effective at herding and retaining hake relative to the AWT (NMFS, 2025a), or could reflect the few numbers of paired trawls and high variability in the types of aggregations that were sampled. Many of the aggregations encountered for the paired trawls were small and patchy and some were mixed with rockfish. These small, patchy, and mixed aggregations likely contributed to greater variability of the catch, and the ability of each ship to adequately sample the same aggregation. Ultimately, proportional differences in catch rates among nets will not influence the apportioning of the acoustic density; however, the duration spent at depth may be reduced if the target sample size of hake is reached more quickly with a more efficient net.

The patterns in catch efficiency based on fish size were less clear. We expected greater escapement of small hake from the AWT relative to the MFT based on differences in the designs of the nets. As expected, the MFT retained a greater fraction of small hake in the codend relative to the AWT, shown by a greater proportion of small fish retained in the codend relative to the AWT in the size-selectivity analysis. This trend was also reflected in the catch efficiency analysis for the comparison of codend catches. Unexpectedly, the paired trawl catch efficiency analysis for the total catch, which included the estimated escapement from each net, suggested that the MFT was slightly less efficient than expected at encountering small hake relative to the mid- and larger-sized hake. It is somewhat unclear why the MFT would not equally encounter small hake entering the net relative to the AWT when fishing on the same aggregation. The uncertainty intervals for small hake were very large and overlapped with the equal efficiency value of 0.5, making it difficult to know if the trend in the slope was real or, more likely, due to low sample sizes of small fish and high variability in the catch efficiency ratios of the paired trawls.

One alternative explanation is that some escapement of small fish may have been missed from the MFT in the sections represented by pocket nets potentially due to the distance of the pocket nets from the codend. The pocket nets were attached to the same 100-mm and 200-mm mesh sections as the AWT, but were farther from the codend for the MFT because of the 2 additional 50-mm mesh panels adjacent to the codend that were not present on the AWT. If we had missed some escapement due to the greater distance of the pocket nets from the codend, this could have underestimated the total catch by the MFT and artificially resulted in a lower-than-expected catch efficiency ratio for small fish entering the net. Any potential missed escapement would not influence the codend catch efficiency analysis and, indeed, the codend catch comparison for the paired trawls showed a greater retention of small hake by the MFT relative to the AWT, with slightly less uncertainty relative to the total catch analysis.

A trawl size-selectivity study of Walleye Pollock (*Gadus chalcogrammus*), which is a similar midwater shoaling species in the North Pacific, found that escapement generally occurs closer to the codend, although this pattern can vary with the response of fish to ship noise (Williams et al., 2011). The large meshes near the mouth of the net act as a herding mechanism for schooling and shoaling species, and escapement is likely to increase as fish density increases near the codend (Williams et al., 2011; Williams et al., 2013). Escapement may also vary due to other factors that influence herding behavior, such as differences in light levels between day and night (Williams et al., 2013); however, all trawls in this study occurred during daylight hours.

**Size-selectivity differs by net**

The size-selectivity analysis, which used pocket net recapture data from all 3 nets, was more conclusive in demonstrating a greater retention of small hake by the MFT compared to both AWTs. Results from the size-selectivity analysis showed that all 3 nets had a greater than 85% probability of retaining age 2+ hake that were longer than 30-cm. For smaller fish, the MFT had a much greater probability of retaining age 0 and age 1 hake between 10 and 30-cm relative to the AWT. The MFT retained nearly all of these sizes and ages, with the probability of relative retention close to 1, with some uncertainty. These findings support our hypothesis that the MFT would retain more small fish compared to the AWT due to differences in the design of the net. The different taper and quicker transition of meshes on the MFT from large mesh size to small mesh size along the net is thought to capitalize on the aggregating behavior of hake and to streamline water flow to effectively funnel fish through the center of the net and into the codend (Melly[5]). Furthermore, the 50-mm mesh panels closest to the codend on the MFT may have improved retention, acting similarly to an extended codend, especially for larger-sized age 1 and age 2+ hake, which we demonstrated were physically unable to fit through the 50-mm mesh size.

All 3 nets encountered nearly the full size range of hake, and large numbers of age 0 and age 1 were encountered by the MFT, as shown by the codend catches. This indicates that such low escapement from the MFT was not due to a lack of encountering small fish relative to the AWTs. In fact, the greater catch efficiency and retention of small fish by the MFT resulted in very large numbers of age 0 and age 1 hake caught relative to both AWTs. Of these small fish, the majority were retained in the codend. Only a single age 0 was recaptured in one of the pocket nets on the 800-mm mesh section of the MFT. Because it was not caught in the 100-mm or 200-mm recapture nets, it was excluded from the size-selectivity analysis, which only included

[5] Melly, S. 2024. Personal commun. Swan Nets, Seattle, Washington, USA.

recaptures from the 100-mm and 200-mm mesh area pocket nets present on all 3 nets. A sensitivity to including escapement from the 800-mm mesh section of the MFT made little difference in the estimated probability of escapement for age 0, 1 and older/larger hake, but slightly modified the size-selectivity parameters (Suppl. 1, Table SM1-3, Fig. SM1-2).

A power analysis simulating data for all 3 nets demonstrated low statistical power to detect a significant difference in the size-selectivity parameters between the 2 AWTs given the number of trawls in our study, even though a difference with the MFT was found. The power analysis also suggested that more than 100 additional trawls for each net would be needed to increase the statistical power to an adequate level to detect differences among all 3 nets, if true. Although a large number, this substantial increase in sample size is not unreasonable given that 50 to 100 trawls are possible during a typical survey and that the processing of pocket net recaptures can be incorporated into existing survey protocols (NMFS, 2024). For the survey of Walleye Pollock in Alaska, the NOAA Alaska Fisheries Science Center regularly collects escapement and size-selectivity information for their midwater trawls on annual ATM surveys, and uses that information to bias-correct for the under sampling of small fish in mixed size aggregations[1].

While understanding potential differences in size-selectivity between the NOAA and DFO AWTs is important, the back-correction of biased size sampling is likely less relevant for DFO's AWT because of the types of hake aggregations encountered in Canada. The Canadian portion of the survey of hake typically encounters fewer small-sized hake since migration into the northern part of the range is typically by larger, age 2+ fish (Thomas et al. in prep), which were fully selected for by both types of nets. When only large fish are present, a net which under-samples small fish will have little impact on biasing the size frequency of catches. The mixing of large adult hake and smaller juveniles in the U.S. portion of the survey is more problematic. Based on our findings, a back-correction in the survey time series to account for the escapement of age 0 and age 1 fish from samples of mixed size aggregations is required to maintain consistency and standardization of survey products following the switch to the new MFT. Also, both portions of the survey can encounter other small pelagic species mixed with hake. Understanding the relative net selectivity for these species is also necessary to fully account for their contribution to the total acoustic backscatter.

**Remaining questions and future research**

Moving forward, a change in trawl system from the AWT to MFT for the hake survey is expected to improve ecosystem information collected by the survey through improved sampling of smaller organisms, including the prey of hake and other forage species along the west coast of the U.S. and Canada. This additional data on these species could be used to develop or improve indices of abundance for important prey and other ecosystem forage species in addition to hake. Based on our findings, the MFT is expected to retain a greater fraction of small age 0 and age 1 hake, and thus catches by the MFT should more accurately reflect the full species and size composition of acoustically detected aggregations. This will improve information for the age 1 index of hake to better inform year class strength of new cohorts entering the fishery, and should increase the accuracy of the biennial estimate of age 2+ biomass by using a less size-biased net. Previous biased size-sampling of mixed aggregations by the AWT will need to be back-corrected to ensure consistency and comparability of survey data products.

Whether some escapement was potentially missed by the MFT due to the farther distance of recapture nets from the codend compared to placement on the AWTs remains an open question. Escapement patterns from the AWTs, and other studies of midwater trawls, indicate that the most escapement occurs closest to the codend where fish density increases as fish are herded into the codend (Williams et al., 2011). Future research should consider placing recapture nets on the MFT to be the same distance from the codend as the AWTs, while also maintaining the original locations of the 100-mm and 200-mm recapture nets for comparison. Updated placement of recapture nets will most likely resolve the question of possible missed escapement, and improve information for the size-selectivity parameters for the MFT.

Future research should also focus on covariates of net escapement, such as the influence of different light levels, density of fish aggregations, and at what sequence in the trawl escapement occurs, such as during net retrieval, or during a sudden change in depth during the trawl that may cause fluctuations in water flow. A better understanding of other factors influencing escapement may help to better understand variability and potential vessel effects in surveys that use more than 1 vessel. Different ocean conditions, including changes in temperature and current strength, may also influence fish behavior and escapement, so it is important to continue to monitor for future change in net selectivity (Williams et al., 2013).

## Conclusions

Understanding biased sampling and accounting for changes in gear selectivity is critical to developing accurate survey methods and the interpretation of results. For ATM surveys, understanding trawl net selectivity is important to accurately use length-frequency information of the catch to apportion the backscatter density of an acoustically detected fish aggregation. Correcting for biased under-sampling of small fish will improve estimates of abundance and biomass of hake at age and length. In this study we estimated initial size-selectivity parameters for the AWT, the net most recently used in the survey of hake, and for the MFT, a new net designed for the integration of the hake survey with the west coast ATM survey of small coastal pelagic species. A change in trawl systems to the MFT benefits the integrated survey in the ability to deploy a single net and trawl system in a midwater mode for hake and in a surface mode for small coastal pelagics. The size-selectivity information collected for both AWTs will be essential for back-correcting the time series of hake biomass and to better understand sampling bias moving forward. The back-correction will also provide insight into how gear selectivity influences the estimate of hake biomass, particularly in years of increase age 1 hake abundance. Last, we showed that a power analysis is a useful tool to contextualize findings and to inform future research design and sampling requirements. Common to many fisheries, maintaining consistency in survey data products, such as comparable abundance and biomass estimates through time, is critical for monitoring changes in population dynamics and to achieve sustainable fisheries management goals.

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**Tables**

Table 1: Relevant differences among trawl nets most recently used to survey Pacific hake (*Merluccius productus*). Measurements are in meters (m), millimeters (mm), or kilograms (kg).

| Category | Description | | |
|---|---|---|---|
| Agency | NOAA Fisheries (NOAA) | | Fisheries and Ocean Canada (DFO) |
| Ship | *Bell M. Shimada* | | *Sir John Franklin* |
| Description | 64-m acoustically quieted fisheries survey vessel; stern trawler | | 63-m Canadian Coast Guard Ship; stern trawler |
| Nets | | | |
| Type | Aleutian Wing Trawl (AWT) | Multi-Function Trawl (MFT) | Aleutian Wing Trawl (AWT) |
| Name | NOAA AWT | MFT | DFO AWT |
| Mouth opening (Height x width) | 20 x 40-m | 22 x 42-m | 20 x 40-m |
| Mesh size of codend liner and pocket nets | 32-mm | 8-mm | 8-mm |

| | | | |
|---|---|---|---|
| Trawl System | | | |
| Doors | Super V Fishbuster 4-m$^2$ | Thyboron Type 22-VK Bluestream 4-m$^2$ | Super V Fishbuster 4-m$^2$ |
| Bridles | Length 82.3-m; Setback 3-m; Parallel configuration | Length 73-m; Setback 5.48-m; V-rig configuration | Length 82.3-m; Setback 3-m; Parallel configuration |
| Cluster weights | 340-kg | 454-kg | 340-kg |
| Net mensuration | Simrad FS70, Kongsberg | Simrad FS70, Kongsberg; PX90 | Simrad FS70, Kongsberg |

Table 2. The number of trawls, sampling dates, and which ship each net was deployed from on the 2 research legs of the study. The nets are the Aleutian Wing Trawl (AWT) and Multi-Function Trawl (MFT).

| Leg | Dates | Ship | Net | No. of trawls |
|---|---|---|---|---|
| 1 | 5 - 25 July 2024 | *Bell M. Shimada* | NOAA AWT | 22 |
| 2 | 10 - 18 August 2024 | *Sir John Franklin* | DFO AWT | 13[a] |
| 2 | 1 - 21 August 2024 | *Bell M. Shimada* | MFT | 21[a] |

[a]12 paired trawls; 11 where both nets caught and measured Pacific hake (*Merluccius productus*)

Table 3: Sampling of Pacific hake (*Merluccius productus*) by net and partition (codend or recapture ‘pocket’ net). All fish caught in pocket nets were measured. Fish caught in the codend were subsampled to collect representative measurements. The nets are the Aleutian Wing Trawl (AWT) and Multi-Function Trawl (MFT). The size range of fish lengths is measured in centimeters (cm).

| | NOAA AWT | | DFO AWT | | MFT | |
|---|---|---|---|---|---|---|
| | Codend | Pockets | Codend | Pockets | Codend | Pockets |
| No. of hake measured | 8024 | 177 | 3861 | 163 | 5724 | 12 |
| Size range (cm) | 4 - 82 | 8 - 43 | 6 - 70 | 8 - 40 | 6 - 78 | 3 - 28 |

Table 4. Parameters of the beta regressions (Eq. 4), which estimated differences in catch rate efficiency by fish length for paired trawls of the Multi-Function Trawl (MFT) and DFO's Aleutian Wing Trawl (AWT) fishing on the same aggregations. The expected proportion of catch rate efficiency of the MFT relative to the combined catch rate is shown for representative small, medium, and large Pacific hake (*Merluccius productus*) with the 95% confidence intervals (CI) calculated from bootstrapping. Lengths are measured in centimeters (cm). A catch efficiency ratio of 0.5 indicates equal catch efficiency between nets.

| Comparison | Beta regression parameters (Eq. 4) | | | Expected proportion of paired trawl catch rate attributed to MFT for different size hake (95% CI) | | |
|---|---|---|---|---|---|---|
| | Mean ($\mu$) | | Precision ($\phi$) | Small 10-cm | Medium 40-cm | Large 70-cm |
| | $\alpha_\mu$ | $\beta_\mu$ | | | | |
| Codend (Retained fish) | 2.07* | -0.01* | 9.48 | 0.88 (0.44 - 0.98) | 0.85 (0.65 - 0.90)** | 0.81 (0.28 - 0.97) |
| Total catch (Codend plus estimated escapement) | 0.72* | 0.03* | 4.88 | 0.72 (0.17 - 0.97) | 0.85 (0.59 - 0.92)** | 0.92 (0.27 - 1.00) |

* $P < 0.05$

** Confidence intervals do not overlap 0.5, indicating a significant difference.

Table 5. Parameters of the logistic size-selectivity analysis (Eq. 5), which estimated the effect of length on the probability that a fish entering the net will be retained in the codend. The derived parameter $L_{50\%}$ is the length at 50% retention, and $SR$ is the selection range between the length at 25% and 75% retention. Lengths are measured in centimeters (cm). The nets are the Aleutian Wing Trawl (AWT) and Multi-Function Trawl (MFT).

| Comparison | Net | Logistic regression parameters (Eq. 5) | | Derived parameters | |
|---|---|---|---|---|---|
| | | $\alpha_k$ | $\beta_k$ | $L_{50\%}$ (cm) | $SR$ (cm) |
| Three nets | NOAA AWT | -1.96 | 0.18 | 11.2 | 12.5 |
| | DFO AWT | -3.19 | 0.17 | 19.3 | 13.3 |
| | MFT | 4.43* | 0.10 | -42.8 | 21.2 |
| Two net-types | Pooled AWTs | -2.26 | 0.17 | 13.5 | 13.1 |
| | MFT | 5.16* | 0.08 | -67.8 | 28.9 |

* $P < 0.05$

**FIGURES**

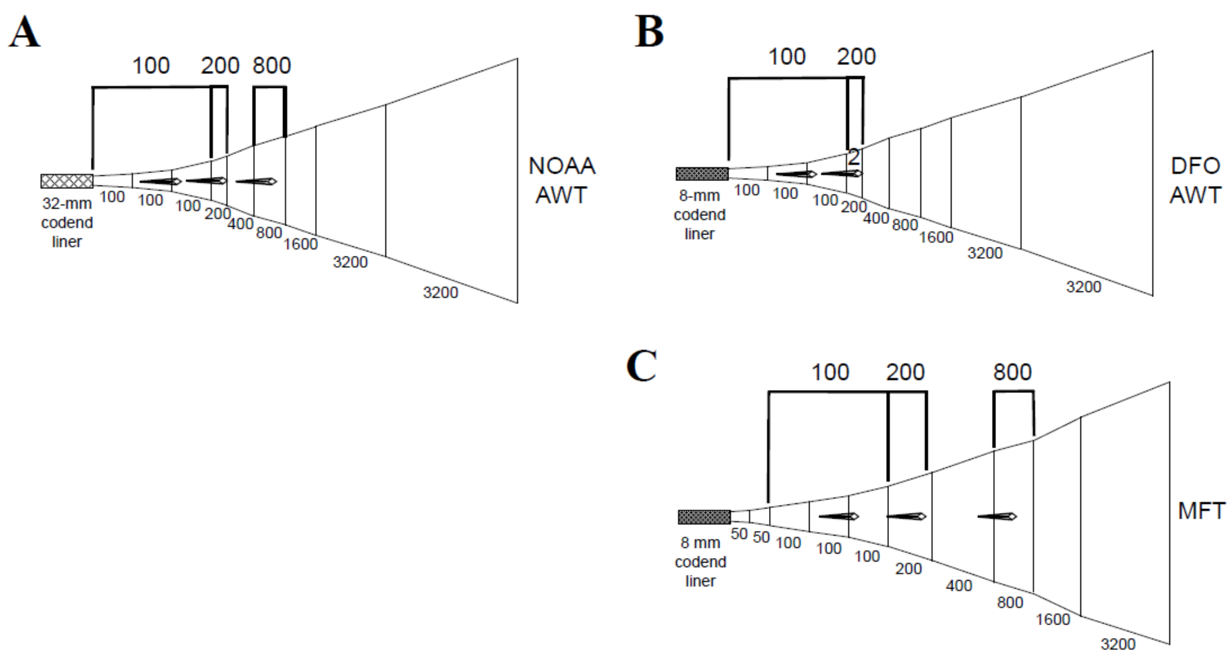


Figure 1. Differences in net designs and pocket net locations of the NOAA Aleutian Wing Trawl (AWT, [**A**]), DFO's AWT (**B**), and the Multi-Function Trawl (MFT, [**C**]). Mesh sizes (in millimeters [mm]), are labeled for each net showing the taper of large to finer mesh from the mouth to the codend for the top side panel of each net. Recapture 'pocket' nets were attached to the 100-mm, 200-mm, and 800-mm mesh size sections on the top, bottom, port, and starboard sides of NOAA's AWT and the MFT. The DFO AWT had 6 pocket nets, of which 4 were attached on all sides of the 100-mm mesh section and 2 on the top and bottom of the 200-mm mesh section.

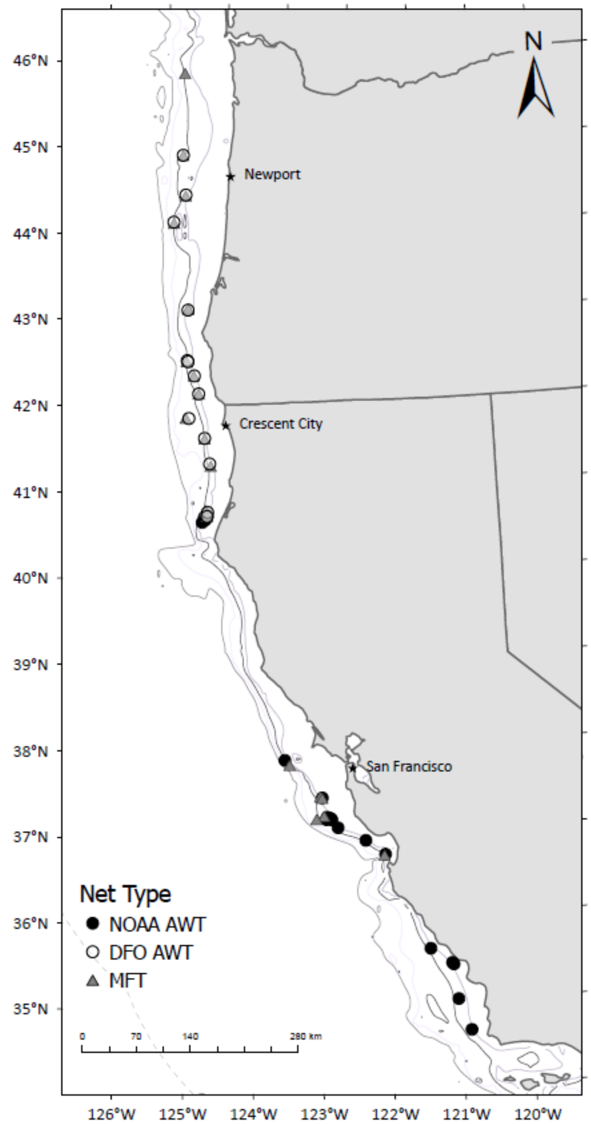


Figure 2. Map of the study area showing trawl locations of NOAA's Aleutian Wing Trawl (AWT) on Leg 1 (solid circles), and DFO's AWT (open circles) and the Multi-Function Trawl (MFT, [triangles]) on Leg 2 of the research survey.

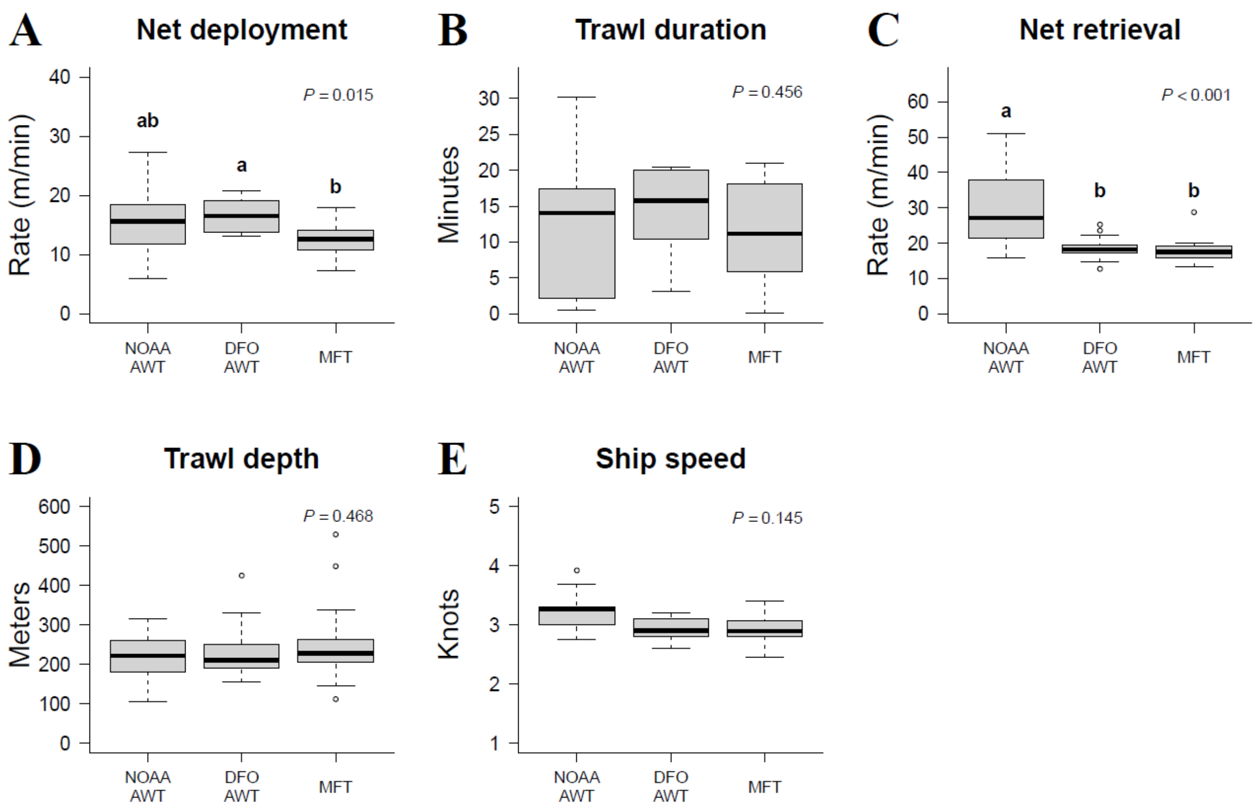


Figure 3. Summary of trawl operations for NOAA's Aleutian Wing Trawl (AWT) on Leg 1, and DFO's AWT and the Multi-Function Trawl (MFT) on Leg 2. Trawl operations included **A**) the rate (meters[m]/minute[min]) that each net was deployed from the surface to the target fishing depth, **B**) the time elapsed from the net reaching the target depth to the time at haul back (trawl duration, [minutes]), **C**) the rate of retrieval from depth back to the surface (m/min), **D**) the mean depth while fishing (meters), and **E**) the mean ship speed (knots). Boxplots show the median (horizontal center line), 25th and 75th quantiles (bottom and top of box), and the range of data within 1.5 times the interquartile range (whiskers). Plotted individual points are outliers. Significant differences are shown by different lowercase letters (ANOVA and post-hoc Tukey).

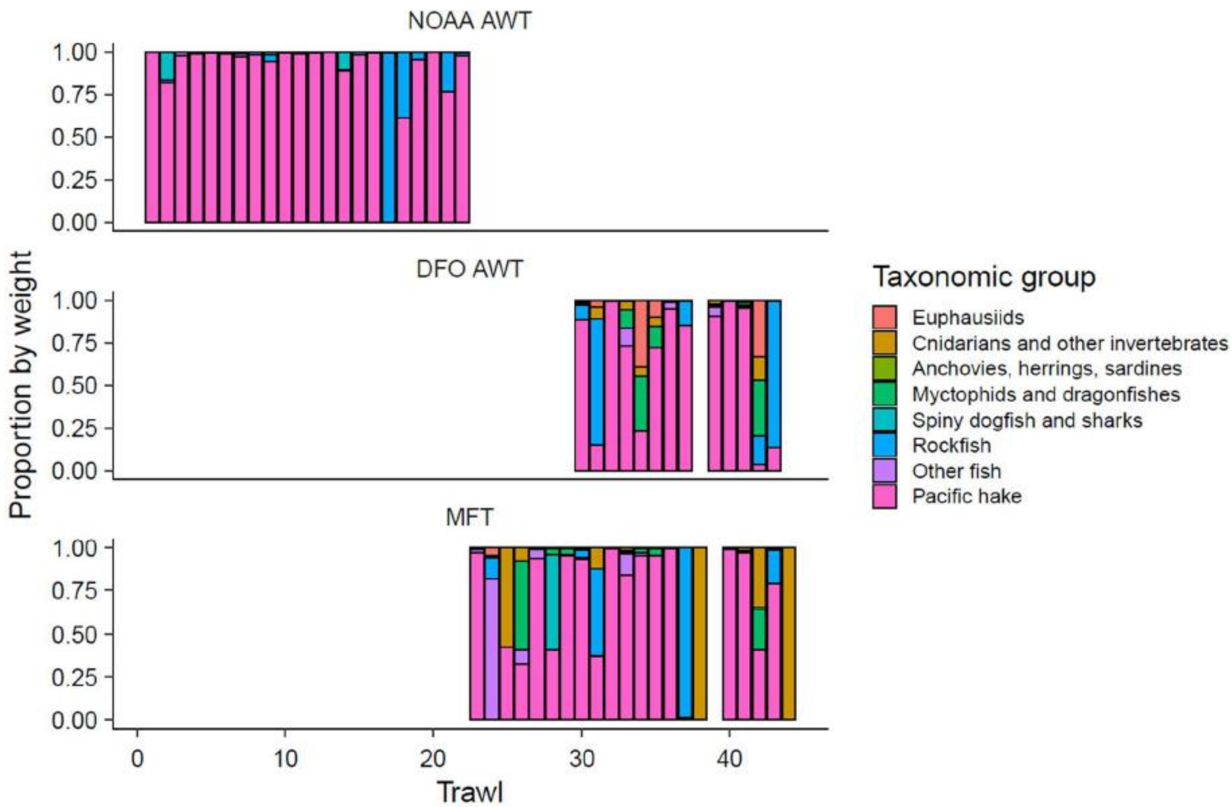


Figure 4. Species composition for each trawl as the proportion of different taxonomic groups by weight (kilograms) showing a qualitatively greater taxonomic diversity of the catch for DFO's Aleutian Wing Trawl (AWT) and the Multi-Function Trawl (MFT) on Leg 2, both of which have the finer 8-mm mesh size codend liner, compared to NOAA's AWT on Leg 1. Trawls are numbered sequentially on the x axis. Trawls in vertical alignment were paired trawls of DFO's AWT and the MFT fishing on the same acoustically-detected aggregation.

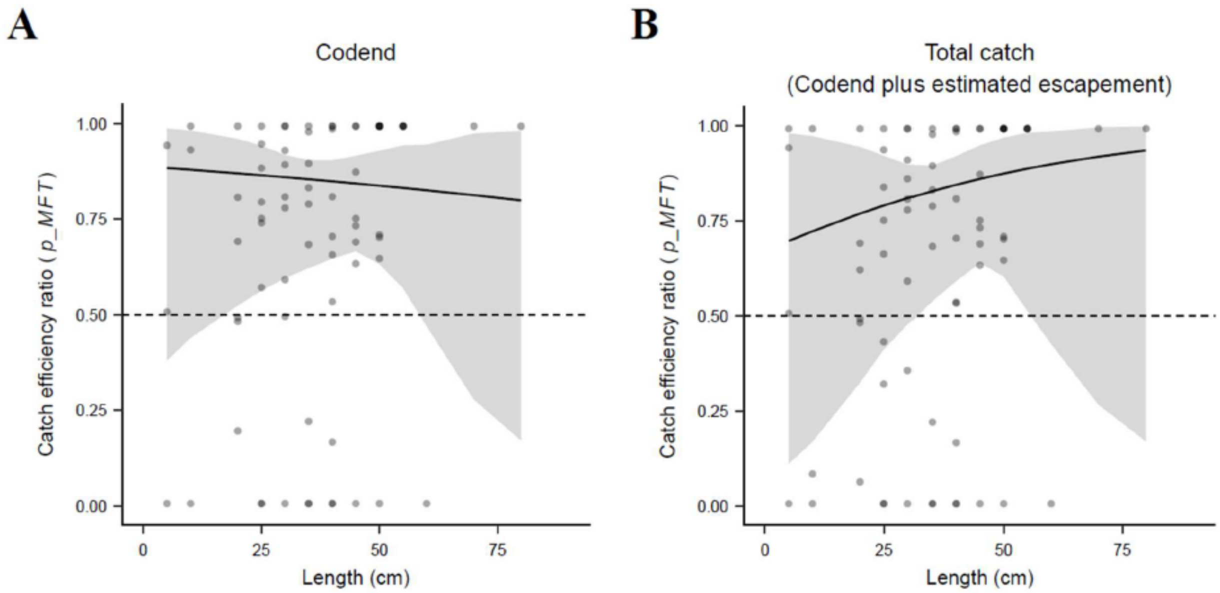


Figure 5. Comparison of catch efficiency for Pacific hake (*Merluccius productus*) of different length from paired trawls of DFO's Aleutian Wing Trawl (AWT) and the Multi-Function Trawl (MFT) fishing on the same aggregations. The data (solid circles) are the proportion of the paired catch rate attributed to the MFT relative to the combined catch rate for different fish length, which were binned by 5-centimeter (cm) increments. A beta regression fit to the data shows the expected mean proportion of the paired catch rate attributed to the MFT (solid line) with 95% confidence intervals from bootstrapping (shaded area). Confidence intervals not overlapping 0.5 indicate a significant difference in the catch efficiency of the MFT relative to the AWT. Data are shown for the codend comparison (retained fish, [**A**]) and for the total catch comparison (codend plus estimated escapement of fish from each net, [**B**]).

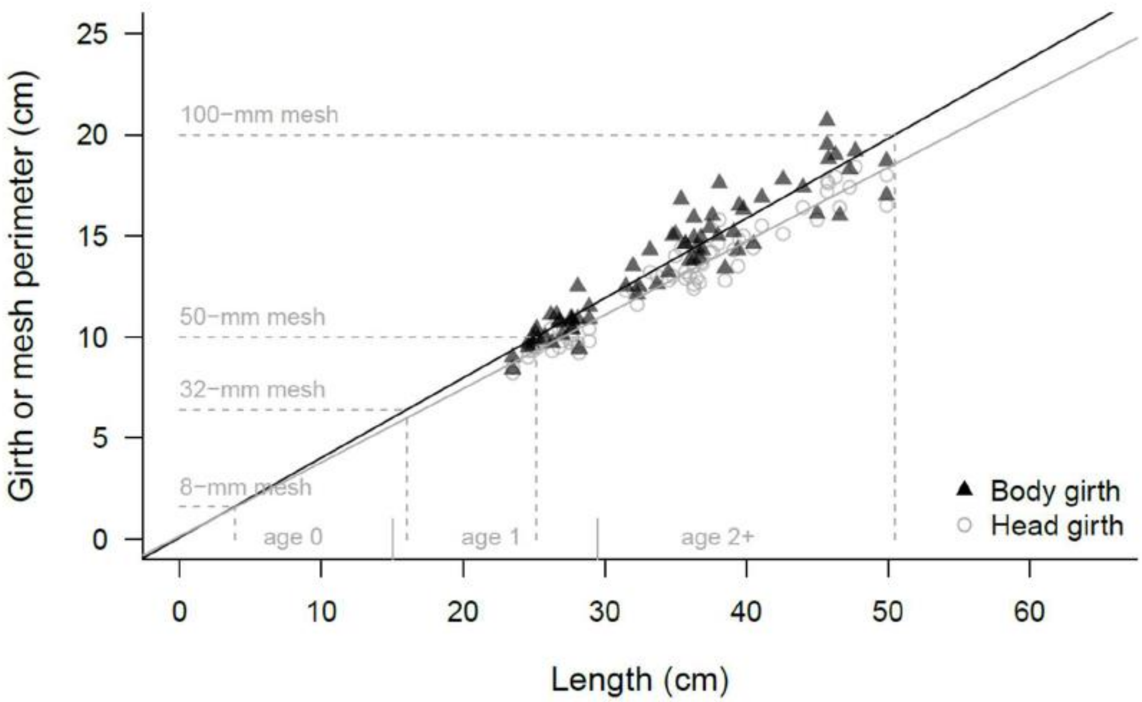


Figure 6. The relationships among Pacific hake (*Merluccius productus*) length (x axis), body girth (solid triangles), and head girth (open circles) compared to the perimeter measurement of different mesh sizes of the nets. Girth and mesh perimeter were measured in centimeters (cm). Fish with a larger girth than the perimeter measurement of a diamond-shaped mesh were assumed unable to physically escape that mesh size. Age classes shown for reference.

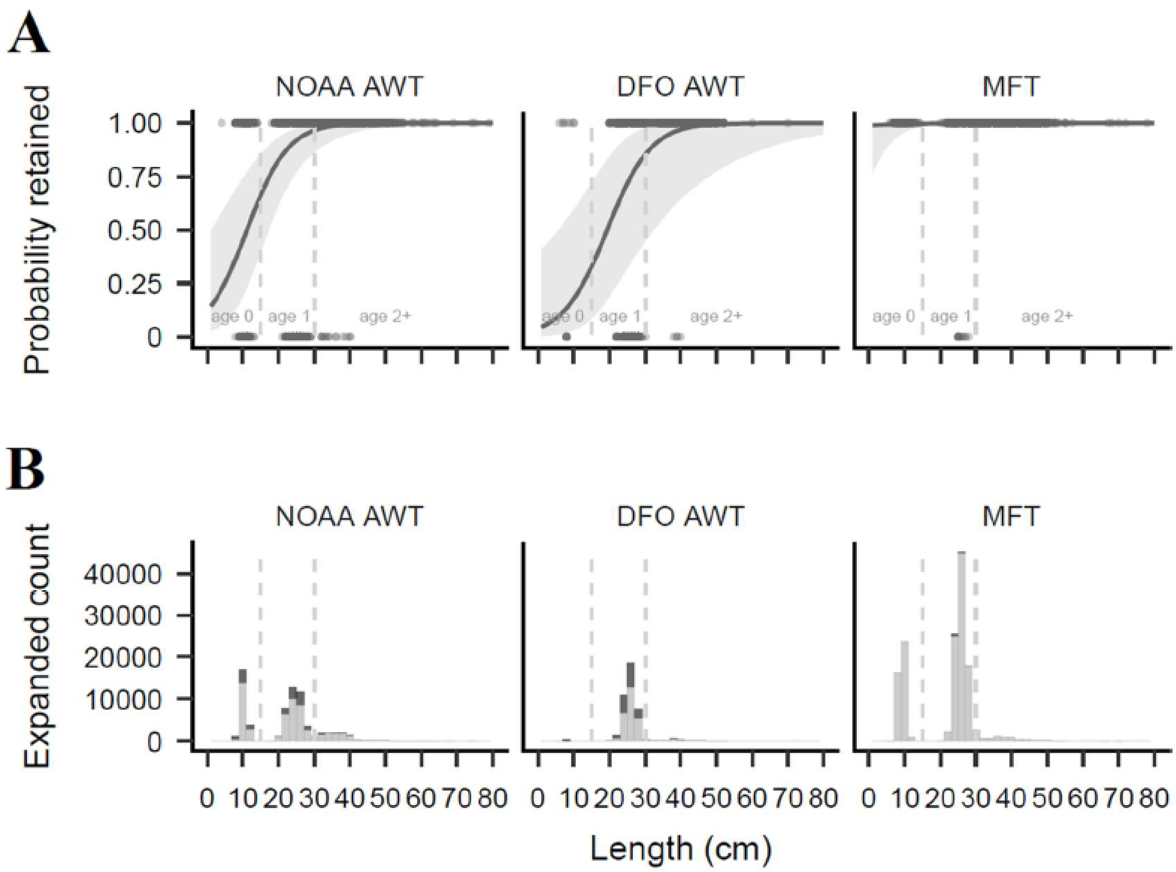


Figure 7: Size-selectivity curves for Pacific hake (*Merluccius productus*) estimated from the 3 net analysis for NOAA's Aleutian Wing Trawl (AWT), DFO's AWT, and the Multi-Function Trawl (MFT, [**A**]). Solid lines are the expected probability of retention-at-length and shading is the 95% confidence interval. The raw, unweighted data are shown as 0 for fish escaping the net into recapture nets and 1 for fish retained in the codend (circles). The vertical dashed lines are length-based age cutoffs to show differences in the probability of retention for age 0, age 1, and age 2+ hake. The bottom panel (**B**) shows the expanded length frequency distributions of retained hake (light gray bars) and estimates of escapement (dark gray bars) from the 100-mm and 200-mm mesh sections represented by pocket nets for each net.

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**Supplementary Materials 1**

**Mesh expansions for pocket net catches**

***NOAA AWT and MFT***

Both NOAA's AWT and the MFT had 12 pocket nets attached to each net. The locations of the pocket nets were on the 100-mm, 200-mm, and 800-mm mesh size sections of each net attached to the top, bottom, starboard, and port sides. The size-selectivity analysis using the 'direct' comparison method, which includes only the pocket net recaptures from the 100-mm and 200-mm mesh pocket nets present on all 3 nets, excludes escapement through meshes greater than 200-mm, and excludes any potential, unmonitored escapement from the additional 50-mm mesh size sections just forward of the codend on the MFT. Pocket nets were not attached to the 400-mm mesh section in between the 800-mm and 200 mm-mesh sections to prevent pocket nets from overlapping and interfering with one another while fishing and during trawl deployment and retrieval.

The 'direct' expansion method expanded the pocket net catches to the respective 100-mm and 200-mm mesh size area of each net. A second, 'full' expansion method was conducted as a sensitivity of the size-selectivity parameters to the unused escapement information from the 800-mm mesh section on NOAA's AWT and the MFT (the DFO AWT did not have pocket nets attached to the 800-mm section). The 'full' expansion method divided the net into general areas of fore, mid, and aft, which included the area of the 400-mm mesh. The area of the 400-mm mesh section was evenly divided and attributed to catches from either the 800-mm or 200-mm pocket nets, similar to how unrepresented areas are apportioned in other midwater net selectivity studies (Williams et al., 2011, [Fig. SM1-1]).

***DFO AWT***

The DFO AWT had 6 pocket nets attached to the net. The fewer number of pocket nets was due to supply chain issues and a lack of 8-mm mesh material to build all 12 pocket nets as originally planned. Four pocket nets were attached to the top, bottom, starboard, and port sides of the 100-mm mesh section, similar to NOAA's AWT and the MFT. The remaining 2 pocket nets were attached to the top and bottom of the 200-mm mesh section.

For all comparisons, the catches from each of the 2 pocket nets on the 200-mm section were doubled. For the 'direct' comparison method, the 100-mm and the doubled 200-mm pocket net catches were expanded to their respective mesh size areas of the net. For the 'full' expansion method for DFO's AWT, the 200-mm catches were expanded to also include half of the 400-mm section, similar to the 'full' expansion method for NOAA's AWT and the MFT recaptures (Fig. SM1-1). The other half of the 400-mm mesh area section was not included because there were no pocket nets in the neighboring 800-mm section.

Table SM1-1. Expansion factors for pocket net catches used in the ‘direct’ expansion method comparison of the Aleutian Wing Trawls (AWTs) and the Multi-Function Trawl (MFT). Expansion factors are shown for pocket nets attached to the 800-mm mesh size section but were not used in the analysis because DFO’s AWT did not have pocket nets in the 800-mm section.

| Mesh size | Panel | NOAA AWT expansion factor | DFO AWT expansion factor | MFT expansion factor |
|---|---|---|---|---|
| 100-mm | top | 85.87 | 85.87 | 149.08 |
| 100-mm | bottom | 85.87 | 85.87 | 149.08 |
| 100-mm | port | 85.87 | 85.87 | 149.08 |
| 100-mm | starboard | 85.87 | 85.87 | 149.08 |
| 200-mm | top | 25.46 | 50.32 | 99.89 |
| 200-mm | bottom | 25.46 | 50.32 | 99.89 |
| 200-mm | port | 24.86 | N/A | 99.89 |
| 200-mm | starboard | 24.86 | N/A | 99.89 |
| 800-mm | top | 89.72 | N/A | 189.45 |
| 800-mm | bottom | 89.72 | N/A | 189.45 |
| 800-mm | port | 75.17 | N/A | 189.45 |
| 800-mm | starboard | 75.17 | N/A | 189.45 |

Table SM1-2. Expansion factors for pocket net catches used in the ‘full’ expansion method comparison. Description follows table SM1-1.

| Mesh size | Side panel | NOAA AWT expansion factor | DFO AWT expansion factor | MFT expansion factor |
|---|---|---|---|---|
| 100-mm | top | 85.87 | 85.87 | 149.08 |
| 100-mm | bottom | 85.87 | 85.87 | 149.08 |
| 100-mm | port | 85.87 | 85.87 | 149.08 |
| 100-mm | starboard | 85.87 | 85.87 | 149.08 |
| 200-mm | top | 53.97 | 104.08 | 215.42 |
| 200-mm | bottom | 53.97 | 104.08 | 215.42 |
| 200-mm | port | 50.11 | N/A | 215.42 |
| 200-mm | starboard | 50.11 | N/A | 215.42 |
| 800-mm | top | 118.23 | N/A | 304.99 |
| 800-mm | bottom | 118.23 | N/A | 304.99 |
| 800-mm | port | 100.43 | N/A | 304.99 |
| 800-mm | starboard | 100.43 | N/A | 304.99 |

Table SM1-3 Sensitivity of derived size-selectivity parameters of length at 50% retention ($L_{50\%}$) and the selection range ($SR$) to estimation using either the 'direct' or 'full' pocket net expansion method.

| Net | 'Direct' expansion (100 mm and 200 mm pocket nets) | | 'Full' expansion (All pocket nets present) | |
|---|---|---|---|---|
| | $L_{50\%}$ (cm) | $SR$ (cm) | $L_{50\%}$ (cm) | $SR$ (cm) |
| NOAA AWT | 11.2 | 12.5 | 10.9 | 14.0 |
| DFO AWT | 19.3 | 13.3 | 19.9 | 12.2 |
| MFT | -42.8 | 21.2 | -14.0 | 13.3 |

**Supplemental 1 Figures**

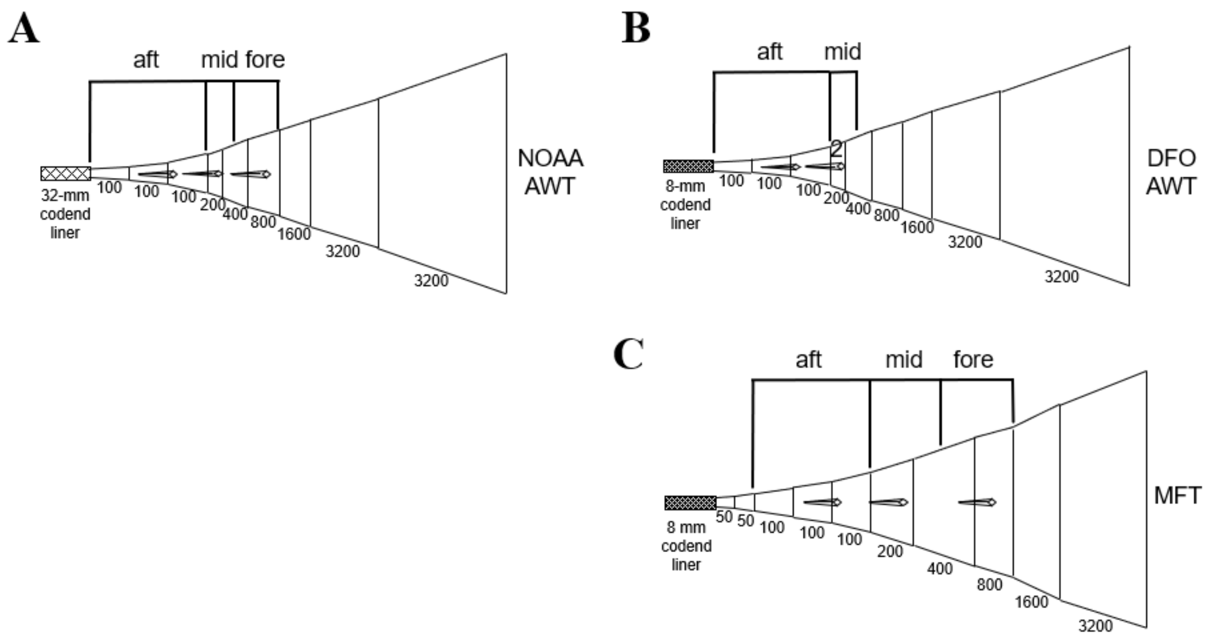


Figure SM1-1. A diagram of NOAA's Aleutian Wing Trawl (AWT, [**A**]), DFO's AWT (**B**), and the Multi-Function Trawl (MFT, [**C**]), which shows the 'full' mesh area expansion method to expand pocket net catches to their respective aft, mid, and fore sections of each net. Only the top panel of each net is shown. The DFO AWT did not have pocket nets on the 800-mm mesh area section and only 2 pocket nets, attached to the top and bottom panel of the 200-mm mesh size section. The 'full' mesh area expansion attributes half of the unrepresented 400-mm mesh size area to recapture in pocket nets attached to the 200-mm and 800-mm mesh size sections.

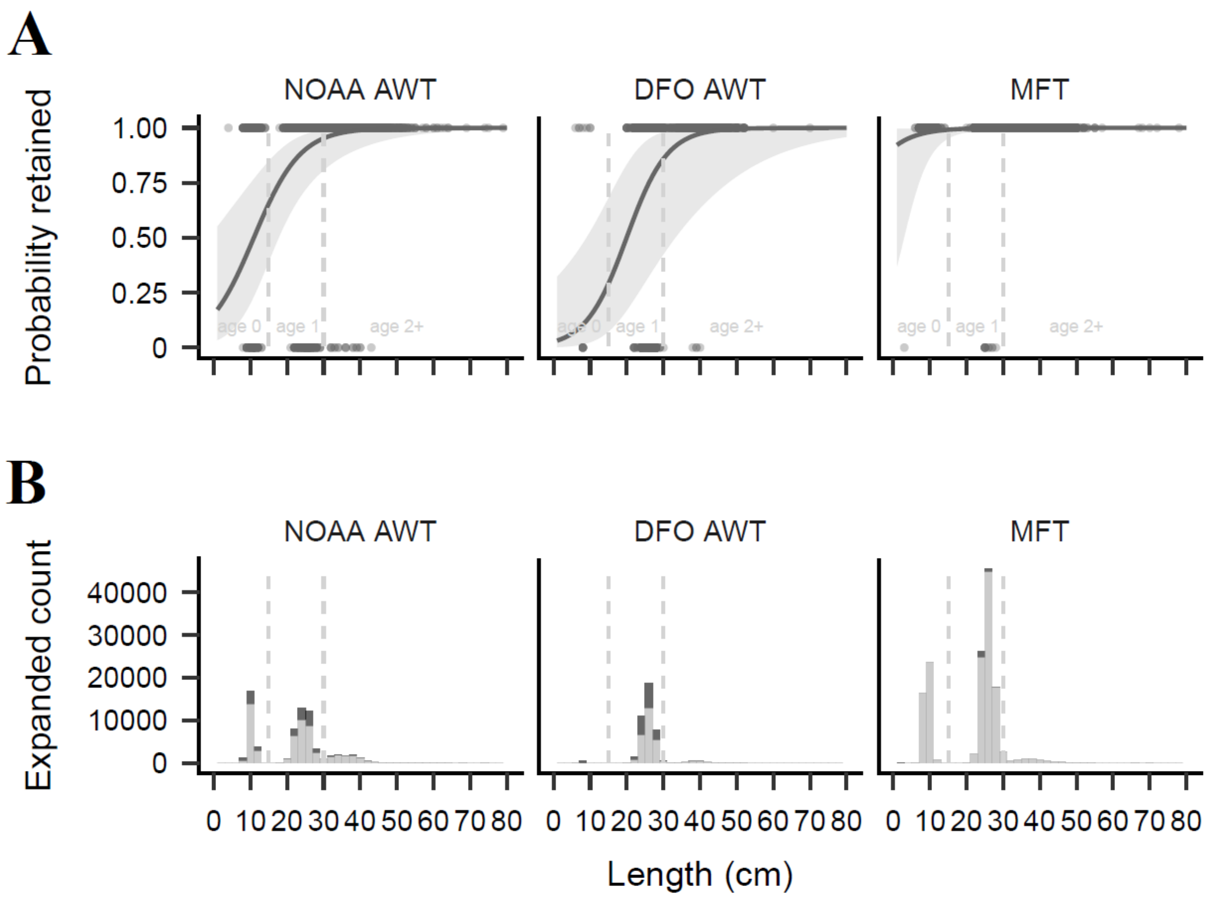


Figure SM1-2. A sensitivity of using the ‘full’ mesh area expansion method to estimate size-selectivity parameters for NOAA’s Aleutian Wing Trawl (AWT), DFO’s AWT, and the Multi-function Trawl (MFT). The top panel (A) shows the selectivity curves and the bottom panel (B) shows the length frequency information for retained fish in the codend (light gray bars) and estimated escaped fish (dark gray bars).

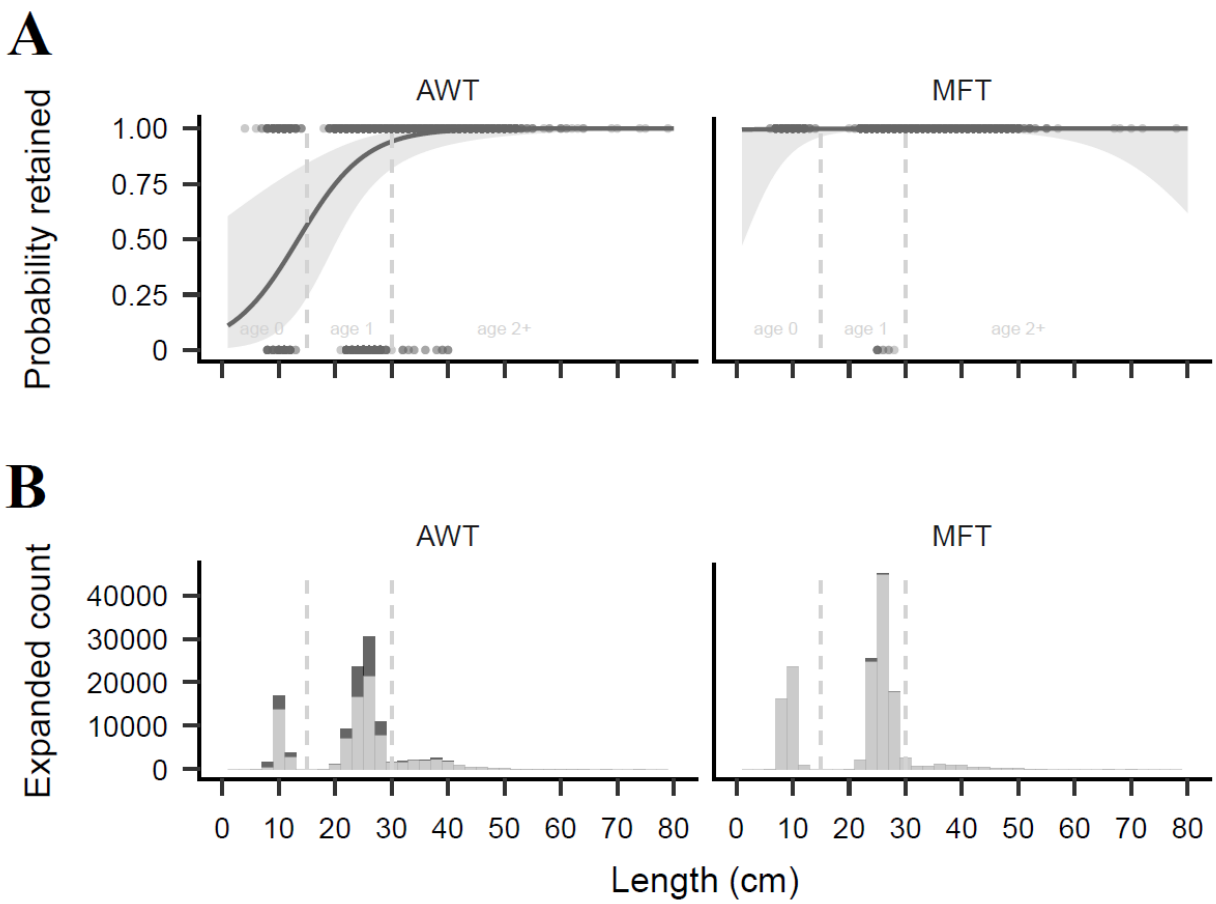


Figure SM1-3. Size-selectivity curves (A) and the corresponding expanded length frequency information (B) for the 2 net-type comparison using the 'direct' mesh area expansion method, which pooled the NOAA and DFO Aleutian Wing Trawl (AWT) data to again compare with the Multi-Function Trawl (MFT). Graphical features are the same as for figure SM1-2.

**Supplementary Materials 2**

**Power analysis**

The power analysis was conducted by simulating new data sets from the data collected in this study and testing for significant differences in the intercept parameter of all 3 nets. Below are the detailed steps of the simulation.

***Step 1.* Simulate the size of the catch.**

A negative binomial was fitted to the distribution of expanded catch sizes from the net testing dataset. The total catches (codend plus estimated escapement) of all 3 nets were combined. We used the parameters of the fitted negative binomial to randomly draw catch sizes of simulated trawls (Fig. SM2-1). The maximum catch size of hake in our dataset was 50,362 so catch size was capped at 55,000. Any larger simulated catches were replaced with the maximum of 55,000.

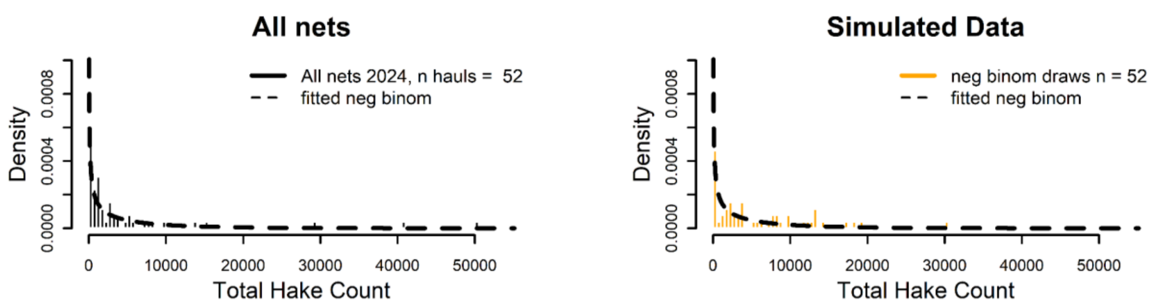


Figure SM2-1. Data of all catches used to fit a binomial distribution (left) and simulated catches for an equal sized data set (right). The total count of hake on the x axis is the estimated total number of hake entering each net, which is the expanded codend and pocket net catches. The y axis shows density (not frequency) to compare directly with the fitted negative binomial curve.

***Step 2:* Simulate the length of each fish in the catch.**

Fish length for each fish in the simulated catches was assigned by randomly sampling from the combined empirical length frequency distribution for all nets with replacement (Fig. SM2-2).

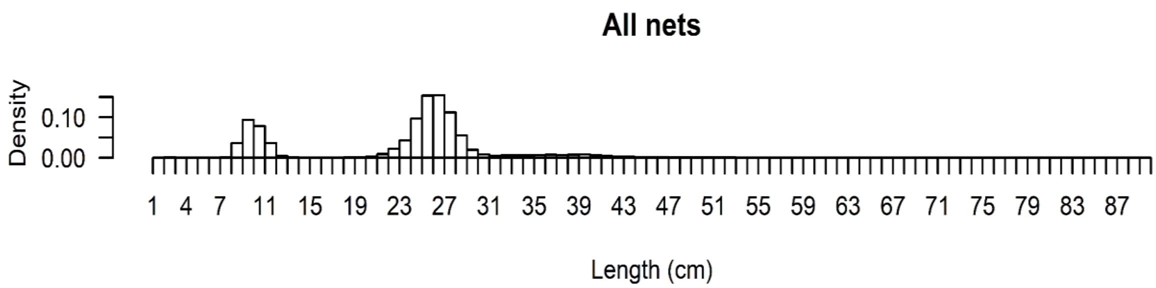


Figure SM2-2. The empirical length frequency distribution.

***Step 3:* Simulate whether each fish was retained or escaped the net.**

Retention of a fish in the codend was assigned for each fish based on the net-specific, length-based probability of retention (size-selectivity curves). For each fish, retention or escapement was assigned by a random draw from a binomial distribution with a size of 1 and mean equal to the expected size-dependent probability of retention for each net (Suppl. Fig. SM2-3).

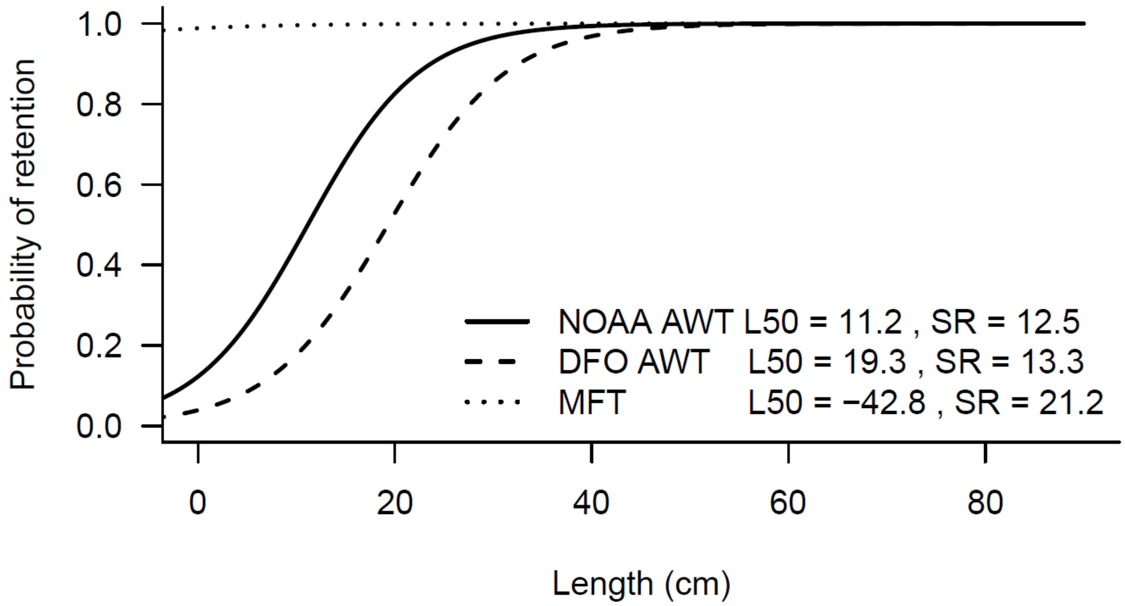


Figure SM2-3. The net-specific, size-selectivity curves, which were used to simulate the ‘true’ selectivity of each net for the power analysis. The selectivity curves are shown for NOAA’s Aleutian Wing Trawl (AWT, [solid line]), DFO’s AWT (dashed line), and the Multi-Function Trawl (MFT, [dotted line]). Fish length is shown on the x axis and the probability of retention in the codend on the y axis. Reference parameters are show for the length at 50% retention (L50) and the selection range (SR) in units of centimeters (cm).

***Step 4:* Test for a significant difference in the intercept parameter of all 3 nets in the simulated data.**

Define significance as $P < 0.05$. Run the simulation 100 times and record statistical power as the number of positive detections at $P < 0.05$ out of the 100 simulations. Start with the original number of trawls to test for the statistical power to detect differences in all 3 nets from the 2024 dataset and then run 100 simulations for increasing the number of trawls per net to estimate how many trawls are needed to obtain adequate statistical power of an 80% detection rate. The number of trawls were increased in increments of an additional 15 trawls per net greater than the 2024 number of trawls (Fig. SM2-4).

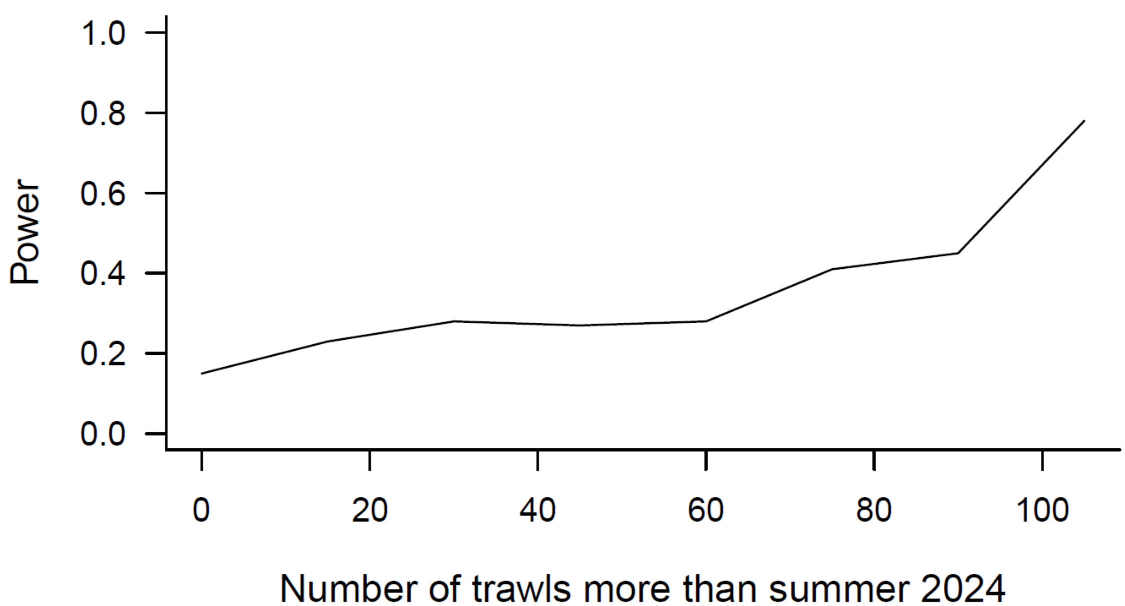


Figure SM2-4. The power analysis showing the probability of detecting a significant difference in the size-selectivity parameters of all 3 nets (y axis), given the number of trawls and patterns observed in this study (NOAA's AWT = 22 trawls, DFO's AWT = 13 trawls, and the MFT = 17), and a hypothetical increase in the number of trawls (x axis) needed to obtain an adequate statistical power of 80%.