# Is Pacific cod (*Gadus macrocephalus*) survey selectivity dome-shaped? Direct evidence from trawl studies

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## Abstract

The selectivity of a demersal trawl survey can be viewed as a function of the availability of the various biological components of the stock to the sampling gear and the sampling efficiency of the gear. A dome-shaped function in which trawl selectivity decreases with larger-older fish, such as that estimated for the eastern Bering Sea Pacific cod (*Gadus macrocephalus*) in the current stock assessment model, would seem appropriate if large cod avoid capture. To test this assumption, a field study was conducted to determine if large cod escape capture by either outswimming the survey trawl or by swimming above the trawl. Our results show that cod do not outswim the trawl because catches did not increase when we increased towing speed. Additionally, cod do not routinely swim above the trawl because analysis of acoustic backscatter collected concurrently with trawls indicated that only 4% of acoustic scattering attributed to cod occurred at heights above the headrope. We found no evidence of differential survey efficiency (swim speed) or availability (vertical distribution) for cod at size (age) that supports the use of a dome-shaped selectivity function in the cod assessment model.

## Introduction

Fisheries stock assessment surveys are intended to produce an index of relative stock abundance that varies over time in constant proportion to the true stock abundance. In stock assessment models, the scaler relating the modeled abundance to the survey index is often considered a product of a constant catchability, and a fish age- or length-dependent selectivity function, (hereafter, for reasons of simplicity, we refer to length-dependent functions but the same applies to age-dependent functions). Both catchability and selectivity are typically estimated when the stock assessment model is fit to data, although in some cases the catchability coefficient is fixed *a priori* (Thompson, 2014). The selectivity of a survey can be viewed as a function of the availability of the various biological components of the stock to the sampling gear and the sampling efficiency of the gear (i.e., the proportion of encountered animals that are captured). However, the relative importance of availability (e.g., small fish occur shallower than survey depths) and sampling efficiency (e.g., small fish pass through trawl mesh) in determining the shape of a selectivity function is difficult to determine without additional information.

The shape of the survey selectivity function is at issue for the assessment model of the eastern Bering Sea (EBS) Pacific cod (*Gadus macrocephalus;* hereafter referred to as cod; Thompson, 2014). The assessment model, conducted using the Stock Synthesis package (Methot and Wetzel, 2013), is fit to commercial catch data dating back to 1977, as well as fisheries-independent data from the annual National Marine Fisheries Service EBS demersal trawl survey (hereafter referred to as the survey). The survey provides estimates of relative abundance and length compositions dating back to 1982, and age compositions from 1994 onward (Lauth and Nichol, 2013). The current assessment model accepted for management, in addition to several historical model configurations, includes a flexible survey selectivity function that, after being fit to the data, decreases at larger fish sizes (Thompson, 2014; Fig. 1, Table 1). This functional form, referred to as "dome-shaped", has rising and descending limbs to either side of the top. The descending limb suggests that larger fish are less vulnerable to the survey in some way, perhaps because they are better able to escape the trawl or spatially separated from smaller fish. In contrast, the more traditional asymptotic function implies that the survey is sampling a greater proportion of the large fish in the population. If the model is not well informed by the data, it may be uncertain whether the shape of the estimated function reflects the survey sampling processes or parameter confounding. The difference between interpretations may have a pronounced effect on the determination of stock size and recommended harvest rates.

Field studies designed to describe survey gear efficiency and stock availability provide a source of "direct" evidence and can assist in the fitting of the selectivity function (Cadrin et al, 1999; Clark and Kaimmer, 2006; Nichol et al., 2007; Somerton et al., 2007; Somerton et al., 2013; Weinberg et al., 2004). This paper presents the results from a new study, and reviews results from previous works, to determine whether direct evidence from field studies corroborates the dome-shaped survey selectivity function estimated by the current cod assessment model. Whereas this paper focuses on Pacific cod, the concept that field experiments to better inform assessment models is applicable worldwide.

If it is assumed that the survey covers the entire geographic range of EBS cod, then a dome-shaped selectivity function might result from a progressive decrease in trawl sampling efficiency for larger fish sizes. Sampling efficiency is dictated by three processes: vertical herding, horizontal herding, and escapement, all of which are dependent on trawl design, fishing procedures, fish behavior, and swimming endurance. Together these processes play an important role in the survey estimates of abundance and size composition of groundfish resources (Godø and Walsh, 1992). The evidence collected from field and laboratory studies clearly demonstrates that fish swimming stamina and reactions to trawling are species-specific (He and Wardle, 1988; Winger et al., 1999), size-dependent (Main and Sangster 1981; He and Wardle, 1988; Winger et al., 1999), temperature-affected (He, 1991; Winger et al., 1999), light-responsive (Glass and Wardle, 1989; Walsh, 1991a), and often density-dependent (Godø et al., 1999; Kotwicki et al., 2014). We note that not all studies have come to the same conclusions for all species, or even within the same species in all cases, but the most universal observation is the inverse relationship between swimming speed and endurance; the faster a fish swims, the more energy required and the less time it is capable of sustaining such speed. If a fish is able to swim fast enough and long enough to outpace a survey trawl, sampling efficiency will be reduced. Likewise, if large cod, more so than smaller cod, have the strength and stamina to outswim the survey trawl, survey selectivity will be reduced for the larger animals.

In addition to the possibility that larger cod avoid capture by outswimming the trawl, it is also possible that larger cod occur higher in the water column and are more likely to swim over the headrope of the survey trawl. This can be examined using acoustic data collected simultaneously while trawling. Analysis of acoustic data to estimate abundance has not been attempted for cod due to concerns stemming from the confounding of backscatter signals close to the seabed (i.e., separating the weaker fish signal from the stronger seabed signal), in the area known as the acoustic deadzone (Ona and Mitson, 1996), and the inability to separate species–specific backscatter when multiple swimbladdered species such as cod and walleye pollock (*Gadus chalcogrammus*) co-occur.

The objective of this paper is to report the results of an experiment aimed at examining survey trawl efficiency for large-sized cod avoiding capture by either: simply outswimming the trawl, or by demonstrating less vulnerablity to capture by passing over its headrope. If differential, size-specific, survey efficiency exists or the vertical availability of cod makes them less vulnerable to the survey trawl, then these data would support the application of a dome-shaped function.

## Materials and methods

### General design

Our experiment was designed to test the hypothesis that a substantial proportion of large cod avoid capture by outswimming the survey trawl when fished using standard protocols (Stauffer, 2004). Secondarily, we were also able to provide a test of the hypothesis that a substantial proportion of cod are unavailable to the survey by occurring in the water column above the headrope of the survey trawl. Our definition of "large" cod, ≥ 55 cm, was based on lengths at the right tail of the selectivity schedule estimated in the 2013 stock assessment of EBS Pacific cod (Thompson, 2014), for which estimated trawl selectivity was less than 1.0 (Table 1, Fig. 1). The experiment took the form of paired parallel towing in which one vessel trawled at the survey standard 1.5 m $s^{-1}$ (3 kn = "slow") speed while the other towed at a faster 2.1 m $s^{-1}$ (4.0 kn = "fast") speed. Bering Sea commercial cod trawlers report towing speeds generally ranging from 1.25 to 2.25 m $s^{-1}$ (2.5 - 4.5 kn), depending on vessel power, mesh size, and other trawl design features. We felt the upper limit for towing the survey trawl, should be no more than 2.1 m $s^{-1}$ in order to maintain proper fishing configuration (Weinberg, 2003). As such, we were 0.15 m $s^{-1}$ short of the fastest commercial trawling speeds reportedly achieved. If the number of large cod captured in the standard slow tows was no different than in the faster tows, then we would conclude that cod do not outswim the survey trawl.

## Field operations

Fieldwork was conducted during 3-5 August immediately following the 2013 survey aboard the same 2 chartered survey trawlers. All trawling utilized the standard 83-112 eastern demersal survey trawl. This is a 2-seam flatfish trawl having a 25.3-m long (83-ft) headrope, and a 34.1-m long (112-ft), 5.2-cm diameter, footrope (details provided in Weinberg, 2003; Lauth and Nichol, 2013). The footrope is weighted with 75 kg of chain hung in equal loops along its length from which the nylon netting is attached. Mesh size varies from a maximum of 10.2 cm in the wings and throat to a minimum of 3.2 cm used for a liner in the codend. Each side of the net is attached to a 1.8 x 2.7-m steel V-door weighing approximately 816 kg by a pair of 54.9-m-long, 1.6-cm-diameter bare wire bridles. Because faster trawling has been shown to exacerbate inconsistencies in seabed contact of this trawl (Weinberg, 2003), an additional 34 kg of weight was secured to the footrope, then monitored with a bottom contact sensor for all tows in this experiment.

The major difference between experimental and standard survey tows was towing speed. All other trawling procedures followed those used during the survey, e.g., straight-line towing, locked winches with equal lengths of warp, standard warp length to depth ratios, and setting/retrieval methods designed to get the net down on the seabed in fishing configuration quickly at the start of the tow and off the seabed at the end of the tow. Our balanced-pair design called for repetitive parallel towing. On odd numbered pairs, one vessel was randomly selected to tow at the survey standard 1.5 m $s^{-1}$ speed, while the other towed at the faster 2.1 m $s^{-1}$ speed. On even-numbered pairs the vessels switched towing speed. To reduce potential bias from sea conditions, the faster boat was randomly appointed to fish either the port or starboard side of the slower boat.

When fishing with two boats at different speeds, we had a choice of enforcing either consistent tow duration (time) or consistent tow length (distance). Because it has been shown that variation in tow durations (15 and 30 min) did not affect the catch size distribution for some Atlantic species including Atlantic cod (*Gadus morhua*; Godø et al., 1990; Walsh, 1991b), we elected to reduce the duration of the faster tows so that the distance fished and swept area of the two tow speeds were similar (Wileman et al., 1996). Hence, the duration of the slow 1.5 m $s^{-1}$ and fast 2.1 m $s^{-1}$ tows were set at 30 and 22.5 min, respectively, measured from the time the nets were on bottom and the winches were locked to when trawl retrieval was initiated.

Parallel demersal tows were made at safe distances within 0.25 nm of the other vessel. Towing occurred at two independent sites, one at 136 m (deep) and the other at 86 m (shallow) in depth. Ten successful pairs of fast-slow tows were made at the deep site and 14 at the shallow site. All captured cod were measured (unsexed) to the nearest cm (fork length).

## Data analysis

### Swept area

Swept area for each haul was estimated as the average net width from data collected with a Marport[1] (Marport, Snohomish, Washington) acoustic net mensuration system, multiplied by the

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

length of the tow path, measured by GPS positioning of the vessel at first and last footrope contact with the seabed, which was determined using a bottom contact sensor (Somerton and Weinberg, 2001). Outlier net width measurements were removed using a sequential outlier rejection algorithm and the remaining data were fit with a smoothed spline from which the average net width was calculated for each tow (Kotwicki et al., 2011).

Measuring the swept area of each tow was complicated due to net mensuration instrument failure during some tows. As such, only a subset of all tows produced valid net width data. Paired t-tests were used to test for a difference in the swept area between the fast and the slow tows of each pair, considering only pairs where net widths were available for both tows. If the difference was found not to be significant ($p > 0.05$) in this subset of tows after thoroughly examining the data from our bottom contact sensors for anomalies that would suggest the likelihood of high variability in net width during a tow, then we assumed swept area was not different between any fast-slow paired tows and the raw catch (counts) from all tows was used as the dependent variable in subsequent analyses.

**Effect of towing speed on catch**

The alternative hypothesis that the catch of large cod at a fast tow speed ($c_f$) was greater than the catch of large cod at a slow tow speed ($c_s$) was examined using paired-sample tests (the null hypothesis being no difference between the catch of large cod at either speed). First, the probability of either tow speed being equally likely to obtain greater catch was calculated with a sign test, i.e., the binomial probability that $c_f > c_s$ in X pairs (successes) out of the total Y pairs of tows (trials) observed if the null hypothesis of no speed effect on catch was true. A paired t-test was then conducted to further confirm the result of the less-sensitive, but more robust, sign test. The null hypothesis of the t-test was no mean difference ($\bar{d}$) between ln($c_f$) and ln($c_s$) of the paired tows ($H_0$: $\bar{d}$ = 0, i.e. the mean ratio $\overline{c_f/c_s}$ = 1), assuming that the differences between pairs were normally distributed. The power (1-β) of the t-test was calculated for a 1-sided ($H_a$: $\bar{d} > 0$) alternative hypothesis based on the t-distribution, observed standard deviation (sd) of ln($c_f$) - ln($c_s$), sample size (*n*) of 24 pairs of tows, and significance level ($\alpha$) of 0.05. The power was calculated for a range of $\bar{d}$ for $H_a$ from 0.1 to 1.0, where $e^{\bar{d}} = c_f/c_s$.

Finally, we estimated $\hat{\bar{d}}$ based on the length-derived, double normal selectivity schedule from the EBS stock assessment model for Pacific cod (see appendix A in Methot and Wetzel, 2013; Thompson, 2014). For this study we assumed that at the fast tow speed, no large cod can escape the net and all available fish are caught; at the slow tow speed, the large cod available can escape the net in the proportion indicated by the selectivity function. In order to increase our sample size, we pooled the numbers of fish caught in this experiment into length groups with the same selectivity, rounded to the first decimal place (Table 1). The total expected catch in a tow based on the curve, $c_e$, was calculated as the sum of the catch in each length group in the slow tow ($c_{s\_l}$) divided by the selectivity for that length group ($s_l$): $c_e = \sum_{l=1}^{L} c_{s\_l} / s_l$. Based on the assumptions, $c_e$ would be the expected catch in a fast tow. Therefore, the mean ratio of expected catch to the catch of the slow tow for the *n* pairs of tows, $\frac{\sum_{i=1}^{n} c_{e\_i}/c_{s\_i}}{n}$, would be the expected mean ratio of catch in the fast tow over the slow tow.

**Vertical distribution**

Both vessels used calibrated Simrad ES60 echosounders (Kongsberg Maritime AS, Kongsberg, Norway) operating at 38 and 120 kHz with a sampling rate of 1-2 pings per second to collect acoustic backscatter data. The sampling resolution of these data was approximately 0.2 m vertically and 0.8-2.1 m horizontally at ship speeds of 3 and 4 kn (1.5 and 2.1 m $s^{-1}$). Given nominal beam widths of 7° at both frequencies, depths of the hull-mounted transducers (4 m), and depth of the seafloor at the deep study site (136 m), the area ensonified by each ping was approximately a 16 m diameter circle (close to the average net width for this depth) covering a 205 $m^2$ area. These data were analyzed with Echoview, vers. 5.4.90 (Myriax Software Pty Ltd, Hobart, Australia) affording us the opportunity to detect whether cod occurred above our net opening at the moment they were ensonified by the vessel. The difference between mean volume backscattering strength ($S_v$, dB re 1 $m^{-1}$; cf. MacLennan et al., 2002) at 120 and at 38 kHz in 20 pings by 5 m vertical bins was used to identify backscatter consistent with that of swimbladdered fish, according to concurrent trawl catch and $S_v$ data in De Robertis et al. (2010). Only bins where the backscatter had a signal-to-noise ratio of at least 10 dB (De Robertis and Higginbottom 2007) were included in the analysis. Bins in which the difference between $S_v$ at 120 and 38 kHz was between -10 and 8 dB were classified as fish. Fish backscatter per unit area ($s_A$, $m^2$ $nmi^{-2}$) was then integrated in several depth layers referenced to a 0.25 m backstep above the seabed echo (0.25-2.0, 2.0-2.5, 2.5-3.0, 3.0-7.0, and 7.0-16.0 m), using an $S_v$ integration threshold of -70 dB. The upper bounds of the first depth interval match the mean headrope height of this experiment. Similarly, a height of 2.5 m corresponds to a survey-wide average (Nichol et al., 2007), a height of 7.0 m corresponds to a survey-wide average for the AFSC poly Noreastern survey trawl used to assess cod in the Gulf of Alaska region (Nichol et al., 2007), and a height of 16.0 m corresponds to an estimated effective fishing height for EBS walleye pollock by the 83-112 survey trawl (Kotwicki et al., 2013) that perhaps may apply (but difficult to show), to cod as well.

The results were examined for evidence of fish above the headrope height (mean 2.0 m) during the time the demersal trawl was in contact with the seabed, after accounting for horizontal setback of the trawl behind the vessel (approximately 3-4 min ahead of the trawl net pending vessel speed). The acoustic assessment was restricted to the deep study site, where catches consisted almost exclusively of cod and flatfish, because it was reasonable to assume that any swimbladdered fish backscatter was due to cod. It was not possible to do this at the shallower study site, because the catches were dominated by walleye pollock which cannot be acoustically distinguished from cod.

## Results

### Catch summary

A total of 1462 cod, ranging in size from 34-105 cm, were caught from 48 experimental tows, in which bottom temperatures ranged between 2.6 and 2.7°C, but only two fish were larger than 90 cm (Fig. 2). Of these, 701 individuals were large (≥ 55 cm) and included in further analyses.

### Swept area

Of the 24 pairs of tows made, 16 had reliable net mensuration data from which we could test differences in swept area by pair. The mean difference in swept area between paired tows (fast-slow) was -0.072 ha, which was not significant (t = -0.492, df = 15, $p$ = 0.63). The fast tows swept a greater area than the slow tows during half the pairs and vice versa (8 of 16). Bottom contact sensors provided reliable data on all tows indicating trawl footropes were firmly in contact with the substrate supporting our decision to use all 24 pairs of data in subsequent analyses.

**Effect of towing speed on catch**

Fast tows had larger catches of large cod in only 10 of 24 paired tows. In those 10 pairs, the catches from fast tows were 1.1 to 2.7 times (mean = 1.6) greater than the catches from slow tows (Table 2). A sign test indicated that larger catches were not significantly more frequent in fast tows (successes = 10, trials = 24, $p$ = 0.924); larger catches in at least 18 of the 24 pairs would be required for significance at $p \leq 0.05$.

The mean difference $\bar{d}$ between $\ln(c_f)$ and $\ln(c_s)$ was -0.08 ± 0.55 (sd), and was approximately normally distributed according to a $X^2$ goodness-of-fit test ($X^2_{5\text{-}2\text{-}1}$ = 1.226, $p$ = 0.54; Fig. 3). The mean of $c_f/c_s$ was 1.1 ± 0.58 (range 0.3 – 2.7; Table 2). A paired t-test indicated that the difference in ln(catch) between fast and slow tows was not statistically significant ($t_{23}$ = -0.69, $p$ = 0.50). The expected mean ratio of catch of large cod in fast tows over slow tows ($c_f/c_s$) was 1.5 (range = 1.3 – 1.9). If the expected ratio of 1.5 were true, the power of a 1-sided t-test ($H_a$: $\bar{d} > 0$) would be 97% in rejecting $H_0$ (Table 3).

**Vertical distribution**

Measured demersal fish backscatter was fairly low, as would be expected given the low numbers of cod captured. The strongest demersal fish backscatter ($S_v$ ~ -45 dB) appeared very close to the acoustically detected seabed; fish backscatter farther off the seabed was generally weaker in comparison ($S_v$ ~ -65 dB). The demersal fish backscatter observed below the average headrope height of 2.0 m during this study was a very large fraction of fish backscatter integrated over all depth layers examined (median proportion 0.96; Fig. 4). In an absolute sense, the highest demersal fish backscatter values were found within the 0.25-2.0 m layer (Fig. 5); the median fish $s_A$ in this layer was more than 14 times that in any other depth layer.

## Discussion

Our findings showed no difference between the catch rates of large cod using the 83-112 Eastern survey demersal trawl when towing at 1.5 and 2.1 m $s^{-1}$ speeds. Therefore, we surmise that if the dome-shaped selectivity estimated in recent stock assessments (Thompson, 2014) is due to a decrease in trawl efficiency for cod of large size, this decrease is not attributable to large fish outswimming the net. Of the many species studied for their swimming capabilities, the Atlantic cod is most closely related to Pacific cod. Winger et al. (2000) performed a comprehensive tank study on the swimming stamina of Atlantic cod and deduced that the catching efficiency of this species would be impacted by changes in towing speed. In their study, Atlantic cod were subjected to slower water velocities than our towing speeds, but temperatures close to those in our study (2.6°C). At speeds conducted by fishers in the NE Atlantic (1.0 m $s^{-1}$), Atlantic cod were able to maintain sustained swimming speeds for 10 min, but at 1.5 m $s^{-1}$ (or 3 kn, our ‘slow’ trawling speed), they could maintain swimming speed for only 1 min. If Pacific cod swimming capabilities are indeed similar to those of Atlantic cod, then, given our experimental trawling speeds of 1.5 m $s^{-1}$ or greater, we expect that Pacific cod maximum sustained swimming speeds would not be enough to elude capture even during our shorter, 22.5 min experimental towing durations.

If large cod are not outswimming the trawl, then perhaps they are swimming over the headrope, which would also explain a drop in selectivity for large fish related to both trawl sampling efficiency and availability. Here, we used fish backscatter to within 0.25 m of the seabed to assess the vertical distribution of cod near the seafloor during our experimental tows. This process discards potential backscatter from fish in the so-called "acoustic dead zone" (Ona and Mitson, 1996) located very close to the seabed, which could be an area of concern for an absolute estimate of all fish $s_A$. However, this is less important for our main interest of detecting cod occurrence relative to the headrope height of the trawl; indeed, if most cod are in the acoustic dead zone, then they clearly are not above the headrope height during vessel passage. Analysis of the acoustic backscatter while towing indicated that only 4% of the total backscatter attributed to cod occured above the height of the survey headrope, although the backscatter was measured at the vessel rather than at the net itself, which would allow subsequent upward movement to go undetected. Studies of walleye pollock (Kotwicki et al., 2013) and Atlantic cod show that these two commercially important gadids were stimulated to dive, rather than rise, as their response to trawl warps may be both acoustically as well as visually driven according to Handegard and Tjøstheim (2005). This behavior is also acknowledged by commercial fishing practices whereby fishers tend to drag their nets below schools. Based on this information, there is little indication that cod swam over the headrope during this experiment.

We are unaware of prior studies specifically investigating Pacific cod swimming stamina relative to trawling, burst swimming speeds, or the tendency for cod to swim over a bottom trawl. Nichol et al., (2007) however, on the basis of 11 archival tags, did provide evidence of a significant off-bottom component to the cod vertical distribution during daylight hours (the time during which the survey is conducted). Specifically, their findings showed that when in an undisturbed state (i.e., deployed in the absence of vessel noise or oncoming trawl gear), large cod swim above the survey average height of the trawl (2.5 m) approximately 53% of the time and within 10 m of the seabed 95% of the time. While based on an interpretation of estimated tidal activity, their study has had a pronounced impact on the current stock assessment model, such that the catchability coefficient was fixed so that the average product of catchability and selectivity across cod sizes 60-81 cm is 47% (Thompson, 2014). Although we agree with Nichol et al. (2007), that it seems unlikely for the survey trawl to catch 100% of the cod in its path 100% of the time, our study casts doubt on the conclusion that more than 50% of the large fish swim above the trawl. However, just as that study was based on a small sample, our study lacked broad geographical range, over areas with varying habitat complexity, light intensity, and temperatures which (although never shown) may all have an effect on cod vertical distributions or perhaps even swimming speeds (Ferno et al., 2011). Further research on these topics would shed additional light on the subject.

Selectivity functions in stock assessment models are designed to be a parsimonious representation of the relative size-dependency of the survey sampling process. However, stock assessment models can be quite complex, often including hundreds of parameters that must be estimated when the models are fit to data (Maunder and Punt, 2013; Methot and Wetzel, 2013), and such complexity can lead to parameter correlation and confounding during model fitting.

One example of this is the correlation between survey selectivity parameters and the natural mortality rate (Thompson, 1994), which can lead to ambiguity in ascribing unexpectedly low catches at a particular length to either reduced survey selectivity or underestimation of the natural mortality rate. If the model is not well informed by the data, it may be uncertain whether the shape of the estimated function reflects the survey sampling processes or parameter confounding. The difference between interpretations may have a pronounced effect on the determination of stock size and recommended harvest rates.

In conclusion, based on direct evidence from this and other field studies investigating trawl sampling efficiency, we are unable to corroborate the dome-shape for the Pacific cod survey selectivity. Large cod do not escape capture by outswimming the survey trawl as catches when towing at the faster speed were no different than when towing at the slower survey speed. This suggests once cod reach the trawl mouth they lack the means to swim fast enough or long enough to escape forward around the wing ends. *In situ* video evidence shows this species tends to hold station in front of the footrope for only brief periods before slipping back into the net.[2] Large cod are unlikely to swim over the net because acoustic backscatter shows that most cod, when in the presence of a trawler, occur very close to the bottom within the vertical fishing dimensions of the trawl, and findings from previous studies on gadid behavior indicate trawl gear elicits a diving response to elude capture, not a rising response. The remaining avenues for escapement, that could explain lowered trawl efficiency, are if large cod were to swim through the small mesh of the survey net, which is physically impossible; or, if they were to escape beneath the footrope, the frequency of which has been previously shown to be negligible (Weinberg et al., 2002).

[2] Rose, C.R. 2010. Unpubl. data. Alaska Fisheries Science Center, RACE Div. 7600 Sand Point Way NE, Seattle, WA 98115.

If the model's estimated selectivity function is indeed correct, then the mechanism(s) that explain the steep descent of the right-hand tail must consist of something other than sampling efficiency. Three possible explanations for this are 1) large fish migrate out of the survey grid, hence becoming unavailable to the survey; 2) large fish remain in areas of rough bottom considered untrawlable by this survey gear, such as very nearshore to St. Mathew and the Pribloff Islands and some parts of the Alaska mainland (which accounts for a very small proportion of the total survey area), hence unavailable to the survey; and 3) the relationships between availability/efficiency and catchability/selectivity are complicated enough that studies of availability or efficiency alone are insufficient to explain catchability or selectivity (see Appendix). If something is misspecified in the assessment model (e.g., perhaps the natural mortality rate is too low, or varies with size), then the selectivity of the survey for large cod would be closer to unity and could lead to a change in the harvest quotas. We suggest further research on these subjects to clarify the responsible mechanisms.

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Table 1. Survey selectivity (rounded to one decimal place) by length (cm) groups based on the 2013 eastern Bering Sea Pacific cod assessment model's length-based schedule.

| Survey selectivity | Lengths(cm) |
|---|---|
| 1.0 | 34-54 |
| 0.9 | 55-60 |
| 0.8 | 61-65 |
| 0.7 | 66-69 |
| 0.6 | 70-74 |
| 0.5 | 75-79 |
| 0.4 | 80-88 |
| 0.3 | 89-105 |

Table 2. Catch of large (≥55 cm) Pacific cod at fast ($c_f$) and slow ($c_s$) tow speeds for each pair of tows. Pairs 1-10 were deep tows. Pairs 11-24 were shallow tows. The expected catch $c_{e1}$ and $c_{e2}$ were calculated based on the selectivity curves $s_1$ and $s_2$ as described in Materials and methods.

| Pair | $c_f$ | $c_s$ | $c_f/c_s$ | $c_{e1}$ | $c_{e1}/c_s$ | $c_{e2}$ | $c_{e2}/c_s$ |
|---|---|---|---|---|---|---|---|
| 1 | 17 | 22 | 0.8 | 29 | 1.3 | 33 | 1.5 |
| 2 | 16 | 6 | 2.7 | 7 | 1.2 | 8 | 1.4 |
| 3 | 14 | 10 | 1.4 | 14 | 1.4 | 19 | 1.9 |
| 4 | 11 | 15 | 0.7 | 21 | 1.4 | 26 | 1.8 |
| 5 | 5 | 12 | 0.4 | 16 | 1.3 | 18 | 1.5 |
| 6 | 7 | 26 | 0.3 | 35 | 1.3 | 42 | 1.6 |
| 7 | 5 | 5 | 1.0 | 7 | 1.4 | 8 | 1.5 |
| 8 | 7 | 9 | 0.8 | 12 | 1.4 | 15 | 1.7 |
| 9 | 9 | 9 | 1.0 | 12 | 1.3 | 15 | 1.6 |
| 10 | 15 | 13 | 1.2 | 17 | 1.3 | 19 | 1.5 |
| 11 | 14 | 14 | 1.0 | 18 | 1.3 | 20 | 1.4 |
| 12 | 19 | 42 | 0.5 | 53 | 1.3 | 57 | 1.4 |
| 13 | 22 | 10 | 2.2 | 12 | 1.2 | 14 | 1.4 |
| 14 | 17 | 15 | 1.1 | 18 | 1.2 | 19 | 1.3 |
| 15 | 17 | 16 | 1.1 | 20 | 1.3 | 22 | 1.4 |
| 16 | 22 | 36 | 0.6 | 45 | 1.2 | 50 | 1.4 |
| 17 | 11 | 27 | 0.4 | 34 | 1.3 | 38 | 1.4 |
| 18 | 22 | 19 | 1.2 | 26 | 1.4 | 31 | 1.6 |

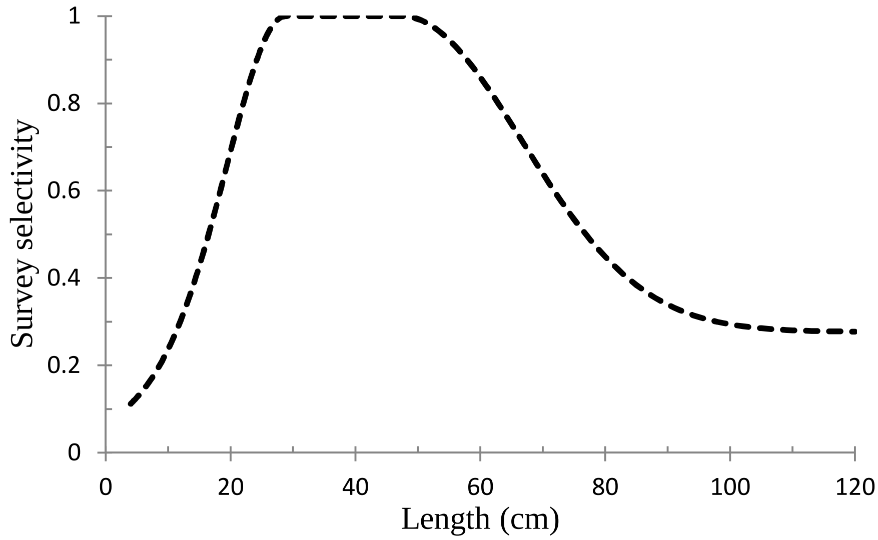
| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 19 | 16 | 23 | 0.7 | 29 | 1.3 | 32 | 1.4 |
| 20 | 16 | 15 | 1.1 | 19 | 1.2 | 20 | 1.4 |
| 21 | 15 | 8 | 1.9 | 11 | 1.4 | 13 | 1.6 |
| 22 | 7 | 7 | 1.0 | 9 | 1.3 | 10 | 1.5 |
| 23 | 6 | 7 | 0.9 | 9 | 1.2 | 9 | 1.3 |
| 24 | 16 | 9 | 1.8 | 11 | 1.3 | 13 | 1.4 |

Table 3. Power of t-test (probability of rejecting $H_0$ when it is false) for the mean difference $\bar{d}$ between $\ln(c_f)$ ($c_f$ - catch of fast tows) and $\ln(c_s)$ ($c_s$ - catch of slow tows), where $H_0$: $\bar{d} = 0$, against one-sided $H_a$: $\bar{d} > 0$ alternative hypotheses. The t-distribution was used with degrees of freedom (df) = 23 and significance level ($\alpha$) = 0.05.

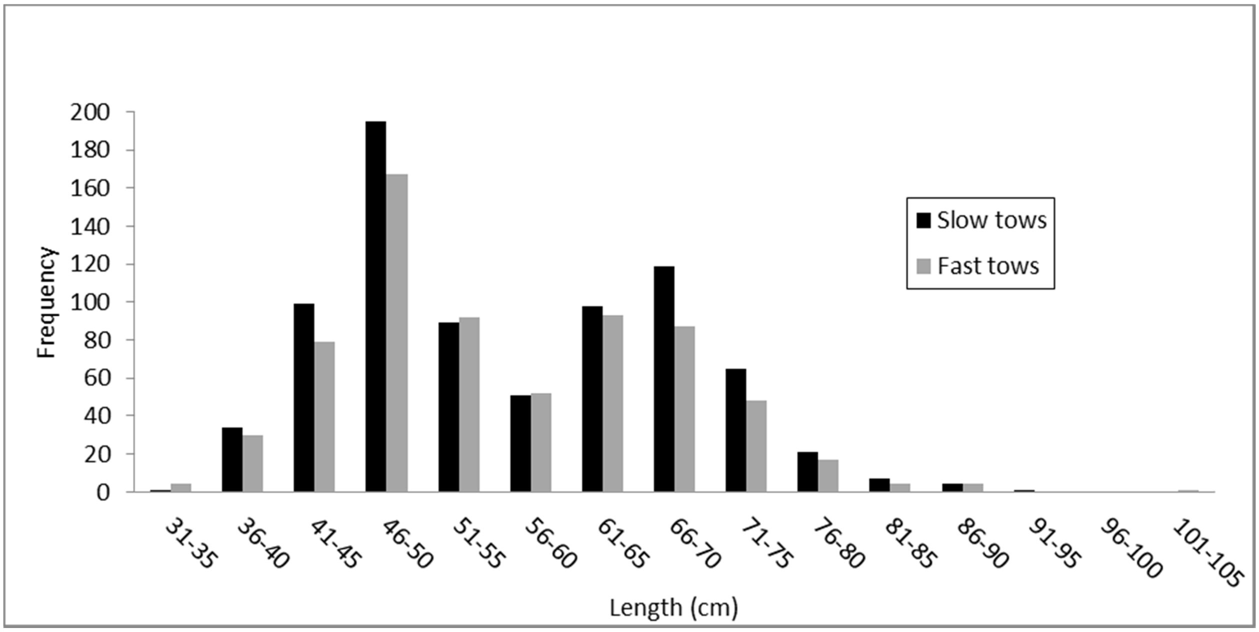
$H_a$: $\bar{d} > 0$

| $\bar{d}$ | $e^{\bar{d}} = c_f/c_s$ | power |
|---|---|---|
| 0.1 | 1.1 | 0.21 |
| 0.2 | 1.2 | 0.53 |
| 0.3 | 1.3 | 0.83 |
| 0.4 | 1.5 | 0.97 |
| 0.5 | 1.6 | 0.99 |
| 1.0 | 2.7 | 1.00 |

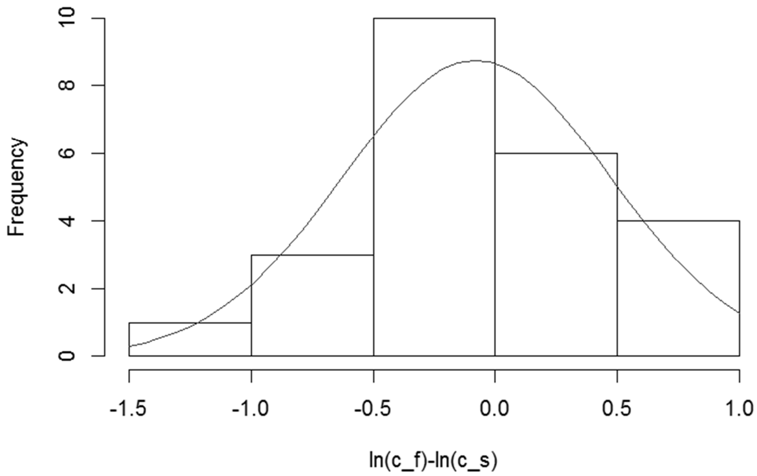
## List of Figures



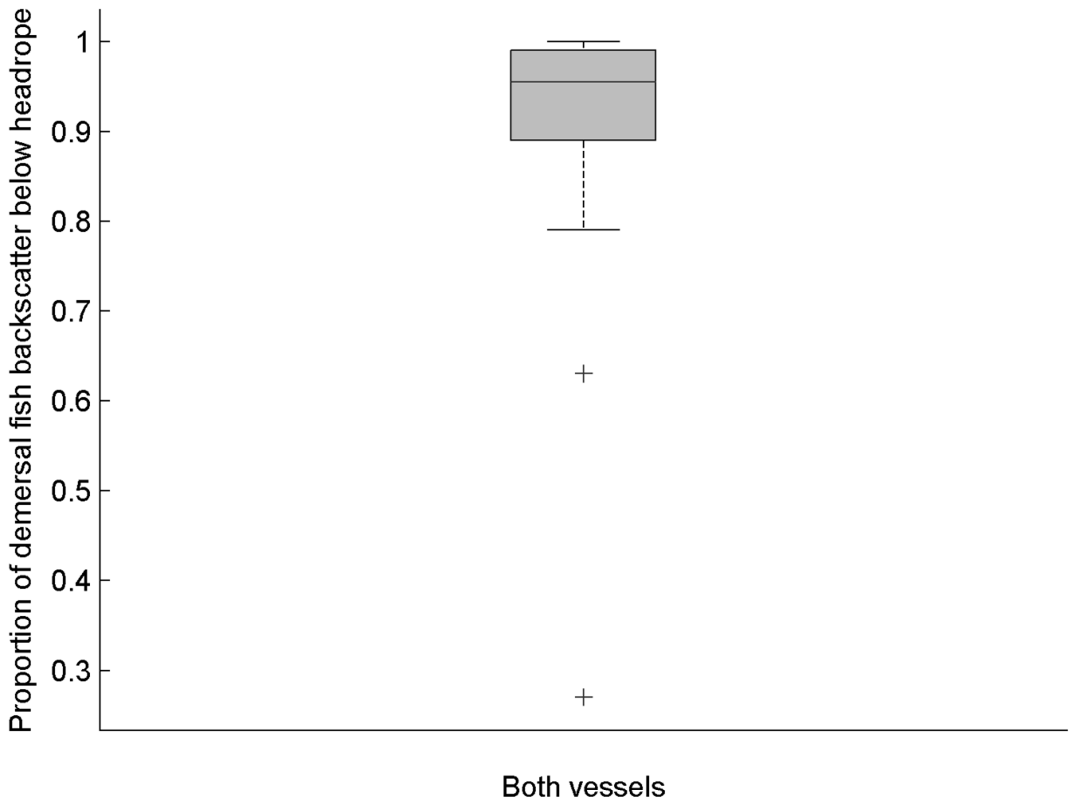

Ken Weinberg - Figure 1




Ken Weinberg - Figure 2.




Ken Weinberg- Figure 3.

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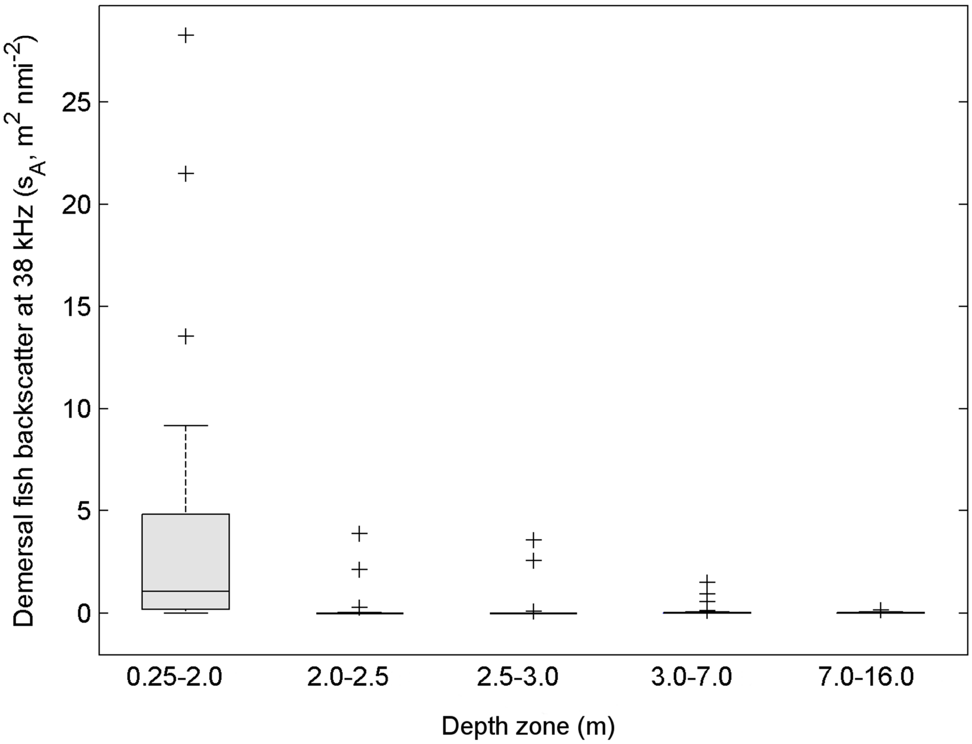


Ken Weinberg - Figure 5.

## Appendix: The potentially complicated relationships between availability/efficiency and catchability/selectivity

### Introduction

Describing a simple set of relationships between the terms “availability” and “efficiency,” as typically used by survey scientists, and the terms “catchability” and “selectivity,” as typically used by assessment scientists, would help to guide research on the behavior of sampling gear and the use of survey results in stock assessment models. Unfortunately, the relationships have the potential to be complicated, except in very special circumstances.

Either availability or efficiency, or both, might vary with respect to fish age, fish length, or both. To keep the notation from becoming too complicated, it will be assumed here that both availability and efficiency vary with age, but the argument would be the same if they varied with length or both age and length.

To keep things simple, assume that the survey in question is a bottom trawl survey, with stations based on a simple random sampling design within a defined survey area. For any given tow and any given age, there will be some true biomass of fish in the water column above the ground swept by the net. Availability is typically defined as the proportion of the *true* biomass that the net *encounters*. Efficiency is typically defined as the proportion of the *available* biomass that the net *actually captures*.

As typically used by assessment scientists, catchability and selectivity both involve the following ratio:

$$ratio_{age} = \frac{survey\_total\_biomass_{age}}{true\_total\_biomass_{age}} \quad ,$$

where “total” is included as a modifier of “biomass” in both the numerator and denominator above to emphasize that these quantities pertain to the entire stock, not just an individual tow.

Catchability is typically defined as the maximum (across age) value of the above ratio, and selectivity is typically defined as:

$$selectivity_{age} = \frac{ratio_{age}}{catchability} \quad .$$

**Case 1**

An extremely simple case can be defined by the following assumptions: 1) both availability and efficiency are constant across tows, 2) the stock is distributed evenly throughout its range, and 3) the survey area is equal to the stock’s range. In this case, the survey’s estimate of biomass at any given age can be expressed by the following equation:

$$survey\_total\_biomass_{age} = availability_{age} \times efficiency_{age} \times true\_total\_biomass_{age} \quad .$$

Given the very restrictive assumptions specified for this case, when the right-hand side of the above is substituted into the ratio of survey total biomass to true total biomass, the true total biomass terms cancel, and the ratio is simply the product of availability at age and efficiency at age.

Thus, although neither availability nor efficiency is *equivalent* to either catchability or selectivity in this special case, both of the latter terms can be defined easily in terms of the *product* of the former. Even in this extremely simplified case, however, it is important to recognize that selectivity at age does not necessarily vary directly with either availability at age or efficiency at age, because it is the *product* of availability and efficiency that matters.

**Case 2**

If the extreme assumptions imposed in Case 1 are relaxed, the relationships become more complicated. For example, if it is no longer assumed that the stock is distributed evenly throughout its range and that the survey area is equal to the stock's range, then the survey's estimate of biomass at any given age becomes:

$$survey\_total\_biomass_{age} = availability_{age} \times efficiency_{age} \times \left( \frac{total\_survey\_area}{ntows} \right) \times \sum_{tow=1}^{ntows} \frac{true\_tow\_biomass_{tow,age}}{area\_swept_{tow}} \quad .$$

Therefore, the survey's estimate of total biomass at age is no longer proportional only to the product of availability at age and efficiency at age, as this product is multiplied by another term that varies with age. When the ratio between survey total biomass and true total biomass is computed, this additional age-dependent term remains in the numerator, meaning that neither catchability nor selectivity can be defined simply in terms of availability and efficiency.

**Case 3**

It is also possible that both availability and efficiency vary not only by age, but also by tow (perhaps reflecting location- or time-specific environmental conditions, pure random variability, or some combination thereof). In this case, the survey's estimate of biomass at any given age becomes:

$$survey\_total\_biomass_{age} = \left(\frac{total\_survey\_area}{ntows}\right) \times \sum_{tow=1}^{ntows} \left( availability_{tow,age} \times efficiency_{tow,age} \times \left(\frac{true\_tow\_biomass_{tow,age}}{area\_swept_{tow}}\right) \right) .$$

Here, the survey's estimate of total biomass at age is no longer proportional to the product of availability and efficiency in any simple way whatsoever, because the product is tow-dependent and is incorporated into the survey estimate as a weighted average, where the weights are both tow- and age-dependent.  When the ratio between survey total biomass and true total biomass is computed, these complications remain in the numerator.

**Conclusion**

Even in the simplest case, there is no one-to-one correspondence between either availability or efficiency and either catchability or selectivity.  As simplifying assumptions are relaxed, the relationships can become very complicated. For example, it is quite possible for selectivity to decline with age even when the product of average (across tows) availability and average (across tows) efficiency increases with age.  Therefore, care should be taken when attempting to infer the shape of the selectivity function from evidence pertaining to availability or efficiency.