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Using acoustics to estimate the fish-length selectivity of trawl mesh

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Estimation of the retention probability of a trawlnet traditionally involves conducting experiments during which the fish escaping through the meshes are recaptured using either small-mesh pocketnets attached to the outside of the net or by enclosing the entire trawlnet in a small-mesh net. A new method of estimating the length selectivity of trawl mesh is demonstrated; it does not require the recapture of escaping fish but instead uses standard acoustic methods to estimate the abundance of fish entering the net before mesh selection. The method was applied to the 83–112 eastern otter trawl used by the Alaska Fisheries Science Center (AFSC) to conduct bottom-trawl surveys in the eastern Bering Sea (EBS), and the Aleutian wing trawl used by the AFSC to collect midwater biological samples of walleye pollock (*Theragra chalcogramma*) during fishery acoustic surveys of the EBS and Gulf of Alaska. The length selectivities of both trawls were also estimated using standard recapture experiments. For both, the estimated lengths at 50% selection (L_{50}) from the acoustic method were similar to the estimates from the recapture experiments, but the estimated selection ranges were narrower. The advantages of the acoustic method are that it is simpler to use than traditional fish-recapture methods and it does not alter normal trawl performance.

Keywords: fish-length selection, hydroacoustics, trawl selectivity, walleye pollock.

Introduction

Fish-length selection by a trawl is the result of a complex interaction of trawl design and fish behaviour. Before entering a net, fish may herd downwards (Aglen, 1996; Handegard and Tjostheim, 2005) or laterally into the towing path (Engas and Godø, 1989a; Somerton and Munro, 2001), or escape under the footrope (Engas and Godø, 1989b; Munro and Somerton, 2002) or out of the mouth of the trawl (Dickson, 1993). However, once inside the net, the primary means of escapement is by swimming through the mesh, which is very much a length-selective process (Wileman *et al*., 1996). As control of the capture length of fish through the use of restrictions on trawl-codend mesh size is an important fisheries management tool, fish-length selectivity of trawl mesh has been studied extensively using a variety of techniques, many of which utilize length frequency data collected from escaped fish (Wileman *et al*., 1996). When applied to the whole net rather than just the codend, one of the most common approaches to obtaining such data involves recapturing escaping fish either by attaching fine-mesh collecting bags (pocketnets) to the outside of the trawl at various locations (Dremiere *et al*., 1999; Polet, 2000) or by completely enclosing the entire trawlnet in a single collecting bag (Polet, 2000). Although the analytical methodologies used to estimate a length-selection function differ between these experimental approaches, both ultimately rest on the assumption that the sum of the estimated number of escaping fish and the number retained by the trawl provide an unbiased estimate of the unselected length distribution of the fish just before entering the net. Another approach to estimating mesh selection is evaluated here; it does not require the recapture of escaping fish but instead uses standard acoustic methods to estimate fish abundance just before entering the net.

To understand better how this approach works, consider an idealized situation in which the fish captured by a trawl are monospecific, of uniform size, and acoustically sampled immediately before they enter the trawlnet. This form of sampling provides two estimates of acoustic backscatter: the measured acoustic backscatter from the fish in the volume of water swept by the trawl, and the theoretical backscatter that would be produced by the captured fish given their abundance, length distribution, and acoustic target strength. If some of the fish entering the net subsequently escaped through the mesh, then the theoretical backscatter would be less than that measured. If subsequent trawl hauls sample areas with different mean fish lengths, then it is possible to estimate a length-selection function by modelling the correspondence between the observed and predicted acoustic backscatter as a function of fish length in the catch.

The process of modelling the relationship between the measured acoustic backscatter and that predicted by trawl catches statistically has been done repeatedly (Neville *et al*., 2004; Mackinson *et al*., 2005; Bez *et al*., 2007; von Szalay *et al*., 2007), and some studies have found a surprisingly low correlation. Although the reasons for this are unknown, trawl catches typically contain more than a single species that could contribute to the measured backscatter, and fish movement between the times when they were insonified and when they entered the net possibly altered the abundance, or the size or species composition of the catch. In this study, however, we focused on walleye pollock (*Theragra chalcogramma*), which provides a nearly ideal situation because they are the dominant component of the backscatter at the acoustic frequency used, and they display weak horizontal (Somerton, 2004) and vertical (von Szalay *et al.*, 2007) herding. Therefore, their abundance and length distribution probably remain unchanged between the time of their acoustic sampling by the vessel and their entry into the net.

We applied the acoustic technique to two types of trawl: the 83–112 eastern otter trawl (Stauffer, 2004) used by the Alaska Fisheries Science Center (AFSC) to conduct the eastern Bering Sea (EBS) bottom-trawl survey, and the Aleutian wing trawl (Honkalehto *et al.*, 2002) used by the AFSC to collect midwater biological samples during the EBS and Gulf of Alaska fishery acoustic surveys. The two trawls differ considerably in size, so different methods were used for each trawl when conducting traditional recapture experiments to validate the length selectivity. However, the fishery acoustic methods we used to estimate length selectivity were identical for both trawls.

Material and methods

The trawls

The 83–112 eastern bottom trawl has a two-seam net with a 34.1-m footrope, a 25.3-m headrope, a 17.0-m mean wing spread, averaged over the EBS survey, and a 2.4-m mean headrope height. Mesh size varies from 10.0 cm (stretched measure) in the wings to 8.9 cm in the intermediate and codend, with a 3.1-cm mesh codend liner. The detailed trawl construction plans and trawling protocols are given by Stauffer (2004). When in operation, the cross-sectional shape of the net opening approximates that of a low, wide rectangle.

The Aleutian wing trawl is a high-opening, four-seam, midwater net with a 90.0-m headrope and a total length of ~140 m. During normal operations, the mouth opening is nearly ellipsoidal and measures an average of 24 m vertically and 45 m horizontally. Mesh size varies from 300.0 cm at the opening to 10.0 cm in front of the codend, with a 3.1-cm codend liner. The detailed construction plans and trawling protocols are given in Honkalehto *et al.* (2002).

Acoustic and catch data collection

For the 83–112 eastern bottom trawl, acoustic and trawl catch data were collected simultaneously during the EBS trawl survey from 1 June to 31 July 2006. The survey uses a systematic sampling design of 375 stations arranged on a 20 × 20-nautical mile grid (Figure 1) sampled by two chartered commercial stern trawlers, the 40-m FV "Arcturus" and the 50-m FV "Northwest Explorer". Data from 362 of these stations were used in subsequent analyses. At each station, a trawl was made that lasted ~30 min and covered ~1.5 nautical miles from first to last contact of the footrope with the seabed as determined using a bottom-contact sensor (Somerton and Weinberg, 2001). During each haul, the net width (wing spread) and headrope height off the seabed were measured continuously using a Netmind acoustic mensuration system (note that reference to trade names does not imply endorsement by the National Marine Fisheries Service, NOAA). The swept volume of each haul was calculated, assuming that the net was approximately rectangular in cross section, as the product of the mean wing spread, mean headrope height, and tow length. Acoustic-backscatter data were collected continuously, while trawling and while running between trawl stations, using a Simrad ES-60, 38-kHz, split-beam echosounder calibrated at the beginning and end of the survey using standardized tungsten-carbide spheres (see von Szalay *et al.*, 2007, for calibration details). The transducer equivalent-beam angle was 7°, the acoustic-pulse length 1024 ms, and the echosounder was operated at a power setting of 2000 W, providing a sufficient signal-to-noise ratio at the maximum depths used in the study.

The catch and the acoustic data were processed as follows. Trawl catches were subsampled if >1000 kg, sorted to species, weighed, and up to 300 fish per species measured for total length to the nearest 1.0 cm. Only the catch information for walleye pollock and Pacific cod, *Gadus macrocephalus*, the only other potential contributor to acoustic backscatter, are considered here. Acoustic backscatter, successfully collected at all selected hauls, was integrated, using Echoview v. 3.30.60, horizontally from the start to the end of each trawl path. Vertical integration was bounded from 2.4 m, the average headrope height of the trawl, to a 0.3-m backstep from the acoustically detected seabed (Ona and Mitson, 1996). Determining the times in the acoustic data corresponding to the start and end positions of the trawl path required vessel speed and an estimate of the horizontal distance between the echosounder transducer and the trawl headrope. This distance was estimated using the method of Wallace and West (2006). During the integration, no correction was made for the systematic error (triangle wave) included in ES60 data (DeRobertis and Wilson, 2006), nor for the occasional missed pings caused by bubble sweepdown over the transducer during stormy weather, but the potential error from these sources is small. A threshold of −70 dB was used in the analysis. The output of the integration was expressed in terms of the volume-backscattering coefficient (s_V; MacLennan *et al.*, 2002).

For the Aleutian wing trawl, catch and fishery acoustic data were collected simultaneously during 217 midwater trawl hauls that contained >95% pollock by weight during acoustic surveys conducted in the EBS between 1997 and 2007 (Figure 2). Surveys before 2007 were conducted on board NOAA's RV "Miller Freeman", and the 2007 survey on board NOAA's RV "Oscar Dyson". Processing of the catches obtained during these hauls was done in a similar way to that described for the bottom trawl, with ~300 randomly sampled pollock measured per haul. Trawl performance was continuously monitored using a trawl sonar positioned on the headrope. The cross-sectional area of the net opening, based on a detailed analysis of 12 representative sonar images, averaged 848 m^2. Trawled volume was computed as the average cross-sectional area times the length of the trawl path measured from when fish were first observed entering the trawl using the Wesmar HD-670 netsounder on the "Miller Freeman", and the Simrad FS70 on the "Oscar Dyson", until haulback was initiated. Acoustic-backscatter data were collected using a 38-kHz split-beam transducer, with a 7° equivalent beam angle, and a Simrad EK60 scientific echosounder, calibrated using a tungsten-carbide sphere (Honkalehto *et al.*, 2009). The acoustic data were collected at the above-mentioned power and pulse-duration settings. Acoustic backscatter was integrated over the trawled volume of each midwater haul using either Echoview software (Honkalehto *et al.*, 2009) or a customized integration program developed at the AFSC in the MATLAB (R2008a, The MathWorks®) computing

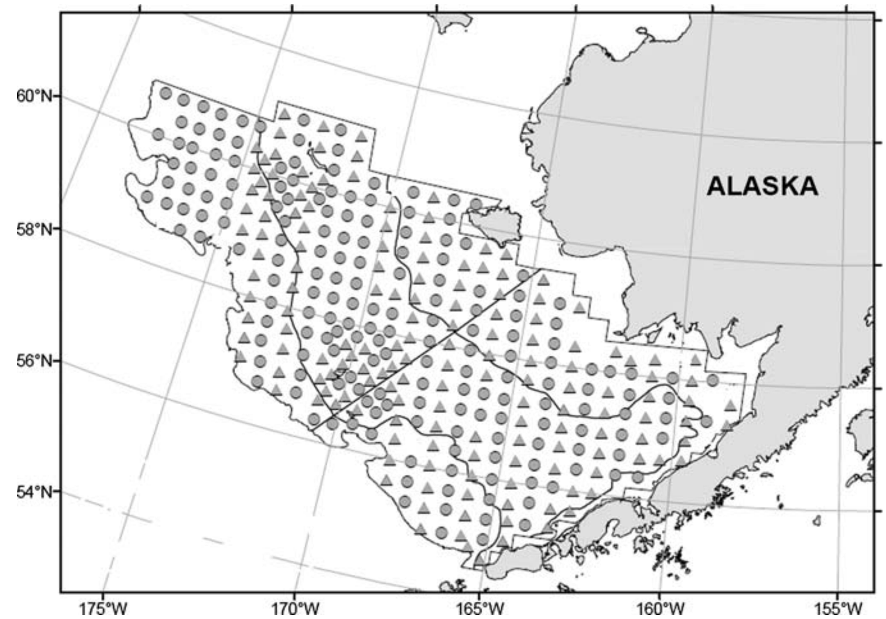

Figure 1. Trawl sampling locations on the 2006 EBS bottom-trawl survey that caught at least one walleye pollock and are used in the analysis. Stations sampled by FV "Arcturus" are shown by triangles, and those sampled by FV "Northwest Explorer" are shown by circles.

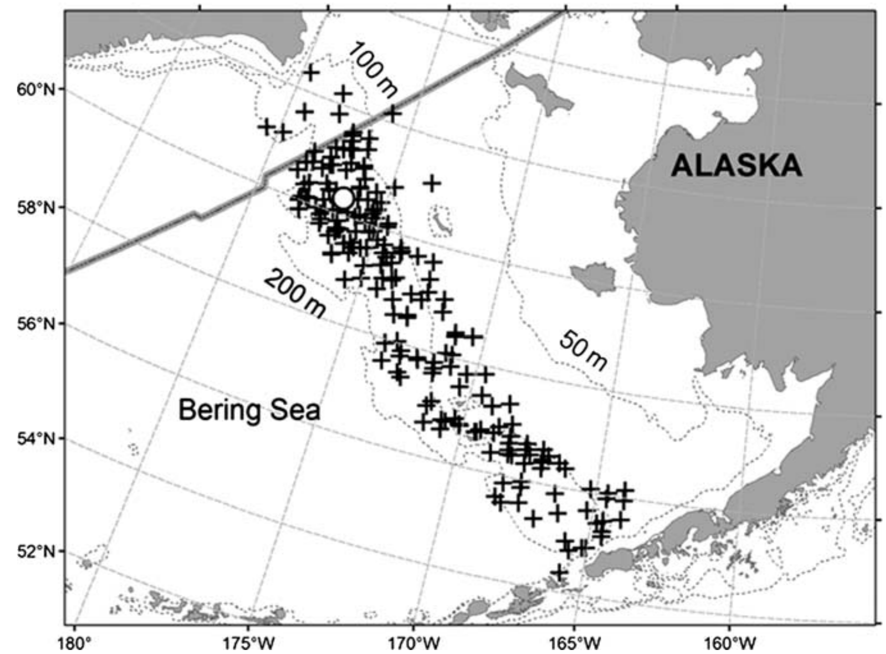

Figure 2. Selected trawl locations used in the acoustic-catch selectivity model and the location of direct-selectivity experiments, with plus signs representing haul locations used in the acoustic-selectivity analysis, and circles the locations of direct measurements of midwater-trawl selectivity using pocketnets.

language (Rick Towler, AFSC, pers. comm.). As in the bottom-trawl experiment, this integration took into consideration the spatial offset between the transducer and the trawl headrope, and its product was expressed in terms of s_V.

Trawl selectivity validation experiments

Experiments were conducted to estimate trawl-selectivity directly by capturing the small pollock that escaped through the mesh; however, the methodology used for the two trawls differed because their sizes differed so considerably. The bottom trawl was sufficiently small, surface area ~550 m^2, and the net could be enclosed completely in fine mesh (3.1 cm) that extended from a net attachment ~3 m behind the footrope to the end of codend. The bag was hung loosely, the bag circumference being about three times the trawl circumference at the centre of the trawl's intermediate section, to minimize occluding the meshes and inhibiting escapement. The experiment was conducted from 26 September to 6 October 1983 near Kodiak, Alaska, on board the "Miller Freeman", which is a stern trawler 63 m long. For each of the five completed hauls, the pollock catches from the trawl and the collecting bag were weighed individually, subsampled if large, then measured for total length to the nearest 1.0 cm: 1844 pollock were measured. A logistic length-selectivity function [Equation (1) below] was fitted to the pooled catch of individual pollock, coded 1 for the trawl and 0 for the surrounding bag, and length data, using maximum likelihood modelling (Munro and Somerton, 2001).

The midwater trawl was so large, surface area $\sim$6500 m^2, that it was impractical to enclose it completely with mesh, so escaping fish were sampled with pocketnets placed at various locations on the outside of the net (Williams *et al.*, 2011). The experiment was conducted in the EBS during 2007 and comprised eight trawl hauls. For each haul, escapement was estimated using catches from 12 pocketnets distributed over the surface of the trawl body and the codend. Trawl selectivity was estimated using a hierarchical model to combine within- and between-haul variation. Details of the model-fitting procedure are provided in Williams *et al.* (2011).

Fitting a selection function

The length selectivity of each trawl was specified as a logistic function of fish length:

$$R_L = \frac{1}{1 + \exp(-k(L - L_{50})/\mathrm{SR})}, \quad (1)$$

where R_L is the retention probability, L the fish length, L_{50} a parameter representing the length at 50% retention, SR a parameter representing the length range between the 25 and 75% retention probabilities, and k a constant equal to $2\log_e(3)$. This notation is a simplification of Equation (6.2.2) in Wileman *et al.* (1996).

The parameters of this function were estimated by modelling the relationship between the measured values of s_V and the values that would be produced theoretically by the number and lengths of pollock in the catch. However, before doing this, the measured s_V from the bottom-trawl experiments, but not from the midwater-trawl experiments, needed to be corrected for contamination by the backscatter of Pacific cod: unlike pollock, Pacific cod are found exclusively near the seabed (Nichol *et al.*, 2007). For this correction, we assumed that Pacific cod and pollock were mixed randomly in the region between the seabed and the trawl headrope. The proportion of the backscatter from pollock alone (P_p) was then calculated from the abundance and length distribution of each species in the catch:

$$P_p = \frac{B_p}{B_p + B_c}, \quad (2)$$

where B_p and B_c are the predicted values of backscatter that theoretically would be produced by the catches of pollock and Pacific cod, respectively. These values were calculated from the catch as

$$B = \sum_L N_L 10^{TS_L/10}, \quad (3)$$

where N_L is the number of fish, and TS_L is the target strength at size L (cm). For both pollock (Traynor, 1996) and Pacific cod, which is assumed to be identical to pollock based on the *TS* value for Atlantic cod (*Gadus morhua*) in Simmonds and MacLennan (2005), the *TS*-to-length function is

$$TS_L = 20\ \log L - 66. \quad (4)$$

In the following text, s_V refers to pollock s_V, i.e. the measured quantity multiplied by P_p.

Values of the volume-backscattering coefficient that would be produced theoretically by the catches of pollock could be estimated similarly by dividing the backscatter [B in Equation (3)] by the swept volume of the trawl path in m^3 (V). However, these estimates are biased by the escapement of small fish through the mesh. An unbiased estimate, denoted as s_V^P, which took into consideration the length-selection function [Equation (1)], was calculated as

$$s_V^P = \frac{\sum_L \left(N_L 10^{TS_L/10}\right)/R_L}{hV}, \quad (5)$$

where N_L and TS_L are the same as in Equation (3), and R_L is the selectivity function [Equation (1)]. An additional parameter (h) was included in the model to account for potential herding by the trawl wings, doors, and bridles and, for the bottom trawl, for the loss of fish within the backstep and acoustic dead zones (Ona and Mitson, 1996). Hence, the values of s_V^P depend on the unknown parameter values of the function R_L.

The parameters of this model (L_{50}, SR, and h) were estimated by iteratively varying them, until the sum of the squared differences between the logarithms of s_V and s_V^P was minimized using either MATLAB for the midwater trawl data or R (R Development Core Team, 2008) for the bottom-trawl data. To determine whether the selection parameters for the bottom-trawl experiment differed between the two vessels, the model was first fitted to the data considering each vessel as having a separate selectivity function (six parameters), then to the data considering both vessels as having the same selectivity function (three parameters). The choice of whether the combined-vessel or separate-vessel model was better was based on the value of the Akaike information criterion (AIC; Burnham and Anderson, 1998).

Modelling the sensitivity of L_{50} estimates to error in the TS_L function

Accuracy in the calculation of s_V^P depends on the accuracy of the TS_L relationship [Equation (4)], especially its slope. The slope value used (20) is fixed based on the theoretical expectation that backscatter changes as the square of length, because backscatter strength is proportional to the dorsal, cross-sectional area (Love, 1971). However, this assumption may not be adequate for all fish (McClatchie *et al.*, 2003), so to evaluate the sensitivity of the selectivity parameter estimates to the slope of the TS_L function, the model described above was fitted to the midwater-trawl data using a range of slope values (18.5–21.5).

Testing the model using simulated data

To assess the sensitivity of the model to uncertainty in observed S_V [here we use the notation $S_V = 10\log_{10}(s_V)$; MacLennan *et al.* (2002)], the model was tested using a simulated set of data with known selectivity. The process had several steps. First, a set of length frequencies was generated that was intended to represent a typical sample from a real population of pollock. Second, the expected acoustic baskscatter per unit volume (m^3) was estimated for each set of length frequencies using the *TS*–length relationship in Equation (4). Third, the expected trawl catch was then estimated by multiplying the length frequencies by a known selectivity function. Fourth, the acoustic-estimation model was fitted to the catch length frequencies and the expected population backscatter with an added normal random error (mean = 0, s.d. = 5), intended to represent the expected difference in observed S_V produced by the spatial offset between the vessel and the trawl. The simulation process was repeated 10 000 times to ensure stable results. Histograms of the 10 000 estimated values of L_{50} and SR were produced to determine whether there was a bias in the estimates relative to the known values used in the simulation.

Results

For the 83–112 eastern bottom trawl, when the logarithm of pollock backscatter predicted from the trawl catch without the correction for selectivity (B/V) was plotted against that measured acoustically (s_V), we expected, based on previous work (von Szalay *et al.*, 2007), to see a strong linear relationship. Although the linearity is evident (Figure 3), many values of $\log(B/V)$ appear to be too small. When the quotient of these values ($\log(B/V)/\log(s_V)$) was plotted against the mean length of pollock in the catch (Figure 4), the anomalously small values of $\log(B/V)$ were primarily associated with catches of small fish. One interpretation of this is that the apparent underestimate of the predicted backscatter stems from the escapement of small fish through the trawl mesh.

In developing the bottom-trawl selectivity model, we first considered whether there was a vessel effect. As the AIC of the combined vessel model was slightly lower (271.0; three parameters) than the separate vessel model (271.6; six parameters), there appears to be little evidence of a difference in length selectivity between the two vessels. An examination of the model residuals also failed to indicate any patterns associated with fish length, demonstrating that the length dependence was explained adequately by the logistic model. The residuals also appeared to be normally distributed.

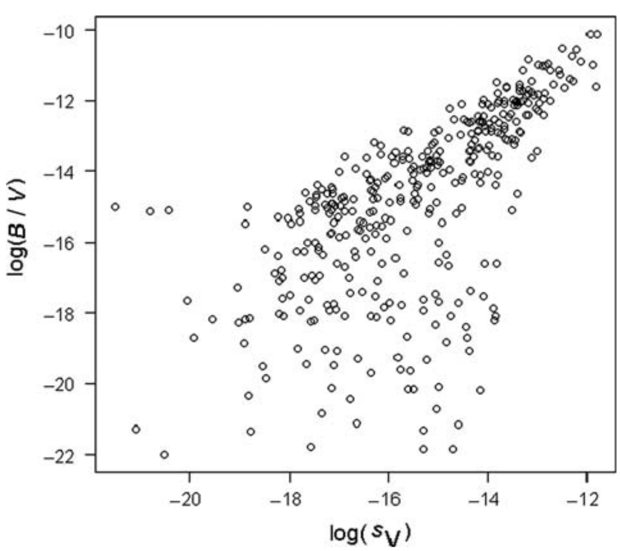

Figure 3. Observed pollock backscatter (s_V) and pollock backscatter predicted from the trawl catch (B/V) plotted on logarithmic axes. If all fish were retained by the trawl, the relationship should be nearly linear, but the values of $\log(B/V)$ appear to be too small, especially at low levels of s_V.

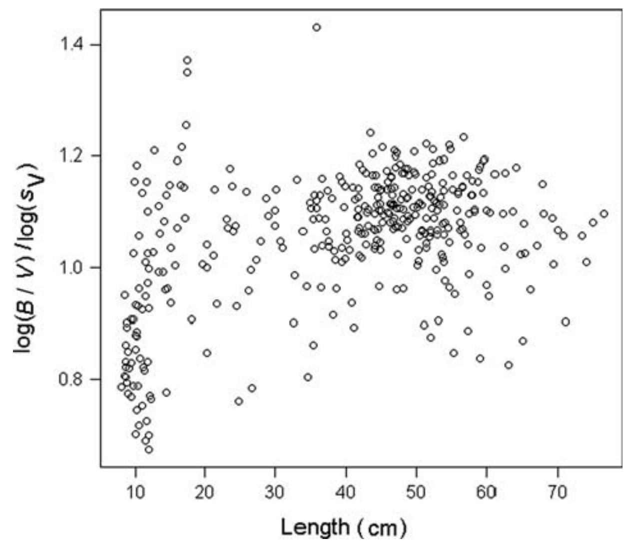

Figure 4. The logarithm of pollock backscatter predicted from the trawl catches (B/V), expressed as a ratio of the logarithm of measured pollock backscatter (s_V), plotted against the mean length (cm) of pollock in the catch. Note that many values of the ratio become relatively low when the mean length is small. One explanation of the apparent underestimate of predicted backscatter is that small pollock escaped through the mesh and were therefore underrepresented in the catch.

For the bottom trawl, the selectivity function estimated from acoustic data had parameter values of $L_{50} = 12.4$ cm and SR = 3.5 cm, whereas the selectivity function estimated from recapture data had parameter values of $L_{50} = 11.9$ cm and SR = 8.5 cm (Table 1; Figure 5). For the midwater trawl, the selectivity function estimated from acoustic data had parameter values of $L_{50} =$ 15.0 cm and SR = 3.2 cm, whereas the selectivity function estimated from recapture data had parameter values of $L_{50} =$ 14.3 cm and SR = 14.4 (Table 2). Hence, for both trawls, estimates of L_{50} produced by the acoustic and resample methods were quite similar, but estimates of SR produced by the acoustic method were considerably smaller than those produced by the resample method. Smaller values of SR then lead to steeper selection functions (Figures 5 and 6).

The dependence of L_{50} estimates on the slope of the TS_L function varied by 0.6 cm over a TS_L slope range of 3 units. As the effect of this change on L_{50} is quite small, the L_{50} estimates appear to be fairly insensitive to the slope of the TS_L function over the range tested. Simulation results showed that with normal error added to S_V measurements, there is a potential for biased estimates of SR, because the frequency distribution of this parameter appeared to be right-skewed (Figure 7), and the proportion of parameter estimates falling below the SR value used to simulate the data is 56.5%. The distribution of the L_{50} values appeared to be more symmetrical, indicating that errors in S_V measurements might not produce a bias in these parameter values.

Discussion

For both the 83–112 eastern trawl and the Aleutian wing trawl, the acoustic method for estimating selectivity produced estimates of L_{50} that were similar to those produced by the traditional

Table 1. Estimates of L_{50}, SR (cm), and h and their standard errors for the experiment using the acoustic method for the 83–112 eastern bottom trawl, and L_{50} and SR estimates and their standard errors for the fish-recapture method (whole trawl-bagging experiment).

Method	Parameter	Estimate	Standard error
Acoustic	L_{50}	12.4	0.35
	SR	3.5	0.31
	h	0.18	0.01
Recapture	L_{50}	11.9	0.26
	SR	8.5	1.04

Parameter estimates correspond to those in Equations (1) and (5).

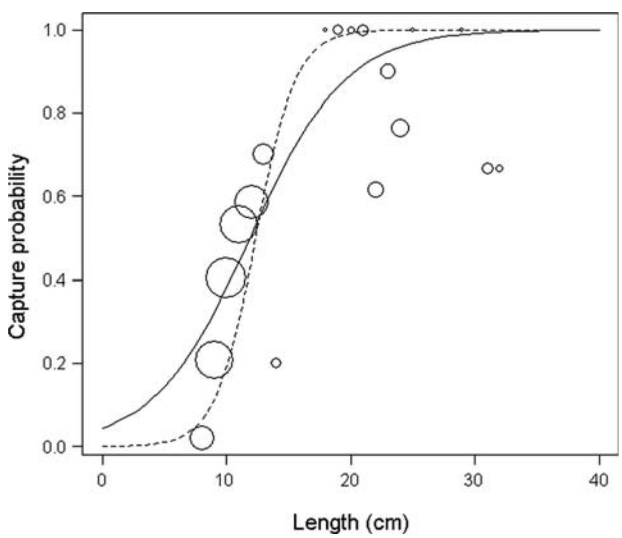

Figure 5. The pollock length-selectivity function fitted to the original unpublished data from the whole-trawl bagging experiment (solid line), with the size of circles being proportional to the logarithm of the sample size in each length category. The pollock length-selection function estimated using acoustics (dashed line) is shown for comparison.

escapement–recapture method, but the acoustic method produced SR values that were considerably smaller. To examine whether this apparent underestimate of SR was inherent in the acoustic method, we conducted a simulation of the acoustic-estimation process by repeatedly generating acoustic and catch data with known selection properties, then analysing the data with the same methodology used on the experimental data. Although the L_{50} values from this simulation were distributed symmetrically and had a median near the true value, the SR values were highly skewed and had a median value somewhat smaller than the true value (Figure 7). The magnitude of the bias, however, was considerably smaller than the apparent bias in the estimates obtained for each of the two trawls based on the field experiments. Therefore, we suspect that the acoustic method may produce SR estimates that are biased low, but the magnitude of the difference from our field experiments could be a chance event.

In addition to the potential bias in SR, there are several other issues that could influence the appropriateness of the acoustic method. First, in other than monospecific cases, the acoustic method requires a good estimate of the proportion of the measured backscatter attributable to the target species. Although

Table 2. Estimates of L_{50}, SR (cm), and h and their standard errors for the experiment using the acoustic method for the Aleutian wing trawl, and L_{50} and SR estimates and their standard errors for the recapture experiment using pocketnets conducted in the EBS in 2007.

Method	Parameter	Estimate	Standard error
Acoustic	L_{50}	15.0	2.5
	SR	3.2	5.3
	h	0.8	0.1
Recapture EBS 2007	L_{50}	14.5	7.2
	SR	14.4	3.7

Parameter estimates correspond to those in Equations (1) and (5). L_{50} and SR in the recapture experiments were estimated using a Bayesian technique (Williams *et al.*, 2011) that expresses the error of the estimate in terms of the 90% credibility limits. For purposes of comparison, the standard errors presented here are approximations assuming that the credibility limits were equivalent to 90% confidence limits.

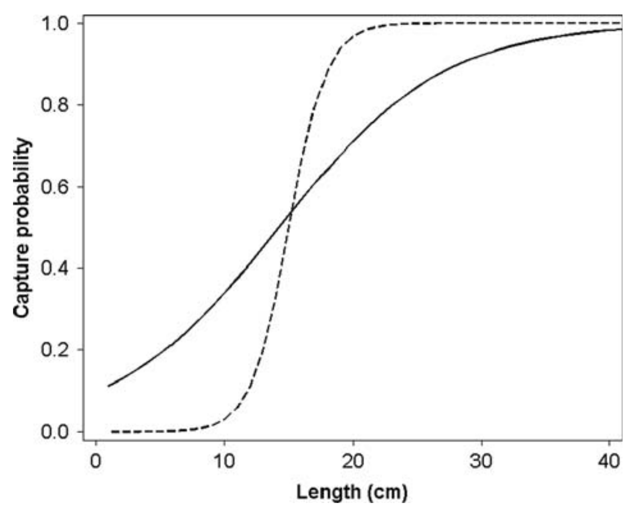

Figure 6. Selection curves from the pocketnet experiment conducted using a midwater trawl compared with the selectivity curve estimated using the acoustic method. The solid line represents the selectivity function derived experimentally and the 95% confidence interval associated with it. The pocketnet selectivity function (dashed line) is from Williams *et al.* (2011).

this was not an issue for the midwater trawl, because there are few sources of backscatter other than pollock, it was an issue for the bottom trawl, because cod backscatter can be important near the seabed (Honkalehto *et al.*, 2009), and the catches were not pure pollock. Although there were only two species to consider, apportioning the backscatter was problematic because we had no data to confirm that these species have identical near-bottom vertical distributions. This is because the vertical distribution of cod has been determined using archival tagging by Nichol *et al.* (2007), but pollock are more difficult to tag. The assumption of equality in the vertical distribution is important because ~30% of the vertical opening of the trawl lies within the backstep and acoustic dead zones, where fish abundance cannot be measured by acoustics so is not included in the acoustic estimate of density. If one species is more common in these depth zones, then the species proportions determined from the trawl catch would be a biased estimate of the proportion in the acoustically assessed fish. A potential solution to this problem, especially in cases where several species could contribute to the backscatter, is to restrict the analysis to

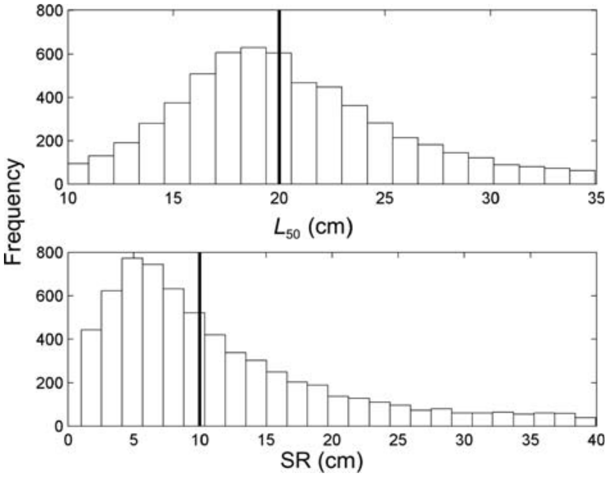

Figure 7. Frequency distributions of selectivity parameter estimates resulting from fitting the acoustic selectivity model to simulated data, with the addition of normally distributed random error to the estimated measurements of s_V. Although the L_{50} parameter appears to have a symmetrical distribution, the SR parameter appears to be right-skewed. Parameter values used to generate the data are indicated by black lines.

only those trawl hauls in which the target species makes up a large proportion of the acoustic backscatter.

Second, we assumed that the density of the fish observed by the echosounder remained unchanged until the fish enter the trawl. However, groundfish species similar to those considered here, including Atlantic cod, saithe (*Pollachius virens*), and haddock (*Melanogrammus aeglefinus*), dive when approached by a bottom trawler, especially between the time of vessel passage, when they are insonified, and trawl arrival, in response to both vessel noise and the visual stimulus of the towing warps (Aglen, 1996; Handegard and Tjostheim, 2005). Such diving would increase the density of fish in the fishing zone of the trawl and inflate the catch. Compared with the Atlantic species mentioned above, pollock seem to be only occasionally and mildly reactive to trawling stimuli. In the study by von Szalay *et al.* (2007), trawl catch per unit effort of pollock was correlated with acoustic backscatter integrated from the seabed up to the headrope and various heights above the headrope. Maximum correlation was achieved with the acoustic data integrated only up to headrope height, indicating a negligible diving response. In comparison, Aglen (1996) found the maximum correlation was achieved with Atlantic cod when the acoustic data were integrated up to 50 m above the seabed, indicating a strong diving response. Our model, like that of von Szalay *et al.* (2007), does not assume that the measured and predicted backscatter are the same, but only that they are linearly related, to account for the acoustically unobserved fish in the near-seabed depth zone. Therefore, the model is sensitive to herding only when it is species- or length-selective. Because of the potential problem that fish movement creates, the acoustic method for estimating size-selection functions would be improved if the position of acoustic assessment could be moved closer to the trawl, e.g. by placing the echosounder on a remotely controlled vehicle that can be positioned directly above the mouth of the trawl.

Third, in the traditional approach using collecting bags, the size distribution of the catch and that of the escaping fish are both known, i.e. the binomial outcome for each fish is known, so it is possible to fit a selection function to the data from each tow. However, this is not true in the acoustic approach; instead, the selection parameters are estimated by relating the observed (s_V) to predicted (s_V^P) volume backscatter as a function of fish length from a number of tows. As a consequence, a good fit of the selection model requires good contrast of mean fish length among hauls. As many fish species have spatial gradients in length, good contrast in fish length can be achieved by a judicious choice of sampling locations.

Fourth, we assumed the *TS*–*L* relationship used to estimate theoretical backscatter from the trawl catch [Equation (4)] to be unbiased at small fish lengths. Although the pollock *TS* function is empirical and based on *in situ* measurements of individual targets from aggregations of fish of uniform size (Traynor, 1996), most of the information has been gathered for adult pollock, because of the needs for stock assessment, so the small-length end of the functional relationship is supported by relatively few data. Consequently, there is little information to test statistically whether the assumed value of the slope is valid: the slope is fixed at 20, and the intercept is estimated empirically. However, the L_{50} sensitivity analysis indicated that this selection parameter-appears to be fairly insensitive to the slope of the TS_L function.

Despite the potential shortcomings of the acoustic method for estimating length selectivity, it has several distinct advantages compared with the use of recapture methods. First, all fishery acoustic surveys and most bottom-trawl surveys collect trawl and acoustic data simultaneously, so the data necessary to estimate the mesh-selection properties of their trawls already exist in all probability. Knowledge of survey-trawl selectivity, to which mesh selection is one of potentially several contributing factors (Dickson, 1993), can be very important when acoustic and trawl data are included in assessment models, and potentially can reduce the bias and variance of model outputs when used instead of the selection functions estimated in the model-fitting process (Somerton *et al.*, 1999). Second, most mesh-selection studies are conducted as experiments, so are typically done over a relatively short period in a restricted location. Mesh selection, however, can vary in response to sea state (O'Neill *et al.*, 2003) and other environmental factors, and such variation may not be seen in isolated, short experiments. The intent of the acoustic method is to acquire mesh-selection data continuously while a vessel is conducting its normal operations. For example, in both the bottom-trawl and acoustic-survey examples considered here, the acoustic estimates of mesh selection are likely to be more representative of the entire surveys than of the individual recapture experiments, because of their greater temporal and spatial coverage. Consequently, data collected using the acoustic method will probably be more representative of average conditions over the survey. Finally, the acoustic method is easier to use than recapture techniques and does not alter the normal fishing properties of a trawl. All recapture experiments involve the fabrication and installation of recapture bags on the experimental trawl, and in all these experiments, there is some question whether the application of the resample bags altered the selective properties of the trawl as a result of, for example, altered water flow or fish behaviour. The acoustic method, on the other hand, does not require modification to the gear or an alteration of fishing methods, except the recording of acoustic data and catch-length measurements, so should provide length-selectivity functions that are more representative of normal survey operations.

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