Available online at www.sciencedirect.com
ScienceDirect
Fisheries Research 86 (2007) 77–83
FISHERIES RESEARCH
www.elsevier.com/locate/fishres

Correlating trawl and acoustic data in the eastern Bering Sea: A first step toward improving biomass estimates of walleye pollock (*Theragra chalcogramma*) and Pacific cod (*Gadus macrocephalus*)?

Paul G. von Szalay *, David A. Somerton, Stan Kotwicki

Alaska Fisheries Science Center, National Marine Fisheries Service, NOAA, 7600 Sand Point Way NE, Seattle, WA 98115, USA

Received 5 March 2007; received in revised form 19 April 2007; accepted 8 May 2007

Abstract

The charter vessels used for the annual eastern Bering Sea bottom trawl survey have recently been equipped with echosounders, which are relatively sophisticated compared to the traditional depth sounders, and are capable of collecting acoustic backscatter data of a quality approaching that of scientific echosounders. Because these echosounders provide a large amount of inexpensive and continuous backscatter data between trawl stations, it is of interest to determine whether these acoustic data can be used in conjunction with the trawl catch data to improve the precision of walleye pollock (*Theragra chalcogramma*) and Pacific cod (*Gadus macrocephalus*) trawl indices of abundance. Catch and acoustic backscatter data collected from 98 stations executed during the 2005 field season were analyzed to estimate the correlation between trawl catch per unit swept area and acoustic backscatter integrated over various layers above the seafloor. The correlation for walleye pollock was good, with the highest correlation obtained for the layer between the seafloor and the headrope ($r^2 = 0.64$). The correlation for layers above the headrope monotonically decreased with increasing height, indicating a lack of vertical herding by pollock. There was no correlation ($r^2 = 0.02$) between trawl and acoustic data for Pacific cod, the only other important fish source of acoustic backscatter.
Published by Elsevier B.V.

Keywords: Trawl surveys; Bottom trawls; Capture efficiency; Acoustic data; NASC values; Catch-per-unit effort; Relative abundance estimates

1. Introduction

The Alaska Fisheries Science Center (AFSC) of the National Marine Fisheries Service has conducted annual multi-species demersal trawl surveys on the eastern Bering Sea shelf since 1982. Recently, the fishing vessels chartered for this survey have been equipped with Simrad ES-60 echosounders, having nearly the same characteristics as scientific echosounders typically used for acoustic stock assessment. Since acoustic backscatter profiles of the water column are now collected continuously throughout the survey area, and provide potentially valuable information on fish distributions between trawl stations, it is of interest to determine whether these acoustic data can be used to supplement the trawl catch data to increase the effective sample size of the trawl survey, and thereby reduce the variance of walleye pollock (*Theragra chalcogramma*) and Pacific cod (*Gadus macrocephalus*) abundance indices.

One approach to utilizing the acoustic data in this way, known as double sampling (Thompson, 1992), has been employed by others to combine trawl and acoustic data (Bouleau et al., 2004; Hjellvik et al., in press). This method utilizes an auxiliary variable, which is correlated with the variable of interest but cheaper to obtain, as a proxy in a statistical estimation procedure producing lower variances than using the original variable alone. In our case, the acoustic data are the auxiliary values since they can be collected continuously at and between trawl stations at virtually no additional cost, and the catch data are the values of the variable of interest. By using the relationship between the two variables, it may be possible to obtain more precise estimators of the pollock and cod biomass available to the trawl.

The trawl catch rate, expressed in terms of weight per unit swept area, and the magnitude of the acoustic backscatter integrated along the trawl path must be strongly correlated for the double-sampling method to be effective. Specifically, high levels

* Corresponding author. Tel.: +1 206 526 4153; fax: +1 206 526 6723.
E-mail address: paul.von.szalay@noaa.gov (P.G. von Szalay).

0165-7836/$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.fishres.2007.05.005

of integrated acoustic backscatter should be associated with large catches of species that contribute substantially to the acoustic backscatter (i.e. species with swim bladders).

Several studies have attempted to correlate trawl catch and acoustic data. The results of these studies have been mixed. Among the first to investigate the potential variance reduction that could be achieved by integrating acoustic data with trawl surveys, Ona et al. (1991) found high correlations between acoustic and trawl catch per tow data for both Atlantic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) in the Barents Sea. Similarly, Krieger et al. (2001) obtained a strong relationship between acoustic and trawl data for rockfishes (*Sebastes* spp.) in the eastern Gulf of Alaska, and Godø et al. (2004) found strong correlations for some species, such as haddock and redfish (*Sebastes* spp.) in the Barents Sea and Norway pout (*Trisopterus esmarkii*) in the North Sea, when the echo traces were subjectively classified to species prior to analysis.

On the other hand, many of the studies that were part of the recent European "Combining Acoustic and Trawl Data for Estimating Fish Abundance" project (CATEFA; Hjellvik et al., in press) were less promising. Mackinson et al. (2005), who used a fuzzy logic model to relate acoustics and other environmental variables with trawl catches, concluded that depth and location were better predictors of trawl catches in the North Sea than the acoustic backscatter in the first 5 m off the bottom. Neville et al. (2004), who used artificial neural networks to correlate trawl and acoustic data, were unable to adequately link the two, and Beare et al. (2004), who used generalized additive models, found only moderately strong relationships for some species in the Barents Sea, but very weak ones in the North Sea. Finally, Hjellvik et al. (in press) failed to obtain a meaningful reduction in variance of Atlantic cod and haddock in the Barents Sea, which they in part attributed to a somewhat low correlation between trawl and acoustic data.

The variability in success among the different studies may at least in part be attributable to vertical herding or diving behavior of the fish in response to the vessel or trawl (Aglen, 1996; Ona and Godø, 1990; Hjellvik et al., 2003). Such diving behavior may vary both temporally and spatially since it is likely a function of environmental variables such as light, depth, temperature, and tidal currents (Aglen, 1996; Michalsen et al., 1996) and therefore reduce the correlation between acoustic and trawl indices of abundance. Diving behavior can be identified by an increase in correlation when echo sign is integrated above the headrope. Thus, to determine whether a given survey area and a particular species are good candidates for trawl-acoustic data integration, it may be prudent to estimate the effective net height (Aglen, 1996) when assessing the correlation between catch and acoustic data to ensure that it agrees with the actual net height.

This study was therefore focused on estimating the effective net height in addition to investigating the relationship between the trawl and acoustic data. Compared to most of the areas where attempts to correlate trawl and acoustic data have been made, the eastern Bering Sea shelf has close to optimal conditions. The bottom is nearly flat and featureless, which minimizes the thickness of the acoustic deadzone layer (ADZ) where fish cannot be detected acoustically (Ona and Mitson, 1996). In addition, there are few fish species that contribute to the acoustic backscatter, so species recognition is a relatively minor problem compared to other areas (Honkalehto et al., 2002).

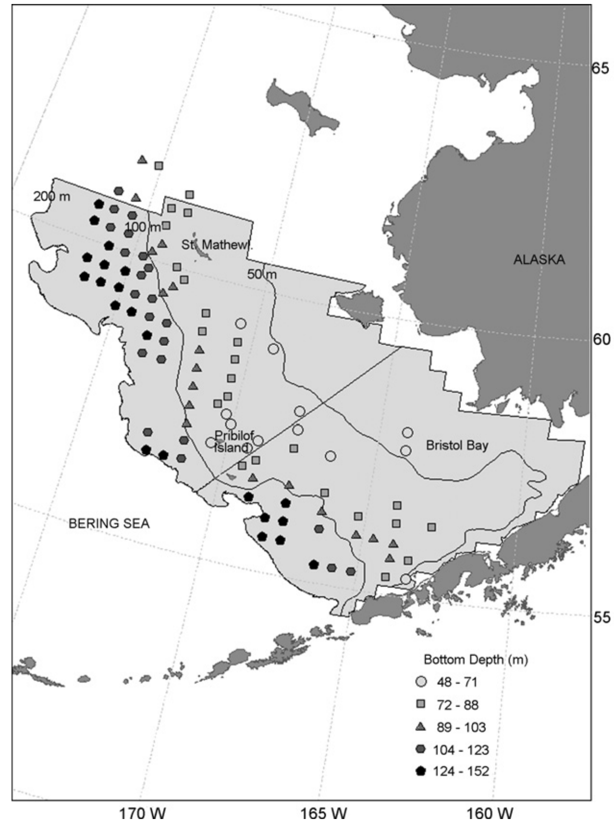

Fig. 1. Locations of *Aldebaran* trawl stations on the eastern Bering Sea shelf used in the regression analysis of cod and pollock CPUE on integrated acoustic backscatter ($n = 98$).

2. Materials and methods

2.1. Survey area, gear, equipment settings, and operational procedures

Both the trawl and acoustic data analyzed in this study were collected during the 2005 annual AFSC eastern Bering Sea shelf bottom trawl survey. Within the survey area (Fig. 1) bottom depths range between 20 and 200 m (99% of trawl stations are at depths less than 150 m), bathymetry is generally smooth and uniform with depths increasing gradually along a southwest-oriented gradient, and sediments are dominated by fine-grain particles ranging from mud to sand (Smith and McConnaughey, 1999). The survey design is systematic with stations spaced regularly in a 20×20 nautical mile grid. Acoustic data were collected continuously at and between the trawl stations.

Two nearly identical 40 m stern trawlers, each equipped with a Simrad ES-60 echosounder,[1] were chartered for the 70-day survey. The vessels collected samples along alternating columns of

[1] Reference to trade names does not imply endorsement by the National Marine Fisheries Service, NOAA.

the survey grid by trawling at the center of each grid square for 30 min (timed from when the trawl settled on the bottom) at a speed of 1.54 m/s (3 knots) relative to the ground in the direction of the next station. The quality of the acoustic data collected by one of the vessels, the *Arcturus* (38 kHz), was somewhat compromised by interference from a secondary transducer (50 kHz), which was inadvertently turned on during much of the survey. Because of this, we decided not to use any of the 2005 *Arcturus* data and restricted our analysis to the 2005 *Aldebaran* data.

Steel "V" doors measuring 1.8 m × 2.7 m are used to spread the net of the 83–112 eastern otter trawl, which has a footrope and headrope measuring 34.1 and 25.3 m, respectively (von Szalay and Somerton, 2005). The mean net spread in fishing configuration is approximately 17 m, and the mean headrope height is 2.4 m. The mesh size is 10.0 cm in the wings and the body of the net, 8.9 cm in the intermediate and codend sections. In addition the codend is lined with 3.1 cm mesh. The area swept by the net is calculated as the product of the mean net spread, determined by acoustic sensors attached to the wings of the net, and the distance fished, determined using a bottom contact sensor as the distance traversed by the net between the point where it first makes bottom contact and when it leaves the bottom (Somerton and Weinberg, 2001).

The echosounder on the *Aldebaran* was equipped with a split-beam transducer with a 7° beam width (to –3 dB), which operated at 120 kHz. The power output was set to 500 W and the pulse length was 1.024 ms. We did not correct for the periodic systematic error (triangle wave), which to some extent degrades the quality of the ES-60 echosounder data. The maximum value that this error can obtain is a 1 dB difference in acoustic measurements on single pings, but the errors in echo-integration measurements, where large numbers of pings are averaged, are substantially smaller (De Robertis and Wilson, 2006). A numerical simulation study to estimate the uncertainty of the integrated acoustic measurements by De Robertis and Wilson showed that the systematic error would introduce an almost negligible uncertainty of 0.2% while trawling.

The echosounder was calibrated twice during the survey: once immediately prior to the survey and then again approximately one-third of the way into the survey to check for drift in the calibration settings. The calibrations were carried out in a bay where the sea state was calm and vessel drift was minimal. Care was taken to ensure that there were few, if any, acoustic targets (e.g. fish) in the water column. The calibration procedure consisted of lowering a tungsten sphere into the water, approximately 20 m directly below the transducer by means of three winches attached to the railings of the vessel. The amount of line paid out by the winches was adjusted until the calibration sphere was centered as close as possible on the acoustic axis. Backscatter data from the sphere were then recorded for a minimum of 20 min, resulting in over 1200 individual target recordings. Because vessel drift and even minimal wave action causes the position of the calibration sphere to oscillate slightly about the acoustic axis, only hits within 0.1 dB of the acoustic axis were used in the analysis. The calibration constant (i.e. S_A correct), which was calculated as the difference between the echo-integrated gain (S_v gain) and the target-strength gain (TS gain) required to obtain a measured target strength of the calibration sphere, is used when the trawl-acoustic data relationship is applied to estimate the absolute fish density between trawl stations and to account for any drift in echosounder settings that may occur between surveys.

2.2. Data analysis

The acoustic data, which were processed using SonarData Echoview v. 3.30.60, were carefully examined for quality assurance prior to integration. Echograms from each trawl station were reviewed with respect to the echosounder-detected bottom line. After applying a 0.3 m back-step to the bottom line to minimize occurrences of seafloor integration, we ensured that the new line did not intercept the seafloor. This was essential to obtain accurate integration values because even small amounts of seafloor integration may overwhelm the backscatter due to fish.

The acoustic backscatter was integrated horizontally between the point where the net first touched bottom and the point where the net started to leave the bottom, determined using the bottom contact sensor attached to the footrope to measure the times and a GPS receiver to determine the locations of these events. The horizontal offset between the vessel and the net was estimated geometrically (Wallace and West, 2006) as

$$\sqrt{\text{scope}^2 - \text{depth}^2},$$

where scope is the warp length not corrected for curvature. This was then converted to a temporal offset on the echogram by dividing the horizontal offset by the trawl speed.

The strength of the relationship between the trawl and acoustic data was assessed using simple linear regression on the log-transformed catch (in kilograms) per unit swept area (CPUE) estimates of walleye pollock and Pacific cod, and the log-transformed nautical area scattering coefficients (NASC). No other species were considered because they are predominantly confined to the ADZ where they are acoustically invisible (e.g. flatfishes, skates, eelpouts, most invertebrates), they are poor sources of acoustic backscatter due to their lack of swim bladders (flatfishes, invertebrates), or they are not sufficiently abundant on the Bering Sea shelf (rockfishes). The data were log-transformed in order to reduce the undue influence of outliers. The strength of the relationship was determined by the proportion of explained variation (r^2).

We examined the acoustic data for evidence of vertical herding responses by walleye pollock using a methodology similar to that described by Aglen (1996). The water column was divided into six layers parallel to the bottom, with the first layer defined as the area between the bottom and the mean headrope height of the 83–112 eastern otter trawl (2.4 m). The tops of the remaining layers were at 4, 8, 15, 25, and 50 m above the seafloor. The acoustic backscatter was integrated between the seafloor and the top of each layer for all stations, and simple linear regressions on the log-transformed pollock CPUE estimates and log-transformed NASC values were performed. NASC values were also obtained for the non-cumulative layers above the headrope,

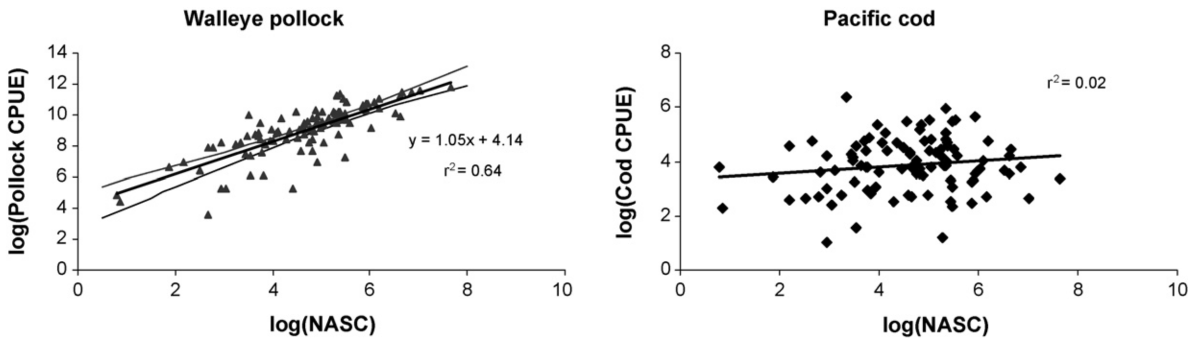

Fig. 2. Regression analysis of log-transformed pollock and cod catch-per-unit swept area estimates on log-transformed integrated acoustic backscatter values. The thin lines on either side of the regression line for walleye pollock are the 95% confidence interval of the regression line.

and separate simple linear regression models were derived in a similar fashion for these layers after log-transforming the data. Multiple regression analyses using the non-cumulative layers were performed starting with the most comprehensive model, which included the layers as independent variables and the log-transformed pollock CPUE estimate as the dependent variable. Models were simplified (backward deletion) until all *P*-values of the individual non-cumulative layers were less than 0.05. The presence or absence of a diving response was determined by comparing the trends in r^2 values of the different regression lines for the cumulative layers with increasing distance above the seafloor, and by any statistically significant layers above the headrope in the multiple regression analyses.

Only stations with a NASC value greater than 100 in the 25 m thick layer closest to the seafloor were included in the analysis, provided the corresponding catch size was commensurate with the low backscatter. This restriction was implemented to eliminate stations with extremely low fish densities, which tend to be dominated by plankton. A total of 64 stations were eliminated because of this restriction. We also excluded 13 stations (primarily in Bristol Bay) with NASC values greater than 100 where the backscatter pattern on the echogram were indicative of jellyfish rather than walleye pollock or Pacific cod (i.e. uniform medium-density backscatter spread out over the majority of the water column without blotches of higher than average density).

Of the 417 stations sampled by the two boats during the 2005 survey, 98 *Aldebaran* stations were included in the final analysis.

Following the technique described by Ona and Mitson (1996), we applied a correction to the acoustic data collected on board the *Aldebaran* during the 2005 Bering Sea survey to account for the acoustically undetected fish in the ADZ. This was done to assess whether the correlation between the trawl and acoustic data could be substantially improved. Ona and Mitson's method estimates the size of the dead zone as a function of beam width, pulse length, and bottom depth. The amount of undetected fish backscatter in the ADZ is then estimated by making the assumption that the fish density in the ADZ is equal to that in an arbitrarily "thin" layer immediately above it, where it is possible to measure the density acoustically. This assumption is probably conservative because the density of walleye pollock is likely higher in the layer adjacent to the bottom than any layer above it. We used the 1 m layer above the ADZ for our estimate of fish density in the ADZ.

3. Results

The correlation between trawl and acoustic data was high for walleye pollock ($r^2 = 0.64$) but quite low ($r^2 = 0.02$) for Pacific cod (Fig. 2). The correlation between trawl and acoustic data decreased when echogram integration extended above the headrope. The correlation was highest for the layer between the seafloor and the headrope, then decreased monotonically when integration extended to increasingly greater heights above the headrope (Fig. 3). The rate of decline in r^2 with increasing height above the seafloor was exaggerated by the elimination of stations with a NASC value less than 100 in the 25 m layer closest to the bottom. This is because the left part of the point-cloud is partly or completely eliminated from the regressions of layers above the headrope, resulting in lower r^2 values. However, the r^2 values with the eliminated data reintroduced in the regression analyses also decrease monotonically, albeit less dramatically (Fig. 3).

The only non-cumulative layer with a high correlation for pollock was the one between the seafloor and headrope. The layer immediately above the headrope (2.4–4 m), which had the second-highest correlation ($r^2 = 0.15$, Table 1), was not significant and was therefore not included in the final multiple regression model ($P = 0.41$). These findings suggest that walleye pollock do not engage in vertical herding in response to the oncoming vessel and trawl.

The correlation between trawl and acoustic data did not substantially improve by correcting for acoustically undetectable fish in the ADZ. The two regression lines, one in which the NASC values are unadjusted for the missing fish in the ADZ and the other in which the NASC values are adjusted, have very similar slopes (1.05 versus 0.98) and intercepts (4.14 versus 3.93) with only minor differences in r^2 values: 0.64 and 0.62

Table 1
Regression parameters (a = slope, b = intercept) and r^2 values of the acoustic vs. trawl data relationship for the non-cumulative layers specified in the top row, where the distances are relative to the bottom

	0–2.4 m	2.4–4 m	4–8 m	8–15 m	15–25 m	25–50 m
a	1.05	0.41	0.20	−0.013	0.06	−0.088
b	4.14	7.68	8.25	9.10	8.80	9.46
r^2	0.64	0.15	0.03	<0.01	<0.01	<0.01
P	<0.00001	0.41	0.54	0.50	0.36	0.62

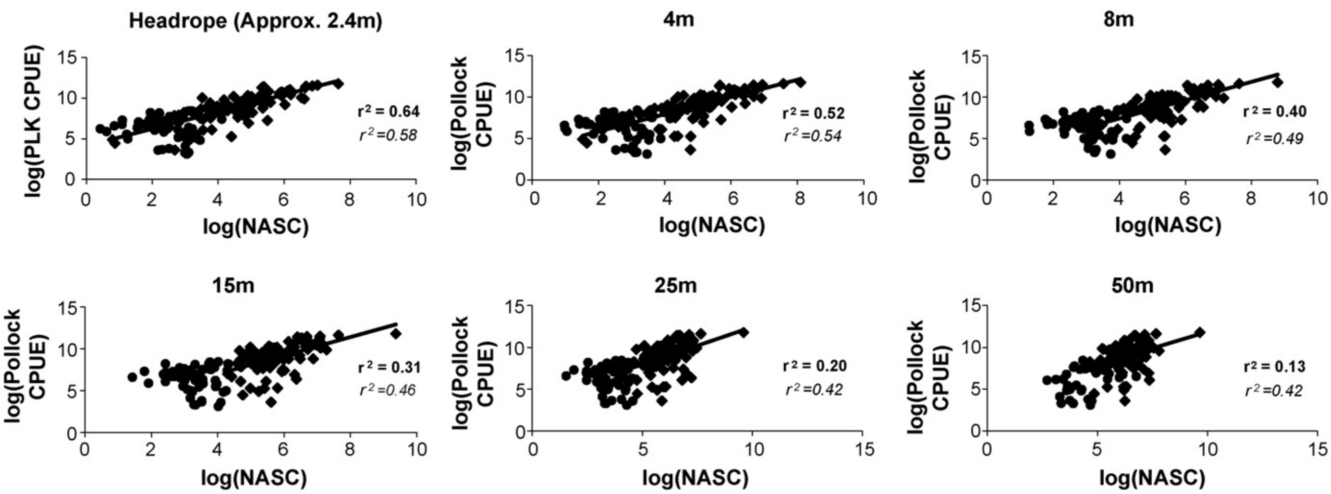

Fig. 3. Estimating the effective net height for pollock. Acoustic data were integrated between the bottom and the indicated height at six different altitudes. The boldfaced (upper) r^2 values are the coefficients of determination corresponding to regressions of data that were used in the analysis (black diamonds, $n = 98$). The italicized (lower) r^2 values are the coefficients of determination corresponding to regressions of data (regression lines not shown), which also include stations that were excluded from the analysis (open circles, $n = 64$) because of low NASC values (NASC < 100 between the seafloor and 25 m above the seafloor).

Table 2
Calibration of the *Aldebaran* ES60 echosounder

Date	Reference TS (dB)	Range (m)	Measured TS (dB)	System gain (dB)	TS gain (dB)	S_v gain (dB)	S_A correct (dB)
1 June 2005	−39.56	18.90	−39.63	27.00	26.97	26.60	−0.37
18 June 2005	−39.56	18.25	−37.22	27.00	28.17	27.67	−0.50

Reference TS is the specified target strength of the 38.1 mm tungsten calibration sphere used in the calibration exercise, and the range is the distance between the transducer face and the calibration sphere. The system gain refers to the gain setting of the ES60, which results in the measured TS, whereas the TS gain and the S_A correct are system settings required to produce the reference sphere TS value.

for the unadjusted and adjusted data, respectively. Because of this, no dead zone correction was applied to the data shown in Figs. 2 and 3.

The calibration exercises were successful and resulted in minor adjustments to the acoustic data (Table 2). The discrepancy in the calibration constants obtained between the two exercises may be attributable to the presence of some fish during the second calibration procedure.

4. Discussion

The proportion of explained variation obtained in this study for pollock ($r^2 = 0.64$ for log-transformed data) compares favorably with other studies that have used this metric or a correlation coefficient to measure the quality of the trawl-acoustic relationship for gadoid species. Hjellvik et al. (in press) obtained r^2 values ranging from almost no correlation (0.01) to 0.53 for haddock and cod in the Barents Sea. The highest values were obtained in the last 2 of the 6 years studied and they were substantially higher than what was obtained in other years for the same species. Beare et al. (2004) obtained even lower values for haddock and saithe (*Pollachius virens*) in the North Sea ($r^2 = 0.06$–0.12), but they obtained considerably higher values in the Barents Sea (0.30–0.64). Aglen (1996) obtained poor correlations for haddock, cod, and saithe ($r^2 = 0.05$–0.45) when integrating the acoustic data between the bottom and the headrope, but he obtained considerably higher r^2 values when integrating between the bottom and 10 to 30 m above the headrope ($r^2 = 0.11$–0.86). Maximum r^2 values obtained by other researchers include 0.40–0.64 for cod and haddock, respectively, in the Barents Sea (Godø et al., 2004), 0.62 for an assemblage of species dominated by cod and haddock in the Barents Sea (Ona et al., 1991), and 0.69 for rockfishes in the Gulf of Alaska (Krieger et al., 2001).

There are several potential factors that can adversely affect the relationship between the two measures of fish abundance. First, because ocean currents near the bottom are generally not aligned with the tow direction, the trawl is often off to the side rather than right behind the boat so that the trawl and boat paths do not coincide (Engås et al., 2000).

Second, when fish are too close to the seafloor in the ADZ, the trawl may catch fish, which the echosounder is unable to resolve from the stronger bottom signal. This would not necessarily be problematic if the proportion of the fish population in the ADZ were temporally and spatially invariant, but for semi-pelagic species such as walleye pollock and other gadoids, this is usually not the case. Several factors have been shown to affect the proportion of gadoids in the ADZ including age composition and fish density (Godø and Wespestad, 1993), time of day (McQuinn et al., 2005), stock size (Godø and Wespestad, 1993; Hjellvik et al., 2003), light levels (Michalsen et al., 1996; Kotwicki, personal comm.) and tidal currents (Michalsen et al., 1996). Complicating matters further, most of these factors also affect the proportion of fish in the water column available to the trawl gear. The fact that we did not observe a substantial improvement in the correlation between trawl and acoustic data when correcting for the fish in the ADZ may be due to the inaccuracy of the assumption that the fish density in the layer immediately above the ADZ is equal to the density in the ADZ itself. In addition, if the pollock density in the vicinity of the headrope is substantial (which it often is), then the ADZ correction may overcompensate because fish slightly above the headrope, but off the acoustic axis and apparently within the layer between the bottom and the headrope, will at least partly compensate for the missing fish in the ADZ. This assumption simply shifted all of the data points toward higher NASC values by an approximately fixed percentage.

A third factor that can impact the quality of the relationship between the trawl and acoustic data is that the acoustic backscatter may be comprised of more than a single target species. Whereas the species composition from a trawl catch is obvious, it is usually very difficult to distinguish acoustic signals due to pollock from that of other species with satisfactory precision.

In the Bering Sea, walleye pollock account for approximately 80–90% of the fish biomass in the approximately 2.4 m thick layer next to the bottom, with the remainder primarily due to Pacific cod (Acuna, 2006). The proportion of acoustic backscatter due to fish accounted for by pollock in that same layer is probably at least as great as this because much of the cod biomass is confined to the ADZ. This situation favors a strong relationship between trawl and acoustic data for pollock. In contrast, the number of potential target species in the North Sea are more numerous and considerably more complex than either the Bering Sea or Barents Sea. Using artificial neural networks to model the relationship between acoustic and trawl data in the North Sea and Barents Sea, Neville et al. (2004) obtained considerably better results in the Barents Sea than they did in the North Sea where species richness is greater.

Finally, various fish reactions to the vessel or trawl may disturb the local fish distribution after the vessel has passed, and the extent to which fish respond is likely a function of environmental variables (Michalsen et al., 1996; Ona and Godø, 1990).

Aglen (1996) found that for the majority of species he considered off the coast of Norway, the strongest correlation between trawl and acoustic data was achieved by integrating up to 30 m or more off bottom, well above the 4 m headrope used in his study. This observation agreed with the findings of Ona and Godø (1990), who showed that pelagic cod (*G. morhua*) off the Norwegian coast have a strong tendency to dive immediately after the passage of a trawling vessel from distances as far as 50–100 m above the bottom for large individuals. In the case of walleye pollock in the Bering Sea, however, there was no evidence of diving behavior, which may help explain why the correlation between acoustic and trawl data is relatively strong in the Bering Sea compared to areas such as the North Sea and Irish Sea, where many of the CATEFA investigators had limited success.

The lack of correlation between trawl and acoustic data for Pacific cod, but not for walleye pollock in the Bering Sea, is most likely due to the low abundance of cod compared to walleye pollock. Because it is very difficult to tease out the backscatter from these two species, the walleye pollock backscatter overwhelms the cod backscatter when correlating trawl and acoustic data for cod. In contrast, the cod backscatter is a relatively minor source of contamination when correlating trawl and acoustic data for pollock.

Furthermore, cod tend to be considerably more benthic than walleye pollock. Their closer proximity to the bottom means that cod are more likely to be in the ADZ. Evidence for differences in time spent on the seafloor can be found in their differing feeding habits. Walleye pollock tend to prey on items such as copepods and euphausiids (Dwyer et al., 1987; Shuntov et al., 2000), which are generally off the seafloor, whereas the diet of cod is dominated by benthic organisms such as polychaete worms, decapods, clams, and eelpouts (Yang, 2004).

These differences between pollock and cod, and the resulting discrepancies in the trawl versus acoustic relationship, may explain the mixed results of other researchers who have tried to correlate catch and acoustic data.

While we are not ready to definitively report the level of variance reduction that can be achieved for pollock biomass estimates by incorporating the between-station acoustic data with the trawl data, we estimated the potential variance reduction by analyzing data from the Alaska Fisheries Science Center's 2004 biennial eastern Bering Sea acoustic survey. This survey runs parallel transects spaced 20 nautical miles apart, the same as the spacing between neighboring stations for the trawl survey, and covers approximately the same area as the trawl survey. We only considered the acoustic data within 3 m of the seafloor, which closely approximates the layer accessible to the trawl survey (2.4 m), and calculated the first order autocorrelation for this data ($\rho_{\mathrm{auto}} = 0.71$). Using the findings of Hjellvik et al. (in press), who generated theoretical variance reduction curves as a function of first order autocorrelation in the acoustic data and for different levels of correlation between the acoustic and trawl data, we estimated the potential variance reduction for pollock to be approximately 45–50%.

Acknowledgements

We greatly appreciate the assistance of Paul Walline and Taina Honkalehto who provided us with the acoustic data from the 2004 eastern Bering Sea EIT survey. We are also grateful for the comments provided by Robert Lauth, Martin Dorn, Alex de Robertis, and two anonymous reviewers, which resulted in substantial improvements to the initial manuscript. We also thank all of the individuals involved in collecting the data on board the *Aldebaran* and *Arcturus* during the 2005 Eastern Bering Sea shelf survey.

References

Acuna, D. (compiler), 2006. 2004 Bottom trawl survey of the eastern Bering Sea shelf AFSC Processed Report 2006-09. Alaska Fisheries Science Center, National Marine Fisheries Service, NOAA.

Aglen, A., 1996. Impact of fish distribution and species composition on the relationship between acoustic and swept-area estimates of fish density. ICES J. Mar. Sci. 53, 501–505.

Beare, D.J., Reid, D.G., Greig, T., Bez, N., Hjellvik, V., Godø, O.R., Bouleau, M., van der Kooij, J., Neville, S., Mackinson, S., 2004. Positive relationships between bottom trawl and acoustic data. ICES CM, 2004/R 24, 1–15.

Bouleau, M., Bez, N., Reid, D.G., Godø, O.R., Gerritsen, H., 2004. Testing various geostatistical models to combine bottom trawl catches and acoustic data. ICES CM 2004/R 28, 1–19.

De Robertis, A., Wilson, C.D., 2006. Walleye pollock respond to trawling vessels. ICES J. Mar. Sci. 63 (3), 514–522.

Dwyer, D.A., Bailey, K.M., Livingston, P.A., 1987. Feeding habits and daily ration of walleye pollock (*Theragra chalcogramma*) in the eastern Bering Sea, with special reference to cannibalism. Can. J. Fish. Aquat. Sci. 44, 1972–1984.

Engås, A., Godø, O.R., Jørgensen, T., 2000. A comparison between vessel and trawl tracks as observed by the ITI trawl instrumentation. Fish. Res. 45, 297–301.

Godø, O.R., Wespestad, V.G., 1993. Monitoring changes in abundance of gadoids with varying availability to trawl and acoustic surveys. ICES J. Mar. Sci. 50, 39–51.

Godø, O.R., Hjellvik, V., Greig, T., Beare, D., 2004. Can subjective evaluation of echograms improve correlation between bottom trawl and acoustic densities? ICES CM 2004/R 23, 1–11.

Hjellvik, V., Michalsen, K., Aglen, A., Nakken, O., 2003. An attempt at estimating the effective fishing height of the bottom trawl using acoustic survey recordings. ICES J. Mar. Sci. 60, 967–979.

Hjellvik, V., Tjøstheim, D., Godø, O.R., in press. Can the precision of bottom trawl indices be increased by using simultaneously collected acoustic data? The Barents Sea experience. Can. J. Fish. Aquat. Sci.

Honkalehto, T., Williamson, N., de Blois, S., Patton, W., 2002. Echo integration-trawl survey results for walleye pollock (*Theragra chalcogramma*) on the Bering Sea shelf and slope during summer 1999 and 2000. NOAA Tech. Memo. NMFS-AFSC-125-126.

Krieger, K., Heifetz, J., Ito, D., 2001. Rockfish assessed acoustically and compared to bottom-trawl catch rates. Alaska Fish. Res. Bull. 8 (1), 71–77.

Mackinson, S., van der Kooij, J., Neville, S., 2005. The fuzzy relation between acoustic and trawl surveys in the North Sea. ICES J. Mar. Sci. 62, 1556–1575.

McQuinn, I.H., Simrad, Y., Stroud, T.W.F., Beaulieu, J.L., Walsh, S.J., 2005. An adaptive, integrated "acoustic-trawl" survey design for Atlantic cod (*Gadus morhua*) with estimation of the acoustic and trawl dead zones. ICES J. Mar. Sci. 62, 93–106.

Michalsen, K., Godø, O.R., Fernö, A., 1996. Diel variation in the catchability of gadoids and its influence on the reliability of abundance estimates. ICES J. Mar. Sci. 53, 389–395.

Neville, S., Hjellvik, V., Mackinson, S., van der Kooij, J., 2004. Using artificial neural networks to combine acoustic and trawl data in the Barents and North Seas. ICES CM 2004/R 05, 1–19.

Ona, E., Godø, O.R., 1990. Fish reaction to trawling noise: the significance for trawl sampling. Rapports et Proces-Verbaux des Reunions Conseil Int. pour l'Explor. Mer. 189, 159–166.

Ona, E., Mitson, R.B., 1996. Acoustic sampling and signal processing near the seabed: the deadzone revisited. ICES J. Mar. Sci. 53, 677–690.

Ona, E., Pennington, M., Voelstad, J.H., 1991. Using acoustics to improve the precision of bottom trawl indices of abundance. ICES CM 1991/D 13, 1–11.

Shuntov, V.P., Dulepova, E.P., Gorbatenko, K.M., Slabinskii, A.M., Efimkin, A.Y., 2000. Feeding of walleye pollock (*Theragra chalcogramma*) in the Anadyr-Navarin region of the Bering Sea. J. Ichthyol. 40 (3), 362–369.

Smith, K.R., McConnaughey, R.A., 1999. Surficial sediments of the eastern Bering Sea continental shelf: EBSSED database documentation. NOAA Tech. Memo NMFS-AFSC-104, 41.

Somerton, D.A., Weinberg, K.L., 2001. The effect of speed through water on footrope contact of a survey trawl. Fish. Res. 53, 17–24.

Thompson, S.K., 1992. Sampling. John Wiley & Sons, Inc., NY, p. 343.

von Szalay, P.G., Somerton, D.A., 2005. The effect of net spread on the capture efficiency of a demersal survey trawl used in the Bering Sea. Fish. Res. 74, 86–95.

Wallace, J.R., West, C.W., 2006. Measurements of distance fished during the trawl retrieval period. Fish. Res. 77 (3), 285–292.

Yang, M.-S., 2004. Diet changes of Pacific cod (*Gadus macrocephalus*) in Pavlov Bay associated with climate changes in the Gulf of Alaska between 1980 and 1995 Fish. Bull. US 102, 400–405.