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Determining species composition in mixed-species marks: an example from the New Zealand hoki (*Macruronus novaezelandiae*) fishery

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A model-based method has been developed for partitioning acoustic backscatter from mixed-species marks. This method uses catch-composition data to partition the echo integral, but allows for differences in trawl catchability and acoustic vulnerability between species. It was applied to estimate the biomass of New Zealand hoki (*Macruronus novaezelandiae*) from trawl and acoustic surveys on the Chatham Rise and Campbell Plateau in 2001. Mixed-species layers containing up to 20 different species were present in both survey areas. A total of 224 bottom-trawl surveys (123 on Chatham Rise and 101 on Campbell Plateau) were carried out to determine the species composition and relative densities. Simultaneous acoustic recordings made during each of these trawls were used to estimate vulnerability ratios for the two methods, i.e. acoustic as opposed to trawl surveys, (acoustic : trawl) by non-negative, least-squares minimization. The best-fit model for each survey attributed 14–22% of the backscatter in mixed layers within 10 m of the bottom to hoki. This produced hoki biomass estimates 1.3–1.8 times higher than the standard approach, which divides the echo integral in proportion to the catch assuming equal trawl catchability. The precision of the estimated acoustic : trawl vulnerability ratios depended on the contrast in trawl catch composition, and the ratios for the same species differed between areas. A major problem on the Chatham Rise was the acoustic contribution of small mesopelagic species, which are not caught by the bottom trawl. Despite these difficulties, the model-based approach has good potential for determining the biomass of the target species in a mixed-species mark when the different species cannot be discriminated acoustically.

Keywords: acoustic mark identification, catchability, hoki, mixed species.

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Introduction

One of the first steps in the analysis of fisheries acoustic-survey data is to determine the relative contribution to the backscatter of the different species present. Ideally, the target species occurs in single-species aggregations, and echoes from these aggregations can be recognized either subjectively or objectively (e.g. Rose and Leggett, 1988). However, mixed-species marks are a common feature of many acoustic surveys, and target identification is often problematic. When different species cannot be discriminated acoustically, the proportion of backscatter due to the target species must be determined from ancillary data, such as fishing samples.

The standard method of partitioning the echo integral from a mixed-species mark divides the backscatter in proportion to trawl catch composition and target strength (MacLennan and Simmonds, 1992). This assumes that all species that contribute to the backscatter are caught in the trawl, and that all species have an equal ratio of acoustic vulnerability to trawl catchability. The assumption of equal acoustic : trawl vulnerability across species is probably a poor one. It is known that vulnerability to fishing gear depends on a number of species-specific biological factors, such as size, sensory capability and behaviour, as well as environmental factors such as time-of-day and bottom-type (Gunderson, 1993). Where trawl catchability has been estimated, either by experimentation (see the review by Somerton *et al.*, 1999) or by comparing trawl survey results with stock-assessment models (Harley and Myers, 2001), catchability estimates vary widely between species. Different species may also have varying vulnerability to acoustic techniques through differences in behaviour. For example, demersal species, which occur close to the bottom in the acoustic "deadzone" (Ona and Mitson, 1996), are likely to be less acoustically vulnerable than pelagic species.

In this article, a novel approach is presented for partitioning acoustic backscatter from mixed-species marks. The method uses catch-composition data to partition the echo integral, but allows for differences in trawl and acoustic vulnerabilities between species. Species-specific acoustic : trawl vulnerability ratios are estimated by comparing trawl catches with simultaneous acoustic recordings. The new method was applied to estimate the biomass of New Zealand hoki (*Macruronus novaezelandiae*) from trawl and acoustic surveys of the Chatham Rise and Campbell Plateau areas (Figure 1) in 2001. Acoustic data from these surveys are not used currently in stock assessment because of the problems with partitioning backscatter from mixed-species layers.

Materials and methods

Statistical methods

The standard approach to partitioning acoustic backscatter from a mixed-species mark (MacLennan and Simmonds, 1992) assumes that the backscatter contributed by species i (E_i) is proportional to the product of its trawl-catch rate (c_i) and its mean acoustic-backscattering cross-section (σ_i, where target strength in dB = 10 log σ):

$$E_i = \frac{c_i \sigma_i}{\sum_{j=1}^{n} c_j \sigma_j} E \quad (1)$$

where E is the total acoustic backscatter, and n is the number of species caught in the trawl. In this article, all catch rates (c_j) are expressed as density estimates in kg km^{-2} based on doorspread (not wingspread) swept area, and mean-backscattering cross-sections (σ_j) are expressed per kg (not per fish).

The method allows for differences in the vulnerability of species to the trawl and acoustic gear by incorporating an additional term (v_i), which is the ratio of acoustic vulnerability to trawl vulnerability for species i:

$$E_i = \frac{v_i c_i \sigma_i}{\sum_{j=1}^{n} v_j c_j \sigma_j} E. \quad (2)$$

The trawl vulnerability is the proportion of fish in the swept area of the trawl, i.e. between the doors, that are captured; it is also referred to as catchability. The acoustic vulnerability is the proportion of fish in the acoustic beam that are ensonified and included in the integration of backscatter.

The acoustic : trawl vulnerability ratios for each species in the mixed layer have been estimated by comparing the

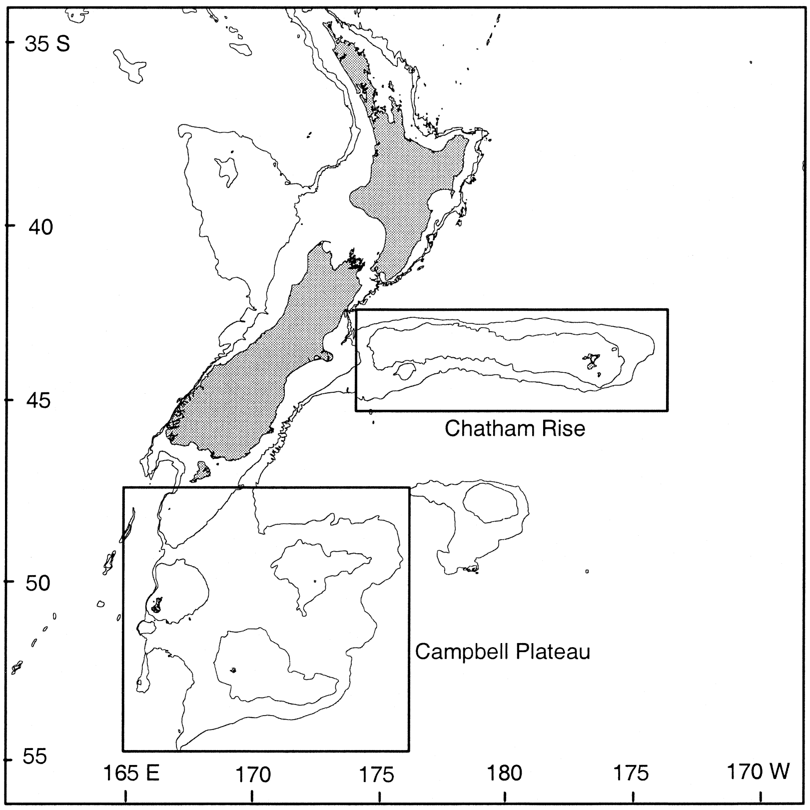

Figure 1. Map of New Zealand showing survey areas. Depth contours are 500 and 1000 m.

trawl catches with the acoustic recordings made during the trawls using a linear regression approach:

$$E_t = \sum_{j=1}^{n} v_j \sigma_{j,t} c_{j,t} + \varepsilon_t. \quad (3)$$

Total acoustic backscatter (E_t) and catch rates ($c_{j,t}$) were measured for each trawl t, and acoustic-backscattering cross-sections for each species ($\sigma_{j,t}$) were derived from length and weight measurements. The estimated acoustic : trawl vulnerability ratios ($\hat{v}_j$) were then calculated using non-negative, least-squares minimization, performed in S-Plus (MathSoft Inc.). The function to be minimized was the sum of the squared deviations between E_t and $\sum v_j \sigma_{j,t} c_{j,t}$. Residuals for each tow (ε_t) were also calculated.

Uncertainty associated with acoustic : trawl vulnerability ratios was estimated by bootstrapping from the residuals. A total of 100 bootstrapped datasets were generated ($m = 1, \ldots, 100$). Acoustic backscatter for trawl t in bootstrap m ($E^*_{t,m}$) was given by:

$$E^*_{t,m} = \sum_{j=1}^{n} \hat{v}_j \sigma_{j,t} c_{j,t} + \varepsilon^*_{t,m} \quad (4)$$

where $\varepsilon^*_{t,m}$ was drawn randomly with replacement from the set of calculated residuals $\{\varepsilon_t\}$. The regression model (Equation (3)) was then fitted to each bootstrapped data set $\{E^*_{t,m}\}$ to get 100 parameter estimates for each species $\{\hat{v}_{j,m}\}$. The 90% confidence intervals for $\hat{v}_j$ were constructed using the 5 and 95% quantiles of the bootstrap distribution.

Survey data

Trawl and acoustic data were collected during stratified, random trawl surveys for hoki on the Chatham Rise and Campbell Plateau (Figure 1) in 2001. The Chatham Rise was surveyed from 28 December 2000 to 25 January 2001, and the Campbell Plateau from 26 November to 21 December 2001. Both surveys were carried out from the 70 m research stern trawler RV "Tangaroa" using the same trawl and acoustic equipment.

The trawl was an eight-seam, hoki bottom trawl with 100 m sweeps, 50 m bridles, 58.8 m groundrope, 45 m headline and 60 mm codend mesh. The trawl doors were Super Vee type with an area of 6.1 m^2. At each station, the trawl was towed for 3 nautical miles at a speed, over the ground, of 3.5 knots. Measurements of doorspread (from a Scanmar 400 system) and headline height (from a Furuno net-monitor) were recorded during each tow. All trawls were carried out during daylight hours. Each trawl catch was sorted into species and weighed on Seaway motion-compensating electronic scales accurate to about 0.3 kg. A random sample of up to 200 individuals of each species from every tow was measured. More detailed biological data that included fish weight, sex and gonad stage were also collected on a subsample of catches.

Acoustic data were collected using a custom-built CREST system (Coombs, 1994) with hull-mounted SIMRAD single-beam 12 and 38-kHz transducers. CREST is a computer-based "software echosounder" that supports multiple channels. The transmitter was a switching type with a nominal power output of 2 kW rms. Transmitted pulse length was 1 ms with 3 s between-transmits. The CREST receiver has a broadband, wide dynamic-range preamplifier and serial analogue-to-digital converters (ADCs), which feed a digital signal processor (DSP56002). Data from the ADCs were complex demodulated, filtered, and a 20 log R time-varied gain was applied. The complex data were then stored for later processing. The 38-kHz transducer was calibrated prior to the surveys following standard procedures (Foote *et al.*, 1987). The 12-kHz transducer was not calibrated. Data collected on 12 kHz transducer were only used to make visual comparisons with 38-kHz data and were not analysed quantitatively.

On the Chatham Rise, additional trawls with corresponding acoustic measurements were targeted at extensive, dense, bottom-referenced layers. When strong layers were encountered, the trawl-survey programme was suspended and the marks were targeted. A standard bottom tow was carried out using the hoki bottom trawl in exactly the same manner as during the normal trawl survey. When the top of a layer was more than 30 m off the seabed, a midwater hoki trawl of approximately 40-m diameter circular opening, with 150 m bridles and a 60-mm codend mesh was towed along the same trawl track as the bottom trawl to help establish the species composition of the mark above the bottom.

Echograms from all bottom-trawl stations were examined, including random trawl-survey stations and targeted bottom trawls (Chatham Rise only). Trawls that did not sample mixed-layer marks, or which also sampled other mark types (e.g. fish schools), were excluded from the analysis. Trawls with poor gear performance, or where the acoustic recording was noisy due to rough sea conditions, were also excluded. For each bottom trawl that sampled the mixed layer, swept-area catch rates (in kg km^{-2}) were calculated using measured tow length and doorspread for all species caught. The corresponding 38-kHz acoustic data recorded during the tow, corrected for the lag of the trawl behind the vessel based on warp length and water depth, were then integrated using the customized software Echo Sounder Package (ESP2) (McNeill, 2001) to calculate the mean area-backscattering coefficient ($m^2\,km^{-2}$) from the bottom-referenced marks. Estimates of v_j from the linear regression model vary depending on the height above the seabed over which the backscatter (E_t) is integrated. In this article, an integration height of 10 m above the acoustic bottom has been used, which is similar to the measured headline height of the trawl (average 7.0 m). This assumes that all fish in the 10-m integration zone were available vertically to the bottom-trawl gear and that fish outside this zone were not caught.

The mean-backscattering cross-section per kg of species in each acoustic-trawl recording was estimated from the length of fish in the corresponding catch using estimated length–weight parameters determined from the subsample of fish weighed during each survey and best available target strength–length relationships (G. Macaulay, pers. comm.).

Acoustic estimates of hoki biomass (B_{hoki}) in the survey area were based on acoustic recordings at all random trawl stations. These data provide representative samples of mixed-layer density throughout each surveyed area. At each station, backscatter from any mixed-layer marks present, and excluding other mark types, was integrated from the bottom up to the maximum height of the layer. Mixed-layer acoustic-density estimates were scaled up over the survey area to obtain a measure of the total acoustic backscatter from mixed-species marks (E). The amount of backscatter due to hoki (E_{hoki}) was calculated from Equation (2) using trawl-catch data with vulnerability ratios estimated by the model. Hoki biomass was then estimated by dividing E_{hoki} by mean hoki backscattering cross-section per kg (σ_{hoki}):

$$B_{hoki} = \frac{C}{\sigma_{hoki}} E_{hoki} \qquad (5)$$

where C is the echosounder calibration factor. Confidence intervals for B_{hoki} were calculated using the 5 and 95% quantiles of $\hat{v}_j$ estimated by bootstrapping.

Results

Data collection

A total of 132 bottom trawls were carried out on the Chatham Rise and 110 on the Campbell Plateau. Trawl performance and acoustic-data quality were usually good, and most trawls sampled the bottom-referenced, mixed-species layer. Only nine trawls were excluded from the analysis in each area giving a dataset of 123 tows from the Chatham Rise, and 101 from the Campbell Plateau. Five midwater trawls to aid mark identification were also carried out on the Chatham Rise.

Bottom-trawl catches from mixed-species layers contained up to 19 major species on the Chatham Rise and 17 species on the Campbell Plateau (Table 1). Major species were defined as those that made up more than 1% by weight of the average catch. Hoki were the dominant species in both areas, averaging 31% of the catch-by-weight on the Chatham Rise and 21% of the catch-by-weight on the Campbell Plateau (Table 1). Mean target strengths for major species are also given in Table 1. Between 15 and 18% of the trawl-catch weight in the two areas was made up of nearly 100 other fish species that individually made up less than 1% of the average catch. The summed weight of minor species was considered as a group ("other"), and an average-backscattering cross-section was assigned (Table 1). The five midwater trawls on bottom-referenced, mixed layers during the Chatham Rise survey also revealed the presence of small mesopelagic fishes, particularly pearlside, *Maurolicus australis*, and myctophids, which were not caught in the bottom trawl.

Although mixed-species layers occurred extensively in both survey areas, marks were much stronger and thicker on the Chatham Rise than on the Campbell Plateau. The average area-backscattering coefficient of mixed layers observed during random tows, stratified by depth, on the Chatham Rise was 26.1 ($m^2\,km^{-2}$; number of random tows, $n = 117$), compared with 2.9 ($m^2\,km^{-2}$; $n = 101$) on the Campbell Plateau. Overall trawl-catch rates, all species combined, were also higher on the Chatham Rise (mean catch rate = 1520 kg km^{-2}) than on the Campbell Plateau (mean catch rate = 780 kg km^{-2}). In both areas, there was a weak positive relationship between trawl-catch rates and acoustic backscatter recorded in the bottom 10 m during the trawl. Spearman's rank correlations were 0.40 for the Chatham Rise and 0.24 for the Campbell Plateau.

Model-based species decomposition

Acoustic : trawl vulnerability ratios estimated by linear regression varied widely between species (Table 1). The best-fit, non-negative, least-squares regression model for each area indicated that eight of 20 species caught in the trawl on the Chatham Rise and five of 18 species caught on the Campbell Plateau did not contribute to the acoustic backscatter (acoustic : trawl vulnerability ratio = 0). At the other extreme, silver warehou (*Seriolella punctata*) on the Chatham Rise were estimated to be 1575 times more vulnerable to acoustics than to the trawl (i.e. very low trawl catchability).

Confidence intervals around acoustic : trawl vulnerability ratios were wide and included 0 for many species (Table 1). The ability of the regression model to estimate precisely the acoustic : trawl vulnerability ratio for a species was related to the degree of contrast in catch composition. The model did best at estimating ratios for species such as hoki, where there was strong contrast in catch composition between tows: some trawls caught a high proportion of the species and other tows caught none. Estimates were more variable for species with lower contrast, such as the pale ghost shark (*Hydrolagus* sp. B). The degree of contrast in catches was more important than the frequency of occurrence of a species. For example, the regression model estimated the acoustic : trawl vulnerability ratio for black oreo (*Allocyttus niger*) on the Campbell Plateau relatively precisely, even though samples were caught in 4% of tows only.

Acoustic : trawl vulnerability ratios for the same species varied between the two areas (Table 1). Many common species, including hoki, ling (*Genypterus blacodes*), hake (*Merluccius australis*), spiny dogfish (*Squalus acanthias*) and shovel-nosed dogfish (*Deania calcea*), were estimated to have higher catchability (lower acoustic : trawl vulnerability ratios) on the Campbell Plateau than on the Chatham Rise.

Table 1. Average trawl-catch composition (% Catch = mean, with range in parentheses, of ($c_{i,t} / \Sigma c_{j,t} \times 100$), where $c_{i,t}$ is the catch of species i in trawl t, and $\Sigma c_{j,t}$ is the total catch in that trawl), derived target strength (TS kg^{-1}) and estimated acoustic : trawl vulnerability ratios ($\hat{v}$) for major species caught in the trawl and acoustic surveys of the Chatham Rise and Campbell Plateau. The ratios were estimated using non-negative, least-squares regression with 90% confidence intervals (CI) from bootstrapping. TS kg^{-1} was determined from mean acoustic-backscattering cross-section (σ) per kg where TS = 10 log σ. "–" indicates species made up less than 1% of the average catch in an area.

		Chatham Rise					Campbell Plateau				
Common name	Scientific name	% Catch	Range	TS kg^{-1}	$\hat{v}$	90% CI	% Catch	Range	TS kg^{-1}	$\hat{v}$	90% CI
Hoki	*Macruronus novaezelandiae*	31	0–78	−40.4	15.1	6.6–21.5	21	0–81	−41.5	5.7	1.9–8.1
Ling	*Genypterus blacodes*	6	0–25	−33.0	25.1	0.0–43.2	16	0–59	−33.4	1.8	1.0–3.6
Javelin fish	*Lepidorhynchus denticulatus*	7	0–29	−32.5	3.9	0.0–11.7	10	0–43	−32.8	4.7	3.5–6.7
Pale ghost shark	*Hydrolagus* sp. B	4	0–19	−45.9	32.9	0.0–419.3	7	0–40	−45.5	76.4	19.8–133.4
Spiny dogfish	*Squalus acanthias*	5	0–25	−45.3	62.5	0.0–241.9	3	0–58	−45.0	0.3	0.0–15.8
Big-eyed rattail	*Caelorinchus bollonsi*	7	0–39	−34.0	1.7	0.0–12.4	–		–	–	
Dark ghost shark	*Hydrolagus novaezealandiae*	5	0–76	−45.1	0.0	0.0–84.1	1	0–60	−45.4	0.0	0.0–63.3
Black oreo	*Allocyttus niger*	2	0–72	−36.6	0.0	0.0–9.6	3	0–93	−36.5	1.2	0.8–1.9
Shovel-nosed dogfish	*Deania calcea*	3	0–38	−44.6	101.1	0.0–375.2	2	0–40	−45.3	8.3	0.0–40.9
Hake	*Merluccius australis*	1	0–12	−37.5	47.6	0.0–153.0	3	0–28	−37.6	1.7	0.0–5.8
Ridge-scaled rattail	*Macrourus carinatus*	–		–	–		4	0–73	−32.4	1.0	0.0–2.3
Southern blue whiting	*Micromesistius australis*	–		–	–		4	0–65	−34.2	0.0	0.0–2.5
Lookdown dory	*Cyttus traversi*	4	0–15	−31.9	0.0	0.0–13.1	–		–	–	
White warehou	*Seriolella caerulea*	1	0–18	−48.5	0.0	0.0–651.7	2	0–70	−49.6	9.0	0.0–35.5
Sea perch	*Helicolenus* spp	3	0–20	−46.7	145.6	0.0–500.0	–		–	–	
Spiky oreo	*Neocyttus rhomboidalis*	2	0–62	−37.2	0.0	0.0–7.1	–		–	–	
Silver warehou	*Seriolella punctata*	1	0–32	−48.3	1 575.4	659.8–1 932.1	1	0–64	−49.2	0.0	0.0–11.2
Smooth oreo	*Pseudocyttus maculatus*	–		–	–		2	0–50	−42.0	0.0	0.0–5.2
Alfonsino	*Beryx splendens*	2	0–67	−36.4	3.2	0.0–8.7	–		–	–	
Small-scaled slickhead	*Alepocephalus australis*	–		–	–		1	0–41	−46.5	0.0	0.0–99.9
Long-nose velvet dogfish	*Centroscymnus crepidater*	–		–	–		1	0–30	−45.4	24.2	0.0–78.8
Baxter's dogfish	*Etmopterus baxteri*	–		–	–		1	0–20	−44.7	104.6	21.3–167.0
Silver dory	*Cyttus novaezealandiae*	1	0–40	−45.1	0.0	0.0–103.8	–		–	–	
Barracouta	*Thyrsites atun*	1	0–27	−34.2	0.0	0.0–17.0	–		–	–	
Common roughy	*Paratrachichthys trailli*	1	0–53	−43.7	26.2	0.0–57.3	–		–	–	
Other		15	1–89	−37.0	0.0	0.0–8.3	18	1–83	−37.0	1.1	0.0–2.8

Fitted values from non-negative, least-squares regression models are plotted against observed acoustic backscatter in the bottom 10 m in Figure 2. The corresponding values of R^2 were 35.4% for the Chatham Rise model and 30.0% for the Campbell Plateau. The Chatham Rise regression model was unable to fit several observations of high acoustic backscatter (Figure 2), and there was an increasing trend in residuals with increasing observed backscatter. Residual patterns for the Campbell Plateau models were satisfactory.

Model-based estimates of hoki biomass were more optimistic than those obtained from the standard species-decomposition method (Equation (1)) in both areas (Table 2). The best-fit model indicated that 22% of the acoustic backscatter on the Chatham Rise was hoki, producing a biomass estimate 1.3 times higher than that from the standard method. On the Campbell Plateau, the model estimate of hoki biomass was 1.8 times higher than the biomass estimated using the standard method (Table 2).

Hoki biomass estimates from the model-based method were relatively insensitive to the target-strength values used for bycatch species. These were often uncertain. Doubling and halving values of the mean acoustic-backscattering cross-section (σ_j) for all species except hoki changed the hoki biomass estimates by less than 10%. The regression model compensated for changes in target strength by adjusting acoustic : trawl vulnerability ratios. For example, in the Chatham Rise model, halving the backscattering cross-section of ling doubled its acoustic : trawl vulnerability ratio from 25.1 (Table 1) to 50.3.

Table 2. Estimates of hoki biomass based on alternative methods of species decomposition. The "standard" method assumes equal acoustic : trawl vulnerability ratios for all species. The "model" method estimates species–species acoustic : trawl vulnerability ratios using non-negative, least-squares regression. "Mean % backscatter" is the estimated acoustic contribution of hoki in mixed-species layers averaged over the entire survey area. The 90% confidence intervals for model-based estimates are given in parentheses.

Area	Analysis method	Mean % backscatter	Biomass ('000 t)
Chatham Rise	Standard	17	7700
	Model	22 (11–28)	10 200 (5100–13 000)
Campbell Plateau	Standard	8	1000
	Model	14 (5–18)	1800 (600–2300)

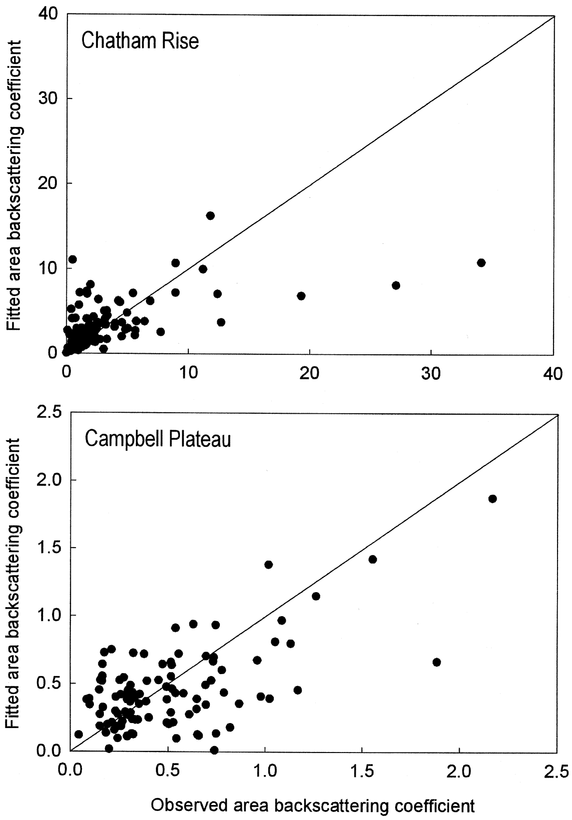

Figure 2. Fitted and observed area-backscattering coefficients ($m^2 km^{-2}$) in bottom 10 m from best-fit, non-negative, least-squares regression models.

Discussion

An attempt to improve on the standard approach for partitioning acoustic backscatter from mixed-species marks was made by using a simple regression model to estimate species-specific, acoustic : trawl vulnerability ratios from paired trawl catches and acoustic observations. It was difficult to assess how well the model performed in the examples provided.

Potentially, one way of "ground-truthing" model results is to compare the estimated vulnerability ratios between species. For example, we might expect a large, fast-swimming species such as hake to have a lower trawl catchability, and hence a higher acoustic : trawl vulnerability ratio, than a smaller, slower species such as javelin fish. This was true on the Chatham Rise, but not on the Campbell Plateau. However, such comparisons might be misleading. The regression-model approach performed best when there was a strong contrast in the species mix caught during the trawls. If most trawls caught a similar proportion of a species then there were many possible explanations for the observed backscatter, and the acoustic : trawl vulnerabilities were poorly estimated. There was insufficient contrast in the data to estimate precisely the vulnerability ratios (or biomass) for many bycatch species, and so comparing ratios between species was not a useful diagnostic. The estimated acoustic : trawl vulnerability ratios may also alias for errors in acoustic target-strength values.

The estimated acoustic : trawl vulnerability ratios were usually higher on the Chatham Rise than on the Campbell Plateau. This was because the acoustic estimates of mixed-layer density were nine times higher on the Chatham Rise, but the average trawl catches were only twice as high. The most consistent hypothesis to explain this difference was that bottom-referenced layers on the Chatham Rise also contained a high proportion of mesopelagic "feed" species, which contributed to the acoustic backscatter, but were not sampled by the bottom trawl. Midwater trawls through mixed-layer marks 40–60 m above the bottom caught pearlsides and myctophids, and many of the hoki caught from bottom-referenced marks contained fresh or partly digested myctophids in their stomachs. Because of their small size, modal length about 5 cm, mesopelagic fish were seldom caught in the trawls with a 60 mm mesh.

Because of the likely presence of much "unaccounted backscatter" from small mesopelagic fish, acoustic-biomass estimates of hoki on the Chatham Rise were almost certainly too high. The approximate acoustic estimate of 5–13 million tonnes was much higher than the total biomass on the Chatham Rise in 2001 estimated by the most recent hoki-assessment model (0.6–1.3 million tonnes; C. Francis, pers. comm.). The model-based acoustic-biomass estimate from the Campbell Plateau of 0.6–2.3 million tonnes was of a similar order as that of the stock-assessment estimates of 0.5–2 million tonnes (C. Francis, pers. comm.). Mesopelagic species are also common on the Campbell Plateau, but tend to form recognizable, discrete layers off the bottom and may not contribute to the acoustic backscatter from the bottom mixed layer.

The best-fit regression models of acoustic : trawl vulnerability ratios were only able to explain 30–35% of the variability in the observed backscatter in the bottom 10 m. There are a number of factors that may lead to variability in acoustic and trawl vulnerabilities within a species. Time-of-day has been shown to have a substantial effect on the trawl catchability of hoki (Livingston *et al.*, 2002). Even though all trawls were carried out in daylight, generalized linear modelling of trawl-catch rates on the Chatham Rise suggested that hoki catchability was about 1.6 times higher at noon than during the 2 h following sunrise (Livingston *et al.*, 2002). Fish size, water depth, bottom-type and weather conditions also vary between trawls and may affect trawl catchability. The acoustic vulnerability of a species may also vary if the proportion of fish in the acoustic deadzone changes with time, depth or bottom-type.

Another potential source of variability in the observed acoustic backscatter relative to trawl catches is a mismatch between the area sampled by trawl and acoustics. The trawl was typically 500–1500 m behind the vessel and, although this lag was corrected for, drift caused by currents or wind may mean that the acoustic and trawl data did not come from the same section of the seabed. A trawl position-monitoring system would refine future comparisons of trawl and acoustic data. There may also have been vertical herding of fish by the trawl (e.g. Aglen, 1996). Backscatter from greater than 10 m above the bottom was not included in the acoustic estimates used by the regression model to estimate the vulnerability ratios.

The simple, least-squares estimation model may not have been ideal, since observations of acoustic backscatter and trawl catches were not normally distributed. However, the estimated vulnerability ratios from least-squares were similar to the results obtained using a more complex, maximum-likelihood estimator (Cordue, 2002), when both methods were applied to another hoki dataset from the west coast of New Zealand (R. L. O'Driscoll, unpublished results). The uncertainty related to the choice of estimation procedure is thought to be small compared with those caused by natural variability in the data, lack of contrast in catch composition and presence of "unaccounted backscatter".

This article describes work in progress. The new statistical method did not produce reliable acoustic-biomass estimates for Chatham Rise hoki, probably because of the acoustic contribution of small mesopelagic species that were not caught by the trawl. This "unaccounted backscatter" would also strongly bias acoustic estimates based on standard methods of species decomposition. Improved sampling of the bottom-referenced mixed layer on the Chatham Rise is required to determine the proportion of mesopelagic fish. The results from the Campbell Plateau are more promising, although the inherent variability in the trawl catches and the acoustic observations made it difficult to assess whether acoustic : trawl vulnerability ratios were estimated accurately. Other New Zealand work on partitioning acoustic backscatter from mixed-species marks has focused on discriminating species based on acoustic properties (e.g. Barr, 2000), and there is increasing use of multiple frequencies to aid species identification. Midwater layers of mesopelagic fish, for example, appear much stronger on 12 kHz than on 38 kHz, which may be associated with swimbladder resonance.

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References

Aglen, A. 1996. Impact of fish distribution and species composition on the relationship between acoustic and swept-area estimates of fish density. ICES Journal of Marine Science, 53: 501–505.

Barr, R. 2000. A design study of an acoustic system for differentiating orange roughy and other New Zealand deepwater species. Journal of the Acoustical Society of America, 109: 164–178.

Coombs, R. F. 1994. An adaptable acoustic data acquisition system for fish stock assessment. International Conference on

Underwater Acoustics, 5–7 December 1994, University of New South Wales, Sydney, Australia.

Cordue, P. L. 2002. An analysis of an acoustic survey of spawning hoki off the west coast of the South Island during winter 2000. New Zealand Fisheries Assessment Report 2002/26. 51 pp.

Foote, K. G., Knudsen, H. P., Vestnes, G., MacLennan, D. N., and Simmonds, E. J. 1987. Calibration of acoustic instruments for fish density estimation: a practical guide. ICES Cooperative Research Report, No. 144. 68 pp.

Gunderson, D. R. 1993. Surveys of Fisheries Resources. Wiley, New York, 248 pp.

Harley, S. J., and Myers, R. A. 2001. Hierarchical Bayesian models of length-specific catchability of research trawl surveys. Canadian Journal of Fisheries and Aquatic Sciences, 58: 1569–1584.

Livingston, M. E., Bull, B., Stevens, D. W., and Bagley, N. W. 2002. A review of hoki and middle depth trawls surveys of the Chatham Rise, January 1992–2001. NIWA Technical Report, No. 113. 146 pp.

MacLennan, D. N., and Simmonds, E. J. 1992. Fisheries Acoustics. Chapman and Hall, London. 325 pp.

McNeill, E. 2001. ESP2 phase 4 user documentation. NIWA Internal Report, No. 105. 31 pp.

Ona, E., and Mitson, R. B. 1996. Acoustic sampling and signal processing near the seabed: the deadzone revisited. ICES Journal of Marine Science, 53: 677–690.

Rose, G. A., and Leggett, W. C. 1988. Hydroacoustic signal classification of fish schools by species. Canadian Journal of Fisheries and Aquatic Sciences, 45: 597–604.

Somerton, D., Ianelli, J., Walsh, S., Smith, S., Godø, O. R., and Ramm, D. 1999. Incorporating experimentally derived estimates of survey trawl efficiency into the stock assessment process: a discussion. ICES Journal of Marine Science, 56: 299–302.