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Original Article

Multispecies acoustic dead-zone correction and bias ratio estimates between acoustic and bottom-trawl data

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In this study, we extended the original work of Kotwicki et al. (2013. Combining bottom trawl and acoustic data to model acoustic dead zone correction and bottom trawl efficiency parameters for semipelagic species. Canadian Journal of Fisheries and Aquatic Sciences 70: 208–219) to jointly estimate the acoustic dead-zone correction, the bias ratio, and the gear efficiency for multiple species by using simultaneously collected acoustic and bottom-trawl data. The model was applied to cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) in the Barents Sea and demonstrated a better or similar performance compared with a single species approach. The vertical distribution of cod and haddock was highly variable and was influenced by light level, water temperature, salinity, and depth. Temperature and sunlight were the most influential factors in this study. Increase in temperature resulted in decreasing catch and fish density in the acoustic dead zone (ADZ), while increasing sun altitude (surrogate for light level) increased the catch and fish density in the ADZ. The catch and density of haddock in the ADZ also increased at the lowest sun altitude level (shortly after midnight). Generally, the density of cod and haddock changed more rapidly in the ADZ than in the catch (from bottom to the effective fishing height) indicating the importance of modelling fish density in the ADZ. Finally, the uncorrelated variability in the annual residual variance of cod and haddock further strengthen the conclusion that species vertical distribution changes frequently and that there are probably many other unobserved environmental variables that affect them independently.

Keywords: acoustics, acoustic dead zone, bottom trawl survey, catchability, density dependence, multispecies.

Introduction

Catch rates and acoustic data from fishery-independent surveys have a long history in fishery science and have been used for stock assessment and management (Hilborn and Walters, 1992; Maunder and Punt, 2004; Simmonds and MacLennan, 2006). Many countries now regularly perform surveys to collect both acoustic and catch-rate data to examine the extent of species distribution and to produce indices of population abundance. Traditionally, these two datasets have been analysed separately (i.e. two independent abundance indices) due to the inherent differences in survey approach (Ianelli *et al.*, 2014). Although the acoustic instrument covers the whole range of the water column except the bottom layer where the acoustic backscatter from the seabed cannot be distinguished from fish—also called the acoustic dead zone (ADZ; Ona and Mitson, 1996), the bottom trawl only samples the seabed and does not detect fish above an effective fishing height (EFH; Hjellvik *et al.*, 2003; the distance from bottom that is effectively fished by the bottom trawl; Figure 1).

Consequently, both techniques provide fish density estimates only in part of the water column (Kotwicki *et al.*, 2015). Moreover, these partial density estimates are biased because multiple factors affect sampling efficiencies of the two techniques, making them difficult to compare and combine. However, the ratio of sampling biases (hereafter referred to as "bias ratio"; Kotwicki *et al.*, 2017) can be used to scale bottom-trawl catch rates to the acoustic estimates. Recently, methodologies to combine acoustic and bottom-trawl survey data have been developed to appropriately tune the information from the two surveys (Kotwicki *et al.*, 2013; Lauffenburger *et al.*, 2017) and create a more accurate estimate of species distribution (Kotwicki *et al.*, 2017). As an example, Kotwicki *et al.* (2013) developed an approach, using the walleye pollock (*Gadus chalcogrammus*) acoustic and bottom trawl data in the Eastern Bering Sea, to estimate the ADZ correction and the bias ratio between the two survey gears while accounting for the influence of environmental covariates. Additionally, their model estimated a density-dependent bottom-trawl efficiency (the proportion of fish in the bottom trawl's effective fishing area that is caught by the trawl) parameter to account for possible herding and/or avoidance behaviour when the animals encounter the fishing gear (Hjellvik *et al.*, 2003; Handegard and Tjøstheim, 2009). Their approach focused on a single species, but multiple species often contribute to the acoustic backscatter signal and are caught using bottom-trawl gear. Therefore, a multispecies model that takes advantage of the species cooccurrence information (in both acoustic and bottom-trawl data) can potentially help to more accurately tune the two survey gears and to improve the estimates of ADZ, bias ratios, and density-dependent gear efficiency.

Here, we extend the original work of Kotwicki *et al.* (2013) to model the ADZ correction, the bias ratio, and the gear efficiency in a multiple species context. Furthermore, we test the effect of environmental variables collected during the survey to potentially improve the predictability of fish density in the ADZ, as in Kotwicki *et al.* (2013). We have chosen Atlantic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) from the Barents Sea for this work because they are important components of the Barents Sea fisheries and often coexist in the same areas. Both cod and haddock are distributed on the bottom and higher in the water column and are often difficult to distinguish from each other solely based on the acoustic backscatter.

Material and methods

Data

The Institute of Marine Research (IMR) in Bergen, Norway has performed acoustic measurements of demersal fish in the Barents Sea since 1976, and a bottom-trawl survey has been combined with the acoustic survey (the Barents Sea winter survey) since 1981 (Figures 1 and 2). Since 1993, the typical effort of the combined survey has been 10–14 vessel-weeks, and about 350 bottom-trawl hauls have been made each year. In most years, three vessels have participated from about 1 February to 15 March. Survey development is described in detail in Jakobsen *et al.* (1997), Johannesen *et al.* (2009), and Mehl *et al.* (2013). The Polar Research Institute of Marine Fisheries and Oceanography (PINRO), Russia, has also participated in the survey since 2000. The data used in this study includes 1997–2003, a period during which the equipment (both acoustic and bottom trawl), procedure, format, and resolution of the data were standardized (Mehl *et al.*, 2013).

The Barents Sea winter survey is a multipurpose survey, but the main objective is to obtain acoustic and swept-area (Alverson and Pereyra, 1969) abundance estimates by length and age for cod, haddock, and redfish (*Sebastes* sp.). Data and results from the survey are used both in the ICES stock assessments and by several research projects at IMR and PINRO.

Acoustic backscatter measurements have been made continuously along the route of the survey vessel and followed a standard scheme (Jakobsen *et al.*, 1997). Acoustic recording was done with a 38-kHz SIMRAD EK 500 echosounder and post-processed using the Bergen Echo Integrator (Foote *et al.*, 1991). Acoustic signal characteristics combined with trawl catches were used for reference when allocating acoustic densities to acoustic species categories. The acoustic density values were stored by species in nautical area scattering coefficient (NASC) units (MacLennan *et al.*, 2002) in a database with a horizontal resolution of 1 nautical mile and a vertical resolution of 10 m starting at the surface. The surface-referred channels were then converted to bottom-referred channels with a 10-m resolution (except the first 10 m

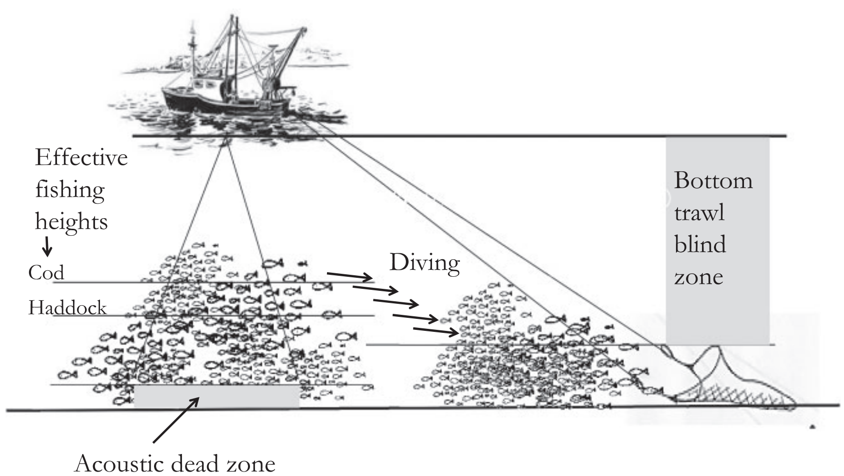

Figure 1. Illustration of simultaneous acoustic monitoring and bottom-trawl sampling in two species scenarios. Note that acoustic data are collected directly under the survey vessel, while the bottom trawl catches fish some distance behind the vessel. Vertical herding occurs in the time between vessel passing over the school of fish and trawl catching the same school.

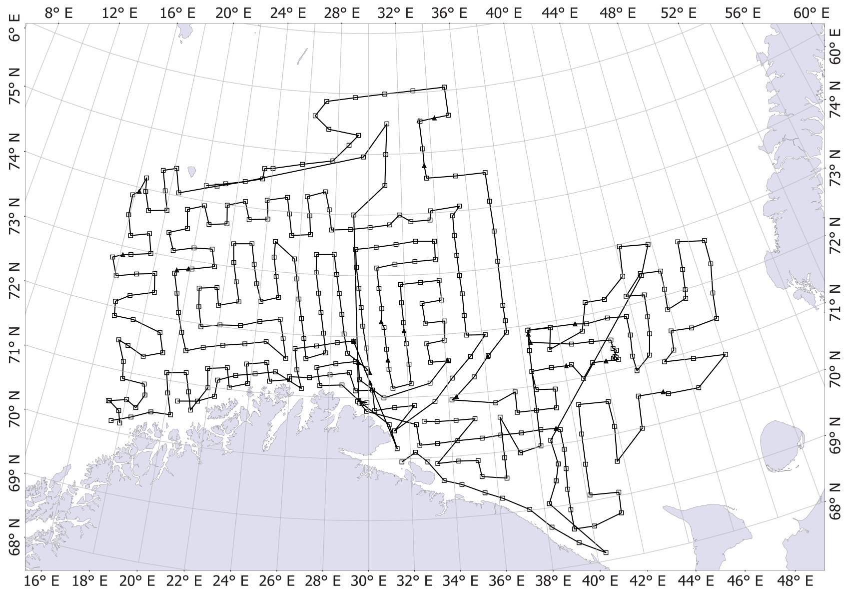

Figure 2. Survey tracks, bottom-trawl stations (squares), and pelagic-trawl stations (triangles) from the Barents Sea winter survey 2001.

from the bottom which had a resolution of 1 m), in accordance with the methods described by Hjellvik *et al.* (2003).

Conversion of catch rates to theoretical NASC

Biological samples used to describe the acoustic NASC values were taken from predetermined bottom-trawl stations. The entire catch or a representative subsample was measured for length (1-cm scale), and catch rates were converted to the acoustic NASC values using the following transformation of bottom-trawl catches into theoretical NASC values, s_A^{catch}(Hjellvik *et al.*, 2003).

$$s_A^{\text{catch}} = \sum \frac{C_L \times \sigma_L}{d \times w_L} \quad (1)$$

where L is the fish length in cm (grouped in 1-cm bins), σ_L is the mean backscattering cross-section for length group L ($\sigma_L = 4\pi 10^{(TS/10)}$ with the target strength calculated as $TS = 20 \log_{10} L$–68), C_L is the catch of length group L, w_L is the effective fishing width for length group L, and d is the towed distance (see details in Aglen, 1996).

Predictor variables

Kotwicki *et al.* (2013) showed that predictions of fish abundance in the ADZ can be improved by incorporating fish habitat/environmental information. We, therefore, tested the effect of several environmental variables collected during the survey on the ADZ correction. Fish fork length, bottom depth, water temperature (bottom and surface), salinity, wind, and sun altitude were the predictors available for the study (Table 1). Hydrographic data (temperature and salinity) were collected at every fixed bottom-trawl station using a CTD probe, bottom depth was measured by the echosounder, wind conditions were logged for each station, and sun altitude was calculated based on geographical position, date, and time of day.

Model building

Data processing

Each datapoint collected in this study contained information on acoustic NASC value, bottom-trawl catch by species (converted to bottom-trawl equivalent NASC values) and both biological and environmental information.

Table 1. Biotic and abiotic variables used in the study.

Abbreviations	Description	VIF[a]
BD	Bottom depth	1.32
ST	Surface temperature	2.69
BT	Bottom temperature	3.22
SAL	Salinity	2.02
FL	Fish fork length	1.4–1.58
WD	Wind	1.12
Sun	Sun altitude above the horizon expressed in terms of sine of the angle	1.29

[a]Variance inflation factor.

We removed all acoustic NASC values below 2 and all bottom-trawl equivalent NASC values below 2.5 and 2 for cod and haddock, respectively. These low values often represent noise in the acoustic backscatter that could come from many small organisms in the water column. Although these noises do not usually affect abundance estimates, because they only represent a small fraction of the backscatter data attributed to the detected fish species, sensitivity analysis was performed to examine their influence on model results (see detail in "Model diagnostics" section). This left a total of $n_{\text{obs}} = 643$ datapoints to use for the analysis.

All covariates in the dataset were standardized (subtracted the mean and divided by two standard deviations) before the analysis (Gelman, 2008) to enable comparison of their relative importance in the model.

Model structure

This study extended the concept of Kotwicki *et al.* (2013) to two species and modeled the relationship between simultaneously collected bottom-trawl catch and the acoustic backscatter signal for cod and haddock to account for their cooccurrence (Figure 3):

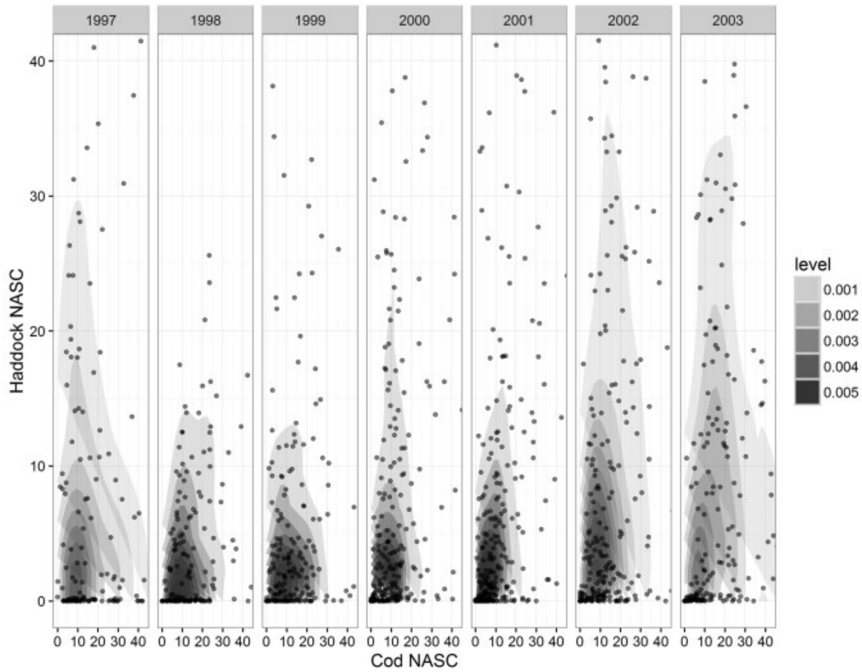

Figure 3. Bi-plot between bottom-trawl equivalent cod NASC and haddock NASC by year to examine potential correlation in NASC values between the two species. Dots represent the actual data, and the polygon shadings are the kernel density estimates (the darker, the denser the points).

$$\begin{bmatrix} \ln(s^{\text{catch}}_{A,\text{cod},j}) \\ \ln(s^{\text{catch}}_{A,\text{haddock},j}) \end{bmatrix} \sim \text{MVN}\left\{ \begin{bmatrix} \ln(\mu_{\text{cod},j}) \\ \ln(\mu_{\text{haddock},j}) \end{bmatrix}, \sum \right\} \quad (2)$$

where $s^{\text{catch}}_{A,i,j}$ is the bottom-trawl equivalent NASC for species i (cod or haddock) and observation j, $\mu_{i,j}$ is the prediction based on acoustic backscattering data, and $\boldsymbol{\Sigma}$ is the covariance matrix. Following Kotwicki *et al.* (2013), we assumed that the bottom-trawl equivalent NASC could be predicted using the acoustic backscatter signal detected above the ADZ (0.5 m from bottom) up to an EFH, an ADZ correction, and a density-dependent bottom-trawl efficiency parameter:

$$\mu_{i,j} = \left[\frac{1}{r_{q,i}\left(\sum_{0.5}^{\text{EFH}_i} s^{\text{acoustic}}_{A,i,j} + \text{ADZ}_{i,j} \right)} + \frac{1}{a_i} \right]^{-1} \quad (3)$$

where $r_{q,i}$ is the bias ratio between the bottom-trawl equivalent NASC and the acoustic NASC for species i, EFH_i is the effective fishing height (Hjellvik *et al.*, 2003), $s^{\text{acoustic}}_{A,i,j}$ is the acoustic NASC for species i and observation j, $\text{ADZ}_{i,j}$ is the ADZ correction, and a_i is the density-dependent parameter controlling the bottom-trawl efficiency. As $\Omega_{i,j} = r_{q,i}(\sum_{0.5}^{\text{EFH}_i} s^{\text{acoustic}}_{A,i,j} + \text{ADZ}_{i,j})$ (which represents fish densities) becomes higher than a_i, bottom-trawl efficiency decreases.

The ADZ correction was modelled as in Equation (C) and (D) from Kotwicki *et al.* (2013):

$$\text{ADZ}_{i,j} = e^{Xb_i} \sum\nolimits_{0.5}^{1} s^{\text{acoustic}}_{A,i,j} + e^{Xc_i} \quad (4)$$

where the correction depends on the acoustic backscatter signal observed right above the bottom (0.5–1 m from bottom) and some biotic and abiotic covariates X (listed in Table 1). X is the matrix of predictors and b_i and c_i are the vectors of parameters to be estimated for each species i. This model is flexible enough to model both linear and non-linear effects of covariates to the ADZ correction by including both linear and quadratic terms for covariates X.

Two different covariance structures were tested in this study.

(i) The base case assumed the same species covariance matrix for all years. ρ is the correlation coefficient between the species bottom-trawl equivalent NASC signal, σ_{cod} is the standard deviation in cod trawl NASC, and σ_{haddock} is the standard deviation in haddock trawl NASC:

$$\boldsymbol{\Sigma} = \begin{pmatrix} \sigma^2_{\text{cod}} & \rho\sigma_{\text{cod}}\sigma_{\text{haddock}} \\ \rho\sigma_{\text{cod}}\sigma_{\text{haddock}} & \sigma^2_{\text{haddock}} \end{pmatrix} \quad (5)$$

(ii) A variant of the model assumed a different covariance matrix by year to account for possible between-year difference in fish behaviour, age structure, and/or fishing conditions:

$$\boldsymbol{\Sigma} = \begin{bmatrix} \boldsymbol{\Sigma}_{1997} & 0 & \cdots & 0 \\ 0 & \boldsymbol{\Sigma}_{1998} & & \vdots \\ \vdots & & \ddots & 0 \\ 0 & \cdots & 0 & \boldsymbol{\Sigma}_{2003} \end{bmatrix} \quad (6)$$

Each year has its own covariance matrix [same structure as in Equation (5)] with different ρ, σ_{cod}, and $\sigma_{haddock}$.

Model fitting and selection

Model fitting was performed using the Automatic Differentiation Model Builder (Fournier *et al.*, 2012), and model selection was conducted as follows:

(i) Choose whether to model the density dependence for each species (four possible combinations) and whether to include a yearly covariance matrix (two options). This led to a total of eight model configurations.

(ii) For each model configuration, determine the optimal EFH_i values for each species i (as in Kotwicki *et al.*, 2013). The optimal values were the ones minimizing the negative log likelihood (LL) of the minimal model. The minimal model only estimated the bias ratio $r_{q,i}$ for species i, the density-dependent factor a_i (if present), and a diagonal covariance matrix (which assumed independence of species observations).

(iii) Using the optimal EFH_i values on the minimal model, conduct a stepwise forward model-selection approach using sample-size-corrected Akaike information criterion (AICc; Hurvich and Tsai, 1989) to select the best combination of covariates (i.e. b_i, c_i, ρ, σ_{cod}, and σ_{haddock}). All variables (Table 1) were included in the model-selection process as they did not show any strong sign of multicollinearity (VIF < 5) (O'Brien, 2007) and all covariates were tested up to their quadratic effects.

(iv) Repeat steps 2–3 for all eight types of models (four possible combinations of species' density dependence and two choices between a unique covariance matrix or annual covariance matrices).

(v) Select the best model across model configurations based on the one that minimized the AICc values.

Model diagnostics

Model diagnostics were performed using residuals analysis such as normal Q–Q plots, histograms of standardized residuals, and scatterplots of observed vs. predicted bottom-trawl equivalent NASC. In addition, the multispecies model estimates were compared against the single species estimates following the approach from Kotwicki *et al.* (2013). A tenfold cross validation (with 100 repetitions) was performed to compare the performance of the multispecies and the single-species model (Kohavi, 1995). Finally, a sensitivity analysis was performed to test the impact of data filtering on the multispecies model estimates. A stricter filter (based on visual inspection of the raw data distribution) was applied to remove more extreme values from the analysis: acoustic NASC values lower than 2.2 and 2 for cod and haddock, respectively, were removed (compared with 2 and 2 for the base case); and bottom-trawl equivalent NASC below 2.7 and 2.2 for cod and haddock, respectively, were removed (compared with 2.5 and 2 for the base case). The sensitivity analysis case had a total of $n_{\text{obs}} = 626$ ($n_{\text{obs}} = 643$ for the base case).

Results

Best model results

Summary

Model diagnostics indicated that the assumption of the multivariate normal error was appropriate for the best multispecies model (Figure 4). The best model included a density-dependent bottom-trawl efficiency effect for cod, but not for haddock, and a variable annual species covariance matrix (Table 2). Models that assumed observation independence between the two species showed a poorer fit in general (higher ΔAICc value in Table 2). The EFH was estimated at 60 m for cod and 40 m for haddock above bottom (Figure 5). Moreover, an analysis of variance performed on the standardized residuals between vessels and species (including the vessel- and species-interaction effects) did not reject the null hypothesis that there was no vessel effect ($p = 0.14$ for the vessel effect and $p = 0.13$ for the vessel- and species-interaction effects). These results confirm that the form of the final model was appropriate.

Bias ratio, bottom-trawl efficiency, and species correlation in catch

The bias ratio between the bottom-trawl equivalent NASC and the acoustic NASC for cod is estimated at 0.38 and 0.47 for haddock (Table 3). Density-dependent bottom-trawl efficiency was estimated at 223.26 for cod and was not present for haddock (Table 3). Correlation in cod and haddock observations was generally low, between –0.01 and 0.40, among years and observation standard deviation changed annually, with haddock showing a larger variation than cod: (0.55, 0.82) vs. (0.51, 0.66) (Table 3).

The influence of environmental variables on species catch

Surface and bottom temperature were the most influential variables and showed a negative effect on cod catch rates (Figure 6a and b). There was, on average, a 90% (140%) increase in the cod catch compared with the average condition at the minimum observed bottom (surface) temperature, and a 27% (20%) decrease at the observed maximum bottom (surface) temperature (Figure 6a and b). Sun angle and salinity were the next most influential variables, with a positive effect on cod catch (Figure 6c and d). At the minimum observed values, the cod catch decreased, on average, by 31 and 24% for salinity and sun altitude, respectively, and increased by 18 and 27% at maximum observed values (Figure 6c and d). Fishing depth decreased the cod catch, with a 19% average increase in catch at the minimum observed depth, while catch decreased on average by 10% at the maximum depth (Figure 6e). Cod size and wind speed did not have any visible effect on the cod catch (Figure 6f and g). In general, the marginal effect plots did not show any large variability around the estimated effect of environmental variables (Figure 6a–g).

Surface temperature was the most influential variable on haddock catch and showed a negative effect (Figure 7a). There was an average of 275% increase in the haddock catch compared with the average condition at the minimum observed surface temperature (but the lower the temperature, the higher the uncertainty), and an average of 26% decrease at the observed maximum surface temperature (Figure 7a). When compared with cod, bottom temperature had an opposite (positive) effect on the haddock catch, with an average of 36% increase in catch at the maximum observed bottom temperature (with larger uncertainty with increasing temperature) (Figure 7b). Sun angle was the second most influential variable, with a positive effect on the haddock catch (Figure 7c). Here again, the confidence intervals around estimated effects were larger than with cod (Figures 6c vs. 7c). The haddock catch increased by an average of 70% under the maximum observed sun altitude, but decreased by 8% at the minimum value (Figure 7c). Fishing depth decreased the haddock catch as it did for cod (Figure 7d). There was an average of a 53% increase in catch at the minimum observed depth (with larger uncertainty at lower temperature) and a 20% decrease at the maximum depth (Figure 7d). Water salinity, wind speed, and fish size did not have much effect on the haddock catch (Figure 7e–g).

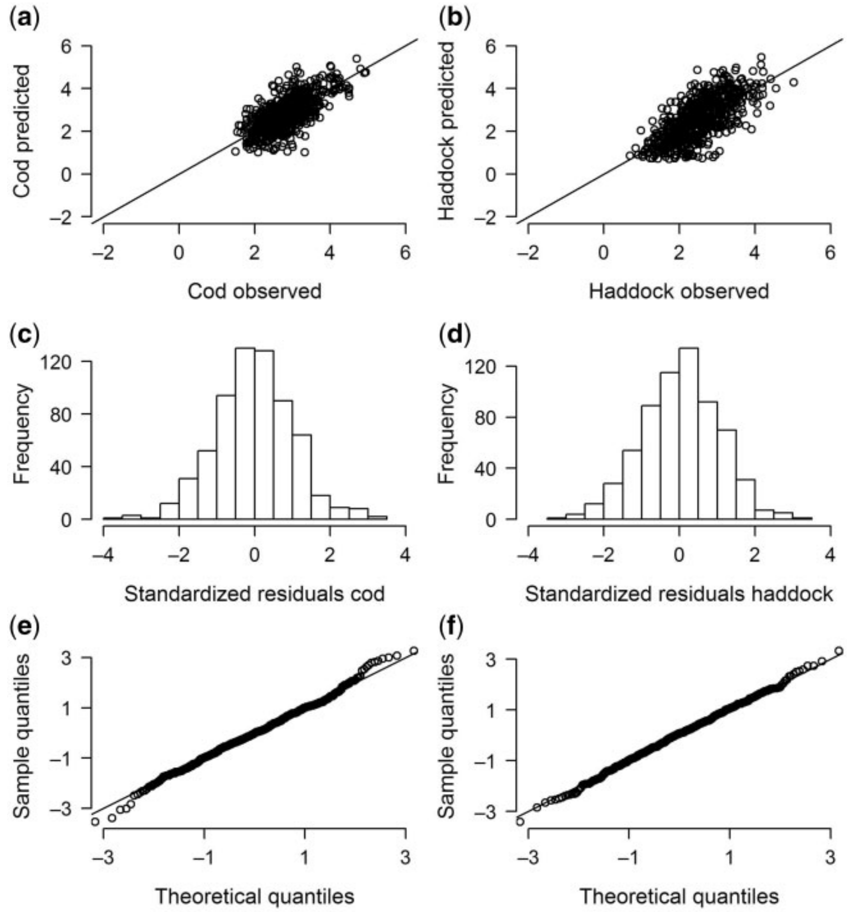

Figure 4. Diagnostics plots for the multispecies model fit (a) scatterplot of log(cod observed) vs. log(cod predicted); line represents $y = x$ relationship; (b) scatterplot of log(haddock observed) vs. log(haddock predicted); (c) histogram of standardized residuals for cod; (d) histogram of standardized residuals for haddock; (e) a Q–Q plot showing sample quantiles (obtained from standardized residuals) vs. theoretical quantiles of normal distribution for cod; (f) a Q–Q plot showing sample quantiles (obtained from standardized residuals) vs. theoretical quantiles of normal distribution for haddock.

Table 2. Model-selection results for each of the eight model configurations.

ID	Density dependence	Annual covariance	Number of parameters	ΔAICc
Model 1	None	No	23	54.12 (88.27)
Model 2	None	Yes	45	4.02 (63.31)
Model 3	Haddock only	No	26	54.49 (88.67)
Model 4	Haddock only	Yes	46	5.31 (64.16)
Model 5	Cod only	No	21	52.30 (86.84)
Model 6	Cod only	Yes	44	0 (62.54)
Model 7	Cod and haddock	No	22	52.45 (87.23)
Model 8	Cod and haddock	Yes	45	2.62 (63.37)

ΔAICc values in parenthesis are for each model configuration, but with diagonal covariance matrix (independence of species observation).

What influences the ADZ correction?

The same environmental variables were important for both cod and haddock density in the ADZ as for catches. For example, bottom and surface temperature were the most influential variables affecting cod density in the ADZ, but with a steeper effect than for catches (Figure 6). At the minimum bottom (and surface) temperatures, there was a 180% (and 290%) increase in cod density in the ADZ compared with a 90% (and 140%) increase in catch (Figure 6). Similarly, fishing depth, salinity, and sun angle had a stronger effect on cod density in the ADZ than for catches, but with larger uncertainty (Figure 6). Haddock density in the ADZ also showed a steeper response to all environmental variables compared with catches, and with greater uncertainty (Figure 7).

Comparison of multispecies model against single-species model

A tenfold cross validation indicated that the multispecies model had better predictive power than the single-species counterpart for cod and a slightly lower predictive power for haddock (Figure 8). Nonetheless, the best multispecies and individual species models produced similar parameter estimates; the absolute relative difference in the model estimates was 19.6% for cod and 13.4% for haddock on average (Table 3). For cod, the single-species model estimated a lower bottom-trawl efficiency than the multispecies counterpart: 188.58 vs. 223.26 (Table 3). The average ADZ correction was slightly higher [exp(3.16) vs. exp(2.92)] in the single-species model, and the same covariates were important in influencing the ADZ correction (with slight difference in estimates; Table 3). For cod, there was a slight difference in variables selected for ADZ correction between multispecies and single-species models (Table 3). Although bottom temperature, fish fork length, salinity, and surface temperature were important for the multispecies model, bottom depth, fish fork length, salinity, and surface temperature were important for the single-species model. For haddock, bias ratio was slightly higher than the multispecies estimate (0.54 vs. 0.47), and fewer covariates (in the ADZ correction) were selected in the single-species model (Table 3). Nonetheless, sun altitude was important in determining the ADZ correction in both models.

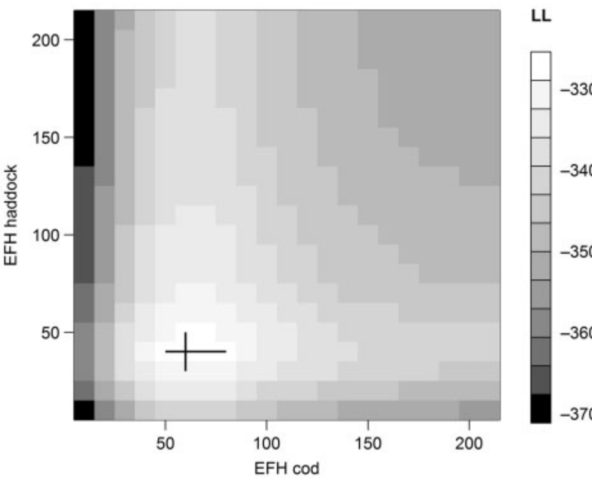

Figure 5. Plot of the log likelihood surface of the multispecies model for different combinations of EFH for both cod and haddock. The black lines represent the 95% confidence limit based on the likelihood ratio (i.e. max(log likelihood)−1.92).

Sensitivity to data filtering

Model estimates were not sensitive to the change in data filtering (Table 4); the absolute relative error rate between the two models was 4.9%. The same covariates were important in both models except $c(\mathrm{BT}_{\mathrm{haddock}})$, $c(\mathrm{SAL}_{\mathrm{haddock}})$, and $c(\mathrm{ST}_{\mathrm{haddock}})$, which were not kept in the model with stricter filtering.

Discussion

Synopsis and interpretation

In this study, we extended the original model of Kotwicki *et al.* (2013) to jointly estimate the ADZ correction, bias ratio, and density-dependent gear efficiency for multiple species by using simultaneously collected acoustic and bottom-trawl data. The model was able to improve its predictive ability compared with a single-species model for cod, but not for haddock. This was not surprising considering that the annual species bottom-trawl equivalent NASC correlation was generally low, with a maximum of 0.40 and lowest of –0.01.

Table 3. Parameter estimates—mean and s.d.—from the best multispecies model along with the single species best models using the approach from Kotwicki *et al.* (2013).

Parameter	Multispecies model		Cod		Haddock	
	Mean	s.d.	Mean	s.d.	Mean	s.d.
q_{cod}	0.38	0.05	0.34	0.05	NA	NA
q_{haddock}	0.47	0.04	NA	NA	0.54	0.04
a_{cod}	223.26	84.63	188.58	75.80	NA	NA
σ_{cod}	c(0.53, 0.56, 0.66, 0.54, 0.51, 0.58, 0.51)	c(0.05, 0.05, 0.06, 0.05, 0.03, 0.03, 0.03)	0.56	0.02	NA	NA
$\sigma_{\mathrm{haddock}}$	c(0.82, 0.55, 0.64, 0.57, 0.59, 0.67, 0.78)	c(0.07, 0.05, 0.05, 0.05, 0.04, 0.04, 0.05)	NA	NA	0.70	0.02
P	c(0.19, 0.40, 0.28, 0.32, 0.22, 0.20, −0.01)	c(0.09, 0.09, 0.08, 0.09, 0.06, 0.06, 0.06)	NA	NA	NA	NA
$b(\mathrm{BD}_{\mathrm{cod}})$	NA	NA	0.51	0.23	NA	NA
$b(\mathrm{BT}_{\mathrm{cod}})$	−0.80	0.34	NA	NA	NA	NA
$b(\mathrm{FL}_{\mathrm{cod}})$	0.04	0.00	0.04	0.00	NA	NA
$b(\mathrm{SAL}_{\mathrm{cod}})$	0.22	0.26	0.47	0.22	NA	NA
$b(\mathrm{ST}_{\mathrm{cod}})$	−1.03	0.26	−1.62	0.21	NA	NA
$b(\mathrm{FL}_{\mathrm{haddock}})$	0.02	0.01	NA	NA	NA	NA
$b(\mathrm{ST}_{\mathrm{haddock}})$	−1.42	0.25	NA	NA	−1.33	0.30
$b(\mathrm{Sun}_{\mathrm{haddock}})$	−0.90	0.47	NA	NA	−1.44	0.43
$c(\mathrm{intercept}_{\mathrm{cod}})$	2.92	0.19	3.16	0.21	NA	NA
$c(\mathrm{intercept}_{\mathrm{haddock}})$	2.71	0.29	NA	NA	2.14	0.16
$c(\mathrm{BD}_{\mathrm{cod}})$	−0.32	0.12	−0.48	0.12	NA	NA
$c(\mathrm{BT}_{\mathrm{cod}})$	−0.21	0.12	−0.30	0.10	NA	NA
$c(\mathrm{SAL}_{\mathrm{cod}})$	0.46	0.16	0.45	0.15	NA	NA
$c(\mathrm{Sun}_{\mathrm{cod}})$	0.82	0.13	0.79	0.12	NA	NA
$c(\mathrm{BD}_{\mathrm{haddock}})$	−0.62	0.12	NA	NA	−0.55	0.11
$c(\mathrm{BT}_{\mathrm{haddock}})$	0.54	0.16	NA	NA	NA	NA
$c(\mathrm{FL}_{\mathrm{haddock}})$	−0.02	0.01	NA	NA	NA	NA
$c(\mathrm{SAL}_{\mathrm{haddock}})$	0.30	0.14	NA	NA	NA	NA
$c(\mathrm{ST}_{\mathrm{haddock}})$	−0.35	0.16	NA	NA	NA	NA
$c(\mathrm{Sun}_{\mathrm{haddock}})$	1.33	0.15	NA	NA	1.42	0.17
$c(\mathrm{WD}_{\mathrm{haddock}})$	−0.20	0.09	NA	NA	NA	NA

NA indicates that the parameter was not present in the model.

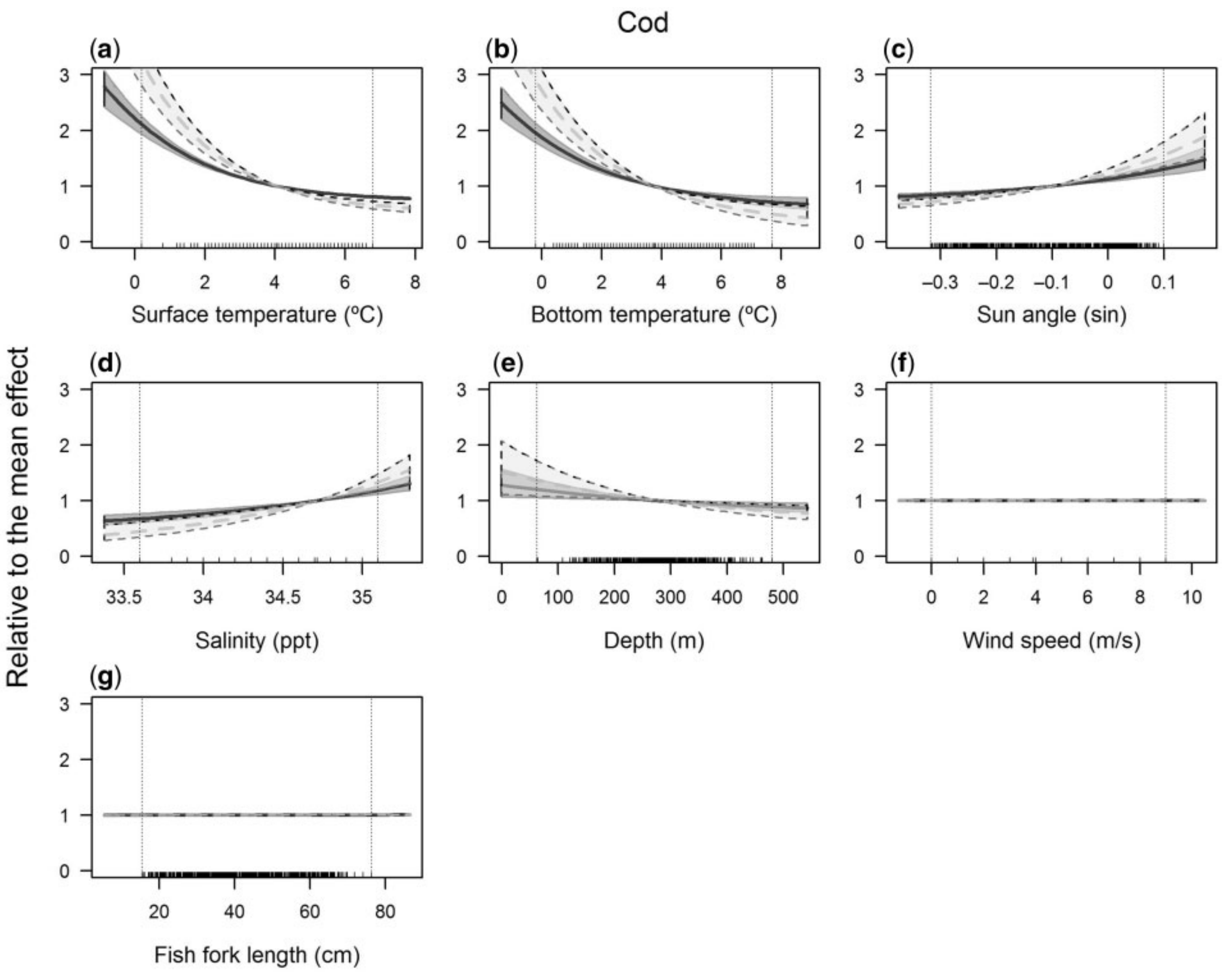

Figure 6. Marginal effect of biotic and abiotic variables on cod catch (solid line is the mean and the darker shading is the 95% CI) and densities in the ADZ (dashed line is the mean, and the lighter shading is the 95% CI). All effects are calculated based on parametric bootstrap (50 000 samples from multivariate normal distribution) of the estimated parameters. The plots are drawn relative to the mean observed biotic and abiotic conditions. The rug plot shows the distribution of observed biotic and abiotic variables, and the dotted vertical bars show the range of observations.

Nonetheless, the model indicated a year-to-year variation in model residual variance, with haddock showing larger variability than cod. This suggests that fish behaviour (in this case, its distribution throughout the water column, especially within the range that is effectively fished by the bottom-trawl gear) often changes (reflected here through annual variability) and is likely influenced by other factors not considered in this study, such as changes in the age structure of the cod and haddock populations or changes in the ecosystem like prey and predator field or unmeasured environmental variables (e.g. oxygen, turbidity). Moreover, the results also show that the underlying phenomena causing this annual fluctuation might differ between species and/or that species respond differently, as the residual variance changes asynchronously between species and correlation between catches also changes.

Effective fishing height

Many species show either some avoidance or herding behaviour in front of a passing trawl gear which affects the effective trawl fishing height and volume. For example, various flatfish species showed some strong sign of herding behaviour along the trawl sweep (Bryan *et al.*, 2014). Similarly, Alaska pollock (*Theragra chalcogramma*) (Kotwicki *et al.*, 2013), Atlantic cod (Ona and Godø, 1990; Handegard and Tjøstheim, 2005, 2009) and haddock (Handegard and Tjøstheim, 2009) have been seen to dive in response to an approaching trawl. In the present study, we estimated an EFH of 60 and 40 m for cod and haddock, respectively, which are similar to the estimates by Aglen (1996) and much higher than those by Handegard and Tjøstheim (2009). Handegard and Tjøstheim (2009) estimated the EFH through a combination of fish swimming trajectory modelling and estimation of capture probabilities (to the bottom trawl and echosounder). In their work, capture probability by the bottom trawl was stable at about 0.35 m up to 12 m off bottom and then decreased to almost zero at about 20 m. One potential reason explaining this discrepancy is that all of the water column above 10 m from the seabed was stored with 10-m resolution in this study (and also in Aglen, 1996), in accordance with the methods described by Hjellvik *et al.* (2003). Due to this difference in resolution, even if a theoretical EFH (with a better fit to data) existed at 12 m, we would have not been able to detect it.

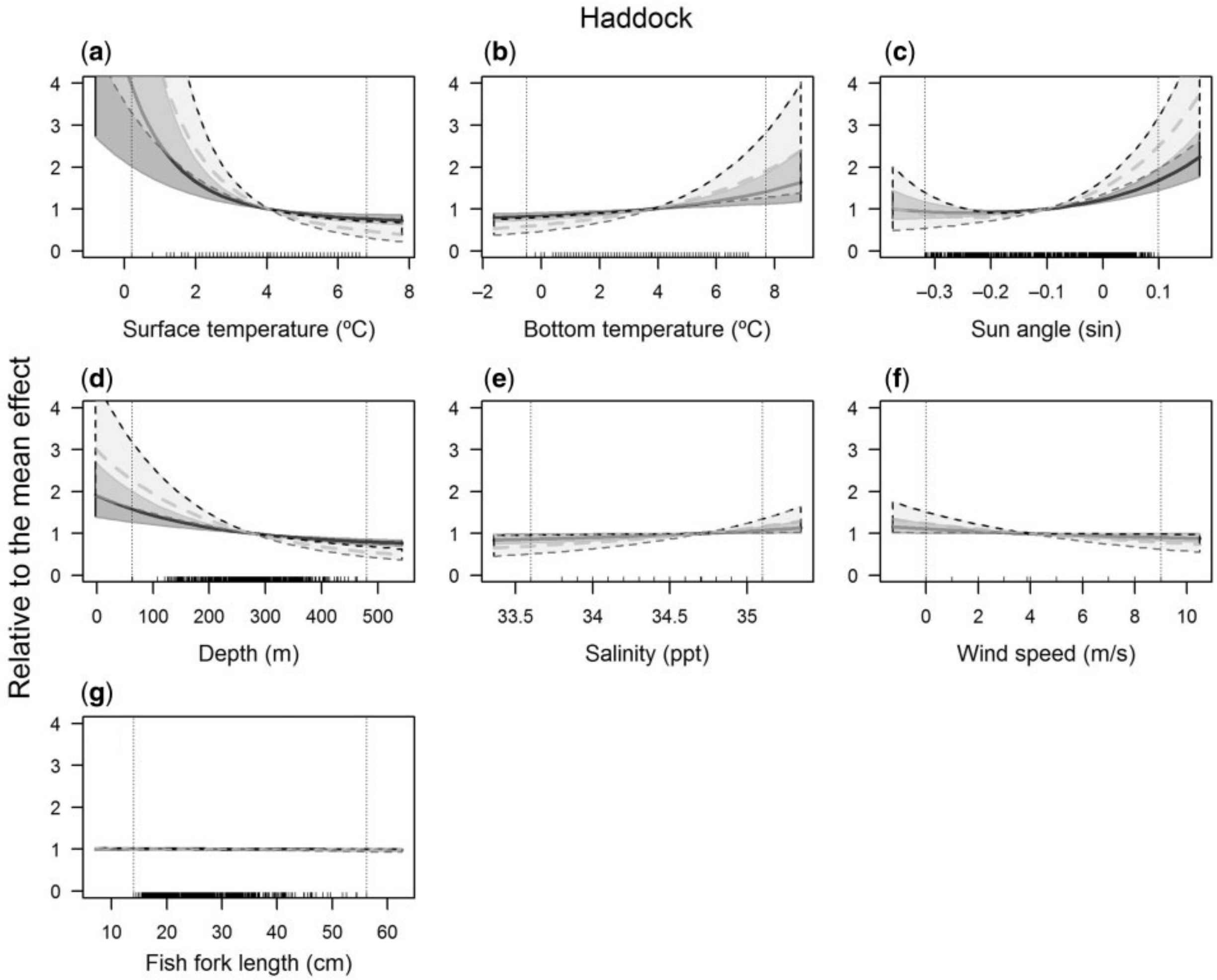

Figure 7. Marginal effect of biotic and abiotic variables on haddock catch (solid line is the mean and the darker shading is the 95% CI) and densities in the ADZ (dashed line is the mean, and the lighter shading is the 95% CI). All effects are calculated based on parametric bootstrap (50 000 samples from multivariate normal distribution) of the estimated parameters. The plots are drawn relative to the mean observed biotic and abiotic conditions. The rug plot shows the distribution of observed biotic and abiotic variables, and the dotted vertical bars show the range of observations.

Bias ratio

Bias ratio is an important parameter because it represents a ratio of all density-independent biases between bottom trawl and acoustic data (Kotwicki *et al.*, 2017). Bias ratio is used in our models to scale bottom-trawl equivalent NASC and the acoustic NASC. Therefore, it can be used to compare the acoustic and bottom-trawl data and to create a combined index of population abundance (Kotwicki *et al.*, 2017). The multispecies model estimated a bias ratio between the bottom trawl and acoustic-derived area scattering coefficient of 0.38 and 0.47 for cod and haddock, respectively. These values were similar to the probability of capture by the bottom trawl, given that fish were observed by the echosounder estimated by Handegard and Tjøstheim (2009) even though their analytic approach was different than ours. This further strengthens the credibility of our results.

Effect of environmental variables on catch and fish density in the ADZ

Overall, we found that fish density was changing more rapidly in the ADZ, due to environmental conditions, than did catch. This suggests that fish concentration on the seabed (first meter from the bottom) changes more rapidly than in the rest of the water column (i.e. effectively fished by the trawl gear) when environmental conditions change. Moreover, this study corroborates the fact that cod and haddock density in the ADZ, like pollock (Kotwicki *et al.*, 2013), is rarely the same as in the layer just above the ADZ, and there are many environmental variables that affect their density.

Water temperature (surface and bottom) was the most influential factor for both cod and haddock catch and density in the ADZ. These two temperature parameters were included in this study as they did not show any sign of severe multicollinearity (VIF < 5; O'Brien, 2007). Moreover, these two parameters are decoupled in the Barents Sea as temperature profile changes depending on geographic location and climate condition (Rudels *et al.*, 1991; Hjelmervik and Hjelmervik, 2013). In general, higher bottom and surface temperature led to decreasing catch and fish density in the ADZ. Some possible explanation is that fish are more actively swimming under warmer conditions (He *et al.*, 1991), therefore, being more widely distributed in the water column (perhaps above the EFH) or actively avoiding fishing gear. For both cod and haddock,

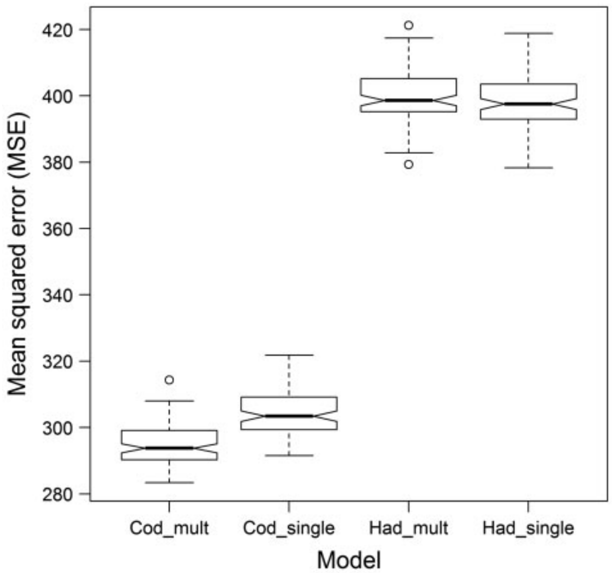

Figure 8. Boxplot of the mean squared prediction error based on 100 replicates of a tenfold cross-validation using the best multispecies model ("Cod_mult", "Had_mult") and the best single-species models ("Cod_single", "Had_single").

Table 4. Sensitivity of the model estimates to the data filtering.

Parameter	Base case	Stricter filtering
q_{cod}	0.38	0.38
$q_{haddock}$	0.47	0.48
a_{cod}	223.26	214.40
σ_{cod}	c(0.53, 0.56, 0.66, 0.54, 0.51, 0.58, 0.51)	c(0.54, 0.567,0.66, 0.54, 0.51, 0.59, 0.51)
$\sigma_{haddock}$	c(0.82, 0.55, 0.64, 0.57, 0.59, 0.67, 0.78)	c(0.79, 0.56, 0.62, 0.58, 0.58, 0.68, 0.77)
P	c(0.19, 0.40, 0.28, 0.32, 0.22, 0.20, −0.01)	c(0.20, 0.40, 0.31, 0.32, 0.23, 0.21, −0.03)
$b(BT_{cod})$	−0.80	−0.82
$b(FL_{cod})$	0.04	0.04
$b(SAL_{cod})$	0.22	0.23
$b(ST_{cod})$	−1.03	−0.99
$b(FL_{haddock})$	0.02	0.02
$b(ST_{haddock})$	−1.42	−1.51
$b(Sun_{haddock})$	−0.90	−0.73
c(intercept$_{cod}$)	2.92	2.80
c(intercept$_{haddock}$)	2.71	2.41
$c(BD_{cod})$	−0.32	−0.33
$c(BT_{cod})$	−0.21	−0.22
$c(SAL_{cod})$	0.46	0.44
$c(Sun_{cod})$	0.82	0.73
$c(BD_{haddock})$	−0.62	−0.63
$c(BT_{haddock})$	0.54	NA
$c(FL_{haddock})$	−0.02	−0.02
$c(SAL_{haddock})$	0.30	NA
$c(ST_{haddock})$	−0.35	NA
$c(Sun_{haddock})$	1.33	1.25
$c(WD_{haddock})$	−0.20	−0.19

the effect of surface temperature was exponential. At 2 °C, cod (haddock) density was almost twofold higher (2.5-fold higher) in the ADZ, compared with an average surface temperature of 4.1 °C, and catch increased by 45% (70%). The effect of bottom temperature on cod catch and density in the ADZ was similar to the surface temperature, but reduced, i.e. at 2 °C, fish density increased by only 55% in the ADZ and catch increased by 25% compared with an average bottom temperature of 3.8 °C. On the other hand, its effect was reversed for haddock, for which catch and density in the ADZ increased with bottom temperature (at 2 °C, fish densities decreased by 20% in the ADZ and catch decreased by 10%).

Increasing salinity increased cod (and slightly haddock) catch and density in the ADZ. This is somewhat surprising especially for cod which is euryhaline (Árnason *et al.*, 2013). However, Hedger *et al.* (2004) showed that cod and haddock abundance increased with salinity within a similar range observed in this study. Therefore, the increase in catch and density in ADZ could simply reflect an increase in underlying abundance at the bottom (at least up to the EFH) when salinity is higher.

Increase in bottom depth lead to a decrease in both cod and haddock catch and density in the ADZ. This is not a surprising result for haddock as they are generally more abundant in the shallow area (Hedger *et al.*, 2004). However, cod are more abundant in the deeper area (Hedger *et al.*, 2004), while it is also possible that they are more spread out in the water column. Nonetheless, the effect of fishing depth on cod catch and density in the ADZ was generally low as changes were within 30% of the average condition, and there was a large confidence interval around the estimated effect.

Finally, increasing sun altitude (which means more light for fish), increased cod and haddock catch and density in the ADZ. This study confirms previous findings that light plays an important role in semi-pelagic fish vertical distribution and catch (Michalsen *et al.*, 1996; Kotwicki *et al.*, 2009). An interesting observation, however, is that the model predicted a tiny increase in haddock density and catch at the lowest sun altitude, i.e. night-time. Michalsen *et al.* (1996) observed two peaks in the descending time each day for cod and haddock (i.e. when they are most abundant near bottom). One peak was during midday when light was at its highest, but they also found another one shortly after midnight. One theory is that haddock might be following some of its prey (e.g. juvenile *Maurolicus muelleri*) who carry out some midnight diving (Staby *et al.*, 2011). Although this might be true, parameter estimates were also quite uncertain; hence, this observation should be interpreted with care.

Trawl efficiency

Density-dependent trawl efficiency is a serious problem because it can lead to hyperstable survey (bottom trawl) indices of abundance, as pointed out by Kotwicki *et al.* (2014). Hyperstability means that fish abundance looks less variable than what it actually is and can, therefore, lead to an overoptimistic view of a declining stock and can lead to a major failure in fisheries management (Hilborn and Walters, 1992). The multispecies model suggested that cod has a density-dependent bottom-trawl efficiency, with trawl efficiency decreasing with increasing density (Figure 9). These findings contradict those reported by Godø *et al.* (1999), who inferred that BT efficiency increased with increasing fish density. However, their study was limited to observations of fish behaviour in close proximity to the trawl opening, whereas we accounted for fish behaviour over the entire water column. Moreover, results similar to ours are known for other semipelagic species, such as capelin (*Mallotus villosus*; O'Driscoll *et al.*, 2002), Atlantic croaker (*Micropogonias undulatus*), white perch (*Morone americana*; Hoffman *et al.*, 2009), and walleye pollock (*T. chalcogramma*; Kotwicki *et al.*, 2013).

We expect the impact of the density-dependent efficiency on the cod stock assessments in the Barents Sea to be limited because 94% of the observations had a trawl efficiency above 90% (based on bootstrapped prediction of the trawl efficiency). This suggest that indices of population abundance for cod calculated solely based on Barents Sea bottom-trawl survey data are not overly affected by density-dependent efficiency. However, with ever-changing ocean conditions, we expect further changes to happen in species distribution and behaviour which might affect trawl efficiency in the future. Therefore, we advocate developing methods for correcting density-dependent efficiency of the bottom trawl and for combining acoustic and bottom-trawl survey data to estimate population indices of abundance.

Future considerations

In recent years, many new approaches to jointly model multispecies distribution have been developed. Among others, there is the latent variable approach (a modelling approach that makes use of variables that are not directly observed in the study, and in the context of the joint multispecies distribution model, it is also used to reduce dimensionality) of Ovaskainen *et al.* (2016), Thorson *et al.* (2016), and Warton *et al.* (2016). In this study, only two species were examined, so the latent variable approach was not necessary. However, future studies aiming at expanding the number of species using this approach should try implementing the latent variable approach as it significantly reduces the number of parameters to estimate without losing too much of its interpretability. Moreover, there has recently been a surge of papers considering spatio-temporal dependence in the ecological literature (e.g. Ovaskainen *et al.*, 2016; Thorson *et al.*, 2016). One could have potentially included a spatial dependence term in this study, but there was not any strong sign of spatial autocorrelation in the model residuals (see Supplementary Material). Finally, future acoustic surveys should consider processing (if feasible) the acoustic data in higher resolution both horizontally (e.g. 0.1 nautical miles) and vertically (e.g. using a 1-m bin up to 60 m) and test their effects on study results. Nonetheless, several past studies have successfully investigated variation in fish vertical distribution using the current survey data (e.g. Ona and Godø, 1990; Aglen, 1996; Hjellvik *et al.*, 2003).

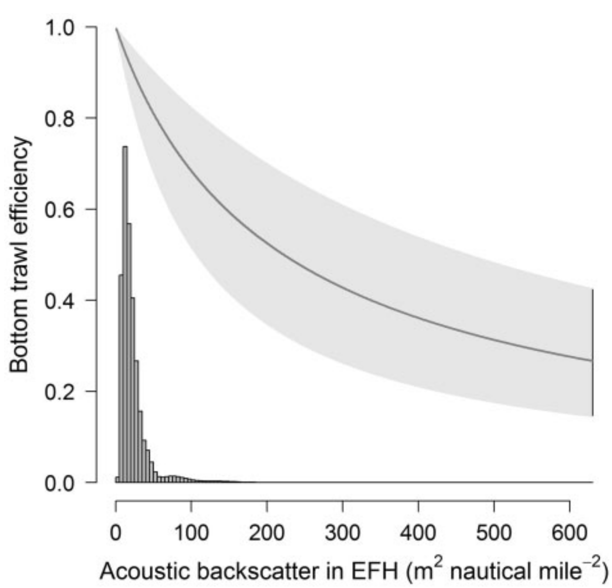

Figure 9. The average predicted bottom-trawl efficiency for cod (solid line), with its 95% prediction interval (light shading) as a function of $\Omega_{i,j} = q_i(\sum_{0.5}^{EFH_i} sa_{i,j} + ADZ_{i,j})$ (acoustic signal up to EFH). The histogram shows the predicted $\Omega_{i,j}$ values based on observed data. All predictions are area-based on parametric bootstrap (10 000 samples from multivariate normal distribution) of the estimated parameters.

Conclusion

In this study, we extended the original work of Kotwicki *et al.* (2013) to jointly estimate the acoustic dead-zone correction, the bias ratio, and the gear efficiency for multiple species by using simultaneously collected acoustic and bottom-trawl data. The model was applied to cod and haddock in the Barents Sea and demonstrated a better or similar performance to a single-species approach and strengthened the importance of environmental variables in modelling the ADZ correction. The proposed model could theoretically be useful in analysing data for any cooccurring species and could be applied to any kind of survey data where both acoustic and catch data are recorded.

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

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