On the target strength of Baltic clupeids

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The acoustic backscattering of Baltic clupeids, herring and sprat, is explored to improve biomass estimation of these ecologically and commercially important species. Modelling approaches that account for the complexity of fish morphology are used to compute the mean backscattering cross section. The input data for modelling are based on X-ray radiographs of Baltic herring and sprat. The backscatter sensitivity to fish morphology and to other biological (fat content), acoustic (frequency), behavioural (orientation pattern), and environmental (depth and salinity) parameters is also analysed. The effect of various parameters on the TS–*L* relationship of Baltic clupeids is studied, and the possibility of using the same TS–*L* relationships for Baltic herring and sprat is discussed. The results improve the understanding of the spatial and temporal variability of the measured target strength of clupeids in the Baltic Sea.

Keywords: Baltic herring, Baltic sprat, fat content, salinity, swimbladder, target strength.

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Introduction

Reliable assessment of fish populations is a basic prerequisite to the sustainable management of marine fisheries. Acoustic surveys efficiently quantify the abundance and distribution of fish stocks (Simmonds and MacLennan, 2005). Echo intensities of detected fish schools are integrated and converted into fish numbers using species-specific, target-strength (TS) dependencies on fish length (*L*), called TS–*L* relationships. The TS quantifies the sound-backscattering potential and acoustic-survey estimates are consequently exceedingly dependent on accurate estimates of fish TS.

A gas-filled swimbladder, if present, is responsible for 90–95% of the total acoustic backscatter by fish (Foote, 1980). Most physostomous fish, including herring (*Clupea harengus*) and sprat (*Sprattus sprattus*), do not have a gas gland that allows them to alter the amount of gas in the swimbladder. The volume of their swimbladders will decrease with increasing pressure at depth according to Boyle's law, causing an associated decrease in TS with increasing water depth (Ona, 1990; Gorska and Ona, 2003a, b; Ona, 2003). As well as pressure-dependent swimbladder behaviour, other factors that may affect TS are the acoustic operating frequency and fish orientation (Nakken and Olsen, 1977; Foote, 1985). In some cases, the physical environment may influence the physiology and morphology of a fish, leading to intraspecies differences in swimbladder size. For example, the TS found for Baltic herring was 3–7 dB higher than for herring in Northeast Atlantic waters (Rudstam *et al.*, 1988, 1999; Hansson, 2004; Didrikas and Hansson, 2004; Peltonen and Balk, 2005). The difference in TS was associated with specific environmental factors resulting in different morphological adaptations (Fässler *et al.*, 2008). In addition to the low water salinity of their environment, herring in the Baltic Sea have a much lower fat content than North Sea or Norwegian spring-spawning herring (Huse and Ona, 1996; Cardinale and Arrhenius, 2000; Ona *et al.*, 2001; Aidos *et al.*, 2002; Kiviranta *et al.*, 2003). Both factors contribute to the requirement for a larger swimbladder to gain neutral buoyancy.

Currently, acoustic stock assessment for the commercially and ecologically important Baltic clupeids, herring and sprat, use the same TS–*L* relationship as that developed for North Sea herring (i.e. $TS = 20 \log_{10} L - 71.2$ dB, with *L* in cm; ICES, 1983). However, recent *in situ* measurements suggest that both herring and sprat may have higher TS values than those currently used (Rudstam *et al.*, 1988, 1999; Didrikas and Hansson, 2004; Didrikas, 2005; Peltonen and Balk, 2005). Fässler *et al.* (2008) demonstrated why the TS–*L* relationship developed for North Sea herring is not accurate for Baltic Sea herring. However, which TS–*L* relationship is reasonable to use for biomass assessment of clupeids in the Baltic Sea remains an open question. *In situ* measurements demonstrated strong variability in Baltic clupeid TS in different regions and seasons with up to an 8 dB difference (Lassen and Stæhr, 1985; Rudstam *et al.*, 1988, 1999; Didrikas and Hansson, 2004; Didrikas, 2005; Peltonen and Balk, 2005; Kasatkina, 2007). As potential reasons for observed variability in TS, Peltonen and Balk (2005) suggested: (i) spatial and temporal biological differences between herring stocks occupying various parts of the Baltic Sea, and (ii) differences in data collection and analysis methods between various studies. Some authors analysed sprat and herring data separately (Peltonen and Balk, 2005; Kasatkina, 2007), whereas others (Didrikas and Hansson, 2004; Didrikas, 2005) did not distinguish between herring and sprat when analysing *in situ* TS of mixed aggregations. Kasatkina (2007) measured *in situ* TS of single-species aggregations of Baltic herring and sprat, and demonstrated that these two species have distinct TS–*L* relationships.

The objective of the present study is to improve the understanding of the measured TS variability of Baltic clupeids.

We analysed (i) the sensitivity of TS to important biological, behavioural, environmental, and acoustic parameters, and (ii) the effects of using *in situ* TS data from mixed sprat and herring aggregations on estimating TS–L relationships for herring.

We measured swimbladder and fish–body dimensions of herring and sprat caught during the 2002 Baltic International Acoustic Survey to ascertain any discrepancies in morphology between the two species. Backscattering models were used to estimate the mean TS of both species using measured swimbladder and body dimensions. Sensitivity analyses were done to examine direct (depth, frequency, and fish orientation) and indirect (water salinity and fish fat content) effects on the TS of Baltic herring and sprat. TS–L relationships based on the modelling results are proposed for both species.

Material and methods

Swimbladder and fish morphology

Herring and sprat samples were collected in October 2002 during the Swedish component of the Baltic International Acoustic Survey (BIAS) in the Baltic proper (ICES Subdivisions 25, 27, and 29). Live fish were selected from the catch and placed in a tank with seawater immediately after they were hauled on board. Fish still swimming upright after 2–5 min were carefully transferred into an anaesthetic bath (4–6‰ clove oil solution) with a small net. The fish were left in the anaesthetic bath for 5 min, then total length (TL, to the nearest 0.5 cm), maximum height and width (to the nearest 0.1 mm) were measured. Then the fish were frozen for later X-raying. Maximum dimensions (length, height, and width) of the swimbladder were measured using X-ray images of herring ($n = 25$; length: 13–24.5 cm) and sprat ($n = 21$; length: 7–13.5 cm) samples. The narrow extensions at the anterior and posterior ends of the swimbladder were excluded from the measurements.

TS modelling

The mean TS of herring and sprat was estimated using a combined backscatter model for fish body and swimbladder components. The output of the model is the expected backscattering cross section $\langle\sigma_{bs}\rangle$, averaged over a fish-orientation distribution, which was converted to TS according to MacLennan *et al*. (2002):

$$\mathrm{TS} = 10\log_{10}\langle\sigma_{bs}\rangle. \quad (1)$$

The fish body and the swimbladder were modelled as fluid- and gas-filled, elongated prolate spheroids, respectively. The total backscattering cross section of a fish (σ_{bs}) was then expressed by summing the components according to Gorska and Ona (2003a):

$$\sigma_{bs} = \sigma_{bs}^{sb}(z) + \sigma_{bs}^{b}, \quad (2)$$

where σ_{bs}^{b} and $\sigma_{bs}^{sb}(z)$ denote the backscattering cross section of the fish body and the swimbladder at depth (z), respectively. The Modal-Series-Based Deformed-Cylinder Model used to estimate the backscattering from the swimbladder and the fish body is described in Gorska and Ona (2003a).

Density– and sound–speed contrasts between material and surrounding seawater were 1.04 and 1.04 for the fish body and 0.00128 and 0.23 for the swimbladder, respectively. Mean values of TS of all fish samples were estimated using actual measured dimensions of the fish body and swimbladder to represent major and minor axes of the simplified scattering objects (prolate spheroids). Swimbladder volumes of the physostomous sprat and herring were assumed to decrease with depth according to Boyle's law (Ona, 1990; Fässler *et al.*, 2009). Swimbladder dimensions (width, a_z; length, b_z) contracted with increasing pressure at depth (z) according to

$$a_z = a_0\,(1 + z\rho g/P_0)^{-\alpha}, \quad (3)$$

and

$$b_z = b_0\,(1 + z\rho g/P_0)^{-\beta}, \quad (4)$$

where g (=9.81 m s^{-2}) denotes acceleration caused by gravity. Normal atmospheric pressure, $P_0 = 101\ 300$ N m^{-2}, and seawater density, $\rho = 1\ 005$ kg m^{-3}, were used. Boyle's law requires the compression factors α and β to behave according to $2\alpha + \beta = 1$. Recent findings (Gorska and Ona, 2003a; Fässler *et al.*, 2009) suggest that the herring swimbladder does not decrease in length with increasing depth. For that reason, the following values were assumed for both herring and sprat: $\alpha = 1/2$ and $\beta = 0$. The angle between swimbladder orientation and the snout-to-tail axis of the fish was assumed to be zero. Unless otherwise stated, a Gaussian tilt-angle distribution with a mean of 0° and s.d. of 5° (Gorska and Ona, 2003a) and acoustic frequency of 38 kHz was used for TS estimations.

For the sensitivity analysis of TS to water salinity and fat content of fish, a model describing the swimbladder volume as a function of these parameters was used. Both salinity and fat content have previously been demonstrated to affect swimbladder volume in herring indirectly (Ona, 1990; Fässler *et al.*, 2008). Salinity (S) in the Baltic Sea was assumed to be $1 \le S \le 10$ psu; herring fat contents range from 1.5 to 5% (Bignert *et al.*, 2007). The same values were assumed for sprat.

Results and discussion

Swimbladder and fish morphology

The swimbladder dimensions of Baltic herring and sprat differed significantly (Figure 1). While there were no differences in the ratio of swimbladder length to fish total length (Student's t-test: $t = -1.39$, d.f. = 44, $p = 0.172$; Figure 1a), Baltic herring had significantly larger ratios of swimbladder height to length (Student's t-test: $t = 5.21$, d.f. = 44, $p < 0.001$; Figure 1b) and swimbladder width to length (Student's t-test: $t = 8.28$, d.f. = 44, $p < 0.001$; Figure 1c). Including the effects of fat content and salinity caused only marginal differences in TS. For both herring and sprat, TS values varied by 0.2 dB over the range of analysed fat contents. Similarly, TS differed by 0.4 dB for both species over the salinity range analysed.

TS–L relationships for Baltic herring and sprat

Figure 2 shows the difference in the modelled TS–L relationships between herring and sprat at a frequency of 38 kHz. It was assumed that fish occupy the near-surface layer (depth $z = 0$ m). The different points in the figure represent the modelled mean TS calculated for each individual fish sample. Regression curves of TS vs. total L (in cm) of the form

$$\mathrm{TS} = m\ \log_{10} L + b, \quad (5)$$

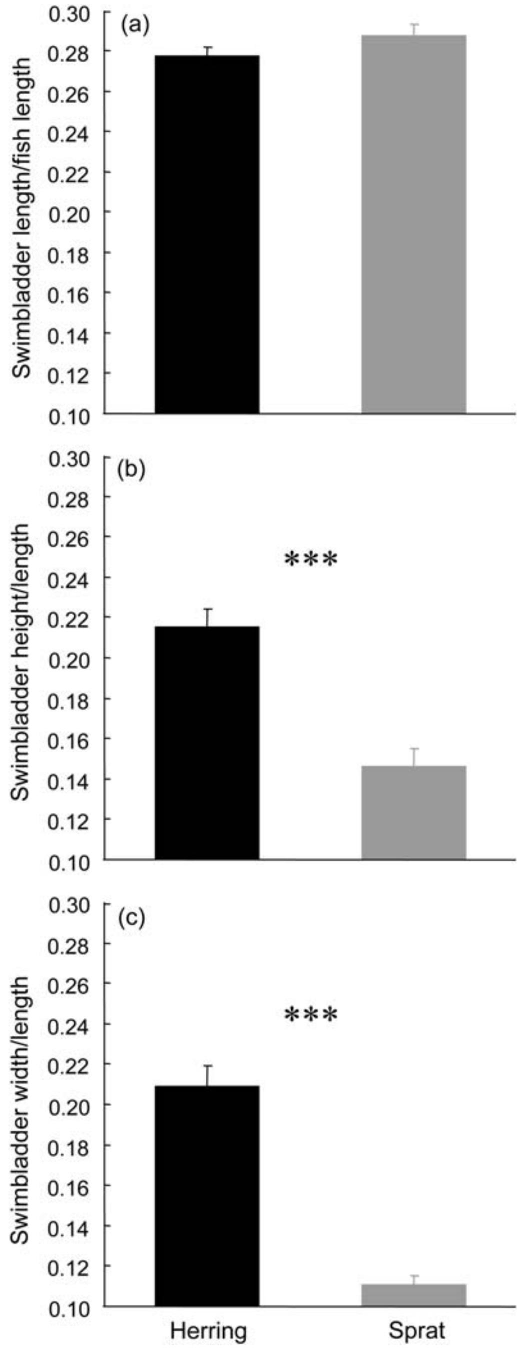

Figure 1. Differences in swimbladder morphology between Baltic herring and sprat. Probability value for differences between swimbladder-dimension ratios is given: $p < 0.001$.

were fitted to the modelled data for herring and sprat. The results were: $\mathrm{TS} = 20.08 \log_{10} L - 64.07$ (s.e. for $m = 2.77$; s.e. for $b = 3.52$) for herring, and $\mathrm{TS} = 27.50 \log L - 73.06$ (s.e. for $m = 2.06$; s.e. for $b = 2.19$) for sprat. Additionally, for each dataset, the commonly applied regression curve $\mathrm{TS} = 20 \log L + b_{20}$ was determined. The intercept b_{20} was estimated as −63.88 dB (s.e. = 0.19) and −65.08 dB (s.e. = 0.17) for herring and sprat, respectively. Figure 2 demonstrates that for fish shorter than 15 cm, the regression equation, Equation (5), gives up to a 4 dB higher TS for herring than that for sprat. If the relationship $\mathrm{TS} = 20 \log L - 63.88$ obtained for herring was applied to estimate sprat abundance, sprat biomass would be underestimated by approximately 40%. Conversely, if the relationship $\mathrm{TS} = 20 \log L - 65.08$ for sprat were used in herring abundance estimation, it would result in an overestimation of herring biomass by the same percentage. Note that sprat samples used in this study cover the typically observed length range of sprat in the Baltic Sea (ca. 6–15 cm). However, this was not the case for the herring samples, because lengths of Baltic herring normally range between approximately 9 and 25 cm (Fässler *et al.*, 2008). Small herring were consequently not sufficiently represented in the dataset. To verify whether Baltic herring of lengths <15 cm might display the same TS–L relationship as sprat, as suggested by Kasatkina (2007), more herring samples covering the same length range as sprat would have been necessary. Nonetheless, based on the results of the present study, the TS–L relationship derived for herring of lengths >15 cm must not be used for abundance estimation of sprat, or vice versa.

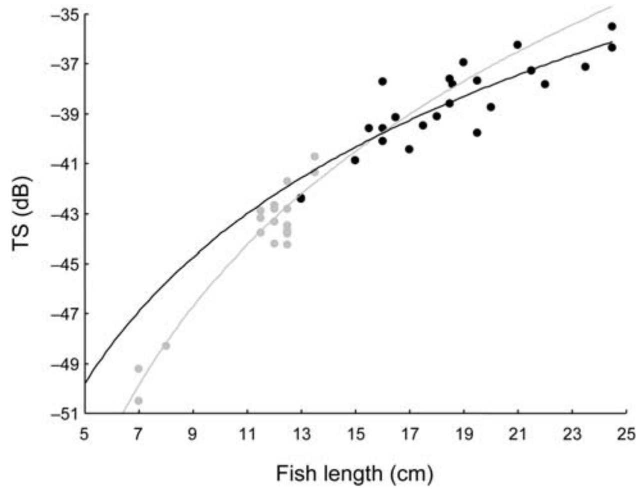

Figure 2. Modelled near-surface TS for Baltic herring (black) and sprat (grey) at 38 kHz, based on the measured swimbladder morphology.

Observed differences in TS between herring larger than 15 cm and sprat can be explained by the different morphologies of these two species. As demonstrated in Figure 1, the width and height of a Baltic herring swimbladder are on average larger than those of a sprat swimbladder for fish of the same length. This means that the insonified swimbladder volume and dorsal-aspect area, which control the backscatter of the fish at different ka_0, where k is the wave number and a_0 is the swimbladder radius defined in Equation (3), are larger for herring than for sprat. The result is a higher TS for herring than for sprat of the same length. The steep slope of the regression line for the modelled TS of Baltic sprat may further suggest that the $20 - \log L$ dependence of TS does not hold for this species (see McClatchie *et al.*, 1996). Observed differences in swimbladder-growth pattern between the herring and sprat samples (Figure 1) would imply that either a shape correction (e.g. McClatchie *et al.*, 2003) or a different TS–L relationship for each species is necessary.

An evaluation of the difference between the two regression curves may explain the large variability (up to 8 dB) of herring TS measured in different parts of the Baltic Sea and in different seasons (Lassen and Stæhr, 1985; Rudstam *et al.*, 1988, 1999; Didrikas and Hansson, 2004; Didrikas, 2005; Peltonen and Balk, 2005; Kasatkina, 2007). As mentioned earlier, *in situ* TS data of Baltic herring and sprat gathered so far were collected and processed in different ways. Some authors collected *in situ* TS data by insonifying single-species aggregations of sprat and herring (Peltonen and Balk, 2005; Kasatkina, 2007), whereas others (Didrikas and Hansson, 2004; Didrikas, 2005) made no distinction between those two species and insonified mixed-species aggregations. Kasatkina (2007) investigated the effects of treating herring and sprat in the Baltic Sea as "acoustically identical", and suggested that care should be taken when using a TS–L relationship obtained for one species in the abundance estimation of other or mixed aggregations of clupeids. Parameters of TS–L relationships for these two species of fish can depend on the length range observed (Kasatkina, 2007). Our study, based on morphological data, demonstrated a 1.2 dB difference between the intercept parameter (b_{20}) of the TS–L relationships for Baltic herring and sprat. These results agree with the conclusions of Kasatkina (2007).

It must be emphasized that estimated intercepts (b_{20}) for both herring (−63.88 dB) and sprat (−65.08 dB) are higher than those

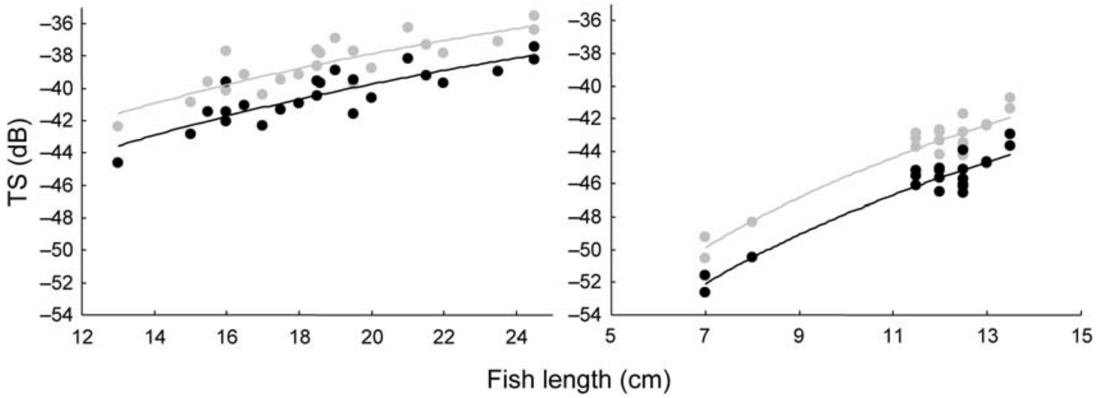

Figure 3. Effect of depth on modelled TS for Baltic herring (left panel) and sprat (right panel). Values were modelled at depth = 0 m (grey) and 100 m (black).

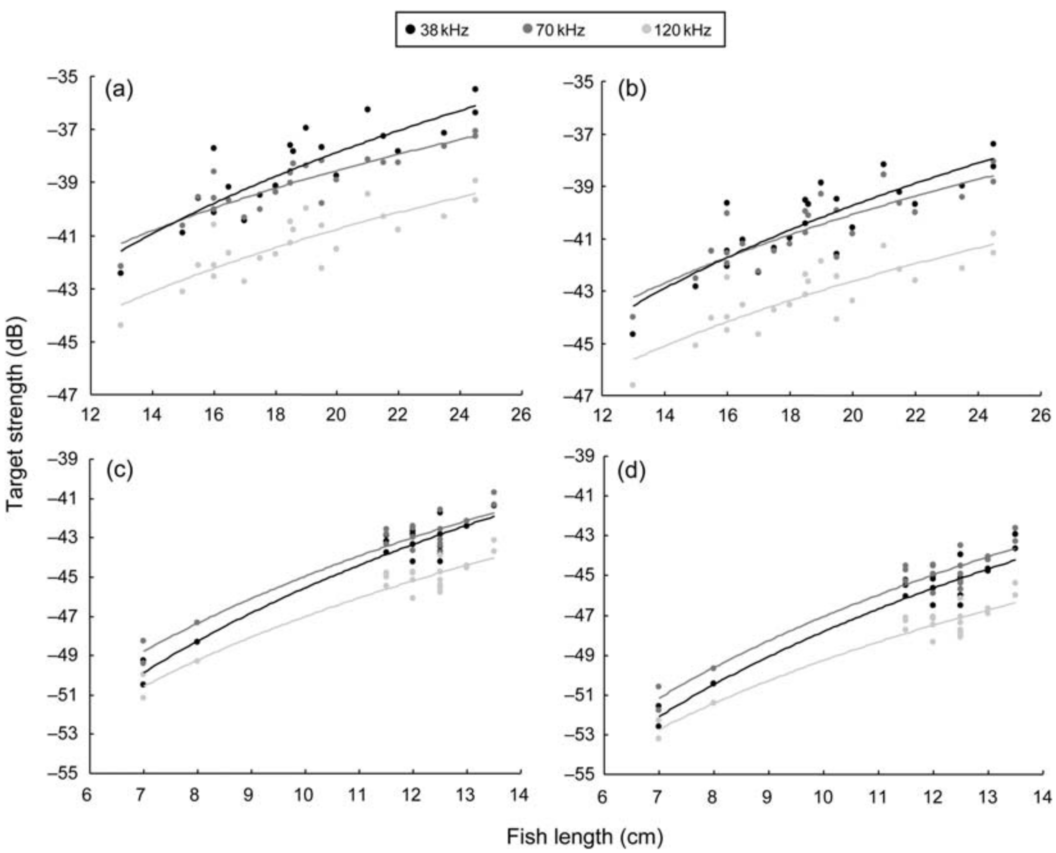

Figure 4. Effect of acoustic operating frequency on modelled TS for Baltic herring (upper panels: a and b) and sprat (lower panels: c and d). Values were calculated for depth = 0 m (left panels: a and c) and 100 m (right panels: b and d).

determined for North Sea herring (−71.2 dB; see ICES, 1982) and currently used in acoustic surveys of Baltic clupeids. These results agree with recent *in situ* TS measurements, suggesting that both Baltic sprat and herring may have higher TS values than those currently applied to assess those stocks (Didrikas and Hansson, 2004; Peltonen and Balk, 2005; Kasatkina, 2007).

Effect of depth on the TS–*L* relationships for Baltic herring and sprat

The results presented in ICES (2006) demonstrate that herring TS decreases with depth, and that the variation, i.e. the difference between maximum and minimum TS over the entire depth range from 0 to 100 m, depends on fish size. Ranges of values were 1.70–2.34 dB at 38 kHz, 1.37–2.23 dB at 70 kHz, and 0.52–1.93 dB at 120 kHz. To understand how fish depth affects the TS–*L* relationship, datasets for depths $z = 0$ and 100 m were calculated for both herring and sprat at 38 kHz. Regression curves using Equation (5) were generated for each dataset. Figure 3 demonstrates that there is an approximately 2 dB difference in TS between fish at 0 and 100 m depth, for both herring and sprat.

Effect of frequency on the TS–*L* relationships for Baltic herring and sprat

To understand the effect of acoustic frequency on herring and sprat TS, the TS–*L* relationship was fitted to the modelled data at the three frequencies (38, 70, and 120 kHz) commonly used in the acoustic-biomass assessment of Baltic clupeids. Figure 4 shows that, for both species, the slope (m) and intercept (b) of the TS–*L* relationship are sensitive to acoustic frequency over the considered depth range (0–100 m). The difference in TS between 38 and 120 kHz varies with *L*; up to 5 and 3 dB for herring and sprat, respectively. At 38 and 70 kHz, the difference in TS can be up to 2 dB for both species.

Figures 4a and 4b reveal only a slight sensitivity of the TS difference to the depth of herring, whereas for sprat (Figure 4c and d) a higher depth sensitivity is observed. For example, for 13.5 cm sprat, the difference in TS between 38 and 70 kHz is negligible for fish near the surface, whereas it is approximately 1 dB for fish at 100 m depth. Moreover, the difference in sprat TS between 38 and 120 kHz increases from 2 to approximately 3 dB with increasing depth. These results further suggest that *in situ* TS data collected for Baltic herring and sprat at 38 and 70 kHz might not represent the same TS–*L* relationship.

Effect of orientation on the TS–*L* relationships for Baltic herring and sprat

As in previous subsections, TS–*L* relationships using Equation (5) were fitted to the modelled TS data of Baltic sprat and herring with different standard deviations (s.d.) of the tilt-angle distribution: 5° and 10°. Figure 5 shows the sensitivity of the TS–*L* relationship with the fish orientation pattern at 38 kHz. For herring, the

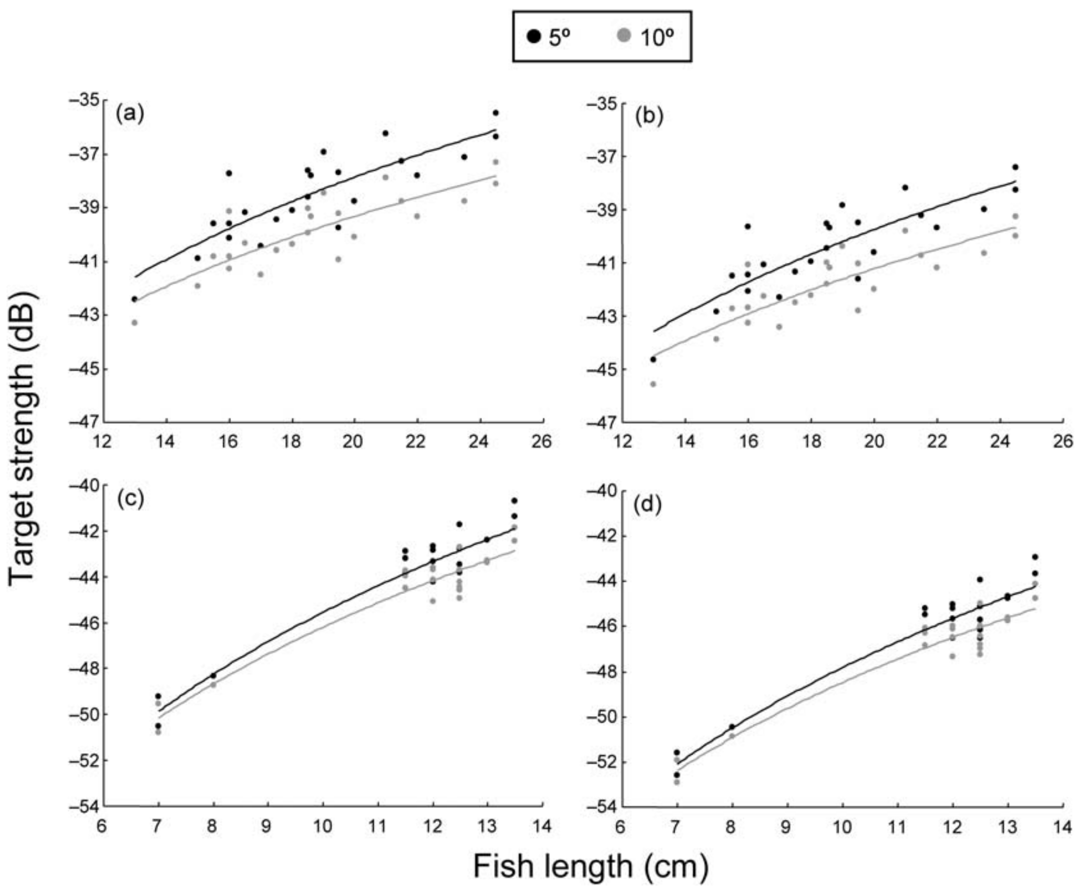

Figure 5. Effect of fish-orientation distribution (s.d. = 5° or 10°) on modelled TS for Baltic herring (upper panels: a and b) and sprat (lower panels: c and d). Values were calculated for depth = 0 m (left panels: a and c) and 100 m (right panels: b and d).

difference in TS between 5° and 10° tilt-angle s.d. increases with L from approximately 1 to 2 dB irrespective of depth of water. The same effect was observed for sprat, but in this case the TS differences for the smallest fish analysed were lower, from 0.3 to 1 dB.

Conclusions

Differences in backscattering properties between the economically and ecologically important Baltic clupeid species, herring and sprat, have been explained here based on differences in morphological proportions. The current analysis is useful to understand the observed variability in empirical TS–L relationships of Baltic herring. The difference in methodology, treating herring and sprat mixtures as one entity, or analysing the two species separately, is one of the major reasons for the observed variability in TS. We have demonstrated that it is important to use different TS–L relationships for Baltic herring and sprat to avoid significant errors when assessing their biomasses. The current analysis supports the results of recent *in situ* measurements suggesting a higher TS for Baltic clupeids than for North Sea or Norwegian spring-spawning herring. The intercepts (b_{20}) estimated for both Baltic herring (−63.88 dB) and sprat (−65.08 dB) are higher than that estimated for North Sea herring (−71.2 dB), which has been used routinely in acoustic surveys of Baltic clupeids.

The sensitivity analysis of modelled backscatter to biological, acoustic, and environmental parameters for Baltic herring and sprat demonstrated the following:

- The TS–L relationships are sensitive to the depth of the fish, the acoustic frequency, and fish orientation. The dependence on these parameters should be included in empirical TS–L relationships used in Baltic clupeid biomass estimation.
- The depth-dependence of the swimbladder volume, the difference in fish orientation patterns, and the different methods of TS data analysis can in part explain the shift of approximately 8 dB between the empirical TS–L relationships obtained by different authors.
- It must be emphasized that to obtain accurate TS–L relationships for Baltic clupeids, controlled TS measurements must be made. Additionally, data on environmental (water temperature, salinity, and depth of observed fish), morphological (fat content), and behavioural (orientation pattern) parameters should where possible be collected to improve the understanding of the observed variability of Baltic herring TS.
- Models should be used to examine backscattering characteristics of fish in different Baltic habitats, and models should be improved by providing appropriate new and more accurate biological information.

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