Size-dependent frequency response of sandeel schools

Espen Johnsen, Ronald Pedersen, and Egil Ona


Annual Norwegian sandeel surveys have been conducted in the North Sea since 2005 to measure the stock of lesser sandeel (Ammodytes marinus). Target identification is often a major challenge in acoustic surveys, and discriminant analyses have been used to separate echoes accurately from schools of herring, mackerel, and sandeel based on their acoustic-frequency responses measured at 18, 38, 120, and 200 kHz. At two fishing grounds during the 2008 survey, 332 schools were identified as sandeel, based on the characteristics of the acoustic signal, and validated by trawl samples. The schools consisted almost entirely of 1-year-old sandeels on one of the grounds, and 2-year-olds on the other. In this study, the potential of acoustic-frequency responses is advanced to classify the sizes of fish in them. A discriminant analysis using frequency responses as independent variables was able to differentiate between sandeel schools comprising 1- and 2-year-old fish (p < 0.001). Approximately 83% of the 2-year-old fish and 77% of the 1-year-old fish were classified correctly. The frequency responses at 18 and 38 kHz were the most important independent variables. Sandeel landings in the North Sea are normally dominated by 1- and 2-year-old sandeels in the first half of the year. This study revealed that these two age classes could be identified acoustically; a finding that may be important for acoustic surveys of sandeels and for management of the commercial sandeel fishery.

Keywords: discriminant analysis, multifrequency, North Sea, sandeel, size identification.

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Introduction

Sandeels (Ammodytidae) are small, laterally compressed, eel-like fish without a swimbladder that form large shoals above sandy substrata into which they burrow at night-time (Macer, 1966; Wright et al., 2000). Of five sandeel species in the North Sea, the lesser sandeel (Ammodytes marinus, sandeel hereafter) is by far the most abundant and is widely distributed in the shallow open-sea and coastal waters (Macer, 1966). From September to March, except during a short spawning period in December and January, sandeels burrow in well-oxygenated substrata of medium to coarse sand with low silt content (Macer, 1966; Winslade, 1974a; Wright et al., 2000). The geographical distribution of sandeel is patchy, because they are restricted to such habitats (Wright et al., 2000). The feeding season starts in spring, and during that season, the sandeels tend to emerge from the substratum at dawn. This behaviour is directly related to food availability, light intensity, and temperature (Winslade, 1974a, b, c), and the proportion of sandeels emerging from the sand may vary significantly between different days (Freeman et al., 2004).

Sandeels are a crucial component of the foodweb in the North Sea, because they provide an important part of the diet for many top predators, such as birds, seals, and predatory fish (Furness, 2002). They also support the largest fishery in the North Sea, with annual landings in the late 1990s exceeding one million tonnes (ICES, 2008a). However, the landings in 2003 and 2004 decreased to ~300 000 t and to ~170 000 t in 2005 (ICES, 2008a). The landings in the first half of each year were mainly 1- and 2-year-old fish. The catches in late summer and autumn had a very high fraction of zero-age sandeels, but since 2005, the sandeel fishery has been closed each year from 1 August (ICES, 2008a).

The 2008 assessment indicates that the spawning–stock biomass of sandeel in the central North Sea had decreased by >50% from 2002 to 2005 (ICES, 2008a). In addition to the financial loss to the fishing industry, the depletion could have large negative effects on sandeel predators, as exemplified by the concurrently reduced breeding success of kittiwakes at the Wee Bankie grounds southeast of Scotland (Rindorf et al., 2000).

An in-year monitoring programme using commercial catch per unit effort (cpue) has been in place for the past few years (ICES, 2008b). However, changes in catch efficiency and fishing-fleet strategy (Shepherd, 1988; Salthaug and Aanes, 2003) and patchiness and variation in the stock distribution (Ulltang, 1980) might violate the assumption of a linear relationship between commercial cpue and sandeel stock size. These problems, and the fact that there are no fishery-independent data in the assessment, are of great concern, and ICES (2008a, b) has emphatically requested the inception of an annual scientific survey to monitor the sandeel stock. Moreover, an improved understanding of the role of sandeel in the ecosystem demands direct and simultaneous observations of multispecies interactions.

Acoustic abundance-estimation methods (Simmonds and MacLennan, 2005) using vertical echosounders have been used to estimate many pelagic stocks since 1970 (Gjesæter et al., 1998). When carefully used, the method provides absolute abundance...
Acoustic identification of sandeel size

Estimates, as demonstrated for capelin (Mallotus villosus) stocks in the Barents Sea (Dommasnes and Røttingen, 1985; Tørseten et al., 1998), Iceland (Vílíjalmssson, 1994), and Newfoundland (Miller and Carscadden, 1990). The relatively large swimbladder in capelin gives strong and omnidirectional echoes, which usually permit easy interpretation of the acoustic recordings. Accurate acoustic species identification and quantification are considerably more challenging for fish without swimbladders, e.g. Atlantic mackerel (Scomber scombrus) and sandeel, because of their low backscattering strength (SB) at 38 and 120 kHz to identify sandeel schools (Hassel et al., 2004; Mosteiro et al., 2004; Mackinson et al., 2005), another investigation has established that combinations of SB at 18, 38, 120, and 200 kHz can effectively identify schools of sandeel vs. mackerel and herring (Mohammed, 2006). In general, backscatter from individuals of various species and sizes produces variation in frequency response from their aggregations (Pedersen et al., 2004). The objective of this study was to identify and exploit differences in frequency responses to classify sizes of sandeel in schools.

Methods

The data used in this study were collected with the RV “Johan Hjort” during a sandeel survey in April–May 2008 on the Vestbanken and Elbow Spit North fishing grounds in the North Sea (Figure 1). The seabed depth in the survey areas ranged from 30 to 100 m.

Acoustic data were recorded with an 18, 38, 120, and 200 kHz, echosounder system (Simrad EK60), which was calibrated before the survey using standard procedures (Foote et al., 1987). The transducers were mounted on a retractable keel in accordance with the settings suggested by Korneliussen et al. (2008). Pulse duration for all frequencies was 1.024 ms, and a ping repetition frequency of typically 4 Hz was chosen to maximize the number of echoes from small sandeel schools (see Table 1 for the other echosounder settings).

The acoustic survey began each morning after the sandeels emerged from the seabed and continued until ~20:00 UTC. The data were post-processed using the large-scale surveying system (LSSS; Korneliussen et al., 2006). The borders of the schools were delineated in the 200-kHz echogram, because the SB from sandeel is strongest and the reverberant noise from gas-bearing phytoplankton is lowest at this frequency. The nautical-area-scattering coefficient (SB; MacLennan et al., 2002) was measured

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (kHz)</td>
<td>18 38 120 200</td>
</tr>
<tr>
<td>Absorption coefficient (dB km⁻¹)</td>
<td>3.08 10.2 34.3 48.10</td>
</tr>
<tr>
<td>Pulse duration (ms)</td>
<td>1.024 1.024 1.024 1.024</td>
</tr>
<tr>
<td>Bandwidth (kHz)</td>
<td>1.57 2.43 3.03 3.09</td>
</tr>
<tr>
<td>Power (W)</td>
<td>2000 2000 250 120</td>
</tr>
<tr>
<td>Two-way beam angle (°)</td>
<td>-17.10 -20.60 -20.80 -20.70</td>
</tr>
<tr>
<td>TS transducer gain (dB)</td>
<td>23.17 27.03 24.11 26.69</td>
</tr>
<tr>
<td>Sₐ correction (dB)</td>
<td>-0.62 -0.61 -0.35 -0.33</td>
</tr>
<tr>
<td>Angle sensitivity alongship (°)</td>
<td>13.90 21.90 21.00 23.00</td>
</tr>
<tr>
<td>Angle sensitivity athwartship (°)</td>
<td>13.90 21.90 21.00 23.00</td>
</tr>
<tr>
<td>3 dB beam width alongship (°)</td>
<td>10.76 6.92 6.95 6.68</td>
</tr>
<tr>
<td>3 dB beam width athwartship (°)</td>
<td>10.84 6.93 7.13 6.60</td>
</tr>
<tr>
<td>Angle offset alongship (°)</td>
<td>-0.05 -0.06 0.12 -0.07</td>
</tr>
<tr>
<td>Angle offset athwartship (°)</td>
<td>0.02 0.12 -0.01 -0.02</td>
</tr>
</tbody>
</table>

The power settings are consistent with the recommendations in Korneliussen et al. (2008).
for each school at each frequency (e.g. Figure 2). The schools were classified to species based on the multifrequency $s_A$ and validated by trawl samples.

Three different trawls were used to catch sandeels: a Campelen 1800 bottom trawl; a Harstad pelagic trawl (originally a 16 × 16 fathom Capelin trawl with 5 mm mesh size in the codend) to catch schools in the pelagic zone and near the surface; and a large, commercial, Steintrawl sandeel trawl with a 700 m headline circumference to sample the entire water column. Trawls targeting acoustically identified sandeel schools were restricted to daytime.

In addition, a 0.23-m$^2$ van Veen grab and a modified scallop dredge were used by day and night to sample fish burrowed into the seabed. These stations were systematically located in areas with a high acoustic sandeel density.

Catches were sorted by species and weighed according to standard procedures (Mjanger et al., 2000). For small catches, the total length ($L_T$) of each sandeel was measured to the nearest 0.5 cm. For large catches, the $L_T$ of 100 sandeels was measured in a random subsample. For a subsample of these measured fish, otoliths were read to estimate their ages.

To compare the frequency responses of each school, the $s_A$ measured at $i$ frequencies ($f_i$) were normalized by the mean $s_A$ for the four values of $f_i$, resulting in proportional frequency responses $r(f_i)$:

$$r(f_i) = \frac{s_A(f_i)}{\sum_{i=1}^{4} s_A(f_i)}.$$

The distributions of $L_T$ differed significantly between the two fishing grounds, with the largest sandeel on Vestbanken (Figure 3). Based on this observation, all the schools detected at Vestbanken ($n = 234$) were classified as “large” sandeel, and all the schools detected at Elbow Spit North (98) were classified as “small”.

This observed difference in fish size was expected to result in a difference in their $r(f)$, as reported by Pedersen et al. (2004). The effectiveness of this categorization was examined with a discriminant analysis (Hubert and Van Driessen, 2004), using the “lda” function in the MASS (Venables and Ripley, 2002) R-package (R Development Core Team, 2008) with prior probabilities of class membership equal to 0.5 for each class, where $r(f)$ is the independent variable. To achieve a more normal distribution, the four $r(f)$ estimates were log-transformed:

$$R(f) = 10 \log(r(f)).$$

A Wilks’ lambda $F$-test was used to test the significance of the model and to examine the importance of each of the four $R(f)$ values to the classification. To study the importance of $s_A$ on the classification success rate, the analyses were repeated for schools with mean $s_A$ [i.e. the denominator in Equation (1)] above the 66th percentile and below the 33rd percentile.

**Results**

Sandeels dominated the catches on the two fishing grounds—only three herring and mackerel were caught. The mean $L_T$ at Elbow Spit North was 11.3 cm, and only 5% of the sandeels were larger.
than $L_T = 13.5$ cm. At Vestbanken, the mean $L_T$ was 16.2 cm and 13% were smaller than 13.5 cm. The age–length distribution of the sampled sandeels (Figure 4) clearly indicates that the sandeels from Vestbanken were mainly 2 years old, and the sandeels from Elbow Spit North were largely 1 year old. Data from the commercial fishery exhibited a similar difference in the length distributions of sandeels between the two fishing grounds. In addition, the landings from Elbow Spit North and Vestbanken were almost entirely 1- and 2-year-old sandeels, respectively (T. Johannessen, IMR, pers. comm.).

For both large and small sandeels, the $R(f)$ values were lowest at 18 kHz and were considerably higher at 38 kHz (Figure 5). For large sandeels, the $R(f)$ values were similar from 38 to 120 kHz, but decreased at 200 kHz. For small sandeels, the $R(f)$ values increased from 18 to 120 kHz, then decreased at 200 kHz.

The discriminant analysis distinguished between the large and small sandeels ($p < 0.001$): 83% of the large fish and 77% of the small fish were classified correctly (Table 2). Overall, 81% of the sandeel schools were correctly classified. $R(f)$ values at 18 and 38 kHz were the most important variables in classifying the dependent variables ($F = 60.8$ for 18 kHz; $F = 82.4$ for 38 kHz), and the $R(f)$ value at 200 kHz was the least important variable ($F = 13.6$). The mean $s_A$ from schools of large vs. small sandeels was not significantly different ($t$-test, $p = 0.08$) at a 5% significance level, but the overall classification success rate was markedly better for schools with higher mean $s_A$ (Table 2).

**Discussion**

The $R(f)$ values were the only parameters examined in the discriminant analyses, because preliminary results indicated that the metrics of school morphology did not provide additional information regarding the sizes of sandeel within a school. The classification success rate was higher for the small (83%) vs. the large (77%) sandeels. Although the mean $s_A$ values were not significantly different for these two groups, the classification success rate markedly increased for both categories when the analysis was limited to schools with high mean $s_A$ values.

A preliminary model of backscattering from sandeels, using a fluid cylinder with material properties equal to fish flesh, indicated that $R(f)$ values at the higher frequencies are very sensitive to changes in incidence angles resulting from fish behaviour (G. Pedersen, Christian Michelsen Research, pers. comm.). Changes in fish behaviour could change their $R(f)$ values at 120 and 200 kHz, possibly affecting the classification rate.

Some of the misclassifications in our analysis could be related to the assumption that sandeel sizes and ages are homogeneous within a fishing ground. In fact, not all sandeel schools within a fishing ground comprise one age group; therefore, a few of the “misclassifications” could have been correctly classified. Worse
still, some fish in each type of school might have been derived from more than one size group. Overall, however, the overlap in sizes between the two grounds was remarkably low, and the large number of correct classifications is encouraging.

The commonly applied technique of validating acoustic classifications with trawl samples (McClatchie et al., 2000) is generally not effective for sandeels. In the shallow water characteristic of the sandeel grounds, the sampling width of the echosounder beam is small compared with the width of the trawl. Therefore, there is a high probability of a mismatch between trawl catches and acoustic observations for small schools in proximity to each other (van der Kooij et al., 2008). Validation efforts during future surveys could include the use of underwater video and multiple-sample nets (Engås et al., 1997), in combination with the sonar tracking of schools.

**Conclusion**

There was a significant size-dependent difference in the normalized frequency response of schools comprising small, 1-year-old, and large, 2-year-old sandeels during a survey in 2008 on fishing grounds in the North Sea. This difference increased when the smallest schools were excluded from the analysis. Therefore, it seems feasible to use inverse methods to estimate the size of the sandeel, as is done for zooplankton (e.g. Pieper et al., 1990). In this way, not only could sandeel schools be identified acoustically, as reported by Mohammed (2006), but their age classes could also be established.

Large sandeels are most valuable, because of their higher oil content (ICES, 2008a, b). Consequently, these results could be useful for both fishery harvesters and managers (ICES, 2008a). Improvements to acoustic, age-structured monitoring of the fishing grounds should help ensure a sustainable harvest of the spawning component of the local stock.

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**Table 2.** Classification matrix of schools of "large" and "small" sandeels, using the log-transformed proportional frequency responses \( R(f) \) at 18, 38, 120, and 200 kHz as independent variables.

<table>
<thead>
<tr>
<th>Input data</th>
<th>Large (predicted)</th>
<th>Small (predicted)</th>
<th>% Correct</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>194</td>
<td>40</td>
<td>83</td>
</tr>
<tr>
<td>Large (actual)</td>
<td>23</td>
<td>75</td>
<td>77</td>
</tr>
<tr>
<td>Small (actual)</td>
<td>75</td>
<td>9</td>
<td>89</td>
</tr>
<tr>
<td>Total</td>
<td>92</td>
<td>14</td>
<td>66</td>
</tr>
<tr>
<td>High</td>
<td>2</td>
<td>27</td>
<td>93</td>
</tr>
<tr>
<td>Total</td>
<td>51</td>
<td>29</td>
<td>74</td>
</tr>
<tr>
<td>Low</td>
<td>52</td>
<td>20</td>
<td>72</td>
</tr>
</tbody>
</table>

*The discriminant analyses were performed with all schools (all): schools with mean \( s_A \) in the highest 66th percentile (high); and schools with mean \( s_A \) in the lowest 33rd percentile (low).*

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**References**


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