Acoustic mapping of pelagic fish distribution and abundance in relation to a seismic shooting area off the Norwegian west coast

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Abstract

In April 1999 seismic investigations started in an area off western Norway as part of an ordinary three-dimensional survey, using a vessel with two seismic sources, each of 20 air guns and 10 hydrophone streamers. The seismic sources, towed at a depth of 8 m, were alternatively fired every 25 m along 51 transects, each 51 525 m long, separated from adjacent transects by 500 m. The possible influence of this seismic activity on pelagic fish (herring, blue whiting and mesopelagic species) was investigated in two ways. First, the distribution and abundance within the seismic area and the surrounding waters up to 30–50 km away were mapped acoustically three times. In all three surveys the acoustic abundance of pelagic fish was higher outside than inside the seismic shooting area, indicating a long-term effect of the seismic activity. Secondly, the acoustic abundance was recorded directly prior to and after shooting along some of the seismic transects. In these comparisons no differences were found, indicating that the shooting had insignificant short-term scaring effects. However, both blue whiting and mesopelagic species were found in deeper waters in periods with shooting compared to periods without shooting, indicating that vertical movement rather than horizontal movement could be a short-term reaction to this noise.

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1. Introduction

In March 1999 the Norwegian Petroleum Directorate (NPD) received an application from PGS Exploration AS to conduct seismic investigations in an area entitled Ringhorne Dome off the Norwegian west coast (Fig. 1) during a period of approximately 9 weeks starting 3 April 1999. Investigations on the distribution of blue whiting and Norwegian spring spawning herring (Holst et al., 1998), suggested that these stocks would be present at high densities in the proposed area and period. Several millions of tonnes of Norwegian spring spawning herring were expected to migrate through the proposed area heading for the feeding area in the Norwegian Sea (Misund et al., 1998) after spawning on the Norwegian continental shelf (Slotte and Dommasnes, 1998). Engås et al. (1996) demonstrated that seismic shooting could have negative effects on local fish abundance and catch rates of cod and haddock at a distance over 30 km from the source. Similar reactions to the strong sound sources used were expected both for herring and blue whiting (Dalen and Knutsen, 1986), either having comparable or better hearing capabilities than cod. Fishery authorities and scientists were therefore concerned that the seismic shooting ultimately could lead
to changing of well-established feeding migration routes. Under such unfortunate circumstances proportions of the stock might be prohibited from areas with high prey densities.

Scientists from the Institute of Marine Research (IMR) advised that the fish distribution and density in relation to Ringhorne Dome should be investigated by means of an acoustic survey at the cost of the seismic company, if the seismic investigation was to be conducted at the indicated time period. This would also imply that the scientists involved in corporation with the Directorate of Fisheries (DoF) had the authority to stop the seismic shooting if high fish abundances, i.e. more than 225 000 t of herring (2.3% of the spawning stock), were recorded within the Ringhorne Dome or surrounding areas up to 30–50 km away. PGS agreed to these terms.

Given these circumstances the objectives of the acoustic investigations were twofold: (1) to map the pelagic fish distribution and abundance within Ringhorne Dome and the surrounding waters up to 30–50 km away; (2) to investigate whether or not the seismic activity had any effect on the fish distribution and abundance.

2. Materials and methods

2.1. Seismic shooting

The seismic shooting was conducted by the vessel “Ramform Vanguard” from 3 April at 11:25 (UTC) and throughout the entire study period with the exception of three major breaks (Fig. 2). The vessel used 2 air gun arrays, each of 20 air guns, and 10 hydrophone streamers. The air gun supply pressure was approximately 141 kg cm$^{-2}$ (2000 psi) and total chamber volume of each source was 50.71 (3090 in.$^{3}$). The two
sources, towed at a depth of 8 m, were alternatively fired every 25 m along 51 525 m long transects separated from adjacent transects by 500 m. Ringhorne Dome consisted of totally 51 transects.

2.2. Acoustic equipment

Acoustic mapping of the fish distribution and density was carried out from the vessel “Dr Nansen”, whose present shipowner was Tananger Offshore. “Dr Nansen” was until 1992 operated by IMR and used in studies of fish resources in developing countries in Africa, Asia and Central America. The vessel was equipped with a Simrad EK400 echo sounder and a “hull mounted” 38 kHz split beam transducer. For this particular experiment a Simrad EK500, 38 kHz echo sounder, connected to the Bergen Echo Integrator Postprocessing System (BEI) (Knudsen, 1990) was installed. Finally, the instruments were calibrated in accordance with standard practices (Foote et al., 1987).

2.3. Survey design

The distribution and abundance of pelagic fish within the seismic area and the surrounding waters up to 30–50 km away were mapped acoustically during three surveys entitled Survey 1–3 (Figs. 1 and 2). Prior to the onset of acoustic mapping with “Dr. Nansen” at 10 April, there was a break in the seismic shooting of almost 5 days. Ideally, the area should have been surveyed acoustically prior to the onset of seismic shooting and also during this break, but “Dr. Nansen” was simply not ready for use during these dates. In between Survey 2 and 3 acoustical mapping was carried out along some of the same transect lines as shot by “Ramform Vanguard”, both prior to and after seismic shooting. Such mapping was intended to give information on immediate or short-term fish reactions to the seismic shooting. Altogether the acoustical mapping could be carried out with only a few occasional breaks; when assisting “Ramform Vanguard” and when wind speeds above 12 m s\(^{-1}\) generated air bubbles in the water column and thus prevented accurate acoustic measurements (Dalen and Løvik, 1981; Ye and Ding, 1995).

2.4. Scrutinising acoustic data

The recorded area echo abundance, i.e. the nautical area backscattering coefficient (NASC), \(s_A\) (MacLennan et al., 2002), was interpreted and distributed to herring, blue whiting and mesopelagic fish. The data were stored with a resolution of 1 nmi on the horizontal scale and 10 m intervals on the vertical scale. “Dr Nansen” was not equipped for trawling, thus identification of acoustic recordings was impossible. Based on years of experience the different species were recognised from the target strength distribution as well as their spatial density and appearance (schooling, layers) in the water column. Given the uncertainty in the identification of species, the proportion of values assigned to herring and blue whiting and the coherent abundance and biomass estimates presented must be regarded as relatively rough.

2.5. Abundance estimation

Conversion of the area echo abundance to numerical fish quantities and biomass was achieved by using the adopted mean target strength, \(\langle TS \rangle\), to length.
L, relationships for herring (Eq. (1)) and blue whiting (Eq. (2)), as used in the standard assessment surveys (Foote, 1987):

\[ \langle TS \rangle (\text{dB}) = 20 \log L - 71.9 \]  
\[ \langle TS \rangle (\text{dB}) = 21.8 \log L - 72.8 \]  

The number of fish, \( N \), within a particular area (A) was computed in the standard manner:

\[ N = \langle s_A \rangle A (4\pi \langle \sigma_{bs} \rangle)^{-1} \]  

where \( \langle s_A \rangle \) is the mean NASC within the area, \( A \) the size of the area (nmi²), and \( \langle \sigma_{bs} \rangle \) the mean backscattering cross-section of the fish species, as estimated from the target strength equation (MacLennan et al., 2002). For herring, \( L \) was set to 32.9 cm, which was the mean length of herring spawning off the Møre region in 1999 (data from Slotte and Dommasnes (1999)). For blue whiting, \( L \) was set at 23.7 cm, based upon samples from the region (own unpublished data). In order to obtain biomass estimates the appropriate mean weights of herring (263 g) and blue whiting (72 g) were also included.

2.6. Data analysis and testing

The horizontal distribution and abundance of pelagic fish in relation to the shooting area was mapped with use of SURFER 6.04 (Anon., 1997) surface mapping system and kriging gridding method. In this analysis, and during statistical testing of geographical differences in acoustic abundance, all species were pooled into one pelagic fish group due to the above-mentioned uncertainties in scrutinising of acoustic data.

Before statistical testing, the extent of the seismic shooting lines and the surrounding area up to 5 km away was defined as the shooting area. Two more areas were defined: one to the west and one to the east of the shooting area, with outer limits 30 km away from the shooting (Fig. 3).

![Image](image-url)
The NASC data were not normally distributed. Thus, before parametric testing they were log transformed to verify the assumption of normality.

All statistical tests were carried out using STATISTICA 6.0 (Anon., 2001). One way ANOVA was used to test for the effect of area as an independent factor on acoustic abundance, whereas Scheffe’s test was used to determine significant differences between group means. A simple t-test was used to test for differences between recordings directly prior to and after shooting along a seismic transect. For all acoustic survey lines crossing the seismic area, a simple linear regression was used to test for the relation between abundance and distance (nmi) to the west and east starting in the middle of the seismic area and stopping 30 km away. Factorial ANOVA with time (1 h intervals) and depth (m) as independent factors was used to test for differences in diel migration between periods with and periods without shooting in an area up to 30 km away from the source. The tests of diel migration were carried out on blue whiting and mesopelagic fish separately, as they were assumed to have a different behaviour. Herring were excluded from these analyses do to a low number of recordings at the same time of day in periods with and without shooting.

**Fig. 4.** Area echo abundance, $s_A$, of pelagic fish (blue whiting, herring and mesopelagic fish grouped together) by vessel log (from west towards east) at lines that overlapped for each survey (see also Figs. 1 and 3). The western and eastern limits of the lines shot prior to and during the surveys are marked.
3. Results

3.1. Total estimates of pelagic fish abundance and biomass

During Survey 1 the biomass estimates of blue whiting and herring were 192,000 and 95,000 t, respectively. During Survey 2 no herring was recorded and the blue whiting was down to 33,000 t, but the area covered was also lower. During Survey 3 the biomass of blue whiting and herring increased to 76,000 and 60,000 t, respectively. The biomass per nautical mile squared of both blue whiting and herring was the highest during Survey 3. The biomass of blue whiting was as expected but the herring biomass was lower than expected. The biomass estimates of herring were not considered large enough to stop the seismic shooting.

3.2. Distribution and abundance of pelagic fish related to the seismic shooting area

With respect to the spatial distribution and abundance of pelagic fish, Survey 1–3 showed similar results (Figs. 3 and 4), i.e. in all surveys area was found to be an influencing factor ($P < 0.001$). In Survey 1 the lowest abundance was found in the shooting area, but only the eastern area had significantly higher values ($P = 0.004$). The abundance inside the eastern area was also higher than in the western one ($P = 0.047$). The same yet more significant differences between the eastern and the two other areas were found during Survey 2 and 3 ($P < 0.001$). Related to these results the abundance during Survey 1 and 2 increased with distance from the middle of the seismic area both in the western and eastern direction (Fig. 5), whereas no such differences were found during Survey 3. During Survey 2 the distance between the shooting area and high fish abundance to the east decreased from line 3 to line 9 (Fig. 3). At the same time there was a 3–4 days break in the seismic shooting (Fig. 2). This westward movement of pelagic fish was even more apparent after the shooting break; during acoustic mapping along some of “Ramform Vanguard” transects and during the start of Survey 3. For the first time high fish densities were observed inside the shooting area, the southern part (see Line 2 in Figs. 3 and 4).

The acoustic mapping along three of the “Ramform Vanguard” transects prior to and after shooting did not result in significant differences in abundance. At one seismic transect “Dr Nansen” and “Ramform Vanguard” met approximately midway, and there was a drop in the acoustic density after this meeting point. However, also at the other mapped lines there was a decrease of the $s_A$ figures at about the same latitude (see Line 2, Survey 3, Figs. 3 and 4), indicating that this was a natural, distributional effect, rather than an effect of the shooting.

3.3. Vertical distribution of fish

The fish were distributed vertically in distinct schools or layers, but at varying depths in relation to the illumination. At night time the herring were mostly distributed in dispersed layers from the surface and down to approximately 100 m depth, whereas at daytime they were mostly distributed in dense schools between 200 and 300 m depth. The blue whiting also
showed a tendency towards vertical migrations in relation to the illumination, but this behaviour was not as distinct as in the herring. In general the blue whiting were distributed in layers peaking at about 400 m depth at daytime and 300 m during darkness. Mesopelagic fish migrated from around 300 m depth in daytime to around 200 m depth in night time, i.e. at depths around 100 above the blue whiting. In both blue whiting and mesopelagic fish, time of day and shooting (and the product of the two factors) had significant influence on vertical migration ($P < 0.001$) (Fig. 6). Blue whiting were on the average found 10 m deeper during shooting compared to non-shooting periods. The same but more distinct difference, 50 m, was found in mesopelagic fish.

4. Discussion

The objectives of the present study were twofold. One objective was to assess the seismic shooting in relation to the biomass of herring inside and in the vicinity of the Ringhorne Dome area. The estimated biomass of herring was significantly less than anticipated, and well below the agreed stop limits for the seismic survey.

Another objective was to investigate whether the seismic activity had any effect on the fish distribution and abundance of prevailing species. There was no convincing evidence of short-term scaring effects of the shooting on the horizontal scale. The acoustic mapping before and prior to the shooting along some of the seismic transects gave no indications of short-term reactions to the shooting. However, both blue whiting and mesopelagic species were found in deeper waters in periods with shooting compared to periods without shooting, indicating that vertical movement rather than horizontal movement could be a short-term reaction to this noise. The overall spatial distribution and density of both herring and blue whiting recorded during the three surveys were not at all random with respect to the seismic shooting area. The density of fish was clearly lower within the shooting area, with increasing abundance at distance from the seismic shooting. The fish density seemed to be higher at about 20 nautical miles from the centre of the shooting area. As this also coincides with the typical approximate reaction distance to seismic shooting observed in species like cod and haddock (Engås et al., 1996), blue whiting and mixed pelagic species (Dalen and Knutsen, 1986), we find this to be an indication of a long-term effect of the shooting activity. These were fish that could have avoided the shooting area or left the area due to the shooting. Possibly some of the fish moving westwards stopped near the shooting area, or rather migrated to the south-west or north-west of the area. The observed westward movement of large masses of blue whiting and herring towards and into the shooting area during Survey 2 and Survey 3, could be a result of the 3–4 days break in the seismic shooting, indicating that migrations will proceed as normal soon after shooting ceases.

The present results support the earlier findings of Engås et al. (1996) on cod and haddock, and Dalen and Knutsen (1986) one blue whiting and mixed pelagic...
species, but one should be aware that both the herring and blue whiting were conducting a large scale feeding migration during this particular investigation possibly ruling some of their behaviour. Compared to the study of Engås et al. (1996), which was designed as a large-scale experiment, where the situations prior to, during and after shooting could be studied in detail, our investigation was not designed to directly measure the effect of the seismic shooting. It is however interesting to observe almost the same distribution patterns of fish surrounding a seismic survey area as the one recorded by Dalen and Knutsen (1986) and Engås et al. (1996).

5. Conclusions

The present results, although they are not conclusive, contribute to the ongoing gain of knowledge about possible effects of seismic shooting. One cannot rule out that the observed difference in acoustic abundance of fish inside and outside the shooting area simply may be a result of natural migrations and fish behaviour related factors like temperature, salinity, currents, food availability, etc. Thus, the study emphasises the importance of further studies on the effects of seismic shooting on fish behaviour. However, future studies should be designed especially to distinguish between possible effects of shooting and other factors that might influence the fish behaviour. Such studies should preferably carry out similar investigations in two areas simultaneously (both containing the target species), the shooting area and a control area out of distance from the noise of the shooting. Data on temperature, salinity, currents, prey availability of the target species, etc. should be collected continuously together with biological data on the target species from trawl catches. Sonars should be used actively as an additional tool to the echo sounder to track directions, sizes and speeds of pelagic fish schools. The present findings of altered fish behaviour from seismic shooting support the basis for management actions in Norway against seismic shooting on and close to spawning grounds and over well-established migration routes to spawning grounds.

References


