ICES Journal of Marine Science, 56: 326–332. 1999
Article No. jmsc.1999.0473, available online at http://www.idealibrary.com on IDEAL

Sound from spawning cod at their spawning grounds

J. T. Nordeide and E. Kjellsby

Nordeide, J. T. and Kjellsby, E. 1999. Sound from spawning cod at their spawning grounds. – ICES Journal of Marine Science, 56: 326–332.

Sound was recorded at five stations at and near the main spawning grounds of the northeast Arctic cod (*Gadus morhua* L.) off the Lofoten Islands, Norway. Recordings were carried out during April 1997 when large numbers of cod aggregated to spawn, and were repeated in September when the cod were no longer spawning and, in fact, most had emigrated. The analysis revealed differences between the two time periods with April showing sound of a transient character with 7–18 dB increased sound level between 50 and 500 Hz. Sound from single cod in captivity has been reported to be located in this frequency range. We argue that the sound recorded is produced by spawning cod and discuss acoustic communication as a potential mechanism in cod mate assessment.

Key words: Atlantic cod, *Gadus morhua*, behaviour, communication, spawning, mate choice.

Received 22 June 1998; accepted 3 March 1999.

Jarle Tryti Nordeide: Department of Fisheries and Natural Sciences, Bodø Regional University, N-8049 Bodø, Norway. Erling Kjellsby: Norwegian Defence Research Establishment, N-3191 Horten, Norway. Correspondence to J. T. Nordeide: tel: +47 7551 7200; fax: +47 7551 7457; e-mail: jarle.nordeide@hibo.no

Introduction

There are only vague accounts of the spawning behaviour of Atlantic cod (*Gadus morhua* L.), despite the commercial importance of the cod fishery and decades of surveillance and research. Field studies by echosounder have shown shoals of cod near the seabed at the spawning grounds off northern Norway (Sund, 1935), and off Newfoundland (Rose, 1993). Such shoals may be relatively dense during daytime compared to the night (Sætersdal and Hylen, 1959). From behavioural observations of cod in tanks, Brawn (1961a,b) suggested that a territorial male showed aggression towards a group of females and males without territories. Single ripe females left the group and swam into the male's territory. The male and female showed courtship display followed by spawning (Brawn, 1961a). Cod in captivity has been reported to produce sound (McKenzie, 1935) during courtship display, aggression, and when frightened (Brawn, 1961b). Sound is produced most frequently over the spawning period (Brawn, 1961b). Moreover both sexes are capable of producing sound throughout the year but only males seem to do so during the spawning season (Brawn, 1961b). The sound is made by striated drumming muscles surrounding the gas-filled swimbladder and each call or "grunt" consists of a series of rapidly repeated pulses (Brawn, 1961b; Hawkins and Rasmussen, 1978; Hawkins, 1986). Brawn (1961b) claimed that sound from single cod from the North Sea kept in captivity had a peak sound amplitude at 50 Hz, whereas the call of cod captured in Scotland consisted of harmonic spacing of about 95 Hz with peak amplitudes at frequencies between approximately 80 and 500 Hz (Hawkins and Rasmussen, 1978).

Producing sound by drumming muscles has energetic costs. From an evolutionary point of view it is therefore likely that making sound has one or several important purposes. It is reasonable to assume that a proximate function of sound production is acoustic communication in connection with aggression and partner choice, a common phenomenon among a wide variety of taxa (Alcock, 1993). Acoustic communication may be an important criterion by which females discriminate between males from different cod populations (or species) as suggested by Møller (1968), and as a criterion for mate assessment at an individual level (Myrberg *et al*., 1986; Höglund, 1989; Andersson, 1994).

If communication by sound is important during aggression and mate choice, we may predict that sound recordings from large aggregations of spawning cod at a spawning ground should reveal sound with peak amplitudes similar to those recorded by Brawn (1961b) and

1054–3139/99/030326+07 $30.00/0

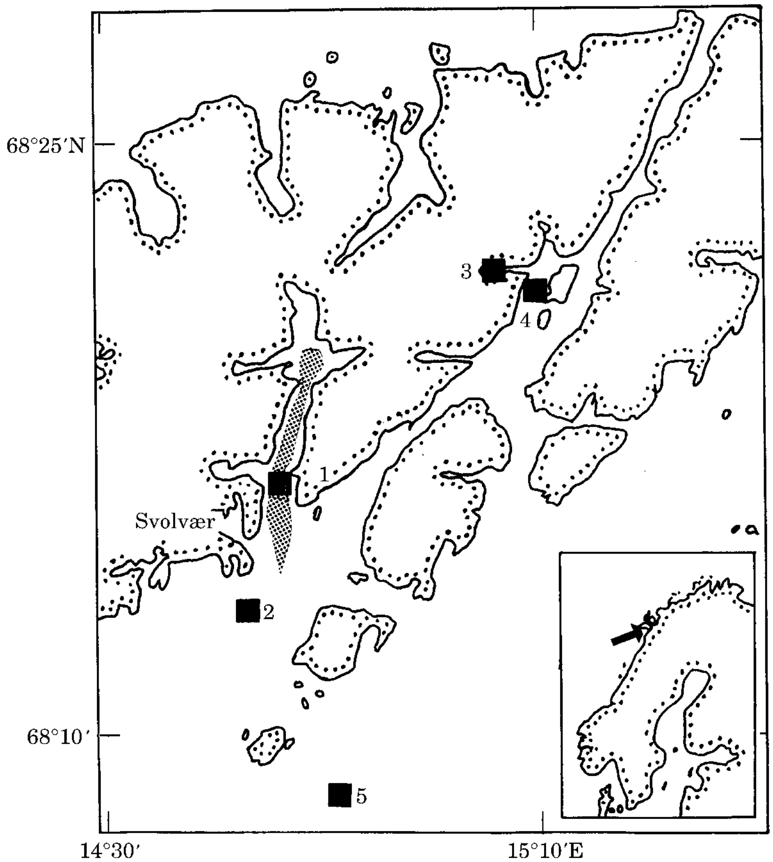

Figure 1. Study area off the Lofoten Islands, Norway, including the five stations where recordings were made. The shaded area shows the approximate distribution of high density spawning cod.

Hawkins and Rasmussen (1978). The aim of the present study is to test this prediction. We present sound recorded at local spawning grounds near the Lofoten Islands when large numbers of cod spawned in the area. These recordings are compared to similar recordings made 5 months later, when few cod were present and none were spawning.

Materials and methods

Study subject

Cod in northern Norway comprise two main groups. The northeast Arctic cod (NAC) migrates from feeding areas in the Barents Sea and near Svalbard to spawning areas along the Norwegian coast, and returns after spawning (Bergstad *et al*., 1987; Brander, 1994). The spawning ground around the Lofoten Islands is the main spawning area of NAC, where 65–75% of the eggs are produced (Brander, 1994). Coastal cod (CC) inhabit coastal areas and fjords, migrate short distances and spawn along the Norwegian coast (Rollefsen, 1954; Jakobsen, 1987) including around the Lofoten Islands (Hylen, 1964; Møller, 1966, 1968; Nordeide, 1998). Most cod spawn during the period March to May (Sars, 1879; Kjesbu, 1988; Brander, 1994), with peak spawning of NAC around 1 April (Pedersen, 1984).

Sound recordings

The recordings were carried out at five stations near the port of Svolvær in the Lofoten Islands in northern Norway (Figure 1), during April and September 1997. The number of spawning cod was not estimated quantitatively but spawning cod were located from RV "Oscar Sund" by a combination of observing the density of fishing vessels and fishing gear and by using the echosounder Simrad EK500 with a 38 kHz transducer. High density of cod was located around Stations 1 and 2, whereas none or few cod were observed close to Stations 3–5 (Figure 1). All recordings, except at Station 5 in September, were carried out during the night between sunset and sunrise (Brahde, 1970), when the fishing vessels were moored at the quayside. Recordings are presented from Stations 1–5 from 8–9 April at 0020,

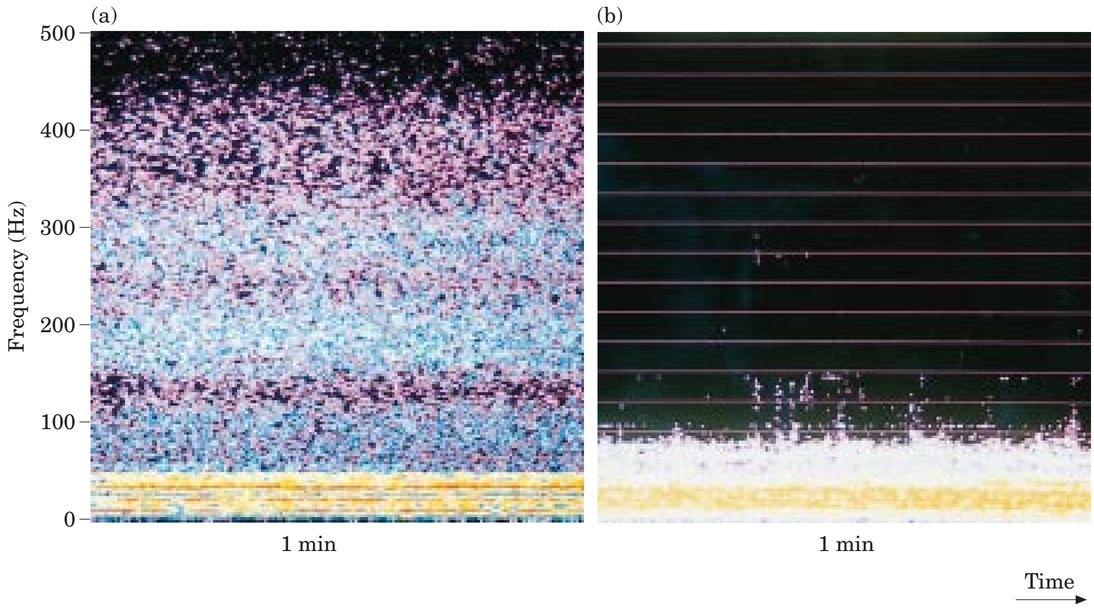

Figure 2. Recordings from Station 1 in (a) April 1997, and (b) September 1997, analysed by Short-time Fourier Transform techniques (STFT). The resolution is low since the figure is a scanned photograph of the monitor.

0220, 0105, 0015, and 0315 h and again on 4 September at 2335, 0020, 0500, 0535, and 0725 h (local summertime). Several recordings were carried out at Stations 1 and 2 during 8 and 9 April but quantification of the sound level was not possible for some of them because the hydrophone frequently came into contact with fishing nests.

The measuring hydrophone with a 32 dB gain built-in preamplifier had a total sensitivity of − 152 dB ref 1 V/μPa within the frequency range of 16 Hz–2 kHz. The long signal-cable was of a soft and slim (5 mm) type in order to minimize vibrations from water drag. The signals were taped on a Sony DAT recorder via an adjustable line amplifier. The length of the signal-cable between the hydrophone and water surface was 75 m at Stations 1, 2, 3, and 5, and 50 m at Station 4. The actual depth of the hydrophone was unknown and less than the length of the signal-cable, due to some drift of the ship. Depth from the water surface to the seabed was 120, 105, 60, 120, and 350 m for Stations 1–5, respectively. The engines on RV "Oscar Sund" were turned off during the recordings. Most of the recordings were carried out during windless periods but the two recordings at Station 1 and 2 in September were made in a moderate breeze.

Analyses of recordings

The tapes were analysed in the laboratory at the Norwegian Defence Research Establishment, Department of Underwater Defence, in Horten. In order to emphasize the transient character in the sound from cod, Short-time Fourier Transform techniques (STFT) were applied. Unfortunately we can only present a low-resolution scanned photography of the result presented on the monitor (Figure 2). A photograph of Figure 2 with higher resolution is available on request. Common Fast Fourier Transform (FFT)-analyses were used to compare the sound with the background noise in the sea. The ambient noise spectrum for windforce 0 m s^{-1} and calm sea, given by Wenz (1962), adapted to the background noise in Norwegian coastal waters was used as one of the bases of comparison.

Results

The sound recorded in April is heard by the human ear as a low rumble and grunts from individual cod could not be recognized. Results from the STFT and the FFT-analyses presented in Figures 2 and 3, respectively, reveal that the most powerful sound contribution is located below 50 Hz. However, this is also where the theoretical background noise is loudest (Figure 3). Above 50 Hz, where the background noise is moderate, there is a marked difference in the spectrum recorded in April compared with the control measurements in September (Figures 2a, b and 3, Table 1). The spectrum from April shows a marked increase in the amplitude around frequencies of approximately 85, 170, 250, 355, and 445 Hz, not found in September (Figure 3, Table 1). The differences are even more marked when comparing levels from April with the theoretical ambient noise in calm sea (Figure 3, Table 1).

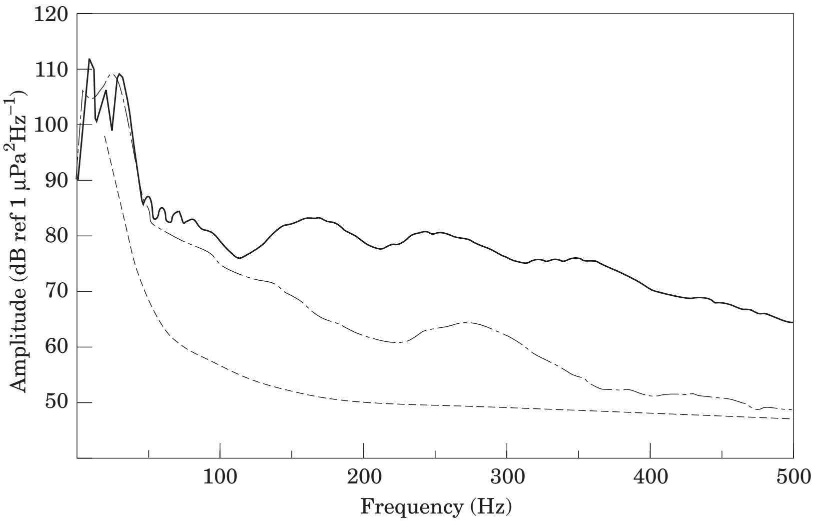

Figure 3. Sound spectrum from the FFT-analysis at Station 1, recorded in April 1997 (——), and in September 1997 (– · – · –), compared with theoretical background noise at a wind force of 0 m s^{-1} (– – –).

Table 1. Spectrum levels for distinctive frequencies in dB re 1 µPa^2 Hz^{-1} and corresponding sound levels in dB re 1 µPa measured at five stations near the Lofoten Islands in April and September 1997.

Station number		Spectrum levels: Frequencies in Hz 85	170	250	355	445	Mean values	Sound levels: Integrated spectrum
1	Apr	83	84	81	76	68	78	105
	Sep	78	65	63	55	51	62	89
	Difference (Apr–Sep)	5	19	18	21	17	16	16
	Difference (Apr–calm)	24	32	31	26	19	26	26
2	Apr	88	88	84	79	72	82	109
	Sep	75	64	63	59	62	64	91
	Difference (Apr–Sep)	13	24	21	20	10	18	18
	Difference (Apr–calm)	28	35	34	31	24	30	30
3	Apr	74	75	72	66	59	69	96
	Sep	63	64	62	50	48	57	84
	Difference (Apr–Sep)	11	11	10	16	11	12	12
4	Apr	82	71	68	63	56	68	95
	Sep	65	55	49	45	43	51	78
	Difference (Apr–Sep)	17	16	19	18	13	17	17
5	Apr	90	83	74	74	76	79	106
	Sep	78	76	71	69	68	72	99
	Difference (Apr–Sep)	12	7	3	5	8	7	7

The difference in the values from April and September are given. For the Stations 1 and 2 the April values and the theoretical background levels with a calm sea (Wenz, 1962) are compared.

The sound between 50 and 500 Hz consists of a large number of grunts of a transient character (Figure 2a) whereas the background noise below ca. 50 Hz is of a continuous character (Figure 2a, b).

The sound levels from April obtained by integrating the FFT-spectrum from 50 to 500 Hz, show values above 104 dB re 1 µPa in Stations 1, 2, and 5, and values below 97 dB at Stations 3 and 4 (Table 1). Differences in sound level between April and September were 7 to 18 dB re 1 µPa, and were highest at Station 2 (Table 1).

Discussion

Differences in spectrum levels and integrated sound levels give a clear indication of increased sound activity of a transient character between 50 and 500 Hz during the spawning season in April compared to September. Below 50 Hz noise from remote shipping traffic together with noise from waterflow on the surface of the measuring hydrophone forms a dominant background noise with a continuous character which masks any possible weak signal from the cod. It is not possible to estimate the sound level of the fish shoal itself since we do not know the exact geometric conditions or the exact number of fish in the area.

We suggest that sound produced by spawning cod is the most plausible explanation of the increased sound recorded above 50 Hz. This suggestion stems from the following considerations:

(1) The increase in sound activity is highest in the frequency range where it has been suggested cod communicate. Single cod in captivity produce sound at frequencies similar to those recorded in the present study (Hawkins and Rasmussen, 1978). Cod hearing sensitivity is highest from 50 to 500 Hz (Chapman and Hawkins, 1973; see also Astrup and Møhl, 1993).
(2) The transient character of the sound above 50 Hz was revealed by the STFT-analyses, and shown as "dots" in Figure 2a. A transient character is expected from cod grunts. Single dots can be separated in Figure 2a, but, below ca. 350 Hz especially, this is impeded by the high number of overlapping dots and the low resolution of the scanned photography presented. At frequencies below 50 Hz, the STFT analysis reveals sound of a continuous character as expected from background noise.
(3) The sound from spawning cod shoals as heard by the human ear has been described in similar terms. A research vessel visiting the Lofoten Islands in 1956 described the sound as "a muffled grunting noise" (Anon., 1957).
(4) A large number of spawning cod were present near Stations 1 and 2 in April, which are within the main spawning area of the northeast Arctic cod (Bergstad *et al*., 1987; Brander, 1994). More than 92% of the male and 78% of the female cod caught at Station 2 5 days before the present recordings were mature and would have spawned within less than ~48 h (Nordeide, 1998). In September cod do not normally aggregate at the spawning areas and most had left the study area.
(5) Cod was the most abundant fish species in the study area in April. Stations 1 and 2 are traditionally considered as important local spawning grounds for the northeast Arctic cod. Cod constituted more than 98% by weight of the fishes in four catches by Danish seine at or near Station 2 only 5 days prior to the present study (Nordeide, 1998). Moreover cod constituted 98% of 1700 tonnes of fish delivered by local fishermen to the fish factories in the study area (Svolvær and Henningsvær), during the period 7–13 April 1997 (O. Halvorsen, Norges Råfisklag, Tromsø, pers. comm.).

It is not clear why the human ear was not able to distinguish between grunts from individual cod and the background "rumble". However, the reason may simply be due to the distance between the hydrophone and the cod, or that grunts from a few cod close to the hydrophone were drowned out by the sound from thousands of cod grunting in the background.

No conclusion that we have drawn should be undermined by the fact that Station 5 was recording during daylight in September, whereas the other nine recordings were carried out during the night. This is because cod have been reported to spawn both during daytime (Kjesbu, 1989; Rose, 1993), afternoon, and night (Brawn, 1961a,b). In any case, if Station 5 had not been occupied the comparisons drawn would have been validated by the results from the remaining data set.

The sound level was also higher in April compared to September at Stations 3–5, even though none or very few nets, fishing vessels, or fish were observed close to them (Table 1). This may be explained by the fish being present near Stations 3–5 but not discovered by either the fishermen nor us and low damping of underwater sound making it possible for sound produced, for example at Stations 1 and 2, to be recorded at Stations 3–5. We cannot reject the possibility that cod could have spawned near Stations 3–5 without being discovered by us. The beam angle of the transducer is 22°, which means that a diameter of ca. 40 m could be observed at 100 m depth. The inner part of Trollfjord (Station 3) was covered by ice which prevented us from examining the whole fjord using the echosounder. Cod spawning occurs occasionally in Trollfjord (Posti, 1991) and could have occurred under the ice in April 1997 without being discovered by either the fishermen or themselves.

It is also likely that sound from grunting cod at high densities at other localities, for example at Station 1, might have produced some of the sound measured at Stations 3–5 in April. An estimated sound level of approximately 77 dB ref 1 μPa could theoretically be measured 10 km away when 1000 cod grunt exactly at the same moment. This estimate is based on a source-level of 127 dB re 1 μPa m^{-1} from one single cod as was recorded from a cod kept in a tank (Kjellsby, pers. obs.), and the calculations are deduced from Urick (1983). It is approximate since the calculations are for damping in the open sea and not within a fjord, and we do not know the exact number of cod at different distances from the recordings, the proportion of cod grunting simultaneously, and whether or not the call differs between individual cod. Although approximate the estimated

77 dB ref 1 μPa is within the same order of magnitude as the difference in sound levels between April and September at each of Stations 3–5 as shown in Table 1.

Suggesting that several thousand cod were present near Stations 1 and 2 is probably a large underestimate of the actual number even though the number of cod at different distances from Stations 1 and 2 was not quantified during the recordings in April. More than ~50 million northeast Arctic male cod, and an unknown but much lower number of coastal cod, spawned near the Lofoten Islands in 1997. The assumptions on which this estimate is based are a northeast Arctic cod spawning stock of 0.84 million tonnes (Toresen, 1998), 65% of this stock spawn near the Lofoten Islands (Brander, 1994), a mean weight of 5 kg per cod, and a 1:1 sex ratio. Moreover the Institute of Marine Research surveyed the distribution of the cod spawning stock in the area 1 week before our recordings. The highest density of cod observed by them was in Austnesfjord (St. 1) and Høla (St. 2) (Knut Korsbrekke, Institute of Marine Research, Bergen, pers. comm.).

Increased spectrum levels in the present study are at similar but not completely identical frequencies compared to sound from single cod in captivity (Hawkins and Rasmussen, 1978, Figure 14a). The minor discrepancies between the two studies may be a result of different kinds of background noise, different methods and equipment for recording and analysis of sound, the sound from one cod being different to the sound from large numbers of cod, differences of sound from cod with size, and from different populations (or species) of cod. Background noise is expected to be responsible for the discrepancy at frequencies below ca. 50 Hz. The last two explanations are particularly appealing since this may enable females to discriminate between males both at the individual and population (or species) levels. This should be examined further in controlled experiments.

Acknowledgements

The authors thank Morten Krogstad, the captain and crew of the RV "Oscar Sund" for assistance, Prof. M. Haakstad and Prof. A. D. Hawkins for valuable comments on previous versions of the manuscript, and "Fiskeriforskningsfondet" and Bodø Regional University for financial support.

References

Alcock, J. 1993. Animal behavior (an evolutionary approach), 5th edn. Sinauer Associates, Sunderland, MA. 625 pp.

Andersson, M. 1994. Sexual selection. Princeton University Press, Princeton, NJ. 599 pp.

Anon. 1957. Sea fisheries research notes, 1956. Fisheries Notice, London, 37: 1–16.

Astrup, J., and Møhl, B. 1993. Detection of intense ultrasound by the cod *Gadus morhua*. Journal of Experimental Biology, 182: 71–80.

Bergstad, O. A., Jørgensen, T., and Dragesund, O. 1987. Life history and ecology of the gadoid resources of the Barents Sea. Fisheries Research, 5: 11–161.

Brahde, R. 1970. Solas stilling i Norge. Universitetsforlaget, Oslo (in Norwegian).

Brander, K. (Ed.) 1994. Spawning and life history information for North Atlantic cod stocks. ICES Cooperative Research Report, 205: 150 pp.

Brawn, V. M. 1961a. Reproductive behaviour of the cod (*Gadus callarias* L.). Behaviour, 18: 177–198.

Brawn, V. M. 1961b. Sound production by the cod (*Gadus callarias* L.). Behaviour, 18: 239–245.

Chapman, C. J., and Hawkins, A. D. 1973. A field study of hearing in the cod, *Gadus morhua* L. Journal of Comparative Physiology, 85: 147–167.

Hawkins, A. D. 1986. Underwater sound and fish behaviour. *In* The behaviour of teleost fishes, pp. 114–151. Ed. by T. J. Pitcher. Croom Helm, London.

Hawkins, A. D., and Rasmussen, K. J. 1978. The calls of gadoid fish. Journal of the Marine Biological Association, UK, 58: 891–911.

Höglund, J. 1989. Size and plumage dimorphism in lek-breeding birds: a comparative analysis. The American Naturalist, 134: 72–87.

Hylen, A. 1964. Coastal cod and skrei in the Lofoten area. Fiskeridirektoratets Skrifter Serie Havundersøkelser, 13: 27–42.

Jakobsen, T. 1987. Coastal cod in Northern Norway. Fisheries Research, 5: 223–234.

Kjesbu, O. S. 1988. Fecundity and maturity of cod (*Gadus morhua* L.) from northern Norway. ICES CM 1988/G:28, 16 pp.

Kjesbu, O. S. 1989. The spawning activity of cod, *Gadus morhua* L. Journal of Fish Biology, 34: 195–206.

McKenzie, R. A. 1935. Codfish in captivity. Progress Report of the Atlantic Biological Station, 16: 7–10.

Møller, D. 1966. Genetic differences between cod groups in the Lofoten area. Nature, 212: 824.

Møller, D. 1968. Genetic diversity in spawning cod along the Norwegian coast. Hereditas, 60: 1–32.

Myrberg, A. A., Jr, Mohler, M., and Catala, J. D. 1986. Sound production by males of a coral reef fish (*Pomacentrus partitus*): its significance to females. Animal Behaviour, 34: 913–923.

Nordeide, J. T. 1998. Coastal cod and north-east Arctic cod—do they mingle at the spawning grounds in Lofoten? Sarsia, 83: 373–379.

Pedersen, T. 1984. Variation of peak spawning of Arcto-Norwegian cod (*Gadus morhua* L.) during the time period 1929–1982 based on indices estimated from fishery statistics. *In* The Propagation of Cod (*Gadus morhua* L.), pp. 301–316. Ed. by E. Dahl, D. S. Danielsen, E. Moksness, and P. Solemdal. Flødevigen rapportserie, 1. Oluf Rasmussen A. S. Skien (in Norway). 895 pp.

Posti, P. 1991. Trollfjordslaget: myter og virklighet. Cassiopeia forlag, Tromsø. 144 pp (in Norwegian).

Rollefsen, G. 1954. Observations on the cod and cod fisheries of Lofoten. Rapports et Procès-Verbaux des Réunions du Conseil International Pour l'Exploration de la Mer, 136: 40–47.

Rose, G. A. 1993. Cod spawning on a migration highway in the north-west Atlantic. Nature, 366: 458–461.

Sars, G. O. 1879. Indberetninger til Departementet for det indre. Departementet for det indre, Christiania, 221 pp.

Sund, O. 1935. Echo sounding in fishery research. Nature, 135: 953.

Sætersdal, G., and Hylen, A. 1959. Skreiundersøkelsene og skreifisket i 1959. Fisken og Havet, 1959: 1–20.

Toresen, R. (Ed.) 1998. Havets ressurser 1998. Fisken og Havet, Særnummer 1. Institute of Marine Research, Bergen.

Urick, R. J. 1983. Principles of underwater-sound. McCraw-Hill, New York.423 pp.

Wenz, G. M. 1962. Acoustic ambient noise in the ocean. The Journal of the Acoustical Society of America, 34: 1936–1956.