https://doi.org/10.17895/ices.pub.8898

ICES Marine Science Symposia, 215: 543–550. 2002

Fluctuations in abundance of Northeast Arctic cod during the 20th century

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Hylen, A. 2002. Fluctuations in abundance of Northeast Arctic cod during the 20th century. – ICES Marine Science Symposia, 215: 543–550.

Annual sampling of Northeast Arctic cod for age determinations during 1913–1929 was based on scales, but beginning in 1932, the sampling was based on otoliths. The Norwegian sampling programme was concentrated on landings of mature cod in the winter and of immature cod in the spring. In the late 1920s and early 1930s, age determinations of mature fish indicated a lower frequency of older fish in scale samples than in otolith samples. Misclassification of age in scale samples of immature cod was assumed to be of minor importance. To overcome the misclassification of age in mature fish, a scale-age/otolith-age "key" was applied to scale-age compositions of mature fish. These annual converted age compositions together with the scale-age compositions of immature cod for 1913–1929 were used to establish total annual catch in numbers at age by years. Similar data for 1932–1945 were based on otolith-age compositions. In conjunction with similar published data for 1946–1999, a virtual population analysis was run for the entire 20th century after 1913. The historic development of total and spawning-stock biomass, fishing mortality, and recruitment at age 3 was investigated. In addition, the lognormal distribution was applied to the recruitment data for the 87 year classes that were analysed, and the Beverton and Holt and Ricker curves were fitted to the spawning-stock/recruitment data.

Keywords: fishing mortality, lognormal distribution of recruitment, Northeast Arctic cod, VPA.

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Introduction

Fluctuations in the abundance of the Northeast Arctic cod stock have been observed for a long time back in history. A systematic analysis was made by Sund (1936) based on catch per unit of effort (cpue) as the number of mature cod caught per man in the fishery for spawning cod in Lofoten during the period 1897–1935. The study was extended by Rollefsen (1954) to include the periods 1860–1896 and 1936–1952. Ottestad (1942) selected four periods of variation out of the seven estimated by Ording (1941) in the series of annual growth zones of Norwegian pine from a district close to Lofoten, the cod spawning area. A combination of four sine curves with periods of length of 11, 17½, 23, and 57 years gave a hypothetical curve representing the number of cod caught annually in Lofoten. This method was further elaborated by Ottestad (1979).

Hjort and his collaborators turned the utilization of representative age compositions of fish stocks into a tool to study stock fluctuations, identity, and vital processes. The use of scales, otoliths, and bones for age determination was known by the beginning of the 20th century, and Hjort saw the prospects of assigning fish stocks to age groups. He suggested in a lecture at the 1907 ICES annual meeting that scientists would find it useful to think in such terms and to keep in mind human population studies (Hjort, 1908). A cooperative programme was conducted through ICES Committee A, but ceased in 1908. However, the work continued at the Institute in Bergen on data from Norwegian spring-spawning herring and Northeast Arctic cod. Scales collected from landings of both species were sampled for age determinations. This method was not accepted at the time by all scientists. The dispute was concentrated on herring scales, and the difficulties were finally settled at a joint practical exercise in Kristiania in 1923.

Even so, there was a remarkable lack of response to Hjort's "messages" during 1907–1914 regarding the importance of stock-age compositions and population theories. ICES called for a special meeting in London in 1929 on "Fluctuations in abundance of the various year classes of food fishes" (ICES, 1930a). A follow-up meeting on nearly the same subject was held in 1930 to discuss the reports from the 1929 meeting (ICES, 1930b). This must be seen as positive acceptance by

European fishery scientists of Hjort's messages of 20 years earlier. Sætersdal (2002) provides a broader discussion of this issue.

The account of this period has largely been based on and restricted to ICES events from the 1930s and 1950s and to some documentation. Several papers dealing strictly with population dynamics (Baranov, 1918; Hjort *et al*., 1933; Graham, 1939) have been of great importance for improving our methods and have all indicated the necessity of establishing yearly age compositions of the landings by population.

Studies of Northeast Arctic cod illustrate some of the activities of ICES after 1957. The Institute of Marine Research (IMR) in Bergen conducted a survey of available Norwegian cod data, including data from 1956–1957. This study indicated an unusually low yield of mature cod during the previous seven years. However, a similar reduction had not occurred in the fishery on immature cod (Sætersdal and Hylen, 1964). The study was submitted as a technical document to the 6th meeting of the Permanent Commission. This body asked the ICES Liaison Committee to encourage a study of all available data on the dynamics of the Arctic cod and associated fisheries, with a view to advising on the need for further regulations. As a first step, Raymond Beverton from the UK's Lowestoft Laboratory visited Bergen in January 1958, and a programme was formulated by Gunnar Rollefsen from the IMR, Chair of the ICES Gadoid Fish Committee, together with Beverton and Gunnar Sætersdal, also from the IMR (Beverton and Sætersdal, 1958). The matter was further discussed in the meetings of the Gadoid Fish Committee (Rollefsen, 1958) and other relevant committees during the 1958 ICES Statutory Meeting, with the result that the Arctic Fisheries Working Group was established. The first meeting of the Working Group was arranged in Bergen in April 1959. Participants from Germany, England, Norway, and the USSR supplied relevant data on cod and haddock from the period 1930–1958. A second meeting in September of the same year was necessary to prepare an adequate report (ICES, 1959).

The Arctic Fisheries Working Group has met every year since 1959, except 1961. Sometimes it was necessary to meet twice a year. Results, methods, and ideas for further research were made available through reports to the entire ICES scientific community. This exchange of experience has been beneficial in developing new methods in fish population analysis.

Extensive age sampling covering several components of the cod fisheries and the introduction of virtual population analysis (VPA; Gulland, 1965) have improved the analysis of fluctuations in spawning and total stock biomass, recruitment, and fishing mortality. A VPA run was performed for the period 1946–1999 (ICES, 2000). Norwegian scientists had, for some years, been looking for the possibility of extending the assessment further back in time. To do so would require access to the old files on age compositions of Norwegian landings from the period 1913–1945 held at the Institute of Marine Research in Bergen.

Material and methods

Relevant data for running a VPA include catches by age in numbers by years. A brief description of the available data is given for three time periods.

1913–1945

Annual cod age distributions based on scales and length measurements from landings of immature and mature cod exist in the Norwegian data files; both series cover the period 1913–1929 (Sund, 1936). Damas (1909) had expressed concern about difficulties in cod age reading based on scales. Dannevig (1920) mentioned that cod otoliths from Skagerrak might be easier to read with a higher level of reliability than scales. Sund (1923, 1927) stressed especially that the narrow outer growth zones on the scales caused difficulties in age reading. Other scientists also became doubtful during the 1920s about the benefit of using cod scales for age determination. Sund (1930) expressed the same opinion for older ages in his paper to the 1929 ICES meeting in London. A serious discussion of this problem must have taken place at the follow-up meeting in 1930 in London. Graham (1930) expressed in his "Notes for discussion" that "we know that older Norwegian scales are unsuitable for age determinations". After the meeting, it was decided to stop the Norwegian sampling of scales from 1930 onwards. In late 1931, Rollefsen (1935) had his method ready for reading otoliths, and sampling of otoliths was introduced in 1932. His analysis indicated a significant underestimate of the older ages using scales compared with studies using otoliths. It was, therefore, necessary to convert the scale-age distributions to otolith-age distributions before relevant data for the 1913–1929 period could be incorporated into the database for running a VPA for the period 1913–1999.

Comparing age determinations by scale and otolith from the same fish may give some insight into how to reduce the bias in ages read from scales compared with those read from otoliths. Such data existed for only one sample of 150 mature cod landed in Lofoten in 1932. According to the files, the scales were read by skilled assistants supervised by Oscar Sund, and the otoliths were read by Gunnar Rollefsen, who introduced the technique of age determination from otoliths at the Institute of Marine Research in Bergen in 1932 (Rollefsen, 1933). These data were grouped in a scale-age/otolith-age "key" to convert the annual scale-age compositions to otolith-age compositions. Unfortunately, no cod of ages 5, 6, or 7 (years), as read by otoliths, were represented in this key. However, they were represented in some of the scale-age compositions from 1913–1929

(Sund, 1936). Compared with the age distribution based on otoliths (Rollefsen, 1933), 5% of the age 5 fish in the scale-age compositions were allocated to age 5 in the converted otolith compositions, and 10% of the age 6 fish were allocated to age 6 in the otolith compositions. The rest of the numbers of these two ages and the total number calculated as ages 7, 8, and 9 in the scale compositions were allocated to these three groups of otolith ages by the following proportions: 1/10, 3/10, and 6/10, respectively, representing the averages in the otolith-age distributions for 1932–1935 (Rollefsen, 1935). The age compositions of the older ages in the scale distributions were calculated by the scale-age/ otolith-age "key".

The vast majority of the cod off the Finnmark coast during spring are immature, younger fish (Sund, 1923, 1936). Some of the fish in the samples were mature, and a conversion from scale age to otolith age should have been made. Unfortunately, no data were available to make such corrections, and the scale compositions had to be accepted.

No Norwegian age data exist for 1930 and 1931. For Norwegian landings of immature cod, German age distributions based on otolith readings from the Barents Sea were used (Lundbeck, 1939). German age distributions of landings from outside the spawning area were not representative of Norwegian landings of spawning cod. Therefore, another approach had to be introduced. Rollefsen (1935) published a method to estimate the age distribution of mature spawning cod the following year. This method was based on the number by age divided into age at first spawning, a total annual survival of 60%, and maturity factors for calculating the number of first-time spawners in the following year. By changing the maturity factors to work the opposite way, the age distribution of the first-time spawners was calculated for the previous year. Based on the 1932 age data, this method gave, for each age, the distribution of age at first-time spawning in 1931, which was the basis for calculating the age distribution for 1930.

The period 1932–1945 was covered by Norwegian age distributions based on otoliths for Norwegian landings of both immature and mature cod. Length distributions of landings by Germany and the USSR were available for the years 1932–1939, and the length groups were divided into age groups by applying Norwegian (longline) age/length keys from catches taken off the Finnmark coast.

Catches for 1913–1929 were obtained from the ICES *Bulletin Statistique* for all Member Countries except the USSR during the period 1914–1929. Senior scientist W. A. Yaragina at the Polar Research Institute of Marine Fisheries and Oceanography in Murmansk kindly provided references to some papers containing statistical data for the USSR during this period. However, the statistics used in the further calculations were not official, but are given here as the author's own estimates. Catch statistics for 1930–1945 by country were taken from ICES (1959). Some supplementary catch and cpue information was taken from Norwegian statistical publications.

Total numbers landed by Norwegian fishermen have been estimated each year by the average weight of fish calculated from extensive length measurements and a length/weight relationship established for the period 1916–1919. An average maturity ogive, calculated for 1938–1952 (Jørgensen, 1990), was applied for the period 1913–1931. Annual maturity ogives for 1932–1945 were taken from the same paper.

1946–1999

The time-series of catch in numbers at age is based on otolith-age determinations. All relevant input data for a traditional VPA are given in ICES (2000). However, the knife-edge maturity ogive for cod 8 years and older, used during the period 1946–1981, was replaced by sigmoid maturity ogives given by Jørgensen (1990). Applying the sigmoid maturity ogives produced a drastic reduction (8-78%) in spawning-stock biomass (SSB) compared with the results obtained by using the knife-edge maturity ogive (ICES, 2000). The large variation was caused by fluctuations in year-class strength and their different availability to the various fishery components.

The sum of products (SOP) for a given year (i.e., the sum over all ages of the total number landed at each age multiplied by the average weight at that age) should ideally be similar to the recorded catch for that year. However, the SOPs have often been below the recorded catch. The Arctic Fisheries Working Group has followed a practice of correcting the age frequencies each year in such a way that the recorded catch and the SOP value agree. The same procedure was followed in the present analysis. A recorded catch/SOP ratio close to 1.00 indicates high agreement. The recorded catch/SOP ratio followed an increasing trend during 1913–1944 from 0.77 to 1.30, and then dropped to about 0.60 for 1946. Its development after 1946 exhibited a similar trend up to 1983 (Jakobsen, 1992). For subsequent years, the recorded catch/SOP ratio fluctuated around 1.00. Three factors are responsible for any bias in the SOP: total number landed, age distribution, and weight-at-age (growth). At this stage, the age distribution has been accepted, and the differences between the recorded catch and the SOP are resolved by raising the catch weights-at-age by the catch/SOP ratio, thus correcting total-stock biomass and spawning-stock biomass.

1900–1912

Landings by country were obtained for 1900–1912 from the ICES *Bulletin Statistique*. Only sporadic Norwegian age distributions were available for 1900–1912, and they were insufficient for inclusion in the database for a

Table 1. Northeast Arctic cod. Estimated quantiles of lognormal and Weibull distributions adapted to the frequency distributions of year-class abundance (millions of fish at age 3).

	Percent quantiles					
Distribution	5	25	50	75	95	99
Lognormal	151	283	440	682	1 281	1 996
Weibull	101	286	485	737	1 173	1 520

VPA run. However, spawning and immature stock biomass were estimated through respective linear regressions between immature-stock biomass and cpue (tonnes per man) in the immature cod fisheries and between spawning-stock biomass and cpue (number of fish landed per man) in the fishery for mature cod for the period 1913–1929. Both series of cpue data were assembled from Norwegian statistical publications. Norwegian fisheries in these areas before 1930 were, to a great extent, based on conventional gear. A small number of trawlers, which took part in the fisheries in the late 1920s, were considered to have little impact on the regressions. It should be mentioned that the stock biomass estimates for the period 1900–1912 have a different status than those for the rest of the century.

Sætersdal and Loeng (1987) extracted data on the 1902–1909 year classes from Sund (1920, 1926, 1936) and presented their assessment of year classes in the categories of low, medium, and high abundance. Only the 1904 year class was classified to be of high abundance, with the 1905 and 1906 year classes rated as medium and the others as low. However, these assessments could not be calibrated to the VPA data.

Results

Stock biomass

Total stock biomass varied between about 2 and 3 million t during the first 20 years of the 20th century (Figure 1a) and in 1923–1927 and 1934–1956 averaged over 3.5 million t annually. In 1957, biomass decreased to about 2.5 million t, and in the 1980s, decreased further to about 1 million t. In the early 1990s, total biomass increased sharply to a high of 2.5 million t in 1993 before declining again to about 1.0 million t at the end of the 20th century.

A similar development occurred with spawning-stock biomass (SSB) (Figure 1a). It varied between 0.5 and 1 million t during the first half of the century, and fluctuated around an average of about 300 000 t during the next 40 years. SSB increased briefly after 1987 to about 800 000 t in 1992, but then declined steadily to only about 300 000 t in 1999.

Fishing mortality

Annual average fishing mortality (F) was estimated for two components of fish in the stock (Figure 1b): ages 4–7 (immatures) and ages 8–12 (matures). The VPA estimated an annual F of about 0.05 for 1913–1929 on the immatures and an average F of 0.3 on the matures. Thereafter, fishing mortality increased on both components during the 1930s to highs of 0.2 and 0.6, respectively. Fishing effort during World War II generated lower fishing mortalities. However, fishing activity quickly built up during the post-war period, and fishing mortality exhibited a steadily upward, although fluctuating, trend until the 1980s. With the exception of a brief increase in 1986–1988, F on the mature component underwent a marked decline from about 1.3 in 1978 to about 0.3 in 1991. F on immatures dropped from about 0.7 in 1987 to about 0.15 in 1990. However, fishing mortality for both components subsequently increased again to about 1.35 for matures and 0.6 for immatures in 1997, with a slight drop thereafter.

Recruitment

Recruitment is measured as the number of age 3 fish (Figure 1c); 87 year classes were spawned during 1910–1996. The two extremes in size were the 1966 and the 1970 year classes, estimated to be 112 and 1191 million fish, respectively; the series average was 538 million fish. Two frequency distributions were fitted to the observations: a lognormal and a Weibull (Figure 2). The main difference between the two is a lower probability, using the Weibull distribution, of getting year classes of extreme high abundance. This difference was the main reason for basing further analyses on the lognormal distribution, the results of which are shown in Table 1. Median recruitment was 440 million cod at age 3, with 75 and 95% quantiles of 682 and 1281 million fish, respectively. The probability of a year class with higher abundance than the highest observed is low.

The relationship between SSB and recruitment has been of concern since the beginning of the 20th century. Various models have been used to describe the relationship, but only two are shown (Figure 3). The Beverton and Holt (1957) model has no maximum, and a wide range of SSB gives nearly a constant number of recruits. The Ricker (1975) model indicates that an SSB of about 400 000 t generates a maximum recruitment at age 3 of about 6 million cod. However, the comparable study, based on data for the 1946–1975 year classes (ICES, 1979), indicated a higher maximum level of recruitment generated by a higher SSB than indicated by the present analysis.

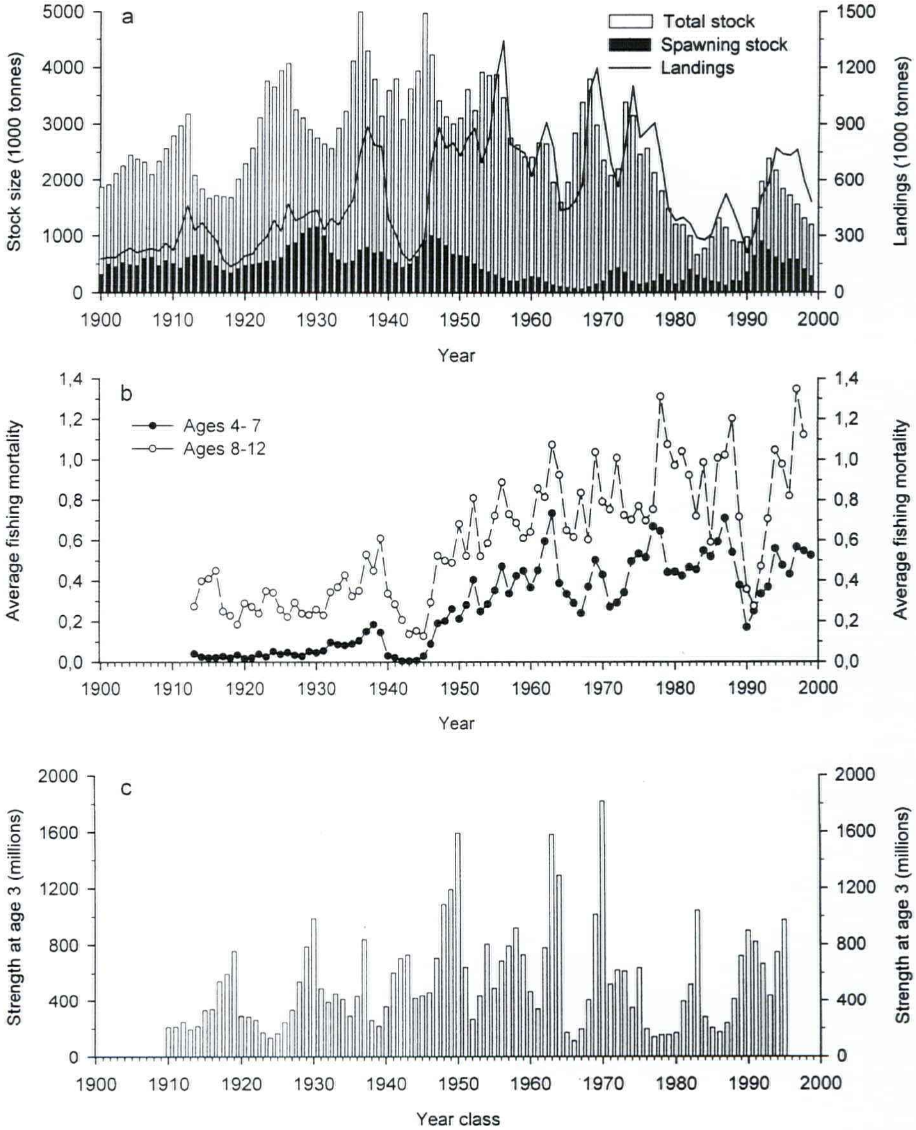

Figure 1. Northeast Arctic cod. a) Fluctuation in total stock biomass (3 years and older), spawning-stock biomass, and total catch (t). Total stock biomass and spawning-stock biomass for the period 1900–1912 are estimated from cpue (see text). b) Average fishing mortality (F) on ages 4–7 and 8–12, representing mainly immature and mature cod, respectively. c) Year-class abundance at age 3 (millions of fish).

Discussion

Sund (1936) was responsible for the Norwegian sampling programme which collected large numbers of length measurements of cod during the period 1913–1929. He analysed the fluctuations in the size of fish from year to year by examining the difference between the length distribution each year and the average distribution for the period. He found that a rich year class was followed by a positive wave through several year classes, while a poor year class was followed by a negative wave. A rich year class would already be evident when the fish reached a length of about 40 cm in the fishery for immature cod off the Finnmark coast, the length corresponding to fish determined to be age 4 (Sund, 1926). Four years later, these year classes would appear in the spawning fishery as age 8. This method provided increasing biological knowledge of the cod stock. How-

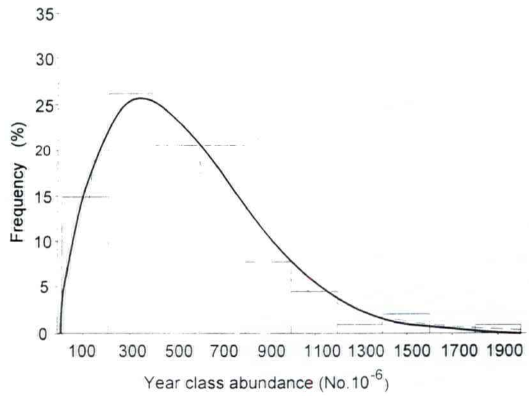

Figure 2. Northeast Arctic cod. Frequency distribution of year-class abundance at age 3 (millions of fish) fitted to lognormal (——) and Weibull (------) distributions.

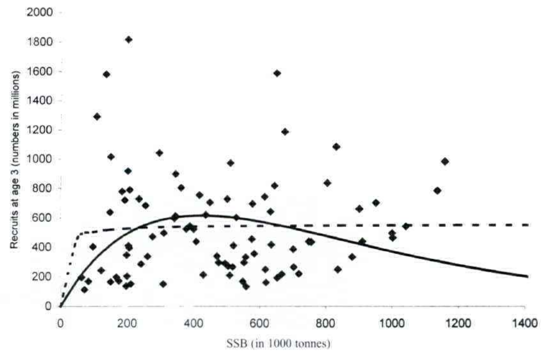

Figure 3. Northeast Arctic cod. Spawning-stock biomass vs. year-class abundance fitted to Beverton and Holt (------) and Ricker (——) curves.

ever, this understanding was improved by reading the age of each fish represented in the samples. In the early part of the 20th century, the Institute of Marine Research in Bergen concentrated on sampling cod scales. However, age determination by scales, as noted earlier, led to an increasing misclassification by age with the number of spawnings.

Systematic errors in age determination will introduce a systematic bias in VPA results. For example, the 1969 year class was estimated by VPA to be of about medium strength, while 0-group and bottom-trawl surveys suggested that this year class was weak. Sætersdal and Loeng (1987) suggested that this was caused by ageing problems, even by otolith reading. This phenomenon might have caused an "overspill" in the VPA data from the strong 1970 year class to the poor 1969 year class. If this discrepancy was caused by ageing problems, other year classes may also have been overestimated, such as the 1949 and 1962 year classes, which were followed by the rich 1950 and 1963 year classes, respectively. A further consequence of misclassification of age would be that the stock/recruitment relationship might be masked (Hilborn and Walters, 1992).

The increase in fishing mortality on the two stock components (Figure 1b) from the late 1920s to the start of World War II was caused by increased fishing effort, especially from the trawler fleets. The trawlers were subsequently withdrawn from the fishing areas in the Northeast Atlantic during World War II, leading to the significant reduction in fishing mortality observed between 1939 and 1945. In the post-war period, trawler fleets were rebuilt and expanded their fishing operations in the area (Sætersdal and Hylen, 1964). Beginning in the mid-1950s, synthetic fibres replaced natural fibres in all fishing gears, and technical improvements occurred in the rigging of the gear and in fish-location equipment. These changes led to a great increase in fishing effort and a consequent upward trend in fishing mortality on both stock components. This increasing trend continued until 1987/1988 when fishing mortality dropped to about 0.2 for both stock categories because of strict quota regulations. This was followed by an observed increase in stock biomass, but the catch quota was set too high, and fishing mortality on ages 4–7 and 8–12 increased to nearly 0.6 and 1.4, respectively, in 1997. The consequence was a drastic reduction in total- and spawning-stock biomass over the next several years.

Year classes of less than 800 million fish at age 3 were produced during all periods (Table 2). However, no year classes with abundance higher than this level were produced in the period 1910–1929. The other periods were represented by 15 year classes with abundance higher than 800 million at age 3. This suggests that the last 70 years of the 20th century were a productive period for Northeast Arctic cod.

Spawning-stock biomass (SSB) has been studied as a factor affecting the number of recruits produced. Myers *et al.* (1995) compiled a summary of worldwide spawner and recruitment data. These data were analysed by Myers *et al.* (1996), who concluded that there is a central tendency for recruitment to be positively correlated with spawner biomass. These authors and others have focused on the Ricker-type stock-recruitment model to describe the central relationship between SSB and recruitment for Northeast Arctic cod (ICES, 1979; Ricker, 1975; Garrod and Jones, 1974). All plots including the one presented in Figure 3 have shown a comprehensive scatter around the Ricker curve.

The underlying assumption behind a positive relationship between SSB and recruitment is that total egg production is proportional to VPA-based SSB. The original theoretical formulation that recruitment was assumed to be dependent on total egg production by the stock was given by Ricker (1954) and Beverton and Holt (1957). This assumption was the subject of studies on Northeast Arctic cod by Garrod and Jones (1974) and Marshall *et*

Table 2. Northeast Arctic cod. The abundance of the 1910–1996 year classes (millions of fish at age 3) for various time periods.

Abundance	1910–1929	1930–1949	1950–1969	1970–1989	1990–1996	Total
0–199	3	–	3	6	–	12
200–399	12	5	2	5	–	24
400–599	3	7	4	3	1	18
600–799	2	4	5	4	3	18
800–999	–	2	2	–	3	7
1 000–1 199	–	2	1	1	–	4
1 200–1 399	–	–	1	–	–	1
1 400–1 599	–	–	2	–	–	2
1 600–1 799	–	–	–	–	–	–
1 800–1 999	–	–	–	1	–	1
Total	20	20	20	20	7	87

al. (1998). The latter authors concluded that "the relationship [between SSB and recruitment] must be placed firmly in the context of the underlying biological, ecological and environmental processes governing the growth, reproduction and mortality of fish".

For many cod stocks, there is a wide range of SSB values where recruitment appears to be unaffected by the size of the SSB (Jakobsen, 1996). However, for Northwest Arctic cod, the incidence of poor year classes increases when SSB is below about 400 000 t (Jakobsen, 1993). A similar study (Figure 3) including the 1910–1996 year classes compared with the 1943–1986 year classes in Jakobsen's study does not strengthen his indication of a critical level of SSB. However, from a biological point of view, the management strategy should be to keep the SSB above a certain level. ICES has, in its management recommendations for this stock, focused on 500 000 t (Jakobsen, 1993). However, this matter is still under consideration by ICES.

Acknowledgements

I am grateful to Dr Kjell Nedreaas, Dr Olvar Bergland, and Dr Gro Hylen for their assistance with the computer work. The advice given by two anonymous referees was also of great help in improving the manuscript, for which I am very appreciative.

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