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An evaluation of the stock structure of North Sea cod, haddock, and whiting since 1920, together with a consideration of the impacts of fisheries and predation effects on their biomass and recruitment

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Time series of population-at-age and fishing mortality rate estimates are extended back to 1921 for North Sea cod, and to 1920 for North Sea haddock and whiting. The extended time series are used to examine the ability of various factors to explain the changes in biomass and recruitment of these roundfish stocks during much of the twentieth century. In particular, the possible impacts of fishing pressure and multispecies interactions are explored.

Key words: extended time series, fishing mortalities, multispecies assessment, predation rate, stock/recruitment.

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Introduction

The North Sea stocks of cod, haddock, and whiting have been important commercial fish resources for the whole of the twentieth century and collectively these roundfish species have supported large demersal fisheries. Hislop (1996) provides details of the development in yields and stock sizes. However, trends in fishing intensity and biomass for these species are less certain. Figure 1 shows trends in fishing mortality estimates (ICES, 1992) obtained by calibrating fishing effort for Scottish trawlers (ICES, 1969) to Virtual Population Analysis (VPA) estimates of fishing mortality rate. Calibration of the effort was performed using data from 1960–1966, where the overlap in the two time series occurred. The calibrated fishing effort was then used to estimate historic levels of fishing mortality for the period 1914 to the beginning of the time series of VPA fishing mortality rates. Such estimates are necessarily tentative because they rely upon unsupported assumptions about changes in fleet efficiency and fleet composition. In particular the high estimates of fishing mortality rates (F) obtained during World War I are frankly unbelievable and should be disregarded. These problems probably result from distortions in the size structure and behaviour of the Scottish fleet during these years. Estimates of fishing mortality rates for haddock would seem to remain unrealistically high until about 1930, but those for whiting and for cod appear more realistic in this period. However, even after making allowance for some upward bias, these estimates would indicate that fishing mortality rates before World War II were not negligible. Daan *et al.* (1994) present an updated version of these calculations for cod, concluding that estimates of cod fishing mortality rate were of the order of 0.4 for the earlier decades of the century, except when fishing was disrupted by the two war periods.

Trends in recruitment and in stock biomass are available from 1963 onwards from ICES (1995a). Before this period some estimates of recruitment trends are available, particularly for haddock (Jones and Hislop, 1978; Sahrhage and Wagner, 1978), but estimates of absolute stock size and recruitment have not been available. The first objective of this paper is to attempt to remedy these deficiencies by estimating fishing mortality rate recruitment, and spawning-stock series based upon VPA calculations for cod and haddock and a stock structure reconstruction model for whiting. This has been attempted using such national and international data sets as were available to the authors. These are necessarily incomplete and thus all results must be regarded as tentative. However, they do provide some insight into

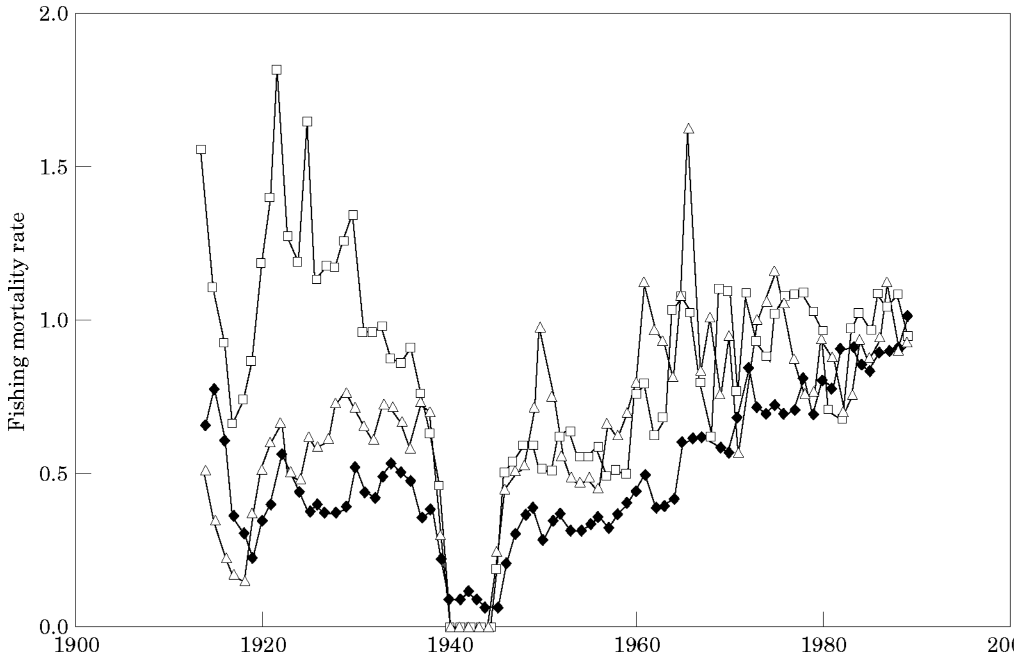

Figure 1. Fishing mortality rates for North Sea cod (—◆—), haddock (—□—) and whiting (—△—) for the years 1914–1989, based on calibrated fishing effort data for years prior to 1960 and on VPA estimates for later years (from ICES, 1992).

the pre-VPA years and also indicate what might be achieved with a more general pooling of archived material.

Many of the changes in yield and stock biomass may be explained by classical ideas of single-species yield per recruit management (e.g. the increases of stock biomass after World War I and II during which the stocks had been rested from fishing). However, the traditional yield per recruit models fail to explain all the changes that have occurred and a number of alternative hypotheses have been proposed. These can broadly be classified as the effect of stock recruitment relationships, multispecies interactions, and environmental variations. A second objective of this paper is to use the extended time series to examine the fisheries hypotheses over a longer time frame. Since even these restricted objectives necessarily cover a broad canvas, the paper is organized into self-contained sections dealing with, (1) the estimation of population trends and fishing mortality rate (2) stock recruitment effects, and (3) multispecies effects.

1. Fishing mortality rate and population estimates

Data sources and methods

Cod

Standard VPA techniques were applied to such commercial catch-at-age data and tuning data as could be assembled. Total international catch-at-age data for the period 1963–1993 were adopted from ICES (1995a). For the earlier period, total international landings (ICES, 1969) were used to raise samples to total international catch-at-age for the period 1921–1962. Catch-at-age data were derived from the following data sets.

(1) An average age–length key (ALK) for the period 1919–1927 for Grimsby trawlers (Graham, 1938) was applied to annual length compositions for the same fleet available from national records for the period 1921–1938.
(2) An average ALK for the period 1956–1962 for North Shields trawlers and seiners was applied to annual length compositions for the same fleets for the period 1946–1955.
(3) Annual age compositions for Grimsby trawlers and seiners, and North Shields seiners were used to construct total international catch-at-age data for the period 1956–1962.
(4) Mean weight-at-age for the period 1921–1955 were taken as the average for the period 1956–1960 from sampled English vessels.

The reliance on English catch sampling for the pre-1963 period is of course a weakness in the approach. This may have caused biases in these estimates and the question arises as to how representative are the English fleet age compositions with respect to the total international landings. The main fishing area for the Grimsby and North Shields fleets in the selected years is likely to have been the central North Sea (ICES Division IVb), with activity more concentrated in the west of the area, especially for the latter fleet (Graham, 1934; MAFF data). Separate age-composition data for Divisions IVa and IVbc as compiled by ICES (1974) indicate that relatively more younger cod are caught in IVbc. This suggests that the international age compositions derived might be biased towards the younger cod. The magnitude of this effect is impossible to quantify, but this question should clearly be further investigated.

For the periods 1921–1938 and 1946–1962, the available ALKs were used to convert length data to catch-at-age by the method of Kimura and Chikuni (1987), as modified by MacDonald *et al.* (1994). These English catch-at-age compositions were raised to total international catch-at-age compositions by the ratio of the landings. A VPA was carried out for two periods. For the period 1921–1938, a separable VPA was run for ages 1 to 6 using the standard defaults in the Lowestoft VPA tuning package (Darby and Flatman, 1994). After some trial runs, terminal fishing mortality rate was set at 0.4 with age 3 as the age of unit selection; selection on age 6 was set at 0.8. For the period 1946–1993, a tuned VPA was run using the XSA method with the standard defaults in the same package. The VPA was run on ages 1 to 7 and treating age 8 as the plus group. Tuning was performed over 10 years, with the recruit age set to age 1 and the lower age for constant catchability at 5.

Haddock

Results for the period 1963–1993 were taken from ICES (1995a); for the periods prior to 1962 simple VPA techniques were run on haddock catch-at-age data raised from Scottish groundfish survey results, an approach pioneered by Garrod, (1973).

Catch-at-age data from the Scottish groundfish survey for the periods 1920–1937 and 1945–1962 were taken from Sahrhage and Wagner (1978; table 34) and were augmented by data presented by Jones and Hislop (1978; table 23) for the years 1938–1939 and 1954–1957, since data for these years were either missing or had reduced age ranges in the former series. Lacking other data, it was assumed that the total international catch would have the same age composition of catch as the survey data, but that some proportion of the catch at each age would be discarded. The proportion of the catch retained-at-age was taken as equivalent to the average of the period 1963–1970 (as available in Working Group files). In the raising procedure, these estimates of the retained proportions and estimates of weight-at-age were first used to estimate an equivalent "landed weight" from the survey catch-at-age data for each individual year. The survey catch-at-age data were then raised by the ratio of the total international weight landed each year (as given in ICES, 1969) to the survey "landed weight" estimate. The weights-at-age used were constructed by first averaging the area based mean length-at-age data for the third quarter using data given in table 25 of Jones and Hislop (1978) for the groups of years reported. The mean lengths-at-age were converted to mean weights-at-age by assuming isometric growth and using a condition factor of 0.012 g cm^{-3}. This condition factor was chosen so that the method, when applied to age 5 length data for the years 1963–1969, gave equivalent results to the observed age 5 weights as available in ICES working group files for the same years.

For the period 1920–1939, a spreadsheet VPA was run on ages 0 to 7 with age 8 as a plus group. Terminal fishing mortality rate in 1939 were based on the estimate of fishing mortality rate for 1939 given in ICES (1992) modified by the average exploitation pattern during the period 1963–1993 (ICES, 1995a). Fishing mortality rate on the 7-year-olds were initially based on the results of ICES (1992), but subsequently modified to correspond approximately (with adjustments for the partial exploitation pattern on the younger ages) to the average fishing mortality rate on ages 2–6.

Whiting

Very little whiting catch-at-age data have been published for the period before 1960, although survey-based catch per unit effort data for age 2 fish and length distribution data (Jones and Hislop, 1978) suggest that some material may exist. Consequently, for the periods prior to 1960 Working Group VPA results for the period 1960–1993 plus the calibrated fishing effort data (ICES, 1992) were used to reconstruct age structure. It should be noted that the VPA catch-at-age data for the whiting are less reliable than those for cod and haddock.

Additional assumptions needed to interpret these data as population numbers and mortality were: (1) mean weights-at-age were the same as for the period 1960–1993; (2) the mean retained proportion-at-age was the same as for the period 1960–1970 (as available in Working Group files); (3) the exploitation pattern was the same as during the period 1960–1970 (ICES, 1995a).

Given these assumptions, the stock recovery method proceeds by first making estimates of the contribution that an average recruit, of each year-class from 1910–1959, would have made to the landings in each year from 1920–1960. These contributions were then multiplied by initial estimates of recruitment for the years 1910 to 1959 to provide estimates of total landings each year. The initial recruitment estimates were then adjusted to reproduce the historic landings and the initial (1960) age structure as closely as possible. The goodness-of-fit criterion adopted was the sum of squared differences between observed and estimated landings. Year-class strengths were constrained to be positive and year classes from 1953–1959 were chosen to replicate the VPA population estimates in 1960. The estimates of recruitment thus obtained will necessarily be poorly determined, but running averages should give some information of the general trends in recruitment. This

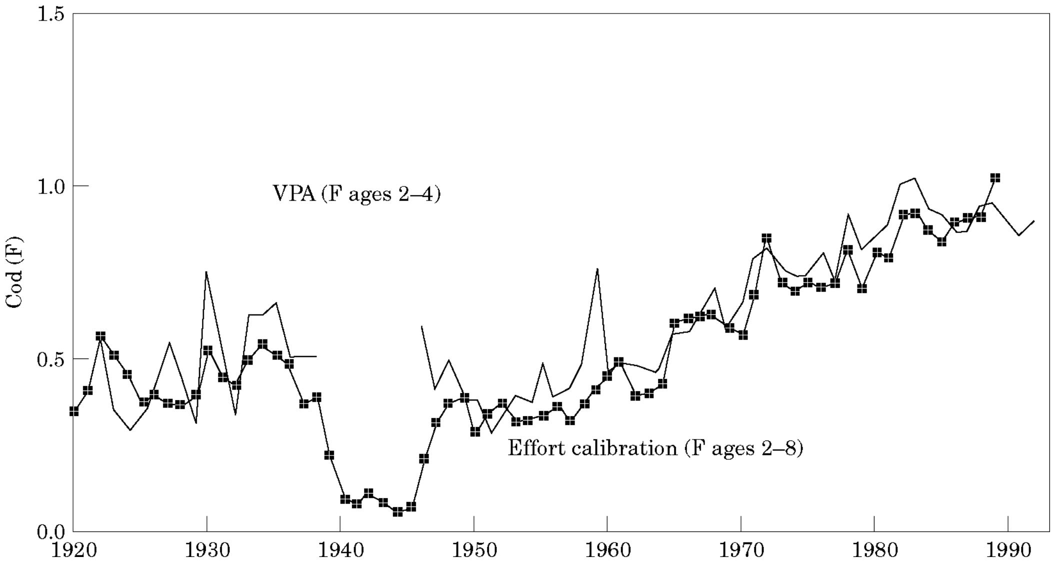

Figure 2. Fishing mortality rates for cod, as estimated by the new VPA (for 1921–1992 as averages of ages 2–4), contrasted with the results (for 1920–1989 as averages of ages 2–8) of ICES (1992).

approach may be seen as a more exact development of that used for North Sea cod by Daan *et al.* (1994).

Results and discussion

The population and mortality time series presented for North Sea cod, haddock, and whiting more than double the number of years results available from traditional VPA (ICES, 1995a). This substantial extension of our knowledge of these stocks may contribute to our perspective on their proper management. However, the methods adopted to make stock estimates for earlier years are based on poorer and less representative data sets than those of the Working Group, and thus the results should be treated with suitable caution. The approximations and assumptions used may have tended to smear year classes together and/or displace year classes. They may also be biased since they are based on partial data sets. These estimates are thus more suitable for examining broad temporal trends than the detail of annual environmental effects. The results for whiting in particular depend critically upon the assumptions made.

With these cautions the following general points are worth noting. Trends in the cod VPA fishing mortality rate (F) correspond closely with those generated by the calibration of fishing effort (Fig. 2). Trends have continued steadily upward since World War II. Trends in the haddock VPA fishing mortality rate (Fig. 3) also correspond closely with those generated by the calibration of fishing effort (ICES, 1992) in the 1930s but are rather higher in the 1940s and considerably lower in the 1920s. Fishing mortality for haddock thus appears (excepting the period of World War II) to have been relatively constant over the entire period. Trends in whiting fishing mortality rate (Fig. 1) were as reported in ICES (1992) and thus might be biased in a similar fashion to the haddock results in that report.

Trends in recruitment confirm the exceptional nature of the period following 1960, particularly for cod (Fig. 4) and haddock (Fig. 5). Pre-World War II recruitments of these species were somewhat higher than those in the period 1945–1960. The stock reconstruction model used for whiting in the pre-1960 period will tend to produce unconditioned answers for annual recruitment (Fig. 6). Thus the large 1944 and 1949 year classes may include numbers from adjacent year classes. It would seem that in the pre-World War II period whiting recruitment was generally lower than in the post-war period, but this finding could have resulted if the estimates of fishing mortality rates used in the reconstruction model had been biased upward during this period in a similar fashion to the equivalent haddock results. However, it is interesting to note that beach seine surveys on the southern coast of Norway also show low numbers of 0-group whiting in this period (Johannessen and Sollie, 1994).

2. Stock/recruitment effects

Methods

Clear relationships are seldom apparent from simple plots of recruitment against spawning-stock biomass. In this respect, the extended results for the roundfish discussed in section 2 proved no exception. Nevertheless,

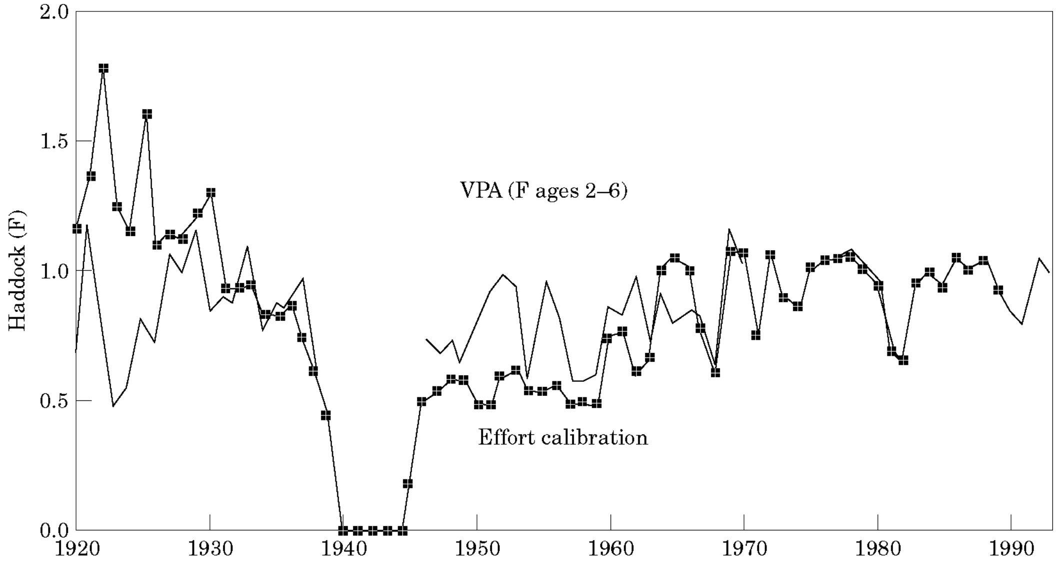

Figure 3. Fishing mortality rates for haddock, as estimated by the new VPA (for 1920–1993 as averages of ages 2–6), contrasted with the results (for 1920–1989 as averages of ages 2–6) of ICES (1992).

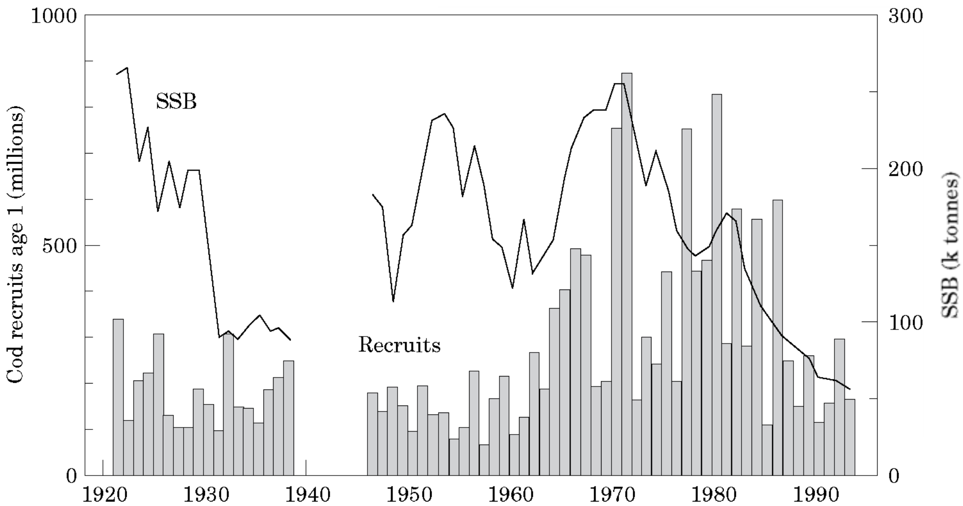

Figure 4. Recruitment (as age 1 fish in millions) and spawning-stock biomass (in thousand tonnes) for cod 1921–1993, as estimated by VPA.

there is a requirement on fisheries scientists to indicate safe and unsafe levels of exploitation. The method adopted here is to use a modification of an approach suggested by Pope in a working paper (ICES, 1993). This method, "Wise Virgins Analysis", has the objective of estimating those levels of fishing mortality rate that would not have eroded the spawning-stock biomass in the period of worst survival conditions experienced in the historic series. The analysis proceeds by estimating the upper and lower replacement envelopes of the 7-year running average of survival. These survival envelopes can then be compared to the equivalent spawning-stock replacement rates that would occur at different fishing mortalities.

The approach uses running averages of survival and spawning stock biomass to smooth out inter-annual effects, on the basis that it is the occurrence of a series of years of poor survival, rather than a single very poor year that is likely to lead to a serious erosion of spawning-stock biomass when fishing mortality rates are too high. Thus it is the sustainable levels of fishing for such periods that the method seeks to detect. The choice

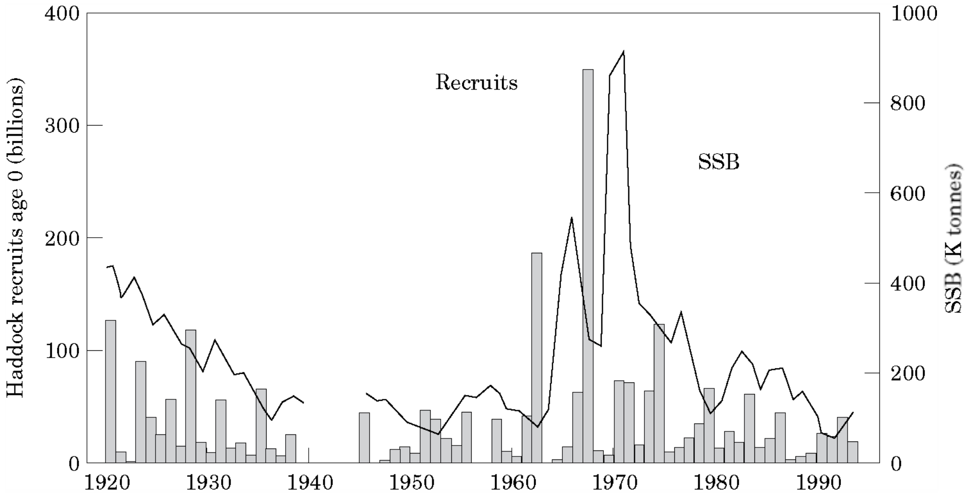

Figure 5. Recruitment (as age 0 fish in billions) and spawning-stock biomass (in thousand tonnes) for haddock 1920–1993, as estimated by VPA.

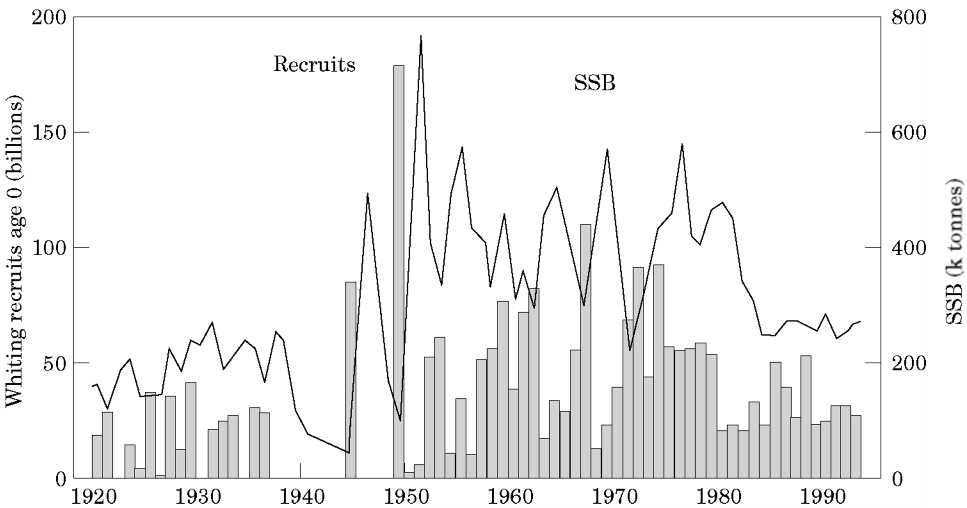

Figure 6. Recruitment (as age 0 fish in billions) and spawning-stock biomass (in thousand tonnes) for whiting 1920–1993, as estimated by the stock structure/recruitment recovery model.

of a 7-year averaging period is arbitrary, based on the biblical 7 lean years (Genesis, Chapter XLI). However, 7 years would cover the time between birth and maturity of the majority of temperate and boreal shelf demersal species and is also of the order of years over which bad management might seriously erode a stock. Thus the object of the analysis is to try to determine levels of fishing which would keep a fish stock's "lamp burning through the dark watches of the night" and hence its title (Matthew Chapter XXV). The choice of a period of 5–7 years is also appropriate given the quality of recruitment estimates before 1963.

This formulation is slightly different from that originally proposed by Pope, which plotted 7-year running averages of recruitment and spawning stock. It was modified because when fish stocks have an age of maturity of less than 7 years, the spawning stocks in the later years of the averaging period results from the recruitment in the earlier years. Thus, with the original formulation spurious correlation would be induced between the two averages. This might be prevented either by choosing an averaging period shorter than the average time to maturity or by averaging survival rates rather than recruitment. The former approach would give an unacceptably short averaging period for whiting and would give different periods for all three stocks, so the latter approach was considered more appropriate.

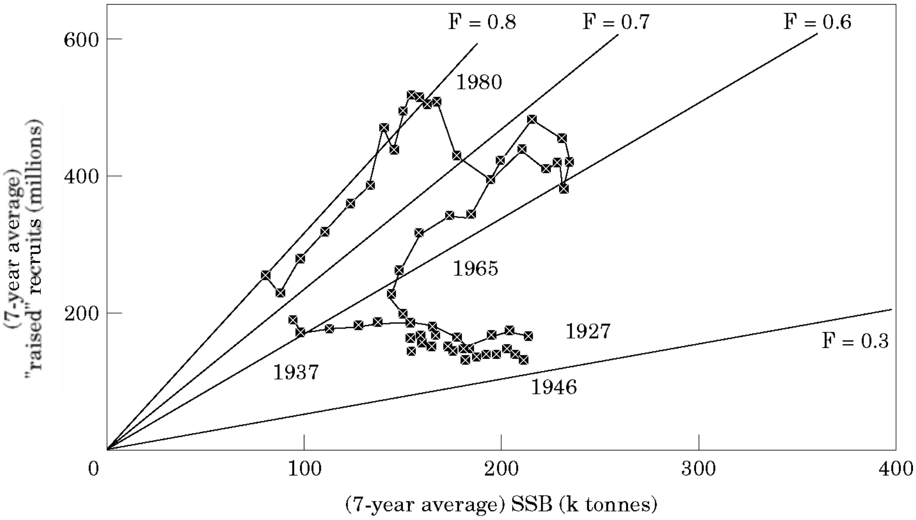

Figure 7. "Wise Virgins" plot for cod for the years 1927–1937 and 1946–1991.

Presentation is in the form of a pseudo-stock recruitment diagram called a "Wise Virgins" plot of the construct $\bar{S}.\ (\overline{R/s})$ against $\bar{S}$, where $\bar{S}$ is the 7-year running average of spawning-stock biomass and $(\overline{R/s})$ is the 7-year running average of the ratio of annual recruitment to annual spawning-stock biomass. For simplicity, the construct is called the "raised recruitment". Although this presentation is readily comparable to usual stock-recruitment plots, the formulation is unsuited to most forms of statistical analysis, owing to the presence of $\bar{S}$ on both sides of the equation, and also to the use of running averages.

Spawning-stock biomasses and recruitment estimates of cod, haddock, and whiting used in the calculations are as reported in section 1. In order to translate survival rates into equivalent replacement fishing mortality rates, exploitation patterns and relevant life history parameters were adopted from ICES (1995a).

Results and discussion

The Wise Virgin plot for cod (Fig. 7) indicates that the relationship of raised recruitment to average spawning-stock biomass has had a number of separate stanzas. In the period 1927–1938 raised recruitment appears to hold constant through a period of declining spawning-stock biomass. A similar behaviour is also observed in the early post-war period until about 1964. A period of increased spawning-stock biomass and raised recruitment occurs between 1965 and 1980, but both have declined during the most recent years. The plot indicates that survival rates have seldom been higher than would give replacement when $F \geq 0.8$, while $F=0.6$ would have provided replacement since 1964 and $F=0.3$ would have allowed replacement in all periods.

Apart from a brief period of low survival following World War II, the raised recruitment of haddock (Fig. 8) has generally been maintained between the replacement lines generated by $F=0.6$ and $F=1.3$. Exceptionally, during the 1960s survival rates were higher than required to provide replacement at a fishing mortality rate of 1.3.

Whiting (Fig. 9) exhibited low survival levels during World War II (N.B. the reconstruction approach allows estimates of recruitment and SSB during the war years). Low survival was also observed in the mid-1950s and in recent years. High survival rates occurred for whiting in the post-World War II period and during the 1960s when levels were observed which were larger than that required to sustain a fishing mortality rate of 1.2.

In summary, evidence from the extended time series confirms that cod in the past decade has experienced higher fishing mortalities than ever before, and replacement has seldom been consistent with such levels. This supports the recent concern of the ICES Advisory Committee on Fisheries Management (ACFM; ICES, 1995b), that cod recruitment might be in decline as a result of fishery-induced declines in spawning-stock biomass and that exploitation is outside safe biological limits.

The case for a similar concern for haddock is less clear. The average F during the last decade (0.83) approximately equates to the mid-range of replacement levels that have been observed historically. However, a lower fishing mortality rate, at about the 0.6 level, would seem entirely safe.

The situation for whiting is even less clear. Although whiting has in some periods replaced itself at levels comfortably higher than the highest F observed in the entire time series, in other periods it has had low

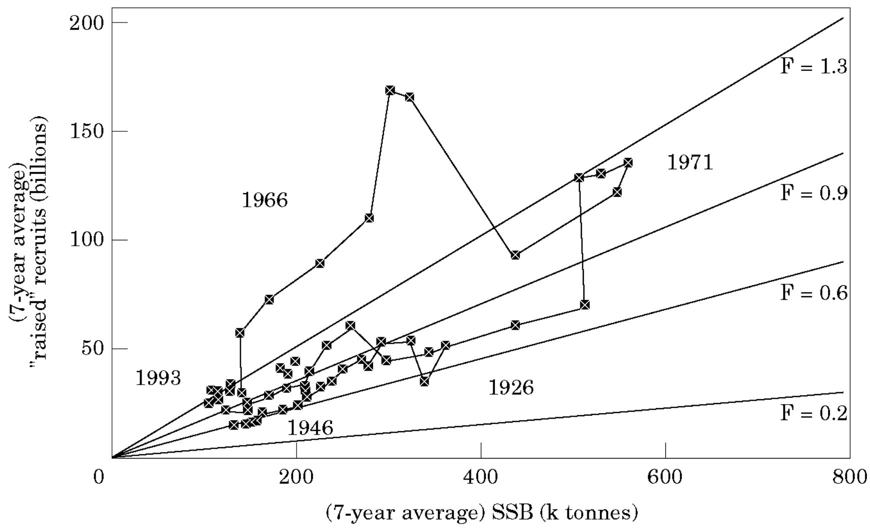

Figure 8. "Wise Virgins" plot for haddock for the years 1926–1937 and 1946–1993.

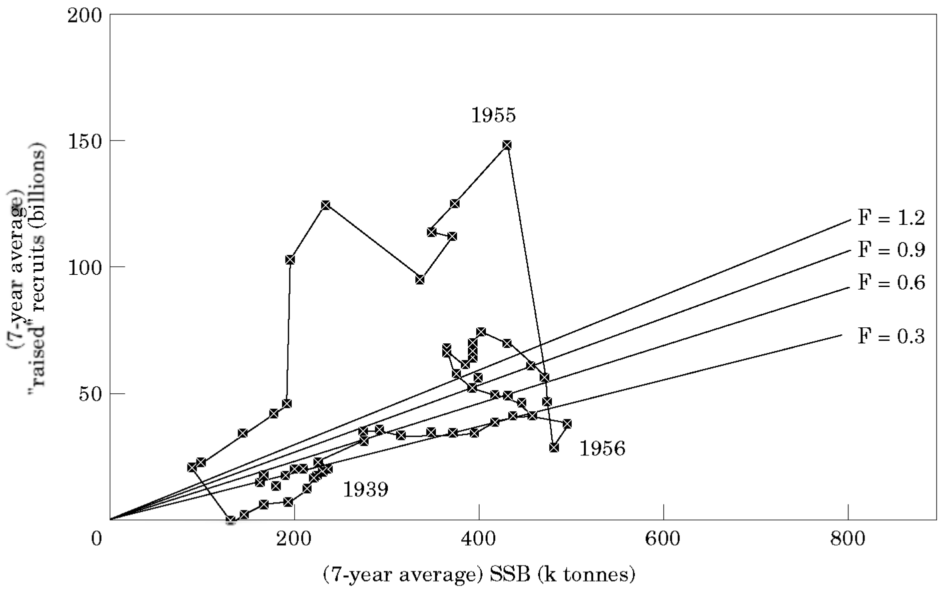

Figure 9. "Wise Virgins" plot for whiting for the years 1926–1993.

replacement rates, which inevitably lead to stock decline unless very low rates of fishing mortality are chosen.

Thus the hypothesis that stock recruitment effects may have caused recent recruitment declines cannot be rejected for cod. For the other stocks, the average replacement levels indicate that replacement, for whatever reason, may remain under average levels for a decade or more. Thus, factors under human control, such as the level of fishing mortality and consequently spawning-stock size, are likely to generate serious downward changes in stock abundance at this time scale and hence the yield of the roundfish stocks.

3. Predation factors

Methods and data sources

Predation mortality may vary through time as a result of changes in the abundance of predators or as a result of changes in alternative prey. Cod and whiting are significant predators of smaller individuals of all three roundfish species, while the reduction fishery species, sandeel and Norway pout, are important alternative prey. The approach used to investigate changes in predation mortality was to form simple estimates of mutual predation between cod, haddock, and whiting and to examine how these rates had changed over the time period 1921–1993. Changes in abundance of alternative prey are also examined.

The multispecies version of Virtual Population Analysis (MSVPA; ICES, 1994) calculates the predation mortality generated on each age of prey by all predators in the model for the years 1974–1992. To run the full MSVPA model requires catch-at-age data for all five predator and nine prey species for each year. These data are not available for some species prior to 1974 and thus the model cannot be run on these years. Pope and Macer (1991) indicated an approximate way of estimating predation mortality rates for earlier years by utilizing the Shepherd (1984) feeding model which supposes that predation mortality rate is purely a function of predator biomass and is unaffected by prey abundance. This approach, rather than the model of Gislason and Helgason (1988) used by the Multispecies Assessment Working Group, was chosen because it does not require estimates of the biomass of all prey species.

Using a similar approach, approximate estimates of predation mortality, generated by cod, haddock, and whiting preying on smaller individuals of these species, were made for each prey species age group by each predator species. This was achieved by:

(1) Creating a matrix UM2 of predation per unit biomass for cod, haddock, and whiting as predator and prey by adapting a standard output of the MSVPA (ICES, 1994). This output provides estimates of the predation mortality M2(s,a,S,A,*) generated by each age (A) of each predator species (S) on each age (a) of each prey species (s) in a reference year * and of the average biomass B′(S,A,*) of each predator age in the reference year. The matrix UM2 has rows equal to the number of prey age, species combinations, columns equal to the number of predator age-species combinations and has elements formed of M2(s,a,S,A,*)/B′(S,A,*).

(2) Creating a matrix $\bar{B}$ of the average biomass in the sea each year (y) of each age of each predator species. This matrix has rows equal to the number of predator age-species combinations and columns equal to the number of years and has elements $W(S,A,y) \cdot \bar{P}(S,A,y)$, where W is the average stock weight and $\bar{P}$ is the average population. The $\bar{P}(S,A,y)$ are derived from the results of the single species models developed in section 1.

(3) Forming the matrix M2 of predation mortality on each age of each prey. This matrix is formed as the matrix product of $UM2*\bar{B}$. Equivalent matrix equations that provide the predation mortality generated by each individual predator species can be derived in a similar fashion.

Results and discussion

Observed changes in decadal recruitment levels are typically a factor about twofold and are thus of a scale that might possibly be explained by variations of less than 1.0 in the cumulative predation mortality rate on individual year classes. Therefore, predation is presented as the cumulative estimate of predation mortality rate for each year class generated by the three species.

The cumulative predation mortality rates are calculated with a series of assumptions and thus have the following limitations:

- predators create a predation pressure on prey proportional only to predator biomass and there is thus no allowance for possible predator satiation or for prey substitution;
- predation estimates make no allowance for predation by other species, e.g. saithe or mackerel;
- a constant predation rate per unit biomass (cf. Shepherd, 1984) may tend to give upwardly biased estimates of predation mortality at times of high abundance of all prey;
- the cumulative predation rates for the year classes immediately preceding World War II and immediately proceeding 1993 are incomplete, because predation will have continued outside the studied period.

In considering the impact of predation mortality rate on the recruitment to the individual stocks, it should be noted that variable predation mortality rates were not included in the population estimation models used in section 1. Therefore, year classes suffering higher cumulative predation mortality rates will have their recruitment underestimated by the single species models.

Of the three predators, cod generated the greater part of the predation mortality on cod before World War II (Fig. 10). Predation mortality rates were highest at the time of the high stock sizes of these species in the period 1960–1980 and were generally lower prior to World War II and in recent years. Cumulative predation rates on haddock (Fig. 11) are similar to those on cod, but are more dependent on whiting predation. They show the same general historical patterns. For whiting, cannibalism is the largest source of predation mortality after about 1960 (Fig. 12). Predation levels on whiting are higher than those on cod and haddock, but show the same general historical patterns. Predation by haddock on all species is negligible.

The results indicate that the cumulative predation mortality created by a subset of predators can vary between decades by as much as 1.0, which would correspond to a 2.7 variation in inter-decadal recruitment. However, the calculated predation mortalities seem to increase rather than decrease estimates of inter-decadal variation in survival, since they are highest at the time

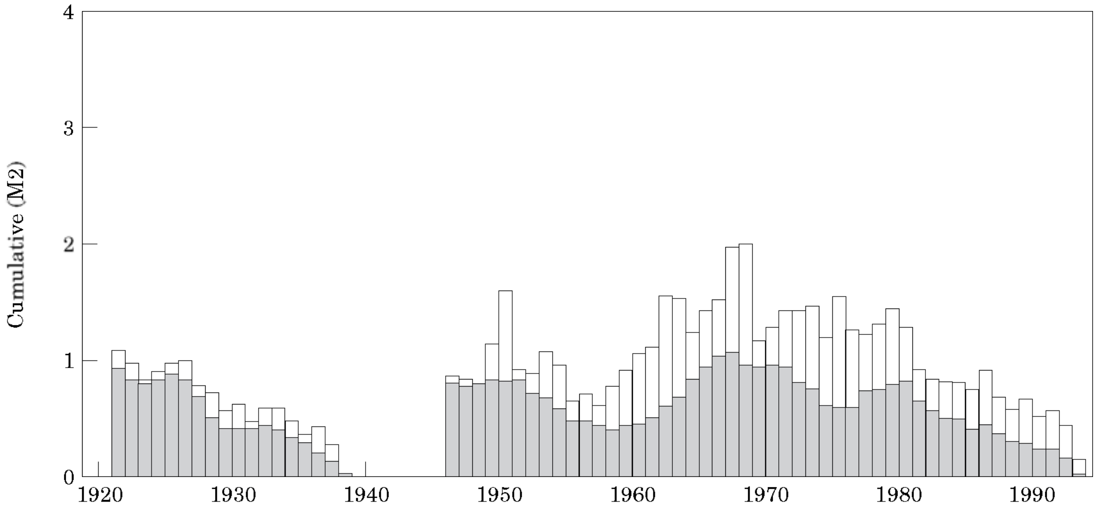

Figure 10. Estimates of the cumulative predation mortality rates on each year class of cod (from 1921–1938 and 1946–1993), as generated by the cod (□), haddock (■), and whiting (□) acting as predators (N.B.: rates are incomplete in the final years of the two time series).

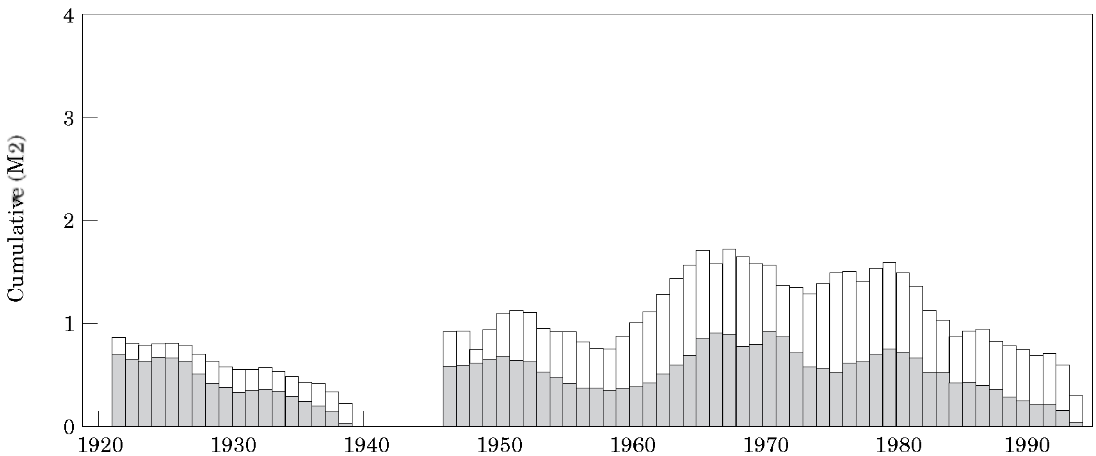

Figure 11. Estimates of the cumulative predation mortality rates on each year class of haddock (from 1921–1938 and 1946–1993), as generated by the cod (□), haddock (■), and whiting (□) acting as predators (N.B.: rates are incomplete in the final year of the two time series).

when roundfish stocks were highest. Thus these results indicate that recruitment must have reached even higher peaks in the 1960s than were estimated by the single species VPAs. Including mutual predation effects would seem to amplify the size of the "gadoid outburst" rather than explain it.

It follows that multispecies factors that might explain the substantial inter-decadal changes in recruitment of the roundfish would have to draw on more subtle effects than changes in the abundance of their direct predators, since these are predominantly the roundfish themselves. Variations in the availability of suitable alternative prey might be a possible mechanism. However, the collapse of the recruitment of North Sea pelagic stocks in the 1960s (Cushing, 1992), and the possibly reduced abundance of larval sandeels noted by Hart (1974), following the increase in industrial landings, might point to downward changes in the general abundance of those prey that are suitable to many predators as substitutes for small roundfish. Therefore, these changes do tend to increase estimates of predation during the period of highest roundfish recruitment and hence not to explain the increased recruitment.

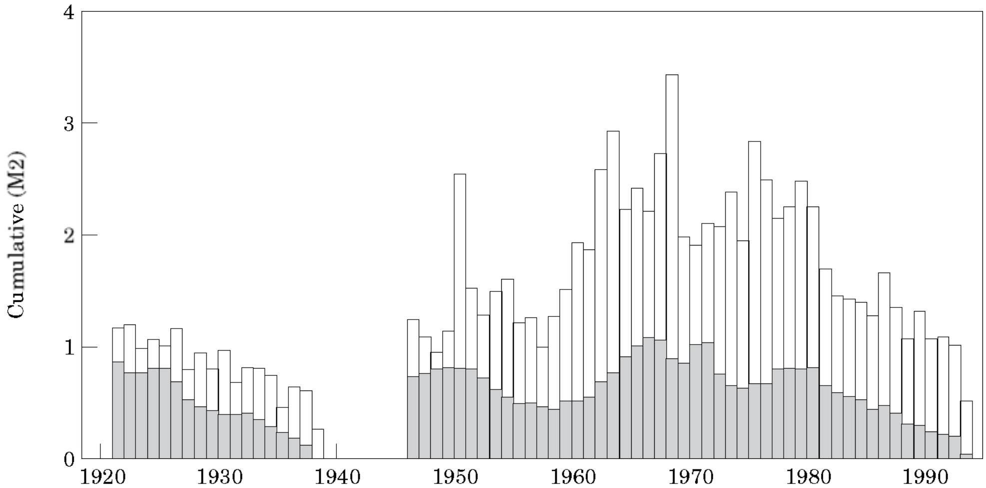

Figure 12. Estimates of the cumulative predation mortality rates on each year class of whiting (from 1921–1938 and 1946–1993), as generated by the cod (□), haddock (■), and whiting (□) acting as predators (N.B.: rates are incomplete in the final years of the two time series).

In summary, while predation effects will certainly have altered recruitment, they do not account for the main trends, and thus seem unlikely as a prime influence.

Conclusions

The extended time series of roundfish recruitment, spawning-stock biomass and fishing mortality provide a perspective for fisheries management and a basis for testing hypotheses about the causes of recruitment variation. Particularly, the extension to years before the expansion of these stocks and the fisheries on them during the 1960s and 1970s lends perspective to the pessimistic views that can be engendered by the assessment time series beginning at a period of high stock.

These extended assessments are necessarily based on partial and possibly biased data and they should be regarded as a tentative rather than as a definitive reconstruction of the earlier development of the stocks. Nevertheless, the different analyses for cod provide essentially the same answers and confirm earlier estimates by Daan *et al.* (1994) that, excepting the war periods, fishing mortality rates fluctuated around 0.5 up to about 1960. Thereafter, fishing mortality rates increased progressively to the current high levels of above 0.8. According to the new results, the haddock fishing mortality rates have been somewhat higher and fluctuated about 0.75 for most of the century. They are thus somewhat lower than the estimates of ICES (1992) but are still substantial. In judging the reliability of these estimates, it should be remembered that the pre-1962 haddock length and age compositions are based on fishery independent survey catches and are therefore not responsive to changes in fleet behaviour.

Despite the caveats caused by raising partial data, the estimates provided a picture of the general state of the stocks and the fisheries on them in the earlier period that will be open to being questioned by the other extant qualitative and quantitative data, whose retrieval they may stimulate.

The extended whiting population series, which are not based on any additional catch-at-age data, should be viewed with particular caution, especially as a statement of the annual effects. Even the recent assessments are generally not supported by independent survey information and the extended series can only be worse. One of the problems is caused by discard practices, and if the lower landings during the early part of the century were due to a smaller proportion of whiting catches being landed during this period than subsequently became the case, the reconstructed population would be strongly affected. However, while whiting is not generally as valuable as cod or haddock the economic circumstances of the 1930s depression might suggest that they would have been landed.

The most striking feature in all three roundfish stocks is the increased recruitment of the late 1960s and 1970s known as the ‘‘gadoid outburst’’. The proper management of North Sea roundfish species requires fundamental answers as to which are the key factors to influence recruitment levels. The major concern is whether recent declines of cod and haddock recruitment represent a return to more ‘‘normal’’ levels or are symptoms of a more serious state of recruitment overfishing. This requires an answer as to whether the substantial changes observed since World War II are a result of environmental changes or result from the effects of fishing acting either directly on roundfish or indirectly on other resources within the ecosystem. This will determine the extent to which fisheries management might be able to influence such changes and to what extent they must be weathered.

Consideration of stock recruitment effects using the Wise Virgins approach indicated that the cod stock may have been fished at unsustainable levels in recent years. Fishing has depressed the spawning-stock size to its lowest level in the time series. However, whether this has caused the resulting lower recruitment of the past decade remains uncertain. The results for haddock and whiting did not indicate that current exploitation levels were unsustainable for these stocks. However, lower levels of fishing mortality on haddock would be prudent.

Changes in natural mortality caused by changes in predation between the three roundfish species are another possible cause of recruitment variation. However, the studies conducted in section 3 suggest that, while the predation mortality certainly fluctuates substantially over the time series, it was elevated at the time of the "gadoid outburst and" will thus tend to have reduced rather than increased apparent recruitment estimates in that period. It would thus seem an important consideration but one which emphasizes rather than explains the main feature of the recruitment series.

Environmental factors (both physical and biological) have been proposed as a major source of variation in the recruitment of North Sea fish stocks. However, the study of these factors is left for future work. A problem will be that over the period of concern only relatively few consistent time series of environmental data exist. Existing partial series can be classified as being those likely to promote inter-annual variation but which have little inter-decadal trend (e.g. temperature) and those which show broader inter-decadal variations. In practice, factors influencing inter-decadal rather than inter-annual variation of recruitment are likely to be more important. In this context it is notable that the period of high roundfish recruitment was also an anomalous period for the North Atlantic Oscillation, the mezozooplankton and phytoplankton abundance as shown by the Continuous Plankton Recorder (North Sea Task Force, 1993) and broad scale hydrographic events (Dickson *et al.*, 1988). Thus results from such series should certainly be tested against the extended recruitment series.

Clearly, the potential causes of inter-decadal variations in the roundfish need further study. What is certain is that longer time series of stock data, on which hypotheses can be tested, provide a valuable perspective. However, their best formulation will be beyond the data or time resources of any one individual or institute, since many institutes may have as yet untapped data in their archives. It follows that a North Sea archive recovery and interpretation study group might profitably be established with the intention of integrating all the information available with the earlier fisheries literature.

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