ICES Journal of Marine Science, 54: 924–933. 1997

Stock trends in six North Sea stocks as revealed by an analysis of research vessel surveys

R. M. Cook

Cook, R. M. 1997. Stock trends in six North Sea stocks as revealed by an analysis of research vessel surveys. – ICES Journal of Marine Science, 54: 924–933.

A model is developed for the analysis of age disaggregated indices of abundance from which stock trends can be estimated. The model is used to examine trends in North Sea cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*), whiting (*Merlangius merlangus*), sole (*Solea solea*), plaice (*Pleuronectes platessa*) and herring (*Clupea harengus*). These are compared with the trends estimated from conventional ICES assessments which use commercial catch-at-age data. The catch data are known to be affected by misreporting which can affect the calculated stock trends. The surveys appear to be able to quantify the trends in recruitment and spawning stock with a high degree of consistency between independent surveys of the same stock and with the conventional assessment. Estimates of catch and fishing mortality rate are more uncertain. The well known problems of catch mis-reporting which affect the conventional ICES assessments do not appear large enough to alter the perception of stock trends.

Key words: North Sea, stock trends, surveys, model.

Received 19 July 1996; accepted 28 February 1997.

R. M. Cook: FRS Marine Laboratory, P.O. Box 101, Victoria Road, Aberdeen AB11 9DB, Scotland, UK. Email: cookrm@marlab.ac.uk

Introduction

In common with other areas, fish stocks in the North Sea (ICES Sub-area IV) have been managed under a total allowable catch (TAC) regime for a number of years. The TAC is the principal tool in trying to regulate the overall level of fishing mortality. For many years TACs were set at levels which did not really restrict fishing activity. From about 1989, however, the tendency for stocks to decline and for exploitation rates to increase, triggered a period where TACs were restrictive. The effect of these restrictions was not so much to limit actual catches but to cause a portion of the catch to go unreported or mis-reported. In the first instance this is an enforcement problem but the disruption of accurate landings data has consequences for stock assessment upon which the TACs are based.

All the ICES assessments of the major North Sea fish stocks have conventionally been based on the analysis of commercial catch-at-age data and in recent years have used analytical methods based on survivors (Doubleday, 1981) and CAGEAN (Deriso *et al.*, 1985) as implemented by Darby and Flatman (1994) or Patterson and Melvin (1996). While these methods make use of fishery independent data from research vessel surveys, the commercial catch data dominate the assessment, particularly that of historical trends. The surveys are used to calibrate the populations around the margins of the number at age matrix. Since the fishing mortality for the stocks considered here is high, the conventional VPA equations converge rapidly (Pope, 1972) and most of the analysis will be determined by a transformation of the raw commercial catch at age data into estimates of population and fishing mortality. Thus, with the exception of the most recent years in the analysis, the stock trends are largely independent of the survey data. Since the estimate of total catch is used to scale the samples of the age compositions, any bias in the catch estimate due to mis-reporting will be translated into bias in the estimated stock size. Clearly, if there is a history of misreporting, there is a danger that the estimated stock trends may be misleading. These difficulties may be exacerbated by poor estimates of other parts of the catch such as discards and by-catch in other fisheries.

Recent estimates of so-called ''unallocated'' landings, that is those which have not been reported, for cod, haddock, sole, plaice and herring have been put as high as 10%, 40%, 60%, 35% and 10% of the reported landings, respectively (ICES, 1996a, b). These are maximum figures and in many years estimated unallocated landings have been much less than this. However, variability in the degree of mis-reporting is worse than consistent mis-reporting when trying to estimate trends. The uncertainty engendered by degraded catch data naturally raises questions about the validity of stock trends determined from recent assessments of the major stocks. Since the evaluation of the state of these stocks is very much dependent on the perception of historical stock trends, it is important to investigate their reliability in recent assessments. The fishing industry, in particular, often argues that the degradation of catch data completely obscures the true trends.

This paper examines stock trends estimated from research vessel data alone. These data are less prone to the biases affecting commercial catch data but are subject to greater measurement error due to a generally smaller sample size. Trends estimated from these data should be less subject to bias but may be more affected by noise. Fortunately, for the major stocks considered, there are usually at least two or three independent surveys which can be compared. The analysis shows that for most stocks the surveys support the stock trends estimated from conventional ICES assessments.

Analytical model for Research Vessel data

One of the major potential problems of surveys is that the sample size is generally small and hence the abundance estimates are likely to be noisy. It is, of course, possible to convert the raw abundance estimates from a survey into relative biomass estimates simply by taking a sum of products of the abundance index and the associated weight at age. Fishing mortality can also be calculated by taking the logarithm of successive abundance estimates and subtracting a value for natural mortality. These, however, are likely to be adversely affected by sampling error. To attempt to reduce this problem, a simple model is used here to try to remove some of the noise. The model used is a modification of the commonly used separable model often used in the analysis of catch-at-age data (Deriso *et al.*, 1985; Pope and Shepherd, 1982; Gudmundsson, 1986; Cook and Reeves, 1993). The underlying assumption is that the fishing mortality rate, F, is the multiple of a year effect, f, and an age effect, s, i.e.,

$$F_{a,y} = s_a f_y \tag{1}$$

where a and y index age and year, respectively. Making the usual assumption that the total mortality, Z, is the sum of the fishing mortality rate and natural mortality rate, M, and that populations decay exponentially over time, the number of fish, N, at the start of the year from a particular cohort with an initial number of recruits, R, is given by:

$$N_{a,a-1+y} = R_y e^{-\sum_{i=1}^{a-1} Z_{i,i-1+y}} \tag{2}$$

Now for an abundance index, u, we may assume the following relationship:

$$u_{a,y} = q_a N_{a,y}. \tag{3}$$

Substituting (3) into (2) we obtain:

$$u_{a,a-1+y} = q'_a u_{ry} e^{-\sum_{i=1}^{a-1} Z_{i,i-1+y}} \tag{4}$$

where u_{ry} is the abundance index at the age of recruitment r in year y and the quantity q′ is the ratio:

$$q'_a = \frac{q_a}{q_r}. \tag{5}$$

If catchability is constant for all age groups this ratio will be unity and can be ignored. It is likely that it will not be constant for one or more of the youngest age groups. In this case estimates of the ratio will be required in order to obtain unbiased estimates of the mortality rates.

From equations (1) and (4) it can be seen that any abundance index, u, can be described in terms of the initial cohort size, u_r, the exploitation pattern, s, and the year effects, f. Now let the observed abundance index, û, be measured with log-normal error such that:

$$\hat{u} = ue^{\varepsilon}, \qquad \varepsilon \sim N(0,\sigma^2). \tag{6}$$

Given A age groups and Y years of data it is now possible to estimate the parameters u_r, s, and f by minimizing the sum of squares:

$$\sum_{a=1}^{A} \sum_{y=1}^{Y} [\log(\hat{u}_{a,y}) - \log(u_{a,y})]^2. \tag{7}$$

Since the year and age effects are multiplied, it is necessary to fix at least one parameter in order to scale all the others. A simple way to do this is to set the mean of the year effects to unity,i.e.

$$\frac{1}{Y} \sum_{y=1}^{Y} f_y = 1. \tag{8}$$

In practice it was found that the estimates of f obtained by minimizing (7) were sensitive to noise in the data. An alternative objective function was therefore used which restrained the estimates using a penalty function, i.e.,

$$\sum_{a=1}^{A} \sum_{y=1}^{Y} [\log(\hat{u}_{a,y}) - \log(u_{a,y})]^2 + \lambda \sum_{y=1}^{Y} \left(\frac{f_y}{f_{y-1}}\right)^2. \tag{9}$$

Table 1. Research vessel survey data used in the estimation of stock trends.

Survey	Acronym	Stock	Data age range	Mean F age range	Year range used	q on youngest age	Data source
Scottish groundfish survey	SGFS	cod	1–7	2–6	82–94	0.37	ICES, 1996a
		haddock	1–7	2–6	82–94	0.25	ICES, 1996a
		whiting	1–6	2–5	82–94	0.70	ICES, 1996a
		herring	2–5	2–4	82–95	1.00	ICES, 1996b
English groundfish survey	EGFS	cod	1–7	2–6	82–94	1.00	ICES, 1996a
		haddock	1–7	2–6	82–94	0.50	ICES, 1996a
		whiting	1–7	2–6	82–94	1.00	ICES, 1996a
International bottom trawl survey	IBTS	cod	1–6	2–5	83–94	0.30	ICES, 1996a
		haddock	1–5	2–4	83–94	0.20	ICES, 1996a
		whiting	1–6	2–5	83–94	1.00	ICES, 1996a
		herring	2–5	2–4	83–96	1.00	ICES, 1996b
Beam trawl survey	BTS	plaice	1–7	2–6	85–94	1.00	ICES, 1996a
		sole	1–8	2–7	85–94	0.50	ICES, 1996a
Solea survey	SOL	sole	2–8	2–7	82–94	0.35	ICES, 1996a
Tridens survey	TRI	plaice	1–3	2	82–94	1.00	ICES, 1996a
		sole	1–4	2–3	82–94	1.00	ICES, 1996a
Herring acoustic survey	ACS	herring	2–8	2–6	84–95	1.00	ICES, 1996b

This minimizes the annual change in fishing effort which is appropriate for fisheries which are in a relatively stable condition over short periods of time. The penalty function can be regarded as describing the process noise in the year effect. Other constraints are possible. For example, it would be possible to fit a non-parametric smoother through the year effects (Cleveland, 1981) which might be expected to have a similar effect. Shepherd and Nicholson (1991) constrained the trend in the year effects to a pre-specified slope when analysing catch-at-age data using a similar model. The constraint used here was chosen because it appeared to perform well on the data sets used but alternative parameterizations are worth investigating.

It is worth noting that it is only possible to estimate $A-1$ selectivities, s, and $Y-1$ year effects, f. This is because the estimates of Z are effectively obtained from the ratio:

$$Z_{a,y}=\log\left(\frac{N_{a,y}}{N_{a+1,y+1}}\right) \tag{10}$$

and for AY observations, there are only $(A-1)(Y-1)$ equations of the form of equation (10). This equation also helps in understanding why it is not possible to estimate q' within the objective function (7). Substituting (3) into (10) gives;

$$\log\left[\frac{u_{a,y}}{u_{a+1,y+1}}\right]=\log\left[\frac{q'_a}{q'_{a+1}}\right]-s_a f_y - M_a \tag{11}$$

from which it can be seen that for constant M at age, q' is effectively a correction to M.

Data

The analysis is based on data used in the most recent assessments for North Sea cod, haddock, whiting, plaice, sole and herring (ICES 1996a, b). These reports give age disaggregated abundance indices for the surveys listed in Table 1. The table also gives the type of survey, age range and range of years used. Although some surveys exist for a longer period of years, the analysis was restricted to the period 1982 onwards to avoid difficulties with the assumption of a constant exploitation pattern in the model. The exploitation pattern is likely to change with time and the separability assumption may break down over extended periods.

In addition to the survey data, basic biological information on weight-at-age, maturity-at-age and natural mortality is required for the estimation of spawning stock biomass. These data have been taken from the same sources (ICES 1996a, b) and are based on the input data used by the working groups for the catch forecast. These values are generally an average calculated from recent years.

Methods

The model described above was fitted to the survey data in Table 1. The value of λ was set to one. This is a fairly arbitrary choice which implies the residual error associated with the abundance data is the same as that for the inter-annual change in F. Trial model fits indicated that this represented relatively weak smoothing so should not introduce much additional bias. Estimated trends in

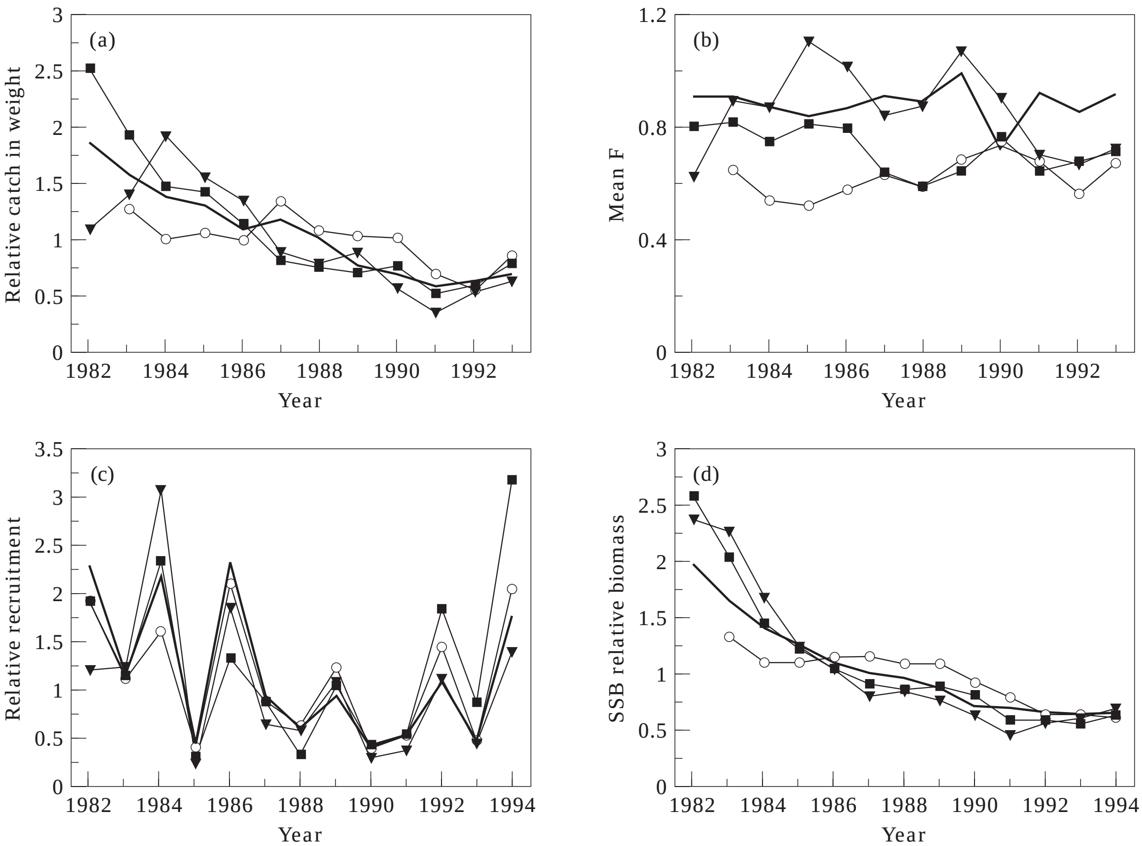

Figure 1. Cod. Trends in (a) catch, (b) mean fishing mortality, (c) recruitment at age 1 and (d) spawning stock biomass for three surveys and the ICES assessment. ■ SGFS, ▼ EGFS, ○ IBTS. The heavy line shows the ICES assessment.

recruitment and spawning stock biomass were not found to be sensitive to the choice of λ.

Another external input required when fitting the model is the specification of q. There is very little information on this quantity. However, only relative values are required for the estimation of trends. Since most of the age composition data are derived from trawl samples, it has been assumed the q is constant above a certain age. In trials, it was found that assuming $q=1$ on all age groups tended to result in negative s values for the youngest age. For this age group, therefore, q was adjusted by trial and error to give a selectivity on the youngest age similar to that obtained from the conventional ICES assessment. The values used are given in Table 1. A value of $q=1$ was retained for all other ages.

After fitting the model, spawning stock biomass was estimated as a simple sum of products of the numbers, weight- and maturity-at-age. A similar calculation enabled the estimation of relative catch biomass. The fitted F values were applied to the fitted numbers at age to estimate the catch in number. The catch in weight was then obtained as the sum of products of the numbers and weight-at-age. Since the value of q used in the analysis was arbitrary, these calculated values are on a relative scale.

Provided the relative values of q have been specified correctly, fishing mortality should be adequately estimated. In common with conventional ICES assessments, a measure of the annual fishing mortality was calculated as the arithmetic mean over a specified age range. The conventional age ranges used in ICES assessments, where data permitted, were used and are given in Table 1.

The four main summary statistics of catch, fishing mortality, recruitment and spawning stock biomass were then compared to the ICES assessment. Since the ICES assessment and the various survey series are all scaled differently, each summary statistic was re-scaled to its mean over the period 1983–1994. This allowed the trends to be compared directly. However, fishing mortality was not re-scaled since these estimates should not be affected by the scale of the abundance indices. The re-scaling procedure means that only the trends for each of the statistics can be compared. Scales across statistics are not comparable.

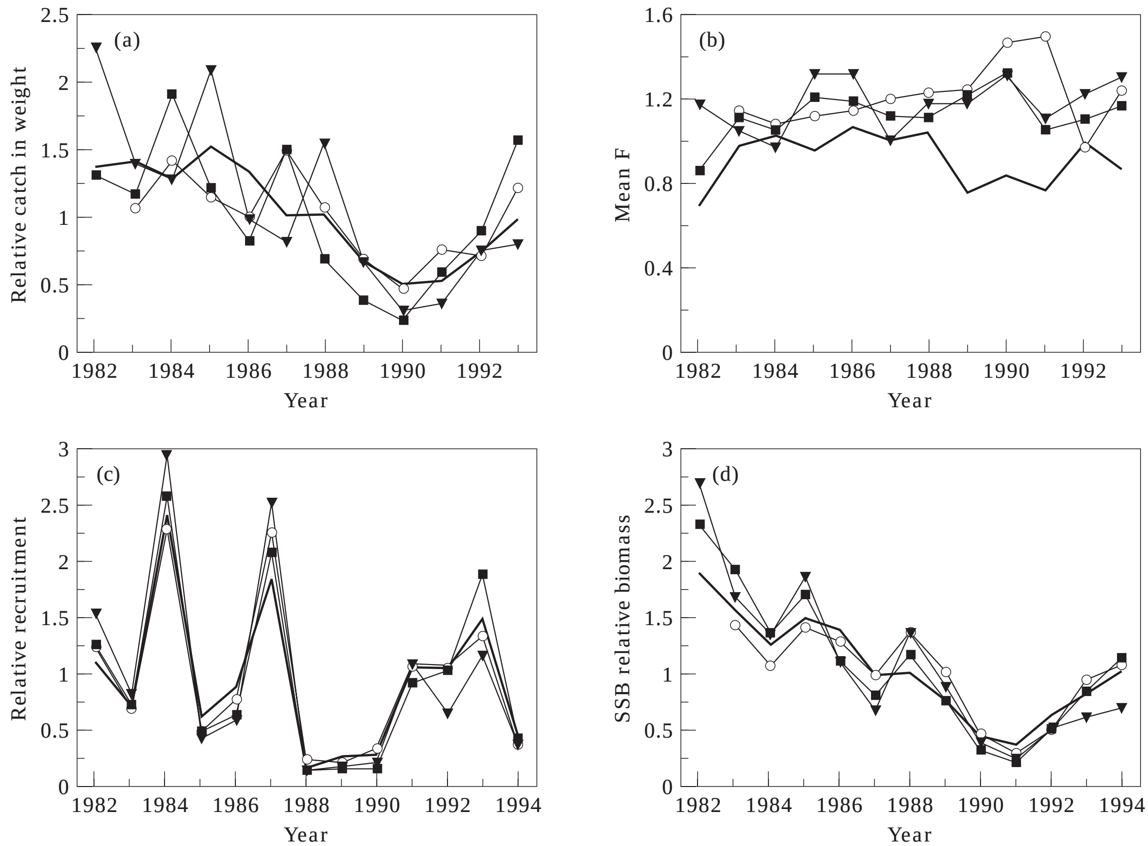

Figure 2. Haddock. Trends in (a) catch, (b) mean fishing mortality, (c) recruitment at age 1 and (d) spawning stock biomass for three surveys and the ICES assessment. ■ SGFS, ▼ EGFS, ○ IBTS. The heavy line shows the ICES assessment.

Results

Cod

The three surveys and the ICES assessment all show similar trends for catch, recruitment and spawning stock (Fig. 1). The similarities are closest for recruitment and SSB. The fishery independent data all support the perceived long term decline in the stock with a stabilization in the most recent years. The fishing mortality rate estimates do not show much similarity. Not only are the trends different, but the overall level shows marked differences between the surveys. In particular, the SGFS and IBTS indicate much lower exploitation levels than the EGFS and the ICES assessment.

Haddock

As with cod, catch, SSB and recruitment show similar trends for all time series (Fig. 2). The survey estimates of catch appear to be noisy although the decline in the late eighties and early nineties is reflected in all surveys. The surveys all show similar deviations from the ICES assessment in spawning stock, having higher peaks and lower troughs. Since these surveys are independent this may be an indication of systematic bias in the ICES assessment. Myers *et al.* (1995) have pointed out that correlations can exist between surveys as a result of the use of the same survey vessel and crew or survey design. This cannot arise here since different vessels and designs were used. The correlations must arise through characteristics of the stock itself.

Estimates of fishing mortality rate (Fig. 2b) are similar in overall level but somewhat higher in the surveys than the ICES assessment. There is a notable difference in the period 1989–1992 when the ICES assessment gives much lower values. This is the main period of catch mis-reporting and may be the cause of this difference.

Whiting

Figure 3 shows the stock trends for whiting. For this stock there is little consistency between the various series except for recruitment. The ICES assessment suggests that the SSB has remained at a fairly constant level since 1984. Two surveys, the SGFS and IBTS suggest that the SSB increased substantially from 1984 to 1990 and then

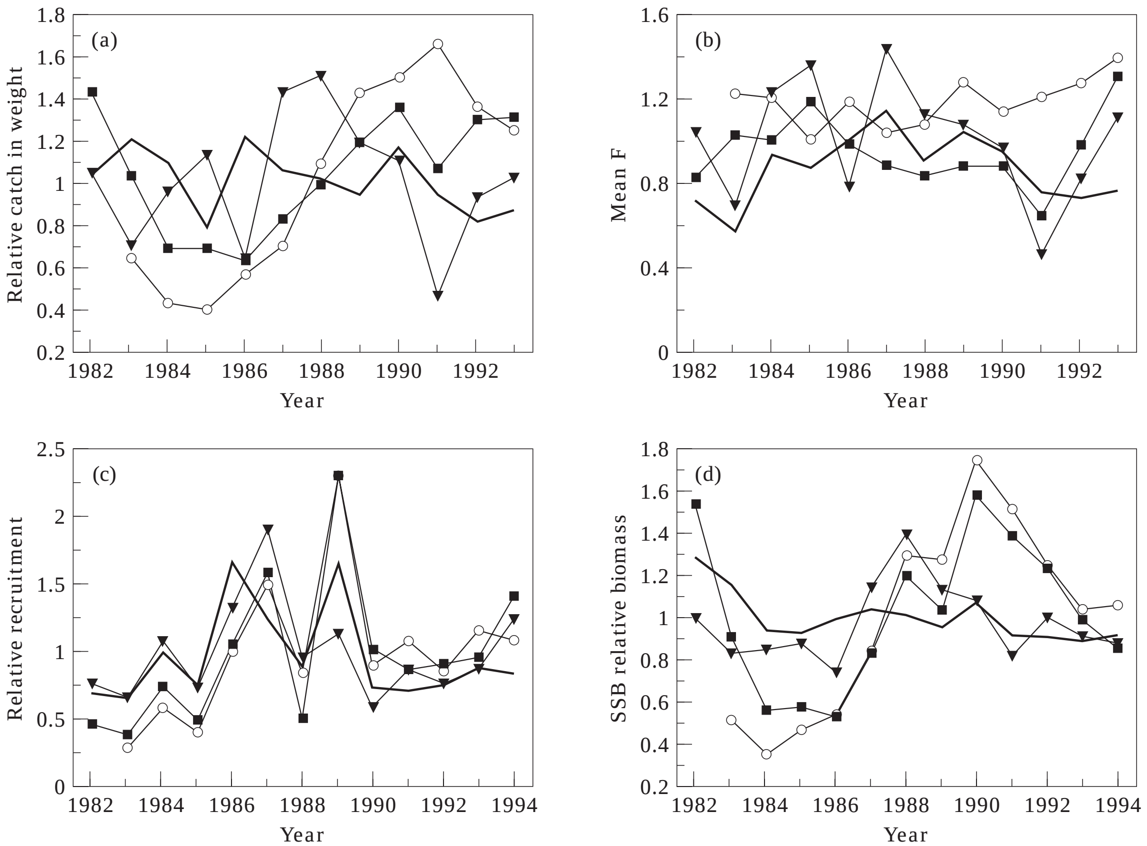

Figure 3. Whiting. Trends in (a) catch, (b) mean fishing mortality, (c) recruitment at age 1 and (d) spawning stock biomass for three surveys and the ICES assessment. ■ SGFS, ▼ EGFS, ○ IBTS. The heavy line shows the ICES assessment.

declined. The estimated catches show a similar trend. No clear trends in fishing mortality rate are evident, although the overall level is similar for all series.

Sole

Only two survey series are available for sole for the estimation of SSB. Both of these series support the recent rise in the SSB estimated in the ICES assessment (Fig. 4). There is close agreement in the recruitment series. Fishing mortality trends show some similarity though there is little change over the time period. Estimated catch shows little consistency.

Plaice

With the exception of recruitment, there is very poor agreement between the surveys and the ICES assessment (Fig. 5). The surveys both suggest much higher SSB values in the late 1980s than the ICES assessment with a steeper decline in recent years. The surveys also suggest very much higher mortality rates, unrealistically so in the case of the Tridens survey. This disparity may be due to the absence of discard estimates in the ICES assessment which would lead to an underestimate of fishing mortality for the younger ages.

Herring

The estimation of stock trends for North Sea herring has proved problematic in recent years because of the lack of consistency between the catch-at-age data and trawling surveys on the one hand, and acoustic surveys on the other (ICES, 1996b). This is evident in Figure 6 where it can be seen that the acoustic surveys estimate the stock to have reached a peak in 1990–1991 while the other data suggest this occurred two years earlier. There is agreement in so far as all series show an increase in the early 1980s as the stock recovered from collapse and a decline again more recently. However, there is considerable disparity in the most recent years with one survey (SGFS) indicating a sharp increase and another (IBTS) a sharp decrease.

The recruitment series agree well (Fig. 6c) but fishing mortality shows little consistency except for a similar overall level.

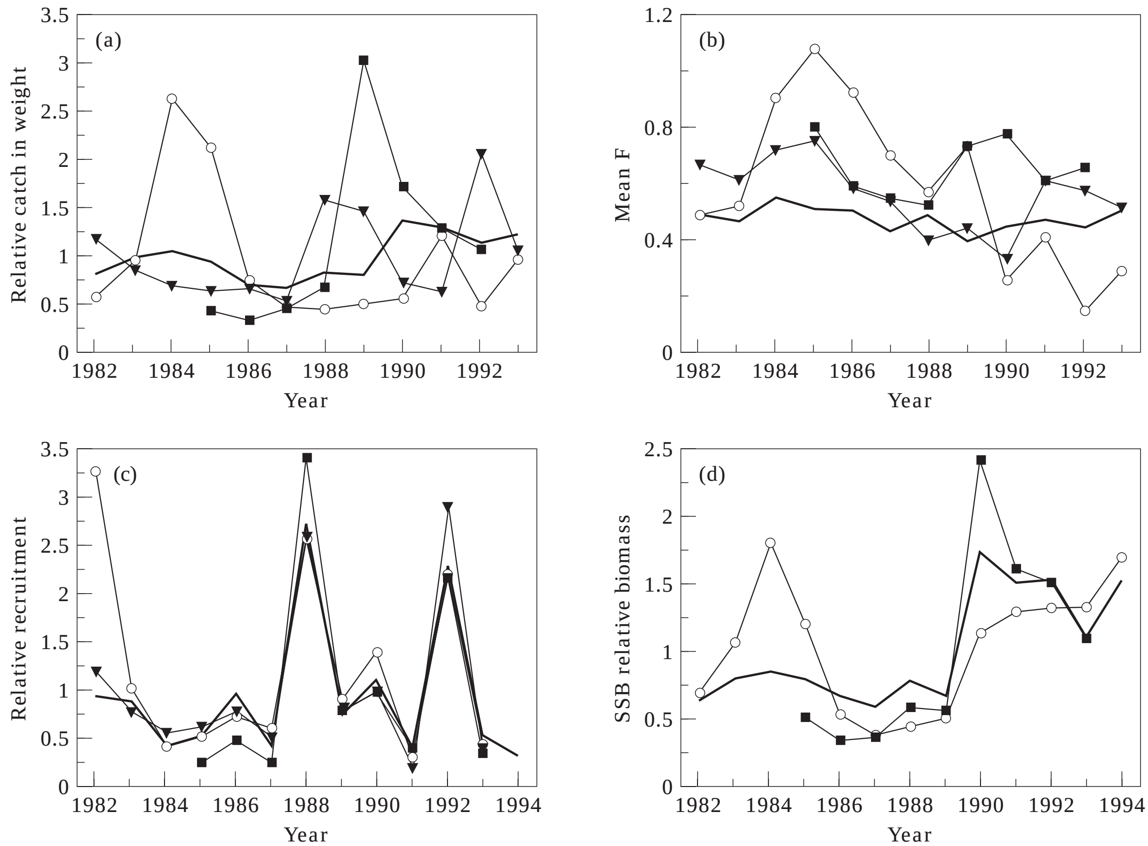

Figure 4. Sole. Trends in (a) catch, (b) mean fishing mortality, (c) recruitment at age 1 and (d) spawning stock biomass for three surveys and the ICES assessment. ■ BTS, ▼ TRI, ○ SOL. The heavy line shows the ICES assessment.

Discussion

The motivation for examining the survey data was to see if the estimated stock trends might give a different picture to recent trajectories obtained from the analysis of potentially biased catch data. Although biases undoubtedly occur, these do not, in general appear to be large enough to distort severely the perception of change in the spawning stock biomass. The stock declines estimated for many of the stocks in recent years are supported by a number of independent surveys. It is more difficult to make a judgement about fishing mortality rate. The surveys appear to provide estimates which are at least similar to the ICES assessments with the notable exception of plaice. It seems reasonable to conclude that the stocks are very heavily fished and this combined with the declines in spawning stock justifies the concerns expressed by ICES about the state of the stocks (ICES, 1996c).

The analyses presented here show that for nearly all stocks, the similarity between the time series from the different surveys and the ICES assessment is greatest for recruitment estimates. This is expected because this quantity generally shows the greatest annual variation and the signal is more likely to be detected above the noise in the data. Furthermore, both the analytical model described here and the conventional ICES assessment methods exploit the repeated measures of year classes throughout their life to improve the estimate of year-class strength. To a lesser degree this is true also of spawning stock biomass and the various time series generally agree well. By contrast, fishing mortality rate tends to be similar from year to year and the noise in the data obscures the relatively small annual changes. As a result, the various estimates do not show a great degree of similarity except in the overall level. Since fishing mortality rate has not been re-scaled, the surveys tend to support the exploitation levels obtained from the ICES assessments.

The estimates of catch also appear very noisy. This is partly the result of the poor fishing mortality rate estimates but will be complicated by the fact that the catch estimated from the survey data will be the ‘‘whole’’ catch including discards, unrecorded by-catch and mis-reported catch. The ICES catch is that resulting from official landings plus estimates of the missing

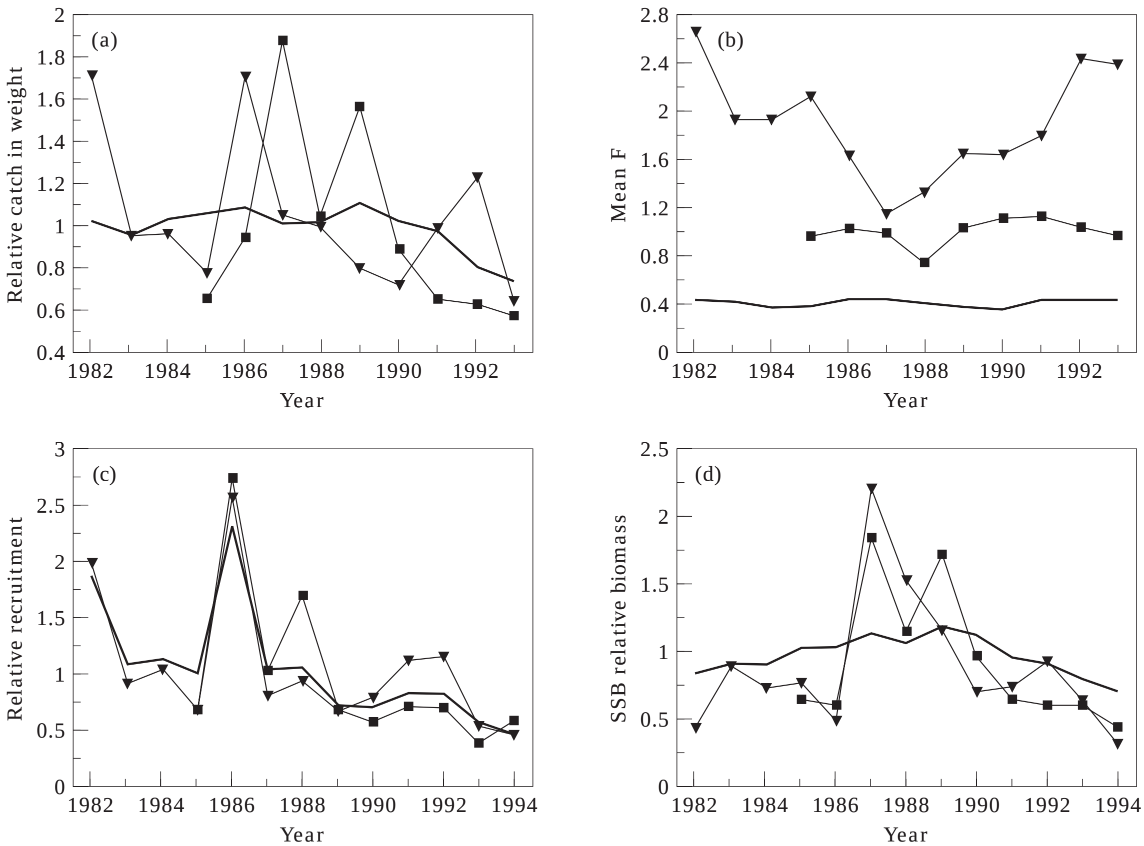

Figure 5. Plaice. Trends in (a) catch, (b) mean fishing mortality, (c) recruitment at age 1 and (d) spawning stock biomass for two surveys and the ICES assessment. ■ BTS, ▼ TRI. The heavy line shows the ICES assessment.

components where these are available. Thus the survey estimates are likely to differ from the ICES assessment. Because the survey data only provide a relative estimate of catch, it is not possible to detect consistent underestimates. However, in the case of plaice, the very low fishing mortality rate estimates from the ICES assessment suggets there may be bias due to a missing catch component. Figure 7 compares the exploitation pattern obtained from the ICES assessment with that from the beam trawl survey. The patterns appear to converge at age 5 with a wide discrepancy for ages 2–4. Discards would be expected to affect the younger age groups more and their absence from the ICES assessment may be the cause of the discrepancy.

For whiting, there is a tendency for the various surveys to agree more closely among themselves than with the ICES assessment. The inconsistency with the ICES assessment may partly explain the poor performance of the ICES assessment noticed by the working group (ICES, 1995) since the surveys are used to ‘‘tune’’ the catch-at-age analysis yet clearly do not estimate the same trends. The underlying cause of this divergence is less obvious. A major component of the catch of whiting consists of a by-catch in the industrial fisheries which has been poorly sampled in the past (ICES, 1991). Similarly many whiting are discarded but estimates of these quantities are only available for part of the exploiting fleets. These components of the catch which are poorly estimated may be the cause of the poor agreement between the ICES assessment and the surveys. If it is the main cause, then the surveys should provide a better indication of stock trends. The fact that two of the surveys, which are independent, the IBTS and SGFS, show similar trends provides some support for this hypothesis.

Given that survey data tend to be subject to high measurement error, the analysis of such data for stock trends is most likely to be successful for those stocks where there is large contrast in the data. It is noticeable that those stocks exhibiting the largest recruitment variation, cod, haddock and to a lesser degee sole, show the greatest consistency between the various time series. Recruitment, at least over the period considered, in whiting, plaice and herring is less variable with consequent weaker agreement between the series. High fishing mortality rates will also produce greater contrast in the

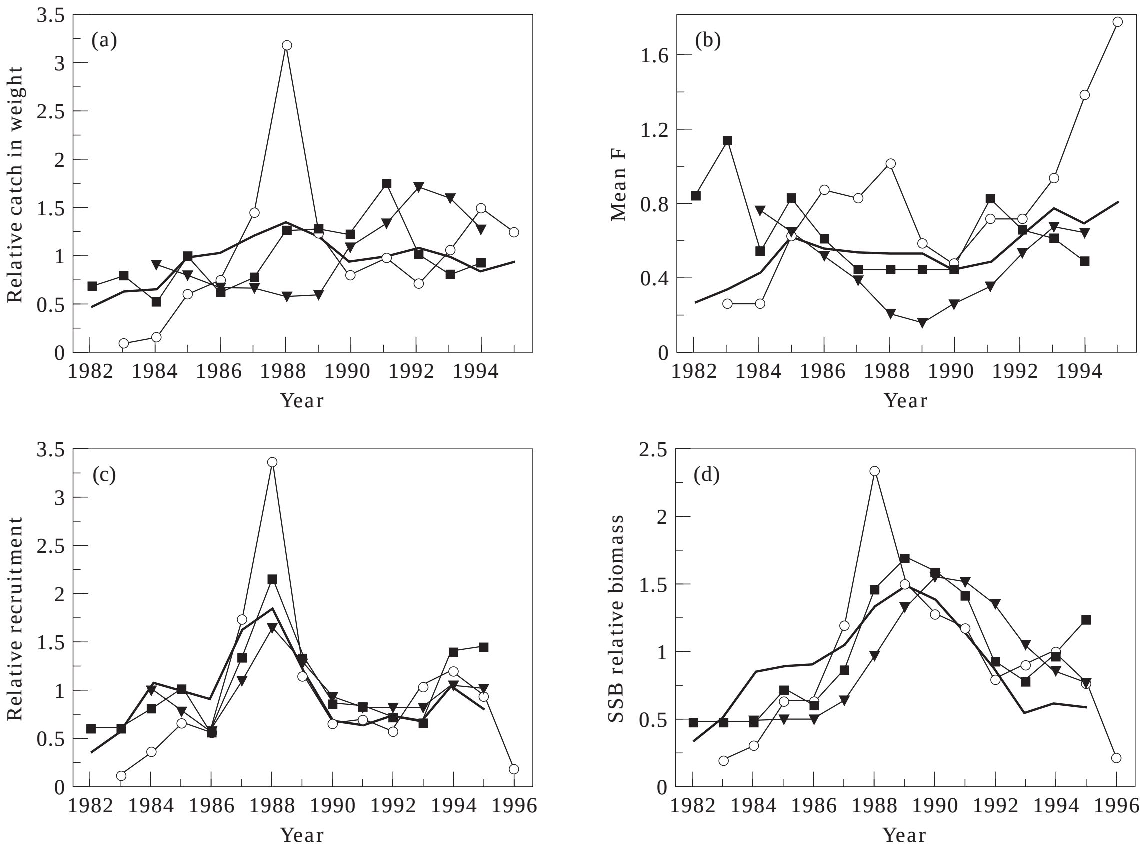

Figure 6. Herring. Trends in (a) catch, (b) mean fishing mortality, (c) recruitment at age 1 and (d) spawning stock biomass for three surveys and the ICES assessment. ■ SGFS, ▼ ACS, ○ IBTS. The heavy line shows the ICES assessment.

data and once again, cod and haddock, with this characteristic, show the greatest consistency in the trends.

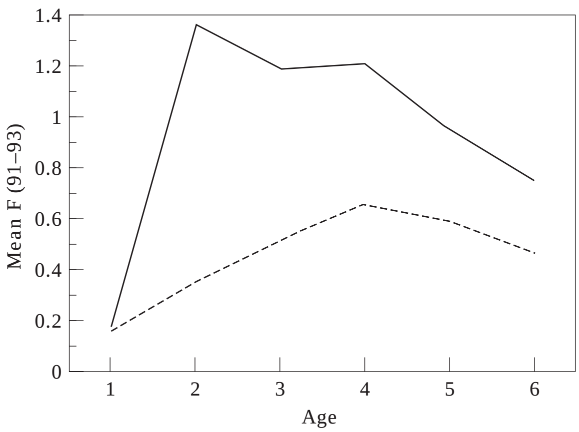

Figure 7. Mean fishing mortality for plaice for the period 1991–1993. Solid line is for the Beam Trawl Survey (BTS) and the broken line for the ICES assessment.

The analysis described here assumes that the survey catchabilities, q, are fixed above the youngest age. This will affect the estimated selectivity pattern. Clearly from the results obtained, this assumption does not appear to be important in the estimation of trends in spawning stock biomass and recruitment. It may have an important effect on the fishing mortality estimates and catch and it would be desirable to obtain independent estimates of q from real data. One way to achieve this would be to use the catchabilities obtained from the standard catch-at-age analysis in the ICES assessments, since these are a routine output. While these may provide adequate estimates of q, the problem for the comparisons in this paper is that such a procedure may force agreement between the survey trends and the ICES assessments and has not therefore been used.

An important assumption made in the model used in the analysis is that of separability of fishing mortality into an age and year effect. This essentially assumes that the exploitation pattern is constant over the period of observation. This assumption is not tested here and is likely to be violated at least to some degree. Exploitation patterns are likely to evolve over time and this is the main reason for limiting the analysis to a period of less than fifteen years. Trial analyses were also performed where the raw estimates of abundance from the surveys were used to estimate recruitment and spawning stock biomass. These produced similar overall trends but greater variability, as might be expected. It suggests that departures from the separability assumption are not sufficient to affect the perception of trends in spawning stock and that the noise is reduced by making this simplifying assumption.

References

Cleveland, W. S. 1981. LOWESS: A program for smoothing scatterplots by robust locally weighted regression. The American Statistician, 35: 54.

Cook, R. M. and Reeves, S. A. 1993. Assessment of North Sea industrial fish stocks with incomplete catch-at-age data. ICES Journal of Marine Science, 50: 425–434.

Darby, C. D. and Flatman, S. 1994. Virtual population analysis: version 3.1 (windows/dos) user guide. MAFF Information Technology Series no. 1, Directorate of Fisheries, Lowestoft.

Deriso, R. B., Quinn II, T. J., and Neal, P. R. 1985. Catch-at-age analysis with auxiliary information. Canadian Journal of Fisheries and Aquatic Sciences, 42: 815–824.

Doubleday, W. G. 1981. A method of estimating the abundance of survivors of an exploited fish population using commercial catch-at-age and research vessel abundance indices. *In* Bottom trawl surveys. Ed. by W. G. Doubleday and D. Rivard, pp. 169–178. Canadian Special Publication Fisheries and Aquatic Sciences, 58. 273 pp.

Gudmundsson, G. 1986. Statistical considerations in the analysis of catch-at-age observations. Journal du Conseil International pour l'Exploration de la Mer, 43: 80–90.

ICES. 1991. Report of the industrial fisheries working group. ICES C.M. 1991/Assess: 14.

ICES. 1995. Report of the working group on the assessment of demersal stocks in the North Sea and Skagerrak. ICES CM 1995/Assess: 8.

ICES. 1996a. Report of the working group on the assessment of demersal stocks in the North Sea and Skagerrak. ICES CM 1996/Assess: 6.

ICES. 1996b. Report of the herring assessment working group for the area south of 62°N. ICES CM 1996/Assess: 10.

ICES. 1996c. Report of the ICES advisory committee on fishery management 1995. ICES Cooperative Research Report, no. 214.

Myers, R. A., Mertz, G., and Barrowman, N. J. 1995. Spatial scales of variability in cod recruitment in the North Atlantic. Canadian Journal of Fisheries and Aquatic Sciences, 52: 1849–1862.

Patterson, K. A. and Melvin, G. D. 1996. Integrated catch-at-age analysis version 1.2. Scottish Fisheries Research Report, no. 58.

Pope, J. G. 1972. An investigation of the accuracy of virtual population analysis using cohort analysis. I.C.N.A.F. Research Bulletin, 9: 65–74.

Pope, J. G. and Shepherd, J. G. 1982. A simple method for the consistent interpretation of catch-at-age data. Journal du Conseil International pour l'Exploration de la Mer, 40: 176–184.

Shepherd, J. G. and Nicholson, M. D. 1991. Multiplicative modelling of catch-at-age data and its application to catch forecasts. Journal du Conseil International pour l'Exploration de la Mer, 47: 284–294.