ICES Journal of Marine Science, 62: 996–1005 (2005)
doi:10.1016/j.icesjms.2005.03.003



# Using survey data independently from commercial data in stock assessment: an example using haddock in ICES Division VIa

D. J. Beare, C. L. Needle, F. Burns, and D. G. Reid

Beare, D. J., Needle, C., Burns, F., and Reid, D. G. 2005. Using survey data independently from commercial data in stock assessment: an example using haddock in ICES Division VIa. – ICES Journal of Marine Science, 62: 996–1005.

Currently standard fish stock biomass estimates are based most directly on commercial catch-at-age data. The main contribution made by research-vessel trawl survey data to the stock assessment process is to "tune" trends in the commercial data and provide estimates of incoming year-class strength. In this process much of the information contained with the survey data (e.g. spatial detail) is lost because the data are first aggregated into numbers-at-age indices for given areas. Another problem is that increasingly restrictive total allowable catches (TACs) imposed on the fishing industry have led to what is suspected to be widespread misreporting, i.e. the scientists do not know how many fish have been landed. This leads to negative biases in the catch data, low stock abundance estimates by scientists, even lower TACs, followed by even more misreporting. One potential way to escape this downward spiral is to explore scientific trawl survey data in more detail since trawl surveys are more straightforward to regulate. Traditionally, there has been resistance to this idea since, in comparison to commercial catch-at-age data, trawl survey data are very sparse in space and time. In this study, the potential for using trawl survey data independently in stock assessments is explored for the case of ICES Area VIa haddock, using two different tools. Findings suggest that it is possible to get qualitatively useful information from trawl survey data alone as well as quantitative, spatially resolved, estimates of fish abundance by making simple swept-area assumptions. In addition, interesting differences between survey and commercial data are highlighted by the study. The mean age of fish reported by the commercial fleet, for example, is higher than that reflected by the survey data, while fishing mortality estimates tend to be higher when estimated from survey data alone.



Keywords: fisheries stock assessment, research-vessel survey data, spatio-temporal assessment, survey-based assessment, time-series analysis.

Received 21 July 2003; accepted 15 March 2005.

*D. J. Beare, C. Needle, F. Burns, and D. G. Reid: Fisheries Research Services, Marine Laboratory, PO Box 101, Victoria Road, Aberdeen AB11 9DB, Scotland, UK. Correspondence to D. J. Beare: tel: +44 1224 295314; fax: +44 1224 295511; e-mail: d.beare@marlab.ac.uk.*



# Introduction

## Background

Severe biomass declines in several demersal fish species have been observed in recent years in ICES Areas, particularly gadoid stocks in the North Sea, West of Scotland, and Irish Sea. Fisheries for these stocks are managed by quota systems whose goal is to control exploitation via total allowable catch (TAC) limitations. Declines in stock biomass led to increasingly restrictive TACs in recent times, which have had little real impact on fishing effort. Instead, the management regime has generally led to increased incentives for fishers to discard, misreport, or otherwise distort catch records (Anon., 2004).

The standard assessment techniques used by ICES Working Groups, such as Extended Survivors Analysis (XSA; Darby and Flatman, 1994); Integrated Catch-at-age Analysis (ICA; Patterson and Melvin, 1996); and Time-Series Analysis (TSA; Fryer *et al.*, 1998, 1999), are all based predominantly on reported catch-at-age data, with survey indices performing a largely calibrative role. In all these methods, the relationship between total catch and population numbers is estimated using assumptions implicit in the "Baranov Catch Equation" (Baranov, 1918), which is central to fisheries stock assessment science. The method exploits mortality signals between age classes along a single cohort and assumes that mortality rates are adequately summarized by the negative exponential relationship. The current concern over the quality of reported catch-at-age data suggests that this type of assessment method might be generating misleading scientific advice to fisheries management, with serious implications for sustainability.

It is important that assessment methods that incorporate data from research-vessel surveys be investigated more rigorously. While such data are likely to be more variable than catch-at-age data, as they are collated from fewer samples, they are also under direct control and unlikely to be affected by misreporting biases. Recently, two Working Documents to the ICES Working Group on the Assessment of Demersal Stocks in the North Sea and Skagerrak (Casey, 2002; Needle, 2002) discussed the need for survey-based assessments, and presented relative-trend assessments for North Sea whiting using two simple methods known as RCRV1A (Robin Cook Research Vessel 1A) and RVS (Research Vessel Survey). The aim of this paper is to extend that work and apply it to the haddock stock west of Scotland (Division VIa; Figure 1), using both a separable survey-based assessment method (SURBA) and estimates derived directly from considerations of survey swept area (STA). The resultant population estimates are contrasted with those from the standard TSA assessment results for that stock.

## Material and methods

### Exploring standard assessment input data

Input data, as used in the standard TSA assessment, were obtained from Fisheries Research Services, Marine Laboratory, Aberdeen. They consist of commercial, time-varying catch-at-age and weight-at-age data. They are derived from market sampling and discarding programmes carried out within Scotland. Survey "index" data, collected by research vessel cruises on *Scotia*, are expressed as individuals caught per 10 h fished. Calculation routines and regions over which the data are aggregated and used in the construction of these data sets are described in detail in the Northern Shelf Demersal Working Group Reports (e.g. ICES CM 2003/ACFM:01).

### Time-series analysis assessment (TSA)

Implementation of the fisheries stock assessment method used in this study, known as Time-Series Analysis or TSA, has been described in previous ICES Working Group meeting publications (e.g. ICES CM 20037; Fryer *et al.*, 1998, 1999). Details on the Kalman filter algorithm, which is central to the methodology, are available in the statistical literature (Harvey, 1989; Jones, 1993; Gudmundsson, 1994).

The Kalman filter TSA algorithm is a recursive procedure that represents the variables of interest (stock numbers and fishing mortalities at age) as unobserved state variables that evolve forward over time. Each year, observed catch-at-age data are used to update the estimates of the state variables. Year-class strength is estimated according to a Ricker stock-recruitment model. Model fitting proceeds by examining standardized catch prediction errors (equivalent to model-fit residuals) and inflation of permitted variance on year-age pairs where errors are high. Each estimate of historical mean $F_{2-6}$ and stock numbers is produced with an associated standard error, allowing a statistical evaluation of the uncertainty in the assessment. The model is also able to roll forward and produce estimates for all parameters in the years following the last historical year.

TSA has several advantages over more traditional VPA-based assessment methods (XSA, ICA), which have meant that it has become the standard assessment model for most Northern Shelf and North Sea demersal gadoid stocks. Among these are:

(i) Realistic standard errors on model parameter estimates and summary statistics, thus giving an indication of the uncertainty of management population metrics (which may be high, particularly in recent years). Note: the standard errors are realistic because they are based on an accepted statistical technique (Kalman filter), whereas traditional VPA-based techniques are simple recursive numerical data transformations that do not recognize model error (measurement or process) of any sort.
(ii) Any number of surveys can be included, the catchabilities of each being modelled and allowed to evolve over time via fitted ogives.
(iii) Landings and discards can be modelled separately, thus allowing for the inherent noisiness of the latter. If this option is taken, discards are expressed by another set of fitted ogives.
(iv) Entire years of catch-at-age, discard, and survey data can be treated as missing.

The principal disadvantages are:

(i) TSA population estimates are driven largely by catch-at-age data, which may become increasingly biased as quotas become more restrictive.
(ii) There is not yet a robust and general version of the code available, and the knowledge base of practitioners experienced with TSA is very limited.
(iii) The computer program takes a long time to run on a Personal Computer with a Pentium III processor ($>1$ h), limiting the potential for hands-on experimentation with model settings.

### Survey-based assessment (SURBA)

SURBA 1.03 (survey-based assessment, version 1.03, dated 02 September 2002) is a recent development of RCRV1A, extending its functionality and flexibility. RCRV1A was an implementation by Robin Cook (FRS Marine Laboratory) of the separable survey model described by Cook (1997). In brief, it assumed that fishing mortality $\mathbf{F} = [F_{a,y}]$ is separable into an age effect $\mathbf{s} = [s_a]$ and a year effect

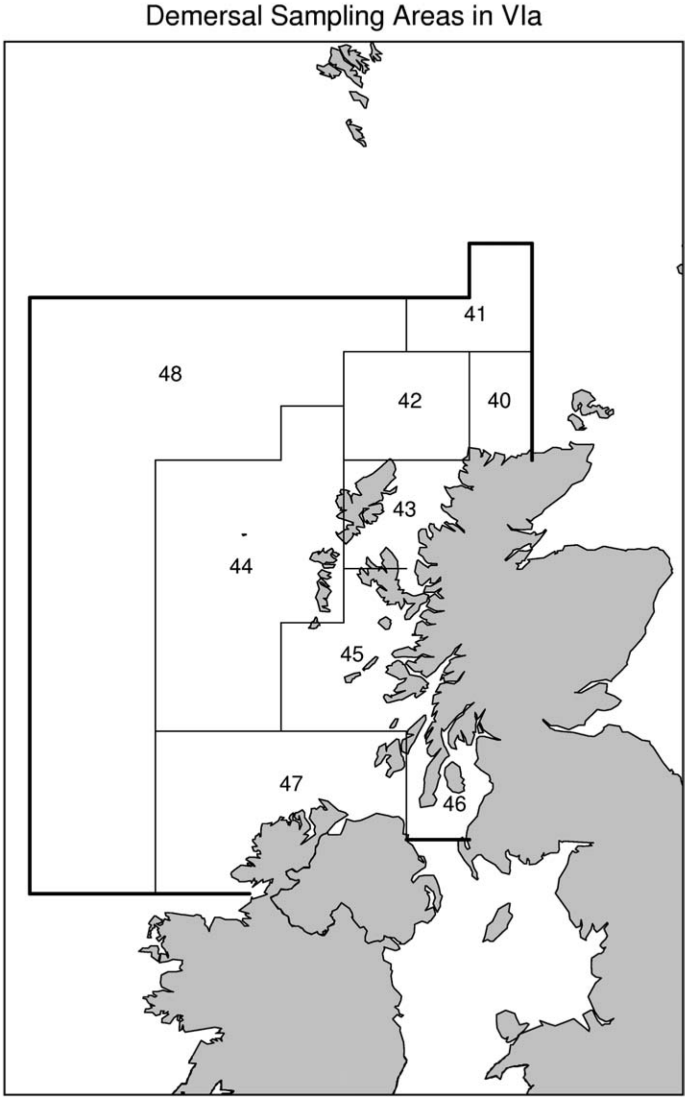


Figure 1. Location of ICES Division VIa showing Demersal Market Sampling Areas, 40–48.

$\mathbf{f} = [f_y]$, so that $\mathbf{F} = \mathbf{s} \times \mathbf{f}$. It estimates these **s** and **f** parameters, along with a year-class effect **r**, by minimizing the sum-of-squared differences between observed and fitted survey-derived abundance, using an assumed fixed vector of catchabilities-at-age $\mathbf{q} = [q_a]$, which does not depend on year. Since these abundances are relative indices only, the model can only be used to estimate relative, rather than absolute population numbers. These, however, can be used to summarize population trends suggested by any particular survey. The model improvements implemented in SURBA in terms of estimable quantities include time-dependent weight, maturity and natural mortality data, catchability-estimation algorithms, and inverse-variance age-weighting. SURBA is currently under development, and beta-test versions are available from Fisheries Research Services (FRS), Aberdeen (contact Coby Needle: c.needle@marlab.ac.uk).

## Spatio-temporal assessment (STA)

This method directly exploits the spatio-temporal dependence of numbers-at-age data derived from surveys and is similar to other "absolute" measures of abundance estimated in the past for gadoids in ICES Area VIa (e.g. Fernandes and Rivoirard, 1999). Firstly, numbers-at-age for haddock in ICES Division VIa were calculated by individual statistical rectangle for each quarter 1 (i.e. those done between 1 January and 31 March each year) survey performed by FRS between 1985 and 2002. The total distance covered during each trawl was calculated assuming an "effective gear width" of 30 m (Sangster and Breen, 1998; Reid *et al.*, 2000). From this, the total numbers of haddock from each age group per $m^2$ of seabed were calculated. Fish of an age greater than eight were pooled into an age 8 plus-group. Haddock numbers-at-age $m^{-2}$ were then modelled separately for each year, as functions of their location and age using a class of regression called generalised additive models (GAMs; Hastie and Tibshirani, 1990).

Due to the high number of statistical rectangles returning zero catches, a two-stage modelling process was adopted using GAMs (Borchers *et al.*, 1997a, b; Augustin *et al.*, 1998). The first model was fitted to presence/absence data using a GAM with a binomial link function (Cox, 1989). In the second step, a GAM was fit to the positive component of the data only, i.e. log-transformed numbers $m^{-2}$ by age. In each step, dependence on location (longitude and latitude) was estimated using two dimensional, locally-weighted regression (loess smooth) functions (Cleveland and Devlin, 1988), which allowed longitude and latitude to interact or covary simultaneously with each other (Beare and Reid, 2002; Beare *et al.*, 2002). This meant that in the model outputs, numbers $m^{-2}$ haddock, could and indeed did vary differently by latitude, depending on the level of longitude and *vice versa*. Fish age entered the models as a discrete eight level "factor". Experimentation showed that fits were generally better when the age factor interacted with the location covariate (longitude and latitude). The advantage of these configurations allow spatial distributions, or patterns, output by the model(s) to be different for each age group. This is biologically realistic since it is well known that fish of different ages tend to aggregate in different areas: older haddock, for example, tend to be more prevalent offshore (Tormsova, 1984; Brander and Hurley, 1992), whereas the younger fish are most common inshore. The degree of smoothing in either step was selected by trial and error using Chi-squared tests for the binary data (Cox, 1989) and visual examination of the residuals, i.e. residuals were plotted against the spatial covariates and, if there was no organized spatial pattern remaining in the data, it was considered to be an adequate model. After pairs of suitable models were found for each year, a "grid" was built to represent ICES Area VIa, and the area of each grid rectangle calculated according to the formula, $\text{area} = \cos(\text{latitude})\,(30^2)\,(1853.2^2)$. Parameters from the models described above were then used to interpolate over the grid, producing the following estimates at each grid node by age: (i) the probability of presence by age, and (ii) numbers by age $m^{-2}$. The product of these two values then equals the numbers by age $m^{-2}$ of haddock at a particular grid node. This quantity was then raised to the total numbers caught over each grid rectangle and finally summed to represent the total numbers caught over the entire grid area (e.g. see Figure 2). The input data and SPLUS code


Figure 2. Division VIa haddock: long-term change in the spatial distribution of age 2 haddock in ICES Division Via. [Note: units are log numbers haddock $m^{-2}$ estimated by STA via the two-stage generalized additive modelling (GAM) process.]

for haddock in ICES Division VIa are available from the authors (contact email: d.beare@marlab.ac.uk).

## Results

### Standard assessment input data

Summaries of the data input to the standard TSA assessment are plotted in Figures 3 and 4. Commercial catch-at-age-data (Figure 3a), weight-at-age data (Figure 3b), and research-vessel abundance index data (Figure 3c) are all plotted against year, by cohort. Each line in Figure 3, therefore, describes the fate of successive cohorts as they enter the population. Although the data are noisy clear patterns do emerge. Figure 3a, for example, suggests that there are fewer mature haddock in the fishery now than in the past, because the lines tracing each cohort are not as long as they were in the past.

In order to summarize the mortality and growth of each of the cohorts described in Figure 3, simple linear regression models were fitted to each one, and the gradient term or slope coefficient was extracted and plotted against year (see Figure 4). Results suggest that the growth rate of haddock has decreased (Figures 3b, 4c) gradually over the past four decades. We accept that this process provides a crude summary of mortality and growth rates, and that they are less reliable at the start and end of the time-series owing to incomplete cohorts. According to the commercial data, mortality rates have been fairly stable since 1965, although there has been a gradual rise (Figures 3a, 4a) from



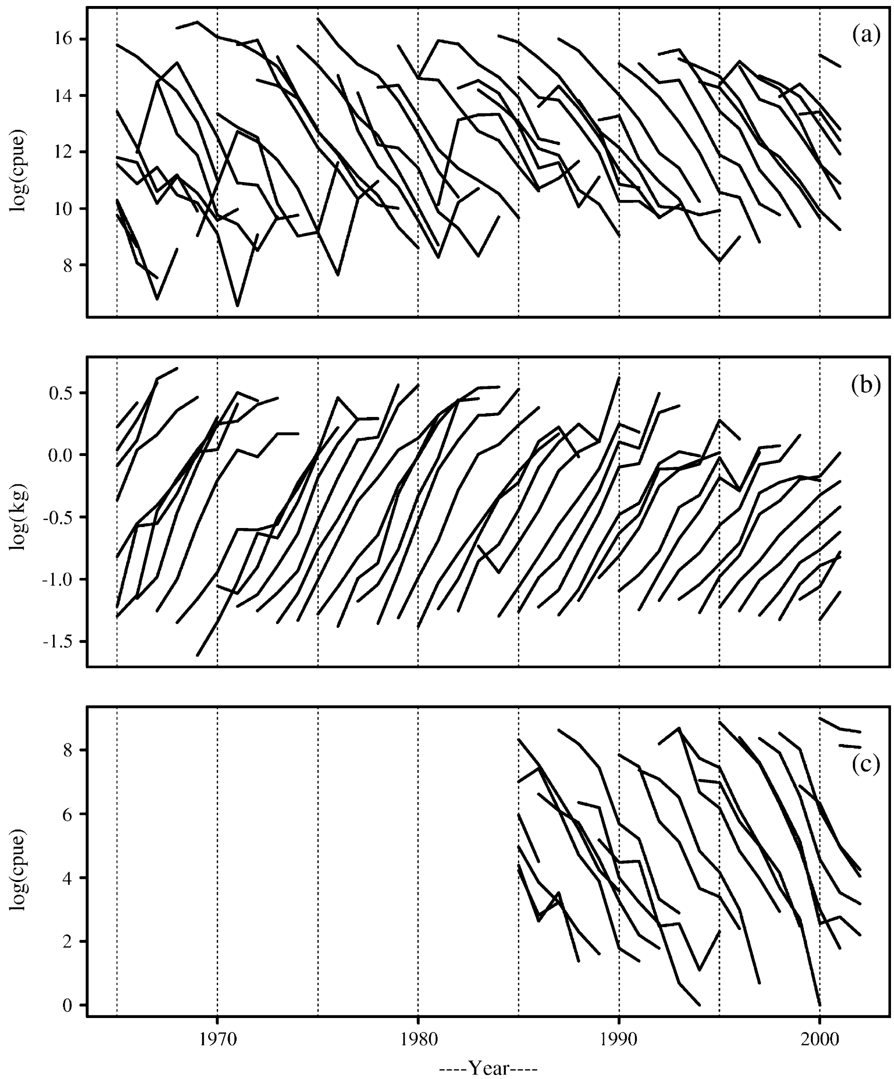


Figure 3. Commercial catch-at-age (a), weight-at-age (b), and Scottish groundfish survey index (c) data for haddock in ICES Division VIa between 1965 and 2002. Data are summarized as cohort trajectories.

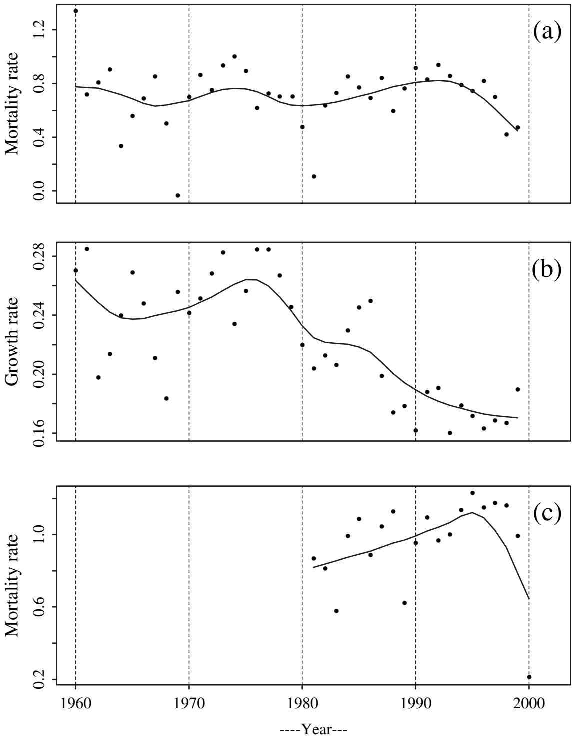


Figure 4. (a) Total mortality estimated from commercial catch-at-age data; (b) growth rate estimated from commercial weight-at-age data; (c) total mortality estimated from research vessel index data. These quantities were estimated by fitting linear models to the trajectory of each cohort (see Fig. 3) and plotting the gradient term against year.

1980 to the mid-1990s: a pattern which can also be seen in the survey data (Figure 4c). It should be noted that the survey data suggest slightly higher mortality on average than the commercial data. The most striking feature of these analyses, however, is the decline in haddock growth rates since the mid-1970s (Figures 3b, 4b).

### Comparing TSA, SURBA, and STA

Numbers-at-age (N), fishing mortality (F), spawning-stock biomass (SSB), and recruitment (Rec) for the three stock assessment methods (TSA, SURBA, and STA) are compared in Figures 5, 6, 7a and 7b, respectively. The standard TSA assessment and STA ("absolute" estimates) are compared on the same left-hand axes, while SURBA estimates are plotted against the right-hand axis since they are relative measures of abundance. The first point to note is that STA appears to underestimate N, as compared with the TSA assessment, and this negative bias appears to increase as haddock mature (Figure 5). SURBA and STA, however, both exhibit similar long-term trends, with N rising between 1985 and the present for younger age fish (ages 1−4), and falling markedly for older fish. In general, the long-term trend in N estimated by the standard TSA assessment is more stable.

Fishing mortalities calculated using the three methods (Figure 6) show that in every case other than age 1, F was lower for TSA than for either of the methods based on survey data. The TSA assessment indicates a gradual increase in F since the mid-1980s, although there is recent evidence of a decline. Trends in F are parallel for SURBA for all age groups owing to the assumption of a time-invariant age effect. Nevertheless, the method also suggests rising fishing mortality. For STA, F was calculated rather crudely from the total population numbers-at-age using the formula, $F = -[\log(N_{a+1}) - \log(N_a)] - 0.2$ (Note: $N_a$ = numbers-at-age and 0.2 = natural mortality). The value of 0.2 is assumed by ICES Assessment Working Groups (see Anon., 2003). The value of F is very noisy, rather high, and the data suggest that trends in fishing mortality can be dramatically different for each age group.

Spawning stock size and recruitment estimated using TSA, SURBA, and STA are described in Figure 7. SSB is calculated using the ICES Working Group on the Assessment of Northern Shelf Demersal stocks haddock maturity ogive, which assumes that no age 1, 57% of age 2, and all age 3+ are sexually mature. According to the standard TSA assessment, haddock SSB in ICES VIa fell between the early 1980s and 1990s, then rose in the mid-1990s and then fell again until 2000. Recently, there has been a sudden rise in haddock SSB owing to large recruitment in 2000. All three methods reflect this pattern, although SSB estimated by STA is generally lower than that estimated by TSA (see also Figure 5). Long-term trends in haddock recruitment (numbers of age 1s) are also similarly captured by the three different approaches; all of which suggest a slight increase since the mid-1980s.

## Discussion

The SURBA method, although incomplete and still under development, does appear to provide consistent estimates of relative trends in population parameters from research-vessel survey indices. The method is becoming widely used in ICES Demersal Working Groups (see, for example, the 2002 report of the Northern Shelf Demersal Working Group) and can provide much useful information, given certain caveats. Relative estimates of SSB and recruitment are sufficient if relative-trend management is being practised. Descriptive models such as SURBA may become more and more important as TACs become more restrictive.

However, SURBA is based on collated research-vessel indices and does not take advantage of the rich detail available from that source. Spatio-temporal analysis (STA), on the other hand, does utilize spatio-temporal dependence

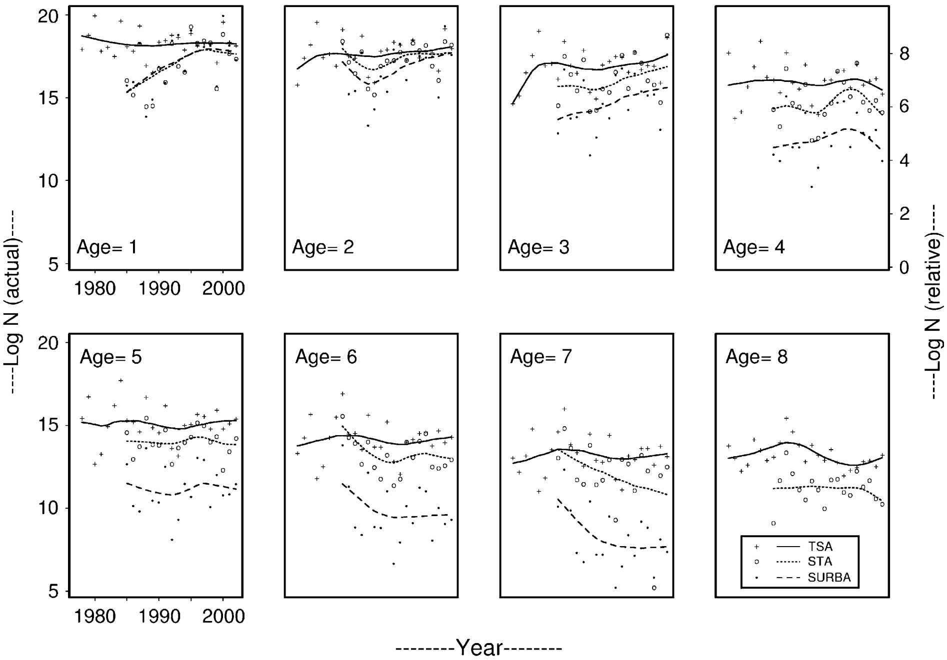


Figure 5. Division VIa haddock: long-term trends in population numbers-at-ages 1–8 estimated using TSA, STA, and SURBA stock assessment models. Patterns in the long-term trends are summarized using a simple smoothing function. [Note: TSA and STA attempt to estimate the "actual" number (N) (right-hand vertical axes) in the population whereas SURBA provides only a "relative" estimate of numbers.]

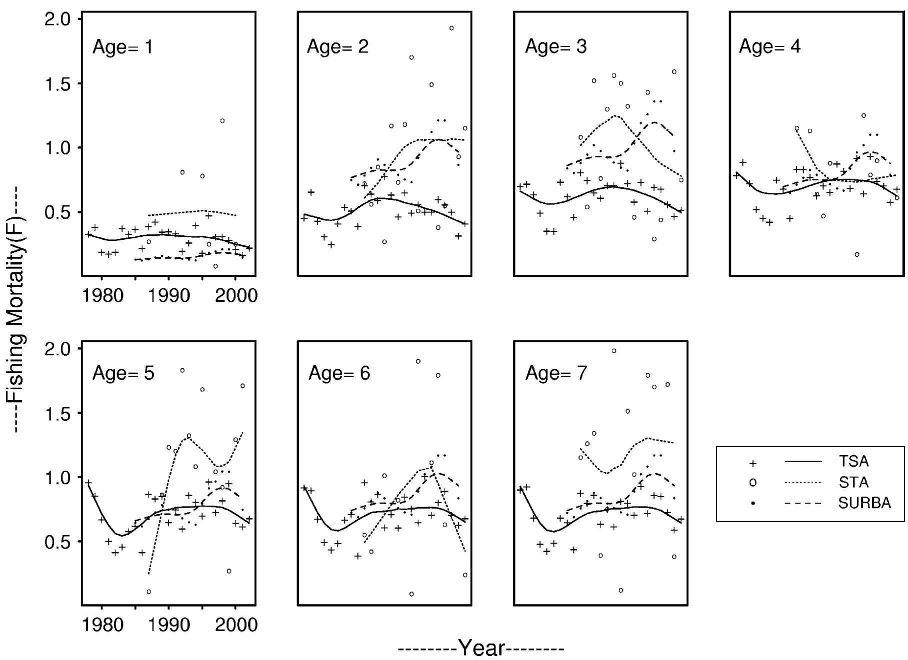


Figure 6. Division VIa haddock: long-term trends in fishing mortalities between ages 1 and 7 estimated using TSA, STA, and SURBA stock assessment models. Patterns in long-term trends are summarized using a simple smoothing function.

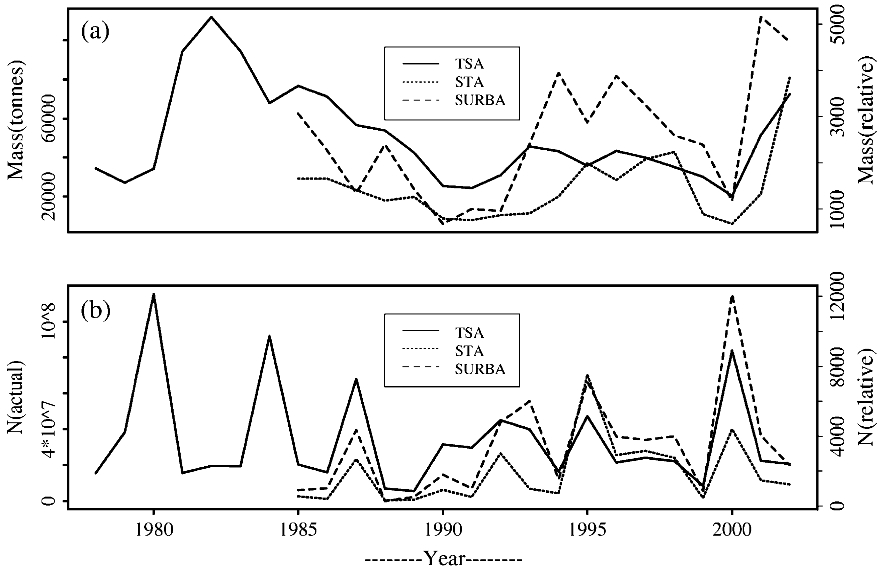


Figure 7. Division VIa haddock: spawning-stock biomass (a); and recruitment (b) estimated using TSA, STA, and SURBA stock assessment models between 1978 and 2002. [Note: TSA and STA attempt to estimate the "actual" biomass in tonnes and the actual number of age 1 fish (N) (right-hand vertical axes) in the population whereas SURBA provides only "relative" estimates of both biomass and numbers.]

in the data, and also provides an "absolute" estimate of population numbers. Overall, however, this estimate is much lower than that expected from the standard TSA assessment (see Figures 5 and 7). There are many factors that could be responsible for the disparity. It is possible that outmoded trawl gear, general fishing skill, and techniques used by research vessels catch haddock poorly relative to commercial fleets. Alternatively, the extremely sparse spatial coverage during surveys may miss important hotspots of haddock abundance that fishers target more actively. Further, it is also extremely difficult to quantify the effective swept area of the trawl gear, and it is well known that headline height and the distance between trawl doors vary with respect to depth, bottom type, and topography (Reid *et al.*, 2000). It is hoped that STA estimates might eventually be improved by incorporating such factors in a more dynamic or realistic way.

It is often bemoaned in the fisheries literature how small a part environmental information plays in the entire stock assessment process. In STA-type stock assessments, other data such as bottom depth, bottom type, salinity, stratification, temperature, predation, and food availability could, in theory, all be incorporated directly (Ulltang, 1998). Standard statistical tests, built into the model selection process, would then help to determine the usefulness of each variable. Perhaps, the real value of STA type assessments, however, are the standard, spatio-temporally resolved outputs themselves. STA allows, for example, stock assessors to: (i) see how the abundance of specific age groups varies interannually (e.g. age 2 in Figure 2); (ii) follow the fate of individual cohorts as they enter the fishery, migrate, and die (e.g. Figure 8); and (iii) ascertain

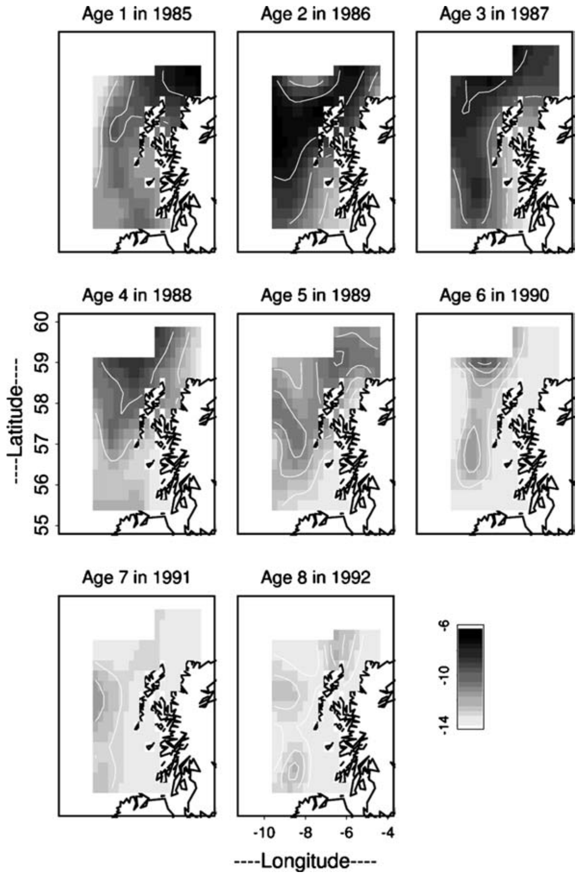


Figure 8. Division VIa haddock: a spatial summary, estimated using STA, of the fate of the 1984 haddock year class. (Note: units are log-transformed actual numbers $m^{-2}$.)

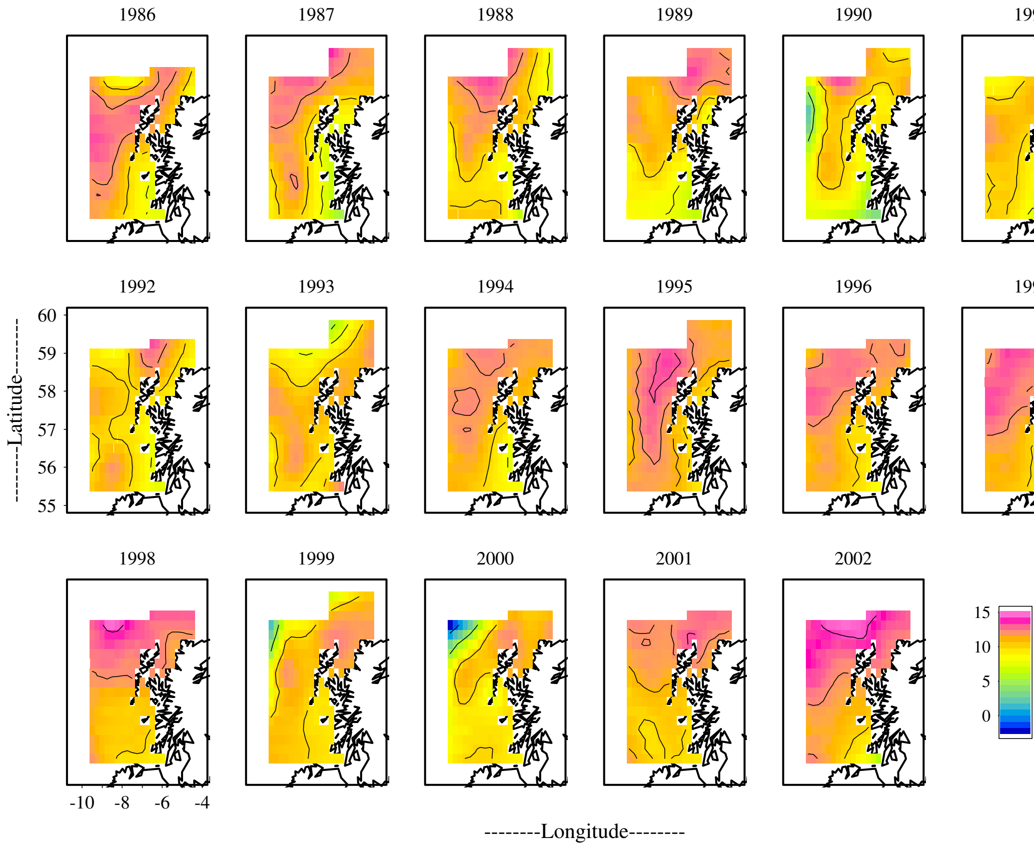


Figure 9. Division VIa haddock: interannual change in the spatial distribution of haddock spawning-stock biomass estimated by combining the population numbers estimated with STA and the commercial weight-at-age data displayed in Figures 3a and 4a. (Note: units are metric tonnes.)

how the location of the main component of spawning-stock biomass varies interannually (e.g. Figure 9).

Such maps have the potential to allow fisheries managers to distribute fishing effort much more effectively, thereby maximizing the economic value of each stock.

It is clearly possible to get more detailed information from survey data and to use them for stock assessments in the complete absence of commercial catch-at-age data. TSA, SURBA, and STA exhibit very similar long-term trends in population numbers (N), spawning-stock biomass (SSB), and recruitment of age 1 to the fishery (Figure 6). This consistency is important because it means that low estimates of fishing mortality (F) from TSA (standard assessment), compared with those estimated by SURBA and STA, can be interpreted with confidence. Annual declines in the abundance of individual cohorts (mortality) are steeper when estimated from survey data alone, than from commercial catch-at-age data. There are many possible causes for this observation. It could be due, for example, to the impact of variable catchabilities (Millar and Fryer, 1999). The smaller trawl mesh size used by research vessels, as compared to the commercial fleet, could easily lead to disproportionately larger catches of younger fish (Halliday, 2002). Similarly, the trawling duration (h) of commercial vessels tends to be much longer than that of research vessels (30 min). This disparity potentially leads to the capture of more older fish by commercial vessels/professional fishers because the older fish can swim faster and tire less quickly than their smaller counterparts. Nevertheless, the factor most likely to lead to the higher levels of F seen in the survey data is misreporting by fishers, and various discarding biases. Larger (older) haddock fetch better prices at market and it is clearly economically advantageous for fishers to land as many large fish as possible. The smaller individuals caught would then either be discarded, or perhaps allocated to different species and/or different locations.

The problem now is knowing how to interpret and then to use the disparate information emerging from the commercial and research survey-derived catch-at-age data. In this example, it is not possible to know whether the higher fishing mortalities estimated for haddock using research survey data should be used in management or whether the Fs estimated from commercial data are more realistic.

Simulation studies, where the characteristics of the real populations are known exactly, may provide the answers, and we intend to use such approaches in the future development of these models.

## Acknowledgements

We thank all the staff at Fisheries Research Services (FRS), particularly Andrew Newton, Kevin Peach, Maggie Bell, and Ken Coull, who have collected and stored the survey and commercial data upon which this paper is based. Free softwares (GNU Linux, PERL, and R) have been used extensively in this work and we thank all those involved in their development. Alexander Brownlee helped organize the data from ICES Division VIa into the necessary formats for analysis. Valuable comments from two anonymous referees and the editor, Bernard Megrey, also helped improve an earlier version of this manuscript.

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