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Report of the Workshop on the Integration of Environmental Information into Fisheries Management Strategies and Advice (WKEFA)

18–22 June 2007

ICES Headquarters, Copenhagen, Denmark



ICES

International Council for
the Exploration of the Sea

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Executive summary

Following a preparatory meeting in February which developed a strategy and identified a number of relevant case studies, the main workshop co-sponsored by ICES, EUR-OCEANS, and GLOBEC met from 18–22 June 2007. Fourteen cases studies involving a wide range of demersal and pelagic stocks, as well as some generic stock simulations were presented over the first two days. The main results from the case studies and the demonstrated influence of environmental change on the stocks are summarised in the report. Over the remaining 2½ days these cases were then used to discuss and formulate generic concepts for improving fisheries management strategies and advice considering interactions under four main aspects,

- a) Entries and exits from populations (recruitment, natural mortality and migration)
- b) Internal population processes, encompassing a range of aspects associated with growth maturation and reproduction.
- c) Location and habitat (including such aspects as vertical and horizontal movement)
- d) Multispecies interactions

While it has been long accepted that we are providing fisheries advice within the context of a varying environment, the workshop considered that we need to take into account not only of stochastic variability but also trends and shifts in the environment as we develop scientific advice. We recognise that changes in physical drivers at many scales of space and time act together and this will result in changes in habitat. Through complex linkages these changes will result in differences in fish location, growth, maturation and reproductive potential. These differences may then influence recruitment and abundance leading to changes in natural mortality due to different species interactions. The workshop concluded that the effects of environmental change on fisheries management are better addressed by separating variability according to the time-scale of the changes.

Some aspects such as catastrophic events can only be dealt with though a willingness to remain aware and the collection of information, observing and accounting for unusual events causing migration, mortality or recruitment failure.

Some short term changes can be observed, estimated and brought into advice even where the complexity of the drivers is unknown. For example changes in growth and maturation can be brought directly into methods for estimating spawning stocks one or two years ahead and for estimating catch where TACs are required. Combining such information can improve the performance of management but only if the errors in the information are included appropriately. There are a number of instances where environmental drivers have been clearly shown to explain variability in recruitment, but once in use some have shown problems. This indicates that testing the utility of indicators in management simulations must be a requirement before they are formally applied, including developing implementation frameworks that are informative and robust to errors.

As habitats changes, spatial distributions of fish change, both horizontally and vertically. These changes can interact with surveys, and fisheries leading to the requirement monitor and account for change in catchability in assessment tuning series.

Medium term change cannot be predicted in the same way as short term effects. The approach needs to follow two avenues. Where explicit relationships exist between stock and the environment the mean of stochastic projections can be modified accordingly. Such situations include average temperature dependence, species interactions and food availability for different exploited stocks. Where no explicit relationships exist or there is no basis for predicting environmental drivers into the future, advice should be based on scenario testing, along the lines of the evaluations of SGMAS management plans.

As a general recommendation the workshop concluded that in the light of climate change, rather than assuming that the mean of a given parameter derived from the (recent) past will best define the future we should consider trends and attempt to estimate them. This calls for

the development of a number of tools that evaluate estimates of current values and current trends in the presence of noise in both measurement and environment. The workshop concluded with a number of specific recommendations under changes in:

- Productivity regimes that require adapting management procedures or procedures robust to regime shifts.
- Habitat influencing measurement and stock carrying capacity.
- Growth and maturation influencing short and medium term advice.
- Recruitment changes due to environmental influence in the short and medium term.

Recommendations also include the use of multispecies models primarily for hypothesis testing and testing management procedures. Finally we recognise the need for longer term prediction and thus for developing climate scenarios for sensitive areas such as the Baltic Sea.

1 Terms of Reference

2006/2/ACFM24 A Workshop on the Integration of Environmental Information into Fisheries Management Strategies and Advice [WKEFA] (Co-chairs: John Simmonds, UK and Manuel Barange, UK), co-sponsored by ICES, EUR-OCEANS, and GLOBEC, will be established and will meet at ICES Headquarters, Copenhagen, Denmark, from 21–22 February 2007 (scoping meeting during WGRED and AMAWGC) and 18–22 June 2007 to:

Scoping meeting

- a) assemble and evaluate a small number of illustrative case studies in which environmental factors can be shown to have had a significant impact on exploited fish population dynamics, including information on the processes which may be responsible;
- b) evaluate the availability of data/ information and define necessary work/ actions to be taken before the main WK

Main workshop

- c) estimate the consequences of environmental variability (including “regime shifts”) for the biological reference points and other measures which are currently used to guide fisheries management;
- d) carry out analyses and formulate short, medium and long term integrated advice for the selected cases. Compare this with traditional methodology
- e) bearing in mind possible fisheries and ecosystems objectives, identify, develop and evaluate procedures for improving fisheries management strategies and advice by including environmental information. Identify future directions and needs, including operability, to bring forward the process of incorporating ecosystem advice.

WKEFA will report by 29 June 2007 for the attention of the ACFM, ACE, Oceanography, Living Resources and the Consultative Committee (ConC).

2 Agenda

Monday 18 June / Tuesday 19 June

Introduction, Adoption of agenda, overview. Simmonds/Barange

Presentations of case studies:

- a) Management adaptations to identified environmental variability
 - a. Greenland cod – Wieland
 - b. Bering Sea flatsfish – Spencer
 - c. NS Cod - Brander
 - d. NE Atlantic sardine - Cabanas
- b) Management adaptations to the consequences of environmental variability
 - a. North Sea herring – Dickey-Collas / Simmonds
 - b. Bering Sea Pollock – Ianelli
- c) Management Including Multispecies aspects
 - a. NE Arctic cod – Svensen
 - b. Baltic Sea Cod - Köster
 - c. Baltic Sea sprat – McKenzie
 - d. MSVPA - Pinnegar
- d) Direct applications of environmental information
 - a. Bay of Biscay Anchovy Roel
 - b. California sardine – Hill
- e) Simulating management under productivity regime shifts
 - a. South African Anchovy - Roel
 - b. Generic short and long-lived species–King

Wednesday to Thursday

Discussion and draft text preparation

3 Introduction

3.1 History

This workshop follows the developments from the Working Group on Ecosystem effects of fishing activities (WGECO), the Working Group on Regional Ecosystem Descriptions (WGRED), the Workshop on the Decline and Recovery of cod Stocks throughout the North Atlantic (WKDCRS), the ICES/GLOBEC Working Groups on Cod and Climate Change (WGCCC) from 2003–2006 and the Study group on management strategies (SGMAS) from 2005–2007. The workshop is also co-sponsored by the European Network of Excellence EUR-OCEANS, responding to their goal of establishing the scientific basis for the development of the Ecosystem Approach to Marine Resources (EAMR) in the European research area, and the need to develop direct applications of GLOBEC and GLOBEC-like science. Simultaneous to these developments, the environmental conditions in the ICES area have undergone major changes in recent decades. For example sea surface temperatures in the early 2000s in the North Sea and Baltic Sea are warmer than anytime in the instrumental record since the 1860s–1880s (MacKenzie and Schiedek, 2007), the NAO has been in a predominantly positive phase during most of the last 10–15 years (Brander, 2005) and regime shifts have been suggested which have affected abundances, distributions and life histories of marine communities over wide areas of the northeast Atlantic and Baltic Sea (Beaugrand *et al.*, 2002; Reid *et al.*, 2003; Alheit *et al.*, 2005). Expected changes in future climate and consequently hydrography during the coming decades will lead to further major changes in fish populations and marine ecosystems.

The primary purpose of the workshop is to draw together information from a wide range of expertise in and outside ICES to formulate an approach to the problem of bringing the effects of environmental change into the provision of ICES fisheries advice. For the purpose of this workshop environmental information was considered to include both abiotic (e. g., temperature, ocean circulation) and biotic factors (e. g., abundances of prey and predators).

3.2 Rationale–ICES/European single species

The approach taken derives directly from the type of advice currently required by fisheries clients. The main policy drivers for this advice are the declaration from The World Summit on Sustainable Development at Johannesburg 2nd to 4th September 2002, paragraph 31 (a) which gave a, “commitment to restoring fish stocks to levels that can produce maximum sustainable yields (MSY) by 2015”, and paragraph 29d “encourage(d) the application by 2010 of the ecosystem approach”. In a European context this refers to a non-paper from the EU Commission services (2006) “Implementing sustainability in EU Fisheries: strategies for growth and employment”. This paper stated that “In the long term, stock size depends on recruitment and natural and fishing mortality rates. Recruitment depends on various aspects of the environment and on stock size. Fmsy is the fishing mortality rate that will, on average, result in a stock size that produces the maximum sustainable yield. Fmsy is a more achievable measure than the stock size that produces maximum sustainable yield, because it is less dependent on the marine environment and ecosystem effects is a potentially manageable quantity. “

The EU Commission and European coastal states currently manage fisheries through single species catch controls allocated among countries, though in some cases fleet based effort controls are also used. This approach leads to a requirement to develop Fmsy, by species and ideally a management plan by species or small groups of species.

This leads to the current need for single species or management unit advice. It is in this context that WKEFA has considered how change due to environmental factors can be included directly in this advice. This approach, therefore, is narrower than that is expected in the development of the Ecosystem Approach to Marine Resources (EAMR, Garcia *et al.*, 2003) but is a step in this direction by explicitly recognising the complexity and interconnections among ecosystem components.

The existing ICES advice system was designed to respond to change by providing advice only on a very short term basis: one year ahead based on recent past. As we now move to provision of longer term advice in a more rapidly changing environment there is a need to alter the way we consider the future and to provide advice that is both more robust and more adaptive to change.

3.3 Approach to the workshop

A planning meeting was held in February to select case illustrative studies and define the work plan. Following the plan developed in February, the workshop has been organised with 14 case studies which have been chosen to stimulate discussion of a wide range of issues. These were prepared by participants in advance of the meeting and presented during the first two days. The case studies and the influence of environmental change are summarised in the next two sections. The discussion of these cases was then used to formulate generic solutions to identify, develop and evaluate procedures for improving fisheries management strategies and advice by including environmental information.

The main workshop ToR have been dealt with firstly by using the case studies to show detailed evaluations. These are summarised in the report as tables in Annex 3. The ways in which environmental change has been dealt with in management (ToR d) are summarised from the case studies and presented in section 4. The final ToR is discussed in Section 5 where the conclusions for each aspect considered are presented in detail. The main overall conclusions and a series of specific recommendations are presented in Section 6.

4 Case studies-influence of environmental change on management

This section collates the information from the cases studies examined in the workshop. In some cases environmental influence on individual species could be assigned to specific drivers (or driver proxies), mostly water temperature: Greenland cod, Bering Sea flatfish, North Sea cod and NE Atlantic sardine. In other cases the management was adapted to the consequences of the environmental variability without a specific driver being identified: North Sea herring and Bering Sea Pollock. More complex interactions including multispecies interactions were highlighted for NE Arctic cod, Baltic Sea Cod and Baltic Sea sprat. In addition multispecies issues were considered within the context of multispecies modelling (MSVPA) in the North Sea. Two cases were chosen where environmental drivers are or have been used to determine stock exploitation rates, recruitment or/and stock abundance: Bay of Biscay anchovy and California sardine. More generically two management simulations involving changes of productivity regimes were presented: The first was a specific case related to the mixed South African anchovy and sardine fishery. The second examined several generic cases of short, medium and long lived species under high, medium and low exploitation rates. Both simulations assessed the value of incorporating regime specific harvest control rules.

For each of the cases studies the main ways in which environmental factors affect the management are highlighted below.

4.1 Greenland cod (Annex 4)

Cod in Greenland waters derives from three components labelled by their spawning areas: i) an offshore spawning stock off East and West Greenland, ii) Icelandic spawned cod that irregularly drift to Greenland as larvae, and iii) inshore West Greenland fjord populations (Storr-Paulsen *et al.*, 2004).

The offshore fishery started in the 1920s at West Greenland and culminated with landings of 440 000 t in 1962. At that time relatively warm conditions prevailed and a healthy offshore spawning stock existed (Buch *et al.*, 1994). The productivity of the Greenland offshore stock measured as the number of recruits per unit of spawning stock biomass (mean $R_{age\ 3}/SSB = 0.21$; 1935–1966) appeared to be lower than in other North Atlantic cod stocks, e.g. Icelandic cod ($R_{age\ 3}/SSB = 0.94$; 1955–2002), and an equilibrium fishing mortality (F_{MSY}) for the age groups 5 to 12 would have been 0.2 (Hovgård and Wieland, in prep.). Actual fishing mortalities, however, were about 0.8 in the mid 1970s. As a consequence the stock declined drastically, and recruitment became mainly dependent on larval drift from Iceland. This situation might have been prevented by an appropriate reduction in fishing effort.

The offshore fishery completely collapsed in 1993 and ACMF recommended that no fishing should take place until a substantial increase in biomass and recruitment is evident. However, neither have these levels been defined nor has a recovery plan established.

In the mid 1990s temperature in Greenland waters increased to record high values and recruitment improved from the end of the 1990s. The 2003 year-class, which is estimated to be relatively strong, shows the characteristics usually associated with cod that have drifted as larvae from Iceland. Indications of cod spawning off East Greenland since 2004 were found based on fishermen reports. A quota of 1000 t for experimental fishing was set, designated to determine biological sampling needs in the area north of 63°N off East Greenland. Dense concentrations of large spawning cod were found in this area in April 2007, and the length distribution of the catches (modal length of ~ 95 cm corresponding to mean length of age groups 8 to 9 in the survey; ICES, 2007b) may suggest an immigration of adult cod from Iceland have occurred in addition to the inflow of recruits in 2003. For 2008, ICES recommends that no fishing should take place to allow for the rebuilding of the spawning stock. For future management, however, it appears highly desirable that a more detailed recovery plan is developed, which may also include a harvest control rule option that allow the inclusion of environmental conditions in the future. In addition to temperature as a general indicator, recent changes in biomass and migration of capelin in the East Greenland / Iceland region and of seals at West Greenland should be considered in that process.

4.2 Bering Sea flatfish (Annex 5)

The eastern Bering Sea has exhibited substantial variability in temperature in recent decades, and has shown a marked warming trend in recent years. These changes in temperature could affect the catchability of the annual trawl survey for groundfish species if fish distributions and/or fish behavior are related to temperature. For example, for yellowfin sole temperature-dependant catchability may arise from changes in availability (i.e., changes in the proportion of the stock in the survey area) and/or changes in gear efficiency (i.e., changes in the proportion of the fish in the path of the trawl actually captured). Yellowfin sole spawning adults are known to spawn in spring in shallow bays outside the survey area, and timing of migration to the summer feeding grounds could vary with temperature and thus produce temperature-dependant availability. Additionally, gear studies indicate that eastern Bering Sea flatfish are herded into the net path from the trawl bridles, and if the flatfish swimming behaviour is affected by temperature then the degree of herding may also be affected. Although identifying the relative influence of these two hypotheses remains a task for future research, current stock assessment models estimate significant relationships between estimated catchability and temperature for yellowfin sole (*Limanda aspera*) and flathead sole (*Hippoglossoides elassodon*).

Using yellowfin sole as an example case, we explored three methods of estimating survey catchability and evaluated their implications for management advice. First, survey catchability was estimated as a constant parameter over all survey years without regard to temperature. Second, the current method of estimating time-varying catchability was evaluated, in which catchability is a function of the annual temperature averaged over the entire survey area (referred to below as a “global” catchability model because the catchability at each survey station in a given year is expected to be the same). However, spatial differences in temperature between survey tows may result in differential responses to the trawl gear. Thus, we also evaluated a “local catchability” model in which the estimated survey catchability at a given trawl was a function of the local temperature for that trawl. Of particular interest was a trend of increasing temperatures from 1999 to 2005 and how this might have influenced estimated population size.

For yellowfin sole, both methods of estimating temperature-dependant catchability resulted in a positive relationship between catchability and temperature. The increasing trend in EBS temperatures from 1999 to 2005 had a substantial effect on estimated yellowfin sole biomass and harvest recommendations. For models run through 2005, the estimated 2005 total biomass declined from 1904 kt to 1770 kt when the “global” temperature-dependant catchability model was used as compared to a constant catchability, and the resulting one-year harvest recommendation declined 7% from 132 kt to 123 kt. In 2006 a sharp reduction in bottom temperature occurred, ending the trend of increasing temperature from 1999 and resulting in the estimated spawning stock biomass being similar between the three methods. The decline in estimated 2006 harvest recommendation from the constant catchability model to the “global” temperature-dependant catchability model was reduced to 3%. These results indicate that identification of temperature-dependant catchability may be most critical during trends of increasing or decreasing temperatures whereby spurious trends in survey biomass may occur. Further simulation modelling was conducted to evaluate the effect of 10-year trends in temperature. When temperature-dependant catchability occurs but is not estimated, harvests are lower during runs of cold temperature and higher during runs of warm temperature relative to the case of estimating temperature-dependant catchability, leading to increased variance in catch. In the assessment in eastern Bering Sea yellowfin sole this issue is potentially avoided by estimating temperature-dependant catchability in the current assessment procedure.

4.3 Findings from the ICES/GLOBEC Cod and Climate Change (CCC) programme which should influence assessment and advice on fish stocks

4.3.1 Background

The principal objective of the CCC programme has been to develop our understanding of the structure and functioning of marine ecosystems and how they respond to changing physical

forcing, with the aim of helping to bring this information into the management of fisheries. Like other ICES WGs, WGCCC acts as a catalyst and coordinator for research and a forum for cooperation. The programme budget covers only the work of the ICES/GLOBEC coordinator; therefore the only directly attributable products are ICES reports (including several CRRs), symposia and papers which carry acknowledgements, including all those by the coordinator. Many additional publications and work programmes have benefited from participation in CCC programme, but cannot be described as products of the programme. A short account of the achievements of the programme and a list of some major publications is shown on a poster available on the website: <http://www.ices.dk/globec/data/presentations/poster.jpg>. The website also provides a large amount of information (including datasets) from past workshops. Newsletters back to 1997 provide accounts of the major areas of work, including related regional and national programmes. Many of the subjects which the programme has addressed have become part of the scientific background which is already taken into account by WGRED and other groups, but it is worth reading reports such as CRR 252 on Growth Dynamics. <http://www.ices.dk/pubs/crr/crr252/CRR252.PDF>. It includes reviews of factors explaining variation in growth, construction of growth models, estimation of ambient temperature, effects of size-selective mortality, effects of variation in stock biomass, density dependence, use of bioenergetic models and genetic variability, plus many recommendations and case studies. The recent report of the Workshop on Decline and Recovery of Cod Stocks (ICES CM 2006/ACE:03) is topical and relevant for WKEFA. <http://www.ices.dk/reports/OCC/2006/WKDRCS06.pdf>. It gives an overview of the declines and recoveries for all cod stocks and proposes definitions of “prolonged period of decline” and “collapse”. It evaluates the role of fishing and environment in causing declines and recoveries and discusses the interaction between the two. It evaluates the causes of observed changes in rates of survival, growth and maturation, the consequences for stock resilience of change in mean size and age/size diversity and the role of cod forage species and predators. It comments on past projections of stock recovery, evaluates whether they were correct and draws conclusions concerning improvement of projections in future. It documents historic evidence of stock recoveries and the environmental and fisheries circumstances in which these occurred, including the role of changes in marine ecosystems.

4.3.2 Comments on the application of environmental information

Environmental information can be useful at many stages in the formulation of management advice, not only in stock assessment. Some of these are discussed below and are used to structure the following case studies, but others are being developed.

Reviews of the use of environmental information in assessment and advice have been carried out recently by WGECCO, WGRED, SGRAMA, SGPRISM, SGMAS and others. [“Environmental information” is used here to denote all information concerning biological, physical and chemical states and processes, other than the basic fisheries derived information currently used in the assessment process.] Environmental information may help to improve the quality of fisheries assessment, and also plays a part in establishing and evaluating management strategies. Environmental information should be considered for inclusion in relation to the four key components of management strategy evaluation: objective setting, control procedures including harvest control rules (HCR), operating models and robustness testing.

There are real problems in including environmental information because models should be kept as simple as possible and extra factors have to satisfy a number of criteria. The operational relationships which are put forward (e.g. effect of temperature on recruitment) are often based on proxy time-series and represent only part of a more complex process. A caveat against incorporating environmental information is that the proposed functional relationships (based on exploration of past data and process information) cease to fit after a while and have to be discarded. However, in spite of almost universal lack of fit, this caveat is, quite understandably, not used to discard stock/recruit relationships on which fisheries management is based, because they represent a necessary relationship between reproductive output and subsequent recruitment, even if these are difficult to measure and the relationship also depends on many other factors. A more balanced approach to Type II errors and to improving all such

relationships should be based on understanding the processes and producing better (more appropriate) datasets on physical and biological variables and states. Relationships between environmental factors and fish population variables (growth, recruitment, maturity, fecundity, survival) are generally provisional and should be regarded as “pre-operational”, but can justifiably be used in assessments, if they are better than the alternatives. Three criteria which should be met are: (i) the consequences of including the environmental factor should make a difference to the outcome (ii) the data on the environmental factors must be timely and affordable (iii) the processes by which the environmental factor acts should be explained.

Annually updated fisheries assessments are short term forecasts of biomass and are less likely to benefit from inclusion of environmental information (because the biomass next year consists largely of fish which are already alive and being counted). When projecting further into the future (e.g. in evaluating management strategies) the forecasts rely increasingly on assumptions about future growth, recruitment, mortality and distribution. Such assumptions can be based on part or all of the past record, but since many environmental factors (temperature, windfields, climate indicators, advection) are expected to be systematically different in future the steady state assumption is poor. Alternative future scenarios are being used to evaluate future risks and uncertainties for management in most areas of human activity (e.g. banks will no longer provide loans for development of skiing in the Alps) and fisheries management can make use of the ongoing work on future climate scenarios. The CCC programme held one workshop on future ocean climate (ICES CM 1998/C:14) and has another planned for 2008. It has also interacted with programmes such as GOOS and GODAE in specifying what monitoring and operational oceanographic products will be useful for fisheries management.

4.4 NE Atlantic sardine (Annex 6)

Preliminary work relating the NE Atlantic Sardine recruitment variability with atmospheric and oceanographic large scale indices (such as NAO and AMO) and local scale oceanographic events, as upwelling and coastal currents, has been considered. The model fitted to data for the period 1978–1990 explains 58% of the recruitment variability. After that a succession of poor recruitment resulted in a poor fit to the data.

Significant interannual trends in climatic, oceanographic and ecosystem variables integrated in the NW Iberia and Bay of Biscay region observed since 1990 are indicative of a possible regime shift and also of global warming in the region.

No application to assessment/management was made on the basis of this recruitment model. Before such a relationship could be operationalised it may be necessary to identify non-linear responses (regimes) and possibly the impacts of global warming on the Atlanto-Iberian ecosystem in general and on sardine in particular.

4.5 North Sea herring (Annex 7)

The incorporation in management of environmentally induced variability in the production of North Sea herring has increased in recent years. The drivers for the variability are unclear; however both changes in growth and recruitment have been included in the short term projections and simulations of medium term stock development. Cohorts with reduced growth and maturity are now modelled separately within the projections and a recent change in the recruitment (5 sequential years of poor recruitment) is now incorporated into the advice as reduced recruitment in the short and medium term projections. Whilst the mechanisms for change are unclear (see ICES 2007d), the effects are detectable. Further work is required, however, to investigate the potential scenarios for herring production in the North Sea for the medium to long term. The inclusion of variable M derived from MSVPA showed consistency for parts of the time-series did not fit with survey observations on juveniles for a period when mackerel and horse mackerel predation were thought to be higher, suggesting some incompatibility.

4.6 Bering Sea pollock (Annex 8)

Advice to managers is adjusted to account for environmental conditions for Eastern Bering Sea pollock. Formally, the adjustments occur through the added stochastic components of environmentally driven demographic shifts (e.g., mean weight-at-age) and through the shape of the assumed stock-recruitment relationship. The latter is justified based on analyses of stomach content data coupled with models to show that cannibalism has an impact on subsequent recruitment levels. The stochastic components (measurement errors together with environmentally driven process errors) affect quota recommendations by increasing the uncertainty of the F_{msy} estimates. Higher uncertainty in F_{msy} estimates result in lower values for quota recommendations due to analyses (shown in the original amendment to the Fishery Management Plan) that have determined that the harmonic mean value is appropriately risk-averse. Explicit qualitative adjustments to the pollock quota recommendations are done through the process communicating apparent ecosystem changes (e.g., increased predation by arrowtooth flounder for Gulf of Alaska pollock and the lack of acoustic back scatter seen in the Bering Sea during summer survey of 2006). The latter effectively lowered the ABC recommendation by 118 000 t.

Environmentally affected components of stock productivity that were reviewed included recruitment, growth, mortality and the spatial distribution of the stock. Recruitment affects quota recommendations by the functional form, and the uncertainty of that form. Information on the impact of different climate regimes on pollock recruitment appears to be relatively weak, though during the late 1950s and 1960s, recruitment (based on relatively poor data) appears to have been well below the average from 1970 through 2000. The importance of pre-recruit surveys was evaluated through simulations of likely data outcomes for 2007 and shows that without a survey, the likelihood for exploiting at higher rates was greater. The importance of direct observations on pre-recruits as opposed to environmental proxies (e.g., correlative studies on factors related to recruitment success).

Stochastic components due to growth variability were shown to lower advice on quota recommendations by about 20 000 t, a relatively small percentage of the total. However, this evaluation did not account for possible trends in mean weight-at-age which may reduce the adjustment and provide a better basis for short-term projections.

Retrospective analyses are useful to evaluate errors in model structure that should be included for testing purposes. For example, retrospective patterns may be caused by a combination of factors including recruitment processes, natural mortality, somatic growth, and distribution (stock availability to fishery and surveys). Linking information on multispecies modelling results may help to determine the extent that unaccounted natural mortality is contributing retrospective patterns compared to other possibilities such as movement.

4.7 California sardine (Annex 9)

Environmental Information in a Population Assessment Model

For nine consecutive years (1995–2003, e.g. Hill *et al.*, 1999, Conser *et al.*, 2003), the annual stock assessment for California sardine was performed using the statistical catch-at-age model ‘CANSAR’ (Deriso *et al.*, 1996). CANSAR used three-season SST_{SIO} data and spawning biomass to constrain recruitments using Jacobson and MacCall’s (1995) modified Ricker function:

$$\tilde{R}_y = S_y e^{\alpha + \beta S_y + \gamma T_y}$$

where R_y was the predicted number of age-zero sardine on 1 July of year y ; S_y was spawning biomass in April of year y ; and T_y was the running average of SST_{SIO} for the preceding three seasons (July-June). Values for the parameters (α , β , and γ) were fixed based on Jacobson and MacCall’s (1995) estimates. The assessment lacked a YOY survey so, apart from age compositions derived from the fishery catches-at-age, the model contained very little information concerning the most recent few year classes. To obtain more reasonable

recruitment and biomass estimates for the youngest year classes, model emphasis on spawner-recruit predictions were increased linearly in the final three model years. The affect on management was in the form of changes to stock biomass which resulted in changes to TAC based on the Harvest Control Rule (HCR).

Environmental Information in a Harvest Control Rule

The HCR for California sardine (PFMC 1998), which uses SST_{SIO} to modulate harvest rate, has been used to establish U.S. sardine harvest limits for the past eight fishing seasons (PFMC 2007). The HCR has the form:

$$H_{y+1} = (B_y - E) U f$$

where: H_{y+1} is the TAC for the pending fishing season; $H_{MAX}=200,000$ mt; B_y is the current year biomass (ages 1+); E is the minimum biomass escapement threshold (150,000 mt); U_{MSY} is the harvest rate based on $SST_{SIO}(T)$ calculated using:

$U_{MSY} = 0.248649805 T^2 - 8.190043975 T + 67.4558326$ (such that $0.05 \leq U_{MSY} \leq 0.15$); and f is the average portion of the stock residing in U.S. waters. To date, SST has had no affect on management based on changes to TAC from the HCR. Due to prevailing warm conditions in the California Current, the SST component of the HCR has remained at the maximum possible value ($U_{MSY}=0.15$).

4.8 NE Arctic cod (Annex 10)

Predation from cod on cod (cannibalism) is included in the natural mortality estimate $M=M1+M2$ where $M1=0.2$ is assumed and $M2$ being the cannibalism part. The predation estimation includes the use of stomach evacuation rate models with temperature as an important variable.

Weight-at-age in the stock is predicted according to Brander (2002) but the choice of “reference period” is chosen to be the one that best corresponds to the current perception of environmental factors such as the status of the capelin stock.

Similarly, the natural mortality is projected forward using the last 3 year average, but the report states clearly that this is a choice made after inspecting a visualization of $M2$ with capelin biomass overlayed. A working document dealing with models for predicting has been presented in the working group.

A working document titled “Potential improvements of the management advice of Northeast arctic cod by active use of environmental information” was presented at the workshop. The WD focused on 3 aspects:

1. Changes in the geographical distribution

Around 1980, intense cooling caused a redistribution of the cod in the Barents Sea towards the south and west. These areas experienced a maintenance of high fish densities and thus catch per unit effort, in spite of the stock declining rapidly. The result was advices of too high TAC. It is referred to similar problems e.g. with the thorny skate in Canadian waters. In Norwegian waters regular bottom trawl surveys were initiated to account for such effects based on swept area considerations. However around 1990, the temperatures increased considerably, and the distribution of young cod was extended towards northeast, well beyond the survey area. This resulted in several years of underestimates of the recruitment.

2. Recruitment predictions

Different methods of recruitment predictions including environmental information are evaluated. Two statistical models are used, one purely based on observations of temperature, capelin and 1-group cod, and one purely based on numerical model result of volume transport and primary production. By going back in time, the actual predictions made by ICES annually are compared with the predictions we could have made at the same time by using the recently obtained methodology. The results are also compared to the converging VPA, and the potential of early warnings to rapid changes and/or previously bad advices are evaluated. The

third method is based on analysing the influence from temperature and pre-recruit cannibalism on stock- recruitment relations through probabilistic prognosis with a multispecies population dynamics model.

3. Food availability and growth

The growth of cod has shown to be quite dependent on the availability of capelin. The ICES growth prediction in 1987 was too high for the next two years, while the prediction in 1989 was too low. This analysis demonstrates how different the short term catch advice would have been for 1988 and 1990 if the growth (and thus weight-at-age) had been predicted correctly.

4.9 Baltic Sea cod (Annex 11)

Baltic cod spawning requires water of a sufficiently high oxygen content and salinity for eggs to survive. The amount of water with these characteristics depends on the inflows of high salinity water from the North Sea. Since the mid-1980s there have been only two major inflows from the North Sea into the Baltic (in 1993 and 2003), thus leading to poor conditions for egg survival. The reduced salinity has also affected the main larval food for larval cod, *Pseudocalanus* sp. Currently only the Bornholm spawning area is sustaining the stock, benefiting from regular minor inflow events. Climate predictions suggest that the frequency of inflows will not increase in the foreseeable future.

As a result of the above ACFM (2007) classifies the Eastern Baltic cod stock as suffering from reduced reproductive capacity and, based on the present fishing mortality (F of 0.98) in relation to precautionary limits (F_{lim} of 0.96), as harvested unsustainably. In the absence of an agreed management plan, the exploitation boundaries for this stock are based on the precautionary limits ($B_{pa}=260.000$ t). As this biomass cannot be reached in 2009 it has been recommended that no catch should be taken in 2008 and a recovery plan developed as a prerequisite to reopening the fishery. AGLTA (ICES 2005a) and SGMAB (ICES 2005d) have conducted medium- to long-term simulations exploring the possibilities to rebuild the stock to B_{pa} and concluded that at present the precautionary fishing mortality (F_{pa} of 0.6) is too high to rebuild the stock to B_{pa} or even B_{lim} .

WKREF (ICES 2007f) conducted a review of data sets and methodology used to determine the present limit reference points for Eastern Baltic cod. The F reference points determined in 1998 are based on an assessment revised in 1997 with respect to catch-at-age, weight-at-age and maturity ogives, while the biomass reference points are based on an older assessment conducted in 1996. After 1998 also discards have been included in the assessment, which have been considered in neither reference points. The biomass reference points are not based on the full dataseries from 1966 onwards available, but are based on a time-series starting in 1976, covering a period of outstanding high recruitment, while the F reference points are based on the entire time-series. As such the F and biomass reference points are not consistent and the biomass reference points cannot be considered as adequately determined and need revision. According to SGPA (ICES 2002) and SGPRP (ICES 2003c), the apparent change in productivity of the Baltic Sea in the 1980s should be considered by identifying environmental regimes, either by separating time-series into shorter periods of similar environment, or preferably by incorporation of the environmental drivers into stock recruitment relationships. However, WKREF (2007) was unable to give guidance on methodology to be applied for the determination of limit reference points under shifting environmental conditions.

As presented during the workshop, there is a significant impact of the SSB on recruitment, however, explaining only a limited amount of the variance and being of importance rather a high than at low stock sizes, the latter being a prerequisite for the determination of B_{lim} . This result is robust against using different measure of reproductive effort (e.g. female SSB, potential egg production) and can thus not be explained by the SSB being an inadequate measure of the reproductive potential. SSB appears to be especially important in eastern spawning areas after major Baltic inflows, i.e. having a sufficient large stock available to utilise the available favourable conditions for reproduction.

If we continue to use biomass limit reference points for providing management advice there is a need to at least consider the existence of two reproductive regimes (only Bornholm Basin vs. all basins having reproductive conditions). A determination of biomass reference points for a specific productivity regime though requires rules on revision procedures to be evoked if the regime shifts into another state as well as the necessity to evaluate harvest control rules against limit biomass values (WKREF, 2007).

Vinther and Köster (2007) conducted a preliminary evaluation of the harvest control rule in the EU management plan for Baltic cod stocks adopted in June 2007, which can be summarised as follows: *reduce F by 10% compared to the year before, until F (4–7) is 0.3. Interannual changes in TAC are restricted to $\pm 15\%$, except if $F > 0.6$ (ages 4–7), then TAC may be reduced by $> 15\%$.* Simulation results indicate that the proposed HCR is precautionary at moderate level of assessment uncertainty and implementation noise, but tolerates only limited assessment bias or implementation bias. The latter is considerable as the TAC since 2000 has been on average exceeded by ca. 30%. The harvest control rule is not robust against such implementation failures and the risk for the stock to fall below Blim exceeds 5% for implementation errors of 15–20%.

In the simulations, a hockey stick stock recruitment relationship with a breakpoint at 90 000 t SSB was used, based on a recruitment time-series from 1987 onwards. This procedure, also adopted by AGLTA (2005), considers the period of unfavourable environmental conditions only, but evaluates the HCR against the present Blim of 160 000 t determined on basis of a period with predominantly high recruitment. This is a conservative approach, as it would have been more consistent either to use the same year range in the stock recruitment relationship as used in the determination of Blim or to adapt Blim as breakpoint in the hockey stick stock recruitment relationship, which has been suggested by WGBFAS (2005).

The sensitivity of the performance of the HCR was tested using different stock recruitment relationships. As can be expected, if the recruitment scenario is low (for a given stock size) the risk to Blim is high. This implies also that the target F is higher for the higher recruitment scenario, so that environmental conditions affect not only limit biomass reference points, but also target fishing mortalities. It should be pointed out that the slopes of the two S-R regressions are very similar. The only difference is a higher breakpoint, thus allowing a higher recruitment at increasing SSB. Therefore, recovery rates at low stock sizes are similar, but recruitment at higher SSB is truncated at 90 000 tons. This is justified because; following arguments above, the SSB distributed in eastern spawning areas will not contribute to reproductive success.

The simulations conducted by AGLTA (2005) and Vinther and Köster (2007) ignore density dependent processes, such as growth changes depending on stock abundance and cannibalism, both described for the Eastern Baltic cod stock. Multispecies projection (ICES, 2001c) demonstrated that reproductive success is the main driver of the stock, but that cannibalism is important at high stock sizes due to overlap between adult and juvenile cod (Uzars and Plikshs, 2000). Simulations extended by SGMAB (2005) showed that decoupling recruitment from the SSB delays recovery and resulted in lower yields.

SGMAB (2003) tested the behaviour of density dependent weight-at-age and environmentally sensitive and spatially explicit stock recruitment relationships in a simplified multispecies projection framework (Gislason, 1999). However, these attempts have to be considered as preliminary, as process models and environmental scenarios still lack realism and testing to be the basis for management advice. However, the sensitivity of short-term predictions with respect to changes in weight-at-age has demonstrated a clear potential for improving the quality of prediction by considering trends in weight-at-age. SGMAB (2007) worked on statistical relationships which may be used for such an improvement.

Finally STORE (2003) explored the possibility to utilise the significant relationship between larval abundance and recruitment described by Köster *et al.*, (2003a). Retrospective test predictions using this predictor outperformed the procedure applied by WGBFAS for 1998 to 2002 based on RCT3 runs with bottom trawl survey results. However, it is important to note that the regression did not predict recruitment better than survey results but (STORE, 2003).

The introduction of new bottom trawl survey gear in 2001 has increased the catchability of juvenile cod, and combined with an additional autumn survey suggest that the need for additional pre-recruit information is now limited. 0-group survey indices from the autumn survey would be as effective as larval surveys, although an extra year lead may be achieved through prediction of potential egg production in March/April of the assessment year.

4.10 Baltic Sea sprat (Annex 12)

Sprat spawner biomass in the Baltic Sea is presently above B_{pa}. However relationships between spawner biomass and recruitment are uncertain and statistically insignificant. The ICES assessment working group presently uses a long-term geometric mean for making short- and medium-term predictions of catch and spawner biomass. Recruitment at current spawner biomass levels is likely driven by ecosystem processes such as effects of abiotic variables (e.g. temperature) or trophic interactions (e.g. predation, cannibalism). No environmental information is presently used in either short-term or medium-term projections of recruitment, spawner biomass, yields or reference points.

We have conducted several analyses to investigate how knowledge about recruitment processes (especially climate/temperature variability) can be used in assessment and stock projection work. All of the results have been presented at the Baltic assessment working group and some have been included in its annual reports where it is used on an *ad hoc* basis for interpreting past variations and trends (ICES, 2006c). However environmental information is presently not used to formulate advice about future development of the biomass or yields.

Retrospective analysis of recruitment prediction quality. A comparative retrospective analysis using data available in the year of prediction showed that recruitment predicted by environmental variables (i. e., water temperature, a winter index of the North Atlantic Oscillation and Baltic Sea ice coverage) yielded smaller and less variable deviations from observed recruitment than recruitment estimated with methodology currently used by ICES (MacKenzie and Köster, 2004).

Improvement of predictive horizon for recruitment forecasts. The ICES assessment working group meets too early in the year to use the best environmental correlate of recruitment for current year predictions. We show how this difficulty can be overcome by identifying and using the seasonal chain of links between climate variability, sea conditions and sprat recruitment. This chain gives 2–3 months additional predictive horizon and allows the WG to predict current year recruitment from ecosystem information (MacKenzie and Köster, 2004).

Sensitivity analysis of short-term predictions of spawner biomass and yield to environmental variability. We assimilated climate-oceanographic-recruitment linkages into the standard ICES assessment procedure to predict key advisory-related variables such as spawning stock biomass (SSB) and landings (MacKenzie *et al.*, 2007). We use a concrete, real-world example to illustrate these effects. Predictions of recruitment made using the North Atlantic Oscillation for the 2006 year class showed that spawner biomass would be 15% lower than spawner biomass calculated using the ICES standard methodology. The difference in perception of future biomass does not affect the advice for the stock because $SSB > B_{pa}$. However, when this is not the case, or when it is desirable to broaden the ecosystem basis for fisheries management, it may be beneficial to include recruitment processes knowledge.

Influence of climate variability and exploitation on medium term projections of spawner biomass and yield. Combinations of climate variability/regimes and exploitation which have different probabilities of maintaining the spawner biomass above B_{pa} were identified (MacKenzie and Köster, 2004). For example fishing at F_{pa} under a cold climate (defined as long-term mean temperature–1 standard deviation) increases the risk of $SSB > B_{pa}$ from 0% to 18%, compared to a scenario involving fishing at F_{sq} under long-term mean temperature conditions).

4.11 Bay of Biscay anchovy (Annex 13)

The Bay of Biscay anchovy is a short-lived species with highly variable recruitment, with a population that consists largely of 0-, 1- and 2-year-old fish. Its dynamics is strongly

dependent on annual recruitments, and as a result has large annual fluctuations in biomass. At the time of the annual TAC advice there is no direct estimate of forthcoming recruitment (De Oliveira *et al.*, 2005), and so the advice is based on catches, DEPM and acoustic biomass estimations.

Two environmental-based recruitment indices have been considered during the last 10 years, an upwelling index (Borja *et al.*, 1998) and an index combining upwelling and stratification breakdown (Allain *et al.*, 2001). In 2006 ICES undertook a revision of both indices (WHMHS Report 2006). A linear regression from the Borja's *et al.* (1996, 1998) upwelling index, the ICA assessment and the standard Biomass based model yielded a probability of being due to random of 0.02 for the ICA series of recruitment and of 0.08 for the Biomass based model, but with a coefficient of determination of past recruitments of only 29% or 16.3% respectively.

The IFREMER anchovy recruitment index (Allain *et al.*, 2001) is based on a multi-linear regression of anchovy abundance on 2 environmental indices: upwelling and stratification breakdown. The anchovy abundance considered is the abundance at age 1 on January 1 of year y , as estimated by the ICES WG. The environmental indices are extracted from the IFREMER hydrodynamic model for the French continental shelf of the Bay of Biscay. The period considered for constructing the index is March 1 to July 31 of year $y-1$. The series was fitted by a multiple regression linear model to the recruitment at age 1 estimates from the Biomass Bayesian Model (WGMHSA Report, 2006) and to the ICA numbers at age 1 estimates. The series related well to the strength of next coming recruitment provided by ICA over the period (1987–2002), however the most recent failures of recruitment were not explained by the model. The fitted multiple regression model is still statistically at Alpha of 10%, with a probability of being due to random of 0.03 for the ICA series of recruitment and of 0.07 for the Biomass based model, but with a coefficient of determination of past recruitment of only 27% or 19% respectively (R-squared -adjusted for d.f.-).

As a result, and despite promising starts, the environmental indices are disregarded in the most recent assessments given their poor predictability particularly in recent years. The strong message is that spawning dynamics in relation to environment has changed since 2002. As there are no clear signs of recent environment change (temperature, river discharges, wind regimes: Planque, WGMHSA WD, 2005), it is suggested that the changes may be in the spawning stock or in the critical period of early life mortality.

A simulation study undertaken by De Oliveira *et al.*, (2005) highlighted the factors that appear to be relevant when using environmental indices to provide management advice. They showed that precautionary approaches such as the below average historic recruitment mean to predict recruitment may perform better in terms of increasing yields and reducing risk, than consideration of uncertain or moderate to weak environmental effects.

4.12 South African anchovy and sardine (Annex 14)

A number of environmental drivers have been identified as having an influence on anchovy recruitment strength (Hutchins *et al.*, 1998). Although, this knowledge was incorporated in the management advice as a way of qualitatively explaining some of the extreme recruitment events observed, none of the indices identified has been used directly to formulate the TAC in the combined anchovy- sardine management procedure (De Oliveira and Butterworth, 2005, Cunningham, 2007 *pers comm.*). However, this example has the added complication that the fishery for anchovy (*Engraulis encrasicolus*) also takes sardine (*Sardinops sagax*) as bycatch, a factor incorporated in current management procedures. A Management Strategy Evaluation approach was recently used by (De Oliveira, 2006) to investigate different harvesting strategies in the combined fishery in order to identify improved general approaches to management in the face of potential out-of-phase regime cycles between both species. Two aspects were considered, namely defining estimators that provide information about the regime cycle, and developing decision rules (and hence alternative MPs) that use this information.

It was concluded that management procedures that result in a reduction of juvenile sardine bycatch when sardine is in a trough of its biomass cycle offer the best performance under

regime cycles of varying amplitude. Furthermore, for sardine, the indirect estimator D1 based on survey estimates of the biomass outperforms estimator D2 (which provides information on the position of the cycle) in terms of *Loss*, *Net Product Value* and *Catch* for a range of MP options. Any gains in terms of *risk* would need to be judged against the feasibility and likely cost of obtaining sufficiently precise information on the underlying position in the cycle at any time.

4.13 Managing under conditions of regime shifts for different types of population and levels of exploitation—A simulation study (Annex 15)

Population simulations with regime-like shifts in productivity have illustrated that productivity regime specific fishing mortality management strategies can be used as a tool for contending with decadal-scale climate or environmental variability. These management strategies outperformed constant fishing mortalities management strategies by providing a balance between benefits (high yield) and trade-offs (fishery closures).

Regime specific fishing mortality management strategies allowed for rebuilding of spawning stocks from periods of low productivity to periods of improved productivity. The adjustment of harvest rates did not need to coincide with regime shifts in productivity, but could be lagged by the age of recruitment to the fishery.

For both short-lived and long-lived species, constant harvest rate strategies that are typically employed can not maintain sustainable stock or optimize fisheries when productivity is greatly reduced. If constant fishing mortality management strategies are employed across productivity regimes, these rates need to be very low (e.g. $F=0.25 \cdot M$) and are partnered with the trade-off of much reduced yield that will have potential significant economic and social impacts.

5 Discussion of issues

There is an extensive range of ways that environmental change affects the assessment, projection and management of fisheries. This section contains a brief overview of a number of issues. Their consideration is based mostly on how parameterisation is required in the type of fisheries management framework ICES proposes through the work of SGMAS. There are different ways to consider these issues and to break them down for discussion. At WKEFA we consider the interactions under four main aspects:

- a) Entries and exits from populations (recruitment, natural mortality and migration)
- b) Internal population processes encompassing, a range of aspects associated with growth maturation and reproduction.
- c) Location and habitat (including such aspects as vertical and horizontal movement)
- d) Multispecies interactions

We recognise that many of these factors act together and as the result of complex linkages, physical drivers may affect food supply or reproductive habitat, resulting in changes in location, growth, maturation and reproductive potential. This leading to changes in recruitment followed by changes in natural mortality due to different species interactions. We observe variability at a wide range of scales of space and time, and impose concepts of stochastic stability and regime shift that are useful for consideration of problems we face rather than a perception that there are a number of stable states that can be defined and that we may move between in either predictable or unpredictable ways.

In discussing environmental change we use a number of concepts which have loose definitions. We consider regimes as being quasi stable states around which we observe variability, such states are useful concepts for management; we are not concerned here with formal identification of regime shifts in the sense of linear and nonlinear processes. We discuss stocks on the basis of carrying capacity, productivity and depensation. For clarity carrying capacity relates to the mean level a stock might reach and within the framework of an S/R relationship is the recruitment that is expected when it is independent of stock size. Productivity expresses the rate of recovery from a depleted state or the rate of decline under heavy fishing pressure and relates to the slope of the S/R relationship near the origin. Depensation is the reduction in reproduction that results from stock size related effects.

5.1 Entries and exits from populations

Recruitment and natural mortality are the main source of population growth and loss (apart from fishing mortality), and are affected by environmental variability and change in short and medium term. In addition, environmental variability and change may affect migration rates in and out of the assessment/management area, and thus perturb advice. These aspects are considered here in terms of their influence on assessments, projections and/ or management considerations.

5.1.1 Migration

Variability in population migrations has been identified as an important issue that requires adequate parameterisation and estimation. There are several applications that are relevant to WKEFA.

NE Atlantic sardine-A Bayesian state-space model was developed as part of the Sardine dynamics and stock structure in the North-East Atlantic (SARDYN) project, EU RTD (Q5RS-2002-00818), explicitly accounting for the assumed migratory characteristics of the population by allowing stock- and age-dependent movement between model divisions at the beginning of each quarter of the year (ICES, 2006b, ICES CM 2007/ACFM:25:36). In the Bayesian state-space model, migration matrices denoting the proportion of fish from one area moving into another area at the beginning of each quarter of the year were fixed using input from scientists closely

working with the stock. These fixed migration matrices resulted in some good fits of the model to the observed data, in particular to the proportions-at-age by division. An update of the model to take account of data available up to the end of 2005 (results at the posterior mode) estimated likely emigration from ICES divisions VIIIb to VIIIc(east) for 1-year-olds (posterior mode of $\varepsilon_{imm} = 0.4$) and also estimated likely immigration (at a smaller rate) into VIIIc(east) for 2+ s (posterior mode of $\varepsilon_{em} = 0.17$). The proportion of the total stock biomass resulting from immigration into the assessed area was estimated to range between 1 and 4%. The effect of this immigration on the stock distribution throughout ICES division VIIIc (east) was much greater contributing, on average, 19% of the biomass in VIIIc (east).

Horse mackerel-Fisheries of horse mackerel take place during autumn in the Norwegian economic zone of the northern North Sea and in the southern Norwegian Sea. Since this fishery is not regulated it is assumed that the catches reflect the availability and abundance of horse mackerel. Analysis of the simulated inflow of Atlantic water during winter has shown to be highly correlated to catches (in the following autumn) in the North Sea, suggesting that migration is an important consideration in estimating the size of the stock in each ICES division. At this time the Atlantic water is relatively warm and nutrient-rich, and strong inflows favour the movement of horse mackerel into the North Sea. This provides the basis for half a year prognosis for the fisheries, routinely performed since 1996 (Figure 5.1). For 2006 the catches became nearly identical with the prediction of 29 kt.

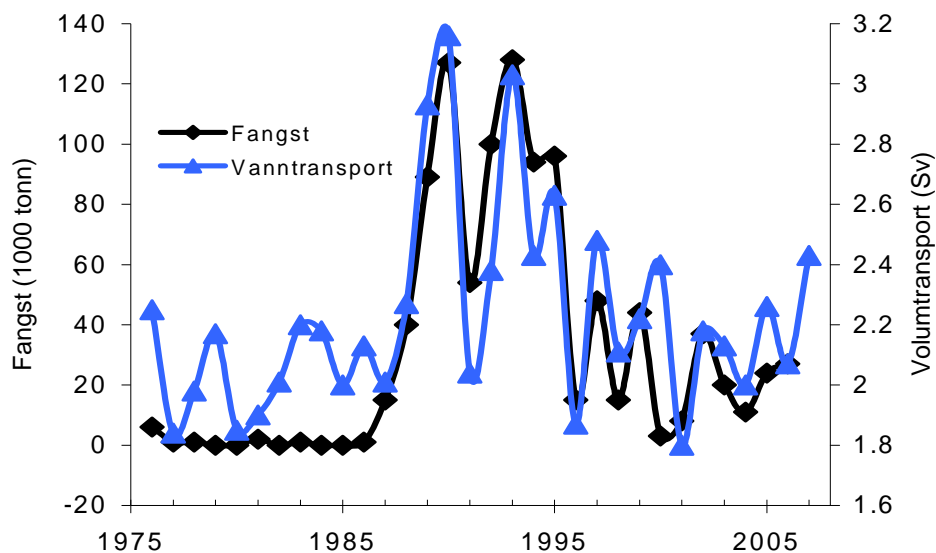


Figure 5.1. Modelled total volume transport (106 m³s⁻¹) for the first quarter southward into the North Sea through an east-west section from Norway to the Orkney Islands for the period 1976–2007. Catches (black line) of horse mackerel the following autumn in the North Sea.

Greenland cod-migration is handled through a larger M-No analytical assessments of cod in Greenland waters were accepted by ACFM after 1996 due to insufficient data after the collapse of the stock in the early 1990s. In previous assessments natural mortality (M) was set at 0.2. To account for emigration of maturing fish back to Iceland an emigration coefficient (E) of 0.1 was added to M for all age groups of age 5 and older in most years. Higher values for E were used in some cases, e.g. for the 1984

year-class, which originated to large extent from Iceland, E was set a value of 0.7 for age 6. The values of E used in the historic assessment should be considered arbitrary (ICES 2007b, Report of the North-Western Working, ICES CM 2007/ACFM: 17) and an improvement of this approach appears desirable for managing a recovered stock in the future.

North Sea plaice-Twentieth century mark-recapture studies of conventionally tagged plaice suggested that the maximum exchange rate of fish between the North Sea and the eastern English Channel did not exceed 10%. However, recent studies with electronic data storage tags have suggested that this figure may be significantly greater. Kell *et al.*, (2003) used a simulation framework based on the current management regime and simple assumptions regarding mixing, to explore the consequences of ignoring migratory behavior between independently managed stocks. Results indicate that the effects of stock mixing can generate considerable bias in the perceived state of a stock relative to its true state and that changes in the management applied to one stock may cause changes in the level of bias for neighboring stocks.

North Sea Autumn Spawning herring-Short-term predictions for North Sea herring (autumn spawners) were carried out by fleet and area for a number of years, ICES (2001a). A split factor was used to estimate the proportions of North Sea autumn spawners being present in the North Sea and Division IIIa. Some of the split factors are directly estimated from surveys, other values are estimated from a general linear model (GLM) which relates the proportion of 1-ringers in Division IIIa to a survey index (the MIK index of 0-ringers). The assumption is that the spatial distribution occurs as 0-ringers. 1-ringers remain in the area where they ended up as 0-ringers, and only migrate back to the North sea from Division IIIa as 2-ringers. This assumption and the origin of the split-factors used in the short-term predictions are illustrated in the text table below.

Table 5.1 (ICES, 2001a) showing the source of data used for estimating proportions of North Sea herring at 0 and 1wrings in Area IV and area IIIa.

Year	0-ringer distribution	1-ringer distribution
Last yr in Assessment	This split-factor is equal to the split-factor of IBTS 1- ringers in next year	This split-factor is obtained from estimated for the 1-ringers in the IBTS the proportions in the last year in the assessment
Current year	This split-factor is equal to the regressed 1-ringer distribution of Next year obtained from the MIK in the current year and the GLM	This split-factor is obtained from the proportions estimated for the 1-ringers in the IBTS in the current year
1 year ahead	This split-factor is equal to that of 1-ringers in next year, i.e., estimated by taking the average MIK index for the year classes 1981 to 1999 and the GLM to predict the split.	This split-factor is obtained from the MIK value for the current year, and a general linear model (GLM) to predict the split.
		This split-factor 2 years ahead is estimated by taking the average MIK index for the yr classes 1981-2000 and the GLM to predict the split-factor.

The process of for the projection was essentially carried out in two steps. The first was to compute local partial fishing mortalities for each fleet, corresponding to the stock in the area where the fleet operates. Local partial Fs were introduced in the predictions with the aim of ensuring that the observed changes in distribution were included in the predictions. The next step was to project the stock forwards, starting with the stock numbers at the start of the first prediction year taken from the assessments, and applying the local fishing mortalities, each raised by an F-factor. Catches by fleet, the ensuing overall fishing mortality and the SSB were computed and presented.

A study was undertaken to investigate whether the use of the area split factor resulted in better short-term predictions of the catches by fleet and population numbers at age for the North Sea autumn spawner herring. The study consisted of a hind-cast of predicted catch and numbers at age with and without making use of the split factor to estimate partial F_s . The largest differences between the numbers at age predicted in the catches by the two prediction methods and the observed were found in the human consumption fleet, 1 ringers, and industrial fleet D, 0 ringers, and in both cases the method with split factor seemed to perform slightly worse. With some exceptions B, both methods performed similarly for the fleets that target juveniles. Differences between predicted and observed were generally larger for the second year of the predictions. The two methods performed similarly in predicting the numbers in the population. The overall results seemed to suggest a slightly better performance in the predictions that did not use the split-factor.

Although the study was based on a limited number of observations where the split factor generally varied around intermediate values (0.55–0.80) ICES also recognised that a number of assumptions made in this approach had not been tested. The calculation of local F_s relied on being able to estimate the local population for 0 and 1wr herring and predicting the selection pattern in the fleets exploiting these areas. The relationship ignored any changes in the abundance of Western Baltic Spring Spawning herring and assumed the relationship would hold even though no mechanistic relationship had been postulated. If however, the prediction broke down or the selection patterns changed because the fishery adapted to availability of herring in the differing abundance of each year class, the catch predictions could deteriorate. ICES stopped using the split-factor in the North Sea herring predictions after the HAWG evaluated the results from the study briefly described above in 2001.

Pacific whiting—The migratory Pacific whiting (Helser *et al.*, 2006) is managed as a shared resource between the U.S. and Canada. The extent of its migrations is known to be affected by ENSO events and by population age structure (younger fish tend to move less far than older fish). However, these facts are not formally incorporated in the proportional allocation between Canada and the USA.

The examples demonstrated that migration changes and trends affect:

- Timing and extension of assessment surveys
- Timing and extension of closed areas
- Timing of fishery allocation
- Proportion of the population used in projections

It was agreed that environmental-driven migrations are significantly important and should be quantified in all cases when neighbouring (and very different) stocks mix. It was concluded that practitioners should check for inconsistent cohort signals, and use tagging results and other spatial analyses to ensure that these migrations are taken into account. Regarding modelling tools available for this purpose it was mentioned that GADGET (Taylor and Stephenson, 2004) is spatially explicit and allows for migrations in key species. MULTIFAN CL (Hampton and Fournier, 2001) is a spatially disaggregated age structured model that includes migration, and growth tuned primarily to length frequency and tagging data. Lehodey *et al.*, (1997) used measures on the extent of warm waters in the western Pacific to delineate regions of high skipjack tuna abundance. The combinations of these types of studies mean that migration/movement rates could feasibly be predicted based on environmental signatures. Assessment software such as CASAL (<http://www.niwasience.co.nz/ncfa/tools/casal/>) allows for spatially disaggregated analyses. For example, applications of management strategy evaluations have been developed and applied for New Zealand hoki.

5.1.2 Mortality (in single species models and projections)

Natural mortality is a process that is subject to large variability connected to environmental variability and change. Estimating natural mortality is one of the most difficult problems we face and as a result it is often set as a constant value between years and across ages. There are case studies where estimates of M are used in evaluations but variable values are not applied

or recommended to be used in assessment. Clark (1999) found that specifying a conservative (lower) natural mortality rate is typically more precautionary when natural mortality rates are uncertain.

Natural mortality of older stages demersal fish (juveniles and adults) has been relatively poorly studied (Vetter, 1988). Julliard *et al.* (2001) use capture-mark-recapture (CMR) techniques to estimate M in a coastal cod population within the Norwegian Skagerrak coast. A total of 36 728 reared 6-month-old, and 2415 wild-caught individually tagged cod were released in four consecutive years, leading to 4155 recaptures by fishermen. Natural mortality was found to be high in the 6–12 month range, but subsequently it decreased rapidly. Fishing mortality was negligible for fish younger than 1-yr-old, intermediate for 1-yr-old fish, and high for older fish. The seasonal pattern of fishing varied much between age classes, with 2-yr-old fish mostly taken by recreational fishermen in summer, and older fish mostly taken by professional fishermen in winter. Total mortality varied little between years, except during similar to 5 month after a major algae bloom in May 1988, when fish disappeared at a high rate whatever their age. The authors conclude that mortality of adult fish may be an important determinant of the stock size.

Sinclair (2001) suggested that the closure of the cod fishery in Canada's southern Gulf of St Lawrence, and the existence of a reliable research vessel (RV) survey of the stock, has provided a unique opportunity to directly estimate the instantaneous rate of natural mortality (M). The results indicated that M is currently in the range of 0.4, which is higher than the value of 0.2 assumed in the past. An M of 0.4 is not inconsistent with the observed age range of cod in commercial catches and with recent growth characteristics of the stock. There is evidence that M may have increased in the early 1980s. Adequate estimation of M has important implications for the success of recovery plans, Fu *et al.*, 2001.

Of specific interest are catastrophic mortalities caused by anoxia, lethal temperatures or harmful algal blooms, all of which threat to become more prevalent under global warming scenarios. Peperzak (2003) has attempted to evaluate whether harmful algal blooms are likely to occur more or less often over the next 100 years in the North Sea, and Harvell *et al.* (1999, 2002) consider that marine life is at growing risk from a range of diseases whose spread is being hastened by global warming among other reasons. Trends in anoxia in the Baltic Sea and Gulf of Mexico have also been of concern. None of these factors are currently used in direct fisheries management advice.

Retrospective analyses can be used to determine inconsistencies in cohort patterns that would help in the identification of variable M rates. Natural mortality variation is one plausible explanation that should be evaluated relative to alternative hypotheses (e.g., movement into or out of an area).

The necessity to include predation in medium-term projections (e.g. Bax *et al.*, 1998) and the determination of biological reference points (e.g. Gislason, 1999) been widely accepted. For several pelagic species and some young age groups of demersal species (e.g. different eastern Atlantic cod stocks) predation mortality estimated by multispecies models (see Section 5.4) are used in assessments and predictions. However, short-term interannual variability is assumed to be limited and thus fluctuations are ignored in short-term predictions. This assumption does likely not hold for pelagic prey species (Stephenson, 1997), especially in ecosystems with few dominating and fluctuating predator species, e.g. capelin in the North Atlantic (e.g. Carscadden *et al.*, 2001) and sprat in the Baltic (e.g. Köster *et al.*, 2003b).

5.1.3 Recruitment

Estimation of recruitment in the face of environmental variability and change is a crucial aspect of successful assessment and management programmes. Change can be detected directly, through recruitment surveys (preferred) or indirectly through commercial cpue, VPA or Environmental-based recruitment estimates. Regarding the latter, however, there are currently few examples where environmental estimators have stood the test of time (see Section 4.11), although an environmental signal is included in the S/R relationship and harvest control rules of the California sardine (see case study). In this regard the group noted that

significant correlations do not equate to predictive power (see Section 4.11). Detecting recruitment changes is particularly important in short-lived species (anchovy, sandeel, capelin, etc.), where the catch consists mostly of recruits, and in heavily exploited stocks, where successful recruitment is crucial to maintain populations at exploitable levels. In longer-lived species, however, one should be able to pick up trends before the fish recruits to the fishery. Whatever method is used to derive recruitment from simple means to information based methods there is a need to develop decision making rules regarding the use of R estimates in management plans. As more complex methods are developed it is important to ensure the error structure of the method is fully accounted for. In particular some environmental indicator methods may be non linear and have asymmetric error structures. It is important that the rules used are evaluated with these possibilities in mind.

Recruitment variability has sometimes reflected changes in habitat and distribution. For example, the fishery of the Icelandic capelin has been regulated by preliminary catch quotas set prior to each fishing season (July-March). Predictions of TACs have been computed from autumn survey data the year before on the abundance of 1 and 2 year old capelin. The process includes historical relationships between such data and the back-calculated abundance of the same year classes, growth rates and stock in numbers, natural mortality and the provision of a remaining spawning stock biomass of 400 000 t. Final catch quotas for each season have then been set according to the results of acoustic surveys of the maturing, fishable stock, carried out in autumn (October-November) and/or winter (January-February) in that fishing season. A detailed description and test of this method for the period 1979–2001 was given by Gudmundsdottir and Vilhjálmsen (2002). However, since 2001 until 2005 (inclusive) the juvenile distribution areas have changed and it has not proven possible to locate them but in part, if at all. The above catch procedure could therefore not be used. This has been tackled by setting very low or no, summer/autumn TACs and the fishery not been opened until a 'reliable' fishable stock assessment has been obtained, usually in January of the season.

With regards to management consequences of recruitment variability it was recognised that environment changes would affect reference points that are tied to estimates of stock productivity (for example the stock recruitment relationship). In practice, however, harvest control rules are developed with relatively static reference points and the sensitivity of these to natural fluctuations are rarely evaluated. It was recommended that operating models should be developed to reflect plausible hypotheses about these changes so that the relatively static harvest rules can be evaluated. Kell *et al.* (2006) and Dickey-Collas and Simmonds (North Sea herring case study) present approaches where the environment affects the stock recruitment relationship both regarding stock productivity (initial slope at the origin) and carrying capacity parameters. The former was shown to be most critical for severely depleted stocks whereas carrying capacity had the largest impact for stocks that were declining from relatively high levels abundance. The Baltic cod is an example for the latter, where environmental change affected first of all the carrying capacity, while the slope at the origin appears to be rather stable during periods of favourable and unfavourable conditions for reproduction (ICES 2005a, AGLTA).

Recruitment estimation is also used in medium to long term projections. For example, British Columbia sablefish stock assessments provide advice for upcoming annual harvest levels based on a combination of future recruitment scenarios (low, average, high) and performance measures in relation to a biomass reference point (Haist *et al.*, 2005). The relative abundance of juvenile sablefish in research surveys and commercial trawl fisheries is provided as additional indicators of year class strength prior to recruitment to the fishery. Climate and ocean indices of year class success of sablefish (King *et al.*, 2001) are given *ad hoc* consideration. These additional indicators of upcoming (5 year) recruitment can be used in selecting the most likely future recruitment assumptions when selecting appropriate annual harvest levels. US West Coast sablefish stock assessments (Schriipa 2007), on the other hand, utilize coastal sea surface height and coastal zooplankton (copepod) anomalies tuning indices for recruit deviations from a Beverton-Hole stock recruitment function. Previous research has identified possible mechanisms for sablefish year class strength and has linked these environmental conditions to year class success (McFarlane and Beamish, 1992; Schriipa *et al.*, 2005). Current estimates of recruitment strength in recent years, are used to forecast

biomass trends under optimum yield assumptions and provide an indication of where the stock will be in relation to management reference points in 10 years.

An area needing future development involves the use of IPCC methodology and Global Climate Model outputs to produce stock projections under climate change scenarios. The biggest difficulty at present is the lack of adequate tools to downscale Global Climate Model outputs to the scales of biological relevance, as well as the inability of GCMs to capture all the variability in shelf seas. ICES should take note of recent developments in this regard. For example, three-dimensional baroclinic coastal-ocean models (Holt and James, 2001, Holt *et al.*, 2001) are being developed for all the shelf seas (from the coastline to ~200 km from the shelf-break, <http://www.resc.rdg.ac.uk/twiki/bin/view/Resc/GcOMS>), at resolutions of $1/10^\circ$ and including tides, stratification, river runoff, ocean-shelf exchange and upwelling. These models will soon be interfaced so as to be forced from UK Hadley Centre and other Global Climate Models, thus providing tools for projecting the state of the environment over medium term scales. In cases where R appears connected to processes such as upwelling/stratification (Bay of Biscay anchovy, South African anchovy), ventilation/salinity/temperature (Baltic cod and sprat), etc., this development could provide innovative ways to look at medium-long term scenarios.

5.1.4 Conclusions to entries and exits from the population

Accounting for migration can involve different approaches at different levels. Adapting surveys, and modifying data collection has proved useful in many northern areas. However, including migration within the provision of advice has proved very difficult. Even where the past can be resolved, estimating or predicting the future has proved difficult. Fisheries advice requires not only estimating the migration of the population but also predicting the response in the fishery; evidence suggests this is very difficult to do well. We conclude that where possible in estimating stocks migration should be considered, as part of survey planning and assessment, but management advice should be made robust to variability in migration rather than trying to measure and predict the response in the fishery.

In all cases it is preferable to try to measure recruitment. Prediction of recruitment in the short term should consider that recent recruitment may be a better indication of current recruitment than longer term geometric means. Recruitment series should be evaluated for autocorrelation or trends and more recent values used. The process should be monitored and validated through retrospective analysis.

Inclusion of physical environmental drivers in the estimation of recruitment is a compelling concept. We have seen several examples of time-series showing relationships between physical systems that are known to drive recruitment and the magnitude of observed year classes (NE Arctic Cod). However, there are a number of cases, two illustrated here (NE Atlantic sardine and Bay of Biscay anchovy) where relationships which have held for a while have then broken down. This is probably because the controlling processes are more complex than were allowed for and other factors than those explicitly included have had a large influence.

Nevertheless, there is information in environmental signals that can be informative. The approach we recommend for such information is to assess its content, particularly the 'error' structure or variability between driver and response. Simulation should then be used to evaluate the utility of the information and to evaluate how best to use it. Simulations of the type used for Bay of Biscay Anchovy (De Oliveira *et al.*, 2005) and South African anchovy (De Oliveira and Butterworth, 2006) are examples of the appropriate approach.

We see from the case studies that trends in recruitment may occur even without a clear identified explanation. Management needs to be tested under such circumstances, it is therefore important to include changes in environment within management simulations. Firstly, the uncertainty in S/R relationships should be included through the use of multiple models and parameter uncertainty. Secondly where there are explicit responses to environmental drivers, such as cod and temperature, these can and should be used directly to modify mean recruitment. Without explicit relationships potential environmental influence can

be included either as separate scenarios (as with NS herring Annex 7) or as simulations drawing recruitment from a range of models. (Alaskan Pollock Annex 8).

5.2 Individual biological parameters

The workshop discussion centred around biological factors for which data was generally available and that had a direct impact on management advice, these were growth, maturity, sex ratio, age structure and fecundity. These factors separate into two main aspects: first growth rates that influence weights-at-age in the catch advice, growth and maturity and their combined influence of management rules that involve spawning stock biomass. Secondly, all the other aspects which together with growth and maturation contribute to the spawning potential of a stock.

5.2.1 The detection of change

For many stocks weight-at-age and fraction mature are measured directly, and although very long time-series of these factors may not be available there is often sufficient data to obtain measures of recent change. While it is acknowledged that weight-at-age and fraction mature do not describe spawning potential completely, they are considered in some cases to capture a substantial part of the variability (for example Baltic Cod Annex 11). Examination of assessment data series are expected to provide a simple indication of major changes. The magnitude of the influence of these factors is stock specific, varying widely with species and latitude. Data on the parameters needed to provide good information on full spawning potential are not generally available (Marshall *et al.*, 2003) and while it might be preferable to monitor full reproductive potential this requires more detailed data than is currently available for many stocks. Generally there is more information about growth and maturity than for sex ratio, sex specific maturity or fecundity, for reviews on data availability see Morgan *et al.* (2003) and Tomkiewicz *et al.* (2003). The parameters themselves respond to various kinds of ecosystem changes (e. g., temperature, food abundance).

5.2.2 How important are biological parameters?

Growth and maturity: Firstly growth and maturity variations can have important effects on assessment and management related variables because they are used directly to estimate biomass and yield. Secondly they provide indications of the health of a stock and its environment. Variations in growth or maturity can be due to changes in temperature or food supply; variations in environmental factors can therefore potentially influence biomass and yields at a variety of time-scales. The WS noted that the variations in growth and maturity were probably more important for cod and haddock than for herring in the North Sea, (Needle *et al.*, 2007). Density dependent growth (e.g., saithe) appears to be quite significant and can be strongly cohort related in haddock (ICES, 2006a). Canadian cod growth and maturation are linked to food quality, availability and environmental conditions (Campana, 1995 and Drinkwater, 2001). For Baltic cod (Annex 11), these linkages are less well defined (although the variability is high). Growth in Baltic herring has decreased substantially in the last 10–15 years (Möllmann *et al.*, 2005; Casini *et al.*, 2006), partly due to climatic and density-dependent factors. North Sea herring has exhibited variable growth over time but recently has shown reduced growth and maturation on a single cohort (Annex 7). In some stocks, maturation data are limited and ogives from other stocks are applied, clearly this practice can lead to problems in management if changes in one area are not seen in the other stock.

Sex ratio: Variations in sex ratio are larger for some stocks/species than others. For flatfish and *Nephrops*, there are strong indications that harvesting rates are different by sex, in the case of flatfish because of differences in growth and for *Nephrops* due to differences in behaviour. Differences in sexual maturation and related behaviour have been hypothesised to cause different natural mortality of male and female Northeast Arctic (Jakobsen and Ajiad, 2000) and Baltic cod (Tomkiewicz *et al.*, 1997). In Baltic cod males mature earlier in life, arrive earlier and stay on average longer on spawning grounds (Tomkiewicz and Köster, 1999). This affects as well their fishing mortality as especially pre- and early spawning aggregations consisting of a high proportion of males suffer from high fishing pressure. Sprats also have

peculiar sex ratio patterns (Grygiel and Wyszynski, 2003) that should be evaluated more fully. The assumptions about sex ratios should be more fully evaluated and proportions in catch and population established as a matter of routine.

Age structure: Indicators on population age structure are being considered as part of ecosystem approaches to management. These need to be evaluated against the suite of potential impacts (e.g., effective reproductive potential). The relationship between age-structure indicators, stock productivity (Marteinsdottir and Thorarinsson, 1998) and management actions needs to be more clearly understood. Nevertheless, simple relationships may suffice because, for most stocks the increased biomass associated with extending the age range of stocks is expected to be a good indication of the state of the stock.

Fecundity: Estimates of individual fecundity are important assessment parameters for some species such as NE Atlantic mackerel (ICES, 2007e) because they are used directly as part of the abundance estimation process. Fecundity may be a useful parameter if biomass is a poor proxy for reproductive output. Nevertheless for some species e.g. Baltic cod, studies show that trends in fecundity, although significant, are not the major cause of recruitment fluctuations (Krause *et al.*, 2002). For review of information available on cod fecundity, see Lambert *et al.* (2003 and 2005). However, studies where such trends might be revealed in other species are rare, and the extent of the issue is not well known. Environmental variations including food availability can have other effects, such as the frequency of skipped spawning (Jorgensen, 2006) viability of eggs, and rates and incidence of atresia (ICES, 2007e) Variations in individual fecundity can be due to variations in food supply (e. g., zooplankton, other fish species) and condition (e.g. Marshall *et al.*, 2003) or temperature (e.g. Kjesbu *et al.*, 1998).

Stock reproductive potential: Overall a combination of biological characteristics and traits of adults have impacts on potential production of both eggs and recruits, partly because these traits are correlated with other reproductive parameters (Murawski *et al.*, 2001; Marshall *et al.*, 2003; Spencer *et al.*, 2007). For example the mean and variability of spawning times and locations are size- and/or age-specific affecting offspring survival. Furthermore, the quality of eggs and larvae can be influenced by parental characteristics (e.g. Trippel, 2000). As a result recruitment per spawner and overall stock productivity in some populations differs depending on biological parameters of adults. These differences can become a management issue if rebuilding projections are based upon stock-recruitment curves and reference points are derived using incorrect biological descriptors of adult populations (Marshall *et al.*, 2003; Morgan and Brattey, 2005; Spencer *et al.*, 2007). Effects of differences in population characteristics on SR parameters, recovery rates and reference points could be compared to illuminate the differences.

5.2.3 Conclusions to individual biological parameters

There is considerable potential for incorporating environmental information in management aspects related to individual biological parameters such as growth and maturation. This is because relatively large amounts of data are collected annually on weight-at-age and maturity-at-age. Short-term responses we observe, even without a cause being determined, may be expected to continue allowing short-term (deterministic) projection, whereas medium-term projection may require an understanding of the relationship between an environmental driver and the parameter of interest.

For the longer term, as all of the biological parameters respond to environmental forcing at a variety of scales, environmental factors could be used directly in calculations of biomass, yield and reference points. In this case the decision to include or not should be based on the information content, if incorporating change in a parameter adds information to the management that exceeds the uncertainty in the parameter.

There are a number of areas for immediate action:

Growth and Maturation:

Stage 1: Evaluate changes by cohort and over time, separating influence of variability or noise in the data and predictable change. The modelled results should be used for short-term projections. This should avoid the kind of errors in catch and SSB that have been seen in the past (e.g., effect of weight differences in NE Arctic cod).

ICES should arrange the provision of projection software that can handle these types of issues. There should be appropriate rationales for assumptions used in projections. Where long-term means are supported by the data they should be used, but where trends or short-term correlated variability is observed this should be modelled and taken into account. The aim is to provide cohort and year effect based short-term prediction software to replace the current approach. Methods should involve detection of ‘signal’ (real change) in ‘noise’ (annual variability in either growth or measurements) using statistical methods and apply appropriate prediction methods to give growth and maturation one or two years forward. Retrospective analysis should be used to monitor the performance of the methods chosen.

Other fixed demographic parameters used in projections should be evaluated against known ranges of measurement variability. The impact of sex ratio changes and age structure differences should be evaluated.

Stage 2: Understanding processes so that medium to long-term projections reflect process-oriented studies that document how changes in food availability and hydrography affect growth and reproduction. As a starting point, to investigate the impact of year-class effects, temperature, and density dependence on maturity and growth.

If there are apparent trends in the effective reproductive output due to environmental changes, then proxies for reproductive output (e. g., SSB, Bpa) could be affected (and hence accounting for this would be important). For short-term predictions, variability in effective fecundity is taken into account as part of the expected interannual recruitment variability and can not practically be provided for as a separate effect in management adjustments. However, this information could provide added information on subsequent medium-term recruitment (see above). The assessment working groups should provide medium-term projections that account for trends and uncertainties in effective reproductive output if these have been identified (see above). Where trends in parameters are found which change the reproductive potential the impact on biomass reference points should be considered.

Age structure: Indicators on population age structure as part of management goals should be evaluated, recognizing that some fishing actions (e.g., population truncations) have medium and long-term impacts on life history traits and recruitment.

5.3 Habitat issues

5.3.1 Changes in horizontal movements (including contraction/expansion)

This topic has been dealt with in detail under ACE (2007) (Ref special request OSPAR request). Here we bring only those examples discussed within the workshop.

Changes in horizontal distribution from/to the survey/assessment area are important when abundance estimates are tied to Survey/cpue results, particularly if the distributional changes have trends (e.g. movement towards the poles), as expected under climate change and already observed (Perry *et al.*, 2005). They may be less important if fishing management areas coincide with survey areas (as increases/decreases in population size between areas would balance each other), but this is not always the case. Contraction/ Expansion processes inside the assessment area are particularly significant in effort-based management systems and where cpue is used to estimate stock size. Change can be detected from spatial trends in cpue, analysis of bycatch or predator/prey fields, tagging (data storage), monitoring ecosystem properties (hydrography, circulation), use of ichthyoplankton surveys, and survey consistency (e.g. missing a cohort).

Changes in assessment and management methodologies in response include adaptation of survey to changes in fish distribution, corrections in catchability and improved coordination

between assessment areas. For example, yellowfin sole spawn in spring in near-shore areas of the eastern Bering Sea, and the timing of horizontal migration to the summer feeding grounds (and survey area) may depend upon temperature. Temperature-dependant catchability has been estimated for yellowfin sole and could potentially result, in part, from availability of spawning fish to the survey area being influenced by temperature. Temperature-dependant catchability may also arise from environmentally induced changes in fish metabolism (i.e. swimming speed), which could affect the gear efficiency of survey trawls. Flatfish in the eastern Bering Sea have been observed to be “herded” into the trawl path, and the hypothesized mechanism is that contact with trawl bridles forces fish to swim toward the net path. Temperature-dependant catchability could occur if the degree of herding is temperature-dependent (due to changes in swimming speed). Carefully planned field observations will likely be required to distinguish whether temperature-dependent catchability occurs primarily due to changes in availability or gear efficiency.

In North Sea plaice juvenile stages are concentrated in shallow inshore waters and move gradually offshore as they become larger. The nursery areas on the eastern side of the North Sea contribute most of the total recruitment. In recent years juvenile plaice have been distributed more offshore (Keeken *et al.*, 2007). Surveys in the Wadden Sea have shown that 1-group plaice is almost absent from the area where it was very abundant in earlier years. This is probably linked to environmental changes in the productivity or changes in the temperature of the southern North Sea, but these links have not been shown as yet.

In addition, environmentally induced changes in growth (Rijnsdorp *et al.*, 2004) will affect the catchability of fish, and thus discarding behaviour of fishing fleets (Keeken *et al.*, 2003). Changes in distributions and migration caused by the environment may also impact on discarding behaviour of fishing vessels when species which are normally targeted individually begin to mix, or visa versa (Hofstede & Dickey-Collas, 2006; Borges *et al.*, submitted). This means that the environment not only impacts on the ecology and dynamics of fish but also on the behaviour and impact of the fishers.

5.3.2 Changes in vertical distribution

Under an ocean warming scenario assessing the potential changes in vertical distribution of fish resources becomes paramount. These changes affect the percentage of the population available to survey/fishing gear, and in the case of acoustically-estimated populations it may affect the unit of reflectivity (or Target Strength, Simmonds and MacLennan, 2005). In pelagic stocks vertical distribution changes may affect their acoustic detection if they move too close to the seabed or above the transducer (Simmonds and MacLennan, 2005). While these effects are well appreciated and considered in assessment, changes in catchability of demersal and semi-demersal resources can result in undetected survey/cpue biases.

For example, in Bering Sea pollock, recent studies have shown that light levels affect the vertical distribution of pollock. In years and areas with high turbidity, pollock are less likely to be close to the bottom since they are visual predators. If light intensity varies in systematic trends over time, this could bias estimates from bottom-trawl surveys where constant average availability is assumed.

In demersal and semi-demersal resources it is recommended to use hydroacoustic and bottom trawl surveying to estimate the percentage of the population off the bottom. This could be used to correct cpue.

Not all responses have minor effects on population parameters. We know of at least one example where catastrophic mortality accompanied resulted from vertical distribution changes in North Sea sole; sea water became too cold near bottom, driving sole towards the surface. This process was linked to large-scale mortalities in the population (ICES Flat fish WG 1979).

5.3.3 Suitable and reproductive habitat mapping

We look at two specific issues related to suitable habitat-changes in catchability or standardisation of cpue and changes in Carrying Capacity. We conclude that changes in

catchability are generally not very significant, except in effort-based management systems and systems where CPUE is used to estimate stock size. For example, the case study on East Bering Sea Pollock presented an evaluation of change in “suitable” habitat based on bottom temperature preference. The impact on the survey catchability (correcting survey abundance levels) was shown to be weak. However, accounting for environmental factors for CPUE indices is important for the deeper-water bigeye tuna both for delineating the habitat (Bigelow *et al.*, 2002). In this study, information on the environment coupled with estimates of hook depth affects relative density estimates needed for deriving annual effects needed for assessments.

On the other hand, changes in Carrying Capacity are known to occur as a result of environmental change (e.g. Jacobson *et al.*, 2001), and this is in some cases applied in the assessment. For example, SST off California is used as a proxy for sardine Carrying Capacity, and changes are applied through S/R relationship and in the application of harvest control rules (see Annex 9, Jacobson *et al.*, 2005).

Blanchard *et al.* (2005) suggested that the spatial extent of optimal cod habitat appears to have decreased from 1977 to 2002, reflecting a gradual warming of the North Sea. According to ideal free distribution theory, populations contract into areas of highest habitat suitability as their abundance decreases. This study detected density-dependent habitat selection by juvenile Atlantic cod (*Gadus morhua*) (ages 1 and 2) and compared the observed distribution-abundance relationships with those predicted from a model based on knowledge of optimal temperatures for growth, where temperature was used as a measure of suitability. The combined negative effects of increased temperature on recruitment rates and the reduced availability of optimal habitat for growth may have increased the vulnerability of the cod population to fishing mortality and/or predation.

One of the methods which can be used to evaluate distribution changes is to define a “suitable habitat” or “bioclimate envelope” from the tolerance or physiological limits of a species in relation to the physical and chemical environment. Such limits may relate to a particular life history stage (e.g. eggs) and are used to define the bounds for their survival (e.g. reproductive volume in Baltic cod).

Critiques of the bioclimate envelope models (e.g. Hampe, 2004) raise concerns over (i) biotic interactions (predation, competition, mutualism, pathogens) (ii) adaptive genetic variation (edge populations may be better adapted to extreme conditions, but are also more vulnerable) (iii) dispersal limitation (iv) model validation. Taking these in turn:

Distributions within fish and shellfish communities can be expected to change due to exploitation and the effects may be indirect (e.g. could the observed population explosion of snake pipefish be due to fishing down a pelagic predator, rather than to climate?). WGSE has ascribed a number of observed changes to changes in forage fish which are heavily exploited.

Fishing has been held responsible for inducing adaptive change in Canadian and other cod stocks. This has potential impacts on the surplus production and future abundance of these populations, but it is not yet clear whether the changes in ocean climate and the existing geographic variability in maturation have been fully taken into account in assigning population changes to fishing or climate.

The marine environment has in general been thought to present fewer barriers to dispersal than terrestrial systems, but there may be hydrodynamic requirements for life history closure which impose restrictions. This issue may also interrelate with adaptive genetic variation and also with the issue of model validation.

The report of WGECO (ICES CM 2007/ACE:04, Sections 8 and 9) deals extensively with changes in distribution of marine biota caused by hydrographic and sea temperature changes.

Finally, reproductive habitat has been estimated in the Baltic Sea as a way of explaining recruitment success in Baltic cod (Annex 11 Baltic Cod). It would appear that changes in reproductive habitat are very important, both for assessment and for projections, but possibly

geographically specific, which means that utilisation of the suitable spawning habitat by the spawning stock for egg production defines overall egg survival, not the availability alone.

It is generally recommended that practitioners be aware of changes in habitat and use available technologies (e.g. hydrographic surveys, Log-books from commercial vessels, Global monitoring (GOOS), Satellite data, model outputs and food distribution maps) to detect and evaluate change.

5.3.4 Conclusions to habitat

As habitats change due to environmental drivers, this can have many different consequences. While we have chosen to discuss changes in recruitment and migration within Section 5.1, some consideration of habitat change leads to additional consideration of these aspects which we bring out here. The primary consideration is how habitat change influences stock carrying capacity or productivity (see Baltic Cod Annex 11).

If stock carrying capacity changes then biomass targets based on a different carrying capacity may no longer be achievable. If productivity changes the risks to the stock and the potential for recovery will be changed. We conclude that when the habitat has changed such that mean recruitment is altered or growth rates are changed for the medium term it is necessary to consider if previous biomass or fishing reference points are still applicable. There is a need to re-evaluate reference points under such circumstance. However, re-evaluation should include consideration not only of the current carrying capacity but also the potential for further stock depletion and the ability of the stock to recover should the habitat return to previously observed conditions. This leads to biomass limit points that infer maintenance of recruitment in the current stock status and inclusion of the possibility to recover if the habitat changed again. For fishing mortality limits, if productivity has changed fishing mortality limits should allow stock expansion under both regimes.

5.4 Multispecies interaction and modelling

The workshop discussion centred round multispecies interactions in low diversity boreal systems such as Barents, Bering, and Baltic Seas, the waters around Iceland, and the more complex North Sea (Annex 16).

5.4.1 The detection of change in multispecies interactions

The Primary method for detection of change comes from stomach contents analysis combined with estimated abundance of the predator and prey stocks. This may involve more than commercial species and should include changes in plankton which may be important as indicators of food, such as the changes in the North Sea in the late 1980s (Pitois and Fox, 2006). Additional factors such as the arrival of new species in an area can also be an indicator of change.

5.4.2 How important are multispecies interactions

Potentially this is very important for medium to long-term expectations. The effects may be less important for short term advice. So far results from studies such as those presented in the case studies of Baltic (Appendices 11 and 12) and Barents Sea (Annex 10) tend to provide clear larger signals when areas are occupied by smaller numbers of species. The effects in more diverse areas, such as the North Sea, may be less pronounced and the need to consider multispecies aspects of predator and prey interaction may be less important for the understanding single species evaluation. In situations where most of the forage fish are depleted it may however be necessary to examine the situation in a multispecies context also in these higher diversity areas.

5.4.3 How and where to incorporate multispecies aspects in advice

Currently the method used for estimation for most areas is based on a series of single stock assessments using natural mortality which in some cases have been derived from multispecies

models (e.g. MSVPA in the North Sea). Though a multispecies model (Bifrost) is used for capelin management in the Barents Sea (Tjelmeland, 2005).

Detailed multispecies models have been developed for a number of situations. Gadget has been used in Iceland, Barents Sea, Bay of Biscay, Celtic Sea and the Mediterranean. MSVPA has been used in the North Sea, Baltic Sea, East Bering Sea, Gulf of Alaska, Aleutian Islands, Georges Bank. There are extensive number of examples of the use of Ecopath, Ecosim and Ecospace. Rarely have these models been used directly for annual fisheries advice so far.

The main achievement of the ICES multispecies modelling activity in the North Sea has been the provision of more realistic estimates of M2 (predation mortality) which have subsequently been fed into and improved single-species stock assessments. Experience with MSVPA, has generally indicated that natural mortality rates on juvenile prey fish are higher than had previously been assumed (Pope, 1991), and that traditional single-species estimates of M, can lead to overestimates of stock biomass per recruit. Similar results were noted in models of Atlantic cod stocks in the Gulf of St. Lawrence, the Scotian Shelf and the Barents Sea (see Hollowed *et al.*, 2000a).

Multispecies interactions are now routinely included in the single-species assessment and management of the capelin, cod and haddock stocks in the Barents Sea. Predation by cod on mature capelin is included in the assessment of Barents Sea capelin (Gjøsæter *et al.*, 2002; ICES 2006a). Also predation by cod on cod and haddock is included in the assessment of the cod and haddock stocks (ICES 2006a). It has been demonstrated how predation by minke whale on herring could be modelled for use in the assessment of Norwegian Spring-spawning herring (Tjelmeland and Lindstrøm, 2005). The philosophy has been to include important multispecies interactions into existing assessment models (e.g. by M2 values which vary between years), which is a somewhat different to what has been done e.g. with the MSVPA in the North Sea. Such an approach may be useful for boreal system which are relatively simple and with few main species and interactions, but probably less so in more complicated systems like the North Sea.

Sparholt (1996) has advocated the inclusion of cannibalism in the stock assessment for Baltic Sea cod, and sprat predation on cod eggs as well for the prediction of future recruitment patterns. At present predation mortalities from MSVPA's being variable over time are applied in Baltic sprat and herring assessments (ICES 2006c). Similarly, Hollowed *et al.* (2000) has attempted to include predation by arrowtooth flounder (*Atheresthes stomias*), pacific halibut (*Hippoglossus stenolepis*) and Steller sea lion (*Eumetopias jubatus*) in the single-species stock assessment model for walleye pollock (*Theragra chalcogramma*) in the Gulf of Alaska, whereas Livingston and Methot (1998) have included cannibalism, predation by pacific cod (*Gadus macrocephalus*) and northern fur seals (*Callorhinus ursinus*) in the walleye pollock assessment for the eastern Bering Sea. Together these studies demonstrate that one can use the outputs from multispecies models to inform assessments, and yet continue to use single-species management.

Multispecies forward projections are possible but substantially more complex than single species models. However, some of their difficulties such as stability of species selection rates for fisheries are common to single species management but are often put to one side in providing advice. MSVPA has been used to test HCRs for stock recovery on a multispecies basis in the North Sea (ICES 2003a). This model has also been used for evaluation of potential effects for selectivity changes that could result from technical measures, in this case theoretical responses to changes to mesh size (Pope, 1991). Similarly, to the North Sea the effect of changes in trawl selectivity after introduction of the BACOMA 110 mm where simulated with multispecies projections (ICES 2003b), and target fishing mortalities as central part of the harvest control rule of the new Baltic cod management plans (ICES 2005a) have been tested in multispecies simulations (ICES 2005d). The simulations indicated lower equilibrium biomass and yield in the Eastern Baltic stock if not considering cannibalism, but with major driver being recruitment variability caused by environmental conditions. However, with inclusion of weight-at-age and maturity-at-age being dependent on the food supply, the projected medium-term yield at various combinations of fishing effort directed to both cod and

clupeids stocks change considerably in comparison to ordinary standard multispecies predictions (ICES 2001c).

The influence of environmental change though invasion of different (new) species might be tested through multispecies models. Though prediction under conditions of new species invasions are very difficult due to uncertainty in the necessary parameterization. Parameterisation of interactions requires extensive data and probably needs spatial aspects as well when more than two species interact differently in space and time. Most models rely on the stability of 'suitability factors' to parameterise proportions of prey when stomach contents data is limited as is often the case. Some multispecies models, notably GADGET, are able to accommodate stomach content data from different geographic areas (see Taylor & Stefánsson, 2005 for multispecies versions of GADGET applied to cod-capelin-shrimp interactions in Icelandic waters). However, most existing models (such as MSVPA) have been parameterized in a non-spatial form, and in some instances this has caused problems (see Kempf *et al.*, 2006).

Larsen & Gislason (1992) reported the phenomenon of 'negative switching', where the suitability of a particular prey item declined as the abundance of the prey increased. They suggested that this might be an 'artefact' caused by changes in the relative spatial distribution of prey and predators (e.g. herring retreating into the Norwegian trench, where they are consumed by saithe) and that a spatially disaggregated MSVPA would be needed to disentangle behavioural changes from changes in relative distribution. Rindorf *et al.* (1998) also explored the 'negative switching' phenomenon, and came to the conclusion that "the suitability model is simply not an appropriate framework for describing prey choice by the predators." In MULTSPEC the effect of the geographical overlap of cod and capelin in the Barents Sea is modelled using a scalar overlap index variable (Tjelmeland & Bogstad, 1998). Similarly, de Winter (1991) has attempted to develop appropriate overlap coefficients to correct for non-linear local differences in abundance between a predator and its prey in the North Sea MSVPA. In the Central Baltic, different areas within the stock distribution area were simply handled as separate stocks in MSVPA assessments, with the output being analysed for different recruitment patterns and used to infer indications of migration between different areas and in comparison with survey results (Köster *et al.*, 2001)

In the short-term, the ICES advice for each species might be expanded to include standardised plots of what each species eat, and what predators consume the species of concern, as is already the case in NE Pacific stock assessments (see above). This would help to indicate whether or not strong interactions exist between particular species, and hence whether further multispecies modelling work would be beneficial in the future. An example of such an approach is Eastern Bering Sea and Gulf of Alaska pollock, ecosystem input data are presented in summary form (e.g., Figure 5.3.1). Within ecosystem models (i.e., ECOSIM), evaluations can be drawn by perturbations to gain some insight on the response of the system (e.g., Figure 5.3.2). Additionally, comparisons of mortality due to predation and fishing relative to production for a wide range of species are useful to determine stocks that may be more or less sensitive to fishing (e.g., Figure 5.3.3).

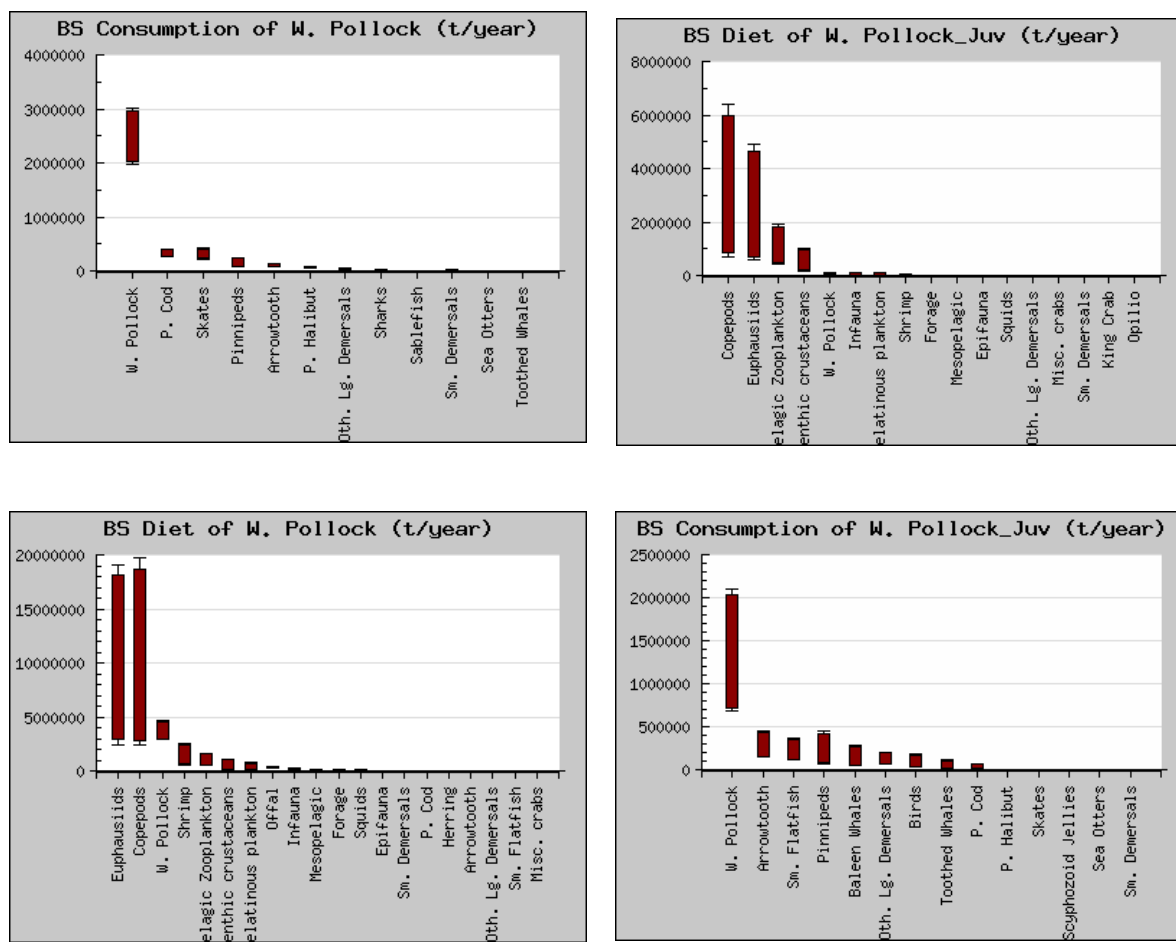


Figure 5.3.1. Diet (top) and mortality sources (bottom) for EBS pollock adults (left) and juveniles (right) based on data from 1990–1994. Error bars represent uncertainty of propagated consumption rates and population variance.

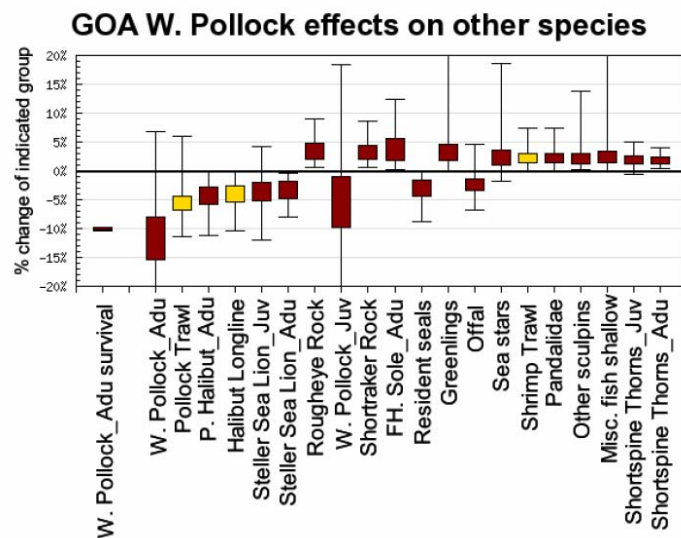


Figure 5.3.2. Ecosystem model output (percent change at future equilibrium of indicated groups) resulting from reducing adult pollock survival by 10%. Dark bars indicate biomass changes of modelled species, while light bars indicate changes in fisheries catch (landings+discards) assuming a constant fishing rate within the indicated fishery. Graphs show 50% and 95% confidence intervals (bars and lines respectively) summarized over 20 000 ecosystems drawn from error ranges of input parameters (see Aydin *et al.*, 2005 for methodology). Only the top 20 effects, sorted by median, are shown for each perturbation.

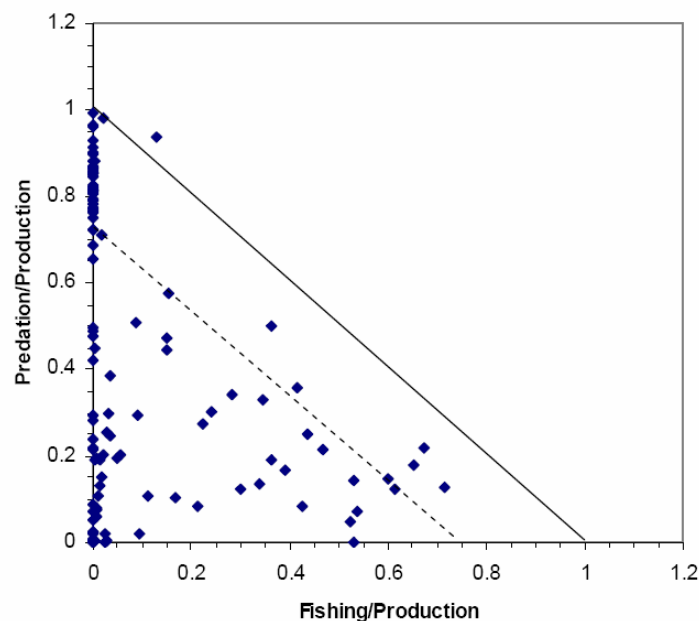


Figure 5.3.3. Sources of mortality relative to production for GOA species. Fishing/Production ratio versus Predation/Production ratio for the Gulf of Alaska for 2005 (based on stock assessment biomass and catch levels and biomass dynamics reconstructions for unassessed species). Solid line indicates level above which $(Fishing + Predation) = 1.0$ Dotted line indicates level above which $(Fishing + Predation) / Production \geq 0.75$.

The next step required to move to multispecies management advice would have to be a set of multispecies population estimates for an area. To do this would require extensive evaluation and comparison of the current assessments with multispecies versions, which given the resource implications is unlikely to happen in the near future. Initial comparison of MSVPA based NS herring assessment with the traditional assessment indicates a much poorer fit to recruit survey data, with residuals increasing by a factor of two (Annex 7), suggesting some issues with the stability of suitability parameterisation. Testing multispecies models includes testing the sensitivity of the model to its parameterisation, including numbers of species and prey selection criteria. This might be first done in the areas where small numbers of exploited species are dealt with. For example, incorporation of predation by cod stabilizes the tuning procedures in Baltic sprat (ICES 1999), i.e. cod acts as an additional tuning component.

Increasing model complexity may not necessarily be the most rewarding route. Several authors have argued that in highly complex systems such as the North Sea and Newfoundland, where many different prey resources (both fish and invertebrate) exist, there may be little point in trying to construct multispecies models, because relationships between particular predator-prey pairs will always be weak (Link, 2002). The philosophy is keep the approach “as simple as possible and as complex as necessary”. The effort needs to be allocated outside ICES assessment WGs before it should be considered for routine stock management.

In 1991 and 1992, following a special meeting (in Bergen) to consider multispecies work in ‘boreal’ systems, the ICES Multispecies Assessment Working Group (MAWG) engaged in a series of comparative studies (using GLMs), contrasting 6 “cod-rich ecosystems” namely-the Baltic Sea, North Sea, Barents Sea, Iceland, Newfoundland-Labrador Shelf, and Georges Bank/Gulf of Maine. The group considered whether cod growth and weight-at-age is influenced by changes in prey availability and concluded that “boreal systems are functionally different from highly-networked feeding webs such as the North Sea”. The working group found that cod growth in ‘boreal’ systems (e.g. Barents Sea and Iceland) was influenced by the availability of capelin, since there is little potential for cod to compensate for low capelin abundance with any other alternate prey type. In more diverse systems such as the North Sea but also the Baltic, where there are many alternative prey types, the working group found less variability in cod growth and weight-at-age and hence little evidence that these are influenced by the availability of any particular prey type (ICES 1992, 1991).

Fulton *et al.* (2003a) argued that complex models have often acquired a poor reputation (see Jørgensen *et al.*, 1992), primarily because of two factors. First, the models are often so large that they may not be cost-efficient, with most modelling resources spent in development rather than application. Second, complexity introduced for the sake of completeness accomplishes nothing if the resulting model is actually of poor quality. While modern computing power makes ecosystem models attractive as computational restraints are lifted, this does not solve the problems of uncertain model specification, parameterization and system understanding. Studies have tended to indicate that the relationship between model detail and performance is non-linear (e.g. Costanza and Sklar, 1985; Håkanson, 1995). Too much complexity leads to too much uncertainty and renders the model’s dynamics and predictions difficult to interpret. Too little detail results in models that do not produce realistic behaviours (Fulton *et al.*, 2003).

Multispecies models can also be used effectively as a biological operating model for management simulations. Plagányi & Butterworth (2004) have argued that one of the most important roles of multispecies and ecosystem models in the future might be to provide “operating models” of the ‘true’ resource dynamics as part of an Operational Management Procedure (OMP) (Butterworth and Punt, 1999), or analogously Management Strategy Evaluation (MSE) framework (Cochrane, 1998). Such frameworks are currently used by the International Whaling Commission (IWC), CCAMLR and increasingly by fisheries scientists (Fulton *et al.*, 2004b). The ‘Atlantis’ modelling framework (Fulton *et al.*, 2005) has been closely aligned to efforts to evaluate ecosystem indicators using a MSE approach. Within South Africa, multispecies models are also being used in association with the OMP approach. For instance, a spatial multispecies OMP is being developed for the Antarctic Peninsula krill-predator-fishery system (Plagányi *et al.*, 2007). In Europe efforts are well underway to

interface both MSVPA and Gadget with the FLR (Fisheries Library for R) framework (Kell *et al.*, 2007) as part of the EU FP6 'UNCOVER' project.

5.4.4 Conclusions to multispecies modelling considerations

To date the most extensive use of multispecies modelling directly applied in advice is the use of natural mortalities in single species models derived from more complex multispecies models. While this approach is not so sensitive to changes it does at least improve the scaling of total biomass from the catch. We conclude that this practice should continue and be expanded to other stocks.

Currently a move to multispecies modelling for a full range of single species advice would require extensive development and testing. The work evaluated here suggests the stability of suitability functions for selection of prey may not be stable enough to provide good annual single species advice. So to progress in this direction would require considerable resources. Exceptions may be simple systems in which single predator and very few prey species may be tightly coupled.

The other main use of multispecies models is to allow hypothesis testing. This can take the form of full Management Plan evaluation, or examination of issues such as the compatibility of multispecies objectives. Multispecies modelling should continue to develop such frameworks.

5.5 Composite (ecosystem) issues in advice

Many of the influences discussed above throughout Section 5 can occur together when regime shifts due to climate/ocean forcing occur. Special consideration needs to be given to such situations because the changes can be of sufficient magnitude to change the dynamics, necessitating changes to management.

5.5.1 Bio-physical models

One way to approach the problem is through biophysical modelling (BPM). Presently, BPMs are being developed to investigate the sensitivity of fish to environmental variability. These are aimed at different life stages of fish. WKEFA was unaware of any BPMs that are currently used and incorporated into advice and management. The usefulness of BPMs is highly dependent on the specific characteristics. For example, if the BPM does not incorporate any processes that are directly or indirectly affected by water temperature, comparing the model results with a water temperature time-series is meaningless. Therefore, the BPM must incorporate all potentially relevant processes (although not necessarily explicitly). Simplicity and transparency are also important components of advice, and whilst BPMs may provide useful tools with which to investigate sensitivity of organisms to change, their results may be difficult to interpret and incorporate into advice.

5.5.2 Adapting management to shifting regimes

An alternative approach is to detect the shift in regime and respond accordingly. It is unlikely that a single management strategy will be optimal under all different regimes even if these could be defined and parameterised. Even if a robust management strategy for several sets of conditions might be achievable it is likely to be suboptimal in the most favourable conditions. This leads us to evaluate management in a changing or shifting environment (King and McFarlane, 2006; Annex 15). Detecting such shifts is important so that management strategies can be amended. Simulations suggest that fishing mortality based management strategies are more robust to regime shifts than biomass related management strategies (Kell *et al.*, 2005), because regime changes often result in changes in carrying capacity leading to different equilibrium biomass. The necessary time frame to detect regime shifts in fish communities depends on the life history, the age of recruitment to the fishery and the exploitation rate (MacCall, 2002; King and McFarlane, 2006). Shorter lived species with low age of recruitment and high exploitation rates require rapid detection of change. Management for very short lived species normally involves rapid response to fluctuating recruitment, so such

management regimes tend to have to respond to change quickly anyway, thus making them more adaptable under conditions of regime shift. If the management regime for short lived species is not robust, changes in regimes will make the situation even worse (Polovina, 2005). In contrast long lived species exploited at a low rate and with older age of entry to the fishery allow for slower management response (King and McFarlane, 2006).

6 Overall conclusions and recommendations

While it has been long accepted that we are providing fisheries advice within the context of a varying environment, the workshop recognised that in the face of global environmental change we need to take into account not only of stochastic variability but also trends and shifts in the environment as we develop scientific advice. This opened a perspective in the provision of advice that permeated the discussions during the workshop and is represented in the conclusions and recommendations given below. Most of the conclusions and recommendations given below are drawn from specific examples that have already been shown to work, in some stocks advice already follows these concepts, though there is a need to extend these approaches more generally and to clearly show what is being done.

When we observe variability we see this at a wide range of scales of space and time, and for convenience we impose two concepts, stochastic stability and regime shift, treating the short term as variable around a stable point and the long term as potentially different centres of stability. This way of thinking provides a useful framework that we use to describe the oceans but this does not mean that we consider that there are a fixed number of stable states, that can be identified, and that we move between them in either unpredictable or predictable ways. Rather we use these two concepts, of short term variability and regime shift, for consideration in providing advice, conveniently allowing us to consider different styles of change at different timescales.

We recognise that changes in physical drivers at many scales of space and time act together and this will result in changes in habitat. Through complex linkages these changes will result in differences in fish location, growth, maturation and reproductive potential. These differences may then influence recruitment and abundance leading to changes in natural mortality due to different species interactions. For fisheries management there is a need to provide advice in this changing environment. For stocks in a relatively healthy state the dominant characteristic for consideration is the carrying capacity (recruitment at medium to high biomass), reflecting available long term yield. For those in a depleted or recovery phase, the productivity (rate of increase in recruitment with biomass at low biomass) will be the dominant factor. The importance of understanding how the environment influences these two aspects therefore depends not just on the stock but also its state.

The workshop has concluded that variability on different timescales must be treated separately.

Some aspects such as catastrophic events can only be dealt with through a willingness to remain aware and the collection of information, observing and accounting for unusual events causing migration, mortality or recruitment failure.

Some short-term changes can be observed, estimated and brought into advice even where the complexity of the drivers is unknown. For example changes in growth and maturation can be brought directly into methods for estimating spawning stocks one or two years ahead and for estimating catch where TACs are required. This leads to the recommendations on predicting growth and maturation below.

We observe that physical environmental drivers influence recruitment each year, we see also that the links are complex and unstable with time. While there are a number of instances where environmental drivers have been clearly shown to explain variability in recruitment, once in use some have shown problems. Indicator based recruitment estimates may be non-linear, with asymmetrical error. Combining such information only improves the performance of management if the errors in the information are included appropriately. This leads to a requirement to test the utility of indicators in management simulations and derive ways of using them that are informative but robust to errors. This is a critical step in the inclusion of factors which explain only a small part of the variability.

As habitats changes, spatial distributions of fish can change, both horizontally and vertically. These changes can interact with surveys, and fisheries leading to the requirement monitor and account for change in catchability in assessment tuning series (see below).

Medium term change cannot be predicted in the same way as short term effects. The approach needs to follow two avenues. Where explicit relationships exist between stock and the environment the mean of stochastic projections can be modified accordingly. Such situations include average temperature dependence, species interactions and food availability for different exploited stocks. Where no explicit relationships exist or there is no basis for predicting environmental drivers into the future, advice should be based on scenario testing, along the lines of the evaluations of management plans. However, it is important to remember that medium term advice may include uncertainties or changes in carrying capacity that may not only affect yield but also need to be reflected in examination of biomass related targets and reference points used in the management plans.

The issue of productivity regimes was given special consideration. On the basis of simulations we concluded that regime specific fishing mortality management strategies can be used as a tool for contending with decadal-scale climate or environmental variability. These management strategies outperformed constant fishing mortalities management strategies by providing a balance between benefits (high yield) and trade-offs (fishery closures).

As an overall conclusion it is recommended that rather than assuming that the mean of a given parameter derived from the (recent) past will best define future, we should expect trends and attempt to estimate them. This calls for the development of a number of tools that evaluate estimates of current values and current trends in the presence of noise in both measurement and environment.

6.1 Habitat

Some of the case studies (e.g. Bering Sea yellowfin sole) have suggested that the timing of horizontal migrations to/from feeding grounds can be affected by environmental drivers such as bottom temperature. Likewise, recent studies (e.g. Bering Sea Pollock) have shown that light levels can affect the vertical distribution of demersal and semi-demersal stocks. In the context of potential trends in environmental parameters due to global environmental change such effects need to be investigated in ICES stocks to ensure that they do not result in catchability biases in surveys or commercial catch rates used for tuning assessments. However, the development of corrections through incorporation of such processes requires investigation of causal links in addition to the evaluation of the effects.

Availability and utilisation of suitable spawning habitats has been demonstrated to affect the reproductive success of cod in the central Baltic. It is expected that quality of spawning habitat affects recruitment also in other stocks, specifically if being at the border of the species distribution range. If available, measures of reproductive habitat should be integrated into the evaluation of reference points and construction of environmental sensitive stock recruitment relationships to be used in medium- to long-term projections. The value of using such information in short-term predictions depends on the availability and performance of pre-recruit surveys, and if these are not available or reliable on the understanding and predictability of other processes affecting reproductive success.

6.2 Growth and maturation

Both growth and maturation have been observed to be sensitive to environmental changes in both short and medium term. These parameters affect management through estimation of SSB and catch. Current practices range from cohort-based modelled projection to the use of long term means. We recommend ICES develops generic software to evaluate how weights and maturation should be projected forward for each stock and to provide cohort and year effect based short-term prediction software to replace the current approach (Needle *et al.*, 2005). Methods should involve detection of 'signal' in 'noise' using statistical methods and apply appropriate prediction methods. Retrospective analysis should be used to monitor the performance of the methods chosen.

For improving medium to long-term simulations, coupled growth and maturation models need to be developed, considering changes in ambient abiotic and biotic environment. The former may include temperature and other physical variables affecting physiology and behaviour, while the latter may include estimates of prey availability. The Multispecies WG should be tasked to review and develop corresponding model approaches.

6.3 Recruitment

Knowledge and prediction of recruitment is obviously one of the most critical aspects for setting TACs, particularly for short lived species. Estimation of recruitment is considered at two ways, short-term advice for setting TACs, medium-term advice for management plan evaluation or longer term prognosis and related determination of targets and biological reference points.

6.3.1 Short-term estimation

This should ideally be through direct estimation, which is our main recommendation. If direct estimation is not possible or can be augmented or replaced with an environmental indicator this should be considered. However, the indicator approach should be evaluated and incorporated in short-term projections if performance is shown to improve prediction. This evaluation should consider the error structure, relative information content and functional relationship of any indicator in selecting its use. If recruitment estimates are required in the absence of any direct or indirect estimation method, the current practice of geometric mean can be replaced by examining time-series of recruitment and using recent values or autoregressive models to provide values. These techniques should be evaluated by retrospective analysis as part of the validation before using them in advice.

6.3.2 Medium to long term

Medium-term simulations used for management evaluation or illustration of stock trends should include evaluations under different environmental regimes. This should include both the uncertainty in the parameter estimates for stock-recruit relationships and the different formulations need to deal with more complex environmentally-dependent stock-recruit relationships that may depend on external drivers (see Annex 9) or stock demographic composition. The consideration should be primarily for robustness to different plausible possibilities, rather than expecting to optimise management under all conceivable options. In the case where specific environmental variables have been mechanistically linked to recruitment success (e.g Baltic Sea sprat and cod) it is recommended that applications be developed to use downscaled Global Climate Model outputs to drive long-term projections (<http://www.resc.rdg.ac.uk/twiki/bin/view/Resc/GcOMS>).

6.4 Ecosystem issues

6.4.1 Multispecies interactions

Several multispecies and ecosystem models for potential use either directly or within OMP (Operational Management Procedures, Cochrane, 1998) and MSE (Management Strategy Evaluation) (ICES 2007a) frameworks have recently been developed (see above). These efforts should continue as they form a basis for a variety of applications for hypothesis testing that are impossible outside a simulation framework.

Results to date in considering predation mortality in assessments show greatest success in areas such as Baltic and Barents Seas where there are interactions between small numbers of exploited species, and further developments in this direction should be encouraged as applications of the Ecosystem Approach to Fisheries Management in the ICES area. This should include consideration of the effect of prey availability and competition on growth and maturation (see Section 6.2). However, in complex systems where many different prey resources (both fish and invertebrate) exist, it may more difficult to incorporate a representation of the complex interactions into management advice.

6.4.2 Regime shifts

Special consideration needs to be given to both naturally occurring and fishery induced regime shifts due to climate/ocean forcing. Such situations can generate productivity changes of sufficient magnitude to necessitate changes to management, as it is unlikely that a single management strategy will be optimal under different regimes. Simulations suggest that fishing mortality management strategies are more robust to regime shifts than biomass related management strategies.

The necessary time frame to detect change in regimes depends on the life history and age of recruitment to the fishery and the exploitation rate. Short lived species with low age of recruitment and high exploitation rates would require very rapid detection, but their management, which normally involves rapid response to fluctuating recruitment, may already be more adapted to conditions of regime shifts. However, if their management is not robust, changes in regimes will make the situation even worse. In contrast long lived species exploited at a low rate and with older age of entry to the fishery allow for slower management response.

If stock carrying capacity changes then biomass targets may no longer be appropriate. If productivity changes the risks to the stock and the potential for recovery will be changed. Under such circumstances it is necessary to re-evaluate previously defined biomass or fishing reference points. However, re-evaluation should include consideration not only of the current carrying capacity but also the potential for further stock depletion and the ability of the stock to recover should the habitat return to previously observed conditions. This leads to biomass limit points that infer maintenance of recruitment in the current stock status and inclusion of the possibility to recover if the habitat changed again. For fishing mortality limits, if productivity has changed they should allow stock expansion under both regimes. Assessment working groups are encouraged to take this into consideration medium to long term projections and in the determination of biological reference points that are relevant to specific productivity regimes. Management targets and precautionary limits should be revised accordingly.

6.5 General

As part of standard practice ICES stock assessment WGs should provide a very brief environmental change description for each stock. This should include how data (surveys and assessment data) has been investigated for trends, where environmental covariates are used for provision of advice and where trends or observed changes are at present or could be included in numerical basis for advice.

6.6 TOR for climate change workshop

A number of marine ecosystems are particularly vulnerable to environmental change and there is a need to evaluate consequences for the medium to long term. For this purpose we require advice from climate experts (e.g. the Cod and Climate Workshop on Future Climate planned for 2008) It is recommended that the following TOR be included for this workshop:

Develop 20–50-year probabilistic projections of future temperature and salinity for application in multi-decadal scale projections of fish population dynamics and distribution in the North and Baltic Seas.

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Annex 1: List of participants

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Annex 2: Recommendations

We suggest that each Expert Group collate and list their recommendations (if any) in a separate annex to the report. It has not always been clear to whom recommendations are addressed. Most often, we have seen that recommendations are addressed to:

- Another Expert Group under the Advisory or the Science Programme;
- The ICES Data Centre;
- Generally addressed to ICES;
- One or more members of the Expert Group itself.

RECOMMENDATION	ACTION
1.Add TOR for Climate Change Workshop	For att of ACE and possibly ACFM
2.	
3.	
4.	
5.	
6.	

After submission of the report, the ICES Secretariat will follow up on the recommendations, which will also include communication of proposed terms of reference to other ICES Expert Group Chairs. The "Action" column is optional, but in some cases, it would be helpful for ICES if you would specify to whom the recommendation is addressed.

Climate Change Workshop Term of Reference:

Marine ecosystems which are particularly vulnerable to environmental change and for which we require advice from climate experts (e.g. the Cod and Climate Workshop on Future Climate planned for 2008)

TOR to be added-Develop 20–50-year probabilistic projections of future temperature and salinity for application in multi-decadal scale projections of fish population dynamics and distribution in the North and Baltic Seas.

Justification

Background:

Future climate change is expected to have major impacts on marine ecosystems in the North and Baltic Seas, and consequently on the dynamics and distribution of fish populations. In the North Sea, cod populations produce fewer recruits and move to deeper and more northern areas when temperatures rise (Beaugrand *et al.*, 2004; Blanchard *et al.*, 2005; Rindorf and Lewy, 2006). The mechanisms leading to these changes are unclear but are most likely related to large-scale climatic effects on larval survival, juvenile habitat preference and growth rates. If temperatures continue to rise, it is likely that cod abundance will continue to decrease in the North Sea (Drinkwater, 2005). However, the presence of exploitable cod populations in the North Sea during earlier warm periods similar to those expected in the coming century, but under lower fishing mortality (Enghoff *et al.*, 2007), suggests that sustainable populations could be maintained if exploitation were reduced (Cook and Heath, 2005; Kell *et al.*, 2005). Additional details regarding the role of climate variability on North Sea cod are given in earlier sections of this report.

Future climate change will also affect populations in the Baltic Sea, but in a more complicated manner than in the North Sea. In the Baltic Sea, strong horizontal and vertical gradients in salinity, temperature and oxygen concentration restrict the distributions and dynamics of

marine and freshwater species. Because of its low salinity, the number of marine species in the Baltic is much lower than in the North Sea.

Salinity in the Baltic Sea is currently decreasing due to reduced inflows of high salinity water from the Skagerrak and increased precipitation. Cod is particularly close to its physiological tolerance limits (requiring salinities >11 psu) and therefore vulnerable to further freshening. The shallow, complex topography of the Baltic and its entrances and the short timescales of the weather events which drive inflows make it very difficult to predict the frequency of future Baltic inflows (Meier *et al.*, 2006a). Recent climate-ocean modelling projections of salinity in the Baltic Sea for 2070–2100 are therefore uncertain and indicate that salinity could decrease by 7–47% (Meier, 2006; Meier *et al.*, 2006b). Such decreases in salinity will further restrict the spatial distributions of marine species, including cod, in the Baltic Sea. Moreover, those warm-adapted species whose spatial distributions are shifting northwards (Brander *et al.*, 2003; Perry *et al.*, 2005) will be less likely to enter and colonize the Baltic Sea if salinity will decrease in the future. As a consequence, the overall richness of marine fish species in the Baltic could decrease under future climate change (MacKenzie *et al.*, 2007).

In order to improve projections of how the Baltic fish community and fisheries might react to future climate change, it will be necessary to have probabilistic forecasts of likely future salinity (and oxygen) regimes. These forecasts would provide the basis for forecasting future species changes and the productivity of fish species, and support some existing qualitative projections of how the Baltic fish community might respond to future climate change (MacKenzie *et al.*, 2007).

The limited exchange of high salinity water between the Baltic and North Sea has additional impacts on Baltic biota. Oxygen conditions in the deep layers decrease between major inflow events and can become low enough to kill organisms living in the benthos and sub-halocline layers (Helcom, 2003). Oxygen concentrations themselves are influenced by both biotic (e. g. consumption, production) and abiotic (temperature) factors. As a result increases in temperature that are predicted to occur as a consequence of future climate change will likely reduce oxygen concentrations and further threaten the presence of especially benthic marine species, such as cod, in the deeper parts of the Baltic Sea. Cod reproductive habitat, which can be estimated volumetrically (Plikshs *et al.*, 1993; MacKenzie *et al.*, 2000) given thresholds of salinity and oxygen concentration required for successful egg fertilization and hatching (Wieland *et al.*, 1994; Vallin *et al.*, 1999), will likely decrease due to both an increase in temperature and a decrease in salinity. However, these changes have not yet been quantified.

The changes in temperature, salinity and oxygen conditions will have impacts on other fish species and how they interact with each other and the zooplankton community. Growth and condition of herring and sprat depend on availability of prey.

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Annex 3: Case study summary tables

AREA/ STOCK	CASE STUDY				EVALUATION OF CASE STUDY				
	STOCK ASSESS PARAM	HYPOTHESIS/ PROCESS	CLIMATIC CONTEXT	RELEVANCE TO MANAGEMENT	UNDER- STANDING OF PROCESS	TIMESCALE OF APPLICATION	DATA/ METHODS	PREDICT ABILITY NOW- CASTING	PREDICT ABILITY FORECASTING
EAST AND WEST GREENLAND COD (OFFSHORE) / ICES XIV & NAFO 1	Growth	1) Temperature	1) Ocean temperature depends on climate and possible changes in the current system	High: Realistic growth predictions would directly affect the annual TAC advice	1) Medium				
		2) Prey availability	2) Climate/physics regulating the prey abundance and distribution (e.g. Northern shrimp and capelin)		2) Low: Biomass and distribution of capelin not known (no survey)				
	Mortality	1) Eggs: temperature	1) & 2): see above	High: effects on recruitment and trawlable biomass	Medium:				
		2) Larvae: temperature and prey availability	3) & 4) Climate affects the distribution of the (shrimp) fishery and potential predators of cod		1) & 2) quantitative data scarce				
		3) Juveniles: bycatch in shrimp fishery			3) probably less important than previously assumed				
		4) Adults:							
		a) fishery,			4a) stock collapse due to intense fishing				

AREA/ STOCK	CASE STUDY		CLIMATIC CONTEXT	RELEVANCE TO MANAGEMENT	EVALUATION OF CASE STUDY			PREDICT ABILITY NOW- CASTING	PREDICT ABILITY FORECASTING
	STOCK ASSESS PARAM	HYPOTHESIS/ PROCESS			UNDER- STANDING OF PROCESS	TIMESCALE OF APPLICATION	DATA/ METHODS		
		b) predation by seals			($F \gg F_{MSY}$; $F_{MSY} \approx 0.2$ at favorable environment) 4b) might have become important in recent years but quantitative data are lacking				

		CASE STUDY			EVALUATION OF CASE STUDY				
AREA/ STOCK	STOCK ASSESS PARAM	HYPOTHESIS/ PROCESS	CLIMATIC CONTEXT	RELEVANCE TO MANAGEMENT	UNDER- STANDING OF PROCESS	TIMESCALE OF APPLICATION	DATA/ METHODS	PREDICT ABILITY NOW- CASTING	PREDICT ABILITY FORECASTING
	Recruit	Transport of eggs and larvae - East to West Greenland - SW Greenland towards north - from SW Iceland across Denmark Strait to East Greenland	Varying transports of larvae/juveniles to suitable settling and nursery areas, Recruitment pulses from outside Greenland waters	Low for annual TAC, high for medium term forecast	Medium				
	Spatial Issues	1) Emigration of year classes originated from Iceland when becoming mature 2) Immigration of adults from Iceland	1) southward migration off West Greenland accelerated when temperature decreases 2) related to changes in prey (capelin) distribution	High: direct effect on annual TAC for Greenland waters	1) Medium: documented by tagging experiments 2) Low: first indication in 2006				
EASTERN BERING SEA FLATFISH	Survey catchability	1) Temperature-dependant availability 2) Temperature-dependant	1) Warming trend in Eastern Bering Sea 2) Changes in fish response to	Medium to high: spurious trends in survey biomass due to changing catchability can affect estimation	Low-medium. Field data on the response of fish to survey gear under different temperatures	Temperature-dependant catchability can currently be treated in assessment	1) Statistical assessment models 2) Management Strategy	medium	low-medium, due to difficulty of forecasting future temperature

AREA/ STOCK	STOCK ASSESS PARAM	CASE STUDY			EVALUATION OF CASE STUDY				PREDICT ABILITY NOW- CASTING	PREDICT ABILITY FORECASTING
		HYPOTHESIS/ PROCESS	CLIMATIC CONTEXT		RELEVANCE TO MANAGEMENT		UNDER- STANDING OF PROCESS	TIMESCALE OF APPLICATION		
		vulnerability	survey and/or distribution function temperature	gear stock as of	of stock status and short-term and medium-term forecasts	does not currently exist.	models	Evaluations		regimes

AREA/ STOCK	STOCK ASSESS PARAM	CASE STUDY			EVALUATION OF CASE STUDY				
		HYPOTHESIS/ PROCESS	CLIMATIC CONTEXT	RELEVANCE TO MANAGEMENT	UNDER- STANDING OF PROCESS	TIMESCALE OF APPLICATION	DATA/ METHODS	PREDICT ABILITY NOW- CASTING	PREDICT ABILITY FORECASTING
NORTH SEA COD (INFORMATION HAS BEEN EXTRACTED FROM CRR 274 AND SOURCES CITED BELOW. A TEXT SUPPLEMENT IS PROVIDED)	Mortality	Predation mortality on juvenile cod (e.g. by gurnard and adult cod).	1. & 2. might change as climate influences predator-prey overlap, and new predators might emerge.	Medium-high, single-species models assume that cod recruit at age 1, thus mortality-at-age 0 not too much of an issue	Low-medium, MSVPA & SMS have provided some insight into predation mortality (M2), but probably do not include all of major predators – some (e.g. cetaceans) are missing	Time-series of variable M2 values already available from MSVPA and sometimes used in single-species assessments.	M2 values from multispecies models (MSVPA, SMS etc.)	'Nowcast' probably OK with MSVPA & SMS	Probably main role for multispecies models, however
		Predation mortality on adult cod (e.g. by seals)					Tagging studies (M1+M2)		
		Residual mortality (e.g. by disease and old age)	3. might change with temperature, as diseases are expected to become more prevalent with climate change (Harvell <i>et al.</i> 1999 & 2002), as are harmful algal blooms (e.g. Peperzak 2003)	Residual mortality thought to be important but very difficult to estimate	Residual mortality (M1) very poorly understood	Full 'ecosystem' models are a longer term prospect. Better information on M1 probably in the distant future.			
NORTH SEA AUTUMN SPAWNING HERRING	Growth	Varies by year and sometimes by cohort	Condition does vary in NSAS herring, but the link to climate is still not clear. Changes in growth have also not as yet to	Medium, both the estimation of TAC and the SSB are effected by predictions of growth, this results in variability in the	Unclear	2–3 years, once studies of growth completed	Statistical models bioenergetics models	medium	medium

CASE STUDY				EVALUATION OF CASE STUDY					
AREA/ STOCK	STOCK ASSESS PARAM	HYPOTHESIS/ PROCESS	CLIMATIC CONTEXT	RELEVANCE TO MANAGEMENT	UNDER- STANDING OF PROCESS	TIMESCALE OF APPLICATION	DATA/ METHODS	PREDICT ABILITY NOW- CASTING	PREDICT ABILITY FORECASTING
			been demonstrated to be linked to climate, cohorts effects have been link to large year classes suggesting density dependence	error associated in projections rather than bias.			simulation studies		

AREA/ STOCK	STOCK ASSESS PARAM	CASE STUDY			EVALUATION OF CASE STUDY					
		HYPOTHESIS/ PROCESS	CLIMATIC CONTEXT	RELEVANCE TO MANAGEMENT	UNDER- STANDING OF PROCESS	TIMESCALE OF APPLICATION	DATA/ METHODS	PREDICT ABILITY NOW- CASTING	PREDICT ABILITY FORCASTING	
	Mortality	Survival of the larvae seems to have changed (see below) Natural mortality on fish may change dependent on predation by mackerel and horse mackerel Reported parasite infestations have occurred but are not detectable in the fish dynamics data	As climate impacts on other species in the North Sea, the predation on NSAS herring will change. The North Sea MSVPA has demonstrated that the variability in natural mortality due to predation appears to greater in the younger ages.	High for larvae (see below) Low for adults	Larvae- unclear Adults reasonably well described	Unknown for larvae Already working for adults	Coupled IBM/3-D hydrodynamic models SVPA assessment models simulation studies	Poor and medium	Poor and medium	
	Recruit	There are periods of different stock to recruitment relationships	ICES SGREVAP has suggested that the changes in recruitment are linked to changes in the environment of the North Sea which are climatically driven	High- serial poor recruitment has impact on management and the sustainable exploitation of the stock	Unclear	Unknown	Coupled IBM/3-D hydrodynamic models simulation studies	Poor	poor	
	Spatial	The productivity of the spawning	No climate linkage has been	Medium- spatial TACs operate	Unclear	2–5 years	simulation	poor	poor	

AREA/ STOCK	CASE STUDY				EVALUATION OF CASE STUDY			PREDICT ABILITY NOW- CASTING	PREDICT ABILITY FORECASTING
	STOCK ASSESS PARAM	HYPOTHESIS/ PROCESS	CLIMATIC CONTEXT	RELEVANCE TO MANAGEMENT	UNDER- STANDING OF PROCESS	TIMESCALE OF APPLICATION	DATA/ METHODS		
	Issues	components vary	found, as yet.	based on no robust science			studies		

AREA/ STOCK	CASE STUDY				EVALUATION OF CASE STUDY				
	STOCK ASSESS PARAM	HYPOTHESIS/ PROCESS	CLIMATIC CONTEXT	RELEVANCE TO MANAGEMENT	UNDER- STANDING OF PROCESS	TIMESCALE OF APPLICATION	DATA/ METHODS	PREDICT ABILITY NOW- CASTING	PREDICT ABILITY FORECASTING
EASTERN BERING SEA POLLACK	Growth	1) Density dependence 2) Environment temperature	1) Secondary biotic conditions 2) Warming trend in Eastern Bering Sea	1) and 2) Medium: change in expected yields	Low-medium. Field data extensive, relationships	Near-term average wts at age reasonable over 2–3 yr time horizon	Data processing, assessment modelling	Medium	Low-medium, due uncertain future temperature and density
	Recruitment	1) Cannibalism f(SSB) 2) Survival	1) Degree of adult overlap with juveniles 2) Environmental Forcing	Medium to high: Basis for yield recommendations (MSY=OFL)	Low-medium. Cannibalism apparently declining, survival multifaceted	1960s-present	Survey data and statistical assessment models, Mgt Strat. Eval.	Medium	Low-medium--future environment uncertain
	Spatial issues	1) Temperature dependent 2) Light dependent 3) Movement out of zone	1) Extent of cold pool during summer survey 2) Light attenuation affects water column distribution 3) Distributional shifts out of region	Medium to high: 1)–2) survey biomass uncertainty inflated 3) Availability w/in US zone	Medium. Field data lacking	1) available currently 2) data available only for the past few years 3) at least 10 years, with planned field program	1)–2) Survey records and evaluation in statistical assessment models 3) Tagging, modelling	1)–2) Med. 3) Low	1)–2) Medium, since assessment improvement should improve forecasting performance 3) low
CALIFORNIAN SARDINE	Growth	Sub-population differences Regional or seasonal differences from stock mixing or	Higher growth during warm regimes. High stratification	Medium: weight-at-age affects current biomass estimate; growth differences affect productivity for	Poor: interactions between 1–3 are unclear.	Growth data used in annual stock assessment; Reference	1) Statistical catch-at-age models for assessment 2) surplus	Medium	Forecasts not performed in 1); in theory, 1–3

AREA/ STOCK	CASE STUDY				EVALUATION OF CASE STUDY				PREDICT ABILITY NOW- CASTING	PREDICT ABILITY FORECASTING
	STOCK ASSESS PARAM	HYPOTHESIS/ PROCESS		CLIMATIC CONTEXT	RELEVANCE TO MANAGEMENT	UNDER- STANDING OF PROCESS	TIMESCALE OF APPLICATION		DATA/ METHODS	
		emigration		limits growth.	reference points		points	re-	production	years
		Possible dependence	density	Strong upwelling promotes growth and fecundity.			estimated ~every 10 yr.		simulations for reference points	

AREA/ STOCK	STOCK ASSESS PARAM	CASE STUDY			EVALUATION OF CASE STUDY				
		HYPOTHESIS/ PROCESS	CLIMATIC CONTEXT	RELEVANCE TO MANAGEMENT	UNDER- STANDING OF PROCESS	TIMESCALE OF APPLICATION	DATA/ METHODS	PREDICT ABILITY NOW- CASTING	PREDICT ABILITY FORECASTING
	Mortality	<p>1) Eggs: advective loss; predation by clupeids</p> <p>2) Early larvae: food availability, predation, and advection</p> <p>3) 0- and 1-group: cannibalism, predation</p> <p>4) Adults: fisheries & predation</p>	<p>1) T affects development rate and survival to hatch; wind & current affect advective loss. 1) & 2). Survival affected by too weak or too strong upwelling in 1) & 2).</p> <p>2) Habitat overlap for predator-prey affected by S, O_2 and T.</p> <p>3) T and upwelling affect distribution & catchability in 3) & 4).</p> <p>4) Stratification affects vertical distribution and vulnerability to predation.</p>	<p>High:</p> <p>1)to 3) affect recruitment</p> <p>3) & 4) affect late juvenile/adult survival & egg production</p>	Medium to high	?	<p>1) Satellite and CalCOFI survey data</p> <p>2) 3-D Hydrodynamic models</p> <p>3) Stock assessment models</p>	Medium	One year maximum
	Recruit	See growth & mortality above; spatial issues below							

AREA/ STOCK	STOCK ASSESS PARAM	CASE STUDY			EVALUATION OF CASE STUDY				
		HYPOTHESIS/ PROCESS	CLIMATIC CONTEXT	RELEVANCE TO MANAGEMENT	UNDER- STANDING OF PROCESS	TIMESCALE OF APPLICATION	DATA/ METHODS	PREDICT ABILITY NOW- CASTING	PREDICT ABILITY FORCASTING
	Spatial Issues	1) Size of spawning habitat	1) T , S , and upwelling affect spawning habitat size	Medium to high: 1)–3) affect recruitment	Medium to high	?	1) Satellite and CalCOFI survey data	Medium	Six to 12 months.
		2) Eggs: production in unfavorable habitat,	2) current speed affects advection and persistence of warm core eddies.	4)–5) adult survival & egg production			2) 3-D Hydrodynamic models 2) Spatially- explicit stock assessment models		
NE ARTIC COD		3) Larvae: retention in or transport to areas with suitable food (e.g. warm core eddies)	3) late juvenile distribution dependent on spatial spawning success, adult distribution dependent on						
		4) conditions affect avail to predators	hydrography						
		5) coastal conditions affect availability to fisheries							
NE ARTIC COD	Growth	- Prey availability - Temperature effects	Climate/physics regulating the prey abundance and distribution	High: Realistic growth predictions would directly affect the TAC advice	Low (related to prediction)	2-3 years with reasonable effort (e.g. within RECLAIM)	- Statistical models - bioenergetics models	high	medium

AREA/ STOCK	STOCK ASSESS PARAM	CASE STUDY			EVALUATION OF CASE STUDY				
		HYPOTHESIS/ PROCESS	CLIMATIC CONTEXT	RELEVANCE TO MANAGEMENT	UNDER- STANDING OF PROCESS	TIMESCALE OF APPLICATION	DATA/ METHODS	PREDICT ABILITY NOW- CASTING	PREDICT ABILITY FORECASTING
EASTERN BALTIC COD	Recruit	-Transport of larvae/ juveniles -Spring PP is good -Food availability -Cannibalism	-Varying transports of larvae/juveniles into bad areas Climate vs PP -Lack of food increase cannibalism	-Low for TAC -Higher for medium term as early warning	Medium	Now	-Numerical models of physics and PP -Statistical models	high	medium
	Spatial Issues	-CPUE no good due to fish density changes -Survey no good without covering the stock	Distribution changes due to climate.	High: Directly affects the assessment of stock size (and thus predictions and advice)	Medium-high	Now		medium	low
	Growth	1) Density dependence 2) Oxygen limitation 3) Spawning time 4) Prey availability	2) Lack of inflows 3) Temperature 4) Recruitment of sprat & herring depending on temperature	Medium: affects short-term forecasts to a certain extend, medium- to long- term projections more, and also reference points	Interactions of 1–4 unclear	2–3 years with reasonable effort (which is at present not allocated)	1) Statistical models 2) bioenergetics models 4) extended MSVPA	Growth	1) Density dependence 2) Oxygen limitation 3) Spawning time 4) Prey availability
	Mortality	1) Eggs: salinity & oxygen concentration &	1) Lack of inflows, increased	High: 1)–3) affect recruitment	Relatively high	Due to complexity of interactions	1) Deterministic process models	Mortality	1) Eggs: salinity & oxygen

AREA/ STOCK	STOCK ASSESS PARAM	CASE STUDY			RELEVANCE TO MANAGEMENT	EVALUATION OF CASE STUDY			PREDICT ABILITY NOW- CASTING	PREDICT ABILITY FORCASTING
		HYPOTHESIS/ PROCESS	CLIMATIC CONTEXT			UNDER- STANDING OF PROCESS	TIMESCALE OF APPLICATION	DATA/ METHODS		
		predation by clupeids	precipitation & run-off, winter severity	4) affect late juvenile/adult survival & egg production			rather 5 years	2) Coupled IBM/3-D hydrodynamic models		concentration & predation by clupeids
		2) Early larvae: food availability	2&3) Habitat overlap predator & prey forced by salinity, O2 and T					3) SMS & 4M		2) Early larvae: food availability
		3) 0- and 1-group: cannibalism						4) usual assessment models		3) 0- and 1-group: cannibalism
		4) Adults: fisheries	4) Catchability depends on habitat volume					1)-3) Statistical models		4) Adults: fisheries

		CASE STUDY				EVALUATION OF CASE STUDY				
AREA/ STOCK	STOCK ASSESS PARAM	HYPOTHESIS/ PROCESS	CLIMATIC CONTEXT	RELEVANCE TO MANAGEMENT	UNDER- STANDING OF PROCESS	TIMESCALE OF APPLICATION	DATA/ METHODS	PREDICT ABILITY NOW- CASTING	PREDICT ABILITY FORCASTING	
	Spatial Issues	1) Eggs: production in spawning areas with unfavorable environment, floating depths in relation to oxygen depletion. 2) Larvae: retention in or transport to areas with suitable food 3) 0- and 1-group: overlap with adults as predators 4) Closed areas for fisheries	1) Lack of inflows, increased precipitation & run-off, winter severity 2) Wind forcing 3) Oxygen concentration in deep water vs. temperature in shallow areas 4) late juvenile distribution dependent on spatial spawning success, adult distribution dependent on hydrography	Medium to high: 1)-3) affect recruitment 4) adult survival & egg production	Low	Due to complexity of interactions rather 10 years	1+2) Coupled IBM/3-D hydrodynamic models 4) first spatial specific models, but data missing in necessary resolution	Spatial Issues	1) Eggs: production in spawning areas with unfavorable environment, floating depths in relation to oxygen depletion. 2) Larvae: retention in or transport to areas with suitable food 3) 0- and 1-group: overlap with adults as predators 4) Closed areas for fisheries	
BALTIC SPRAT SD 22-32	Mortality	See below for eggs and larvae.	See below.							
	Recruit	Recruitment higher when temperature	Yes; climate change and	1) short-term predictions of	Reasonable. Based on many	Relationships available for	many years of ichthyoplankton	Is possible based on	Is possible based on	

		CASE STUDY			EVALUATION OF CASE STUDY					
AREA/ STOCK	STOCK ASSESS PARAM	HYPOTHESIS/ PROCESS	CLIMATIC CONTEXT	RELEVANCE TO MANAGEMENT	UNDER- STANDING OF PROCESS	TIMESCALE OF APPLICATION	DATA/ METHODS	PREDICT ABILITY NOW- CASTING	PREDICT ABILITY FORECASTING	
		warmer; effects of temperature on egg production, survival, larval feeding and survival	regime shifts. Increasing frequency of warm year, and effects on eggs, larvae, zooplankton prey, and adult maturation.	recruitment, spawner biomass, yield 2) medium-term predictions of recruitment, spawner biomass, yield 3) identification of regimes	years of ichthyoplankton sampling, laboratory experiments and 50 years of consistent temperature-recruitment relationship	both short-term and medium-term projections; improvements possible and likely in coming years.	sampling, laboratory experiments; 50 years of temperature-recruitment data; IBM and other process modelling of ELH stages and ocean circulation.	statistically significant relationships	statistically significant relationships	
BAY OF BISCAY ANCHOVY	Mortality	1) Larvae: high mortality would have a negative impact on recruitment.	1)) major westerly gales causing stratification breakdown	Potentially high: affects recruitment	Low. Larvae survival may not always be central to explain recruitment.	Due to complexity of interactions rather 10 years	3-D hydrodynamic physical model (IFREMER, Brest)		Low-medium	
	Recruit	1) Early larvae and juveniles: survival enhancement. 2)Adults: expansion of spawning habitats	1)NE winds of medium-low intensity result in weak upwelling	Potentially high	Low. Other processes may be more influential at times.	Due to complexity of interactions rather 10 years	1) 3-D hydrodynamic physical model (IFREMER, Brest) 2) Statistical models		Low-medium	

Annex 4: Environmental aspects relevant for the management of Atlantic cod (*Gadus morhua*) in Greenland waters

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Abstract

At Greenland, periods of high recruitment of Atlantic cod have historically been associated with relatively warm conditions. Cod is known in the Greenland areas through historical time but appears to have significantly increased during the general warming in the beginning of the 20th century. Commercial fishing was gradually introduced between 1915 and 1925 but the effort remained limited until 1950 allowing the stock to grow very abundant off West Greenland and to produce frequently rich year classes through the 1930s and 1960s. However, even in this period the productivity of the West Greenland cod stock appeared to be substantially lower than those of other North Atlantic cod stocks. A prolonged period of decline in stock biomass was observed in 1950 to 1975, which can be attributed to deteriorating climatic conditions and excessive fishing. The stocks collapsed completely in the beginning of the 1990s and cod catches have been insignificant for many years. Air and ocean temperature at Greenland increased again since the early 1990s, and reached historical highs in 2005. At present the stock situation is clearly improving: the offshore Greenland spawning population has been increasing since 2000 mainly off East Greenland, an inflow of a significant strong 2003 year-class of cod spawned off Iceland is detected off South Greenland and the annual yield from the inshore stocks is increasing. Protection of the rebuilding of the offshore spawning populations off East and West Greenland is obviously needed to allow the stock to benefit from the improved climatic conditions.

Annex 5: Temperature-dependent survey catchability for eastern Bering Sea flatfish

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Abstract

The eastern Bering Sea has exhibited substantial variability in temperature in recent decades, and has shown a marked warming trend in recent years. These changes in temperature appear to significantly affect trawl survey catchability of yellowfin sole (*Limanda aspera*) and flathead sole (*Hippoglossoides elassodon*) based on analyses from stock assessment models. These models use a “global catchability” in which estimated temperature-dependent survey catchability is a function of the annual temperature averaged over the entire survey area. However, spatial differences in temperature between survey tows may result in differential responses to the trawl gear. Thus, we evaluated a “local catchability” model in which the estimated survey catchability at a given trawl station was a function of the local temperature. For yellowfin sole, both the global and local methods result in a statistically significant positive relationship between catchability and temperature. The increasing trend in EBS temperatures from 1999 to 2005 had a substantial effect on estimated yellowfin sole biomass when adjusting for temperature-dependent catchability. For example, the estimated 2005 total biomass declined 7% when global temperature-dependent catchability was used and the harvest recommendation dropped by nearly 10 000 t. To assess the importance of including factors affecting survey catchability, a management strategy evaluation (MSE) was developed. The MSE analysis showed that failing to account for temperature-dependent catchability resulted in underestimates of biomass during periods of low catchability and overestimates during periods of high catchability. Our results show that current assessment methods should include factors affecting survey catchability to reduce the variability in catch.

Introduction

The eastern Bering Sea (EBS) is currently experiencing a warming trend and appears to be transitioning from an Arctic to sub-Arctic system. This can affect flatfish distribution and abundance in a number of ways. In particular, the amount of sea ice and its southern extent is diminishing, and the timing of ice melt has shifted about three weeks earlier in the spring (Overland and Stabeno, 2004, Stabeno *et al.*, 2001, Grebmeier *et al.*, 2006). These changes can potentially affect the distribution of fish. For example, the timing of the migration between summer and winter distributions for juvenile and adult yellowfin sole is thought to be related to the avoidance of ice cover (Wilderbuer *et al.*, 1992). Movement of larvae of shelf-spawning flatfish to nearshore nursery areas is also affected by environmental conditions (Wilderbuer *et al.*, 2002).

Changing temperatures can also affect survey catchability, a parameter typically estimated within stock assessment models. Changes in catchability of scientific surveys are generally explained by either changes in availability of the fish distribution to the survey area, or changes in the proportion of the fish in the net path captured by the gear (reflecting the gear efficiency). For yellowfin sole, these mechanisms are consistent with the observation of temperature-dependent survey catchability. Yellowfin sole spawn in late spring in nearshore shallow areas outside the EBS survey area, and if the timing of the migration of spawners to the summer feeding areas (and survey area) is delayed in cold years, then this would affect the availability of fish to the survey. Additionally, field experiments show that several species of flatfish are “herded” into the trawl net from beyond the trawl path, and the mechanism is thought to be the physical contact of trawl bridles stimulating fish to move away from the oncoming bridle into the net path (Somerton and Munro, 2001). If the responsiveness of fish is diminished in colder temperatures, it is plausible that the degree to which flatfish are herded is diminished. A positive relationship between survey catchability and temperature has also been estimated for flathead sole and arrowtooth flounder.

Identifying the relative importance of these mechanisms will likely require additional field research. However, if temperature affects survey catchability via gear efficiency then catchability would be expected to differ between tows conducted at different temperatures and this can be evaluated with existing data. Survey catchability can generally be thought of as the ratio between the observed (with appropriate area swept factors included) and actual biomass, and in stock assessment models is commonly evaluated at the scale of the entire population. At the scale of the individual tows, catchability is the ratio of observed cpue and local population density in the path of the tow and is affected by vertical and horizontal herding. Thus, allowing survey catchability to vary between tows may produce improved statistical fits to the survey estimates.

The purpose of this manuscript is to estimate survey catchability under a variety of assumptions and evaluate the effect upon estimated spawning stock biomass and harvest recommendations. The standard age-structured stock assessment model for EBS yellowfin sole was used for this example application. Survey catchability was estimated with three methods: 1) estimated constant catchability across all years; 2) estimated catchability varies between years as function of annual average temperature, but is constant between tows within a single year (“global” catchability); and 3) estimated catchability is varies between tows as function of temperature (“local” catchability). Finally, a management strategy evaluation (MSE) is used to evaluate the potential management implications of trends in temperature-dependent survey catchability.

Methods

EBS groundfish are sampled annually with the EBS bottom trawl survey, which has used a consistent sampling gear and survey design since 1982. The survey is conducted during the summer months at approximately 356 stations location on a 20 nm × 20 nm grid. Each survey station is sampled for 30 minutes at 3 knots and catch-per-unit-effort (cpue) is recorded as kilograms per square kilometer (Acuna and Kotwicki, 2006).

The current Bering Sea/Aleutian Islands yellowfin sole assessment model (Wilderbuer and Nichol, 2006) was modified to allow estimation of catchability with the three different methods. The assessment is a standard separable catch-at-age model with annual estimates of fishery catch, fishery and survey age composition, and survey biomass used as input data. Model parameters are statistically fit by comparing predicted quantities to observed quantities via maximum likelihood estimation given distributional assumptions of the observed data.

Survey catchability (q) can be generally defined as a scalar that relates “true” stock abundance to estimated stock abundance

$$B_y = q\hat{B}_y e^{\varepsilon_y}, \quad \varepsilon_y \sim N(0, \sigma_y^2) \quad (1)$$

where \hat{B}_y is the estimated value of biomass in year y from a stock assessment model and B_y is the observed survey biomass value assumed to be lognormally distributed with sampling variance equal to σ_y^2 . Because the survey estimate of biomass is a weighted sum of a series of tows, survey catchability can also be defined for an individual trawl as the scalar relating true density in the path of the trawl to observed catch-per-unit-effort (cpue).

Three methods were used to estimate yellowfin sole survey q . First, a constant q across all survey years was estimated from Eq. 1. Second, estimates of survey catchability that vary between years as a function of temperature, $q_y = f(T_y)$, was estimated from

$$B_y = q_y \hat{B}_y e^{\varepsilon_y} \quad (2)$$

where

$$q_y \equiv f(T_y) = e^{\alpha + \beta \gamma_y - \frac{\beta^2 \sigma_y^2}{2}}, \gamma_y = T_y - \bar{T} \quad (3)$$

and γ is the temperature anomaly in year y . Temperature anomalies were used to ensure that the expected value of q_y is e^α , which can be fixed to particular value in cases where it is not estimable.

If survey catchability varies as a function of temperature due to gear efficiency, then catchability would be expected to vary according to temperature at each survey station. A “local” catchability at each tow in a given year ($q_{y,tow}$) relates stock density ($D_{y,tow}$) to observed catch per-unit-effort (cpue), and the observed cpue can be divided by $q_{y,tow}$ to produce estimates of stock density at each tow.

$$\frac{CPUE_{y,tow}}{q_{y,tow}} = D_{y,tow} e^{\delta_{y,tow}} \quad (4)$$

where

$$q_{y,tow} \equiv g(T_{y,tow}) = e^{\eta + \lambda T_{y,tow}} \quad (5)$$

and $\delta_{y,tow}$ is random error and $T_{y,tow}$ is the temperature in year y at a specific tow. The steps for this procedure are:

- reading the original cpue data and stratum areas into the assessment model;
- computing an adjusted cpue dataset based on trial estimates of η and λ ;
- computing adjusted survey biomass estimates (expanded for stratum areas) and standard error for each year;
- computing the likelihood values using adjusted estimates from 3); and
- iterating steps 2)–4) until all assessment model parameters are estimated (maximizing the total likelihood).

The management implications of estimating temperature-dependent catchability were evaluated by comparing harvest recommendations (the “allowable biological catch”, or ABC) and end-year stock biomass between the three methods. In the North Pacific Fisheries Management Council (NPFMC) system, the ABC represents a target catch level based upon a fishing mortality control rule in which fishing mortality is $F_{40\%}$ for stocks with spawning stock biomass (SSB) larger than $SSB_{40\%}$, and less than $F_{40\%}$ for stocks smaller than this threshold (Figure 1). Markov-chain Monte Carlo (MCMC) simulations were used to develop posterior distributions of ABC and end-year estimates of SSB. Also, since the increasing temperature trend from 1999 to 2005 was followed by a sharp decline in 2006 a separate sensitivity analysis was conducted with data through 2005 only.

A management strategy evaluation was used to assess how trends in temperature-dependent catchability could affect quota recommendations (Figure 2). An MSE generally refers to a simulation model incorporating the feedback between the “true” population (arising from an operating model), errors in estimation in stock status given sampling of data (the estimation model), and recommended catch based upon estimated stock status (i.e., harvest control rules; Smith, 1994). In this application the “observed” survey biomass levels are derived from the operating model (subject to previous years fisheries removals) as affected by “true” temperature-dependent catchabilities. Thus, errors in biomass estimates and harvest recommendations may compound over time. The operating model is specified with recruitment variability, growth, natural mortality, fishery and survey selectivity and other assessment parameters as estimated for yellowfin sole. Other data simulated from the operating model included survey and fishery age composition information. The period of simulations was 40 years with four alternating, increasing and decreasing ten-year trends in temperature (Figure 3). Temperature-dependent survey catchability was modeled with the global catchability model (Eq. 3), and parameter values were chosen such that catchability ranged from 0.85 to 1.21. The

current yellowfin sole assessment model (Wilderbuer and Nichol, 2006) was used as the estimation model, and the NPFMC F_{abc} control rule was used to set recommended fishing mortality (Figure 1). The F_{abc} was used to produce a recommended catch based upon fishing selectivity and estimated stock size by age, and this catch is removed from the “true” population for each yearly increment from each simulation.

The MSE consisted of 50 simulations in which a global temperature-dependent catchability (Eq. 3) was estimated in each assessment year was conducted, as well as a separate set of 50 simulations in which constant catchability was estimated. Each simulation trajectory had an identical pre-assessment period in years 1–20 with assessments conducted from years 20 to 40; this meant that a single simulation was completed after 21 “assessments” were done (2100 “assessments” for the entire MSE). Simple statistics on catch were tallied and estimation performance between assessment approaches relative to the true biomass was assessed.

Results

Application of BSAI yellowfin sole data

In the models fit to data through 2005, the fit to survey biomass is improved when temperature-dependent catchability is estimated (Figure 4). The global catchability and local catchability models produced negative log-likelihoods of 1309.55 and 1318.94, respectively. These statistical fits represented significant improvements over the negative log-likelihood obtained with the constant catchability model (1339.02), although the local catchability model did not improve the fit over the global catchability model. The estimate of constant survey catchability is 1.17 and fits a smooth line to the observed survey biomass, but with high variance in the residuals. The residual pattern indicates trends of declining survey biomass estimates during the early portion of the time-series (1983–1986) and increasing survey biomass estimates in recent years (1999–2005). Fitting the global temperature-dependent catchability produced survey biomass estimates that more closely matched the observed data, with declining survey biomass estimates from 1983–1986 and increasing estimates from 1999–2005. Fitting the local temperature-dependent catchability adjusts the original cpue data and shifted the observed estimates downward, reflecting catchability values > 1 , and the revised survey estimates showed a smoother trend; in particular, the increasing trend from 1999–2005 is less pronounced.

Both the global and local methods of estimating temperature-dependent catchability show slightly increasing catchability with temperature (Figure 5). Under the global catchability method, the expected value of catchability at a temperature anomaly of zero is 1.21. The habitats occupied by yellowfin sole generally shows a temperature range of 1° to 5° C, and the estimated local catchability for these values ranges from 0.95 to 1.51.

The average catchability estimates for the global and local catchability models are 1.22 and 1.20, respectively (Figure 6), similar to the estimate of 1.17 obtained under the constant catchability model. For the local catchability model, an estimate of annual catchability was obtained by dividing the observed survey biomass estimate by the adjusted survey biomass estimate. The global and local catchability models each produce a similar temporal pattern in catchability, with the global estimates being slightly less variable. Also, the temporal trends in catchability correspond to the trends in annual EBS temperatures. For example, the increasing temperatures from 1999 to 2005 is matched by increasing estimates of catchability, indicating the assessment model is interpreting the increased survey biomass estimates during this period as partly a function of increasing catchability. This can also be seen in the estimates of adjusted survey biomass; for the constant and global catchability models, this is the observed survey biomass estimate divided by the annual catchability estimate. The adjusted survey biomass estimates for the global and local catchability models is generally flat from 1999 to 2003, only increasing in 2004 and 2005 (Figure 7).

Temperature decreased sharply from 2005 to 2006, thus ending the trend of increasing temperatures since 1999, and this had the effect reducing the difference between the end-year biomass estimates between the three methods. For models run through 2005, the estimated

2005 SSB declined from 548 kt with the constant catchability model to 514 kt with the global catchability (a 6% decrease); the local catchability model was intermediate with 529 kt (a 3% decrease; Figure 8). For models run through 2006, the 2006 SSB estimate for the constant and local catchability models were 552 kt and 549 kt, respectively, and the estimate from the global catchability model was 536 kt (a 3% decline from the constant catchability model). A similar pattern occurred with the recommended harvest; in 2005, the recommended harvest from the global and local catchability models were 7 % and 4% less than the recommended harvest from the constant catchability model, respectively, and in 2006, the declines in recommended harvest for the global and local catchability models were reduced to 3% and <1% of the constant catchability model, respectively (Table 1).

The coefficients of variation (CV) of the adjusted survey biomass estimates under the local catchability model were generally lower than those from the original survey estimates (Table 2). Increased CVs in the local catchability model only occurred in 6 of the 24 years, in each case less than 5%. In contrast, decreased survey biomass estimates occurred in the remaining 18 years, with 6 years showing decreases > 5%.

Management strategy evaluation of the effect of trends in temperature

Management strategy evaluations indicate that for the case where catchability is positively related to temperature, trends in temperature would result in the constant catchability assessment model underestimating biomass during cold periods and overestimating biomass during warm periods (Figure 9a). For example, the initial estimate of total biomass in year 20 underestimates the true biomass by 21%. This is because the model interprets a declining trend in survey biomass estimates to be reflective to true biomass, and the underestimate increases to 25% in year 23. An increasing trend in temperature and catchability results in estimated biomass increasing at a faster rate than true biomass and the maximum overestimate of biomass of 13% occurs in year 34.

In contrast, estimating temperature-dependent catchability in the assessment model results in more accurate estimates of stock size (Fig 9b). The initial estimate of biomass in year 20 is still underestimated, but only by 11%, and by year 25 the estimated biomass estimates track the true biomass levels fairly closely. The ratio of estimated biomass to true biomass for each assessment model is shown in Fig 9c.

Because errors in estimation of biomass affect recommended catches, the time-series of true biomass obtained from each of the assessment models differs (Figure 10). The underestimation of biomass during cold periods results in lower catches, which allows the stock to attain higher levels of biomass in subsequent years relative to the assessment model where temperature-dependent catchability is estimated. In contrast, the overestimates of biomass during warm years leads to higher catches, which reduce the stock biomass at relatively faster rate. On a proportional basis, the relative change in future stock biomass levels from the two assessment models is not as large as the change in catch. The maximum difference in biomass between occurred at year 30, where the constant catchability model resulted in a biomass 3.8% percent larger than that resulting from a temperature-dependent catchability model. In contrast, the catch resulting from the constant catchability model in year 22 was 19% less than catch resulting from the temperature-dependent catchability model, and catch in year 34 was 14% larger. Over assessment years 20 to 40, the CV of catch resulting from the constant catchability model was 20% as compared to 11% with the temperature-dependent catchability model.

Discussion

The two methods of fitting temperature-dependent catchability each showed similar temporal patterns of survey catchability for yellowfin sole, with the estimated catchability closely matching the observed temperature trends. For yellowfin sole, temperature dependent catchability is consistent with current knowledge on availability of spawners to the survey area and the potential effect of temperature on fish herding to the trawl. Further insights on the relative importance of these two factors will require additional field research documenting: 1) how distribution of yellowfin sole between spawning areas and survey area may differ with

temperature; and 2) how gear efficiency may change with temperature. Information on the distribution in spawning areas may be gained from fisheries data and will be pursued in future work, although periodic closures of the fishery due to Pacific halibut bycatch constraints may limit the data available. The current procedure in the assessment model of adjusting survey catchability as a function of temperature significantly improves the statistical fit to the data, and estimated within the assessment model so that adjustments to catchability is consistent with uncertainties associated with all other data sources for the stock.

It is notable that both methods of estimating temperature-dependent catchability produce a significantly improved fit to the data relative to a constant catchability model, but the local catchability model did not provide an improved fit over a global catchability model. This can be interpreted as showing an effect of year on temperature-dependent catchability, but not a spatial effect that would differ between trawl stations. Because yellowfin sole typically choose to occupy some range of preferred temperatures of about 1° to 5° C, the variability of annual EBS temperatures over the entire survey area is typically greater than the variability of temperatures between stations occupied by yellowfin sole in a given year. Thus, differences in catchability between trawl stations may be more subtle and difficult to detect in the presence of random observation errors. In addition, the potential for estimating differences in temperature-dependent catchability between stations is most enhanced when survey catchability is solely a function of temperature-dependent gear efficiency, but some portion of the catchability is likely due to changes in availability as well.

Either method of adjusting catchability for temperature essentially reduces the variance of the observed survey estimates by accounting for some portion of the survey biomass estimates that would otherwise be attributable to random error. Under the local catchability model, the relative reduction in the CVs of adjusted survey estimates from the original survey estimates was fairly large, but because the original CVs were small (< 0.1) the absolute reduction in CVs were small. Thus, there was not an appreciable reduction in the variance of estimates of biomass or harvest recommendations. One would expect that in situations where the absolute reduction in survey biomass CV was larger to result in more precise estimates of population biomass, and one could evaluate this with further simulations.

Temperature-dependent survey catchability can affect management advice either through spurious trends in survey estimates or increased variance of population biomass and harvest recommendations. In the latter case, if a spurious trend in survey biomass does not exist but variability is increased due to temperature-dependent catchability, the resulting point estimates of population biomass and harvest reference points may remain unchanged after correcting for temperature-dependent catchability but the precision may increase. This could affect harvest recommendations in management systems where recommended harvest decreases with the uncertainty in harvest reference points. For example, for “Tier 1” stocks in the north Pacific, the recommended harvest decreases with as uncertainty in F_{msy} increases. In future work, simulating temperature variability with a white noise process (i.e., random, uncorrelated errors) should help characterize the management implications of improved precision of biomass and harvest reference points.

The results from the MSE simulations are intuitive, and indicate that with unrecognized trends in survey catchability one would expect to either overestimate or underestimate the stock size, with resulting errors in harvest recommendations producing increased variance in catch. The alternating pattern of 10-year temperature trends was chosen to most clearly illustrate the effect of temperature trends, and the EBS is currently believed to be experiencing a general warming trend. In future research, several additional models can be taken to evaluate more realistic scenarios. First, a spatial model of fish density across sampling units should be developed in order to evaluate the relative interaction of availability and gear efficiency, and to model the change in survey biomass CV resulting from adjusting individual cpue data by temperature-dependent catchability. Second, more realistic temperature scenarios will be explored, including white noise without trend (as mentioned above) and autocorrelated red noise patterns.

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Table 1. Effect on recommended harvest for the three assessment models applied to yellowfin sole, with data through 2005 and 2006.

ASSESSMENT	ASSESSMENT	HARVEST	PERCENT CHANGE
YEAR	MODEL	RECOMMENDATION (KT)	FROM CONSTANT CATCHABILITY MODEL
2005	Constant catchability	132.16	0.00%
2005	Global catchability	122.53	-7.29%
2005	Local Catchability	126.68	-4.15%
2006	Constant catchability	133.72	0.00%
2006	Global catchability	129.61	-3.08%
2006	Local Catchability	132.99	-0.55%

Table 2. Coefficient of variation of original survey biomass estimates and the adjusted survey biomass estimates obtained from the local catchability model.

	OBSERVED	ADJUSTED	PERCENT
Year	CV	CV	change
1982	0.086	0.076	-11.45%
1983	0.060	0.059	-0.12%
1984	0.059	0.060	0.17%
1985	0.065	0.064	-2.62%
1986	0.080	0.066	-18.34%
1987	0.077	0.077	0.21%
1988	0.088	0.092	4.62%
1989	0.075	0.069	-8.16%
1990	0.069	0.070	0.81%
1991	0.058	0.058	-0.31%
1992	0.086	0.083	-3.35%
1993	0.064	0.063	-1.59%
1994	0.066	0.062	-6.13%
1995	0.071	0.068	-4.52%
1996	0.086	0.073	-14.49%
1997	0.060	0.059	-1.49%
1998	0.064	0.061	-4.92%
1999	0.072	0.073	1.48%
2000	0.064	0.062	-2.74%
2001	0.070	0.065	-6.33%
2002	0.069	0.069	-0.60%
2003	0.093	0.089	-4.34%
2004	0.076	0.077	0.51%
2005	0.129	0.110	-14.81%

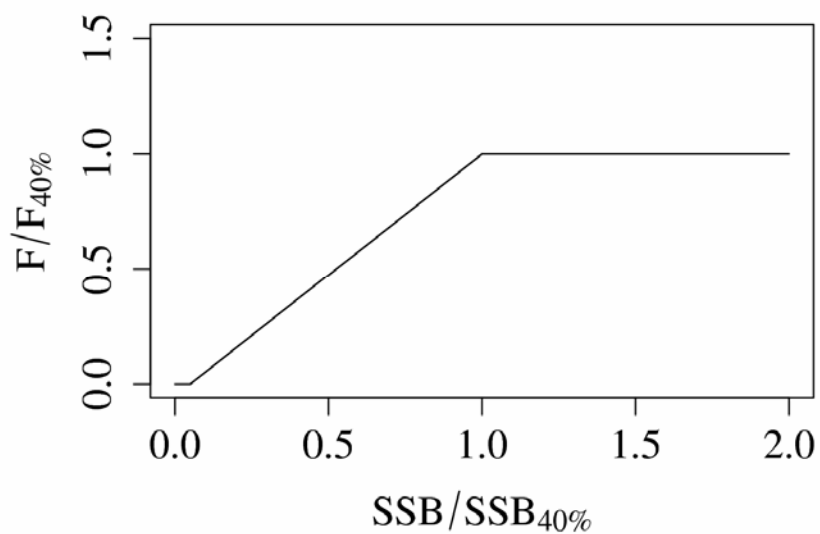


Figure 1. The harvest control rule used by the NPFMC for determining F_{abc} for stocks in which a fishing mortality reference points are based upon $F_{xx\%}$ proxies.

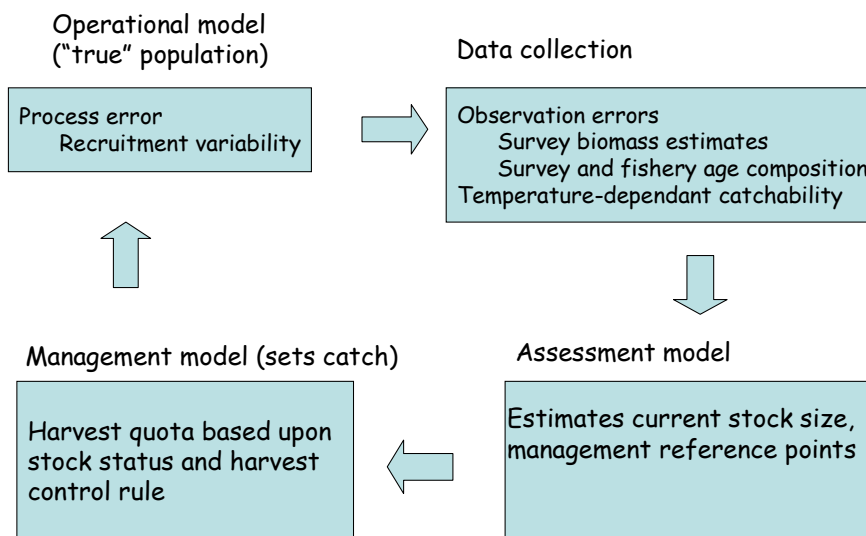


Figure 2. Flowchart of management strategy evaluation simulation model used for assessing the management implications of temperature-dependent catchability.

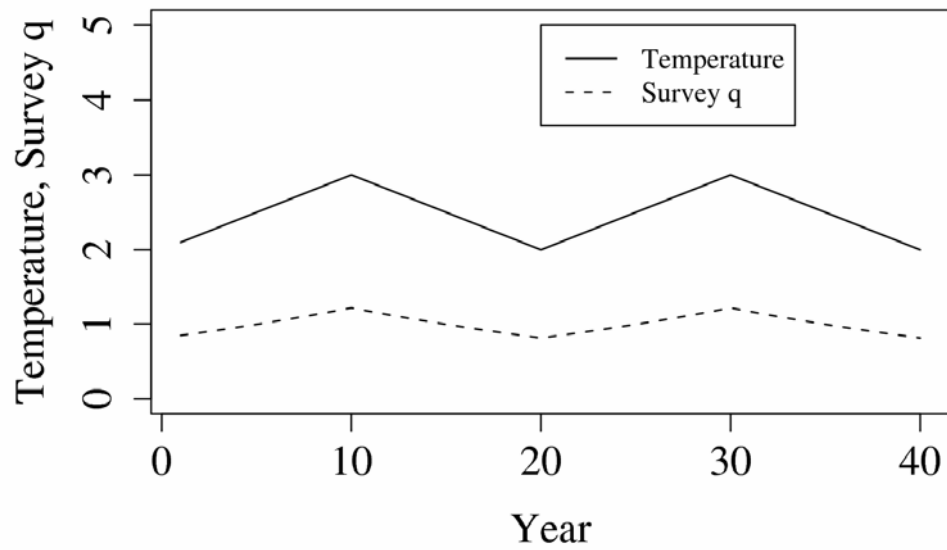


Figure 3. Simulated temperature and survey catchability used in the management strategy evaluation model.

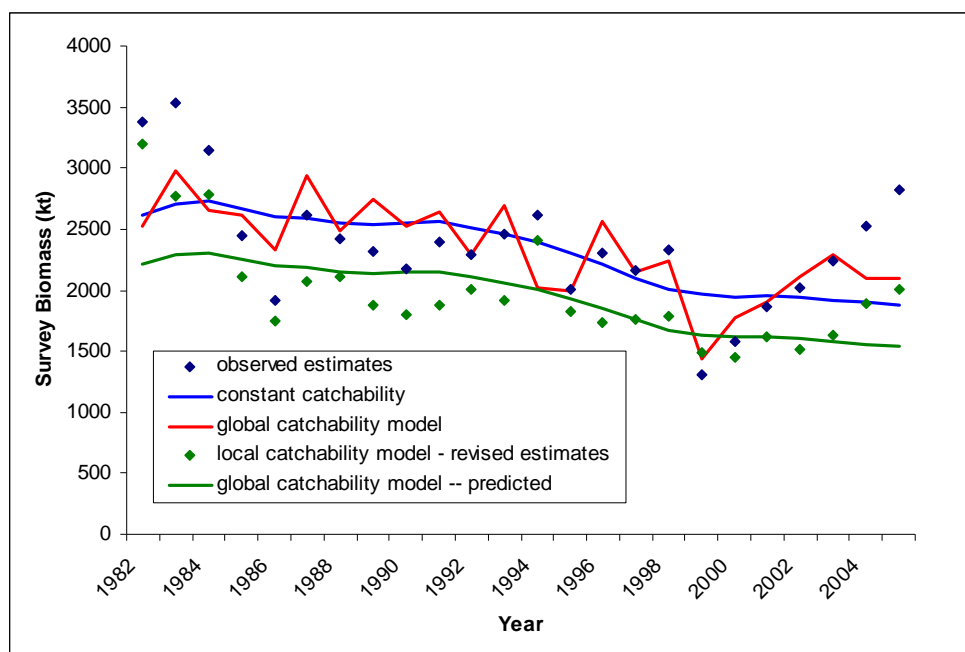


Figure 4. Fit of predicted survey biomass for constant catchability, global catchability, and local catchability assessment models.

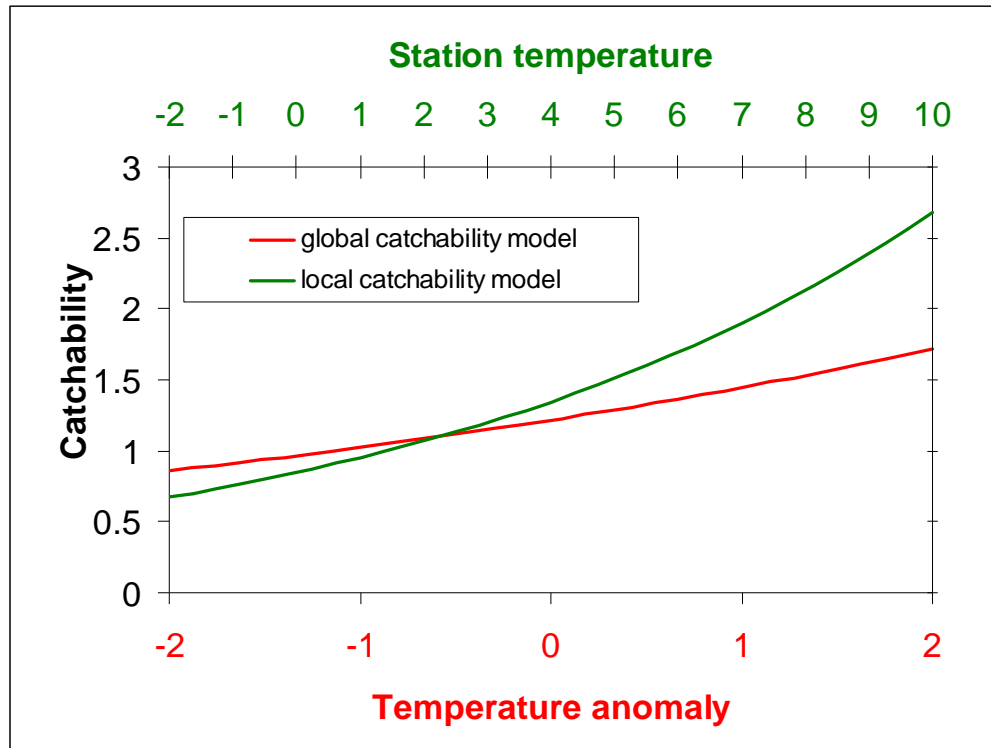


Figure 5. Functional relationship between temperature and catchability for the global catchability and local catchability assessment models.

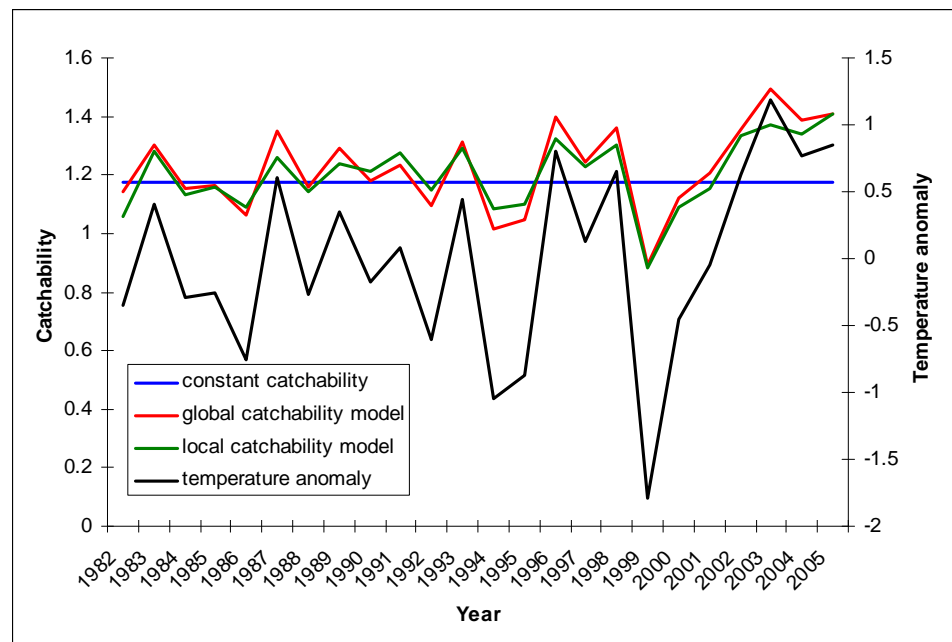


Figure 6. Estimated annual survey catchability for the constant catchability, global catchability, and local catchability assessment models.

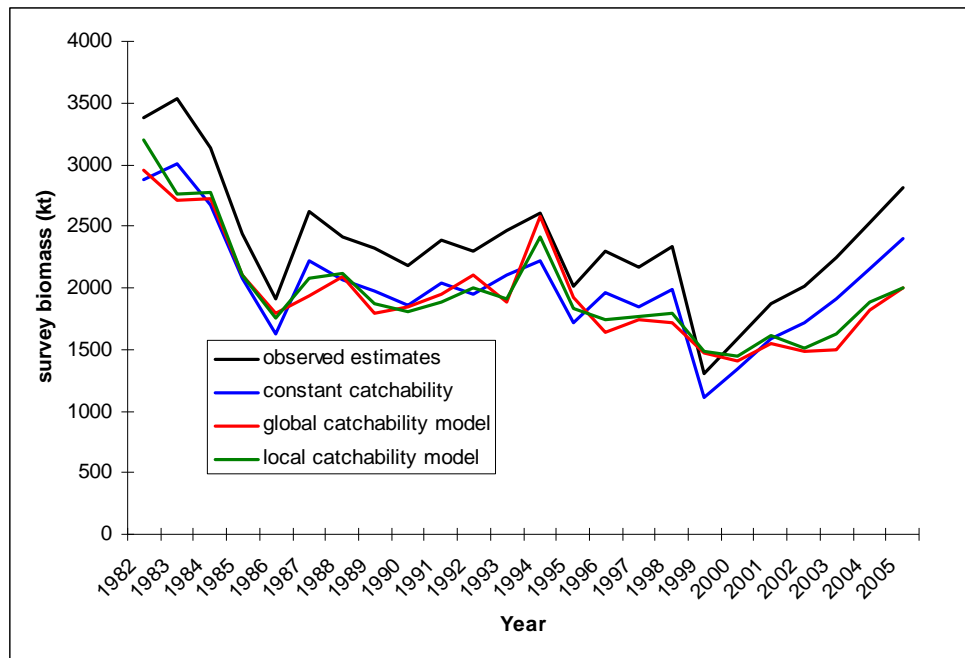


Figure 7. Adjusted survey biomass (obtained from dividing the original survey biomass by estimated survey catchability for each year) for the constant catchability, global catchability, and local catchability assessment models.

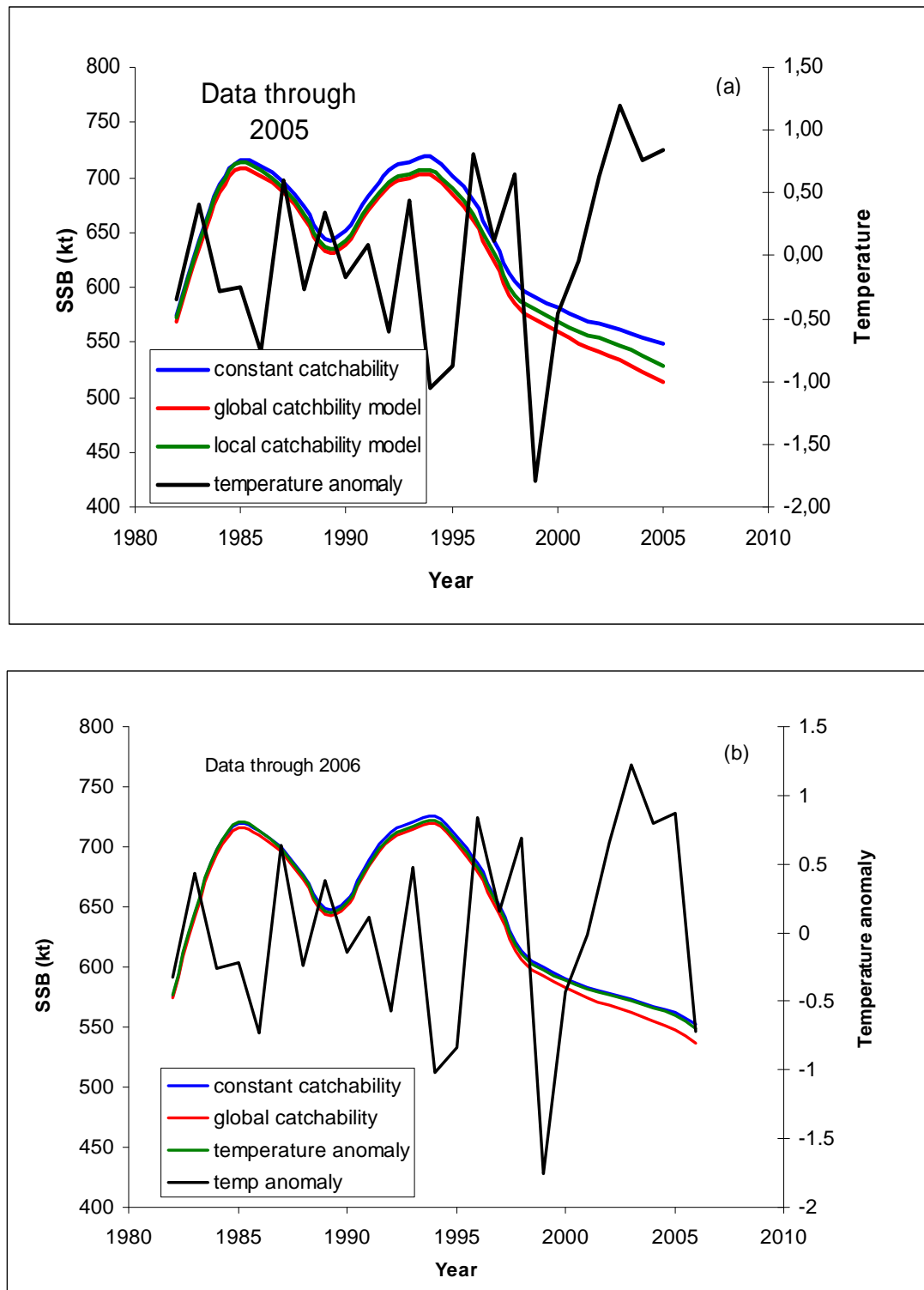


Figure 8. Estimation of spawning stock biomass the three assessment models with data through 2005 (top panel) and 2006 (bottom panel).

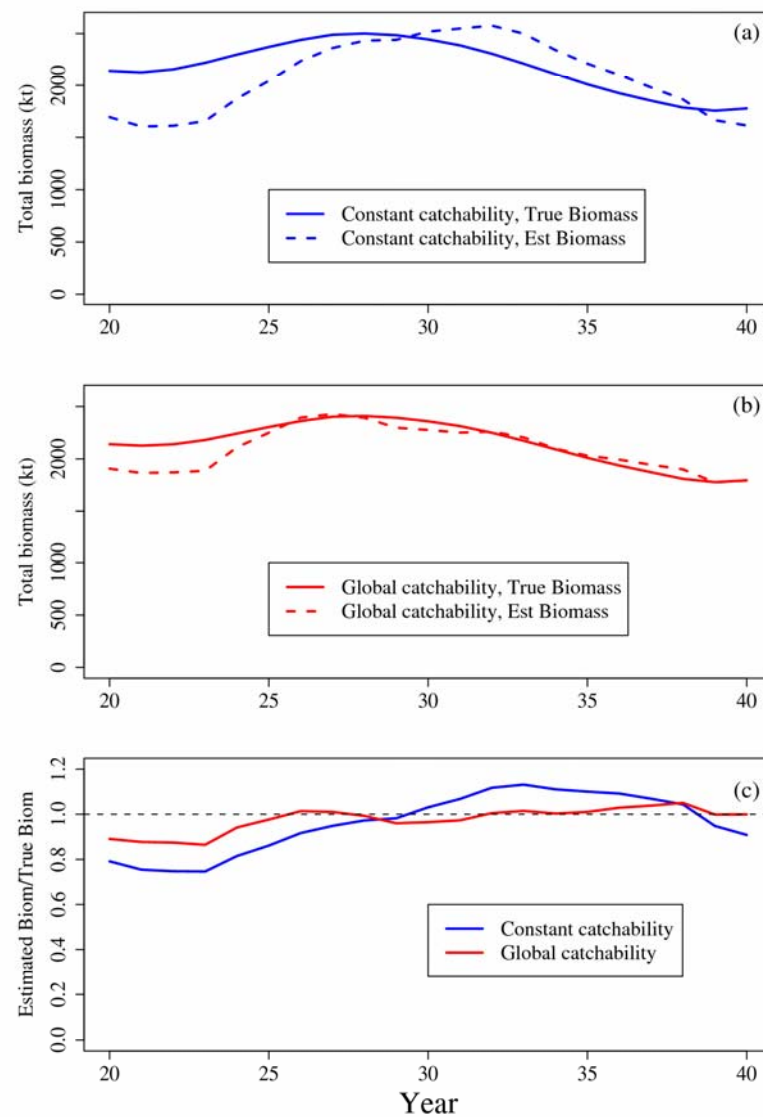


Figure 9. Mean true and estimated biomass for two assessment models used in the management strategy evaluation.

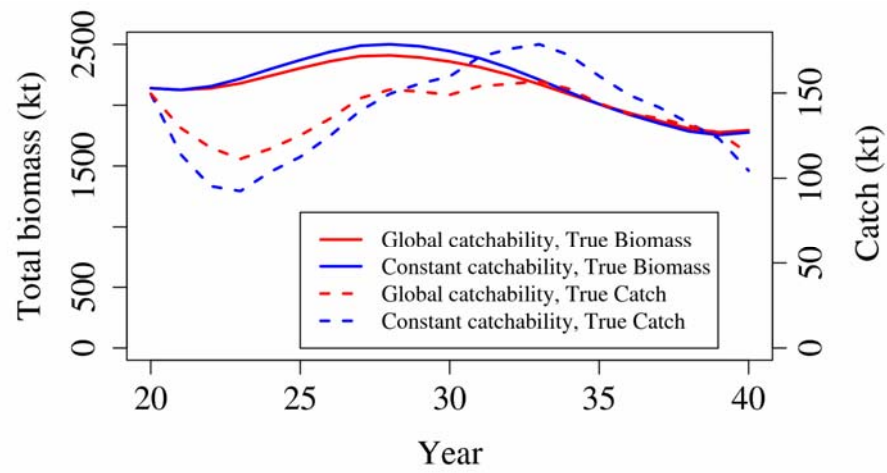


Figure 10. Mean true biomass and catch for two assessment models used in the management strategy evaluation.

Annex 6: The effect of environmental changes in the Galician sardine fishery

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Abstract

The highest catches of the Iberian sardine stock are taken from the southern part of Galician waters (NW corner of the Iberian Peninsula) and northern Portugal. Landings are mainly composed of younger fish, which reflects the proximity of the main recruitment area to the fishery grounds.

Since 1978 there has been an improvement in the knowledge of the biology and stock dynamics of sardine around the Atlantic Iberian waters. In the last decade a consecutive years with poor recruitments result in a depletion of stock below limits previously recorded. The recruitment processes seem to be driven by oceanographic (local) and climatic (global) events, this dependence on both phenomena may explain the fluctuations on the landings in the sardine fisheries in Atlantic Iberian waters.

Given the dependence of the fishery in this area on the strength of the recruitment, different relationship between biotic components (spawning stock size, recruitment, landings and recruitment landings) and abiotic: climatic indices (NAO-winter, Gulf Stream and AMO) and local oceanographic coastal events (upwelling and poleward current) were analysed.

In the analysis of the abiotic series in the period (1978–2005), there appears to be a shift in the general trend in 1995. In addition at the end of the nineties several consecutive years with poor recruitment result in a depletion of the stock below limits previously recorded as well as changes in the distribution area. Before the shift was observed the recruitment variability could be explain by the environmental variables, but since then the correlation is poor.

INTRODUCTION

Iberian sardine, as with most of the clupeoid fish species, occurs in highly dynamic areas in which turbulence regimes are predominant. Turbulence is important because it acts on the advection/retention larval mechanisms and larval-prey encounter rate that ultimately affects recruitment success and eventually the fishery (Cole and McGlade, 1998; Lasker, 1975; Cury and Roy, 1989; Bakun, 1996; MacKenzie, 2000). The occurrence of synchronous events, i.e. either depletion or increase in clupeoids fish species such as anchovies or sardines, over large geographically separated areas has been widely reported, which suggest large-scale climate forcing (Lluch-Belda *et al.*, 1989; Swartzlose *et al.*, 1999). In addition to large-scale forcing, there might be local events such as coastal upwelling or low-range thermohaline currents which can largely contribute to recruitment variability.

The highest catches of the Iberian sardine stock (*Sardina pilchardus*, Walb) are taken from the southern part of Galician waters (NW corner of the Iberian Peninsula) and northern Portugal (Fig. 1). Actual knowledge of this stock states that the bulk of the recruitment at age 0 occurs off the northern coast of Portugal (Anon, 2000; Porteiro and Pestana, 1997) from June-October while the spawning period is October-May (Re *et al.*, 1990; Solá *et al.*, 1990). Spawning occurs in two main areas, off the Atlantic coast of Portugal with a marked peak in winter and in the Cantabrian Sea which peaks in spring. Although Galician waters are outside these main spawning areas and only the southern part of this region is in the vicinity of the main recruitment area, sardine landings in Galicia are important, especially in the middle of the year, suggesting a feeding movement or migration (Carrera and Porteiro, 2002). According to Porteiro *et al.* (1986) there is an age gradient pattern from the Spanish/Portuguese border where most of the fish are younger to the Cantabrian Sea where the bulk of the population are older. This and the lack of juvenile fish in the Cantabrian Sea were also observed in earlier investigations (Fernández and Navarro, 1952).

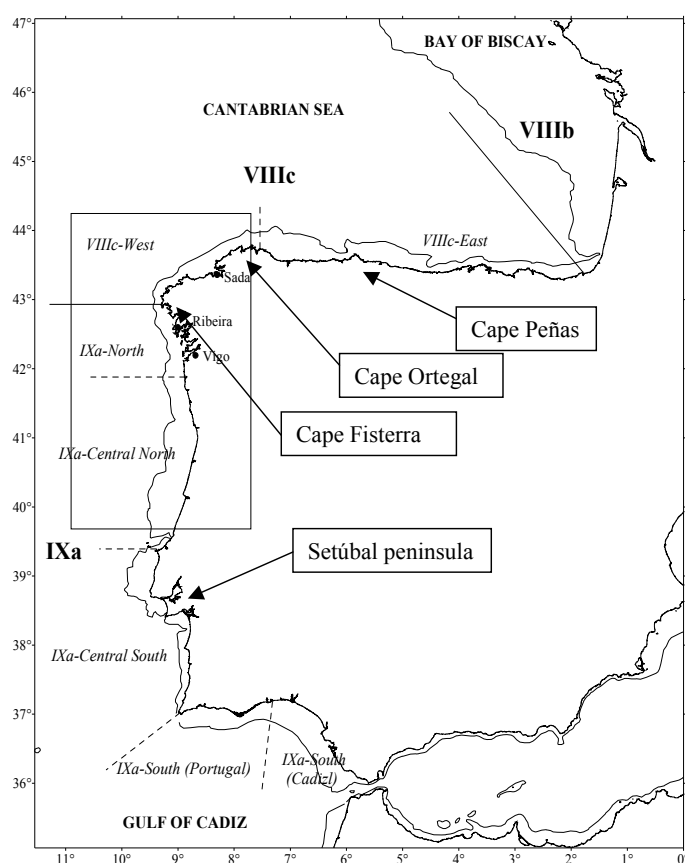


Figure 1: Iberian Peninsula showing the ICES Sub-Division and the sardine main fishery ground surrounded by a box. South Galicia is in IXa North area.

The sardine fishery off south Galicia distinguishes two different market categories. One of the categories is composed by younger fish, termed *xouba*. It achieves high price and mainly occurs between the end of spring and beginning fall, the other category is the adult sardine, mainly <21 cm length (i.e. younger than 4 years). *Xouba* category in south Galicia (i.e. 0 and 1 year classes) represents up to 48% of the total landings in numbers averaged for the period 1978–99. In some years their contribution reaches up to 93% of the total number of fish caught. However, there were also periods of low contribution, especially 1985 in which younger fish only represented 5% of the total. The variation in the relative contribution of this fish category seems to be affected by the strength of the incoming year class. The main fishery occurs in or close to the recruitment areas and the time-series of landings by areas shows important fluctuations. In addition, since 1985 there is a declining trend in the catches in both North Portugal and South Galicia (especially in the latter), achieving the lowest yield of the time-series in the most recent years.

Off the Galician coast, two different wind regimes occur: winter (October-March) and summer (April-September). The winter regime is dominated by southwesterly winds and the summer regime by northwesterly winds. The winter winds contribute to develop a poleward current along the inner shelf. (Frouin *et al.*, 1990). This current with higher salinity and warmer water but relative poor nutrient contents is located at some distance from the coast, due to the inertial and centrifugal forces and by the presence of the Setúbal peninsula. Close to Finisterre Cape this current is located close to the coast and being further deflected by Cape Ortegal when progressing through the Cantabrian Sea, but it turns close to the coast again after Cape Peñas. In the area between Cape Finisterre and Cape Peñas, an inner shore counter-current movement is thus created, which may function as a retention area for eggs, larvae and early juveniles. When south/south-westerly winds are more intense, this poleward current may prolong itself

onto the Cantabrian Sea, close to the coast, and may reach even the French shelf. Under a situation of dominant north-quadrant winds (i.e. the typical summer situation), the whole west coast is dominated by upwelling events (Wooster *et al.*, 1976; Blanton *et al.*, 1984). The poleward current disappears, and it is replaced by an equatorward current close to the shore. The equatorward current starts from the area of Cape Peñas, and moves through Cape Finisterre and along the Portuguese west coast. This current is deflected by Cape Peñas, Cape Ortegal and Cape Finisterre, creating counter-currents downstream, which could act as retention areas.

Distribution area

The Iberian sardine is distributed along the whole continental platform of the Iberian Peninsula. It is mostly distributed close to the coast, not exceeding the depths of 200 m. The juveniles are generally separated from the adults, closer inshore, and associated to the river mouths and the “Rias”.

Spawning areas and seasons

The sardine has three main spawning areas: One in North-Western Portugal, a second in the South Coast of Portugal-Gulf of Cadiz, and another in the Cantabrian Sea.

Spawning season is spread from the start of autumn to the end of summer. The peak spawning is different in the three areas:

Cantabrian Sea: April-May;

Portuguese West Coast: January;

Portuguese South Coast-Gulf of Cadiz: December-January;

Distribution and migration of juveniles and adults

In winter, the eggs laid along the Portuguese coast are transported Northwards in the South-North circulation which is present in the winter period.

In spring, eggs and larvae from the Cantabrian Sea are transported by the currents to the West, to the area of Galicia. In the area there is a more or less permanent gyre, which functions as a retention mechanism for the eggs and larvae in the area. In years when there is a strong upwelling in this area, the eggs and larvae will be transported offshore, and lost to the system. In the years when there is a circulation North-South, the larvae are carried along to the West coast area, rich by the upwelling. When this circulation does not exist, there is instead a global South-North circulation, leading to loss of the larvae/juveniles from the coastal system.

The juveniles concentrate themselves in the area of the “Rias Baixas” from May to September. They also concentrate themselves in sheltered places along the Portuguese coast. By the end of the year (November-December) the juveniles are also spread all along the Portuguese coast.

All conditions which lead to enrichment of the coastal area, and retention of the larvae/juveniles in this area, will contribute to the success of recruitment.

In years when there is important abundance in the Cantabrian Sea, the Cantabrian is dominated by the adults. It has been observed that the age composition is shifted towards older ages as one moves from the South to the North. In “normal” years, the fish along the Portuguese coast include in general fish up to 6 years old, while the sardine in the Cantabrian Sea are mostly older fish, up to age 12.

In these same years, the South coast area was dominated especially by small sardines,

Food and feeding of the different life stages

Sardine are filter-feeders (passive filter-feeders). The evidence presently available indicates that they are opportunistic feeders, and will eat both phytoplankton (with a preference or

exclusivity on diatoms) and zooplankton. There have been some years when the condition factor of sardine was significantly lower than in the other years.

Link to environmental conditions

The link between climate, oceanography, the structure of the ecosystem and pelagic fish in the N Atlantic Iberian waters can be formulated as a conceptual model in which alternative modes of the climatic system lead to divergent oceanographic conditions and in turn to the dominance of alternative plankton and fish species.

On one side, dominance of boreal climatic modes, as those indicated by positive NAO and the influence of northern winds and pressure anomalies is associated to increased turbulence in the surface ocean, relatively low water temperature and high average upwelling intensity. Such conditions favour phytoplankton productivity during upwelling-induced blooms and small copepod species (e.g. *Acartia*) that are able to track the food increase at short time-scales. In turn, the abundance of small copepods and phytoplankton can be used efficiently by sardines through filter-feeding.

On the other side, a growing influence of subtropical climatic components, as indicated by EA, would increase water surface temperature and the stratification of the surface layer, while average upwelling intensity and frequency decrease. Phytoplankton productivity would decrease because of the reduced nutrient inputs, but changes in the dominance of species (i.e. dinoflagellates versus diatoms) or local blooms caused by changes in currents may lead to increases in biomass (Richardson and Schoeman, 2004).

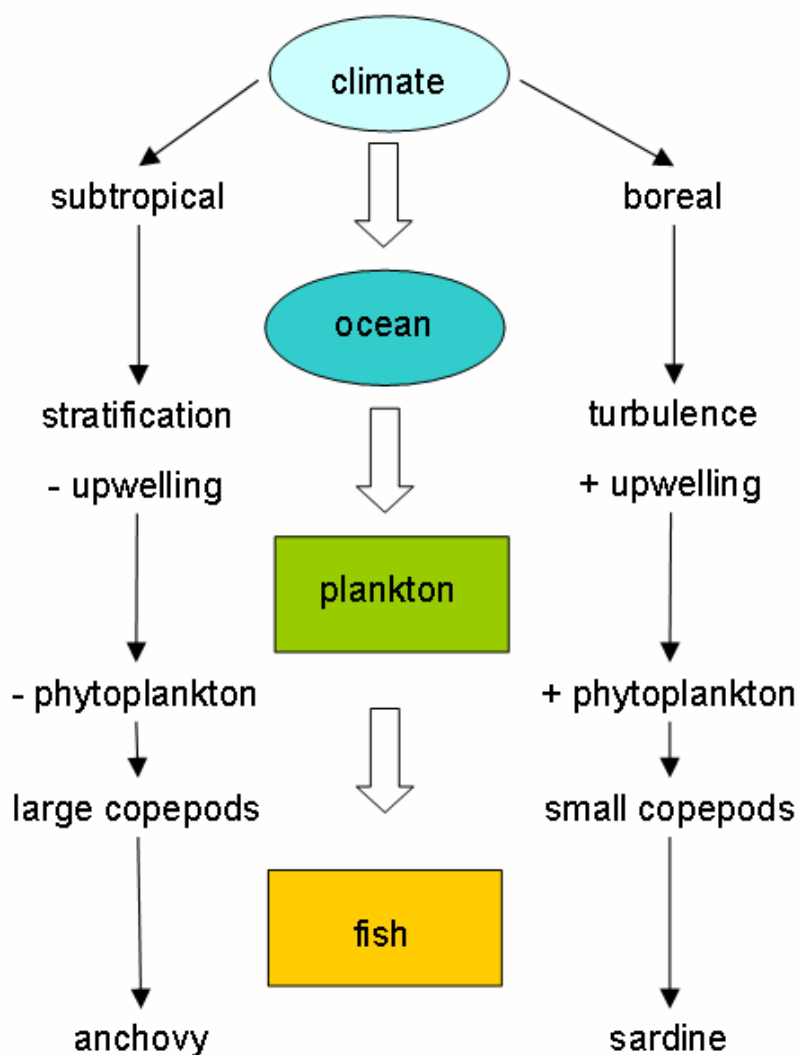


Fig. 2. Conceptual model in which alternative modes of the climatic system From: ICES/GLOBEC Workshop on Long-term variability in SW Europe. Lisbon, 12–16 Feb. 2007.

The reduced upwelling would be a positive factor for anchovy recruitment and large copepods which are able to feed on relatively large phytoplankton, as some dinoflagellates. Also, adult anchovies would find food of appropriate size for sustaining the population and producing large reproductive outputs.

The conceptual model describes the average multiannual dynamics in the main climatic, oceanographic and ecological features in the study region. Also, the terms reduced upwelling or increased stratification must be taken in relative value, as upwelling events never ceased completely in the region.

Regime shifts. The underlying causes of the described variability may also change during the observational period. This is suggested by the match and mismatch of positive and negative anomaly periods when comparing indices. Sudden changes in most series are generally associated to shifts in the oceanographic and ecosystem regimes (e.g. De Young *et al.*, 2004). Similar shifts were recognized in most upwelling regions (Borges *et al.*, 2003, Chavez *et al.*, 2003, Alheit and Ñiquen, 2004, Cury and Shannon, 2004). Large changes in climate related to El Niño-Southern Oscillation (ENSO) were often claimed as one of the major underlying causes of ecosystem shift, mainly in the Pacific (e.g. Chavez *et al.*, 2003) but it also can affect other oceans because of climatic teleconnections (Barnston and Lievezey, 1987). Major changes in the ecosystems of the NE Atlantic have been described for the period between late 1970s and 1990, but the exact timing of the shift varied among the target variables (Beaugrand,

2004, Edwards and Richardson, 2004, Richardson and Schoeman, 2004). Climate effects, as the change in wind speed and direction in the late 1970s, may need a different time to integrate as a clear response in some biological compartments. In this regard, plankton and short-living pelagic fish are among the first to show alterations, but the ability to identify the timing is also dependent of the statistics employed (Beaugrand, 2004). The shift in the late 1970s identified in this study is coincident with a major ENSO-related shift in the Pacific (Chavez *et al.*, 2003, Alheit and Niquen, 2004) and it has been also indicated in zooplankton CPR data from the NE Atlantic (Dickson *et al.*, 1988, Richardson and Schoeman, 2004). One major feature of the shift detected in the Iberian case is the coincidence of peak abundances of both sardine and anchovy species prior to 1975. Fishery data report a marked decrease in the distribution area of Iberian anchovy, formerly well distributed through the shelf (Junquera, 1984) but now restricted to major populations in the E Bay of Biscay and the Gulf of Cadiz (e.g. ICES 2005). In contrast, sardine populations have fluctuated in abundance but never abandoned the main distribution centres (ICES 2005, Carrera and Porteiro, 2003).

METHODS

Three different kinds of variables were used in the analysis, each of them as a time-series between 1978 and 2005. The variables are:

1) Fishery data:

- *landing*: annual landings from south Galicia as reported in Anon (2006)
- *xouba*: annual landings from Vigo harbour from this category
- *Ssb*: Spawning stock biomass Anon (2006)
- *recruits*: estimated recruitment from the Iberoatlantic sardine assessment model (Anon, 2006)
- *recstrength*: is a categorical index estimated from the catch-at-age 0 in number obtained in south Galicia and north Portugal, i.e. main recruitment area. The index for a given year has three values, -1 when the catches at age 0 of the precedent year were higher than the 3rd percentile of the whole time-series; 0 when the catches were between the first and the third percentile and 1 when the catches at age 0 of the precedent year were lower than the first percentile.

Large scale atmospheric and oceanographic events.

- *NAO index*: (Hurrell, J.W., 1995). The index is split in two components;
- *NAOwinter*: Winter component (between December of the precedent year until March of the year in course) which coincides temporally with the main spawning time off Western Iberian Peninsula
- *NAOspring*: Spring component (from March to May), coincident with the main spawning time in the Cantabrian Sea.
- *Gulf index*: from Taylor (1996; <http://www.pml.ac.uk/gulfstream/site>), an annual index of the variability in the position of the Gulf Stream
- *AMO*: Atlantic multidecadal oscillation:
<http://web1.cdc.noaa.gov/Timeseries/AMO/>

Local scale events

- *Iw*: Upwelling index computed for a point off the Galician coast using the atmospheric pressures (April-September) provided by the Spanish National Meteorological Institute (details are described in Lavin *et al.*, 1991).
- *Tewinterupy*: Poleward current index (estimated from the Ekman transport between October and December of the preceding year).
- *SST*: Sea surface temperature for 42°N 10°W. Sst (global) taken from Coads database and split in two periods Sst_w (Oct-March) and Sst_s (Apr-Sept).

The time-series was preliminary analysed by plots of the temporal trends of each of the variables used, as well as with quantile-quantile plots (qq-plots) of the distribution of the observed values in comparison with normally distributed simulated data to test for normality. Also a correlation matrix between all variables (Table 1) is used in the analysis to investigate the relationships between.

Table 1: Correlation matrix (values in red: significant correlation)

Correlations (Tabla_Sardina)													
Marked correlations are significant at p < .05000													
N=28 (Casewise deletion of missing data)													
All Cases: 78-05	RECRUIT. (*1000)	SSB (t)	LANDINGS (t)	Xouba Vigo (kg)	GULF_anual	NAO_w	NAO_mam	Iw	Tewinterupy	AMO	SST_Wint	SST_summ	SST
RECRUIT. (*1000)	1.00	0.02	0.33	0.70	-0.29	-0.06	-0.07	-0.02	-0.17	-0.24	-0.28	-0.34	-0.37
SSB (t)	0.02	1.00	0.76	0.23	0.12	0.09	0.00	0.24	-0.02	-0.56	-0.23	-0.43	-0.41
LANDINGS (t)	0.33	0.76	1.00	0.56	-0.23	-0.03	-0.13	0.32	0.16	-0.67	-0.29	-0.55	-0.52
Xouba Vigo (kg)	0.70	0.23	0.56	1.00	-0.24	0.02	-0.19	0.18	-0.03	-0.27	-0.35	-0.36	-0.42
GULF_anual	-0.29	0.12	-0.23	-0.24	1.00	0.44	0.00	-0.02	-0.11	-0.09	-0.26	0.13	-0.05
NAO_w	-0.06	0.09	-0.03	0.02	0.44	1.00	0.36	-0.02	-0.09	-0.03	-0.06	0.15	0.07
NAO_mam	-0.07	0.00	-0.13	-0.19	0.00	0.36	1.00	0.11	-0.18	-0.11	-0.13	-0.04	-0.10
Iw	-0.02	0.24	0.32	0.18	-0.02	-0.02	0.11	1.00	0.12	-0.31	-0.08	-0.53	-0.39
Tewinterupy	-0.17	-0.02	0.16	-0.03	-0.11	-0.09	-0.18	0.12	1.00	0.05	0.34	-0.14	0.09
AMO	-0.24	-0.56	-0.67	-0.27	-0.09	-0.03	-0.11	-0.31	0.05	1.00	0.43	0.59	0.62
SST_Wint	-0.28	-0.23	-0.29	-0.35	-0.26	-0.06	-0.13	-0.08	0.34	0.43	1.00	0.40	0.79
SST_summ	-0.34	-0.43	-0.55	-0.36	0.13	0.15	-0.04	-0.53	-0.14	0.59	0.40	1.00	0.88
SST	-0.37	-0.41	-0.52	-0.42	-0.05	0.07	-0.10	-0.39	0.09	0.62	0.79	0.88	1.00

Recruitment shows negative correlations with all oceanographic features. *NAOwinter* index shows significant correlation ($p < 0.05$) with *GULF* and *NAOspring* indices. Winter events gave low correlations with recruitment. Large-scale events (NAO indices and Gulf) exhibited higher correlation between themselves than with local-scale indices (Upwelling and poleward current).

Younger sardines account for up to 70 % of the variability found in the total yield in south Galicia ($p < .0001$). Furthermore, a simple linear regression between *xouba* landings from Vigo and the predicted recruitment at age 0, as estimated in the assessment model of this unit stock (Anon 2006), was also significant and accounted for 56% of the variability in the *xouba* landings. The upwelling index is estimated from the Ekman transport during the period from April to September. The Ekman transport in that period is mainly produced by north/northwesterly winds, which are responsible for summer upwelling in the area. The Poleward current index is estimated from October to December of the previous year component of the Ekman transport. The Ekman transport on that period is produced by south/southwesterly winds, which causes among other oceanographic factors the poleward surface current known as the Navidad current (Frouin *et al.*, 1990). Thus, the two components of the Ekman transport (the winter and summer components) are used as indexes for the poleward current and upwelling intensity.

Once the preliminary analysis was completed, an empirical model of the recruitment, based upon standard multiple linear regression, was developed as a function of independent biological and physical variables.

$$\text{Rec}_i = \beta_0 + \beta_1 \text{NAOwinter}_i + \beta_2 \text{NAOspring}_i + \beta_3 \text{GULF}_i + \beta_4 \text{Twinterupy}_i + \beta_5 \text{Iw}_i + \beta_6 \text{Recstrength}_i + \varepsilon_i$$

where the sub-index i is the year, $\beta = (\beta_0, \beta_1, \dots, \beta_6)$ represent the parameter vector estimated by least squares in the fitting procedure, and ε_i are normally distributed errors.

Once the initial model was fitted to the data, a stepwise model selection procedure based on the Akaike Information Criterion (Sakamoto *et al.*, 1986) was carried out, in order to obtain the best possible model given the available covariates. This generic function calculates the Akaike information criterion for one or several fitted model objects for which a log-likelihood value can be obtained, according to the formula $-2 \cdot \log\text{-likelihood} + 2 \cdot \text{npar}$, where npar represents the number of parameters in the fitted model. When comparing fitted objects, the smaller the AIC, the better the fit.

In spite the fitted model matched quite well with the predicted recruitment during the eighties, along the following years the discrepancies between them are in general higher.

Results and discussion

All covariates were retained on account the selection. For the period 1978–2000, the model is significant and accounts for 58% of the variability found in the recruitment. Figure 3 shows the predicted recruitment from the assessment model and the fitted model. In general terms, excluding 1985 and 1986, the model matches quite well with the predicted recruitment during the eighties. Nevertheless for the nineties the discrepancies are higher, and after that a successive years of bad recruitments results in a poor fit of the data.

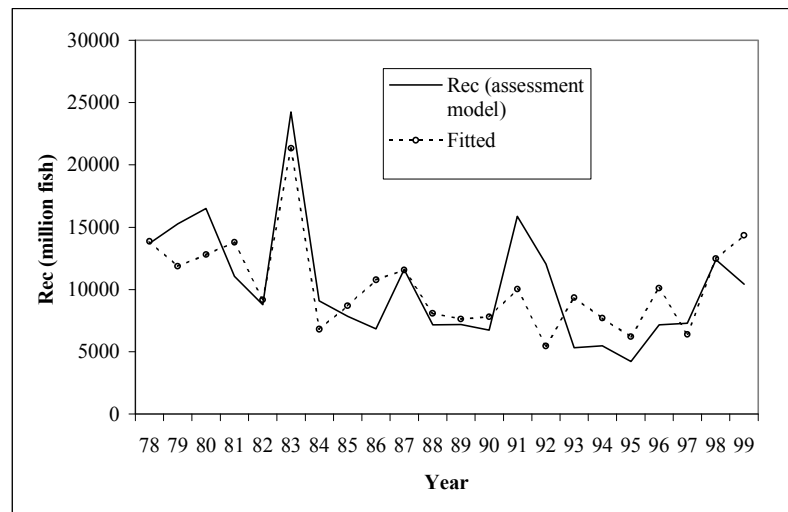


Figure 3: Predicted recruitment from the Assessment model as estimated in Anon (2001) and the fitted model (dotted line).

Regarding the partial effect of each variable on the overall mode, whereas the spring indices, Iw and NAO spring, and the GULF and the strength of poleward current had negative effect, the winter index, NAO winter had positive effect. On the other hand, the strength of the previous year has also positive effect.

The variability observed in the south Galicia sardine fishery is mainly driven by the strength of the incoming year class (i.e. recruitment at age 0). The results suggest that the recruitment of this fish species depends on both, large and local scale oceanographic events but also on the strength of the precedent year classes. The prevalence of younger fish in the same location as the recruitment seems to play an important role.

An increase in the spring indices (i.e. upwelling or NAO) seems to be related with an increase of the turbulence and in the advection processes. As stated by Cury and Roy (1989), higher turbulence is far from the optimal environment window.

On the other hand, recruitment process in sardine is the outcome of a wide space/time integral over different locations subjected to different regimes (from October to April in two main locations, western Portugal and the Cantabrian Sea). In addition, spawning grounds may change on account the size of the stock, as stated in Carrera and Porteiro (2003). In this context, changes in spawning area have recently been observed in this fish stock, which mainly affected the northern Portugal and Western Cantabrian Sea spawning grounds where the spawning area decreased.

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Annex 7: North Sea herring-environmental variability with stable management?

John Simmonds (FRS) and Mark Dickey-Collas (IMARES)

Abstract

North Sea herring has been considered a well managed stock, as a harvest control rule (HCR) initially developed in the mid 1990s was agreed by managers and has regulated and reduced fishing mortality and given flexibility to managers to respond to short term changes in productivity. This occurred against the background of collapse and over exploitation in the 1970s and 1990s respectively Simmonds (2007). However in the last version of the management agreement (implemented in 2004) a year on year limit on TAC change was introduced and the impact of this addition to the HCR had not been tested fully, because autocorrelation in recruitment was not taken into account. Coincident with this change in the rule, the recruitment of North Sea herring appears to have changed. Five poor year classes in a row occurred, and this change in productivity had also not fully been tested in the management simulations.

The chain of poor recruitment has been linked to environmental change in the North Sea. Despite a high spawning biomass producing plenty of larvae, the larvae are not surviving (ICES 2007). It is clear that the northern and central components of North Sea herring are now less productive. Whilst the direct mechanisms are still unknown, this poor larval survival may be linked to the increasing water temperature and decreasing water density in the areas of larval production. The temperature change is also associated with a change in the zooplankton community. The swift reduction in productivity occurring at a time when quota stability was being offered by managers has resulted in a clash of objectives within the management agreement. In essence management must respond to the poor recruitment but has found it difficult to do so.

In an attempt to further investigate the potential impact of environmental variability on the development of management rules, we consider three aspects of variable production:

- i) changes to the stock to recruit relationship (associated with larval survival and trends in the environment)
- ii) variability and trends in natural mortality of post metamorphic fish (as derived from the MSVPA and reflecting the trends in predation pressure)
- iii) changes in growth rate

Whilst the mechanisms for variable fish productivity may not be fully understood, we argue that their association with environmental variability must be taken into account. Management rules based on simulations that use short time-series, especially when compared to meteorological science, must “expect the unexpected” and constraining TAC change may be inappropriate, especially when being developed in a climate of change.

Sources of variability in fish production

Variability in the stock to recruit relationship

Changes in the environment can affect stock to recruit relationships in a range of ways. In a classic Ricker stock to recruit curve changes with habitat availability, predation, toxins, fecundity, stock structure, prey availability, etc (Figure 1.1).

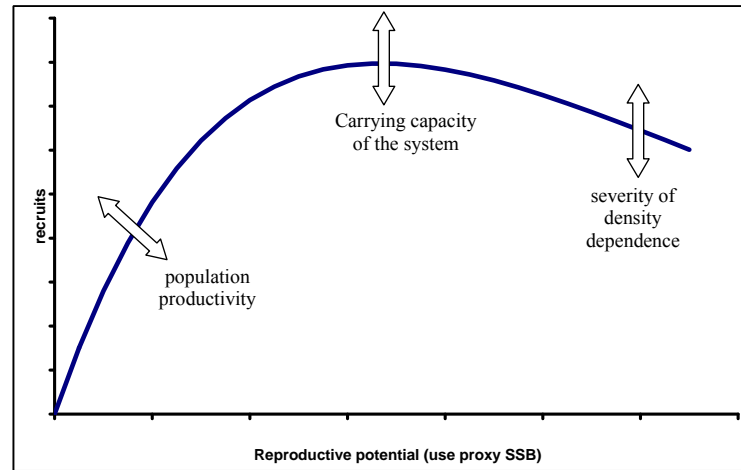


Figure 1.1. Variability in a standard Ricker stock to recruitment relationship.

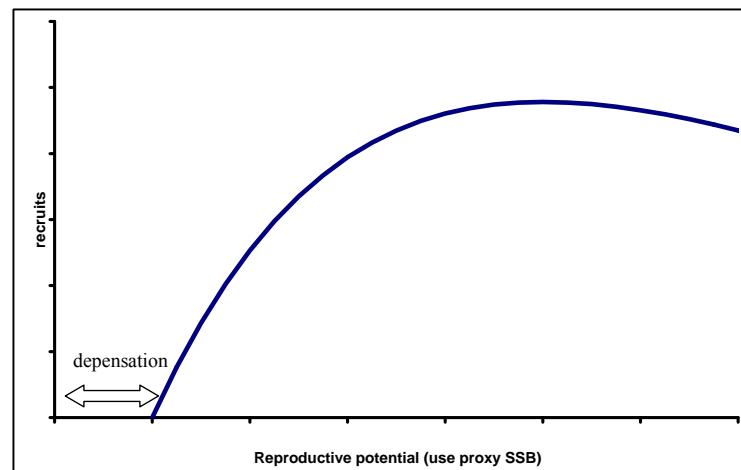


Figure 1.2 Depensation at lower stock size

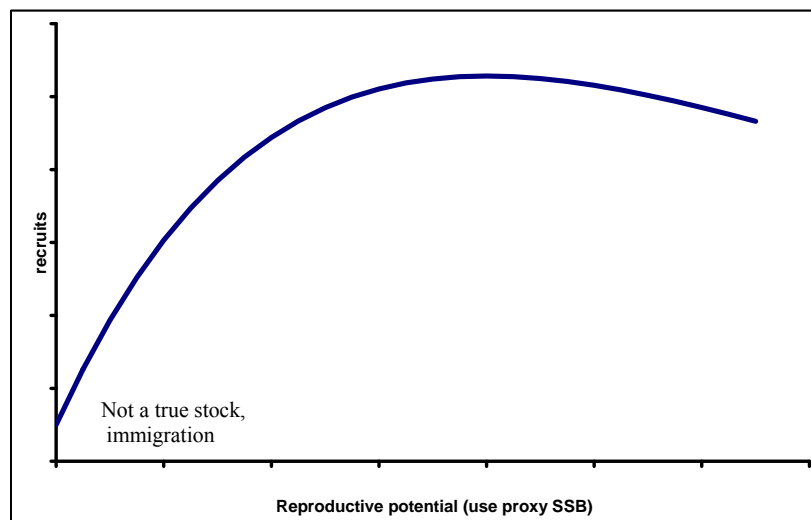


Figure 1.3 Immigration into the population (e.g. English Channel plaice, perhaps west of Scotland herring).

The stock to recruit relationship may also not pass through the origin. Depensation (Figure 1.2), likely when biomass alone is not the only criteria for spawning, e.g. sex ratios, stimulates for mating behaviour, effective population size and inbreeding. When the management unit is not a true stock and immigration can occur even with zero biomass, or apparent reproductive potential rises at very low biomass (Figure 1.3).

Variability and trends in natural mortality

The productivity of a stock can be impacted by changes in non-anthropogenic predation. Most stock assessments use time-series averaged estimates of natural mortality by age, treating the population as a virtual population with variability in natural mortality included within recruitment. As a result of the North Sea Multispecies VPA (MSVPA) programme, annually varying estimates of predation mortality are available for North Sea herring. These can be used to further investigate the changes in productivity of a stock and consider the impact of changes in other fish populations relative to the herring.

Variability in growth

Up until 2000, it was assumed that most variability in growth of herring expressed in year effects. However the very large 2000 year class of herring became very slow growing once it reached the age of 2, and the reduced growth in this cohort has continued to the present day. It is probable that this was a density effect caused by the large size of the cohort. Variability in growth, especially when associated with large year classes can affect both the size of the SSB and the numbers of fish caught under a weight based TAC.

Temporal variability in production of North Sea herring

The North Sea herring stock was examined for changes in productivity over the time-series. It is a long studied and well documented stock in terms of its exploitation and related collapses and recoveries (Cushing and Bridger, 1966, Burd, 1985, Nichols, 2001, Simmonds 2005). The main impact on its productivity was generally thought to be fishing, although the environment may also have had a major impact as well. Each habitat or ecosystem is thought to have a carrying capacity which varies in time (Jennings *et al.*, 2002). To account for the influence of the ecosystem on the productivity of the stocks the methods of Dickey-Collas and Nash (2005) were applied (originally formulated by Dutil and Brander (2003). This method was further developed by HAWG 2007. The data used in this analysis were derived from the assessment outputs from the HAWG in 2007 (2.1.1).

Realised production, net and surplus production of the whole stock, including the recruits, the growth of all non-recruits, the natural and the fishing mortality, were calculated (Figure 2.1). Potential production (Figure 2.2) was estimated by removing the influence of the fishery and its interaction through the spawning stock biomass, a stock recruit relationship was fitted and the year effect on recruitment retained. The hockey stick relationship was chosen to illustrate the assumption of minimal dependence of recruitment on SSB, though the conclusions are not sensitive to the choice of relationship. The parameter values used to fit the models to data for the different species are given in Table 2.1. The residuals or deviations from the fitted S/R relationships were used to define the year effect for recruitment under the assumptions of the differing models. A constant exploitation pattern was generated based on an average selection over the last 10 years and a mean F that could be set at any level. For any chosen fishing mortality two new time-series of recruitments were generated from: the initial starting stock for each of the three species, the recruitment deviations and the S/R relationships based on simulated SSB. The generated populations then represented potential production under different exploitation regimes. The stock size, net production and surplus production could be obtained without the effect of the SSB that was dependent on the original fishery.

Calculation of the surplus production P_s

$$P_s = Br + Bg - M$$

where Br is the biomass of the recruits, Bg the gain of biomass due to growth of all fish excluding the recruits, and M the removal due to natural mortality. The net production equals the surplus production minus the biomass due to fishing with the headline F and fixed selection pattern.

North Sea herring has shown variable production over time (Figure 2.1). The productivity increased markedly after the collapse in the late 70s, supporting the recovery of the stock. In the middle of the 80s the productivity fell to the level before the collapse and even decreased further during the last three years (Figure 2.1). It can be assumed, that fishing must be reduced on this stock and to return to higher catches the productivity must increase again. This is illustrated more clearly when the influence of the fishery is removed (Figure 2.2), the reduction in recruitment from the mid 1990s is quite compelling.

The same method was used with annually varying estimates of natural mortality (derived from the MSVPA). This comparison was chosen to compare whether accounting for annual variability in natural mortality would give a different perception of the stock productivity.

The use of MSVPA as a source of annually varying natural mortality gives a different perception of recruitment, reducing this during the recovery period, increasing it during the early 90s and reducing it again recently. Overall the herring stock is perceived as being lower in the latter half of the time-series. It is probable that the model reconciles the reduction natural mortality caused by reduced numbers of predators and the similar removals by the fishery by reducing recruitment and overall biomass. One aspect that shows up is periods of stability in natural mortality before and after new stomach data. The fit between the observed recruitment at approximately 3 months with an MIK survey and the model predicted recruitment deteriorates considerably, the standard deviation on the residuals doubles. Taken together these two points suggest there may be insufficient data to determine predation adequately.

Table 2.1 Results of fitting the stock-recruitment relationships for each species. α , β and ρ are given for the case where the spawning-stock biomass (SSB) is given in millions of tonnes (Mt), and the calculated recruitment (R) is given in billions of individuals. The Akaike information criteria (AIC) are also shown. Seg-reg is the segmented-regression model, Bev-Holt is the Beverton and Holt model, and Qhstk is the quadratic hockey stick model.

SPECIES	MODEL	α	β	ρ	AIC
Herring	Seg-reg	91.13	0.4489	-	94.08
	Ricker	120.97	1.0075	-	95.39
	Bev-Holt	56.39	0.3841	-	99.28
	Qhstk	94.10	0.4434	0.578	95.81

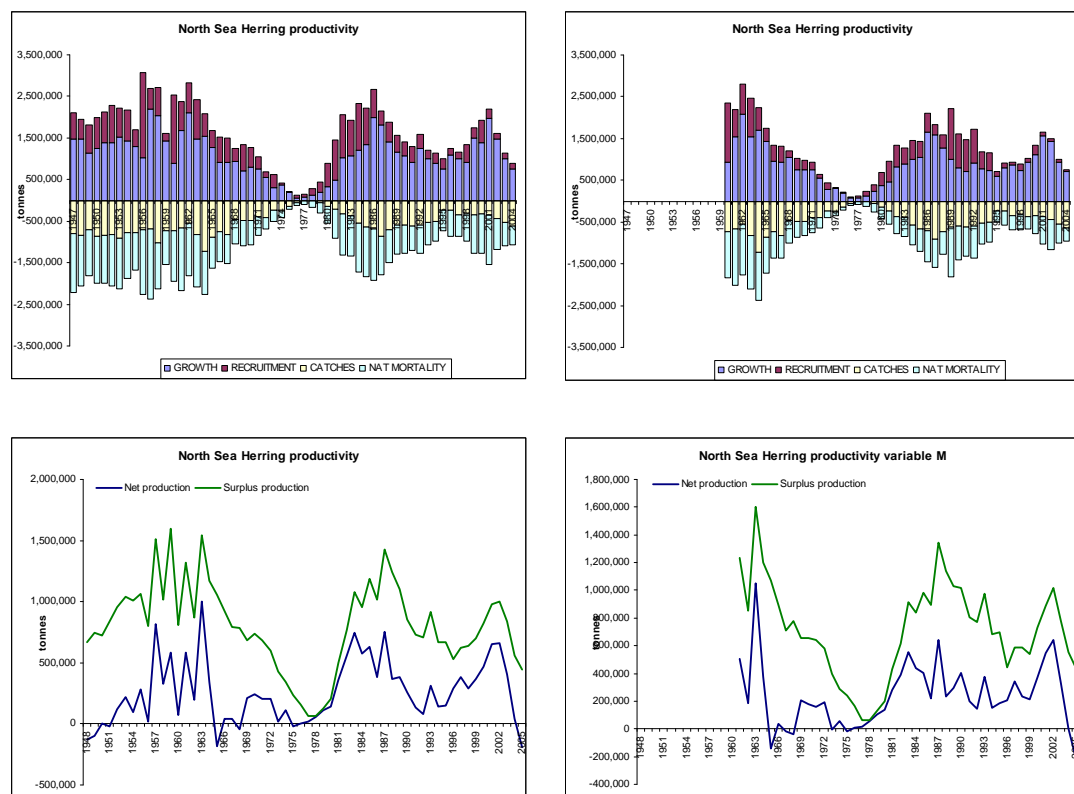


Figure 2.1. Realised production of North Sea herring, estimated from the time-series used by the working group and a new time-series using MSVPA estimates of natural mortality.

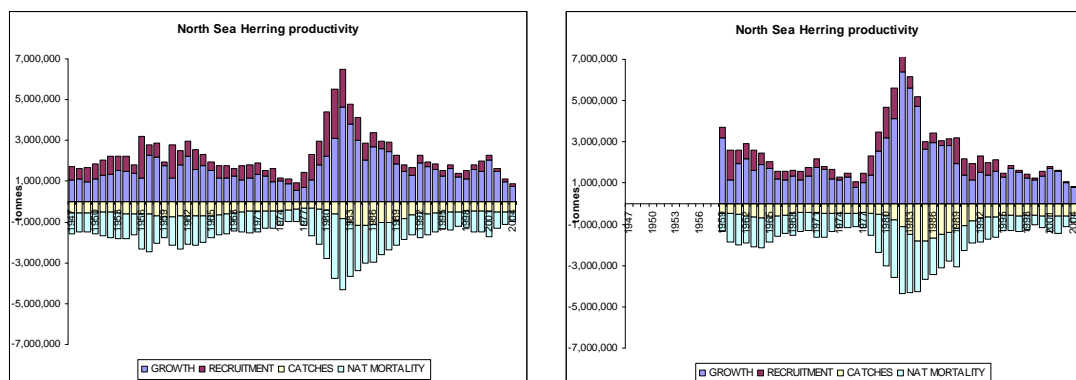


Figure 2.2. Potential production of North Sea herring assuming constant fishing pattern equivalent to the mean of the last 10 years. Using the time-series used by the working group and a new time-series using MSVPA estimates of natural mortality.

Analysis of the stock to recruit relationship in North Sea herring

Various approaches were used to investigate the dynamics of the stock to recruit relationship in North Sea herring. Both the hockey stick (segmented regression) and the Ricker curves were fitted to different time-series (Figure 3.1). From a statistical standpoint these functions best explain the variability (Table 2.1).

The break point of the hockey stick appears fairly robust to the choice of standard (as used by HAWG) time-series (1947–2005 and 1960–2005). Although the choice of time-series does impact the compensatory part of the Ricker curves (Figure 3.1). Importantly the use of annually varying natural mortality (from MSVPA) has a dramatic effect on the stock to recruit relationships with a lower carrying capacity and a higher biomass at which recruitment appears to be impaired. Some of these changes are due to long term differences in natural mortality. This gives similar abundance at older ages while reducing mortality and numbers at young ages in recent years. Variability around the model is not particularly sensitive to the choice of model or period for fixed M , being slightly higher with the Ricker than the hockey stick. Serial autocorrelation is evident in the deviations from the models, for constant M series but similar for all models. The major contrast is between model deviations for fixed and variable M . Variable M shows higher variability, greater autocorrelation and more severe trends at the end of the time-series (Figure 3. 2).

North Sea herring is well known for exhibiting a different stock to recruit relationship prior to collapse and post collapse (Figure 3.3). Whilst the carrying capacity of the stock appears similar in both cases, the biomass point at which spawning is impaired is radically different pre 1978 and post 1978. This could be interpreted as recruitment compensation in the recovering stock. However, there is an alternative hypothesis that only in the presence of high productivity would the stock recover from such a low situation. Thus we see high productivity as part of recovery, but its occurrence may have occurred due to unusually favourable conditions. Without these the stock might have remained low for much longer. It would be important to know whether exceptional environmental conditions or low biomass was responsible for these relatively high deviations before assuming the high productivity relationship is correct.

Hockey Stick

Ricker

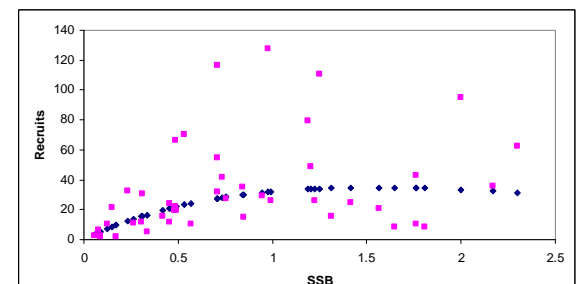
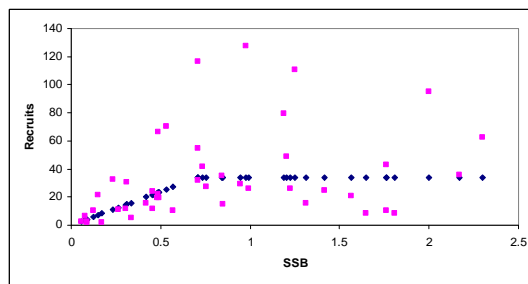
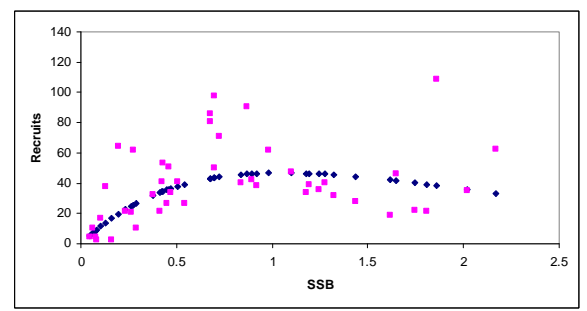
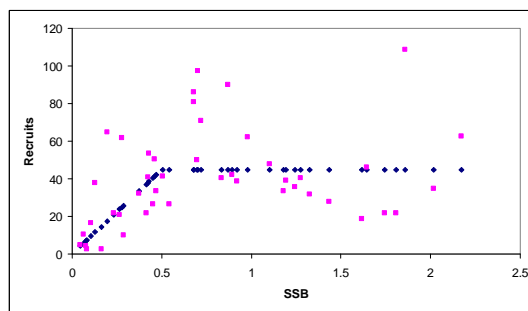
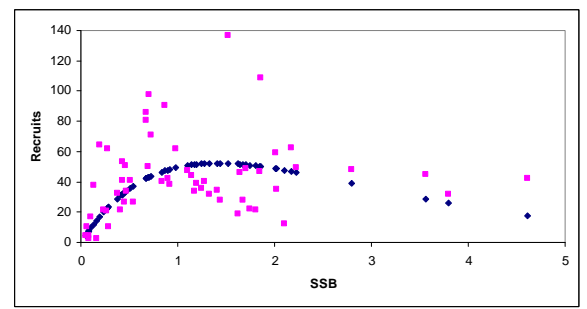
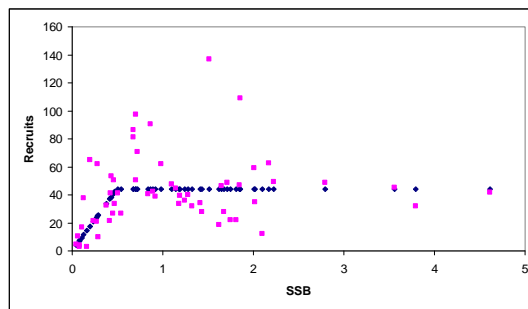


Figure 3.1 Fitted hockey stick and Ricker curves to North Sea herring using different time-series
a) 1947–2005, b) 1960–2005 from HAWG stock assessment, c) Variable MSVPA Natural mortality 1960–2005.

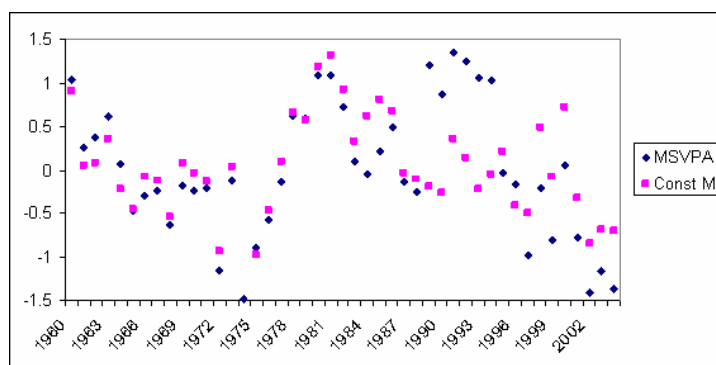


Figure 3.2 Comparison of annual deviations between observed recruitment and S/R models for fixed M hockey stick and variable MSVPA based M hockey stick. Including multispecies effects increases variability, serial autocorrelation and deviance in the last fifteen years.

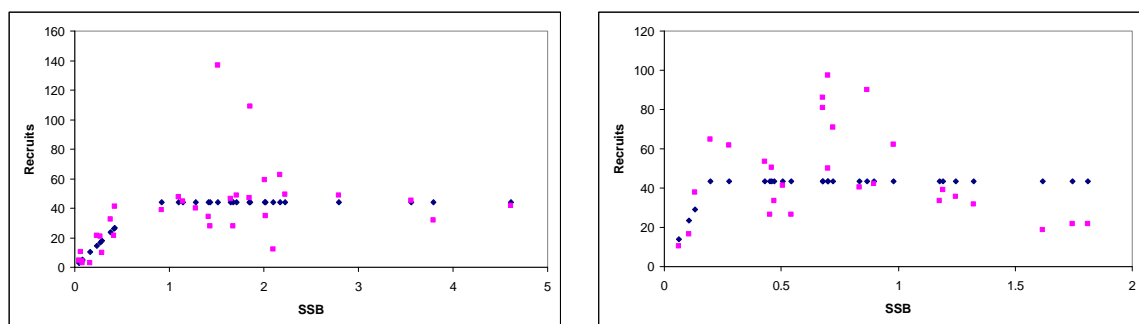


Figure 3.3 Fitted hockey stick curves to North Sea herring using portions of the time-series pre 1978 and post 1978.

Impact of growth

Predicted growth influence both the predicted catch and spawning stock biomass used to set TACs. There is some evidence for cohort related growth rates and large year effects in the surveys used to estimate weight in the stock (Figure 4.1). The 2000 year class shows reduced growth that is thought to be due to density dependent influences. Overall there is a small long term decline in weight-at-age. Some attempt has been made to accommodate this by using recent weights-at-age to estimate catch and SSB in the TAC year. A small bias and some variability are seen in the catch, amounting to 3% standard deviation Figure 4.2a. Recently the 2000 year class has been modelled separately in the predictions; however, assessing the performance of this aspect is not possible as this is the only year class for which a cohort effect has been accounted for. Needle (2006) examined several stocks and concluded that cohort effects were marginal in NS herring. Variability in maturity accompanies the cohort effect in the 2000 year class and also contributes to uncertainty in the SSB. The recent overestimation of SSB on projected SSB (Figure 4.1b) has been caused mostly by underestimation of the fraction mature in the 2000 year class. Variability in catch and SSB are included in the simulations.

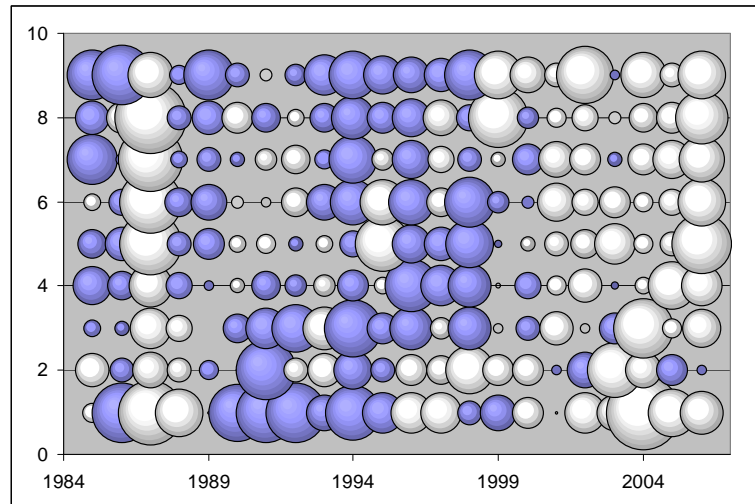


Figure 4.1. Growth residuals between estimated and fitted von Bertalanffy growth model. There are both strong year effects (measurement error) – recent decline and the 2000 year class shows density dependence on this one cohort.

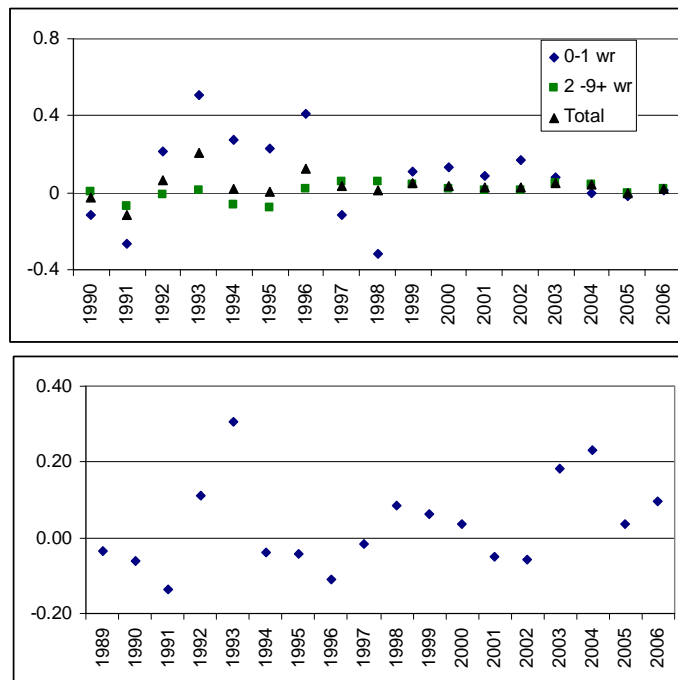


Figure 4.2 Influence of growth and maturity on predicted catch and predicted SSB. $\ln(3 \text{ year mean weight/ realised mean weight})$ a) in catch by fleet and b) spawning stock (including maturity-at-age). Overall 3% variability in catch is due to differences in predicted and realised in weight in the catch. Recent deviations in SSB are due mostly to slow growth and maturation of the 2000 year class.

Simulations

The impact of the variability described above was taken forward into management and advice by carrying out simulations of the current harvest control rule for North Sea herring, the methodology follows the *ad hoc* group on long term management advice AGALTA (ICES 2005) and the ICES study group SGMAS (ICES 2006). The methods and software are by Skagen and are described in an EU Norway report (STECF 2004). Assumptions within the simulations were adjusted to account for the variability described above. The basic scenarios are based on the following:

Starting numbers, maturity and weights as used HAWG 2007 (ICES 2007). Harvest rule as the standard management agreement of $F_{\text{adult}} = 0.25$ above 130 000 t declining to 0.1 at 800 000 t and $F_{\text{juvenile}} = 0.12$ declining to 0.4 at 800 000 t. In all cases a 15% year on year change in TAC is included. While ICES does not recommend this below 1 300 000 t it may happen and it is useful in this instance to show differences in perception of potential stock trajectories. For variable M the fitted S/R relationship are different and it is hard to know how to simulate this because the stock management is in the context of numbers and biomasses linked to fixed M. The use of a standard S/R model implies stationarity in recruitment which is matched to M. So the future needs to conform to similar ideas. So for compatibility future recruitment and M are taken from the whole time-series and to obtain at least a comparable start numbers used to start the simulation come from the standard assessment. In consequence the MSVPA based projections must be treated with caution. In all cases measurement error is a bias of 10% and standard deviation of 10% of estimate. Implementation error is also a bias of 10% with standard deviation of 10%. The 10% random component is included here to provide some variability due to projected and estimated weights in the stock and variability in area misreporting from year to year. The population model is changed for each simulation, where the recruitment is based on a long time-series autocorrelation is included (up to three terms), for those that use only the last 5 years no autocorrelation is included. The stock recruit relationships used are given in Table 3.1. Two models represent the full time-series, Standard and Depensatory, implying independence of recruitment at high biomass or density dependence respectively. Three models using recent recruitment to set the carrying capacity and differing amounts of modified productivity. Two models based on pre and post collapse time periods, which have similar carrying capacity but exhibit very different productivity. Variable natural mortality based on M estimated from MSVPA. Finally a hockey stick model is fitted to the five recent low recruit values, as a worst case scenario.

Table 3.1 Stock recruit relationships derived from historic time-series of North Sea herring and used for simulations of stock development. Years refer to the data years with recruits at 0wr, Type is model type (Hockey stick $R=A(S>B)$, $A*S/B(S\leq B)$, Riker $R=AS^B$) Autocorrelation where used is given at lag year 1, 2 and 3. Standard deviation is the variability of stochastically drawn recruitments expressed as natural logarithms around the model. C= carrying capacity, P= production (slope at origin).

STOCK RECRUIT RELATIONSHIP	YEARS OF DATA/ BASIS	TYPE	A	B	AUTOCORRELATION LAG 1,2,3	SD AROUND MODEL
Standard	1947–2007	Hockey Stick	43 800	489	0.33,0.36,0.08,	0.53
Depensatory	1947–2007	Riker	121	0.00095	0.4,0.4,0.2	0.66
Low P,C	A 2002–7 A*B=standard	Hockey Stick	22 930	934	0	0.35
Low C, Intermediate P	A 2002–7 B=standard	Hockey Stick	22 930	489	0	0.35
Low C, Standard P	A 2002–7 A/B=standard	Hockey Stick	22 930	256	0	0.35
Pre Collapse	1947–1978	Hockey Stick	438	697	0.33,0.36,0.08	0.53
Post Collapse	1978–2007	Hockey Stick	438	195	0.33,0.36,0.08	0.53
Variable M	1960–2007	Hockey Stick	33 580	706	0.39, 0.37, 0.19	0.77
Recent	2003–2007	Hockey stick	21 800	1 600	0	0.35

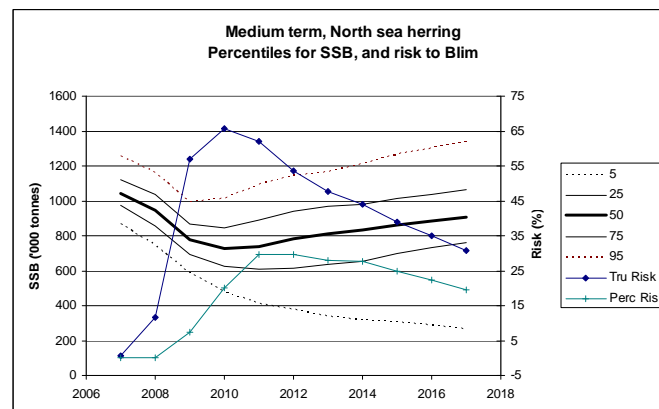


Figure 5.1 Low P, C:-Low productivity and low carrying capacity.

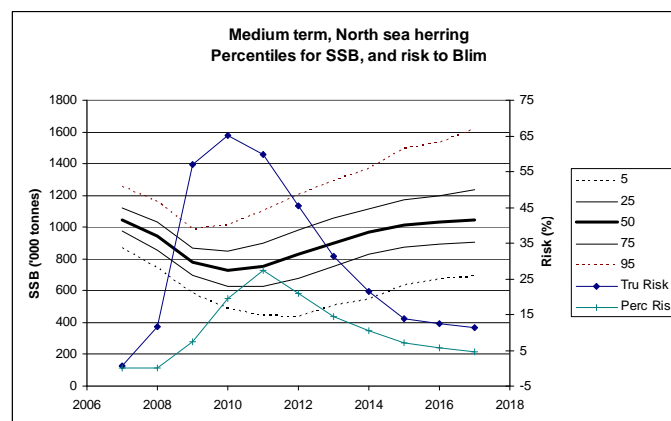


Figure 5.2 Low C, Intermediate or Standard P: Standard on intermediate productivity, with low carrying capacity.

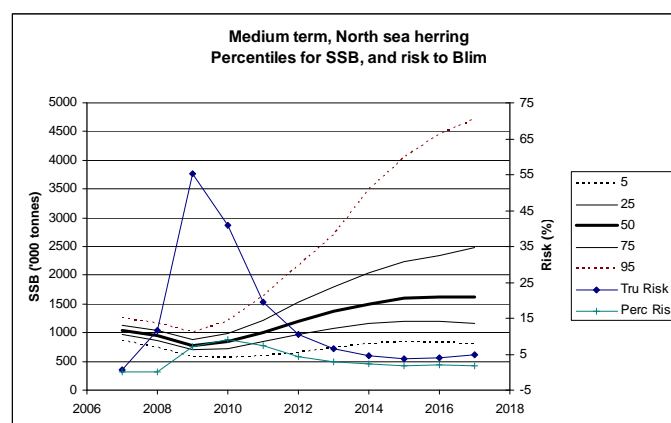


Figure 5.3 Standard. Both carrying capacity and productivity defined from the full data set using a hockey stick stock recruit relationship that implies independence of recruitment and SSB at high SSB.

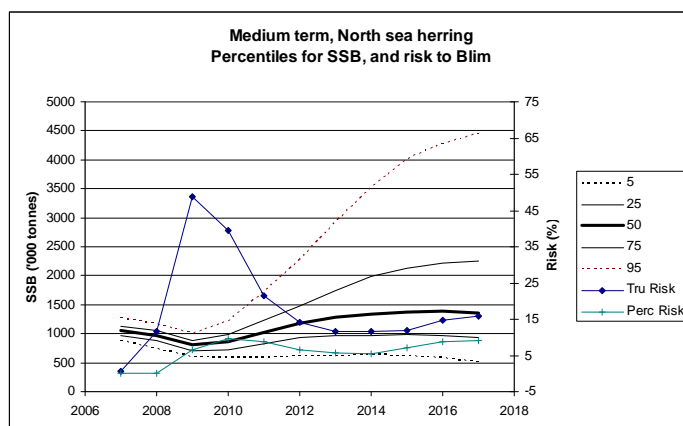


Figure 5.4 Depensatory Both productivity and carrying capacity defined from the full time-series with implied reduced recruitment at high biomass through use of a Ricker model.

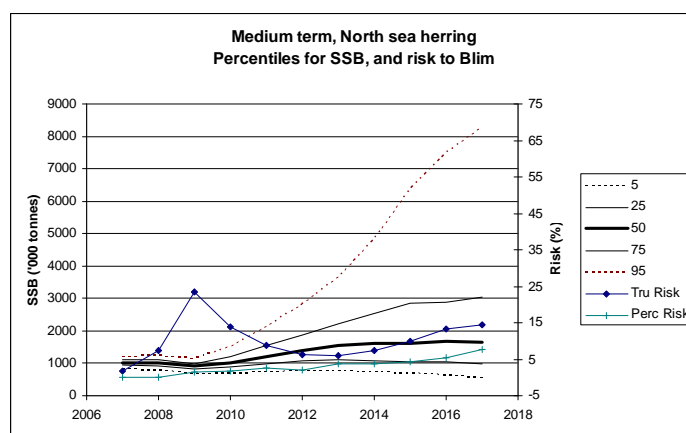


Figure 5.5 Variable M, Hockey stick model fitted to full time-series.

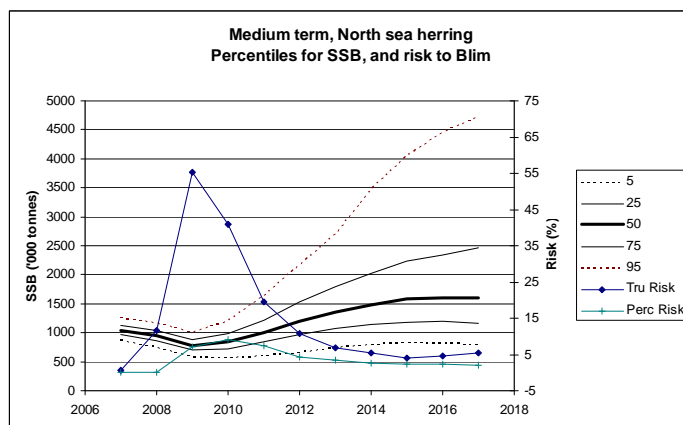


Figure 5.6 Pre Collapse: Standard carrying capacity with low productivity seen prior to the 1978 collapse.

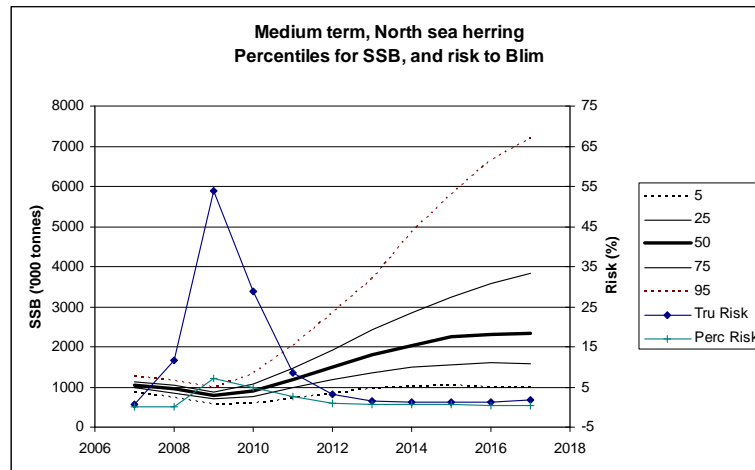


Figure 5.7 Post Collapse: Standard carrying capacity with high productivity seen as the stock recovered from 1978 collapse.

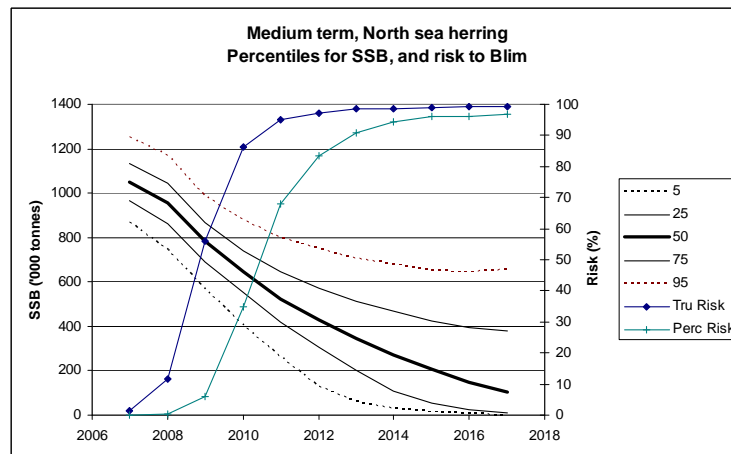
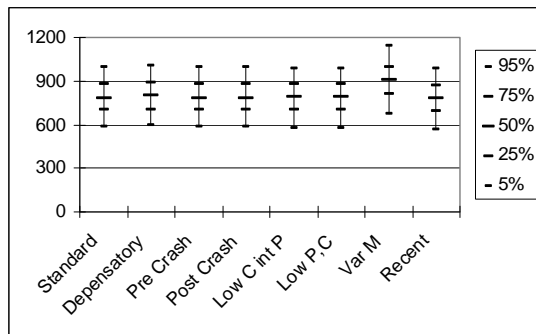
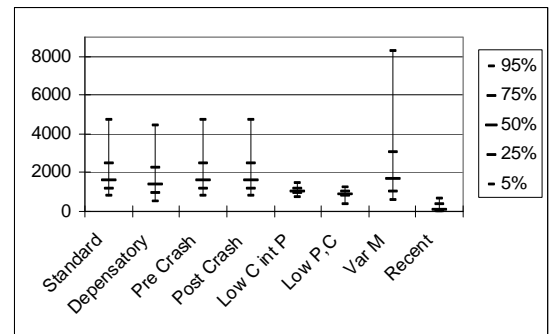


Figure 5.8 Recent: the most extreme case supported by the data, which crashes the stock. A Hockey Stick model fitted to the 5 most recent observed estimates of recruitment and SSB.

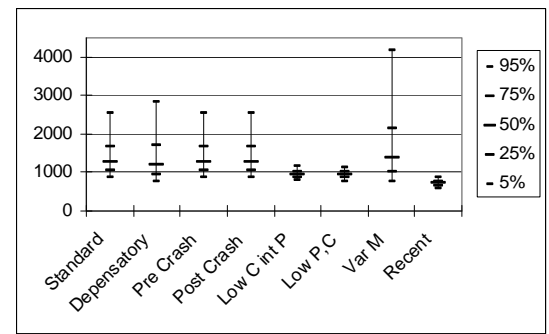
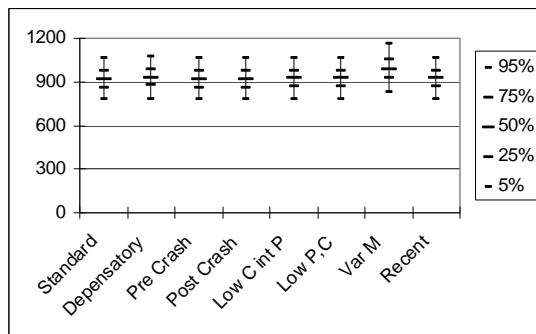
SSB in 2009



SSB in 2017



a) with 15 % constraint on TAC change.



b) without 15% constraint on TAC change.

Figure 5.9 Range (5–95%) for spawning stock biomass in 2009 and 2017 (a) with and (b) without 15% constraint in TAC. The differences in 2009 depend on management strategy, with the constraint on TAC significantly increasing the risk of SSB declining below 800 000 t. The long term outcome depends on carrying capacity of the stock. Removal of the 15% constrain allows catches to recover more quickly and the stock stabilises at a lower level. Including variable M increases the uncertainty, and suggests a greater potential for recovery, because predators are currently less abundant.

The types of S/R relationship given in Figures 1.2 and 1.3 illustrating differences at the origin have not been simulated. The model illustrated in Figure 1.3 would give a more robust response, showing less risk of collapse and would be more productive than the Ricker model shown below. In contrast the model from Figure 1.2 would be more risky, though provided the stock does not go much below the current Blim there is no evidence that reduced recruitment occurs above this level. In fact history favours the hypothesis of Figure 1.3 over 1.2, though relying on this might be dangerous.

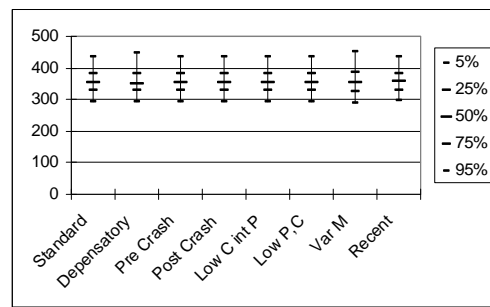
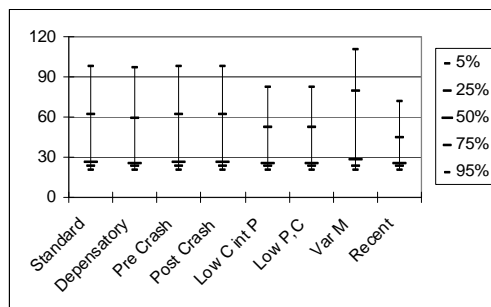
The results of the simulations in terms of SSB show that for almost all of these scenarios the immediate future is similar (Figures 5.1 to 5.7), in almost all cases, the stock is seen to decline for a few years and then increase. The risk of the stock going below Blim is between 50 and 65% for all cases except for Variable M which shows a lower risk of about 25%. This high risk is because the scenarios chosen assume a low rate of reduction in TAC which hopefully will not occur in practice. The final scenario based on a S/R relationship fitted to the last 5 observations of SSB and recruitment crashes the stock (Figure 5.8). However, while this example should be bourn in mind, such a data set provides a very poor bases for advice. The key point is that for all other scenarios the risk is very similar (Figure 5.9), and not very heavily dependant on stock productivity, though higher productivity regimes move out of the

risky region a little faster (comparing Figure 5.7 with 5.6). In contrast to 2009, the main difference is in the medium term expectation which depends directly on the assumption of carrying capacity. Those with high carrying capacity have a high SSB by 2017 (Figure 5.3 and 5.4), those with low carrying capacity (Figure 5.1 and 5.2) show median SSB just over 1M tonnes. Only the last scenario shows a lower SSB, with declining stock with no equilibrium point, further reduced recruitment as the 15% rule maintains catch above replacement. The results for 2017 can be compared in Figure 5.9.

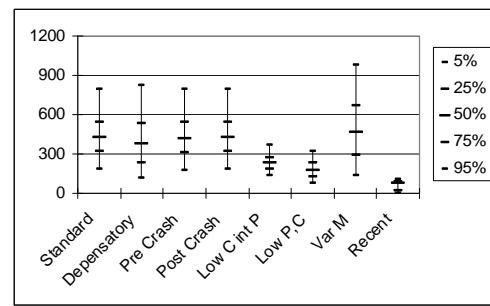
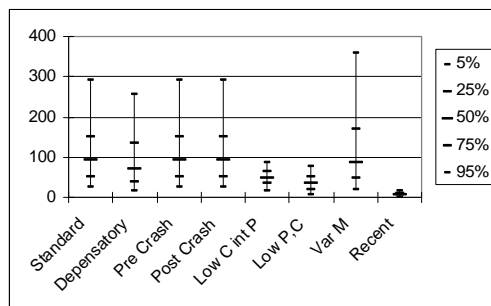
For comparison the 15% constrain on change in TAC was removed. The short and medium term outcomes depend on different aspects (Figure 5.9). In the short term SSB depends on management action. In the medium term the carrying capacity of the stock dominates, but with increased variability seen in the scenario when M is allowed to vary. The resulting catch behaves in a similar way to the behaviour of SSB, for 2008 the outcome is dominated by management decision to implement or exclude a 15% catch constraint (Figures 5.11 and 5.12). In the long term catch outcomes depend mostly on the carrying capacity. Even the last scenario reaches equilibrium at low catch and low SSB but its does not go as low as the situation where the 15% rule is maintained.

Juvenile Fleet exploiting 0-1

Adult Fleet exploiting 2-9+



2008



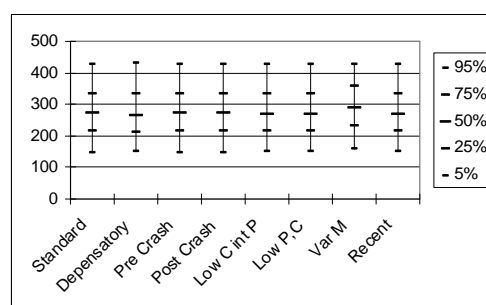
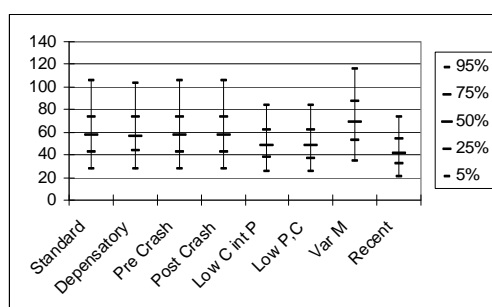
2017

Figure 5.10 Range (5–95%) of catch for year 2008 and 2017 for different assumptions of S/R relationship, with 15% year on year TAC constraint. The catch in 2008 is largely independent of assumptions, while catch in 2017 depends on assumed carrying capacity of the stock. Variable M (based on MSVPA) introduces greater uncertainty, this greater range of catches but little change in mean as changes in other stocks are not included.

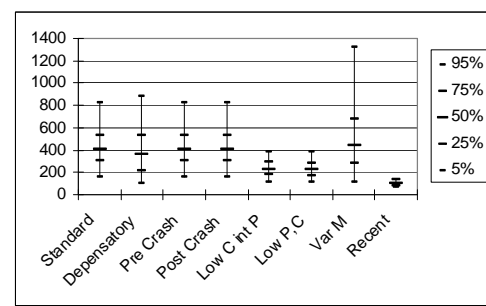
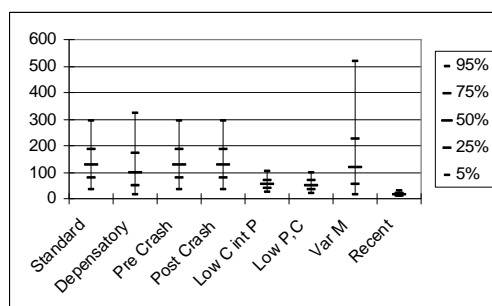
In all the simulations the true risk of SSB falling below B_{lim} is much higher than the perceived risk. In those cases where the true risk is greater than 50%, the perceived risk is less than 10%. Also the true risk rises faster than the perceived risk, reaching a peak earlier and sustaining longer than the perceived risk. This is because of a combination of the bias in the estimation process leading to under-reaction combined with an HCR that increases the rate of reduction at lower biomass. Thus managers need to be aware that conditions can be considerably worse than perceived.

Juvenile Fleet exploiting 0–1

Adult Fleet exploiting 2–9+



2008



2017

Figure 5.11 Range (5–95%) of catch for year 2008 and 2017 for different assumptions of S/R relationship, with no year on year TAC constraint. The catch in 2008 is largely independent of assumptions, while catch in 2017 depends on assumed carrying capacity of the stock. Variable M (based on MSVPA) introduces greater uncertainty, this greater range of catches but little change in mean as changes in other stocks are not included.

Conclusions

Advice in the short term is not heavily dependent on stock dynamics, TACs for 2008 can be set based on assessment and measured recruitment, though without the recruit survey the conclusions might be different. Some error occurs due to forward prediction of SSB in the TAC year due to mean weights and maturity. Improved cohort based modelling may help with this issue. Current considerations include concerns that if TACS are not reduced quickly enough there is a high risk of going below Blim (800 000 t). However, provided recruitment does not deteriorate further and TACs are eventually brought into line with recruitment, the stock should recover under all previously observed regimes. The impact of different stock recruit regimes does not influence short term advice.

The perception of risk is shown to be lower than the true risk, so that it is important not to be complacent.

There is one cautionary note: if the productivity and carrying capacity have really changed to reflect the most extreme inference possible, maintaining the 15% catch regime will crash the stock. It is therefore important as biomass declines that TACs respond to available catch opportunities. The biological space to provide significant socioeconomic objectives requiring higher catches is not available if recruitment continues to decline with biomass.

In the medium term, the outcomes depend directly on carrying capacity of the stock. Understanding the reasons for the low recruitment in 2002 to 2006 is necessary before

determining which regime described here is more similar to the underlying stock dynamics. If yields are to be optimised and the stock depends mostly on the carrying capacity which currently cannot be predicted, the catches need to change to match capacity in the medium term. Given the difficulty in predicting the medium term recruitment, sustainable catches will be maximised through TACs that are not restrained by year on year changes.

The conclusion that you need to manage stocks by fishing mortality when ecosystems are changing was highlighted by Kell *et al.* (2005). Although in the case of North Sea herring both biomass triggers and fishing mortality play a role, the need to maintain low fishing mortality is apparent when ecosystems change. This case study, however, took the analysis further than Kell *et al.* (2005) by clearly distinguishing between variability in carrying capacity and production (what they called juvenile survival) and found that for North Sea herring, it is variability in the carrying capacity that impacts the greatest on management and catching potential whereas changes in productivity play a lesser role.

The current harvest rule (excluding the 15% year on year constraint below $SSB = 1\,300\,000$ t) appears to be robust to known or postulated population parameterisation and potential changes in productivity, though the most severe reduction in carrying capacity would result in significant departure from optimal yield.

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Annex 8: Case study of Eastern Bering sea pollock: impact of environmental variability on management advice

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Abstract

The Eastern Bering Sea (EBS) pollock fishery has averaged over 1.12 million tons of catch for the last 42 years. Strong year classes (cohorts) in recent decades have increased pollock stocks in this region and since 2002 the catch has averaged 1.47 million t. Projections show that the stock is declining from above average levels and adjustments to the recent high quotas are likely. Part of the current management practice is based on a data-intensive single-species stock assessment where stock size estimates and estimates of uncertainty in stock productivity affect quota levels. Understanding how this component of management reacts to changes in pollock abundance is best carried out using management strategy evaluations (MSEs). Developing an operating model for an MSE should cover a broad set of plausible hypotheses and include changes in environmental conditions. Retrospective analyses are useful to evaluate errors in model structure that should be included for testing purposes. For example, retrospective patterns may be caused by a combination of factors including recruitment processes, natural mortality, somatic growth, and distribution (stock availability to fishery and surveys). In this study, the degree that environmentally driven process errors are considered in providing management advice is evaluated. Additionally, the impact of conducting regular pre-recruit surveys is compared for management performance contrast. Including environmentally driven process errors result in generally higher (perhaps more realistic) estimates of stock productivity uncertainty. Given the current risk-averse management policy, this result will mean lower quota recommendations. Using environmentally driven harvest control rules may reduce this degree of uncertainty, but the gains are marginal compared to results from improved surveys and monitoring.

Annex 9: Application of environmental information to assessment and management of California sardine

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Abstract

The California sardine resource undergoes large fluctuations in abundance on a time-scale of approximately 50 to 100 years (Baumgartner *et al.*, 1992). The population collapse of the mid-20th century is now widely considered a result of overfishing coupled with cooling ocean climate conditions unfavorable for sardine reproduction and survival. Links between sardine production and the environment were proposed more than 50 years ago (Clark and Marr, 1955, Marr, 1960, Radovich, 1960). Periods of warm sea surface temperature in the California Current System are associated with good recruitment and higher productivity. Sea-surface temperatures (SST) measured at the Scripps Institution of Oceanography pier (SIO; La Jolla, California) since 1916 are a good proxy for environmental conditions influencing positive or negative surplus production in California sardine. Jacobson and MacCall (1995) explored spawner-recruitment (S-R) models incorporating SST_{SIO} , and determined that a Ricker function with a term for three-year running average SST_{SIO} best explained recruitment variability. While the exact mechanism is unknown, environmentally-dependent surplus production models developed by Jacobson *et al.* (2005) further support the hypothesis linking SST to changes in habitat area, carrying capacity, and surplus production in California sardine.

Environmental information has been applied to both assessment and management of California sardine. Jacobson and MacCall's (1995) environmental S-R model was first implemented in population modelling with the introduction of CANSAR (Deriso *et al.* 1996), a variation of CAGEAN (Deriso *et al.* 1985) tailored to California sardine. Within CANSAR, the S-R model was used to constrain recruitment estimates in the terminal five years. CANSAR was used for annual sardine assessments from 1995 until 2004, when the SWFSC changed to 'ASAP', a more flexible modelling platform (Legault and Restrepo, 1999; Hill *et al.*, 2006). ASAP does not have the ability to include SST in the S-R model, so attempts are underway to resume this practice using 'Stock Synthesis 2' ('SS2'; Methot 2005, 2007). With regard to management, the temperature-dependent S-R model for California sardine was incorporated into simulations to evaluate a range of harvest control rule options for the Pacific Fishery Management Council (PFMC 1998). The harvest control rule adopted by the PFMC has the form: $H_{y+1} = (B_y - E) U f$, with $H_{y+1} < H_{MAX}$, where H_{y+1} is the harvest guideline for coming fishing year $y+1$, B_y is the stock biomass estimate at the beginning of the previous year y , E is a minimum escapement level (150 000 mt), U is the exploitation rate at F_{MSY} , f is the fraction of the stock assumed in U.S. waters, and H_{MAX} is the maximum allowable harvest level (200 000 mt). In an attempt to be responsive to environmental forcing, control rules were constructed with U_y for each year based on a regression function relating U_{MSY} to a range of average SST values. Under the current management policy, U_{MSY} is constrained to range 0.05–0.15 y^{-1} . The management approach for California sardine is unique in that relatively low harvest rates are allowed with the expectation of maintaining relatively high biomass and catch levels over the long term whilst allowing sufficient stock biomass to persist through periods of unfavorable environmental conditions.

Introduction

The California sardine has a well-documented history with respect to population dynamics, fishing, and climate change. The resource supported one of the largest fisheries in the western

hemisphere during the 1930s, but collapsed beginning in the mid-1940s, resulting in serial fishery closures from British Columbia, Canada, to Ensenada, Mexico (Figure 1). By the late-1960s, sardine only occurred off the southern Baja California Peninsula, and the State of California imposed a moratorium on directed sardine fishing that would last for twenty years.

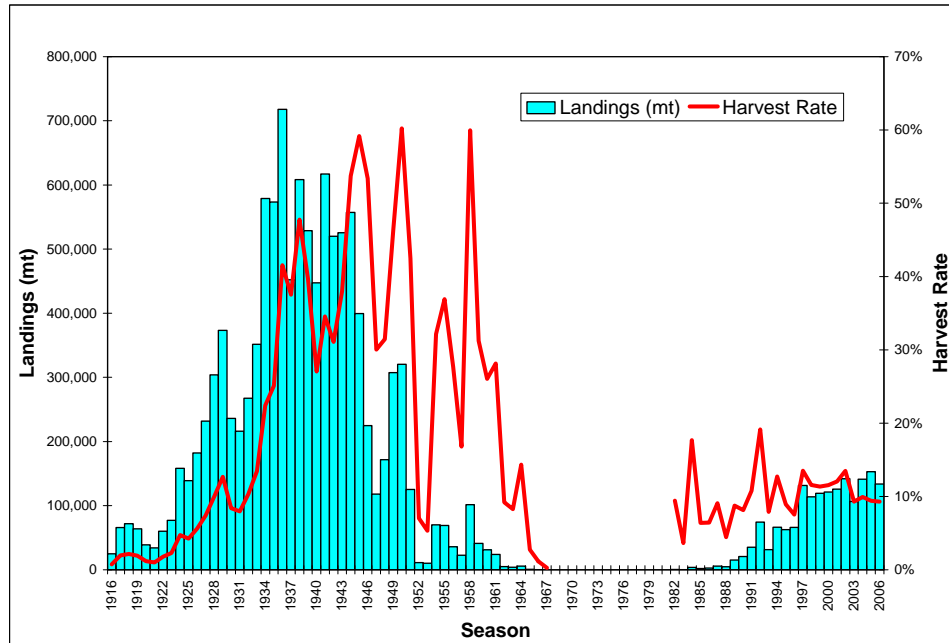


Figure 1. California sardine landings (metric tons) and harvest rate (catch/SSB) for the combined fisheries off northern Baja California, the U.S., and Canada since 1916.

Extreme natural variability and susceptibility to recruitment overfishing are characteristic of clupeoid stocks. Studies of sardine scale-deposition rates in marine sediments indicate extended periods of high and low abundance on a time-scale of approximately 50 to 100 years, even in the absence of fishing (Baumgartner *et al.*, 1992, MacFarlane *et al.*, 2002). The collapse during the mid-20th century is now widely considered a result of high harvest rates (Figure 1) coupled with a shift to cooler ocean climate conditions less favorable to sardine production (Figures 2–4). The most recent rebound (Figure 2) began after a shift to warm ocean conditions in the late 1970s, a change further punctuated by El Niño events in 1983 and 1992. The State of California declared the resource ‘fully-recovered’ in 1998–fostered, in part, through a conservative state management policy.

In anticipation of an expanded coast-wide sardine fishery, a U.S. federal fishery management plan (FMP) was developed in 1996–98 and implemented in 2000 (PFMC 1998). The federal FMP adopted the State of California’s conservative harvest approach for sardine, but also introduced use of environmental information into management advice. California sardine are an important yet relatively unique experiment in resource management. Under the federal FMP, annual catch limits for U.S. fisheries are established using a harvest control rule that accounts for current biomass, the need for a forage reserve, recent environmental conditions, and stock distribution across international borders.

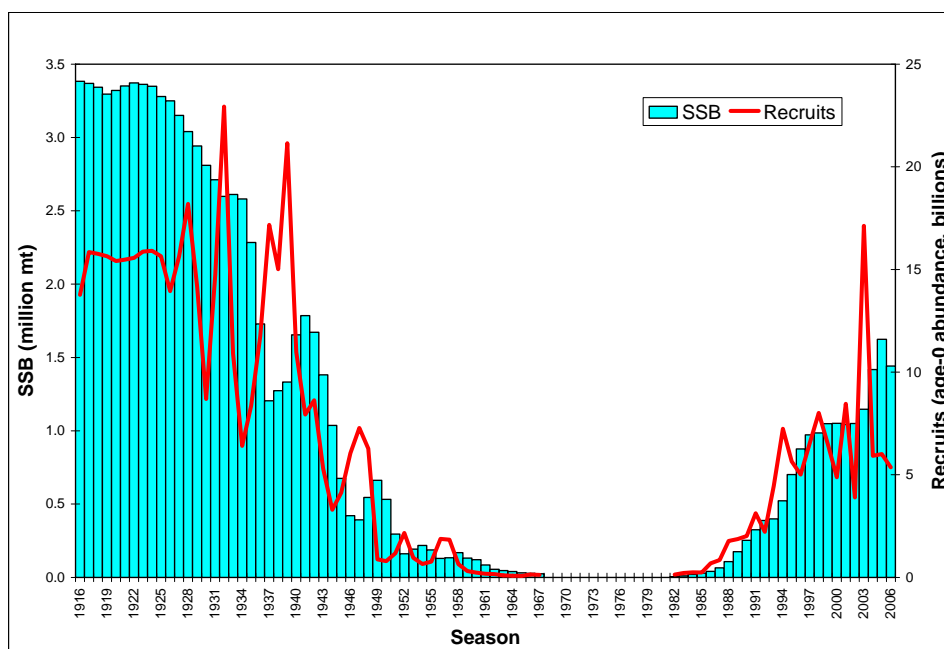


Figure 2. California sardine spawning stock biomass (SSB) and recruitment (age-0 abundance) estimates from an age-structured population model.

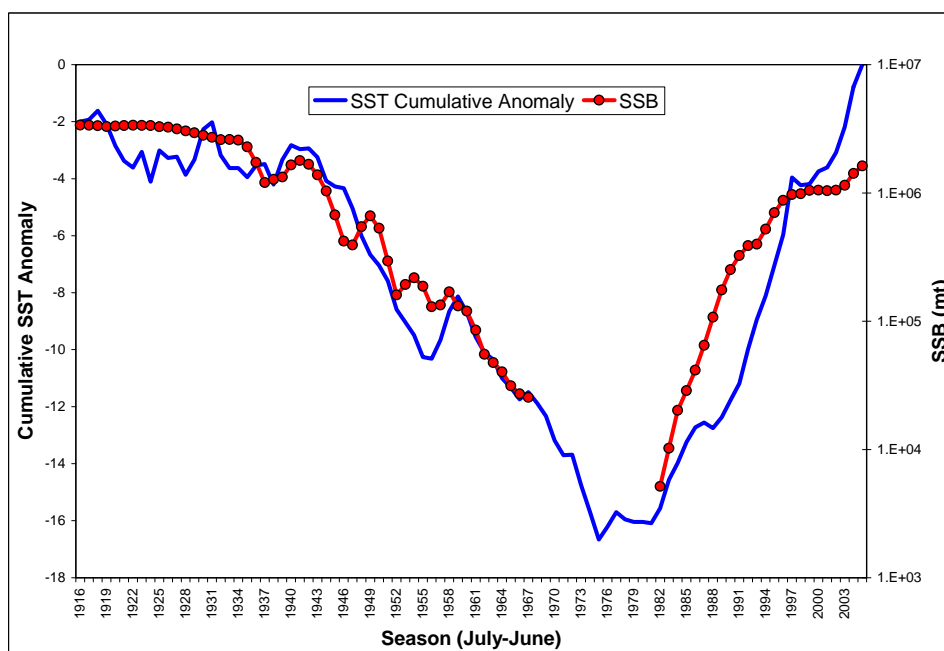


Figure 3. Integrated anomalies of sea-surface temperature at Scripps Pier (La Jolla, California) with California sardine SSB (log scale), since 1916.

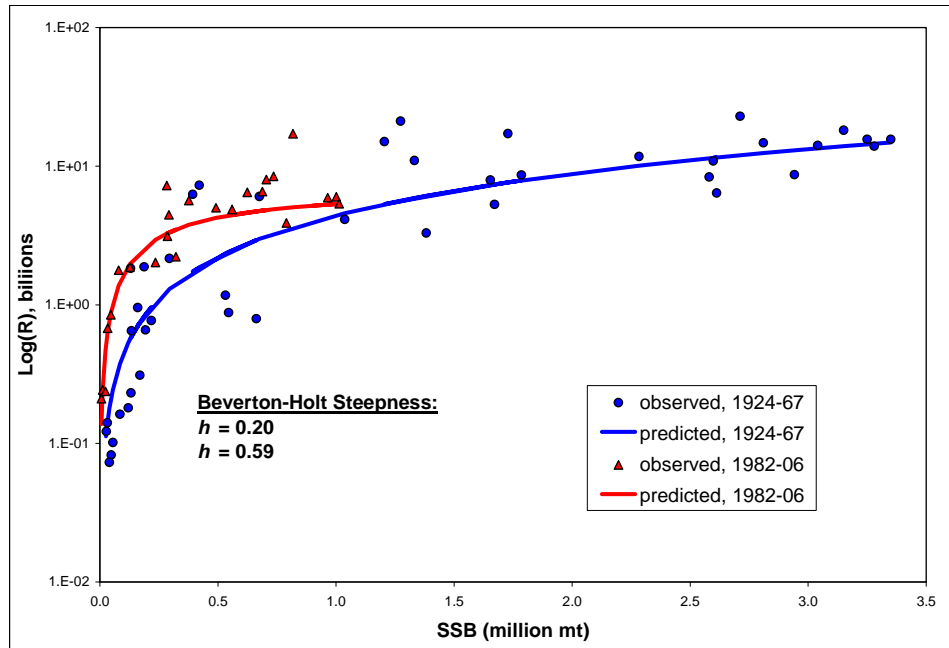


Figure 4. Beverton-Holt stock-recruitment estimates for California sardine during the historic decline (1924–1967) and recovery (1982–2006). Environmental data were not included in the models. The early period was characterized by very low steepness ($h=0.2$) in comparison to the recovery period ($h=0.59$).

Environmentally-Dependent Stock-Recruitment Models

Links between sardine productivity and the environment were proposed more than 50 years ago (Clark and Marr, 1955, Marr, 1960, Radovich, 1960). Major year-class failures and southward distribution shifts were attributed to lower ocean temperatures during the historic period. Conversely, periods of warm SST in the California Current are associated with good recruitment and higher productivity for California sardine (Lluch-Belda *et al.*, 1991, Jacobson and MacCall, 1995, Jacobson *et al.*, 2005).

Sardine recruitment success is generally autocorrelated and affected by environmental processes occurring on decadal time-scales. Sea-surface temperatures measured daily at the Scripps Institution of Oceanography pier ('SST_{SIO}', La Jolla, California) since 1916 are considered a good proxy for environmental conditions in the California Current, and have been widely used due to duration of the data set (Figure 3). Jacobson and MacCall (1995) used this information to develop environmentally-dependent spawner-recruit models for California sardine. They used historic biomass and recruitment estimates (Murphy, 1966, MacCall, 1979) and explored a variety of spawner-recruit models and averaging methods for the SST_{SIO} series. The best model to describe recruitment variability had the form:

$$\tilde{R}_y = S_y e^{\alpha + \beta S_y + \gamma T_y} \quad [1]$$

where R_y was the predicted number of age-zero sardine on 1 July of year y ; S_y was spawning biomass in April of year y ; and T_y was SST_{SIO} for the preceding three seasons (July-June).

Jacobson and MacCall's (1995) results suggest that equilibrium spawning biomass and potential sustained yield is highly dependent upon environmental conditions as indexed by SST. Based on their analyses, U_{MSY} estimates ranged 0.04–0.26 y^{-1} , B_{MSY} ranged from 700 to >4 000 thousand mt, and MSY ranged from 9 to 346 thousand mt for mean three season SST levels 16.5–17.3° C (Table 1). U_{MSY} and MSY were zero when mean three-season SST fell below 16.3° C (<3% of years). U_{MSY} , B_{MSY} and MSY at 17° C (average three-season SST) were 0.16 y^{-1} , 1,272 and 156 thousand mt (Table 1).

Table 1. Predicted equilibrium spawning biomass and MSY for California sardine for the inter-quartile range of temperatures (from Jacobson and MacCall, 1995).

MEAN THREE-SEASON SST (°C) AT SCRIPPS PIER	EQUILIBRIUM SPAWNING BIOMASS (MT)	MAXIMUM SUSTAINED YIELD (MSY)	SPAWNING BIOMASS AT MSY (B_{MSY})	U_{MSY} (%)
16.5	700 000	9 000	274 000	4
17.0	2 700 000	156 000	1 272 000	16
17.3	>4 000 000	346 000	1 819 000	26

Soon after publication, Jacobson and MacCall's (1995) environmental stock-recruitment model was incorporated into the statistical catch-at-age model, 'CANSAR' (Deriso *et al.*, 1996), which was employed for annual assessment and management for nine years (Hill *et al.*, 1999; Conser *et al.*, 2003). CANSAR used three-season SST data and spawning biomass to constrain recruitments to the S-R relationship-values that are particularly difficult to estimate for the terminal model years. Ideally, the model would re-estimate S-R parameters (α , β , and γ) for SST and spawning biomass as new data become available. This was not done in practice, because the assessment model started in 1983 and used shorter time-series with less information than the time-series used by Jacobson and MacCall (1995). For this reason, the model coefficients α , β , and γ of [1] were treated as fixed parameters based on Jacobson and MacCall's (1995) original estimates.

Beginning in 2004, sardine stock assessments changed from CANSAR to using ASAP, a more flexible modelling platform (Legault and Restrepo, 1999; Hill *et al.*, 2006). Unfortunately, ASAP does not have the ability to include SST data in the S-R model, so attempts are now underway to resume this practice using 'Stock Synthesis 2' (SS2; Methot 2005, 2007).

Environmentally-based harvest control rule for California sardine

With the recovery of the California sardine resource underway, and in anticipation of an expanded coast-wide fishery, a U.S. federal fishery management plan (FMP) was developed in 1997–98 and implemented in 2000 (PFMC 1998). In drafting sardine management options for the FMP, the PFMC's Plan Development Team used Jacobson and MacCall's (1995) environmental spawner-recruit model to estimate changes in deterministic MSY reference points. Fishery simulations were used to evaluate a range of parameterizations for the harvest control rule. The harvest control rule evaluated for sardine had the general form:

$$H_{y+1} = (B_y - E) U f \quad [2]$$

where H_{y+1} is the total allowable harvest (U.S.) for the pending management year; B_y is the total biomass (ages 1+) estimate for the middle of year y ; E is a fixed cutoff level for escapement (e.g. 150 thousand mt); U is the maximum harvest rate (that depends on environmental conditions in some cases); and f is the fraction of the stock distributed in U.S. waters (on average). For some simulations, the harvest rate parameter U was constrained to be no more than a maximum value (H_{MAX}) to prevent overcapitalization of the fishery.

The simulation model (written by Drs. Larry Jacobson and Richard Parrish of NOAA-NMFS) was a simple biomass dynamic approach for sardine ages 1 and older, with spawner-recruit calculations based on Jacobson and MacCall's (1995) SST-dependent Ricker model, including three-season SST_{SIO} data. Simulations included: 1) variability in recruitment similar to residuals from Jacobson and MacCall (1995); 2) SST data autocorrelated so that years of good and poor recruitment occurred on a decadal scale; 3) a weak 60-year cycle for three-season temperatures to mimic cycles in abundance described by Baumgartner *et al.* (1992). Simulated catches were based on the control rule [2], with simulated biomass estimates having 50% measurement error. Density dependence was solely assumed to affect recruitment. While model results were not considered completely realistic or accurate, they were useful for finding

patterns among various parameterizations and evaluating management options on a relative basis.

Changes in growth and fecundity of sardine in response to changes in biomass and environmental factors were not included in the simulations, because too little information was available at the time the work was conducted. This omission was unfortunate, because recent assessment research (Hill *et al.*, 2006; Lo *et al.*, 2007) indicates that variation in growth and fecundity is potentially important for sardine and could affect trends in biomass. Recent growth rates, for the period when sardine biomass was low and increasing, were used in the simulations. The simulated sardine stock may be more resistant to overexploitation than the real sardine stock, because relatively high recent growth rates were constant over time in the simulations.

Simulations were performed using the control rule [2] and a range of values for the parameters E , U_{MSY} , and H_{MAX} (Table 2). Values for E , the biomass escapement threshold, were 0, 50, 100, and 150 thousand mt. Values for U_{MSY} were fixed at either a constant value or environmentally-dependent. The environmentally-dependent control rules were constructed with U_{MSY} calculated annually from mean three-season SST based the following regression function fit to U_{MSY} estimates:

$$U_{MSY} = 0.248649805 T^2 - 8.190043975 T + 67.4558326 \quad [3]$$

where T is the average three-season sea surface temperature at Scripps Pier, California during the three preceding seasons. For the range of observed three-season SST values, $U_{MSY,t}$ ranged 0–0.88 y^{-1} (Figure 5). Based on historical SST data, $U_{MSY,t}$ might change from maximum to minimum values in about a decade. To prevent overly drastic changes in harvest rates, U_{MSY} values in the simulations were constrained to range 0.10–0.30, 0.05–0.25, or 0.05–0.15 y^{-1} (Table 2). H_{MAX} , the cap on maximum allowed harvest, was set to either 200, 300, or 400 thousand mt, or infinity. Good harvest control rules should perform at least as well the traditional harvest control rule $H_{y+1}=B_y U_{MSY}$ ($E=0$ and H_{MAX} is infinite), so constant exploitation rate policies were included as one of the standards in evaluating control rule parameters.

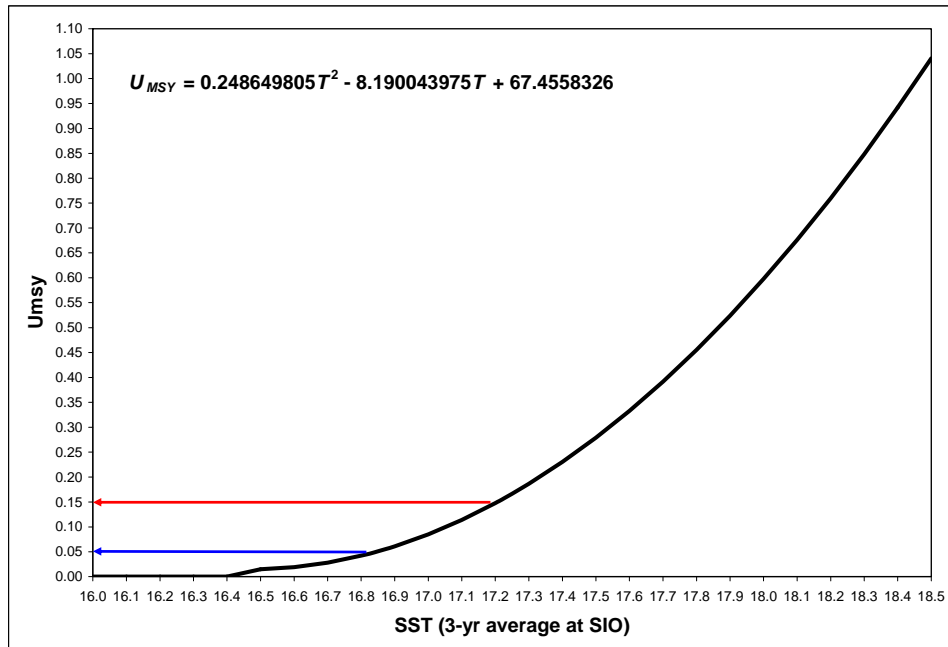


Figure 5. Modeled relationship between Umsy (=MSY/Bmsy) and mean three-season sea-surface temperature at Scripps Pier. Arrowed lines indicate range of Umsy for the adopted harvest control rule.

Performance measures were computed for each MSY control rule option or combination of control rule parameters based on simulations spanning 1 000 years. Performance criteria among options included: relative catch level (mean, median and standard deviation); biomass (mean, median and standard deviation); mean log catch; mean log biomass; proportion of years with biomass greater than 400 thousand mt; and proportion of years with no catch (due to fishery closure when $B_t < E$). Performance measures for the various options were presented to managers as per Table 2. Fishery managers ultimately chose ‘Option J’, where exploitation fraction (U_{MSY}) was environmentally-dependent (per [3]) and constrained between 0.05 and 0.15, escapement threshold (E) was 150 thousand mt, and maximum allowable catch (H_{MAX}) was 200 thousand mt. In practice, the harvest control rule implemented for sardine management has the form:

$$H_{y+1} = (B_y - 150,000) U_{(0.05-0.15)} 0.87 \quad [4]$$

where: H_{MAX} = 200 000 mt and U_{MSY} is based on SST per [3]. Managers chose this option because it: 1) gave biomass and catch levels comparable to or higher than the default management approach; 2) rebuilt overfished stocks in ten years or less; 3) minimized the proportion of years with no catch due to biomass being less than the cutoff level; 4) had relatively high cutoff (E) and low harvest rate (U) values; and 5) had maximum harvest levels (H_{MAX}) high enough to allow substantial harvest when sardine are abundant, while at the same time minimizing risk of overcapitalization.

Table 2. MSY control rule options considered for California sardine (PFMC 1998). Catch and biomass in thousands of metric tons.

OPTION:	A	B	C	D	E	F	G	H	I	J (CHOSEN POLICY)	K	L (STOCHASTIC F _{MSY})	M (DETERM. EQUIL. F _{MSY} IN A STOCHASTIC MODEL)
<i>Control Rule Parameters</i>													
FRACTION (U_{MSY})	20%	U_{MSY} (10-30%)	20%	U_{MSY} (10-30%)	U_{MSY} (10-30%)	U_{MSY} (5-25%)	U_{MSY} (5-15%)	U_{MSY} (5-15%)	U_{MSY} (5-25%)	U_{MSY} (5-15%)	U_{MSY} (10-30%)	12%	8.8%
CUTOFF (E)	50	50	100	100	100	100	100	100	100	150	50	0	0
MAXIMUM CATCH (H_{max})	400	400	400	400	300	400	400	300	300	200	200	Infinite	Infinite
<i>Performance Measure</i>													
Average Catch	151	159	165	171	165	177	179	169	169	145	141	180	170
Std. Dev. Catch	137	140	140	143	113	143	133	105	112	67	72	180	153
Mean Biomass	936	964	1073	1091	1280	1216	1543	1665	1400	1952	1516	1408	1784
Std. Dev. Biomass	27	27	29	28	34	32	39	42	37	49	43	39	43
Mean Log Catch	4.33	4.46	4.44	4.54	4.64	4.62	4.77	4.80	4.70	4.76	4.65	4.72	4.77
Mean Log Biomass	6.24	6.37	6.50	6.59	6.75	6.74	7.06	7.15	6.89	7.34	6.87	6.89	7.24
Percent Years Biomass>400	61%	64%	70%	73%	79%	81%	90%	92%	84%	96%	79%	84%	93%
Percent Years No Catch	5%	2%	7%	4%	3%	2%	1%	0%	1%	0.5%	1%	0%	0%
Median Catch	103	104	119	121	148	131	140	156	158	182	188	128	127
Median Biomass	598	600	700	748	898	850	1248	1349	1048	1648	1099	1500	1049

Responses of harvest and harvest rate to the chosen control rule are presented in Figure 6 for a range of biomass and temperature. During persistent warm conditions (3-season SST ≥ 17.21 °C; $U_{MSY}=0.15$), harvest levels change linearly in response to changes in biomass, ranging from $H=200$ thousand mt at $B=1.69$ million mt, ramping down to $H=0$ mt at $B=150$ thousand mt. Corresponding U.S. harvest rates (H/B) decrease exponentially from 12% down to 0% over the same biomass range. During cooler ocean conditions (3-season SST ≤ 16.84 °C; $U_{MSY}=0.05$), U.S. harvest levels drop to one-third of those allowed under warmer conditions, and U.S. harvest rates do not exceed 4% of the available biomass (Figure 6).

The management approach for California sardine is unique in that relatively low harvest rates are used with the expectation of maintaining relatively high biomass and catch levels over the long-term (Herrick *et al.*, 2006). The approach works well in simulations because exploitation rates, which are lower in general than for most pelagic fisheries, should allow sufficient stock biomass to persist through periods of unfavorable environmental conditions. When simulated environmental conditions become more favorable, stock biomass and catches increase to relatively high levels before the environment becomes unfavorable again. Thus, the best control rule balances the ‘capital reserve’ (B_y with no harvest when $B_y \leq E$) of the sardine stock, the period of environmental changes, stock productivity, and exploitation rate.

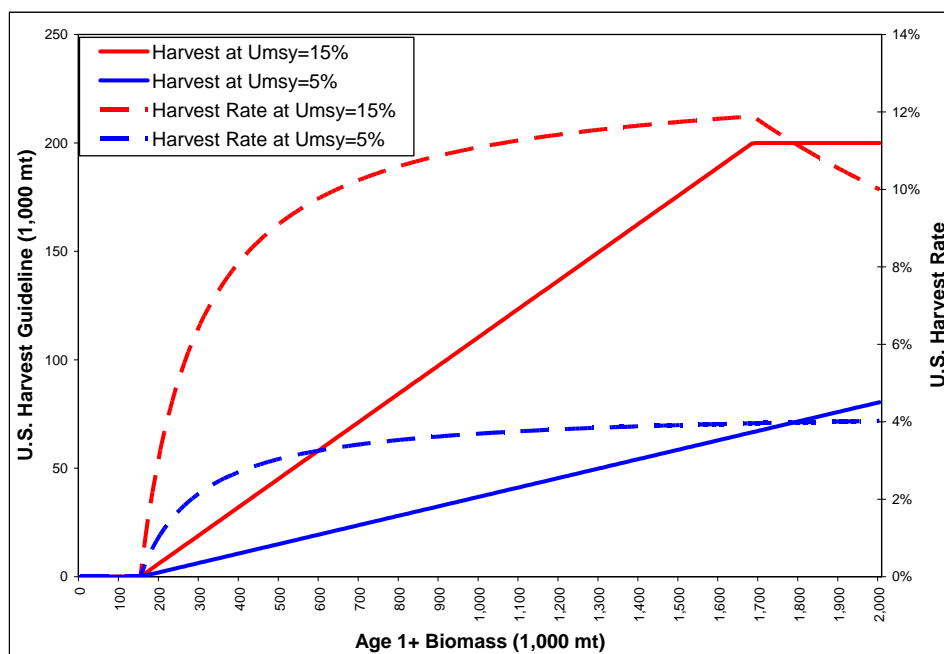


Figure 6. Total allowable U.S. catch and resultant harvest rate under the temperature-based control rule adopted by the Pacific Fishery Management Council.

Harvest control rule performance since implementation

The control rule has been used to establish U.S. sardine harvest limits for the past eight fishing seasons. The resource and fisheries have continued growing, and management has focused more on preventing overcapitalization and restructuring regional allocation. The resource has outgrown expansion of the fishery, so the U.S. fishery has yet to harvest all of the allowable catch for a given year (Figure 7). Effectiveness of the control rule is difficult to gauge during a period of high productivity when catches are lower than allowed levels.

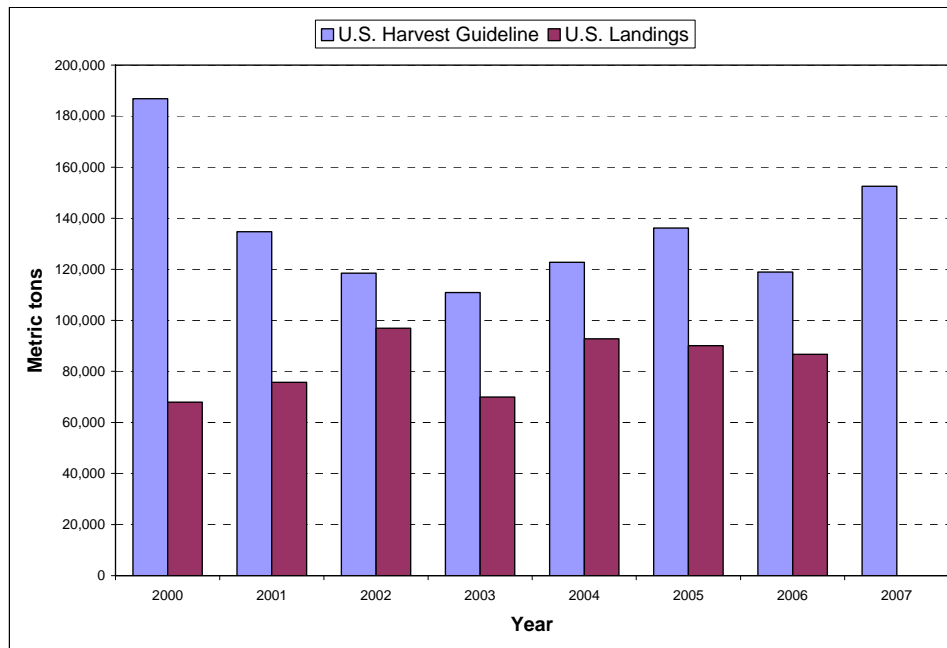


Figure 7. U.S. Pacific sardine harvest guidelines and resultant landings (mt) since the onset of PFMC management in calendar year 2000.

SST data have been used in the harvest control rule throughout a period of productive, warm conditions (Figure 8). The SST component of the control rule has thus far stayed at the maximum value ($U_{MSY}=0.15$). A significant drop in average SST occurred in 2001, and managers came close to invoking environmentally-based reductions in harvest (Figure 8). The use of Scripps Pier SST data-collected from a point source at the southernmost end of California-to manage the coastwide fishery immediately came under criticism from the Oregon and Washington fishing industry, located 1 200 miles away. Some members of the industry made immediate requests for reanalysis of the harvest control rule and inquired as to alternative sources of environmental data. SST has since increased to ‘safer’ levels (Figure 8), so the issue has subsided for the present.

The environmental component has also been criticized for functioning over a very narrow range of temperatures. The control rule constrains U_{MSY} between 0.05 and 0.15 to prevent drastic interannual changes in harvest and create a more stable fishery. The range of temperatures between minimum and maximum U_{MSY} is 16.84 to 17.21°C-a difference of less than 0.4 °C (Figure 8). When the control rule is applied to the three-season SSTs observed since 1916, it is clear that there are relatively few years where U_{MSY} falls between the range (Figure 9).

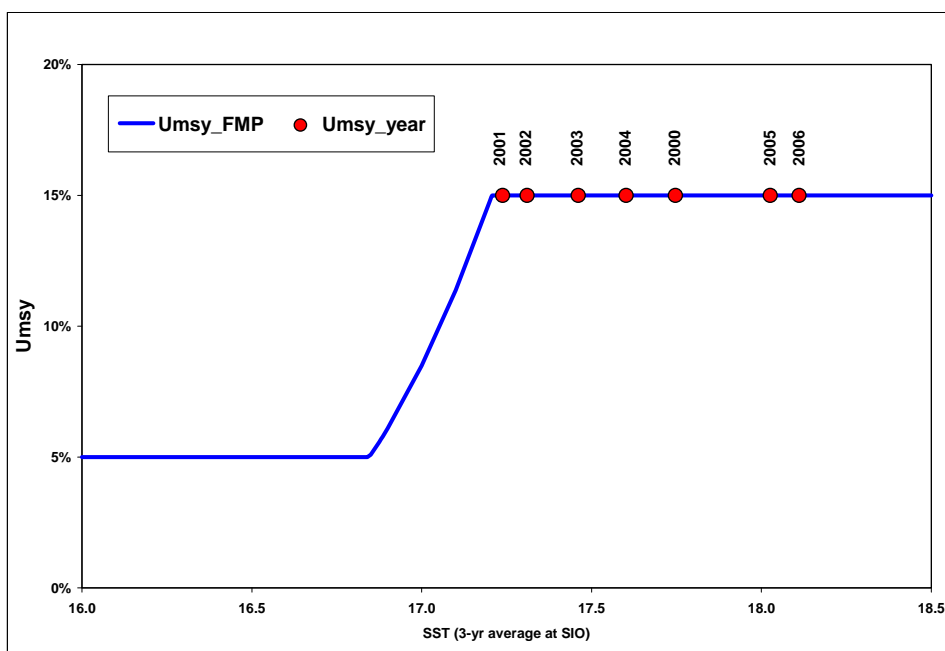


Figure 8. Relationship between Umsy (=MSY/Bmsy) and mean 3-season sea-surface temperature at Scripps Pier as implemented in the harvest control rule since 2000.

The result is a control rule that potentially changes allowable harvest by a factor of three, from one year to the next, based on temperature alone. Fishing industry and some fishery managers have expressed a desire to smooth the transition in harvest rates and prevent such drastic cuts for occurring. One alternative could be to use a constant, but more conservative, exploitation fraction (e.g. $U_{MSY} = 0.08$), perhaps with a higher threshold (E).

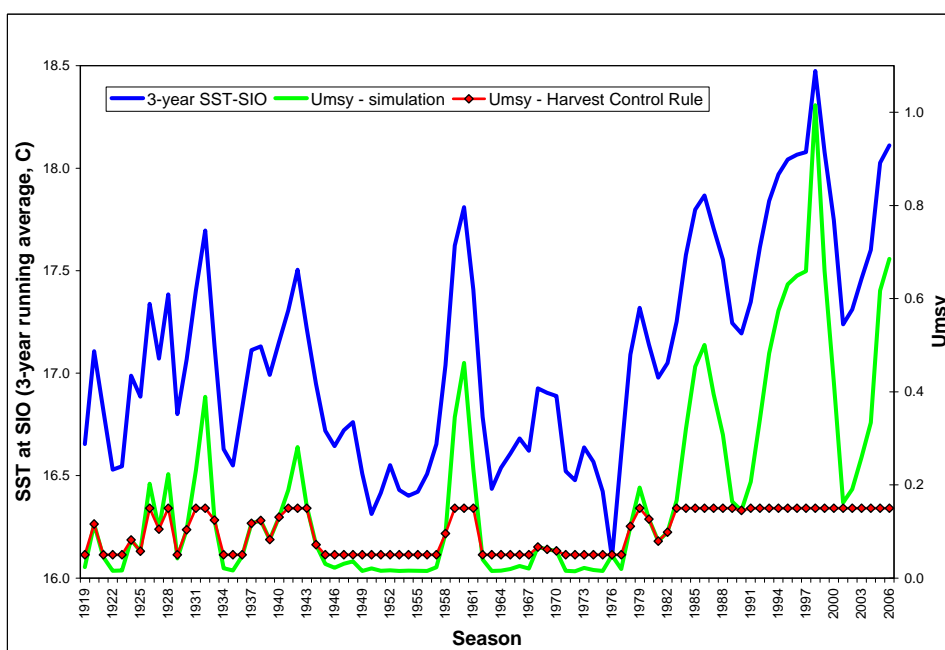


Figure 9. Mean 3-season sea-surface temperature at Scripps Pier, with Umsy as estimated in simulations and as applied in the harvest control rule.

The management approach for California sardine uses low harvest rates relative to other fisheries for small pelagic fishes. The long-term management goal of the PFMC is to maintain relatively high biomass and catch levels, allow for adequate forage reserves, and minimize the number of years with no fishing. The experiment is ongoing and its success may depend more on whether managers maintain low harvest rates, than on the strength, or even the existence, of a link between recruitment and environmental conditions.

Relevance of SST data from Scripps Pier

Questions have arisen as to the relevance of SST_{SIO} to sardine productivity spanning the west coast of North America. The current scientific consensus is that SST_{SIO} is a reasonable index for physical and ecological change in the California Current, and that SST_{SIO} can serve as a reasonable proxy for processes affecting sardine productivity over the short- and long-term. Norton and Mason (2005) compared various physical indices for the Pacific region and found that cumulative change measured in SST_{SIO} was also reflected in Darwin sea-level pressure, SST indices for the equatorial Pacific, among others. SST_{SIO} is correlated with SST collected at other stations along the west coast of North America (Figure 10), and is also correlated with model derived SST from the COADS and Hadley ocean grid databases.

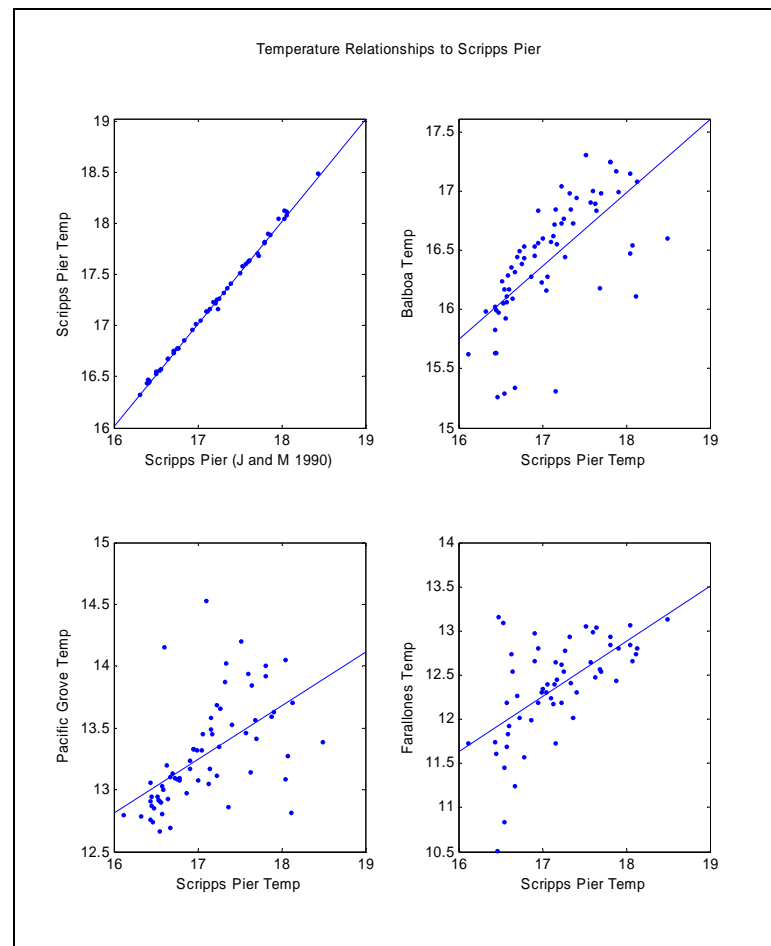


Figure 10. Correlations between mean three season (July 1 to June 30) sea surface temperatures at Scripps Pier, Balboa Pier, Pacific Grove and the Farallon Islands (California) compared to three season mean temperatures calculated by Jacobson and MacCall (1995). Figure courtesy of Christian Reiss, SWFSC.

In absolute terms, SST differs substantially across the geographic range of the stock (northern Baja California, Mexico to British Columbia, Canada and from the coast to at least 320 km offshore in some locations). However, the SIO_{SST} time-series is utilized as a relative measure

of ecological changes affecting system productivity, carrying capacity, sardine spawning habitat size, and/or survival to recruitment. Environmentally-dependent surplus production (EDSP) models developed by Jacobson *et al.* (2005) support the hypothesis linking changes in habitat area, carrying capacity, and surplus production in California sardine. EDSP models fit better than a conventional Fox surplus production model without environmental (COADS) data. Both MSY and B_{MSY} depend on habitat area and environmental conditions.

The SIO_{SST} , biomass, and recruitment time-series used by Jacobson and MacCall to identify environmental and density dependent effects on sardine recruitment had the advantage of being relatively long (1935–1963 and 1985–1990), and the SST values were direct observations as opposed to modeled estimates (e.g. COADS). The management and modelling approaches used for California sardine might not be practical for other stocks with short time-series.

Transboundary management

Management of transboundary stocks is one of the more difficult problems in fisheries. Ideally, California sardine stocks would be managed based on an agreed policy between the U.S., Canada, and Mexico. No such policy exists at present. In recent years, DFO-Canada has set annual catch limits based on a 10% fraction of the U.S. harvest guideline, but their fishery has taken much smaller amounts. Mexico limits minimum fish size, but does not limit total harvest. In the absence of a cooperative management agreement, the default approach in the U.S. FMP sets harvest levels for U.S. fisheries by prorating the total target harvest level according to the average portion of the stock resident in U.S. waters. The current estimate of the portion of sardine stocks in U.S. waters (87%) is controversial. The best management approaches of a single nation will not insure long-term stability of the sardine resource and fishery in the absence of international agreements. The next extended cold period in the California Current will likely result in a collapse in sardine productivity coupled with southward movement of the remaining stock into Mexican waters, where there are no limits on catch. Collaborative assessment and management will be crucial to minimizing severity of the next collapse.

Acknowledgements

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Annex 10: Potential improvements of the management advice of Northeast Arctic cod by active use of environmental information

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Abstract

Three aspects linked to the management advice process of Northeast arctic cod have been studied; 1. Changes in the geographical distribution, 2. Recruitment predictions and 3. Food availability and growth.

Around 1980, intense cooling caused a redistribution of the cod in the Barents Sea towards the south and west. High fish densities and thus catch per unit effort were maintained in this area, in spite of the stock declining rapidly. The result was advices of too high TAC. Similar problems occurred e.g. with thorny skate in Canadian waters. In Norwegian waters regular bottom trawl surveys were initiated to account for such effects based on swept area considerations. However, around 1990, the temperatures increased considerably, and the distribution of young cod was extended towards north and east, well beyond the survey area. This resulted in several years of underestimates of the recruitment.

Different methods of recruitment predictions including environmental information are evaluated. Two statistical models are used, one purely based on observations of temperature, capelin and 1-group cod, and one purely based on numerical model results of volume transport and primary production. By going back in time, the actual predictions made by ICES annually are compared with the predictions we could have made at the same time by using the recently obtained methodology. The results are also compared to the converged VPA. The third method is based on analysing the influence from temperature and pre-recruit cannibalism on stock- recruitment relations through probabilistic prognosis with a multispecies population dynamics model.

The individual growth of cod has shown to be quite dependent on the availability of capelin in some periods. The ICES growth prediction in 1987 for the next two years was too high, while the prediction in 1989 was too low. This analysis demonstrates how different the short term catch advice would have been for 1988 and 1990 if the growth (and thus weight-at-age) had been predicted correctly.

Introduction

In present-day fishery management, species interactions and relations between living resources and the environment are considered only fragmentarily and in rare cases. The management of fish in the Northeast Atlantic is mainly focused on keeping the spawning stock high enough for the recruitment not to be severely hampered (based on limit reference points), with no or little consideration of what is good management in the long run (target reference points).

For many years we have talked about “the ecosystem approach to (marine research and) fisheries (ecosystem) management”. There are many opinions about what this actually means, but with respect to research, we choose to define it simply as: an approach towards considering the most important driving forces on, and the processes within, ecosystems. While there are many important processes involved, the two main driving forces on most ecosystems in the northern North Atlantic are climate (or the physics), and fishing (Svendsen *et al.*, 2007). In some areas, fertilization, pollution, introduction of new species and/or habitat disturbance may also be important drivers, but so far none of these are considered important in relation to the Northeast Arctic cod.

The effects of exploitation on macroecological patterns have received only limited attention (Fisher & Frank, 2004). Abundance-distribution relationships have been found over a broad range of species (Gaston *et al.*, 1998), and such relationships may be useful for highlighting species of concern.

In this paper we consider both interactions between fish stocks as well as information about other parts of the biotic and abiotic environment of the fish stocks as ‘environmental information’. In particular, our emphasis will be on the Northeast Arctic (NA) cod stock for which there are annual assessments and a range of associated studies relating environmental information to stock dynamics.

We discuss the following environment/management advice issues:

- insufficient stock assessment related to varying cod distribution due to varying temperature.

- potential “early warnings” through predictions of cod recruitment regulated by temperature, currents, primary production and/or prey abundance.

- probable impact on TAC advice of better growth (and thus weight-at-age) predictions, based on food availability.

Data and methodology

The assessment data are taken from the latest ICES Arctic Fisheries Working Group (AFWG) report (ICES 2007).

It should be noted that the short-term predictions, from which the TAC advice is derived, are based on estimates of present stock size, as well as predictions of recruitment to the fishery (at age 3 for this stock), weight, maturity and natural mortality-at-age, as well as exploitation pattern. Error in any of these components will cause error in the predictions. The advice is also based on reference points and harvest control rules. As long as these are based on the converged part of the VPA time-series of number-at-age, they will not be directly affected by errors in prediction. However, in a harvest control rule the fishing mortality may be dependent on stock size (e.g. for cod F is reduced when $SSB < B_{pa}$). Thus the effect of the prediction error on the TAC advice may be larger than the error in prediction of stock size alone would indicate.

The numerical model result is taken from Svendsen *et al.* (2007). The NORWegian ECOlogical Model system (NORWECOM) is a coupled physical, chemical, biological model system (Aksnes *et al.*, 1995; Skogen *et al.*, 1995; Skogen and Søiland, 1998) applied to study primary production, nutrient budgets and dispersion of particles such as fish larvae and pollution. The model has been validated by comparison with field data in the North Sea/Skagerrak in e.g. Svendsen *et al.* (1996); Skogen *et al.* (1997); Søiland and Skogen (2000); Skogen *et al.* (2004).

The chemical-biological model is coupled to the ROMS physical model (Budgell, 2005) through the subsurface light, the hydrography and the horizontal and the vertical movement of the water masses. The prognostic variables in addition to the physics are dissolved inorganic nitrogen, phosphorous and silicate, two different types of phytoplankton (diatoms and flagellates), two detritus (dead organic matter) pools (N and P), diatom skeletal (biogenic silica), inorganic suspended particulate matter and oxygen. The model is fully described in Skogen and Søiland (1998).

Results

Distribution and assessment

Changes in the geographical distribution of fish stocks due to environmental effects may seriously influence our perception of stock abundance. Figure 1a illustrates how estimates of catch per unit of effort (cpue) of NA cod were maintained during a period of pronounced stock decline. The major explanation for this paradox is that, in 1979–1981, intense cooling caused

a redistribution of NA cod to the southern and western part of the Barents Sea (Figure 1b), resulting in the maintenance of fish densities and thus catch per unit of effort in the Norwegian fisheries, although the stock declined rapidly. Since cpue time-series at that time was the main data to the stock assessment in addition to the catch-at-age data, stock abundances were overestimated in the annual stock assessments for several years.

In order to improve stock assessments, fisheries independent data on stock abundance were required, and since 1981 a bottom trawl survey has been carried out in February-March in the Barents Sea (Jakobsen *et al.*, 1997). The results from the survey are indices of abundance at age based on swept area considerations. The survey area chosen in 1981 remained unchanged until 1992. It covered well the distribution of cod throughout the 1980s. However in 1989–1990 the sea temperature increased substantially and the distribution area of young cod was extended towards northeast well beyond the area covered by the survey. The result was that the survey indices for the younger ages became too low and the recruitment estimates in the assessments undertaken in the early 1990s also became too low. In 1993 the area covered by the survey was extended considerably.

In comparison the collapse of the northern cod stock at Newfoundland co-occurred with a hyper aggregation of the cod at low stock abundance. This increased the cpue, in spite of a strong reduction in population abundance, and is likely to have contributed to the collapse of this stock (Rose & Kulka, 1999). Knowing how a stock responds spatially to changes in abundance and climate can therefore be important to prevent stock collapse. Another case is presented in Figure 2 for the thorny skate fisheries at Newfoundland (Kulka *et al.*, 2004). The analyses of spatial dynamics from fishery-independent survey data have revealed changes in the skate populations that would otherwise be difficult or impossible to detect, using aggregated statistics from commercial or survey sources. In addition to changes in relative biomass, thorny skate has also undergone substantial changes in its distribution since the 1980s (prior to the beginning of its decline in biomass).

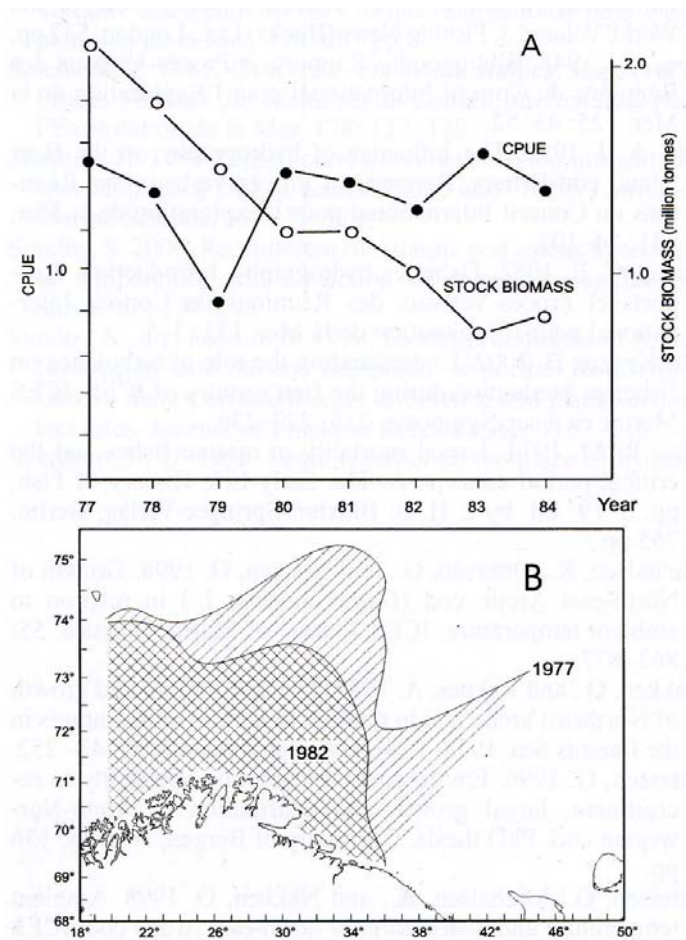


Figure 1. A: Development of the Northeast Arctic cod stock and the catch per unit effort (cpue) during the period 1977–1984. B: Cod distribution in 1977 and 1982

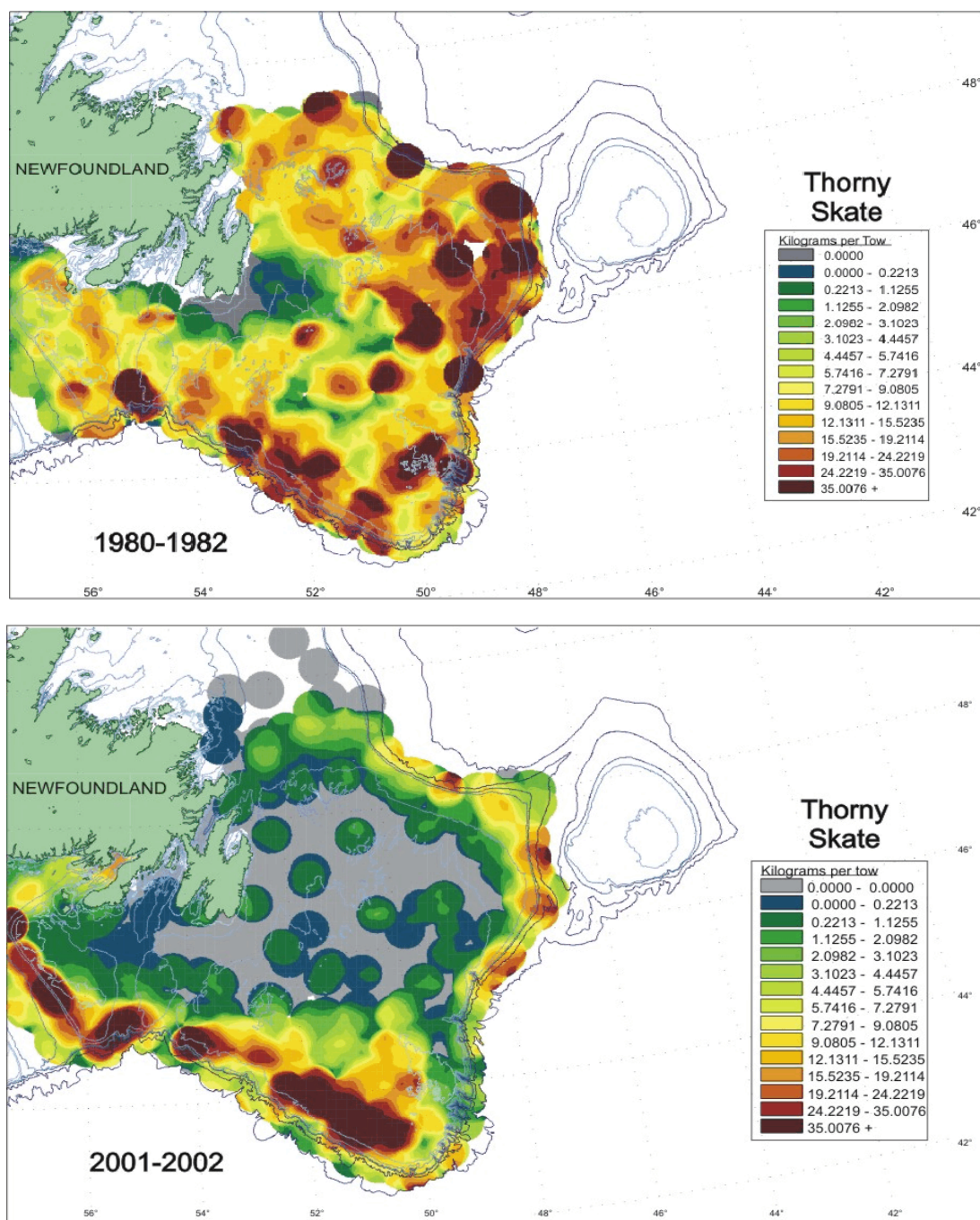


Figure 2: Distribution of thorny skate, 1980–1982 compared to 2001–2003 based on research trawl surveys. Grey area represents surveyed area with no catch. Brown areas represent highest concentrations (after Kulka *et al.*, 2004).

Recruitment predictions

When discussing recruitment to the Northeast Arctic cod stock in an assessment/management advice context, we usually talk about the recruitment of 3-year old fish. In this paper we will only consider short-term predictions of recruitment, and will not address the issue of spawning stock-recruitment relationships.

ICES predicts this recruitment of this stock for the assessment year, for the following year and for the year after. This means that the recruitment of the year classes which have been born, but not yet entered the fishery, is predicted. The predictions have been based on survey estimates of 0, 1, 2 and 3-group fish, and since the late 1980s the computer program RCRTINX2 and its successor RCT3 (Shepherd, 1997) has been the basis for the recruitment estimates. This program makes regressions between multiple recruitment indices and the

recruitment calculated by VPA. The only information used in these regressions is recruitment indices (including spawning stock biomass) and age 3 recruitment as estimated by VPA. The age at which the recruitment indices are observed, is not taken into account. It should be noted that in the recruitment values calculated by RCT3 are not always used in the predictions, e.g. in cases of low recruitment the average value of the 10 weakest year classes has been used.

Recently there has been some work done trying to improve these predictions by taking into account environmental impacts on the larvae and juvenile stages (Svendsen *et al.*, 2007, Huse and Ottersen, 2002, Stiansen *et al.*, 2002, Stiansen *et al.*, 2005). While Svendsen *et al.* do not take into account any survey indices or estimates of stock sizes, and only uses model results of physics and primary production for the cod recruitment prediction, the Stiansen and Huse and Ottersen methods are based on temperatures and different time-series of cod and capelin.

Also the impact of capelin abundance on cod recruitment (due to cannibalism) has been studied e.g. by Hjermann *et al.* (2007) and Yaragina *et al.* (2007). The cod cannibalism-capelin relationship has also been included in various multispecies population models (Bogstad *et al.*, 1997; Schweder *et al.*, 2000, Hamre, 2003, Lindstrøm *et al.*, 2007, Sigurd's models) and one may consider running such models in the future in order to give short-term recruitment predictions for all the species involved.

The two-year prediction based on Stiansen *et al.* (2005) together with the ICES predictions are shown in Figure 3.

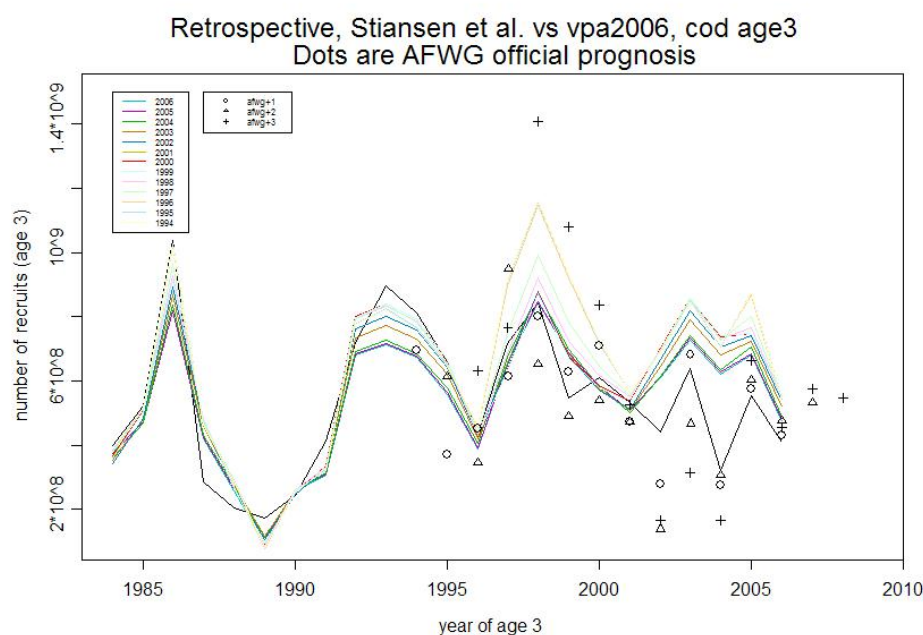


Figure 3. Retrospective analysis of cod recruitment. The black line is the VPA for age 3 from the AFWG 2007 assessment (ICES 2007). The coloured lines are from the Stiansen *et al.*, 2005 model, simulating different periods of knowledge (see legend). The point are the official AFWG prognosis of the recruitment for the given year, estimated 1–3 years before (see legend).

Here it is clearly seen that the Stiansen prediction taking into account the temperature, the amount of capelin (indirectly affecting cannibalism) and the number of one-year old juveniles observed in surveys is superior to the longest ICES predictions (+ in the Figure), while the shorter ICES predictions usually are significantly better due to observations of the younger fish.

Similarly the 2–3 year predictions by Svendsen *et al.*, 2007 (being produced at the beginning of the year after the year of spawning) together with the 2–3 year ICES predictions are shown in Figure 4. This indicates that early blooming is important for zooplankton production, and they hypothesize that too strong flows through the Barents Sea during fall may bring the

juveniles so far north and east that they are hit by the cold bottom water formation during the following winter with massive mortality.

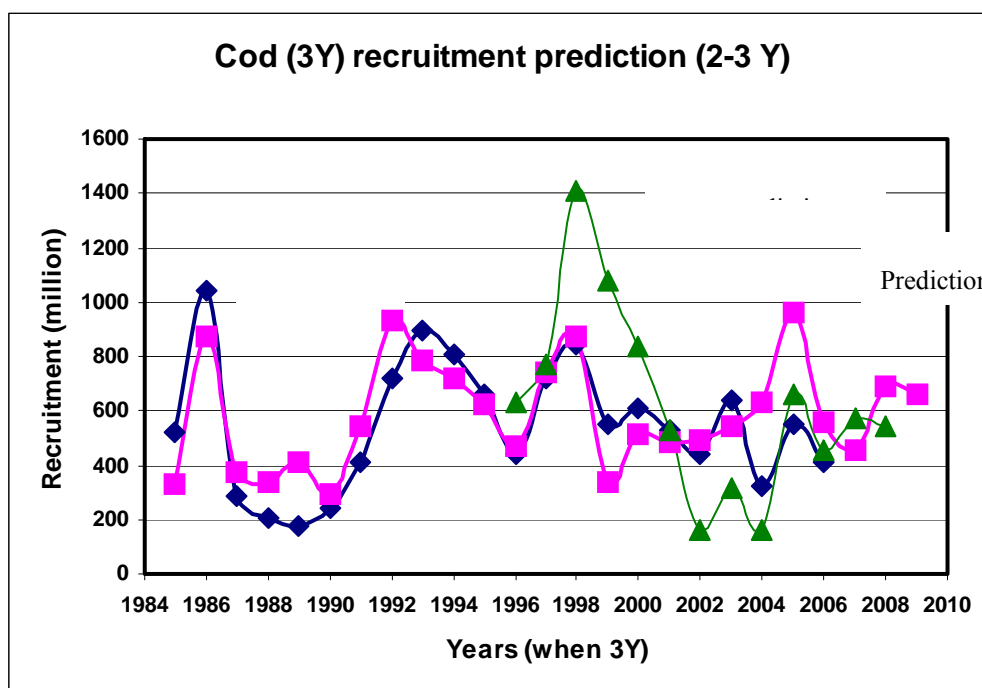


Figure 4. 2–3 year prediction (pink) of the recruitment based on the numerically modeled inflow of Atlantic water to the Barents Sea during autumn and the modeled primary production in April, both during the year of spawning, together with the “converged” ICES latest VPA estimates (black, assumed to be the “truth”) and the 2–3 year ICES predictions (green).

It is interesting to see how far off ICES were in their too high predictions for 1998, 1999 and partly 2000, and their too low predictions for 2002 and 2003, while the Svendsen/Stiansen predictions for these years were quite good. However, it must also be said that the Svendsen/Stiansen methods predicts the 2001 year class (age 3 in 2004) to be around average, while it has shown up as a weak year class in all surveys conducted so far. It is not within the scope of this paper to speculate on what caused the errors in the ICES predictions.

In Figure 5 the 2–3 year prognosis of all the models are shown together, where the prognosis are just based on the information available up to the time of giving the forecast. This means that the first prognosis for 1996 is based on information from 1982 to 1993 (for Svendsen *et al.*). It is interesting to note that all models converge during the last years. Both the Svendsen *et al.* and the Stiansen *et al.* models seem most of the time to give a more correct picture of the recruitment than the official AFWG prognosis. It should be mentioned that the retrospective runs (going back one and one year) uses the VPA 2007 recruitment as response variable in the regressions.

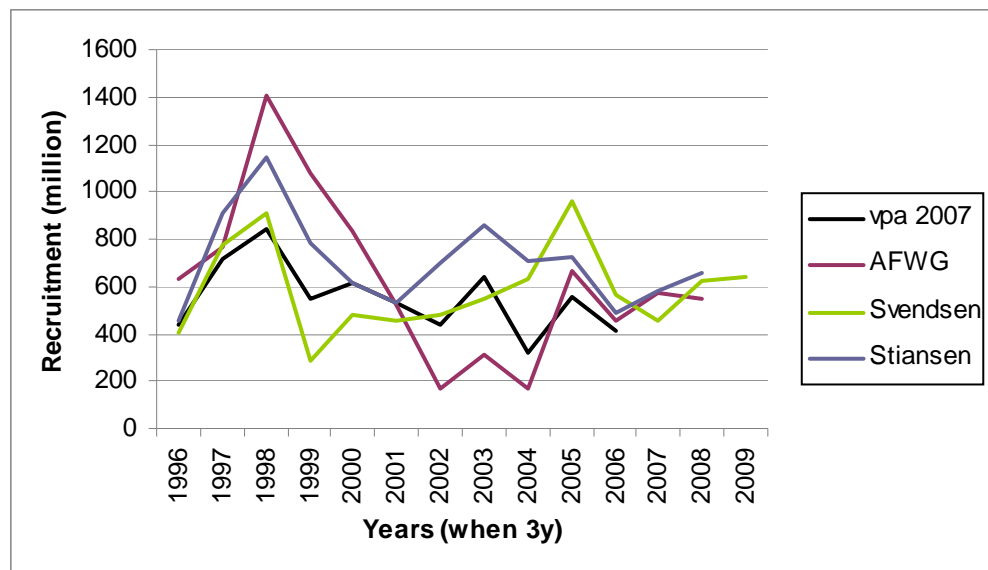


Figure 5. 2–3 year predictions given by AFWG (red line), Stiansen *et al* (purple line) and Svendsen *et al* (green line). The black line is the AFWG 2007 assessment (ICES 2007).

The question is; could these improved predictions just before and after the turn of the millennium have given any improvements to the advice? Probably not, since at this time the main advice was just the short-term advice for the next year TAC. However, we may assume that the too optimistic ICES predictions for the end of the 1990s, given two years earlier, may have contributed to a too optimistic TAC advice which resulted in a declining stock. Similarly, the too pessimistic ICES predictions may partly be the cause for reduced TAC and the following stock increase.

Food and growth predictions

The individual growth of Northeast Arctic cod (*Gadus morhua*) showed large fluctuations in the period 1985–1992 (Mehl and Sunnanå, 1991, ICES 2007, Figure 5). These changes have been related to the collapse and recovery of the Barents Sea capelin (*Mallotus villosus*) stock (Gjøsæter, 1998, ICES 2007, Fig. 5).

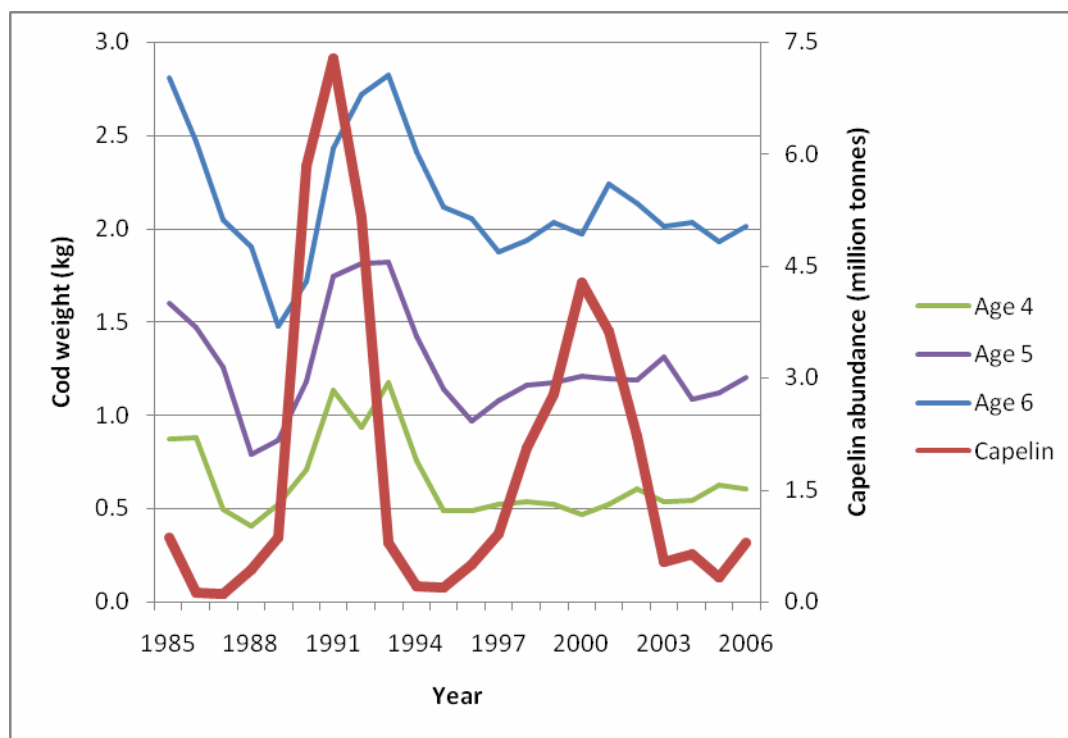


Figure 6. Individual weight-at-age in stock (kg) for NEA cod age 4–6, and capelin stock abundance (acoustic survey estimate) for the period 1985–2006.

These growth variations had dramatic consequences (Nakken, 1994). The 1987 predictions from ICES (Arctic Fisheries Working Group) of stock biomass development in 1987–1989 were too high and so was the recommended catch quota (TAC) for 1988. Conversely, the predictions made in 1989–1990 were too low, as the growth (and thus size-at-age) increased to a level above that observed in 1985 and preceding years. The impact of the catch advice was much less during this period, however.

In this paper, we will calculate what the catch advice for Northeast Arctic cod would have been for 1988 and 1990, if the growth (and thus weight-at-age) had been predicted correctly. Since the advice depends on the spawning stock biomass, which also is a function of the maturity ogive, we make the additional assumption that the maturity-at-age also would have been predicted correctly. Finally, we will discuss what can be learned from this exercise concerning future predictions of cod growth.

The TAC advice for 1988

The predictions and corresponding advice made for Northeast Arctic cod autumn 1987 (ICES, 1988) were revised before the May 1988 ACFM meeting, as it became evident that the predictions of weight-at-age were much too optimistic. It has later also been realised that the estimates of abundance (number-at-age) at the beginning of 1987 made by AFWG in 1988 were too optimistic.

Some key figures are given in Table 1.

Table 1. Stock sizes and TAC advice in 1987–1988 for various assessments and assumptions. (Unit: Thousand tonnes, TSB: Total stock biomass, SSB: Spawning stock biomass, TAC: Total Allowable Catch, F5-10: Fishing mortality, age 5–10 (arithmetic mean)).

ASSESSMENT	SSB 1987	TSB 1987	F5-10 1987	CATCH 1987	SSB 1988	TSB 1988	TAC ADVICE 1988 (F=0.51)
AFWG 1987	351	1499	0.80	545	540	1961	530
AFWG 1987 correct weights and maturity	164	1407	0.93	523	305	1288	384
AFWG 2007	121	1126	0.95	523	203	916	259

The TAC advice for 1988 made by ACFM autumn 1987, based on the 1987 AFWG report, was 530 thousand tonnes. This was revised to 320–360 thousand tonnes in May 1988 based on new information on weight and maturity. The TAC for 1988 was set to 590 thousand tonnes, but revised downwards to 451 thousand tonnes in mid-year following the ACFM advice. The actual 1988 catch was 435 thousand tonnes.

We see that the stock abundance in 1988 was severely overestimated by ICES. Most of this overestimation (difference between first and second line in Table 1) was due to overestimation/too optimistic prognosis of weight and maturity-at-age in 1987–1988. The overestimation was, however, also due to overestimation of stock numbers at the beginning of 1987 and recruitment in 1988, causing the difference between the second and third line in Table 1. In particular, the recruitment at age 3 in 1987–1988 (1984 and 1985 year classes) were overestimated by 50–70%. The recruitment prediction models presented earlier simulate these low recruitments more correctly, but at that time we would not have had enough data available for good parameterisation of the models.

No harvest control rule was in place at this time, so one can only speculate whether the advice would have been based on $F=0.51$ if the information on the development in weight-at-age had been available. However, a SSB of 164 (or 121) thousand tonnes would have been close to the lowest observed value of SSB, a fact which certainly would have caused concern.

The TAC advice for 1990

Some key figures concerning the TAC advice for 1990 are given in Table 2.

Table 2. Stock sizes and TAC advice in 1990–1991 for various assessments and assumptions.

ASSESSMENT	SSB 1990	TSB 1990	F5-10 ADVICE 1990	TAC ADVICE 1990	SSB 1991	TSB 1991	CATCH 1991 (F=0.32)
AFWG 1989	147	596	0.32	143	195	673	163
AFWG 1989 correct weights and maturity	196	650	0.32	165	404	1024	205
AFWG 2007	312	958	0.32	241	668	1514	321

$F=0.32$ equals F_{low} , which at the time was the advised fishing mortality for a rebuilding situation. (The ACFM advice for 1990 was based on F_{low} , but was 172 thousand tonnes, not 143, I have not investigated the reason for this.)

We see that the errors in predictions of weight-at-age did not have a great impact of the catch predictions during this period. The main reason for this is that the predictions for the 1983 year class, which dominated the catches, were fairly accurate.

However, the predictions for SSB and TSB in 1991 would have been much higher (about 100% and 50%, respectively), if the predictions of weight and maturity-at-age had been correct. We also see that the stock abundance (numbers) was severely underestimated at this time (e.g. the 1983 year class was estimated at 85 million at age 7 compared to the present VPA estimate of 148 million).

Discussion

We see from the examples above that in the period 1987–1990, errors in the predictions of weight-at-age had a substantial impact on the short-term predictions and TAC advice for NEA cod. The errors in prediction of growth also caused the medium-term predictions to be far from the actual stock development, and this may also have had an impact on the actions taken by the managers.

However, in the last 15 years, the weight-at-age of the cod stock has been fairly stable, although the capelin stock has shown strong fluctuations and has collapsed twice more. The reason why the two latest capelin collapses have had less impact on the individual growth of cod is probably that more alternative fish prey was available to cod during this period. This is seen from data on cod diet (ICES 2007), and a detailed analysis of this topic will be given in Gjosæter *et al.* (in prep.). Thus, growth predictions for NEA cod need to be based on total prey abundance, not only capelin abundance.

It should also be noted that problems with age readings may have had an impact on the problems with growth predictions around 1990. At that time there were large discrepancies between Norwegian and Russian weight-at-age data, and thus a routine exchange program of otoliths was initiated in 1992. In recent years there has been good consistency between Norwegian and Russian age readings and weight-at-age data. Another challenge when predicting growth is to get consistency between predictions of weight-at-age in stock and in the catch.

Using artificial neural networks, Huse and Ottersen (2002) presented 1–3 year predictions of NA cod biomass developments. Their approach was basically similar to the analyses presented above for cod recruitment. A simple model based on information about cod stock biomass, temperature and capelin stock biomass provided biomass predictions over 1–3 years with r^2 of 0.87, 0.69 and 0.50 respectively. While Huse and Ottersen (2002) used the approach to predict total stock biomass, the same model could easily be modified to predict weight-at-age, which is required in the assessment process.

Conclusions

- Changes in the geographical distribution of fish stocks due to environmental effects may seriously influence our perception of stock abundance.
- We need to know how stocks are responding spatially to changes in abundance and climate → need fisheries independent monitoring (of the total stock).
- Recent development of 2–3 year prediction of cod recruitment seems to be superior to similar traditional predictions by ICES. However, for cod this is not directly important for the short-term TAC advice, since the predicted 3-year old cod at this time is not part of the fisheries. When going to longer-term advice, such predictions may become more valuable, particularly as an early warning for potential recruitment failures.
- Recruitment predictions may be of more value for short-lived species, and as input to medium term advice.
- Errors in the predictions of weight-at-age have had a substantial impact on the short-term predictions and TAC advice for NEA cod.
- The errors in prediction of growth also have caused medium-term predictions to be far from the actual stock development, and this may also have had an impact on the actions taken by the managers.

- Therefore, for improving the management advice it is important to find good methodologies to predict the following year's growth. This must be based on knowledge about food availability and temperature.

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Annex 11: Baltic Sea cod

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Abstract

Background

The upper trophic levels of the Central Baltic changed during the last 25 years from a cod- to a sprat-dominated system. The decline of the cod stock was caused by a combination of recruitment failure and increasing fishing pressure at declining stock sizes. The recruitment failure was mainly driven by: i) anoxic conditions in deep water layers of eastern spawning sites causing high egg mortalities, ii) high egg predation by clupeid predators in the remaining productive spawning area, and iii) reduced larval survival due to the decrease in abundance of the main food item *Pseudocalanus acuspes*. The intensity and significance of all these processes are in one way or the other steered by the hydrographic conditions, which were in the 1990s characterized by low salinity due to lacking inflow of saline water from the North Sea and increased river run off, but as well by warmer thermal conditions. Other processes have added to the limited reproductive success, e.g. high juvenile cannibalism at high stock size during the early 1980s and a truncated age structure during the 1990s affecting offspring survival probability negatively.

The decline of the cod stock released sprat from predation pressure, and in combination with high reproductive success, due to in general favourable temperature conditions, this resulted in exceptionally high sprat stock sizes in the 1990s. The sprat stock affected cod recruitment negatively by acting as predator on cod eggs and on *Pseudocalanus* adults, thus affecting the production of food for cod larvae. Indications for compensatory processes in growth, maturation and individual egg production exist for both species; however, appear to be of limited impact on the overall stock and system dynamics.

Concurrent with a shift from a cod to a sprat dominated system, the meso-zooplankton community showed pronounced changes; while the marine copepod zooplankton declined, the neritic copepod species *Acartia* spec. and *Temora* increased in abundance, mainly caused by increasing winter temperatures. Furthermore, climate mediated changes during the 2nd half of the 1980's are apparent for lower trophic levels as well. This regime shift cannot be allocated to a single year or event, as the response time of different species and life stages depends on whether the critical environmental factor is oxygen concentration or salinity in the deep Baltic basins, or water temperature in bottom or intermediate water layers.

Cod egg survival already declined in eastern spawning areas with the absence of inflows in 1981 and 1982, while it declined in the Bornholm Basin not before 1986. Cod larval survival, being coupled via *Pseudocalanus* production to salinity, was seriously affected in eastern spawning areas in the 2nd half of the 1980s and in the Bornholm Basin after an extended stagnation period and increased predation pressure by sprat in early 1990s. The decline in the cod stock released sprat from predation pressure, but the low temperatures until winter 1986/87 prevented a successful sprat recruitment before 1988. Similarly, *Acartia* spp. production increases first in 1988 sustaining high sprat larval survival.

Implications for scientific advice and management

The present contribution will follow-up on following subjects:

WKREF (2007) reviewed the adequacy of the present biomass reference points for the Eastern Baltic cod stock and concluded that a revision is needed, but could neither agree on a method to determine reference points under changing system productivity nor on alternative candidates of reference points. The discussion focussed on the separation in two different time periods for recruitment in contrast of including the main environmental drivers into the estimation procedure and to estimate a limit reference points dependent on level of variables characterising environmental regimes.

Environmental conditions matter not only for the determination of limit reference points, but also for target fishing mortalities. This is demonstrated by an evaluation of the harvest control rule of a new multi-annual management plan for Baltic cod proposed by the EU commission (COM(2006) 411) submitted to ACFM (2007).

Environmental change affects short-term forecasts, and the necessity and feasibility of an implementation of identified processes and relationships to estimate input variables into short-term predictions is explored based on results of the EU project STORE (2003). Besides the explanatory power of relevant variables, their predictability and related predictive time frames are discussed.

Based on an exploratory statistical analysis conducted by SGMAB(2006), significant variables influencing the reproductive success are incorporated into stock-recruitment models. As reproductive success varies considerably between spawning sites, environmental heterogeneity was considered explicitly. Variables included the potential egg production as a measure of reproductive effort and 0-group abundance as a measure of reproductive success by the stock (thus implicitly considering cannibalism), as well as hydrographic conditions affecting egg survival, predation on eggs by clupeids and copepod prey availability for larvae.

Multispecies medium- to long-term projections are used by SGMAB (2005 and 2006) to predict different scenarios of stock and catch development. Emphasis is given to the impact of predatory interactions (i.e. cod cannibalism) on future stock dynamics as well as the coherence between precautionary biomass and (Bpa) and fishing mortality reference points (Fpa), i.e. does fishing at Fpa lead to Bpa under different recruitment scenarios.

Annex 12: Baltic Sea sprat applying knowledge about recruitment processes in short-and medium-term predictions of recruitment, spawner biomass and yield of sprat *Sprattus sprattus* in the Baltic Sea

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Abstract

Sprat spawner biomass in the Baltic Sea is presently above Bpa. However relationships between spawner biomass and recruitment are uncertain (no significant relationship using Ricker, Beverton-Holt, hockey-stick models). The ICES assessment working group presently uses a long-term geometric mean for making short- and medium-term predictions of catch and spawner biomass. Recruitment at current spawner biomass levels is likely driven by ecosystem processes such as effects of abiotic variables (e. g., temperature) or trophic interactions (predation, cannibalism).

Water temperature, and several processes affected by temperature, influence sprat reproduction (e. g., development of gonads in mature sprat, sexual and gonadal maturation; (Grauman and Yula, 1989; Kraus *et al.*, 2003) and survival of eggs, larvae and 0-groups (Köster *et al.*, 2003; Nissling, 2004; Baumann *et al.*, 2006). We have shown that recruitment is significantly positively correlated with temperature (MacKenzie and Köster, 2004). This relationship, derived for the years 1973–1999, was evident using an independent time-series of catch-derived recruitment indices (1955–1972), and has since been updated for 5 additional yeaclasses (2000–2004); in total the temperature-recruitment relationship to date has been consistent (i. e., significant and positive) for 50 years. The effect of temperature on sprat recruitment differs geographically throughout the range of the species (MacKenzie and Köster, 2004): in the north (Baltic Sea), the relationship is positive, but the relationship is negative in the Black Sea (Daskalov, 1999). This pattern is similar to those seen for Atlantic cod (Planque and Frédou, 1999; Brander, 2000) and some Pacific salmon species (Mueter *et al.*, 2002).

We have conducted several additional analyses to investigate how knowledge about recruitment processes can be used in assessment and stock projection work. The analyses and results are given briefly below and will be explained in detail at the workshop.

1. Retrospective analysis of recruitment prediction quality. A comparative retrospective analysis using data available in the year of prediction showed that recruitment predicted by environmental variables (i. e., water temperature, a winter index of the North Atlantic Oscillation and Baltic Sea ice coverage) yielded smaller and less variable deviations from observed recruitment than recruitment estimated with methodology currently used by ICES (MacKenzie and Köster, 2004).

2. Improvement of predictive horizon for recruitment forecasts. The ICES assessment working group meets too early in the year to use the best environmental correlate of recruitment for current year predictions. We show how this difficulty can be overcome by identifying and using the seasonal chain of links between climate variability, sea conditions and sprat recruitment. This chain gives 2–3 months additional predictive horizon and allows the WG to predict current year recruitment from ecosystem information (MacKenzie and Köster, 2004).

3. Sensitivity analysis of short-term predictions of spawner biomass and yield to environmental variability. We assimilated climate-oceanographic-recruitment linkages into the standard ICES assessment procedure to predict key advisory-related variables such as spawning stock biomass (SSB) and landings (MacKenzie *et al.*, 2007). We use a concrete, real-world example to illustrate these effects. Predictions of recruitment made using the North Atlantic Oscillation for the 2006 year class showed that spawner biomass would be 15% lower than spawner biomass calculated using the ICES standard methodology. The difference in perception of future biomass does not affect the advice for the stock because $SSB > B_{PA}$. However, when this is not the case, or when it is desirable to broaden the ecosystem basis for fisheries management, it may be beneficial to include recruitment processes knowledge.

4. Influence of climate variability and exploitation on medium term projections of spawner biomass and yield. We conducted medium term simulations of the combined effects of climate variability (temperature), spawner biomass and exploitation on 10-year stock and yield projections. We first implemented a hockey-stick recruitment-spawner biomass relationship for different temperature conditions in a standard software program used by ICES and then simulated population development using stochastic inputs to represent realistic levels of variability and uncertainty. We identify combinations of climate variability/regimes and exploitation which have different probabilities of maintaining the spawner biomass above B_{PA} (MacKenzie and Köster, 2004). For example fishing at F_{PA} under a cold climate (defined as long-term mean temperature-1 standard deviation) increases the risk of $SSB > B_{PA}$ from 0% to 18%, compared to a scenario involving fishing at F_{SQ} under long-term mean temperature conditions).

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Annex 13: Potential improvements in the management of Bay of Biscay anchovy by incorporating environmental indices as recruitment predictors

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Abstract

In the absence of pre-recruit surveys, environmental indices could potentially be used as predictors of recruitment to provide management advice for short-lived species such as anchovy. Environment-recruitment relationships have been established for the Bay of Biscay anchovy population, but their performance is still being tested. The purpose of this paper is to investigate under what circumstances incorporating environmental indices would lead to improvements in managing this anchovy stock in terms of increasing yields and reducing the risk of spawner biomass falling below a pre-defined reference level (e.g. B_{lim}). The assessment is made by stochastic simulation of the anchovy population and its management. Management actions resulting from advice based on geometric mean recruitment or on precautionarily low levels of recruitment are compared with those resulting from recruitment predictions. Recruitment predictions could be used directly (expected recruitment used in TAC formulation) or indirectly (expected recruitment used as a trigger to increase or decrease the TAC). Linear models for environment-recruitment relationships with a coefficient of determination (r^2) of 0, 0.25, 0.5 and 1 are considered in the simulations for cases when such relationships are known perfectly or when the parameters are estimated and selected with measurement error. Results highlight factors that appear to be important in determining how much improvement is possible when incorporating environmental indices to provide TAC advice. In particular, they show that precautionary approaches may better ensure successful management, in terms of increasing yields and reducing risk, than consideration of uncertain or moderate to weak (in terms of the relationship to recruitment) environmental effects.

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Annex 14: Long-term harvest strategies for small pelagic fisheries under regime shifts: the South African fishery for pilchard and anchovy

José De Oliveira

Abstract

The work used the Management Strategy Evaluation approach (Kirkwood, 1992, 1997; Butterworth *et al.*, 1997; Kell *et al.*, 1999; McAllister *et al.*, 1999; Smith *et al.*, 1999) to investigate different harvesting strategies in the South African fishery for pilchard (*Sardinops sagax*, also called sardine) and anchovy (*Engraulis encrasicolus*, formerly *E. capensis*), in order to identify improved general approaches to management in the face of both short- and long-term uncertainty. This was represented by regime cycles that had a direct effect on both species' recruitment. The analysis focused on the case where the cycles were out of phase, worse case scenario. Two aspects were considered, namely defining estimators that provide information about the regime cycle, and developing decision rules (and hence alternative MPs) that use this information (as opposed to the existing management procedure (BL) that does not take that information into account).

If there were no operational interaction (that is, the pilchard bycatch) between the pilchard and anchovy fisheries, then given a certain set of TAC constraints, it appears that there would be little (if any) gain in using management procedures markedly different from BL to take account of regime shifts. Nevertheless, gains are possible, particularly for pilchard, when focusing on the operational interactions between pilchard and anchovy. Management procedures that result in a reduction of juvenile pilchard bycatch (landed with anchovy) when pilchard is in a trough offer the best performance for pilchard under regime cycles of varying amplitude. Furthermore, for pilchard, the indirect estimator D1 based on survey estimates of the biomass outperforms estimator D2 (which provides information on the position of the cycle) in terms of *Loss*, *Net Product Value* and *Catch* for a range of MP options. Furthermore, any gains in terms of *risk* would need to be judged against the feasibility and likely cost of obtaining sufficiently precise information on the underlying position in the cycle at any time.

Annex 15: Managing under conditions of regime shifts for different types of population and levels of exploitation

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Abstract

Climate and environmental forcing impacts on fish recruitment can be incorporated into stock assessments as periods of varying relative productivity. Previous research using Beverton-Holt age structured models to simulate regime impacts on a short-lived 'herring-like' fish (maximum age=10; age of maturity=3; $M=0.4$) and a long-lived 'flatfish-like' fish (maximum age 50; age of maturity=5; $M=0.1$) productivity illustrated that regime specific harvest rates reflecting the relative levels of productivity ($F=M$; $F=0.25M$; $F=0.5M$) produced the best balance between benefits (high yield) and trade-offs (fishery closures). Overall this management strategy allowed for rebuilding of spawning stocks from periods of low productivity to periods of improved productivity. This research is expanded to include simulation of intensely exploited fish populations that are more relevant to the ICES regions; an 'anchovy-like' fish (maximum age=5; age of maturity=1; $M=1.2$) and a 'haddock-like' fish (maximum age=10, age of maturity=2, $M=0.2$). In both cases, the populations were exploited such that fishing mortality was similar to historical high levels and current levels, in addition to a levels equal to and proportions of natural mortality (i.e. M ; $0.5 \cdot M$; $0.25 \cdot M$). If spawning stock biomass fell below 25% of the maximum biomass, the fisheries were closed until the populations increased above this threshold. As with the previous simulations, a balance between high yield and no fishery closures was achieved when fishing mortality was adjusted to reflect the relative productivity of each regime. It is possible to use constant harvest rates across productivity regimes, but these harvest rates must be low (e.g. $F=0.25 \cdot M$) and are partnered with reduced yield (42% lower). The adjustment of harvest rates did not need to coincide with regime shifts in productivity, but could be lagged by the age of recruitment to the fishery. However, for these short-lived species with very early ages of maturity, particularly the 'anchovy-like' fish, the realistic difficulty with our ability to detect regimes shifts and to adjust harvest rates within one or two years suggest that constant low harvest rates might logistically be the most appropriate management strategy. Generally, if fisheries scientists provided harvest recommendations representing a range of levels of risk to the stock under different assumptions of productivity, this could be coupled with ecosystem assessments to select the most likely assumption given ecosystem indicators of productivity. This would allow fisheries managers to incorporate information on climate or environmental forcing into the management of marine resources.

Introduction

Climate forcing on marine ecosystems has three temporal scales: interannual (ElNiño-LaNiña (ENSO)-like events); decadal (regimes and regime shifts) and long-term (global warming trends). In fisheries management, the most important scale is the decadal-scale variability. While ENSO events can affect fish survival, these events mainly impact the distribution of fish populations and have short-lived implications for year class success. This of course could change as the frequency, or duration, of ENSO events increases beyond interannual. However, under this scenario the impacts for year class success or abundance in an area becomes analogous to decadal-scale variability. Long-term global warming impacts are yet to be clearly defined and will require the long-range planning of agencies to deal with the likely irreversible consequences of either a loss of a fish species or the introduction of a new species within their jurisdiction. As such, decadal-scale variability of climate-ocean regimes is the temporal scale at which the management of marine resources can. A regime is a period of a decade or more in which the state, or characteristic behaviour, of the climate or ocean system is steady. Year-to-year differences may exist, but overall the state of the system varies around a persistent baseline. A regime shift is rapid, usually occurring within a year, and is a substantial change from one regime period to another. Scientific literature reports regime shifts in the North Pacific occurring in 1925, 1947, 1977, 1989 and 1998 (Mantua *et al.*, 1997; Hare and Mantua,

2000; McFarlane *et al.*, 2000; Minobe, 2000; Schwing and Moore, 2000; Bond *et al.*, 2003; King, 2005).

Numerous studies have illustrated that climate-ocean regimes are associated with fluctuation in fish abundance and population dynamics (Kawasaki and Omori, 1986; Beamish and Bouillon, 1993; Polovina, 1996; Mantua *et al.*, 1997; McFarlane *et al.*, 2000; King, 2005). However, to date few attempts have been made that directly incorporate the dynamics of regimes into the management of fish populations. King and McFarlane (2006) suggested a framework for incorporating climate regime impacts into marine resource management (Figure 1). Their suggested framework organizes several existing processes or areas of fisheries science into a decision-based framework that outlines a priori the responses in management that would result from indications that a regime shift, or a sustained change in the ecosystem, has occurred. *Ecosystem assessment* is the monitoring of climate-ocean indices and indicator species to detect ecosystem changes, i.e. assessing the state of the environment. Many agencies and organizations already conduct these types of assessments, for example the Canadian annual Pacific State of the Ocean Report; the Alaska Fisheries Science Center's annual Ecosystem Consideration Appendices; and the North Pacific Marine Science Organization's Marine Ecosystems of the North Pacific. These assessments could provide the means for the detection of climate-ocean regime shifts and changes in productivity. The framework does not require the prediction of a regime-shift, but would require methods of regime shift detection that are currently being developed (Rodionov and Overland, 2005) simply because the response time of fisheries management needs only to mirror the response time of biota to changes in productivity, which is often lagged by the age of maturity or recruitment. *Stock assessments and risk management* can be conducted under different assumptions of productivity or recruitment (e.g. low, medium and high year class success) and the resultant harvest recommendations could reflect a range of risks (low to high) to the stock. A low level of risk would guarantee a minimal impact of fishing on the stock, but would be associated with a significant economic impact on the industry. A high risk level could increase conservation concerns for a stock but may be chosen for social, economic or political considerations. Economic, political and social factors would be considered when selecting the acceptable level of risk to the stock. The ecosystem assessment would provide an indication which productivity scenario is most appropriate. *Reference points* provide the check system and stop mechanism to help avoid overexploitation. A number of countries have adopted the precautionary approach to managing marine resources and a primary mechanism in its implementation is the use of limit reference points. *Variable harvest rates* is an intuitive approach when recognizing regime period of productivity in fish population dynamics. When productivity is good, the stock can withstand a relatively higher fishing mortality, and when productivity of the stock decreases (i.e. a regime shift to a less productive ecosystem occurs) then fishing mortality should be adjusted downwards. This portion of the framework suggested by King and McFarlane (2006) may not be a current approach taken by many fisheries agencies, since most adopt a constant fishing mortality (e.g. $F=M$) irrespective of changes in ecosystem productivity.

Several studies have investigated the use of constant harvest rates versus *variable harvest rates* as management tools for coping with climate, or environmental, forcing on marine fish populations (Walters and Parma, 1996; Spencer, 1997; Peterman *et al.*, 2000; MacCall, 2002; Polovina, 2005; King and McFarlane, 2006). Walters and Parma (1996) concluded that overall, a constant rate harvest strategy performs well; while other studies suggest that a regime-specific harvest rate strategy is optimum (Spencer, 1997; Peterman *et al.*, 2000). MacCall (2002) suggested that for short-lived species, a regime-specific harvest rate was optimum for maintaining high yield and low variation in spawning stock biomass. Conversely, for a long-lived species (lifespan greater than 30 years), a constant harvest rate was more appropriate (MacCall, 2002).

Polovina (2005) suggested avoiding overfishing during low productivity regimes, the employment of a constant harvest rate strategy would require a rate well below traditional benchmarks (i.e. approximately 10% of the exploitable biomass). The obvious trade-off is that during low productivity regimes, a low harvest rate results in low overall yield. In contrast a regime-specific harvest rate strategy would be beneficial by increasing yield in high

productivity regimes, but might result in fishery closures during regimes of low productivity (Polovina, 2005)

King and McFarlane (2006) recommended that variable harvest rates that reflected relative levels of stock productivity (i.e. high, low, moderate productivity regimes) produced the best balance between benefits (high yield) and trade-offs (fishery closures). Overall, this approach allowed for rebuilding of the spawning stock when productivity improved. For long-lived species, this recommendation is contrary to MacCall (2002) which focused only on optimizing yield and minimizing timeframes for rebuilding. King and McFarlane (2006) had included the additional consideration of avoiding years with fishery closures. Given the dramatic impacts that regime shifts have on productivity, King and McFarlane recommended that constant harvest rates that are typically employed (e.g. $F=M$) can not maintain sustainable stock or fisheries when productivity is greatly reduced. As suggested by Polovina (2005), it would be possible to use constant harvest rates across productivity regimes, provided the rates were very low (e.g. $F=0.25 \cdot M$) and these rates would be partnered with the trade-off of much reduced yield with potential significant economic and social impacts.

The model simulation of King and McFarlane (2006) focused on two hypothetical populations: 1-short-lived species similar to a herring (maximum age=10; age of maturity=3; $M=0.4$); and 2-long-lived species similar to a flatfish (maximum age 50; age of maturity=5; $M=0.1$). This paper expands that research to simulate two hypothetical fish populations that are similar to species found in the North Atlantic (anchovy, haddock).

Methods

Population Models

The approach used by King and McFarlane (2006) to simulate climate forcing on the population dynamics of a short-lived species (a 'herring-like' fish) and a long-lived species (a 'flatfish-like' fish) was applied here to simulate two additional short-lived species: an 'anchovy-like' fish; and a 'haddock-like' fish. The populations were simulated with an age-structured Beverton-Holt model:

$$R_i = \frac{1}{\alpha \cdot \varepsilon_i + \frac{\beta}{P_{i-1}}}$$

where R is the number of young of year in year i , P are the number of spawners at the end of the previous year after any harvest (expressed as number fish), ε is the regime effect assigned to year i , and α and β are parameters (Table 1). Climate forcing was assumed to impact year class success, with impacts modelled as a multiplicative effect (ε) on the slope at the origin. Climate regime periods were modelled as periods (20 years) of varying relative productivity of the stock: the first 20 years as a period of good productivity (Regime 1), the second 20 years as a period of poor productivity (Regime 2) with the final 20 years as a period of moderate productivity (Regime 3). Values of ε were selected such that the resultant unfished biomass approximated 50% in Regime 2 ($\varepsilon = 2$) and 75% ($\varepsilon = 1.35$) in Regime 3 of the Regime 1 biomass.

Recent stock assessments were used for estimates of life history parameters, historical high levels of biomass and fishing mortality (F). Arbitrarily selected were Subarea VIII-Bay of Biscay anchovy (ICES, 2006) and Subarea IV and Division IIIa-North Sea haddock (ICES, 2007). The 'anchovy-like' fish population was modeled such that the period of good productivity (Regime 1) corresponded to approximately 90 000 tonnes of spawning stock biomass. This population was fully mature by age 1, and had a maximum age of 5. A constant rate of natural mortality (M) of 1.2 was applied across all ages. Size-at-age used in this model to estimate tonnes from numbers of fish, was based on the average size-at-age from 1987–2005 (kg) used as input to the Subarea VIII anchovy stock assessment model with a maximum size of 0.42 kg.

The good productivity (Regime 1) of the 'haddock-like' fish population model corresponded to a spawning stock biomass of approximately 400 000 tonnes. The simulated population was based on an age of 50% maturity of 2.5 years and a maximum age of 15. The natural mortality schedule from ICES (2007) was applied across ages, with an $M=0.2$ for ages 5+. The average size-at-age (kg) from 1963–2005 used as input to the Subarea IV and Division IIIa-North Sea haddock stock assessment was used here as size at age to estimate tonnes from numbers of fish. The maximum age for the 'haddock-like' fish population was 15.

Harvest Scenarios

Constant harvest rates-A first set of harvest scenarios used a constant fishing mortality (F) over the three simulated regime periods (i.e. irrespective of changes in stock productivity). Values of F were estimated from reported values in ICES (2006, 2007) and included an estimate of historic high fishing mortality (F_{HIGH}), historic mean fishing mortality (F_{MEAN}), and current fishing mortality (F_{CURRENT}). Typical harvest rates proposed in fisheries management relay fishing mortality as a proportion of natural mortality and include $F=M$ (considered high), $F=0.5 \cdot M$ (considered moderate) and $F=0.25 \cdot M$ (considered low). These constant harvest rates were applied to the model simulations in addition to those above. For the 'anchovy-like' population model these estimates were $F_{\text{HIGH}} = 1.2$ (i.e. $F=M$); $F_{\text{MEAN}} = 0.8$ (i.e. $F=0.66 \cdot M$) and $F_{\text{CURRENT}} = 0.12$ (i.e. $F=0.10 \cdot M$). The F_{HIGH} , F_{MEAN} and F_{CURRENT} estimates used in the 'haddock-like' population model were 1.2 (i.e. $F=6 \cdot M$), 0.8 (i.e. $F=4 \cdot M$) and 0.4 ($F=2 \cdot M$) respectively.

Variable harvest rates-A second set of harvest scenarios included fishing mortalities that varied with productivity (i.e. regime-specific). One group of regime-specific harvest scenarios was based on $F=M$, $F=0.5 \cdot M$ and $F=0.25 \cdot M$ for Regime 1, Regime 2 and Regime 3 respectively. This regime-specific harvest rates might represent a situation where a shift in a productivity regime is detected, however the relative change in productivity is not known, only whether productivity has worsened or improved. The other group of regime-specific harvest scenarios assumed that the relative change in productivity with a regime shift is known, and fishing mortalities of $F=M$, $F=0.25 \cdot M$ and $F=0.5 \cdot M$ were used in the high, low and moderate productivity regimes respectively.

For all of these variable harvest rate scenarios, the timing in which the fishing mortality was switched varied: coincidental with the regime shift year, delayed until age of 50% maturity (rounded to the nearest year i.e. 1 for 'anchovy-like' and 3 for 'haddock-like'), delayed until twice the age of 50% maturity.

Benefits and Trade-offs

The maximum spawning stock biomass over the 60 years without any harvest was used to set the criteria for fishery closures and conservation concerns. The 25% and 30% levels of this maximum were used as representatives of critical spawning biomass and a level for which there would be conservation concerns respectively. These levels are currently used by North American management agencies (Fisheries and Oceans Canada; National Marine Fisheries Service) as minimum spawning biomass reference points. When running the harvest scenarios, the harvest rate would be set to zero if the spawning stock (numbers of fish) fell below the critical spawning biomass. The number of years that the fishery was closed and the total number of years in which there was a conservation concern were totalled for all 60 years. The total yield (tonnes) across the 60 years was calculated for each harvest scenario. The guide price (per tonne) of the European Union for 2006 community fish imports for whole fish (European Union, 2005) was used to quantify the economic benefit (or loss) of differences in total yield between harvest rate scenarios. For anchovy, this price was 1 308 Euro and for haddock it was 998 Euro.

Results

Anchovy-like population

Population dynamics—The simulated unfished population of the ‘anchovy-like’ fish responded to regime shift changes in year class success (i.e. productivity), quickly and the resultant lower or higher spawning stock size stabilised immediately (Figure 2A). As expected, the spawning stock was depleted more quickly and to a lower level as the constant harvest rate increased from $F=0.1 \cdot M$ (F_{CURRENT}) to $F=M$ (Fig. 2A). Conversely the rebuilding level that the spawning stock rebuilt to during the third regime when year class success improved was greater for the lower constant harvest rate ($F=0.1 \cdot M$) scenario (Fig. 2A). The aggressive harvest rates of $F=M$ (F_{HIGH}) and $F=0.66M$ (F_{MEAN}) resulted in years when the spawning stock was below the defined critical spawning stock size. The $F=M$ scenario did not have a population that was able to rebuild with improved productivity in Regime 3 (Figure 2A).

The variable harvest rate scenarios simulations resulted in dramatic fluctuations in population during the regime shift periods (Figures 2B and 2C). The $F=M$; $F=0.5 \cdot M$; $F=M$ scenarios did not rebuild during Regime 3 when productivity improved (Figure 2B). The $F=M$; $F=0.25 \cdot M$; $F=0.5 \cdot M$ scenarios had simulated populations that were well above the critical spawning biomass size during the poor productivity regime and increased when productivity improved in Regime 3 (Figure 2C).

Benefits and trade-offs—The highest total yield was achieved with the $F=M$ constant fishing mortality scenario (Figure 3A). Generally, the total yield decreased with decreasing constant fishing mortality rate, such that the total yield with $F=0.10M$ was only 24% of the total yield achieved with $F=M$ (Fig. 3A). The yields achieved with the $F=0.66 \cdot M$ and $F=0.5 \cdot M$ were very similar because the higher F scenario had close to 10 years with no harvest (Figure 2B). The highest constant fishing mortality scenario that resulted in no years with fishery closures or conservation concerns was $F=0.25 \cdot M$ (Figure 3B). This scenario had only 51% of the total yield that was achieved with $F=M$ (Figure 3A). The difference in yield between these two scenarios would equal a difference of 756 million € at the 2006 guide prices for whole anchovy (EU 2005).

The $F=M$; $F=0.5 \cdot M$; $F=M$ variable scenarios overall produced total yields that were actually higher than that produced with the $F=M$ constant fishing mortality scenario (Figure 3A). However, the high $F=M$ portion of these variable harvest rate scenarios resulted in over 30 years when the stock was below levels that warranted conservation concern (Figure 3B). Overall, the $F=M$; $F=0.25 \cdot M$; $F=0.5 \cdot M$ variable harvest rate scenarios produced total yields that were approximately only 11% less than the highest $F=M$ scenario, but were 42% higher (548 million €) than the $F=0.25 \cdot M$ scenario which had no fishery closures or conservation concerns (Figure 3A). These variable harvest rate scenarios had only one year with a fishery closure (2 year lag scenario), one year with a conservation concern (no lag scenario) or no years with either (1 year lag scenario) (Figure 3C).

Haddock-like population

Population dynamics—The simulated unfished population of the ‘haddock-like’ fish exhibited a more gradual response to regime shift changes in year class success (i.e. productivity) (Figure 4A). Spawning stock biomass was depleted to a lower level as the constant harvest rate increased from $F=0.25 \cdot M$ to $F=6 \cdot M$ (Figure 4A). The constant fishing mortality scenarios $F=M$ through $F=6 \cdot M$ resulted in spawning stock biomass below the defined critical spawning stock biomass, and all four of these scenarios did not have a population rebuild when productivity improved in Regime 3 (Figure 4A). In fact, the spawning stock biomass for the highest fishing mortality scenarios ($F=6 \cdot M$ [F_{HIGH}]; $F=4 \cdot M$ [F_{MEAN}]; $F=2 \cdot M$ [F_{CURRENT}]) fluctuated around a constant low level for the complete 60 year simulation, increasing dramatically as the fishery was closed on intervals (Figure 4A).

The variable harvest rate scenarios simulations with no lag in changes in fishing mortality exhibited a short increase in spawning stock biomass when productivity decreased (Regime 2) and a short decrease when productivity improved (Regime 3) (Figures 4B and 4C). This

reflects the release in fishing pressure (in Regime 2) but the recruitment of more productive year classes (from Regime 1) to the spawning stock and the increase in fishing pressure (in Regime 3) on lower productive year classes (from Regime 2). The opposite was observed for delays of 3 years and 6 years (Figures 4A and 4C). The $F=M$; $F=0.5 \cdot M$; $F=M$ scenarios did not rebuild during Regime 3 when productivity improved and near the shift years had spawning stock biomasses close to the defined critical threshold (Figure 4B). The $F=M$; $F=0.25 \cdot M$; $F=0.5 \cdot M$ scenarios had simulated populations that were above the critical spawning biomass size during the poor productivity regime and increased when productivity improved in Regime 3 (Figure 4C).

Benefits and trade-offs—The highest total yield was achieved with the $F=M$ constant fishing mortality scenario, however the total yield from $F=2 \cdot M$ was only 2% less (Figure 5A). However, there was a dramatic decline in the number of years with a fishery closure or conservation concern with $F=M$ (Figure 5B). There were two trends in the constant fishing mortality scenarios: 1-decreasing total yield going from $F=M$ to $F=6 \cdot M$ (Figure 5A) as a result of increasing years with fishery closures and no yield (Figure 5B); 2-decreasing total yield with decreasing fishing mortality from $F=M$ to $F=0.25 \cdot M$ (Figure 5A). The $F=0.25 \cdot M$ constant fishing mortality scenario had no years with fishery closures and conservation concerns (Figure 5B), but the total yield for this scenario was 58% of the yield for $F=M$ (Figure 5A) which would equal a difference of 649 million € at the 2006 guide prices for whole haddock (EU, 2005).

The $F=M$; $F=0.5 \cdot M$; $F=M$ variable scenarios overall mean total yield were comparable to that produced with the $F=M$ constant fishing mortality scenario (Figure 5A). However, these scenarios had years with fishery closures (4–6 years), and years with conservation concerns (18–29 years) (Figure 5B). The $F=M$; $F=0.25 \cdot M$; $F=0.5 \cdot M$ variable harvest rate scenarios produced total yields that were approximately only 10% less (134 million €) than the highest $F=M$ scenario, but were 43% higher (515 million €) than the $F=0.25 \cdot M$ scenario which had no fishery closures or conservation concerns (Figure 5A). The 6 year lag scenario had 1 fishery closure and 4 years with conservation concerns; the 3 year lag had 1 year with conservation concerns (Figure 5C).

Discussion

Overall the results obtained from the ‘anchovy-like’ and the ‘haddock-like’ population model simulations were similar to those obtained in King and McFarlane (2006) for the short-lived ‘herring-like’ species (Figures 6A–6C) and the long-lived ‘flatfish-like’ species (Figures 7A–7C). The scenarios with no fishery closures, but with highest total yields were scenarios in which the fishing mortality varied by regime period, i.e. changed with changes in productivity (Table 1). The constant harvest scenario of $F=0.25 \cdot M$ consistently resulted in no fishery closures, or no years with conservation concerns, for all four model simulations (Table 1). However, the total yield of this scenario was typically half that produced by the scenarios with variable harvest rates. As illustrated by the rough estimates in Euros, the difference in total yield can have large economic consequences. Taken together, these results seem to suggest that the regime-specific harvest rates that reflected the relative levels of productivity by regime (i.e. high, low, moderate) produced the best balance between benefits (high yield) and trade-offs (fishery closures) and overall allowed for rebuilding of the spawning stock when productivity improved. Delaying the switch in fishing mortality by the age of maturity did not result in differing results greatly for total yield or years with fishery closures. On a final note, the complexity of selecting between harvest strategies that produce high total yield in combination with no years of fishery closures and few years with conservation concerns illustrates the importance and relevance of considering social and economic factors when managing marine resources. This highlights the need for inclusion of these fields of study in building ecosystem-based fisheries management frameworks. If a decision-based framework is in place for incorporating the information from ecosystem assessments regarding productivity into the provision of stock assessment advice, clients can benefit from fisheries managed with regime-specific harvest rates as a tool for contending with decadal-scale climate or environmental variability.

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Table 1: Order by descending total yield of scenarios (RS=regime specific scenarios $F=M$; $F=0.25 \cdot M$; $F=0.5 \cdot M$) for which there were no fishery closures for the four population models, ‘anchovy-like’ and ‘haddock-like’ models are this study, ‘herring-like’ and ‘flatfish-like’ are per King and McFarlane (2006). Models are arranged by ascending maximum age (with corresponding descending natural mortality (M)). Asterisks denote scenarios with no years with conservation concerns.

MODEL	MAXIMUM AGE	AGE AT MATURITY	M	SCENARIO ORDER
‘Anchovy-like’	5	1	1.2	RS 1 year lag*
				RS no lag
				$F=0.5 \cdot M$
				$F=0.25 \cdot M^*$
				$F=0.10M^*$
‘Herring-like’	10	2	0.4	RS 3 year lag*
				RS no lag*
				$F=0.5 \cdot M^*$
				$F=0.25 \cdot M^*$
‘Haddock-like’	15	3	0.2	RS 3 year lag
				RS no lag*
				$F=0.5 \cdot M$
				$F=0.25 \cdot M^*$
‘Flatfish-like’	50	5	0.1	RS 10 year lag
				RS 5 year lag
				RS no lag
				$F=0.25 \cdot M^*$

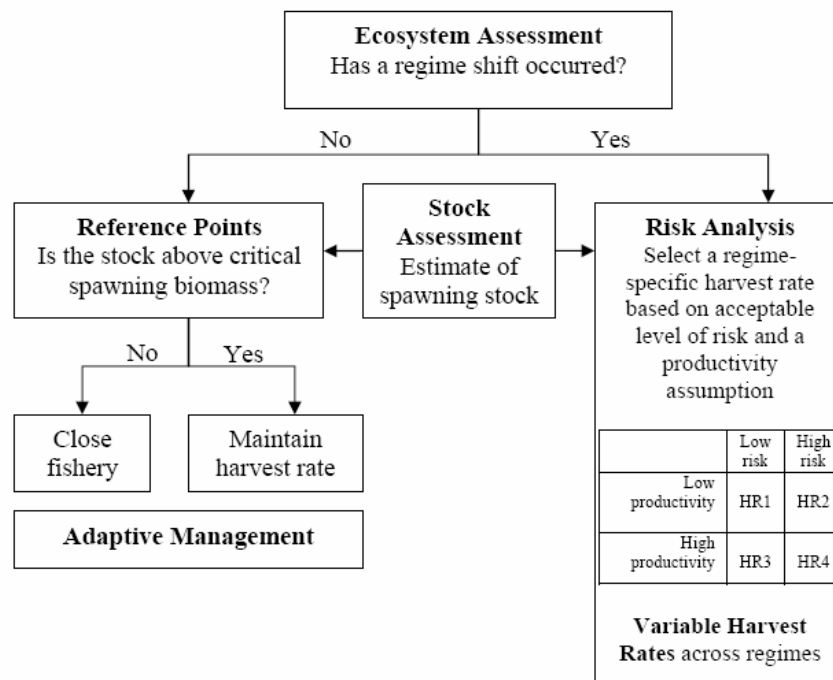


Figure 1. Conceptual decision-rule framework using existing science and management actions available to conduct ecosystem-based fisheries management which includes ecosystem monitoring or assessment for the detection of regime shifts and sets regime-specific harvest rates (HR).

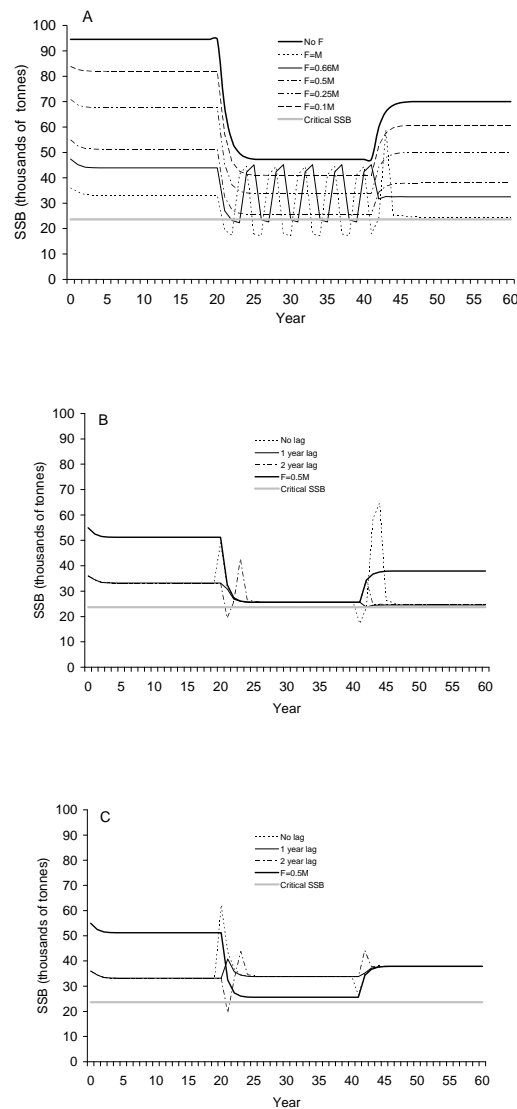


Figure 2. A) Spawning stock biomass (thousands of tonnes) from a Beverton-Holt age structured model for the ‘anchovy-like’ population under various constant F scenarios. B) Spawning stock biomass (thousands of tonnes) from the same model, but with regime-specific harvest rates ($F=M$, $F=0.5M$ and $F=M$) where the switch in harvest rates coincides with the regime shift year, is delayed by age of 100% maturity (1 year), or is delayed by twice this age; the spawning stock size for the constant harvest rate $F=M$ (dotted and dashed line) is redisplayed for comparison. C) Spawning stock biomass (thousands of tonnes) with regime-specific harvest rates ($F=M$, $F=0.25M$ and $F=0.5M$) where the switch in harvest rates coincides with the regime shift year, is delayed by age of 100% maturity (1 year), or is delayed by twice this age.; the spawning stock size for the constant harvest rate $F=M$ (dotted and dashed line) is redisplayed for comparison. In all plots, the horizontal line indicates the assigned critical spawning stock size below which no harvest is permitted. In all model simulations, the first 20 year regime period is high productivity, the second 20 year regime period is low productivity, and the third regime period is moderate productivity.

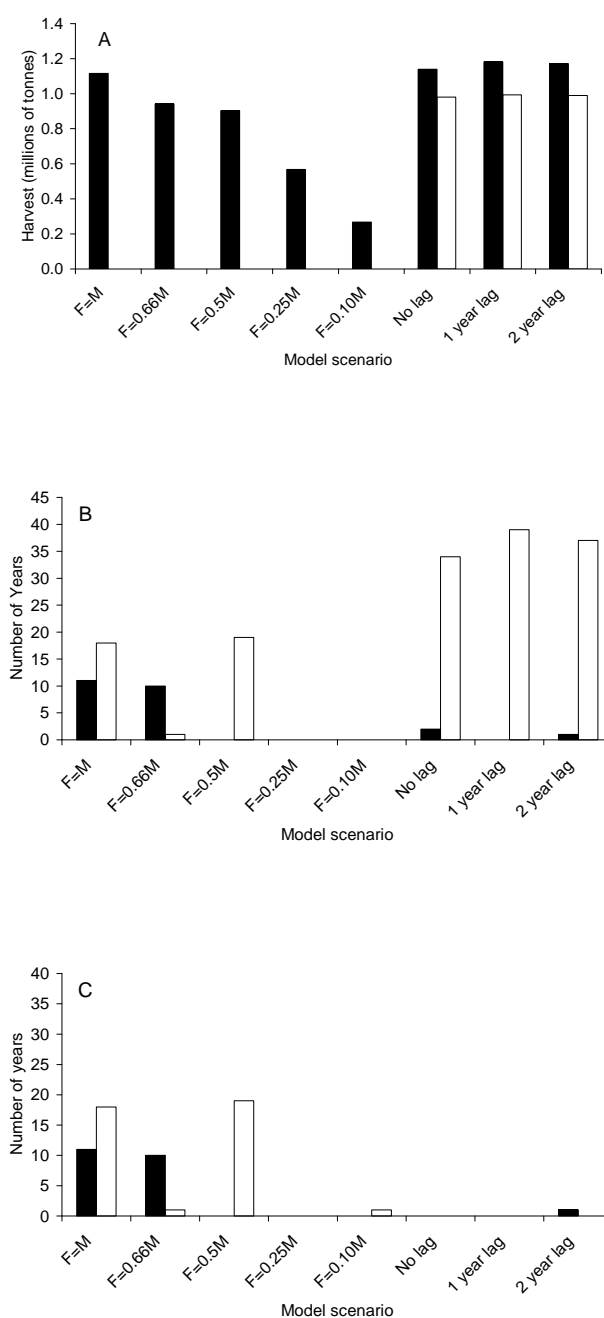


Figure 3. A) The total harvest (millions of tonnes) for the anchovy-like species population; solid bars are the constant harvest rate scenarios $F=M$ [F_{HIGH}]; $F=0.66M$ [F_{MEAN}]; $F=0.5M$; $F=0.25M$; $F=0.10M$ [$F_{CURRENT}$] and the regime-specific harvest rate scenarios $F=M$; $F=0.5M$; $F=M$; open bars are the $F=M$; $F=0.25M$; $F=0.5M$ regime-specific harvest rate scenarios. B) The number of years that the fishery was closed (solid bars) or in which there was a conservation concern (open bars) as defined by 25% and 30% of the maximum unfished spawning stock respectively. Eight harvest rate scenarios are presented: constant harvest rates (F) for 60 years, and regime-specific harvest rates ($F=M$; $F=0.5M$; $F=M$). C) Similar to B) with the constant harvest rate scenarios redisplayed for comparison with the regime-specific harvest rates ($F=M$; $F=0.25M$; $F=0.5M$).

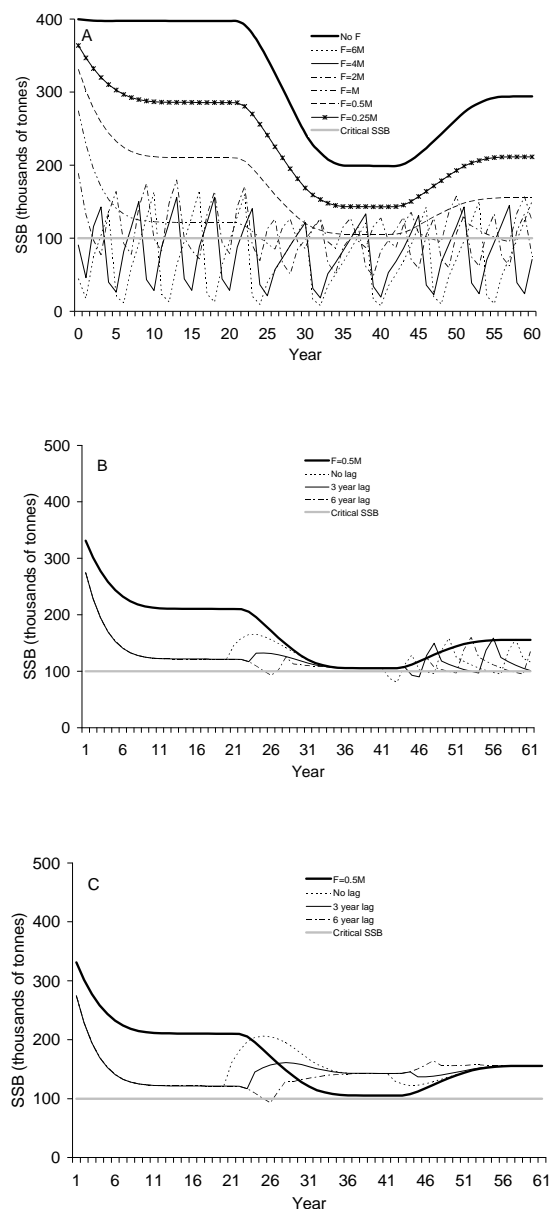


Figure 4. A) Spawning stock biomass (thousands of tonnes) from a Beverton-Holt age structured model for the 'haddock-like' population under various constant F scenarios. B) Spawning stock biomass (thousands of tonnes) from the same model, but with regime-specific harvest rates ($F=M$, $F=0.5 \cdot M$ and $F=M$) where the switch in harvest rates coincides with the regime shift year, is delayed by age of 50% maturity (3 years), or is delayed by twice this age; the spawning stock size for the constant harvest rate $F=M$ (dotted and dashed line) is redisplayed for comparison. C) Spawning stock biomass (thousands of tonnes) with regime-specific harvest rates ($F=M$, $F=0.25 \cdot M$ and $F=0.5 \cdot M$) where the switch in harvest rates coincides with the regime shift year, is delayed by age of 50% maturity (3 years), or is delayed by twice this age.; the spawning stock size for the constant harvest rate $F=M$ (dotted and dashed line) is redisplayed for comparison. In all plots, the horizontal line indicates the assigned critical spawning stock size below which no harvest is permitted. In all model simulations, the first 20 year regime period is high productivity, the second 20 year regime period is low productivity, and the third regime period is moderate productivity.

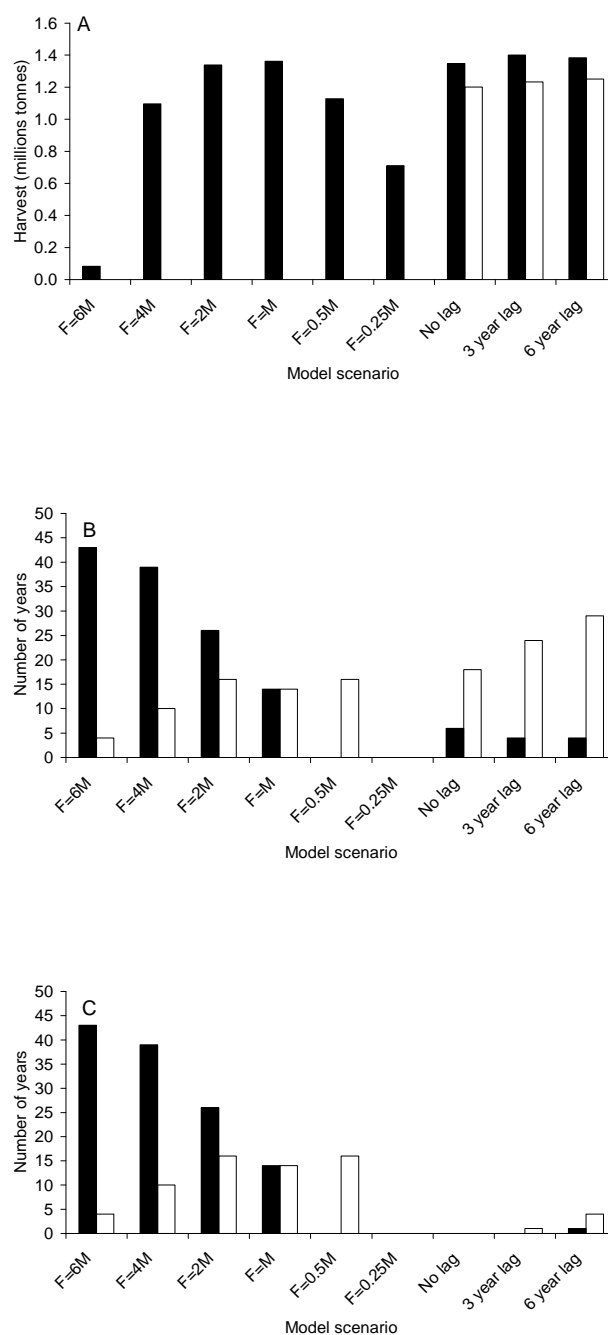


Figure 5. A) The total harvest (millions of tonnes) for the various harvest rate scenarios for the haddock-like species population; solid bars are the constant harvest rate scenarios $F=6 \cdot M$ [F_{HIGH}]; $F=4 \cdot M$ [F_{MEAN}]; $F=2 \cdot M$ [$F_{CURRENT}$]; $F=M$; $F=0.5 \cdot M$; $F=0.25 \cdot M$; and the regime-specific harvest rate scenarios $F=M$; $F=0.5 \cdot M$; $F=M$; open bars are the $F=M$; $F=0.25 \cdot M$; $F=0.5 \cdot M$ regime-specific harvest rate scenarios. B) The number of years that the fishery was closed (solid bars) or in which there was a conservation concern (open bars) as defined by 25% and 30% of the maximum unfished spawning stock respectively. Eight harvest rate scenarios are presented: constant harvest rates (F) for 60 years, and regime-specific harvest rates ($F=M$; $F=0.5 \cdot M$; $F=M$) C) Similar to B) with the constant harvest rate scenarios redisplayed for comparison with the regime-specific harvest rates ($F=M$; $F=0.25 \cdot M$; $F=0.5 \cdot M$).

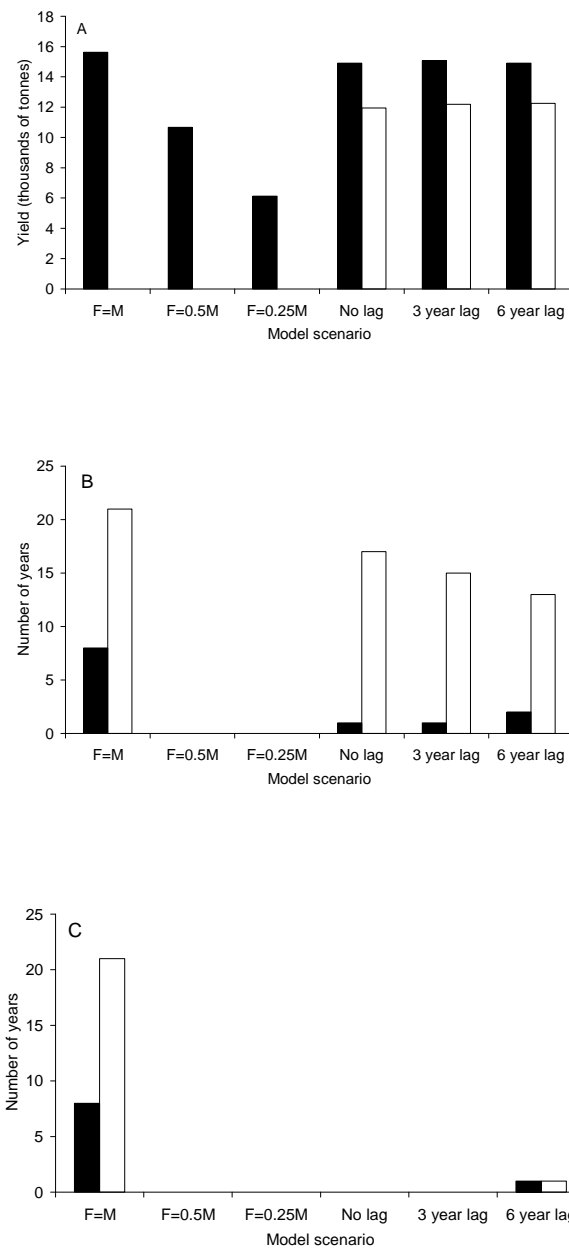


Figure 6. From King and McFarlane (2006). A) The total harvest (thousands of tonnes) for the various harvest rate scenarios for the short-lived species ('herring-like') population; solid bars are the constant harvest rate scenarios and the $F=M$; $F=0.5M$; $F=M$ regime-specific harvest rate scenarios; open bars are the $F=M$; $F=0.25M$; $F=0.5M$ regime-specific harvest rate scenarios. B) The number of years that the fishery was closed (solid bars) or in which there was a conservation concern (open bars) as defined by 25% and 30% of the maximum unfished spawning stock respectively. Six harvest rate scenarios are presented: constant harvest rates (F) for 60 years, F equal to annual natural mortality (M) or $F=0.5M$ or $F=0.25M$; and regime-specific harvest rates ($F=M$; $F=0.5M$; $F=M$) in which the switch in harvest rates coincides with the regime shift year (no lag), is delayed by age of 50% maturity (3 year lag) or by twice the age of 50% maturity (6 year lag). C) Similar to B) with the constant harvest rate scenarios redisplayed for comparison with the regime-specific harvest rates ($F=M$; $F=0.25M$; $F=0.5M$).

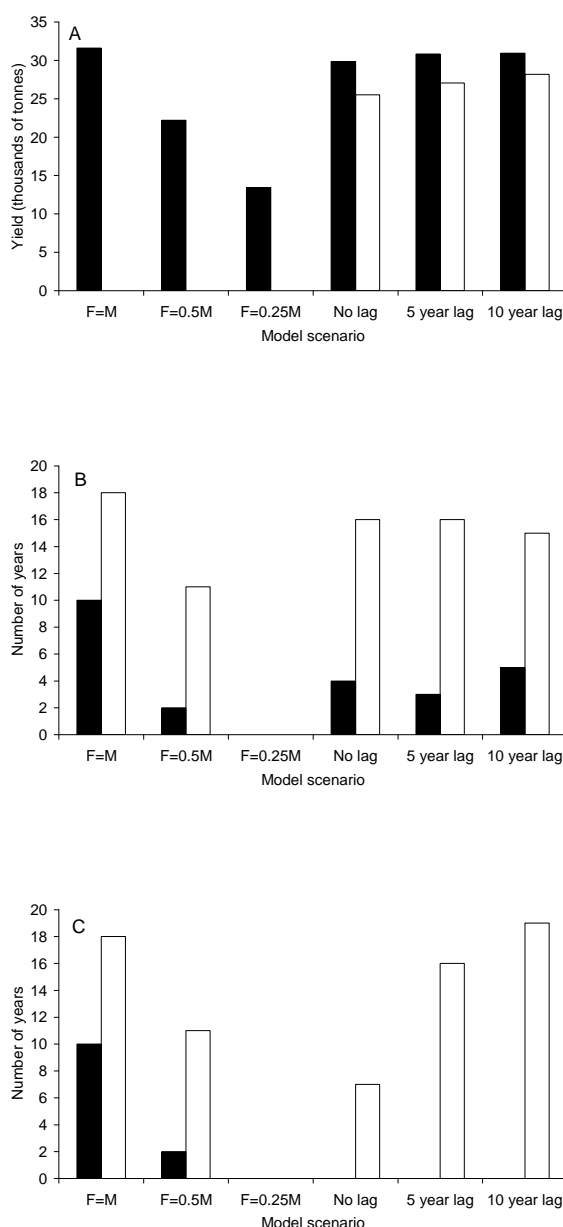


Figure 7. From King and McFarlane (2006). A) The total harvest (thousands of tonnes) for the various harvest rate scenarios for the long-lived species ('flatfish-like') population; solid bars are the constant harvest rate scenarios and the $F=M$; $F=0.5\cdot M$; $F=M$ regime-specific harvest rate scenarios; open bars are the $F=M$; $F=0.25\cdot M$; $F=0.5\cdot M$ regime-specific harvest rate scenarios. B) The number of years that the fishery was closed (solid bars) or in which there was a conservation concern (open bars) as defined by 25% and 30% of the maximum unfished spawning stock respectively. Six harvest rate scenarios are presented: constant harvest rates (F) for 60 years, F equal to annual natural mortality (M) or $F=0.5\cdot M$ or $F=0.25\cdot M$; and regime-specific harvest rates ($F=M$; $F=0.5\cdot M$; $F=M$) in which the switch in harvest rates coincides with the regime shift year (no lag), is delayed by age of 50% maturity (5 year lag) or by twice the age of 50% maturity (10 year lag). C) similar to B) with the constant harvest rate scenarios redisplayed for comparison with the regime-specific harvest rates ($F=M$; $F=0.25\cdot M$; $F=0.5\cdot M$).

Annex 16: Cod, herring and multispecies modelling in the North Sea

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In most single-species assessment models the natural mortality rate is taken as a 'known' value (usually around 0.2), often thought to be constant over all years and with age. In practice we might well expect that natural mortality would vary with age because smaller fish are more vulnerable to predation than larger fish, and we might also expect levels of predation mortality to vary from year to year (Figure 1), because numbers of fish predators and prey vary from year to year (Vetter, 1988). The inclusion of variable predation mortality was one of the major innovations of the (1977) Andersen-Ursin multispecies model for the North Sea. This idea was carried forward into multispecies versions of virtual-population analysis (Helgason & Gislason, 1979) and cohort-analysis (Pope, 1979).

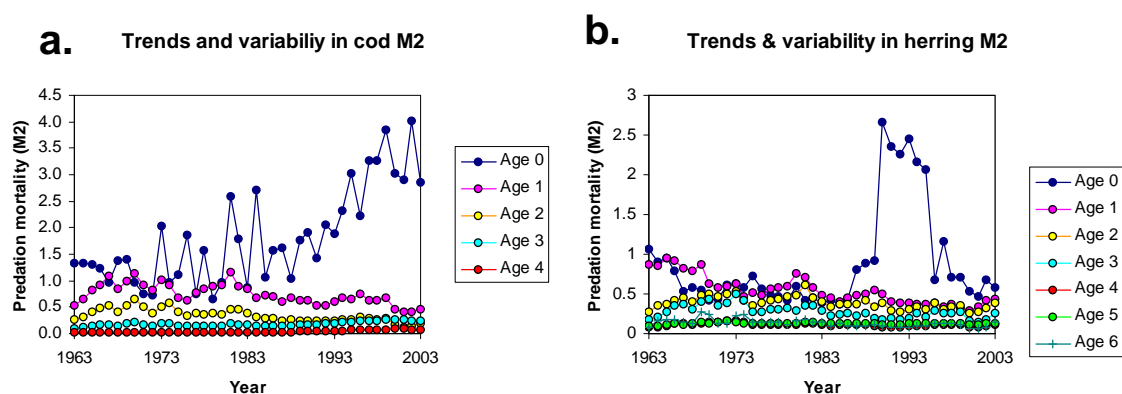


Figure 1. Predation mortality (M2) for cod (a) and herring (b) in the North Sea, as estimated by the most recent 'key-run' of MSVPA.

The main achievement of the ICES multispecies Working Groups convened between 1980 and the present, has been the provision of more realistic estimates of M2 (predation mortality) which have subsequently been fed into and improved single-species stock assessments. Experience with MSVPA, has generally indicated that natural mortality rates on juvenile prey fish are higher than previously assumed (Pope, 1991), and that traditional single-species estimates of M, can lead to overestimates of stock biomass per recruit. Similar results were noted in models of Atlantic cod stocks in the Gulf of St. Lawrence, the Scotian Shelf and the Barents Sea (see Hollowed *et al.*, 2000a).

Multispecies interactions are now routinely included in the single-species assessment and management of the capelin, cod and haddock stocks in the Barents Sea. Predation by cod on mature capelin is included in the assessment of Barents Sea capelin (Gjøsæter *et al.*, 2002; ICES 2006). Also predation by cod on cod and haddock is included in the assessment of the cod and haddock stocks (ICES 2006a). It has been demonstrated how predation by minke whale on herring could be modelled for use in the assessment of Norwegian Spring-spawning herring (Tjelmeland and Lindstrøm, 2005). The philosophy has been to include important multispecies interactions into *existing* assessment models (e.g. by M2 values which vary between years), which is a somewhat different to what has been done e.g. with the MSVPA in the North Sea. Such an approach may be useful for boreal system which are relatively simple and with few main species and interactions, but probably less so in more complicated systems like the North Sea.

Sparholt (1996) has advocated the inclusion of sprat predation and cannibalism in the stock assessment for Baltic Sea cod, and specifically for the prediction of future recruitment patterns. Similarly, Hollowed *et al.* (2000b) has attempted to include predation by arrowtooth flounder (*Atheresthes stomias*), pacific halibut (*Hippoglossus stenolepis*) and Steller sea lion (*Eumetopias jubatus*) in the stock assessment for walleye pollack (*Theragra chalcogramma*) in the Gulf of Alaska, whereas Livingston and Methot (1998) have included cannibalism, predation by pacific cod (*Gadus macrocephalus*) and northern fur seals (*Callorhinus ursinus*) in the walleye pollack assessment for the eastern Bering Sea. Together these studies clearly demonstrate that one can use the outputs from multispecies models to inform assessments, and yet continue to use single-species management.

Species interactions are likely to have direct effects on biological reference points (Brander, 1988), and failure to account for these may lead to undesirable outcomes, such as overexploitation and stock collapses, even if the probability of such outcomes appears to be negligible in a single-species context. Gislason (1999) used single and multispecies models to estimate and compare a few of the commonly used reference points for cod, herring, and sprat in the central Baltic. The results of this analysis clearly demonstrated how single-species reference points are affected by biological interactions. Instead of being point estimates (or targets), they are turned into reference curves. Furthermore, the single-species estimates do not always fall on the curves generated by the multispecies models. Compared to the single-species predictions multispecies models predicted that higher fishing efforts was needed to achieve MSY (maximum sustainable yield) in the pelagic and demersal fleets. The differences between multispecies and single-species predictions raise questions about the utility of single-species reference points in situations where important species interactions are suspected (Gislason, 1999).

In 2003 the ICES Study Group on Multispecies Assessment in the North Sea (SGMNS) was tasked with looking at the extent that reference points derived within a single species context are valid when multispecies interactions are taken into account. The link between B_{lim} and F_{lim} needs to be revisited when moving to a multispecies context, for two reasons:

- 1) The equilibrium F corresponding to a given SSB is no longer unique, because it depends on the state of the other stocks in the system.
- 2) When F -values have been specified for all species, there is an equilibrium with a unique set of SSB values. The opposite may not be true.

In the multispecies setting, the joined limits $SSB > B_{lim}$ for all species translates into a multidimensional parameter space for F . With the exception of haddock, the overall conclusion of the comparison of single and multi species predictions however, was that current F_{lim} values are adequate to ensure B_{lim} , provided recruitment is not impaired at B_{lim} , that is: the M values currently used in single species assessment for the North Sea adequately represents predation mortalities for the current situation (not that surprising, given that they have been revised using values derived from MSVPA). For haddock however, the model predicted a collapse in SSB , due to predation by saithe.

In 2003, the ICES Study Group on Multispecies Assessment in the North Sea (SGMNS) also attempted to evaluate the newly conceived 'harvest-control-rules' for cod, proposed as part of the North Sea cod recovery programme. In total, 17 different HCR scenarios were tested and cod recovery examined using both single and multispecies formulations. When the proposed harvest-control-rules for cod were applied, both single and multispecies models predicted cod recovery. The predicted recovery of cod SSB was however, slower when taking multispecies interactions into account, and the precautionary biomass reference point (B_{pa}) was reached approximately one year later, in 2008 instead of 2006/2007 in the single-species predictions. In terms of the impact of a cod recovery plan on other species in the North Sea, multispecies simulations predicted that Norway pout SSB would fall below B_{pa} after approximately 5 years of the application of the harvest-control-rules for cod, whereas single-species simulations predicted that SSB would remain stable above B_{pa} . Similarly, sandeel (a major prey for cod) was predicted to stay above the precautionary reference limit, when using single-species models. However, under multispecies considerations sandeel SSB was predicted to fall below

the precautionary reference limit and continue to decline in the long-term (ICES 2003). Thus it would seem that it may be impossible to ‘recover’ all species in the North Sea simultaneously, and therefore by implication, it may be impossible to meet commitments under the World Summit on Sustainable Development (WSSD), to “*maintain or restore stocks to levels that can produce the maximum sustainable yield, by not later than 2015*”.

In 1988 and 1990 ICES and STECF (see Pope, 1991; Stokes, 1992) used MSVPA to examine the potential impact of changes in mesh size. This exercise revealed that the direction of stock responses may sometimes be counterintuitive. Mesh size increases (from 70 mm and 85 mm, to 120 mm) in the roundfish fishery were found to result in comparatively smaller increases in the biomass of older cod and haddock than predicted by single-species models. The reason for the different results is that, by implementing a larger mesh size, the selection pattern of whiting was changed in such a manner as to facilitate the escape of larger whiting which predate upon juvenile cod and haddock. Thus, the relatively modest increases in the biomass of older cod and haddock were too small to compensate for the loss of small fish through predation, resulting in an overall decrease in yield as mesh size increased. The above analyses were conducted in response to manager’s questions concerning possible changes to minimum mesh sizes in real fisheries, principally to improve the state of cod and haddock stocks. It is apparent that giving clear answers and advice to managers is not simple. Single-species analyses suggested that mesh increases would be beneficial; multispecies analyses suggested quite the opposite (Stokes, 1992).

In 1992 the EC convened a special group to assess the effects of industrial fishing in the North Sea, and specifically, to ‘predict’ the effects a 40% reduction in industrial fisheries might have on predatory species which are dependent on sandeels and Norway pout as a food, or accidentally bycaught in the fishery (reported in Gislason and Kirkegaard, 1998). Using MSVPA it was found that a 40 % decrease in industrial fisheries, would lead to small increases in SSB and landings of cod, haddock and whiting. The results were however, complex, on the one hand reducing the industrial fisheries resulted in increases in Norway pout, which resulted in the prey more on Norway pout than on cod and other demersal species. On the other hand reducing the industrial fishery for sandeels and pout led to high whiting stocks, which preyed on other demersal species including juvenile cod.

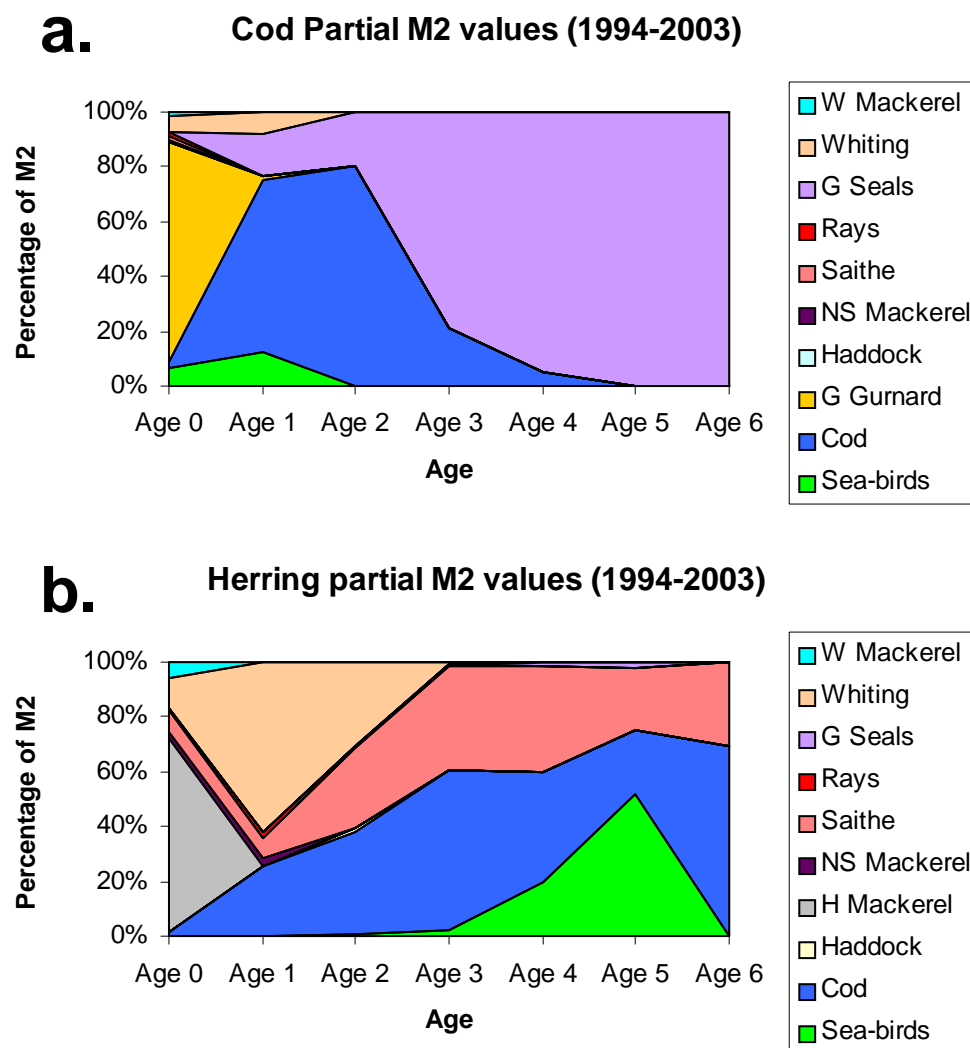


Figure 2. Partial predation mortalities (M2) for cod (a) and herring (b) in the North Sea, as estimated by the most recent ‘key-run’ of MSVPA.

Since the late 1980s, North Sea grey gurnard catch rates in the international bottom trawl surveys (IBTS) showed a pronounced increase. As the 1991 stomach sampling program revealed significant consumption of commercial fish species by grey gurnard, it was included as an “other predator” in the North Sea multispecies virtual population analysis (MSVPA) in 1997. The historic stock trends of “other predators” are not calculated inside the model but are rather given as an external model input. During the 2002 ICES workshop on MSVPA in the North Sea (ICES 2002), the time-series of grey gurnard model input biomass estimates was revised. The MSVPA results estimated grey gurnard to be responsible for approximately 60% of the total predation mortality on age-0 cod (Figure 2a). A recent study questioned whether the apparent increase in grey gurnards in the North Sea has been responsible for the irradiation of juvenile cod in the region as predicted by MSVPA, or whether this is simply an artefact of assuming the wrong ‘functional response’ within the model (a type II rather than a type III) (Floeter *et al.* 2005). The latter was found not to be the case, i.e. cod extinction in multispecies predictions was not due a model artifact; rather it was the unfortunate result of low levels of total available/alternative food and increasing grey gurnard abundance in the model.

It is important to note that grey seals (along with cannibalism by cod) are suggested to be the major predator of larger/older cod in the North Sea. A recent study found marked changes in grey seal diet composition in the North Sea between 1985 and 2002 (Hammond & Grellier, 2007). Much less cod and much more whiting were consumed in 2002 compared with 1985. However, estimates of annual consumption of commercially important fish prey by grey seals

increased markedly from 39 000 tonnes in 1985 to 116 000 tonnes in 2002, in line with the increase in grey seal population size. The estimated amount of sandeel consumed increased from 29 000 t in 1985 to 69 000 t in 2002, and estimated consumption of cod increased from 4 100 t to 8 300 t. Per capita prey consumption was 4.7 kg.d^{-1} ($1.72 \text{ tonnes.yr}^{-1}$). Consumption per seal decreased between 1985 and 2002 for cod (by ~30%) and sandeel (by ~15%), remained about the same for whiting, approximately trebled for plaice, and approximately quadrupled for haddock. Grey seal predation was not significant in 1985; estimated prey consumption was less than 1% of estimated stock size for all species. In 2002, consumptions relative to stock size of most prey species were several times higher but only for cod (3.7%) sandeel (2.7 %) and plaice (1.5 %) were the percentages greater than 1%.

Some Conclusions

Having considered in detail developments in multispecies modelling it is probably fair to agree with Chatfield (1995) and say that “*All models are wrong, but some are useful*”. It is well known that important biological interactions exist, and it is sensible to try to take account of such processes. It is equally well known that all possible interactions can not be included in the models being developed (Stokes, 1992). When does a more realistic model give more believable results than a less realistic one? Is it possible that semi-realism produces less accurate results than parsimonious representations of the systems of interest? The fundamental question is whether or not additional detail adds precision and accuracy or can it lead to errors, confusion and obfuscation?

Multispecies and ecosystem models have not necessarily provided better predictions of future stock status or recruitment, but they have indicated that predation pressure and/or the availability of food resources can, at least theoretically, be important determinants on future fish stock developments. As scientists we have learnt that characterizing predator-prey interactions can be fraught with difficulties and that many highly emotive and political issues are related to trophic interactions. Multispecies models have, to some extent been guilty of ‘muddying the waters’; in that they have allowed fishers and policy makers ‘off the hook’ by blaming, with little justification, other marine predators (other than humans) for stock depletion and/or failure to recover. On the other hand, multispecies models have also offered significant insight both for science and management and they are likely to continue to be needed.

In 1989, ICES sponsored a symposium on multispecies models relevant to the management of living resources. At that meeting, Brugge and Holden (1991) caused considerable annoyance among many participants by apparently suggesting that the ICES multispecies assessment effort of the previous decade had caused more problems than it actually solved. Specifically, Brugge and Holden commented that, despite being more convincing because they are more realistic, models including biological interactions were often difficult to interpret and gave counter-intuitive results. They expressed concern at the lack of demonstrated robustness to model assumptions and to the perceived incompleteness of the models produced so far (i.e. only certain species were included), and stated that the outputs would be very difficult to communicate to industry and politicians. Overall they concluded that approaches incorporating technical interactions (only) produced more useful results for managers. From these two professional managers, the final words were “*species interaction models will not be a manager’s panacea. They are more likely to be his nightmare*” (Stokes, 1992).

At the same meeting, Gulland (1991) also considered the utility of biological interaction models and listed a number of difficulties with the approach. His conclusion though, was somewhat more optimistic: “*In brief, I do believe that multispecies models will lead to better management, but the process will not be automatic, it will require further improvements in the communications between biologists and managers and of course the fishermen themselves*”.

There is a growing recognition from managers and the public alike, that fisheries must be managed as a component of wider marine ecosystems, as mandated through the 2002 World Summit on Sustainable Development, the FAO Reykjavik Declaration (2001), the U.S. Magnuson-Stevens Fishery Conservation and Management Act (MSFCMA) and the 2002

reform of the EU Common Fisheries Policy (CFP). The majority of fishers strongly believe in multispecies interactions: they witness them daily in their fishing operations. The call has never been louder for multispecies advice. Management practices will need to change and adapt, in order meet these ever-broadening expectations as well as international obligations.

Multispecies working groups have acted as a useful conduit, drawing together quantitative outputs from many different assessment working groups, and they have allowed scientists to respond to very real concerns raised by fishermen, fisheries managers and NGOs.

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