View metadata, citation and similar papers at core.ac.uk

brought to you by CORE

provided by CiteSeerX

ICES Journal of Marine Science; doi:10.1093/icesjms/fsq158

Depleted marine fish stocks and ecosystem-based management: on the road to recovery, we need to be precautionary

Anna Gårdmark[1]*, Anders Nielsen[2], Jens Floeter[3], and Christian Möllmann[3]

[1]*Institute of Coastal Research, Swedish Board of Fisheries, Skolgatan 6, SE-742 22 Öregrund, Sweden*
[2]*DTU Aqua, Charlottenlund Slot, Jægersborg Allé 1, DK-2920 Charlottenlund, Denmark*
[3]*Institute for Hydrobiology and Fisheries Science, University of Hamburg, Grosse Elbstrasse 133, D-22767 Hamburg, Germany*

**Corresponding Author: tel: +46 173 46466; fax: +46 173 46490; e-mail: anna.gardmark@fiskeriverket.se.*

Gårdmark, A., Nielsen, A., Floeter, J., and Möllmann, C. Depleted marine fish stocks and ecosystem-based management: on the road to recovery, we need to be precautionary. – ICES Journal of Marine Science, doi:10.1093/icesjms/fsq158.

Received 21 December 2009; accepted 15 September 2010.

Precautionary management for fish stocks in need of recovery requires that likely stock increases can be distinguished from model artefacts and that the uncertainty of stock status can be handled. Yet, ICES stock assessments are predominantly deterministic and many EC management plans are designed for deterministic advice. Using the eastern Baltic cod (*Gadus morhua*) stock as an example, we show how deterministic scientific advice can lead to illusive certainty of a rapid stock recovery and management decisions taken in unawareness of large uncertainties in stock status. By (i) performing sensitivity analyses of key assessment model assumptions, (ii) quantifying the uncertainty of the estimates due to data uncertainty, and (iii) developing alternative stock and ecosystem indicators, we demonstrate that estimates of recent fishing mortality and recruitment of this stock were highly uncertain and show that these uncertainties are crucial when combined with management plans based on fixed reference points of fishing mortality. We therefore call for fisheries management that does not neglect uncertainty. To this end, we outline a four-step approach to handle uncertainty of stock status in advice and management. We argue that it is time to use these four steps towards an ecosystem-based approach to fisheries management.

Keywords: advice, assessment, Baltic Sea, cod, ecosystem-based, ecosystem indicator, fisheries management, stock recovery, uncertainty.

Introduction

Along with climate change, overfishing of the world's fisheries resources is widely regarded as one of the prominent environmental crises facing the world today (FAO, 2009). Although the absolute degree of the overfishing problem is debatable, recent consensus is that after a long history of overexploitation, efforts to restore marine ecosystems and rebuild fisheries are now increasing (Worm *et al.*, 2009). However, almost one-third of all fish stocks assessed worldwide are still overexploited or depleted and require no or very low exploitation rates to be able to rebuild (FAO, 2009). Recent apparently positive examples, such as the seemingly increasing stock of eastern Baltic (EB) cod (Figure 1a; ICES, 2009a) raise the question of how to manage recovering stocks. At the very least, scientific advice needs to be able to distinguish likely stock increases from model artefacts, and fisheries management needs to be able to handle the uncertainty of stock status and stock trends.

As with any model-based estimate, estimates of stock size and fishing mortality depend on the assumptions of the stock-assessment model used. The standard ICES estimates of spawning-stock biomass (SSB) and fishing mortality (F) are, for most stocks, derived using extended survival analysis (XSA; Shepherd, 1999). This is an estimation model in which data on the amount and age composition of commercial catches are combined with indices of population abundance from research surveys or commercial reference fleets to reconstruct stock sizes back in time. An important assumption in the XSA is the practice of shrinkage (Darby and Flatman, 1994; Shepherd, 1999), a practice intended to increase precision in estimates of F (or SSB) by forcing them to vary only slightly between years (Darby and Flatman, 1994; Lassen and Medley, 2001). This may be desirable when there is no systematic change in F or SSB over time, but because the extent of shrinkage influences the most recent trend in estimated F and SSB, it has a profound impact on our perception of whether or not a stock is recovering (Kraak *et al.*, 2008). Another assumption crucial for potentially recovering stocks is that catch per unit effort indices (tuning indices) properly reflect stock development (Kraak *et al.*, 2009). As fish aggregation behaviour often changes at low abundance, trends in catchability are more likely to be found in depleted or recovering stocks (Rose and Kulka, 1999). Reliance on indices drawn from fishing fleets or surveys with a trend in catchability results in an artificial trend in the estimates of stock development.

In addition to the uncertainty attributable to the assumptions of the model, estimates of recent SSB and F are notoriously affected by inaccurate or noisy input data. In particular, assessments commonly suffer from catch under- and misreporting, highly uncertain data on discarding, and differences in sampling methodology or age determination (e.g. ICES, 2009a). Yet, the most common stock assessment model used by ICES (2009b),

© 2010 International Council for the Exploration of the Sea. Published by Oxford Journals. All rights reserved.
For Permissions, please email: journals.permissions@oxfordjournals.org

Downloaded from http://icesjms.oxfordjournals.org/ at Leibniz-Institut fuer Ostseeforschung Warnemuende (IOW) - Bibliothek on October 20, 2011

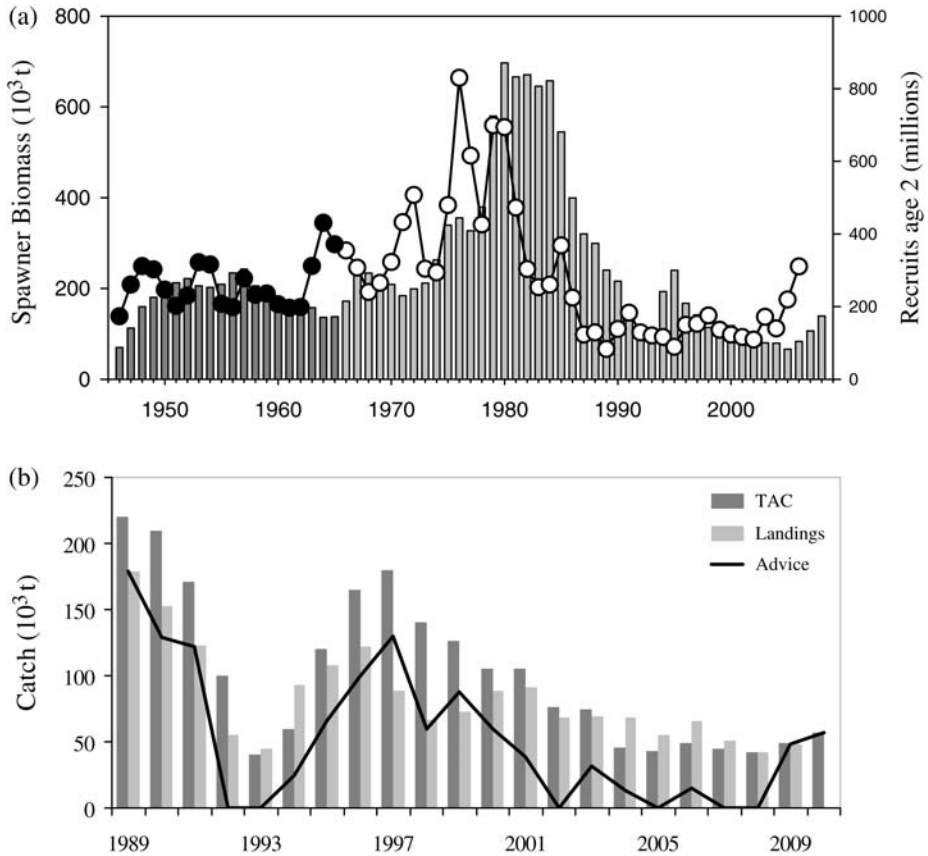

Figure 1. EB cod (a) SSB (bars) and recruitment (circles) estimates, and (b) advised catches (line), official landings (light grey bars), and decided TAC (dark grey bars). In (a), the estimates for 1976–2008 from the latest official stock assessment (ICES, 2009a; open circles and light grey bars) are combined with historical estimates 1946–1975 from Eero *et al.* (2007; filled circles and dark grey bars).

the XSA, is deterministic so does not provide any measure of how such observation uncertainty propagates to uncertainty in the parameter estimates.

It is well known that stock assessments are sensitive to the assumptions on, for example, shrinkage (Kraak *et al.*, 2008), and that sources of observation error in estimated stock sizes are plentiful (Harwood and Stokes, 2003). However, how predominantly deterministic scientific advice from ICES combines with EU management plans based on single trigger and target reference points and results in management of potentially recovering stocks has received little attention (see Kraak *et al.*, 2010, for a discussion on management plan evaluations). Moreover, available information on abiotic and biotic, e.g. food availability, conditions of assessed fish stocks is rarely used in advice on stock status, although they are particularly important for declining and potentially recovering stocks. Here, we use the example of the EB cod, which is an important economic resource of the countries bordering the Baltic Sea, to illustrate the critical interplay between advice and management for recovering stocks. The estimated recent increase in EB cod has been attributed to a number of management measures, such as spatio-temporal closures and effort reduction, which are believed to have caused a reduction in *F*, as well as to improved recruitment (ICES, 2009a). We illustrate how this perception of EB cod stock recovery (ICES, 2009a) arose from the application of a single-species deterministic model. Using the example of EB cod, we demonstrate the illusiveness of this type of deterministic stock assessment and show the uncertainties in the estimates of SSB and *F* by (i) conducting a sensitivity analysis of a key assumption in the assessment model (i.e. *F*-shrinkage), (ii) using a stochastic estimation model (SAM) to quantify the uncertainty of the estimates attributable to uncertainty in the input data, and (iii) developing a system of alternative ecosystem indicators of recovery potential for the stock. Finally, we explore the consequences of uncertain advice, disguised as deterministic point estimates, for implementing EC recovery and long-term management plans (EC, 2007). We thereby demonstrate the danger in basing fisheries advice and management on single estimates of fishing mortality and call for uncertainty measures and ecosystem-based indicators to be incorporated in future advice and management routines.

The eastern Baltic cod example

This stock has displayed the typical boom and bust trajectory of many Atlantic cod stocks. Large recruiting year classes resulted in record high stock sizes during the late 1970s and early 1980s (Figure 1a; ICES, 2009a), mainly caused by favourable hydrographic conditions (Köster *et al.*, 2005). With the deterioration of environmental conditions, however, recruitment collapsed, as did the stock. The collapse was amplified by a far too heavy fishing pressure (Figure 1b), which along with low levels of recruitment resulted in the all-time low stock sizes observed through most of the 1990s and 2000s (Köster *et al.*, 2005).

Downloaded from http://icesjms.oxfordjournals.org/ at Leibniz-Institut fuer Ostseeforschung Warnemuende (IOW) - Bibliothek on October 20, 2011

Altered hydrographic conditions have also resulted in productivity changes in the central Baltic (Möllmann *et al.*, 2009). Therefore, the reference points based on stock size commonly used in ICES advice have been shown to be inappropriate for Baltic Sea fish stocks (ICES, 2008a; cf. Collie and Gislason, 2001), as also found in the face of productivity changes elsewhere (Mohn and Chouinard, 2007). Instead, for EB cod, a target annual *F* of 0.3 has been recommended (ICES, 2005a), which according to model simulations would result in a low risk of harming reproductive potential and high yields during the two decades evaluated (ICES, 2005a; Bastardie *et al.*, 2010). Based on this advice, the European Commission introduced a long-term Baltic cod management plan (EC, 2007), which specified a harvest control rule (HCR) of reducing *F* by 10% year-on-year until $F = 0.3$, through annual reductions in total allowable catch (TAC) and fishing days. In the plan, interannual changes in TAC are to be restricted to $\pm 15\%$, unless *F* exceeds 0.6, in which case the TAC is to be reduced further. Model simulations suggest that the plan, if followed, is likely to rebuild the stock within 15 years (Bastardie *et al.*, 2010), and the plan has therefore been evaluated by ICES as being precautionary (ICES, 2009c).

Recently, an XSA conducted by ICES for EB cod showed recruitment in the final two years (measured as 2-year olds, i.e. the year classes 2005 and 2006) to be above the average of the past 25 years (Figure 1a; ICES, 2009a), and *F* in 2008 was estimated to be below the target of 0.3 (Figure 2; ICES, 2009a). This estimated *F* resulted, in accord with the management plan, in advice for an increase in TAC by 15% (ICES, 2009c). Along with this advice, the countries concerned agreed to raise the TAC for 2010 by 15% to 56 800 t (Council of the European Union, 2009). We show here, however, that the estimate of recent *F* on which this decision was based (and of SSB and recruitment) was highly uncertain, and discuss alternative approaches to scientific advice and management for situations such as this.

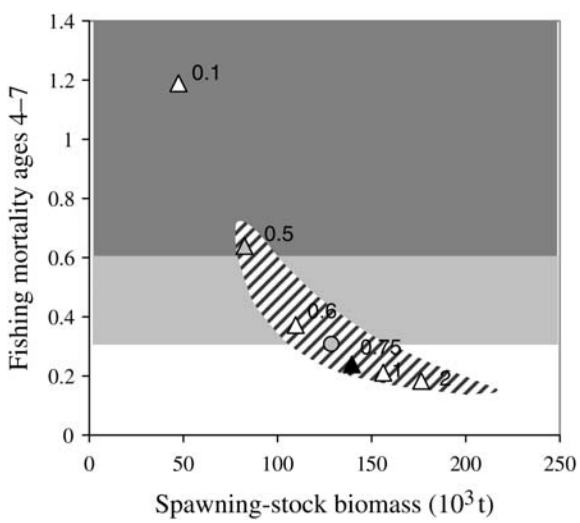

Figure 2. Estimates of EB cod SSB and fishing mortality (*F*) in 2008 using XSA (triangles) or the state-space stock assessment model, SAM (circle). The black symbol indicates the official estimates (ICES, 2009a), the grey symbols exploratory assessment estimates by ICES (2009a), and open symbols additional estimates by the authors using ICES (2009a) settings and input. The hatched area indicates the confidence interval (95%) for the SAM estimates of SSB and *F*. For XSA runs, the number next to the symbol indicates the level of shrinkage used (the s.e. of individual estimates allowed around the mean). The threshold values of *F* for which different rules apply in the management plan for the stock are indicated with shading: annual reduction in fishing days by 10% and TAC resulting in an annual reduction in *F* by 10% (dark grey), annual reduction in TAC by at most 15% and in fishing days by 10% (light grey), or no reduction in TAC or fishing days when fishing mortality is below target $F = 0.3$ (white).

Uncertainty in model-based assessments of stock status

To assess the effect of the level of shrinkage applied in estimating EB cod SSB and *F*, we conducted a sequence of XSAs over a range of shrinkages (s.e. of the *F*-estimates allowed; Darby and Flatman, 1994), based on data used in the standard EB cod assessment (ICES, 2009a). Allowing more variation in *F*-estimates around the mean by increasing from s.e. = 0.5 (as used by ICES, 2008b) to s.e. = 0.75 (as used by ICES, 2009a), reduced the estimated *F* for 2008 by >50% (Figure 2). Concurrently, the trend in estimated recruitment changed: the estimated number of recruits for 2008 changed from slightly above-average recruitment to almost double—the highest level of recruitment in the past two decades (Figure 3).

This exercise shows not only how the perceived stock trend is affected, but also how crucial are the assumptions in assessment models when combined with fixed reference points of *F* in a management plan. The change in only one assumption in the assessment model (in this case increasing the s.e. from 0.5 to 0.75) altered the estimated *F* critical for advice and management decisions from a level ($F = 0.6$) where TACs may be reduced by >15%, to below the long-term target ($F = 0.3$), at which point TACs are allowed to increase (Figure 2).

Stochastic evaluation of stock status

To quantify the uncertainty in estimated values of *F* and SSB in 2008, we applied a stochastic estimation model, SAM, to EB cod (see Supplementary material; freely available at www.ebcod.stockassessments.org) using the same input data as in the standard

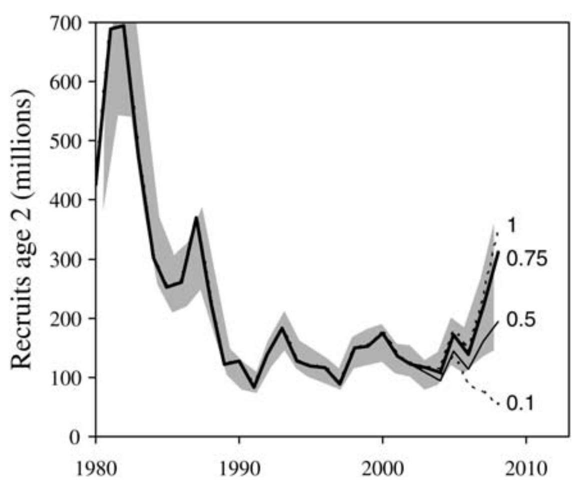

Figure 3. EB cod assessment estimates of number of recruits (2-year olds) using XSA (lines) or SAM (shaded area, 95% confidence interval). The numbers indicate the shrinkage (s.e. of individual estimates allowed around the mean) used in XSA. The heavy line indicates the official estimate by ICES (2009a), the thin line that using the shrinkage of ICES (2008c), and dashed lines additional XSA estimates by the authors using ICES (2009a) settings and input.

Downloaded from http://icesjms.oxfordjournals.org/ at Leibniz-Institut fuer Ostseeforschung Warnemuende (IOW) - Bibliothek on October 20, 2011

EB cod assessment (ICES, 2009a). Model results show that the 95% confidence limits for F in 2008 ranged across both reference levels in the management plan, from >0.6 to well below 0.3 (Figure 2; see also ICES, 2009a). In other words, given the uncertainties in the data, it is likely that F was anywhere between 0.15 and 0.61 (Figure 2); that range cannot be narrowed further unless input data improve. Indeed, the uncertainty is so great that all estimates of the XSA model using shrinkages from 0.5 to 2 fall within the confidence limits of the SAM estimate of F (Figure 2).

We further used SAM to quantify the probabilities that the value of F estimated for 2008 fell below or above the thresholds in the management plan. The best estimate of F using SAM is indeed 0.30 (Figure 2), i.e. the target F. However, this also implies that the case where F was above target is as probable as where F was below target [$p(F > 0.3) = 0.51$, $p(F < 0.3) = 0.49$]. From a precautionary perspective, the probabilities of being above higher F-values may be more important. For example, there is a 21% probability that $F > 0.4$ and a 3% probability that $F > 0.6$ (Table 1).

Correspondingly, the uncertainty in the estimated recruitment level was high (Figure 3). The confidence limits of the estimate from SAM accounting for observation uncertainty covered all XSA estimates using shrinkages from 0.5 to 1. The likely (95% confidence range) number of 2-year olds in 2008 ranged from 146 to 354 million (Figure 3). In other words, the most precise estimate of recruitment was anywhere between the highest recruitment in 25 years, which is more than twice as high as the 1998–2007 average, and average recruitment, which is slightly less than the recruitment level in 2005, displaying no positive recruitment trend at all (Figure 3).

Ecosystem-indicator-based assessment of stock status

The example above clearly demonstrates that quantifying the uncertainty in estimates of F and SSB is crucial and also that it is not a sufficient basis for truly precautionary advice and management. In cases of such great uncertainty about the state of the stock and the impact of the fishery (Figures 2 and 3), auxiliary information is needed, such as provided by ecosystem indicators. Alternative indicators of stock status, of the physical oceanographic environment and the abundance of prey, predators, and competing stocks, as well as indicators integrating this ecosystem context of the exploited species, are important pillars of modern ecosystem-based fishery-management approaches (Link *et al.*, 2002; Hall and Mainprize, 2004; Jennings, 2005; Link, 2005).

For EB cod, there is extensive knowledge of the processes leading to recruitment variability. The main factors are (i) the size/age structure of the parent stock (Vallin and Nissling, 2000), (ii) the levels of salinity and oxygen influencing cod egg survival (Wieland *et al.*, 1994), (iii) the status of the sprat (*Sprattus sprattus*) stock that preys on cod eggs and reduces the zooplankton food for cod larvae (Köster and Möllmann, 2000; Möllmann and Köster, 2002), and (iv) the population size of the copepod *Pseudocalanus acuspes*, known to be important for the survival of cod larvae (Hinrichsen *et al.*, 2002). As these factors are known to influence EB cod recruitment, they can be used as indicators of recruitment conditions, as a complement to direct estimates of the number of recruits, as presented above. Exploring these indicators, we see that the age structure of EB cod is skewed towards young ages (Figure 4a), demonstrating that the stock still lacks older and, hence, larger, highly fecund females producing more viable offspring. Moreover, the individual size (weight) of cod has decreased across all ages during the past 15 years and is continuing to do so (Figure 4b), and the size-at-maturity of EB cod has decreased by ~20% in less than two decades (Vainikka *et al.*, 2009). Additionally, the population size of *P. acuspes* is still low (Figure 4c), indicating low availability of food for cod larvae. Additionally, the sprat stock is assessed to be still above the threshold level (Casini *et al.*, 2009) at which it controls zooplankton biomass (Figure 4d), indicating a negative influence on cod via food reduction for EB cod larvae, and possibly also egg predation.

Changes in these indicator species (Figure 4c and d) and in EB cod are part of a larger reorganization, or regime shift, in the Baltic Sea ecosystem in the late 1980s (Casini *et al.*, 2008; ICES, 2008c; Möllmann *et al.*, 2009), which also altered the interactions between these species (Möllmann *et al.*, 2008; Casini *et al.*, 2009). The reorganization therefore entailed processes with the potential to suppress the cod stock [(iii) and (iv) above]. Changes in the composition of whole ecosystems can be tracked using reduced variables from ordinations of time-series on ecosystem components, such as the recently developed holistic indicators of biotic parts of the Baltic Sea ecosystems (ICES, 2007, 2008c; Möllmann *et al.*, 2009). We updated the holistic indicator for the central Baltic, the core area for EB cod, to assess the ecosystem context of the EB cod stock. This holistic indicator (made of the first two principal components) is based on 31 key species and species groups and shows how species composition has changed over time, with significantly different composition during three "regimes" (Figure 4e; cf. Möllmann *et al.*, 2009). The species composition, and hence species interactions, during the period when the EB cod stock was large is significantly different from the current composition (Figure 4e). Therefore, the indicator suggests no change in the ecosystem configuration to a state favourable for EB cod stock productivity (Figure 4e).

In contrast to the biotic indicators, more positive signs are found in terms of the physical environment. The reproductive volume, a measure of the habitat size supporting cod egg survival bounded by salinity and oxygen levels (MacKenzie *et al.*, 2000), shows above-average values in 2003 and 2006 (Figure 4f). The latter indicates that above-average recruitment (at age 2) in 2008 was possible. Another indicator of the suitability of the physical environment for cod egg development is the depth of the 11 psu isohaline in the Gotland Basin. A shallower depth indicates improved salinity and oxygen conditions in this spawning area but also in the important Bornholm Basin, both crucial for the production of larger year classes of EB cod. This indicator also shows improved conditions for cod recruitment (Figure 4f).

To integrate the information from these indicators, we created an ecosystem-based indicator of EB cod recruitment potential

Table 1. Probabilities of SAM-estimated fishing mortality, *F*, for ages 4–7 in 2008 taking certain values.

Values of *F*	**Probability**
<0.2	0.12
<**0.3**	0.49
>**0.3**	0.51
>0.4	0.21
>0.6	0.03

The upper threshold *F* and the target *F* in the management plan are underlined and emboldened, respectively.

Downloaded from http://icesjms.oxfordjournals.org/ at Leibniz-Institut fuer Ostseeforschung Warnemuende (IOW) - Bibliothek on October 20, 2011

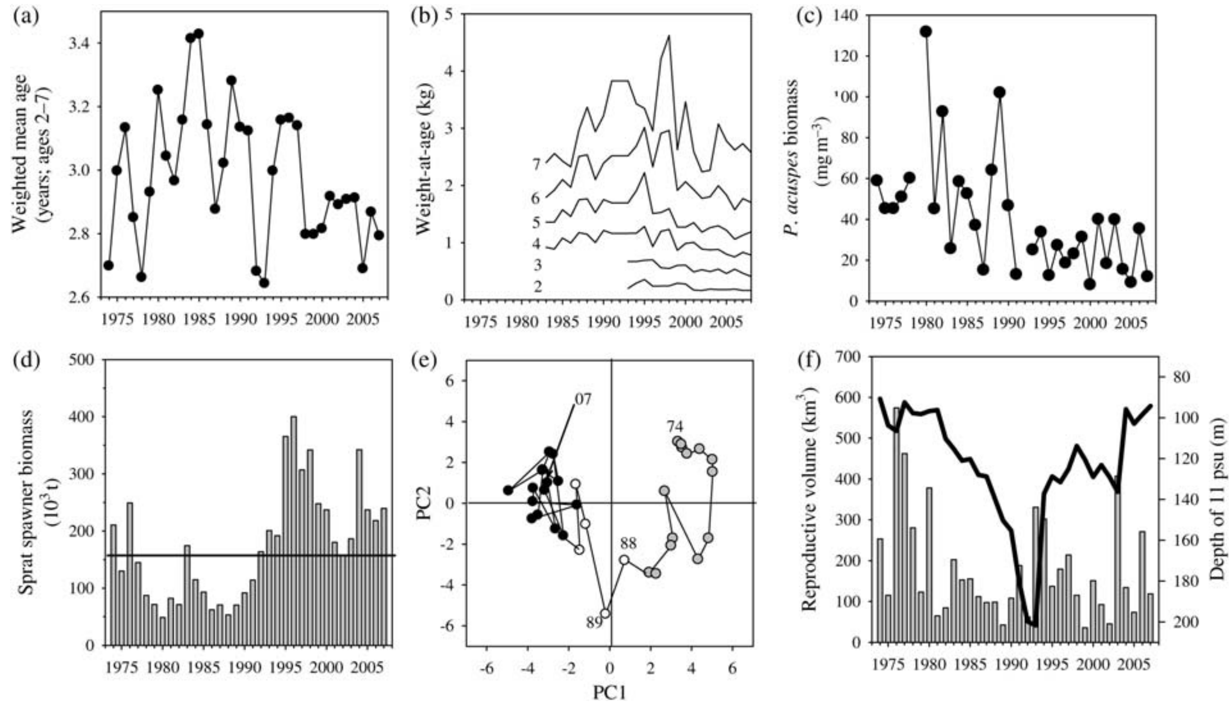

Figure 4. (a–e) Biotic and (f) hydrographic ecosystem indicators of EB cod stock status: (a) mean age in the EB cod stock, (b) mean weight-at-age in the EB cod stock, (c) biomass of the zooplankton *P. acuspes*, (d) SSB of sprat (bars), the horizontal line indicating the threshold biomass above which the sprat stock controls zooplankton biomass, (e) holistic indicator (based on principle component analysis) of the biotic part of the central Baltic ecosystem, where circle shade indicates the different regimes identified by chronological clustering (cf. Möllmann *et al.*, 2009; grey 1974–1987 regime, white 1988–1992 transition period, black 1993–2007 regime), (f) cod reproductive volume (bars) and the 11 psu isosalinity depth in the Gotland Basin (line).

(hereafter referred to as a recruitment potential indicator) from a qualitative recruitment model based on fuzzy-logic networks (cf. Miller and Field, 2002; Jarre *et al.*, 2008). Using fuzzy logic allows us to combine quantitatively very different factors (the two abiotic and four biotic indicators above) into a single indicator, based on how each influences EB cod recruitment, e.g. resulting in above- or below-average recruitment. Qualitative relationships between the six single indicators (Figure 4a–d and f), as well as EB cod SSB, and cod recruitment (number of 2-year olds shifted to the year of birth) as estimated by ICES (2009a) were derived and combined as annual weighted averages into the recruitment potential indicator (Supplementary material). The final indicator of recruitment potential was dominated by cod SSB and the abiotic indicators, whereas sprat and *P. acuspes* biomass made up 12 and 15%, respectively, of the indicator, and cod mean age and cod weight-at-age 5 constituted 1 and 5%, respectively (Supplementary Table S2).

This ecosystem-based indicator of recruitment potential for EB cod suggests beneficial (i.e. above average) recruitment conditions in 2006 (Figure 5, Supplementary Figure S1b). This corresponds to the XSA estimate of the 2006 year class being above average in terms of recruitment. However, the perception of EB cod recovery also comes from the XSA-estimated recruitment of the 2005 year class as being the highest in the preceding two decades (Figures 3 and 5; ICES, 2009a). For that year class, in contrast, the recruitment potential indicator shows the second-worst recruitment conditions in the time-series (Figure 5), failing to corroborate the XSA-based impression of an increasing trend in cod recruitment. The reason for the above-average score of the recruitment potential indicator

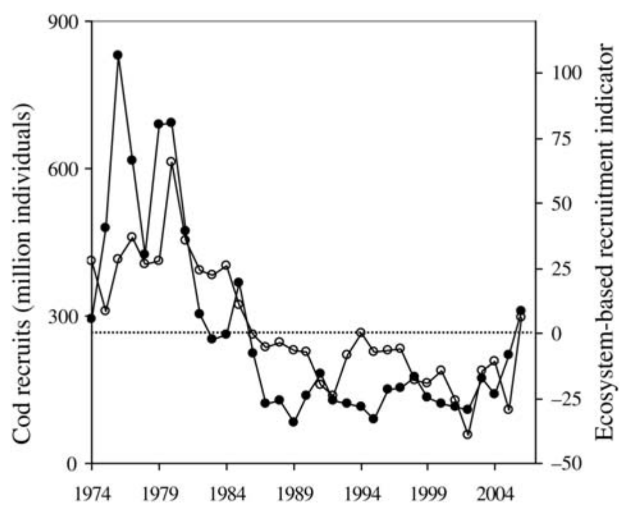

Figure 5. EB cod recruitment trends estimated from XSA as the number of 2-year olds (shifted to year of birth; dots) and from the ecosystem-based indicator of EB cod recruitment potential (open circles), based on a qualitative recruitment model integrating the six ecosystem indicators in Figure 4a–d and f. The horizontal dotted line indicates the average number of recruits during the years 1974–2006 and the zero threshold of the recruitment potential indicator.

for 2006 is the improved hydrological conditions then (Figure 4f), because these single abiotic indicators contribute strongly to the integrated indicator (Supplementary Table S2). However, changes in the biotic environment in response to

Downloaded from http://icesjms.oxfordjournals.org/ at Leibniz-Institut fuer Ostseeforschung Warnemuende (IOW) - Bibliothek on October 20, 2011

improved physical oceanographic conditions are often lagged in time; a development that our biotic indicators (Figure 4a–d) demonstrate has not yet taken place.

Discussion

We have shown the potential danger of neglecting uncertainty in scientific advice and fisheries management. Using the example of the EB cod stock, we demonstrated how deterministic advice combined with management based on single target and trigger fishing mortalities led to (i) illusive certainty of a rapid stock recovery and (ii) TAC decisions taken without awareness of the great uncertainties in *F* and stock status. The EB cod case is not unique; deterministic stock assessments are still the most common in ICES (2009b), and many of the EC management/recovery plans proposed (EC, 2009a, b, c), or in place (EC, 2007, 2008), are based on deterministic rather than probability-based advice. Therefore, the problematic interplay between deterministic advice and management neglecting uncertainty needs to be solved, and urgently.

Our analyses of EB cod accounting for alternative model assumptions and inherent data uncertainties showed that final-year *F* ranged from below the target *F* to more than twice the target, and recruitment ranged from the best in 25 years to around the average of the past decade (i.e. a confidence interval spanning about $\pm 50\%$). Further, the ecosystem-based indicator of recruitment potential indicated above-average-recruitment conditions for the 2006 year class, but very poor recruitment conditions in 2005, contradicting the XSA-based positive recruitment trend (ICES, 2009a). Indeed, the most recent update of the stock assessment (ICES, 2010) shows that these recent year classes obtained by ICES (2009a) were overestimated by 20–30%. The issue of over- (or under-) estimation of recent recruitment or *F* in XSA is well known. Our point is that presenting advice as deterministic estimates in such cases gives an illusion of certainty.

The EB cod case demonstrates that new approaches are needed when translating stock assessments to advice and management. In particular, knowledge of the uncertainty (or certainty) of the status of stocks and fisheries is a prerequisite for efficient fisheries management with good foresight. This can be achieved in four steps: (i) *quantification of uncertainty* in model-based stock assessments, (ii) *reduction of uncertainty* by reducing the uncertainty in model-based estimates and complementing these with alternative (ecosystem) indicators of stock status, (iii) *communicating the uncertainty*, and (iv) management based on HCRs able to *handle the uncertainty*. Below, we discuss the pros and cons, and the execution, of these four steps.

The important first step is to quantify the uncertainty in estimated *F* and stock sizes attributable to model assumptions and observation uncertainty. This can be done by sensitivity analyses (Saltelli *et al*., 2008), model comparisons (Hill *et al*., 2007) in, for instance, Bayesian frameworks (Gelman *et al*., 2004), and correctly propagating observation uncertainties into confidence estimates around the estimated values of SSB and *F* (Schnute and Richards, 1995; ICES, 2008d), as was done here. Sources of uncertainty are manifold, and there is a range of methods available to account for uncertainty in stock assessments (Harwood and Stokes, 2003). The important point is that ranges, rather than point estimates, of likely SSB and *F* values can be derived. Alternatively, the outcome could be a list of point values accompanied by probabilities (e.g. Table 1). Although this type of assessment does occur (e.g. ICES, 2009d), it is far from common practice in ICES (e.g. ICES, 2009e, f, g, see also ICES, 2009b).

Quantification [step (i)] and communication [step (iii)] of the uncertainty of stock and fishery status is necessary to enable decision-makers in management to determine whether efforts to reduce uncertainty [step (ii)] are needed. Traditional means of reducing observation uncertainty in fisheries data are standardization of scientific surveys, improving convergence in age determination, and developing sampling schemes to increase the precision. Such efforts aim to reduce the uncertainty in stock estimates from a particular assessment model. However, there are many sources of uncertainty in stock status beyond observation uncertainty, stemming from, for example, environmental variation (process uncertainty) and model misspecification (model error; Harwood and Stokes, 2003). Therefore, the status of a stock may be uncertain even when estimates from a particular model are very precise. We therefore raise an additional possibility of how to reduce uncertainty in stock status: supporting model-based stock assessments with information from ecosystem indicators. As demonstrated above, alternative indicators of the state of a target stock but also of its biotic and abiotic environment could, and should, be used routinely when developing advice and informing managers (see also Kraak *et al*., 2010). Single-ecosystem indicators and integrated indicators, such as the ecosystem-based indicator of recruitment potential presented above, can be developed for stocks where sufficient knowledge exists on the relevant processes steering their dynamics and the foodweb of which they are part. As model-based stock estimates, such indicators are also subject to observation uncertainty, and their estimates should ideally come with confidence intervals. Moreover, aggregated indicators are sensitive to assumptions on, for example, weighting and type (or lack) of interactions among the partial indicators of which they are composed. When properly derived, however, they, as well as sets of individual indicators, can serve as a basis for management decisions on the credibility of model-based assessments of stock status. Although HCRs may then still be based on ranges (or probabilities) of estimates from single-species models, such alternative indicators provide information for use in deciding on which end of the range of the model-based stock estimates to trust more.

Proposals of alternative indicators to support ecosystem-based fisheries management have been plentiful in the past decade (see Cury and Christensen, 2005, and references therein; Trenkel *et al*., 2007; Petitgas *et al*., 2009), for data-poor and data-rich systems. The indicators we present for EB cod are not meant as an exhaustive analysis of the indicators that are most suitable, but rather as an example of how indicators can complement model-based stock estimates. Indicator systems for this and other stocks in the Baltic Sea are being developed elsewhere (M. Eero, DTU–Aqua, pers. comm.). In contrast to a focus on indicators alone, we propose applying alternative ecosystem indicators as part of a framework translating single-species stock assessments into advice and management and at the same time accounting for uncertainty.

Precautionary management entails making decisions under uncertainty, not making decisions ignoring uncertainty. Therefore, management needs to be able to handle uncertainty [step (iv)]. In the example of EB cod, the management plan is based on single values of *F*, in terms of the thresholds, the targets, and the HCR (EC, 2007). It is not developed to cope with advice on a range of probable values of *F*. Still, the plan has been evaluated by ICES as being precautionary (ICES, 2009c; Bastardie *et al*., 2010) *sensu* ICES–EC STECF that there is a

Downloaded from http://icesjms.oxfordjournals.org/ at Leibniz-Institut fuer Ostseeforschung Warnemuende (IOW) - Bibliothek on October 20, 2011

probability <0.05 that the stock falls below the limit biomass reference point, $B_{\rm lim}$ (ICES, 2009h; see also Kraak *et al.*, 2010), although the biomass reference points for the stock had been deemed inappropriate by ICES (2008a). In our opinion, truly precautionary management needs to be able to handle uncertainty. To do so, management plans (or the HCRs directly) need to include explicit rules on how a decision should be made under uncertainty. No EC management plans, to our knowledge, can handle uncertain advice in the sense of ranges or probabilities of F or SSB. However, some of the EC management plans proposed (EC, 2009a, c) and in place (EC, 2008) have HCRs that depend on the stock size in relation to its precautionary biomass reference point ($B_{\rm pa}$). As the value of $B_{\rm pa}$ in relation to $B_{\rm lim}$ is supposed to reflect the uncertainty in the assessment (ICES, 2005b; or in stock predictions, ICES, 2003; but see Hauge *et al.*, 2007), these plans seem to take rudimentary account of uncertainty. In the plans, however, $B_{\rm pa}$ has been predefined at certain levels (EC, 2008, 2009a, c), although the uncertainty in stock assessments and predictions varies between years as a consequence of the assessment methods used and the quality of the input data. Although this corresponds to how the precautionary reference points often have been applied in practice within ICES (Hauge *et al.*, 2007), it gives no guidance on how to make management decisions based on advice of the type "there is a 20% probability that stock biomass is above biological limit biomass" or, for EB cod, "there is 50% probability that fishing mortality is above target F" (Table 1).

Harvest strategy frameworks able to deal with a broad range of information of varying level of uncertainty are being used in fisheries management in Australia (Smith *et al.*, 2007). In them, the basis for stock status and catch decisions range from quantitative stock assessments to indicators of fishing and stock trends, which are combined in a hierarchical strategy framework (Smith *et al.*, 2007). Moreover, for stocks in poor condition, restrictions on total catch are combined with limits on exploitation rates. Finally, and most importantly, maximum catch levels are reduced along with increasing uncertainty about stock status (Smith *et al.*, 2007). Therefore, the frameworks explicitly link management decisions to the uncertainty of the scientific advice. How management should be developed to account for uncertainty is of course a political issue. Risk-prone managers may want to have HCRs that allow catch increases as soon as recent values of F are below target values despite a 50% probability that recent fishing mortality is above target F, as they did—unknowingly—for EB cod. Alternative, and informed, approaches are possible if the four-step approach outlined above is followed to account for uncertainty. For example, different HCRs may be used at different levels of probability: (i) TAC is allowed to increase by 15% if there is $\leq$10% probability that $F >$ target F, (ii) when the probability of $F >$ target F is between 10 and 50%, the TAC shall remain unchanged, whereas (iii) when that probability is $\geq$50%, the TAC shall be reduced by 15%. Alternatively, managers may decide on a HCR based on the upper confidence limit of estimated recent F ($F = 0.61$ in the example of EB cod) in relation to a target F. There are several possible approaches to ensuring precautionary management in the face of the uncertain state of stocks and fisheries, and examples of its application exist (e.g. Smith *et al.*, 2007). We argue that such political decisions are urgently needed in the upcoming revisions of long-term fisheries management plans (EC, 2007, 2008).

What we outline above is not spectacular, nor complex; it is a rudimentary ecosystem-based fisheries management approach in which probabilistic single-stock assessments supported by ecosystem indicators are combined with precautionary management able to handle the inherent uncertainty about the status of fish stocks and fisheries. Although a full ecosystem-based approach to fisheries management, with management of marine resources accounting for ecosystem processes and functions, is under development, our example of EB cod shows that several steps towards this goal can already be made in data-rich areas such as the Baltic Sea and the North Sea (alternative routes to ecosystem-based fisheries management are needed in data-poor situations; Tallis *et al.*, 2010). Advice based on a combination of single-stock and ecosystem indicators, and that accounts for the inherent uncertainty in estimates derived from fisheries data, can be produced, whereas political decisions on how to treat these uncertainties in management are yet to be taken. In short, we have shown that the tools for a basic ecosystem-based approach to fisheries management are available—it is time to use them.

Supplementary material

The following supplementary material is available at the *ICESJMS* online version of this paper: descriptions of (i) the state-space stock assessment model, SAM, for EB cod, and (ii) the fuzzy-logic ecosystem-based indicator of EB cod recruitment potential.

Acknowledgements

Thanks to Marie-Joëlle Rochet and Kjellrun Hiis Hauge for helpful suggestions on how to structure the paper, to editor Sarah B. M. Kraak for valued comments, to Michele Casini, Lena Bergström, and Magnus Appelberg for comments on earlier versions of the manuscript, and to Margit Eero for discussions on fuzzy-logic-based indicators. The paper is a contribution to the EU BONUS EraNet Project AMBER (Assessment and Modelling of Baltic Ecosystem Response).

References

Bastardie, F., Nielsen, J. R., and Kraus, G. 2010. The eastern Baltic cod fishery: a fleet-based management strategy evaluation framework to assess the cod recovery plan of 2008. ICES Journal of Marine Science, 67: 71–86.

Casini, M., Hjelm, J., Molinero, J. C., Lövgren, J., Cardinale, M., Bartolino, V., Belgrano, A., *et al.* 2009. Trophic cascades promote threshold-like shifts in pelagic marine ecosystems. Proceedings of the National Academy of Sciences of the USA, 106: 197–202.

Casini, M., Lövgren, J., Hjelm, J., Cardinale, M., Molinero, J-C., and Kornilovs, G. 2008. Multi-level trophic cascades in a heavily exploited open marine ecosystem. Proceedings of the Royal Society of London, Series B, 275: 1793–1801.

Collie, J. S., and Gislason, H. 2001. Biological reference points for fish stocks in a multispecies context. Canadian Journal of Fisheries and Aquatic Sciences, 58: 2167–2176.

Council of the European Union. 2009. Agriculture and Fisheries. Press Release from the 2976th Council Meeting, Brussels, 20 November 2009. 24 pp.

Cury, P. M., and Christensen, V. 2005. Quantitative ecosystem indicators for fisheries management. Introduction. ICES Journal of Marine Science, 62: 307–310.

Darby, C. D., and Flatman, S. 1994. Virtual Population Analysis: Version 3.1 (Windows/DOS) User Guide. Information Technology Series, 1. MAFF Directorate of Fisheries Research, Lowestoft. 85 pp.

EC (European Commission). 2007. Council Regulation (EC) No. 1098/2007 establishing a multi-annual plan for the cod stocks in the Baltic Sea and the fisheries exploiting those stocks, amending

Downloaded from http://icesjms.oxfordjournals.org/ at Leibniz-Institut fuer Ostseeforschung Warnemuende (IOW) - Bibliothek on October 20, 2011

Regulation (ECC) No 2847/93 and repealing Regulation (EC) No 779/97.

EC (European Commission). 2008. Council Regulation (EC) No. 1342/2008 establishing a long-term plan for cod stocks and the fisheries exploiting those stocks.

EC (European Commission). 2009a. Proposal for a Council Regulation establishing a long-term plan for the northern stock of hake and the fisheries exploiting that stock. COM(2009) 122 final.

EC (European Commission). 2009b. Proposal for a Council Regulation establishing a multi-annual plan for the western stock of Atlantic horse mackerel and the fisheries exploiting that stock. COM(2009) 189 final.

EC (European Commission). 2009c. Proposal for a Council Regulation establishing a long-term plan for the anchovy stock in the Bay of Biscay and the fisheries exploiting that stock. COM(2009) 399 final.

Eero, M., Köster, F. W., Plikshs, M., and Thurow, F. 2007. Eastern Baltic cod (*Gadus morhua callarias*) stock dynamics: extending the analytical assessment back to the mid-1940s. ICES Journal of Marine Science, 64: 1257–1271.

FAO. 2009. The State of World Fisheries and Aquaculture, 2008. FAO, Rome. 176 pp.

Gelman, A., Carlin, J. B., Stern, H. S., and Rubin, D. B. 2004. Bayesian Data Analysis. Texts in Statistical Science, 2nd edn. Chapman and Hall, New York. 669 pp.

Hall, S. J., and Mainprize, B. 2004. Towards ecosystem-based fisheries management. Fish and Fisheries, 5: 1–20.

Harwood, J., and Stokes, K. 2003. Coping with uncertainty in ecological advice: lessons from fisheries. Trends in Ecology and Evolution, 18: 617–622.

Hauge, K. H., Nielsen, K. N., and Korsbrekke, K. 2007. Limits to transparency—exploring conceptual and operational aspects of the ICES framework for providing precautionary fisheries management advice. ICES Journal of Marine Science, 64: 738–743.

Hill, S. L., Watters, G. M., Punt, A. E., McAllister, M. K., Le Quére, C., and Turner, J. 2007. Model uncertainty in the ecosystem approach to fisheries. Fish and Fisheries, 8: 315–336.

Hinrichsen, H-H., Möllmann, C., Voss, R., Köster, F. W., and Kornilovs, G. 2002. Biophysical modelling of larval Baltic cod (*Gadus morhua* L.) growth and survival. Canadian Journal of Fisheries and Aquatic Sciences, 59: 1858–1873.

ICES. 2003. Report of the Study Group on Precautionary Reference Points for Advice on Fishery Management. ICES Document CM 2003/ACFM: 15. 81 pp.

ICES. 2005a. Report of the *Ad Hoc* Group on Long Term Advice (AGLTA), 12–13 April 2005, ICES Headquarters. ICES Document CM 2005/ACFM: 25. 126 pp.

ICES. 2005b. Report of the ICES Advisory Committee on Fishery Management, Advisory Committee on the Marine Environment and Advisory Committee on Ecosystems, 2005. ICES Advice 2005, 1. 140 pp.

ICES. 2007. Report of the ICES/HELCOM Working Group on Integrated Assessments of the Baltic Sea (WGIAB), 12–16 March 2007, Hamburg, Germany. ICES Document CM 2007/BCC: 04. 71 pp.

ICES. 2008a. Report of the ICES Advisory Committee, 2008. ICES Advice, 8. 102 pp.

ICES. 2008b. Report of the Baltic Fisheries Assessment Working Group (WGBFAS), 8–17 April 2008, ICES Headquarters. ICES Document CM 2008/ACOM: 06. 692 pp.

ICES. 2008c. Report of the Working Group on Integrated Assessment of the Baltic Sea (WGIAB), 25–29 March 2008, Öregrund, Sweden. ICES Document CM 2008/BCC: 04. 145 pp.

ICES. 2008d. Report of the Working Group on Methods of Fish Stock Assessments (WGMG), 7–16 October 2008, Woods Hole, USA. ICES Document CM 2008/RMC: 03: 77–83.

ICES. 2009a. Report of the Baltic Fisheries Assessment Working Group (WGBFAS), 22–28 April 2009, ICES Headquarters. ICES Document CM 2009/ACOM: 07. 626 pp.

ICES. 2009b. Report of the Working Group on Methods of Fish Stock Assessment (WGMG), 20–29 October 2009, Nantes, France. ICES Document CM 2009/RMC: 12. 85 pp.

ICES. 2009c. Report of the ICES Advisory Committee, 2009. ICES Advice, 8. 95 pp.

ICES. 2009d. Report of the Baltic Salmon and Trout Assessment Working Group (WGBAST), 24–31 March 2009, Oulu, Finland. ICES Document CM 2009/ACOM: 05. 280 pp.

ICES. 2009e. Report of the Working Group on the Assessment of Demersal Stocks in the North Sea and Skagerrak (WGNSSK), 6–12 May 2009, ICES Headquarters. ICES Document CM 2009/ACOM: 10.

ICES. 2009f. Report of the Arctic Fisheries Working Group (AFWG), 21–27 April 2009, San Sebastian, Spain. ICES Document CM 2009/ACOM: 02. 579 pp.

ICES. 2009g. Report of the Herring Assessment Working Group for the Area South of 62°N, 17–25 March 2009, ICES Headquarters. ICES Document CM 2009/ACOM: 03. 648 pp.

ICES. 2009h. Report of the ICES–STECF Workshop on Fishery Management Plan Development and Evaluation (WKOMSE), 28–30 January 2009, Copenhagen. ICES Document CM 2009/ACOM: 27. 31 pp.

ICES. 2010. Report of the Baltic Fisheries Assessment Working Group (WGBFAS), 15–22 April 2010, ICES Headquarters. ICES Document CM 2010/ACOM: 10. 621 pp.

Jarre, A., Paterson, B., Moloney, C. L., Miller, D. C. M., Field, J. G., and Starfield, A. M. 2008. Knowledge-based systems as decision support tools in an ecosystem approach to fisheries: comparing a fuzzy-logic and a rule-based approach. Progress in Oceanography, 79: 390–400.

Jennings, S. 2005. Indicators to support an ecosystem approach to fisheries. Fish and Fisheries, 6: 212–232.

Köster, F. W., and Möllmann, C. 2000. Trophodynamic control by clupeid predators on recruitment success in Baltic cod? ICES Journal of Marine Science, 57: 310–323.

Köster, F. W., Möllmann, C., Hinrichsen, H-H., Tomkiewicz, J., Wieland, K., Kraus, G., Voss, R., *et al.* 2005. Baltic cod recruitment—the impact of climate and species interaction. ICES Journal of Marine Science, 62: 1408–1425.

Kraak, S. B. M., Buisman, F. C., Dickey-Collas, M., Poos, J. J., Pastoors, M. A., Smit, J. G. P., van Oostenbrugge, J. A. E., *et al.* 2008. The effect of management choices on the sustainability and economic performance of a mixed fishery: a simulation study. ICES Journal of Marine Science, 65: 697–712.

Kraak, S. B. M., Daan, N., and Pastoors, M. A. 2009. Biased stock assessment when using multiple, hardly overlapping, tuning series if fishing trends vary spatially. ICES Journal of Marine Science, 66: 2272–2277.

Kraak, S. B. M., Kelly, C. J., Codling, E. A., and Rogan, E. 2010. On scientists' discomfort in fisheries advisory science: the example of simulation-based fisheries management-strategy evaluations. Fish and Fisheries, 11: 119–132.

Lassen, H., and Medley, P. 2001. Virtual population analysis. A practical manual for stock assessment. FAO Fisheries Technical Paper, 400. 129 pp.

Link, J. S. 2005. Translating ecosystem indicators into decision criteria. ICES Journal of Marine Science, 62: 569–576.

Link, J., Brodziak, J. K. T., Edwards, S. F., Overholtz, W. J., Mountain, D., Jossi, J. W., Smith, T. D., *et al.* 2002. Marine ecosystem assessment in a fisheries management context. Canadian Journal of Fisheries and Aquatic Sciences, 59: 1429–1440.

MacKenzie, B. R., Hinrichsen, H-H., Plikshs, M., Wieland, K., and Zezera, A. S. 2000. Quantifying environmental heterogeneity: habitat size necessary for successful development of cod *Gadus*

Downloaded from http://icesjms.oxfordjournals.org/ at Leibniz-Institut fuer Ostseeforschung Warnemuende (IOW) - Bibliothek on October 20, 2011

morhua eggs in the Baltic Sea. Marine Ecology Progress Series, 193: 143–156.

Miller, D. C. M., and Field, J. G. 2002. Predicting anchovy recruitment in the southern Benguela ecosystem: developing an expert system using classification trees. South African Journal of Science, 98: 465–472.

Mohn, R. K., and Chouinard, G. A. 2007. Harvest control rules for stocks displaying dynamic production regimes. ICES Journal of Marine Science, 64: 693–697.

Möllmann, C., Diekmann, R., Müller-Karulis, B., Kornilovs, G., Plikshs, M., and Axe, P. 2009. Reorganization of a large marine ecosystem due to atmospheric and anthropogenic pressure: a discontinuous regime shift in the central Baltic Sea. Global Change Biology, 15: 1377–1393.

Möllmann, C., and Köster, F. W. 2002. Population dynamics of calanoid copepods and the implications of their predation by clupeid fish in the central Baltic Sea. Journal of Plankton Research, 24: 959–978.

Möllmann, C., Müller-Karulis, B., Kornilovs, G., and St John, M. A. 2008. Effects of climate and overfishing on zooplankton dynamics and ecosystem structure: regime shifts, trophic cascade, and feedback loops in a simple ecosystem. ICES Journal of Marine Science, 65: 302–310.

Petitgas, P., Cotter, J., Trenkel, V., and Mesnil, B. 2009. Fish stock assessments using surveys and indicators. Aquatic Living Resources, 22: 119.

Rose, G. A., and Kulka, D. W. 1999. Hyperaggregation of fish and fisheries: how catch-per-unit-effort increased as the northern cod (*Gadus morhua*) declined. Canadian Journal of Fisheries and Aquatic Sciences, 56(Suppl. 1): 118–127.

Saltelli, A., Ratto, M., Andres, T., Campolongo, F., Cariboni, J., Gatelli, D., Saisana, M., *et al.* 2008. Global Sensitivity Analysis—The Primer. John Wiley, New York. 292 pp.

Schnute, J. T., and Richards, L. J. 1995. The influence of error on population estimates from catch-age models. Canadian Journal of Fisheries and Aquatic Sciences, 52: 2063–2077.

Shepherd, J. G. 1999. Extended survivors analysis: an improved method for the analysis of catch-at-age data and abundance indices. ICES Journal of Marine Science, 56: 584–591.

Smith, A. D. M., Fulton, E. J., Hobday, A. J., Smith, D. C., and Shoulder, P. 2007. Scientific tools to support the practical implementation of ecosystem-based fisheries management. ICES Journal of Marine Science, 64: 633–639.

Tallis, H., Levin, P. S., Ruckelshaus, M., Lester, S. E., McLeod, K. L., Fluharty, D. L., and Halpern, B. S. 2010. The many faces of ecosystem-based management: making the process work today in real places. Marine Policy, 34: 340–348.

Trenkel, V. M., Rochet, M-J., and Mesnil, B. 2007. From model-based prescriptive advice to indicator-based interactive advice. ICES Journal of Marine Science, 64: 768–774.

Vainikka, A., Gårdmark, A., Bland, B., and Hjelm, J. 2009. Two- and three-dimensional maturation reaction norms for the eastern Baltic cod, *Gadus morhua*. ICES Journal of Marine Science, 66: 248–257.

Vallin, L., and Nissling, A. 2000. Maternal effects on egg size and egg buoyancy of Baltic cod, *Gadus morhua*. Implications for stock structure effects on recruitment. Fisheries Research, 49: 21–37.

Wieland, K., Waller, U., and Schnack, D. 1994. Development of Baltic cod eggs at different levels of temperature and oxygen content. Dana, 10: 163–177.

Worm, B., Hilborn, R., Baum, J. K., Branch, T. A., Collie, J. S., Costello, C., Fogarty, M. J., *et al.* 2009. Rebuilding global fisheries. Science, 325: 578–585.

Downloaded from http://icesjms.oxfordjournals.org/ at Leibniz-Institut fuer Ostseeforschung Warnemuende (IOW) - Bibliothek on October 20, 2011