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Contribution to the Themed Section: 'Integrated assessments'

Original Article

Implementing ecosystem-based fisheries management: from single-species to integrated ecosystem assessment and advice for Baltic Sea fish stocks

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Theory behind ecosystem-based management (EBM) and ecosystem-based fisheries management (EBFM) is now well developed. However, the implementation of EBFM exemplified by fisheries management in Europe is still largely based on single-species assessments and ignores the wider ecosystem context and impact. The reason for the lack or slow implementation of EBM and specifically EBFM is a lack of a coherent strategy. Such a strategy is offered by recently developed integrated ecosystem assessments (IEAs), a formal synthesis tool to quantitatively analyse information on relevant natural and socio-economic factors, in relation to specified management objectives. Here, we focus on implementing the IEA approach for Baltic Sea fish stocks. We combine both tactical and strategic management aspects into a single strategy that supports the present Baltic Sea fish stock advice, conducted by the International Council for the Exploration of the Sea (ICES). We first review the state of the art in the development of IEA within the current management framework. We then outline and discuss an approach that integrates fish stock advice and IEAs for the Baltic Sea. We intentionally focus on the central Baltic Sea and its three major fish stocks cod (*Gadus morhua*), herring (*Clupea harengus*), and sprat (*Sprattus sprattus*), but emphasize that our approach may be applied to other parts and stocks of the Baltic, as well as other ocean areas.

Keywords: Baltic Sea, indicator approaches, integrated advice, integrated ecosystem assessment, strategic modelling.

Introduction

Ecosystem-based management (EBM) is now a central paradigm underlying living marine resource policy worldwide. Contrary to conventional resource management approaches, EBM addresses the cumulative impacts of multiple ocean uses and climate change on multiple ecosystem components (Pikitch *et al.*, 2004; Leslie and McLeod, 2007; Marasco *et al.*, 2007). Hence, the goal of EBM is to find trade-offs between a diverse set of ecosystem services and often conflicting, management goals (McLeod and Leslie, 2009). Although the theory behind EBM is well developed, its implementation lacks behind (Berkes, 2012). A clear example is fisheries management in Europe that is still largely based on single-species assessments and ignores the wider ecosystem context and impacts. The reason for the lack or slow implementation of EBM is a lack of a coherent strategy. Such a strategy is offered by Integrated Assessment (IA). IA is commonly defined as an interdisciplinary process of combining, interpreting, and communicating knowledge from diverse scientific disciplines, in such a way that the whole set of cause–effect interactions of a problem can be evaluated from a synoptic perspective with two characteristics: (i) it should have added value compared with single disciplinary assessments and (ii) it should provide useful information to decision makers (Rotmans and Dowlatabadi, 1997; van der Sluijs, 2002).

IAs were initially developed during the 1970s, fuelled by scientific and public policy efforts to understand and control acid deposition in Europe and North America (van der Sluijs, 2002). Since the 1980s, they have played a role in the development of the international climate policy leading to, and being part of, the work of the Intergovernmenta lPanel on Climate Change (IPCC). In this context, IAs were largely based on IA models (IAMs), computer simulation models combining knowledge from multiple disciplines, and hence suited to analyse environmental problems in an integrated fashion (Rotmans and Dowlatabadi, 1997). Nowadays, it is widely recognized that a complete IA methodology combines IAMs with other analytical tools for integration, such as analyses of large datasets and participatory approaches.

Early developments of IAs within the field of marine living resource management were started in North America and based on analyses of large datasets showing substantial changes in ecosystem states due to climate and human impacts (Hare and Mantua, 2000; Link *et al*., 2002; Choi *et al*., 2005). Only recently, integrated ecosystem assessments (IEAs) have been developed as a formal synthesis tool to quantitatively analyse information on relevant natural and socio-economic factors, in relation to specified EBM objectives (Levin *et al*., 2009). IEAs provide a strategy to overcome the still prevailing single-species and single-sector approaches; they organize science in order to inform decisions in marine EBM at multiple scales and across sectors (Levin *et al*., 2009; Tallis *et al*., 2010).

The goals and objectives of EBM and IEA need to be specified beforehand (Jennings, 2005; Levin *et al*., 2009). The specified goals then define the focal components of the EBM and IEA approach (Kershner *et al*., 2011), which may range from a specific ecosystem-based fisheries management (EBFM) to a full blown cross-sector EBM approach (Leslie and McLeod, 2007; McLeod and Leslie, 2009). Although the ambitious objectives of the European Union (EU) Marine Strategy Framework Directive (MSFD) call for a full EBM approach, fisheries management within the reformed EU Common Fisheries Policy (CFP) still relies on the development and implementation of a more sector-specific EBFM approach.

Here, we focus on the process of implementing EBFM for the Baltic Sea using elements of the IEA approach. IAs and IEAs are generally strategic in that they explore possible future trajectories of human and natural systems under a multitude of natural and anthropogenic pressures (Weyant *et al*., 1996; Levin *et al*., 2009). However, present EU fisheries management requires annual stock assessment and advice. Hence, we attempt to combine both requirements into a strategy that supports the present Baltic Sea fish stock advice, conducted by the International Council for the Exploration of the Sea (ICES). We first review the state of the art in the development of EBFM and IA within the current management framework. We then outline an IEA-based approach that integrates fish stock advice and IEAs for the Baltic Sea. We intentionally focus on the central Baltic Sea and the three major fish stocks cod (*Gadus morhua*), herring (*Clupea harengus*), and sprat (*Spratus sprattus*), but emphasize that our approach may be applied to other parts and stocks of the Baltic, as well as other ocean areas.

Elements of EBM in present operational fish stock assessment

ICES advice on total allowable catches (TACs) to the EU Commission is currently based on targets of fishing mortality at maximum sustainable yield (F_{MSY}) and, for Eastern Baltic cod, on an EU management plan (EC, 2007; ICES, 2012a). The analytical assessments of Baltic fish stocks delivering the basis for the advice are conducted on a stock-by-stock basis. Extended survivor analysis or a state-space fish stock assessment model (www.stockassessment.org), both based on commercial catch-at-age data supplemented by fishery-independent survey indices, are applied to obtain estimates of key stock parameters, such as spawning-stock biomass (SSB), recruitment, and fishing mortality (*F*; Shepherd, 1999; ICES, 2012b). Multispecies interactions are currently only considered for the main forage fish species, namely sprat and central Baltic herring, and for cannibalism on juvenile cod. For these stocks, predation mortality by the top predator cod is derived from multispecies assessment models (previously multispecies virtual population analysis; currently stochastic multispecies model; ICES, 2012a) and used to update the natural mortality input to the single species forage fish stock assessments.

As part of the assessment process, short-term forecasts (3 years) are conducted starting with the latest assessment year and using estimates of recruitment based on empirical spawning stock–recruitment relationships. Environmental data to inform these forecasts are only used for the herring stock in the Gulf of Riga (ICES, 2012b). Data used are the copepod *Eurytemora affinis*, the main prey for larval herring, and water temperature determining the timing and distribution of herring spawning (Cardinale *et al*., 2009). Previously, the winter index of the North Atlantic Oscillation (NAO) and water temperature have been used in forecasts of sprat year-class strength (MacKenzie and Köster, 2004; ICES, 2006), but these are no longer used due to problems with matching environmental time-series updates with the assessment meetings.

Multispecies modelling has a long tradition for the Baltic Sea ecosystem (Sparholt, 1994; Gislason, 1999; Köster *et al*., 2001) but has never been used fully in operational fish stock assessment (aside from providing input to single species stock assessments, see above). However recently, in response to a request by the EU commission, a multispecies assessment has been conducted as a pilot study towards implementing the ecosystem approach (ICES, 2012d; STECF, 2012). The assessment was conducted using SMS that accounts for the mortality inflicted by cod on sprat, herring, and juvenile cod. Simulations revealed all species-specific multispecies F_{MSY}

to be higher than their single-species counterparts. However, particularly for cod and sprat, simulations show that higher fishing mortality will give very similar long-term yields, but result in lower SSBs and a higher risk of stock collapse. Model results further indicate that higher F on cod will result only in a minor increase in cod yield, but in higher sprat and herring yields. However, modelling of F_{MSY} currently ignores structural uncertainty such as variable predator–prey overlap and density-dependent growth. Hence, ICES (2012d) and STECF (2012) concluded that more work is needed to fully understand the results of the multispecies runs and their implications for the Baltic fish stock advice and management.

Indicator approaches to IAs

Integrated trend and status assessments

Despite efforts towards multispecies considerations, Baltic fish stock assessments are mostly single species, ignoring the larger ecosystem context (Casini *et al*., 2011a). As a first step towards developing more integrative assessments, analyses on the state and development of the various Baltic ecosystems have been conducted using large multitrophic datasets (ICES, 2008; Möllmann *et al*., 2009; Diekmann and Möllmann, 2010; Lindegren *et al*., 2010a, 2012a). These so-called integrated trend analyses (ITAs) used multivariate statistics based on an approach developed for the North Pacific and Atlantic, as well as the North Sea ecosystems (Hare and Mantua, 2000; Link *et al*., 2002; Choi *et al*., 2005; Weijerman *et al*., 2005; Kenny *et al*., 2009; Möllmann and Diekmann, 2012). Analyses of these large datasets were conducted using dimension reduction techniques, mainly principal component analysis (PCA; e.g. Legendre and Legendre, 1998) and methodologies to identify step changes in biotic and abiotic variables, such as STARS (Rodionov, 2004) or chronological clustering (Legendre *et al*., 1985).

Here, we present a reanalysis of data from the Central Baltic Sea using 57 annual time-series (1979–2010), in two separate PCAs on 28 biotic variables from phytoplankton to fish and 29 abiotic variables describing the physical conditions and anthropogenic driving forces such as nutrient concentrations and fishing pressure (Figure 1). Connecting biotic year scores chronologically on the first factorial plane (PC1 vs. PC2) results in a time trajectory that shows the regime shift during the late 1980s/early 1990s (Figure 1a). The change in the ecosystem is displayed by the opposition of cod and herring as well as sprat and the copepod *Acartia* spp., showing the strongest loadings on PC1 (Figure 1b). According to Möllmann *et al*. (2009), the period between 1987 and 1992 can be interpreted as a transition period, in which a major reorganization of the ecosystem occurred, due to the interaction of abrupt climatic changes, unsustainable fishing pressure and eutrophication. Our updated PCA confirms that after 1992, abiotic conditions largely returned to values similar to the initial state (Figure 1c), indicating hysteresis and stabilizing feedbacks in the foodweb (Casini *et al*., 2009, 2010; Möllmann *et al*., 2009). The analysis of the major abiotic loadings confirmed that a temperature increase and salinity decrease were major drivers of the central Baltic regime shift (Figure 1d). Similar major reorganizations during the late 1980s/early 1990s were found synchronously for almost all studied Baltic ecosystems (Diekmann and Möllmann, 2010; ICES, 2012c).

Early warning indicators

Ecosystem regime shifts, like those observed in the Baltic Sea, are reported for many other marine ecosystems in the world (Möllmann and Diekmann, 2012). These large-scale reorganizations in ecosystem structure and function bear important social and economic costs and may be difficult to reverse (Scheffer *et al*., 2001; Suding *et al*., 2004). Hence, management strategies that help prevent unwanted change are necessary, and these rely on indicators showing warning signs well before a transition might occur (Scheffer *et al*., 2009). Although the theoretical foundation of early warning indicators has greatly improved (Scheffer *et al*., 2012), the application of potential early warning indicators in real ecosystems is still very limited. Lindegren *et al*. (2012b) applied multiple early warning indicators to monitoring data of key ecosystem components of the Baltic Sea, namely the zooplankton species *Pseudocalanus acuspes* and *Acartia* spp. They demonstrated that the ability of the indicators to forewarn the major ecosystem regime shift in the central Baltic Sea is variable depending on the indicator time-series used. Hence, a multiple method approach for early detection of ecosystem regime shifts is proposed that can be useful in informing timely management actions in the face of ecosystem change (Lindegren *et al*., 2012b).

Indicator approach in support of single-species fish stock advice

Results and data from the above reported integrated trend and status assessments have also been used for developing a set of ecosystem indicators that can support the assessment of the stock status of individual species (Gårdmark *et al*., 2011). Using eastern Baltic cod as a case study, they developed a set of indicators including size/age structure of the target stock, predator, and prey levels for early life-history stages and physical oceanographic conditions. Individual indicators were evaluated for showing support for or against the assessment model-derived stock status and trends. Additionally, individual indicators were combined into an ecosystem-based indicator of cod recruitment potential using fuzzy-logic networks (Jarre *et al*., 2008). Gårdmark *et al*. (2011) thus show how to use ecosystem indicators for reducing the uncertainty in model-based estimates of stock status and for determining more precautionary harvest control rules (HCRs).

Integrated modelling approaches

Ecological models

Like in many other areas, fish stock assessments for the Baltic Sea use single-species fisheries models as a basis for short-term tactical setting of TAC. However, to evaluate the impact of alternative management strategies on the state and dynamics of exploited fish populations, strategic modelling approaches are essential tools. Obviously, an exploited population does not exist in isolation, and its response to a fishing pressure emerges from the feedbacks caused by its interactions with other species in the foodweb, as well as from direct and indirect effects of abiotic pressures. The essence of EBFM is to account for such foodweb mediated feedbacks and indirect effects (McLeod and Leslie, 2009). Hence, strategic modelling for EBFM involves evaluating exploitation effects in the presence of species interactions and under alternative future environments.

For the main exploited species in the central Baltic Sea, strategic modelling for EBFM has been performed using a few approaches. Lindegren *et al*. (2009) developed a stochastic multivariate autoregressive model (BALMAR) of cod, sprat, herring, and their zooplankton prey including the influence of fishing and climate variables. Such a model represents statistically derived relationships between the species, and any management impact analyses using this model (e.g. Lindegren *et al*., 2010b) thus relies on the

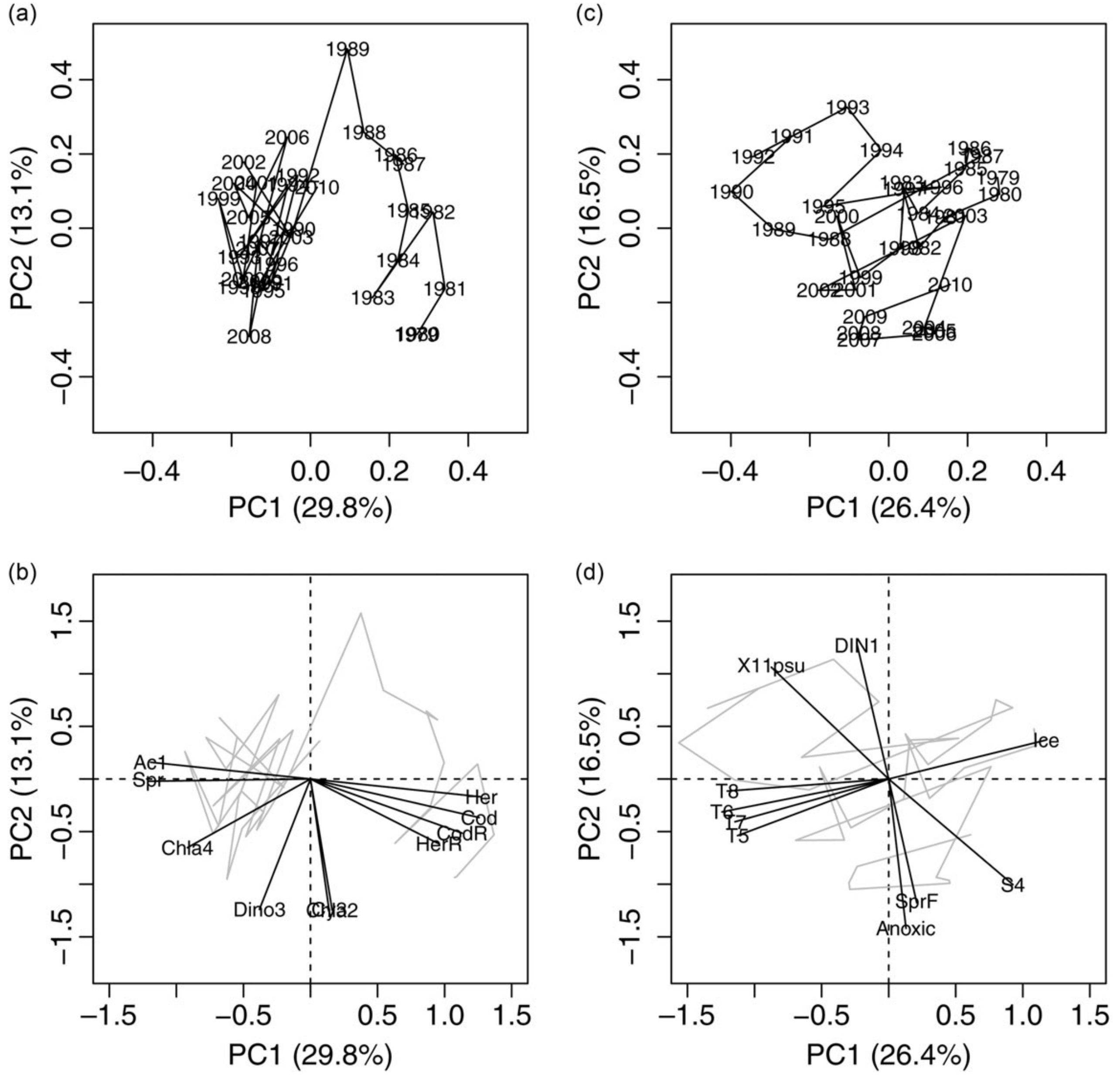

Figure 1. Results of an ITA for the central Baltic Sea ecosystem of biotic (a and b) and abiotic (c and d) variables. (a and c) Time trajectories of PC scores on the first factorial plane based on a normalized PCA. (b and d) Biplots showing the ten variables that were best represented on the first factorial plane (time trajectory in the background; variables and years are scaled symmetrically by square root of eigenvalues). Cod/Her/Spr, cod/herring/sprat; R, recruitment; F, fishing mortality; Ac1, *Acartia* spp. biomass; Chla 2,4, chlorophyll *a* summer concentration in Bornholm and Gotland Basin, respectively; Dino 3, dinoflagellate spring biomass in Bornholm Basin; X11psu, depth of the 11psu isohaline; T 5,6,7,8, midwater temperature in Bornholm and Gotland Basin in spring and summer, respectively; Anoxic, area with anoxic bottom water; S4, deepwater salinity in the Gotland Basin.

assumption that the species interactions (i.e. parameters) do not change outside the estimated range obtained during the period used for model fitting. An alternative is to represent trophic interactions between species in more detail as, for example, is possible with the Ecopath with Ecosim (EwE) modelling approach (Christensen and Walters, 2004). The EwE approach has been applied to the central Baltic Sea foodweb (Harvey *et al.*, 2003; Österblom *et al.*, 2007) and in its present form includes 22 functional groups (Niiranen *et al.*, 2012; Tomczak *et al.*, 2012). However, since interactions occur between individuals rather than populations, a more mechanistic approach towards modelling trophic interactions is to explicitly model individual level processes, such as feeding (predation), metabolism, energy allocation, and resulting growth, mortality, and reproduction, as done in physiologically structured population models (Metz and Diekmann, 1986; de Roos and Persson, 2001). This type of models has been developed for the interactions between Baltic cod, sprat, and their resources (van Leeuwen *et al.*, 2008, 2013), and between herring, sprat, and their resources (Huss *et al.*, 2012), to assess qualitative responses of cod, sprat, and herring to environmental changes under alternative types of interactions. As exemplified by these three modelling approaches, available foodweb (or multispecies) models of the central Baltic

Sea differ greatly in fundamental assumptions on how to represent ecological processes. Simulated responses of exploited species and foodwebs to fishing may therefore depend on model choice.

Biological ensemble modelling approach

To overcome the issue of model choice for impact analyses, Gårdmark *et al.* (2013) developed a biological ensemble modelling approach (BEMA), which can be used to assess the relative influence of model structure on simulated species responses, as well as to formulate fisheries management advice robust to such uncertainty. In the BEMA, a set of seven ecological models (ranging from single-species to foodweb models of varying complexity) was subjected to the same initial conditions and external forcing based on a combination of exploitation and climate change scenarios to simulate the responses of eastern Baltic cod to historically observed high fishing levels vs. fishing at management target levels, including a number of future climate change scenarios (Figure 2). The BEMA ensemble was then used to: (i) identify model assumptions causing key divergence in simulated species responses (by contrasting ensemble subsets), (ii) evaluate the relative importance of model structure uncertainty for overall uncertainty in simulated responses (by contrasting variation among models within a climate trajectory with variation within each model among all climate trajectories), and (iii) formulate robust advice for fisheries management (by identifying conclusions on management effects common for the whole ensemble). Gårdmark *et al.* (2013) demonstrated that assumptions of species interactions greatly impacted simulated cod dynamics, with models lacking stabilizing predator–prey feedbacks showing large interannual fluctuations and a greater sensitivity to the underlying uncertainty of climate forcing. Nevertheless, robust conclusions regarding the effects of alternative fishing levels could be found, e.g. in all models, intense fishing prevented recovery and climate change further decreased the cod population. Although the BEMA (Gårdmark *et al.*, 2013) has so far only been applied to single-species responses, the approach is equally suitable to study indirect effects of exploitation on non-target species (ICES, 2009), groups of species providing particular ecosystem services, as well as indicators of environmental status (ICES, 2012c) as developed for the MSFD.

Coupled ecological–economic modelling

When formulating new fishing rules, basic economic conditions for the relevant fishery are often not understood and therefore ignored. Coupled ecological–economic optimization models have been developed and analysed for Baltic cod, herring, and sprat stocks. These models are available as single-species (Quaas *et al.*, 2013) or as multispecies type, i.e. accounting for cod preying upon herring and sprat (Nieminen *et al.*, 2012). These models are also able to address climate change impacts by using environmentally sensitive stock–recruitment functions. Changes in optimal fishing strategy under climate change scenarios can therefore be computed (ICES, 2010; Voss *et al.*, 2011). Easily understandable, well-defined indicators have proven to be especially helpful to foster transfer and application of economic analyses into "real-world" fisheries management. In this context, a new ecological–economic indicator was developed: the shadow interest rate, SIR (Quaas *et al.*, 2012). The SIR extends economic concepts and considers fish stocks as natural capital stocks. Furthermore, the SIR, as a generic measure, allows quantifying and comparing the economic success or failure of fisheries management across stocks. It captures biological information on stock productivity as well as economic information and allows the trade-off of management objectives to be assessed, e.g. maximizing economic rent, employment, and biomass extraction (Quaas *et al.*, 2012).

A future IEA strategy for Baltic fish stock advice and management

In the following section, we outline how the approaches and tools described above can be combined into an IEA strategy that facilitates the implementation of EBFM for the Baltic Sea (Figure 3). The strategy includes three components: (i) the transition from existing single-species to a multispecies stock assessment, (ii) an ecosystem assessment that integrates environmental information into the single-/multispecies assessment, and (iii) a strategic component that conducts long-term management strategy evaluation using coupled ecological and economic models. Hence, our strategy accounts for both the short-term needs of annual fish stock assessments, conducted for most of the European fish stocks, but also the long-term needs of future strategic EBM advice (Figure 3).

Towards multispecies stock assessments

Single-species assessments are to a large degree still the basis for present day fish stock advice. However, we envisage an increasing use of multispecies assessment models in the future for a more realistic assessment of multispecies MSY reference points, population sizes relative to target levels, and TACs. Multispecies models can be applied indirectly by providing predation mortality rates to be used in single-species models (Figure 3). This procedure is already common practice for some Baltic fish stocks but should be conducted on a more regular, preferably annual, basis. Multispecies assessments may in the future replace the single-species procedures, when the implications for multispecies interactions especially for MSY calculation are sufficiently evaluated, as is recently initiated (ICES, 2013). Furthermore, additional effort is required for improving multispecies assessment models, e.g. with respect to implementing predator–prey feedbacks and density-dependent growth (Gårdmark *et al.*, 2013) as well as the dependence of population processes on environmental conditions. Equally important are improved monitoring systems needed to account for the increased data requirements of multispecies models, especially with respect to data on predator diets and key functional groups affecting fish performance, such as zooplankton. Overall, a replacement of single- by multispecies assessments which account for key species interactions and environmental influences would be a first step towards integrated fish stock advice for the Baltic Sea.

The importance of ecosystem assessments

Accounting for ecosystem effects of fishing, as well as effects of environmental variability on fish stock productivity is a crucial component of EBFM (Pikitch *et al.*, 2004). Fish stock assessments traditionally rely on assumptions regarding stationary (equilibrium) dynamics of populations, communities, and the carrying capacity of ecosystems. However, a large body of research has shown that abrupt changes in productivity, e.g. due to climate, may occur (e.g. Brander, 2007), with far reaching consequences for ecosystem structure and functioning, as well as the provision of important goods and services (Scheffer *et al.*, 2001; Millennium Ecosystem Assessment, 2005). The Baltic Sea, having experienced an ecosystem regime shift (Möllmann *et al.*, 2008), including trophic cascading (Casini *et al.*, 2008; Möllmann *et al.*, 2009), as well as a collapse of the cod stock, clearly illustrates that changes in the environment as well as foodweb interactions need to be considered for sustainable management (Lindegren *et al.*, 2009). Hence, ecosystem

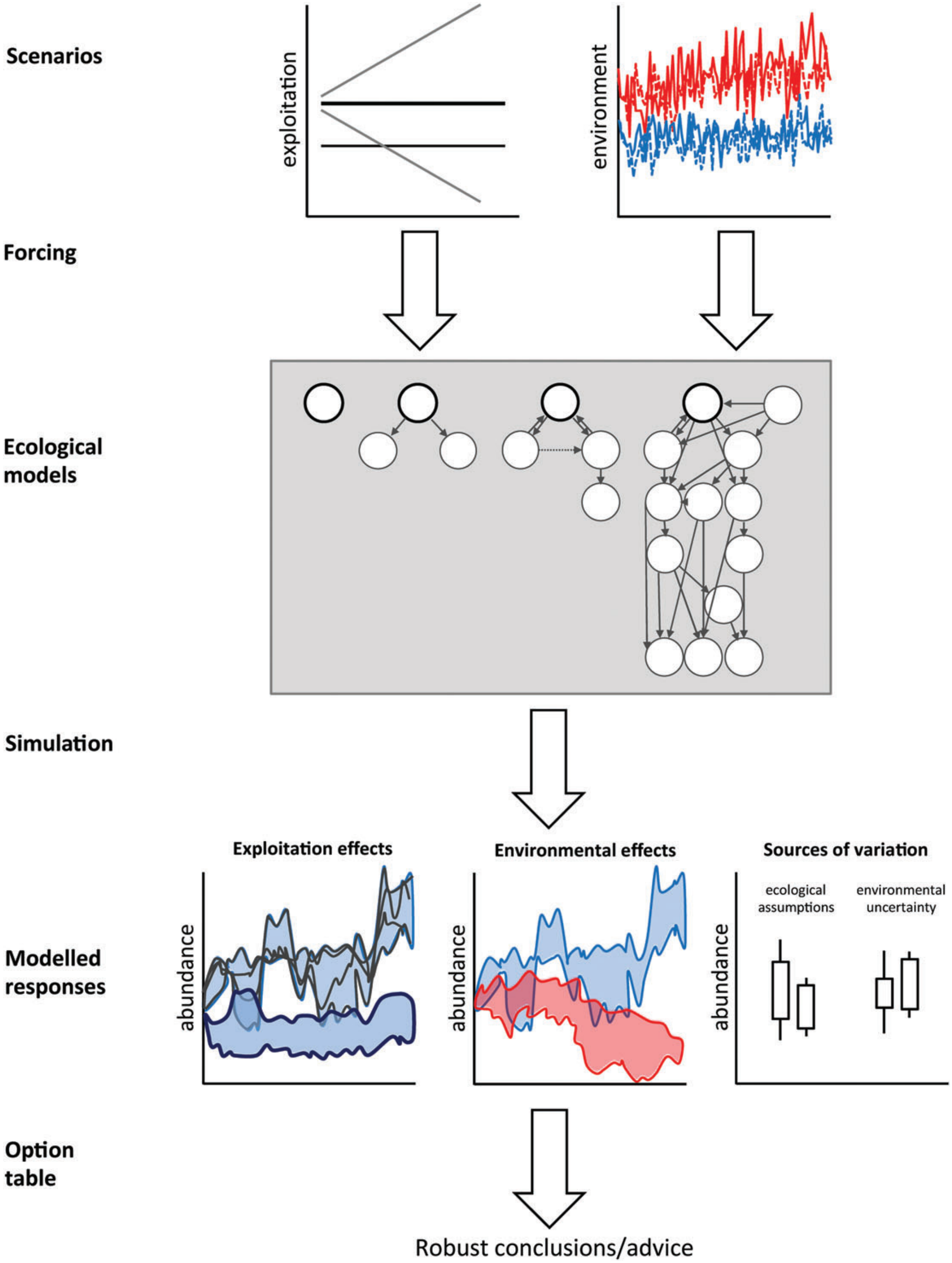

Figure 2. The BEMA (Gårdmark *et al*., 2013) can be used to derive robust, strategic advice for EBFM. Combinations of management and environmental scenarios are used to force a set of ecological models of varying complexity (e.g. single species, multispecies, and foodweb models) to simulate fish stock responses to exploitation in future environments. The performance of management strategies can then be compared across (i) ecological models, (ii) environmental scenarios, and (iii) environmental variation to identify management strategies and HCRs robust to the uncertainties of ecological processes and future conditions.

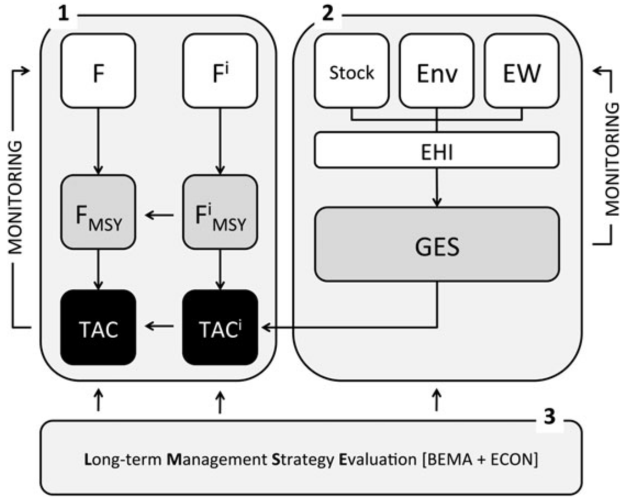

Figure 3. Schematic outline for a future IEA strategy for Baltic fish stock advice and management including (1) multispecies fish stock assessments, (2) ecosystem assessments, and (3) long-term management strategy evaluation: F, fishing mortality; MSY, maximum sustainable yield; TAC, total allowable catch; i, fish species, i.e. cod, herring, and sprat; stock, indicators of stock status and structure; Env, indicators on the state of the abiotic and biotic environment; EW, early warning indicators; EHI, ecosystem health index; GES, good environmental status; BEMA, biological ensemble modelling approach; ECON, coupled ecological/economical modelling.

assessments are an important component of an effective EBFM approach. For the Baltic Sea, we have identified three groups of indicators that are needed to inform fish stock assessments (Figure 3). First, indicators of stock status and structure ("Stock" in Figure 3), other than biomass and abundance, need to be considered (Gårdmark *et al*., 2011; Eero *et al*., 2012). These are also required by the MSFD in its "Descriptor 3" (EC, 2008) and should describe growth and recruitment of the stocks. Second, the state of the abiotic and biotic environment needs to be evaluated ("Env" in Figure 3). Gårdmark *et al.* (2011) propose indicators for the Baltic cod stock related to physical oceanographic parameters important for recruitment, as well as prey and predator effects on early life stages. Similar indicators have been identified also for the other fish stocks in the Baltic Sea (Lindegren *et al*., 2011; Eero *et al*., 2012). In addition, the PC-based holistic indicator from ITAs (see above) can provide important information about the ecosystem dynamics and state in a holistic way (Link *et al*., 2002; Möllmann *et al*., 2009). Finally, early warning indicators ("EW" in Figure 3) are important in providing timely detection of ecosystem change (Lindegren *et al*., 2012b).

A standing difficulty of using ecosystem information in an assessment framework is to translate ecosystem indicator information into decision criteria for management (Link, 2005). A first step would be to combine individual ecosystem indicators into an ecosystem health index (EHI) (Figure 3). EHI indicates the state of the environment relative to its good environmental status (GES), a goal of many environmental policy drivers such as the MSFD (EC, 2008). A number of procedures is available for combining individual indicators, such as fuzzy logic and various weighting schemes (Gårdmark *et al*., 2011; Ojaveer and Eero, 2011; Halpern *et al*., 2012). Eventually, rules have to be defined that modify the HCR (i.e. rules for how the TAC shall be set depending on state in relation to targets) according to the state of the EHI relative to GES. An example for a precautionary approach for Baltic cod is suggested by Gårdmark *et al.* (2011).

Into the future: long-term management strategy evaluation

The fish stock and ecosystem assessments described above primarily focus on short-term, tactical management aspects. However, environmental conditions and impacts on ecosystems and their fish stocks may vary over longer time-scales, especially in the light of expected future climate change (MacKenzie *et al*., 2012; Meier *et al*., 2012). Hence, strategic long-term simulations are needed to define management goals (such as F_{MSY}) and to evaluate how robust these goals are to future climate change (Lindegren *et al*., 2010a, b), to fishing effects on the ecosystem (Lassen *et al*., 2013), and to our ignorance of foodweb interactions in general. In addition, Gårdmark *et al.* (2013) showed that a multimodel approach (i.e. BEMA) would be beneficial for developing management goals robust to uncertainties inherent in such simulations due to model structure and parameterization (Niiranen *et al*., 2012). The proposed long-term management strategy evaluations will be instrumental in developing multispecies long-term management plans (STECF, 2012). Eventually, coupled ecological–economical models can be used to evaluate the economic implications of management strategies relative to environmental conditions (Voss *et al*., 2011; Lassen *et al*., 2013).

Discussion

We have proposed a strategy that integrates the present Baltic Sea single-species fish stock assessment and advice with elements of IEAs. The approach focuses on (i) integrating environmental information into the short-term tactical fish stock assessment and (ii) using existing ecological and coupled ecological–economic models in simulations to evaluate management strategies and to anticipate environmental productivity changes. The strategy is largely based on existing studies and models for the Baltic Sea and should be readily implemented and operational.

However, although many indicators for the ecosystem assessment have been proposed (e.g. Gårdmark *et al*., 2011; Eero *et al*., 2012), a standard set of indicators needs to be developed. Hence, indicator development is a crucial part of the IEA framework (Levin *et al*., 2009) and should comprise (i) a formal and objective indicator selection routine, involving both scientists and stakeholders (Levin *et al*., 2010; Kershner *et al*., 2011), and (ii) an approach for determining target and reference levels based on time-series and ecosystem modelling (Samhouri *et al*., 2009, 2010, 2011, 2012).

After indicator selection, a further important step in our strategy would be an analysis that identifies the risk to the indicators posed by human activities and natural processes. Risk analyses have the goal to determine the probability that an ecosystem indicator will reach or remain in an undesirable state (Levin *et al*., 2009). Various techniques exist that use qualitative expert opinion or quantitative techniques such as statistical analyses and ecosystem modelling (Smith *et al*., 2007; Samhouri and Levin, 2012). As demonstrated here, the necessary data and modelling tools are available to employ these techniques for the Baltic Sea ecosystem to implement this important step of IEA in the here proposed strategy.

The implementation of the outlined approach depends on the development of an integrated monitoring programme that routinely measures the selected indicators. The monitoring programme should combine the present fish stock surveys with environmental monitoring, such as conducted by HELCOM (2011). At present, a number of key indicators are insufficiently sampled, e.g. an indicator of GES of zooplankton in relation to fish stocks (Möllmann *et al.*, 2008). Access to complex biological data, such as zooplankton and phytoplankton, is still difficult and reduced funding poses a serious threat to the important continuation of monitoring and the maintenance of long-term time-series. Furthermore, monitoring should have a wide spatial distribution at an appropriate resolution, since recent studies have shown important changes in the distributions of key species such as sprat (Casini *et al.*, 2011b) and cod (Casini *et al.*, 2012) which have important implications for management (Eero *et al.*, 2012). Eventually, regular predator stomach sampling is required for conducting reliable multispecies assessments.

The utility and implementation of the proposed approach hinges on the development of management plans that can account for the type of information that integrated fish stock advice would provide. Management plans need to include explicit rules on how TACs (and other management measures) are to be determined using information provided by, e.g. ecosystem assessments. Gårdmark *et al.* (2011) give an example how HCRs can account for uncertainty in the advice for Baltic cod, using among others ecosystem information. They suggest HCRs to be modified depending on environmental state, e.g. reflected by the EHI (Figure 3). Furthermore, harvest strategy frameworks able to deal with a broad range of information are being used in fisheries management in Australia using indicators of fishing and stock trends, combined in a hierarchical strategic approach (Smith *et al.*, 2007). The approach to long-term management strategy evaluation we propose can be instrumental in setting up these new EBM plans.

Our strategy described here implicitly demands for a resilience approach to ecosystem management (Folke *et al.*, 2004; Hughes *et al.*, 2005; Levin and Lubchenco, 2008; Fujita *et al.*, 2012). Reducing resilience of populations, communities, and foodwebs to environmental change, through anthropogenic impacts, can cause critical transitions, i.e. regime shifts, as observed in the Baltic Sea. Implementing early warning indicators and evaluating potential future scenarios accounts for a precautionary approach that ensures the health and resilience of Baltic Sea fish stocks. Furthermore, regime-based approach to EBFM can easily be implemented in our framework (King and McFarlane, 2006; Fu *et al.*, 2013; Szuwalski and Punt, 2013).

The approach developed here benefits from the relative simple three species fisheries system of the central Baltic Sea and the availability of long-term datasets and modelling approaches (Casini *et al.*, 2011a). However, our strategy can readily be applied to more complex fisheries ecosystems that usually have (i) fairly developed multispecies fisheries models (e.g. Garrison *et al.*, 2010; Howell and Bogstad, 2010; Kempf *et al.*, 2010; Link *et al.*, 2011a), (ii) long-term time-series for ecosystem assessment (Link *et al.*, 2002; Kenny *et al.*, 2009), and (iii) foodweb and ecosystem models for strategic long-term management strategy evaluation (e.g. Link *et al.*, 2011a, b; Kaplan *et al.*, 2012). Naturally the higher complexity in terms of foodweb structure and related mixed fisheries in ecosystems such as the North Sea (Ulrich *et al.*, 2012) makes ecosystem assessments and long-term modelling approaches more challenging. However, we are convinced that conducting rigorous and goal-specific indicator selection and risk assessment help overcome these challenges. The multimodel approach for strategic long-term simulations advocated here (i.e. BEMA) is less straightforward when applied to more than one target species (as in Gårdmark *et al.*, 2013) or multiple management goals, especially since foodweb models able to address multisector use of ocean ecosystems are rare. Hence, multiple model sets are potentially needed to cover multiple goals, and rigouros management goal-specific selection criteria for model inclusion need to be developed. In general, models should be prioritized that include stabilizing predator–prey feedbacks (Gårdmark *et al.*, 2013), climate as well as anthropogenic drivers, and that allow studying indirect exploitation effects among important target and non-target species.

Eventually implementing our approach requires a fundamental change in how fish stock assessment and advice is conducted (Casini *et al.*, 2011a). More effort needs to be shifted from the regular single-species procedure towards implementing multispecies and ecosystem assessments. This potentially requires a reduction in the temporal frequency of single-species assessments, allowing more effort towards the development of ecosystem assessments. Moreover, fish stock and ecosystem assessments should be combined into an integrative, interdisciplinary framework. Within the ICES framework, the required integration of fish stock and ecosystem assessments is facilitated by the ICES SCICOM Steering Group on Regional Sea Programmes (SSGRSP) and currently supported by the planned revision of the ICES science plan, which gives the development of IEA a prominent position in the organization. But IEA implementation needs an enhanced cooperation with regional conventions such as HELCOM (Helsinki Commission) and OSPAR (Convention for the Protection of the marine Environment of the Northeast Atlantic) and related EU bodies such as STECF (Scientific, Technical, and Economic Committee for Fisheries). However, in the Baltic Sea, as well as in other areas, the data, knowledge, and tools for IEA and EBFM are readily available and should be applied and implemented without further delay.

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