Marine Ecology Progress Series
January 2023, Volume 704 Pages 81-97
https://doi.org/10.3354/meps14227
https://archimer.ifremer.fr/doc/00818/93042/

The rationale for heterogeneous inclusion of ecosystem trends and variability in ICES fishing opportunities advice

Trenkel Verena [1,*], Ojaveer H [2,3,4], Miller Dcm [2], Dickey-Collas M [2,3]

[1] DECOD (Ecosystem Dynamics and Sustainability), IFREMER, INRAe, Institut-Agro - Agrocampus Ouest, rue de l'île d'Yeu, 44311 Nantes cedex 3, France
[2] International Council for the Exploration of the Sea (ICES), H. C. Andersens Boulevard 44-46, 1553 Copenhagen V, Denmark
[3] National Institute of Aquatic Resources, Technical University of Denmark, Kemitorvet Building 201, Kgs. Lyngby 2800, Denmark
[4] Pärnu College, University of Tartu, Ringi 35, Pärnu 80012, Estonia

* Corresponding author : Verena Trenkel, email address : verena.trenkel@ifremer.fr

Abstract :

Incorporation of ecosystem information into fish stock assessments and management advice, a cornerstone of delivering ecosystem-based fisheries management (EBFM), occurs often implicitly, faces multiple challenges, and remains often unquantified in terms of scope and scale. This paper provides a comprehensive overview of the inclusion of ecosystem trends and variability in ICES fishing opportunities advice in the Northeast Atlantic, by covering 87% of stocks corresponding to 99% of landings. Just under 50% of all stock assessments considered ecosystem information and the majority of management strategy evaluations did so in at least one way. Almost 73% of the data-rich stocks incorporated ecosystem trends and variability in at least one way, and almost 55% of short-term forecasts did so. Stock (individual growth rate) and fisheries (landings) characteristics largely explained the observed patterns of incorporation of ecosystem information into advice, with pelagic species and stocks with higher landings having higher instances of incorporation. Early stages of the advice process (closer to data analysis and methods development) had greater inclusion of ecosystem information, though this inclusion was generally implicit and not explicit, e.g. based on a hypothesis of environmental influence on stock dynamics. Moving towards explicit instructions and routine documentation of the inclusion of ecosystem information in fishing opportunities advice will accelerate the path to the EBFM in a consistent and transparent manner.

Keywords : Ecosystem-based fisheries management, ICES advice, Productivity change · Stock assessment, Forecast, Management strategy evaluation

1. Introduction

Reforming fisheries management towards ecosystem-based fisheries management (EBFM) requires both a shift in paradigms and additions to the fisheries science tool box. The rationale for, and commitment to, incorporate greater understanding of ecosystem variability into stock assessments and management advice is seen as a cornerstone of EBFM. The narrative has been consistent from Garcia and Cochrane (2005), and Rice (2008), Rice (2011) to Karp et al. (2019), and Howell et al. (2021). As ecosystem trends and variability affect fish and fishing opportunities, new management actions are called for (Bastardie et al. 2021). While ecosystem models are increasingly used to inform of ecosystem change, single species models are expected to maintain a central role and key to successful EBFM (e.g. Mace (2004)).

There is a commitment under the United Nations fish stocks agreement to use "best scientific evidence available" to manage fisheries (UN 1995). This commitment has resulted in many scientists implicitly incorporating ecosystem trends and variability in productivity into single stock advice without acknowledging the incorporation as delivering a key element of EBFM, possibly because it is not explicitly required by the advice process. The degree to which current stock assessment models used for advice include ecosystem processes generally varies (Skern-Mauritzen et al. 2016), though it might be increasing in the USA (Marshall et al. 2019) and Canada (Pepin et al. 2022). However, as different methodologies were used by these studies, direct comparisons remain uncertain concerning the progress made. The unequal inclusion might partially be due to difficulties with incorporating time-varying processes in standard stock assessment frameworks, a lack of relevant knowledge of data or processes, or lack of reporting and documentation of ongoing practices that do account for trends and variability.

There is growing use of the definitions of Link and Browman (2014) categorisation of the terminology ecosystem-based (fisheries) management (EB(F)M), ecosystem approach to fisheries (EAF) and classic fisheries management (FM). These categories can prove useful (see Link et al., 2020). ICES has not incorporated these definitions into its approach as it recognises the many definitions of ecosystem-based management provided by intergovernmental and science organisations (ICES, 2020). ICES suggests that certain key phrases illustrate the central tenet of these ecosystem approaches: "*management of human activities, consideration of collective pressures, achievement of good environmental status, sustainable use, optimization of benefits among diverse societal goals, regionalization, trade-offs, and stewardship for future generations*" (ICES 2020, p. 2). Thus to align with the ICES statement, we use the broader concept of providing evidence into ecosystem based fisheries management in this manuscript rather than the more prescriptive approach of Link and Browman (2014).

1.1 Incorporating ecosystem variability into the evidence base for fisheries management

It is important to incorporate trends and ecosystem variability when they impact fishing opportunities, the management system and resource availability (Worsøe Clausen et al. 2018, Plaganyi et al. 2019, Tableau et al. 2019, Barbeaux et al. 2020, Blamey et al. 2021, Muffley et al. 2021). In stock assessments and forecasts, there is a trade-off between precision afforded by long time series and bias created by environmental and process changes making assumptions of stationarity invalid (Zhang et al. 2021). Conceptual guidance on what matters for single species stock assessment is provided by Burgess et al. (2017), who apply the concept of abstraction to derive the process properties, that bias single-species stock assessments. Processes, which have dynamics either much faster or slower that the stock of interest could generally be safely ignored. In contrast, processes operating at the same time scale need to be incorporated in the assessment model. The time scale over which process parameters (e.g. natural mortality) can safely be assumed constant will depend on the species' dynamics and also the speed of ecosystem trends. Further, processes operating on a long time scale (i.e. slow change) will primarily bias reference point estimates, or impact the assumptions incorporated into evaluations of harvest control rules, and should be considered in relation to the temporal cycle of the stock assessment and advice process .

On the population level, ecosystem variations manifest themselves via variations in biological processes such as individual growth, natural mortality and recruitment. For example, Stawitz et al. (2019) simulated the effects of ignoring growth variations when estimating the ratio between current biomass and unfished biomass (i.e. stock depletion). This analysis found that ignoring these variations biased depletion estimates, but the magnitude of the bias could be superseded by uncertainties related to other factors. Similarly, Szuwalski et al. (2018) investigated the bias introduced into abundance and reference point estimates by ignoring time varying growth, natural mortality and fisheries selectivity. While ignoring these variations in the stock assessment models led to retrospective patterns as expected, these "retros" could be diminished by allowing the wrong process to vary in time. This indicates that it is not possible to identify the process that might have varied in time simply by trying to identify which parameters if allowed to vary in time reduces retrospective patterns. Knowledge on potential changes in biological and ecological processes needs to be gained outside the population dynamics model fitting process.

Assuming the evidence for time-varying ecosystem processes has been assessed and its relevance for stock assessment and/or reference point estimation evaluated positively, the issue is how to include the processes in the model and for reference point estimation. Various population features relevant for population dynamics are expected to be impacted by changes in ecosystem processes (table 2 in Link et al. 2020). For example, size-at-age and weight-at-length can increase due to increased habitat quality, reduced competition, increased prey abundance, modified physiological processes or predation release (Link et al. 2020). These metrics can be seen as aggregators of ecosystem processes. While a change in habitat quality might not affect maturity-at-age (ogive), reduced competition, increased prey or physiological changes can (Link et al. 2020). Using varying maturity ogives in stock assessment models will account for processes affecting maturation, whatever they are. Similarly for sex ratio. Natural mortality (preferably by age) is notoriously difficult to estimate and even more so any changes. If however, a way for obtaining updated natural mortality estimates was available, for example from applying a multispecies model as done for various fish stocks in the North Sea (Rindorf et al. 2017), using the time series of estimated natural mortality values as input to the stock assessment model would be one way for accounting for such changes. Another way would be to estimate natural mortality and its changes directly in the stock assessment model fitting procedure (Stock & Miller 2021) or include co-variables that drive natural mortality changes (Cao et al. 2017). For short term forecasts, assumptions made for recruitment strongly impact projected abundance, in particular for short lived species or severely depleted stocks with truncated age distributions. One way to deal with this variability in short term forecasts is to truncate the recruitment time series considered for parameterising the forecast.

Management Strategy Evaluation (MSE; Butterworth et al. 1997, Punt et al. 2014) is used to develop Harvest Control Rules (HCRs) for setting catch opportunities that are intended to be robust to biological and environmental uncertainty, including changing productivity. By constructing a reference set of plausible realties (operating models) relating to potential future trends in ecosystem processes, HCRs can be tested against a range of future scenarios to ensure their performance is robust to time-varying ecosystem and fishery processes. Most commonly, alternative scenarios of temporal variation in recruitment, other biological parameters (e.g. growth, maturity, natural mortality) and fishery selectivity are examined. However, spatial structure and movement, and species interactions can also be key considerations that should be accounted for (Siple et al. 2021). While predominately conducted as a single species analyses at present, there is scope to expand MSEs to be more relevant for multi-species and ecosystem-based management, for example through the inclusion of ecosystem models as operating models (Fulton et al. 2014, Kaplan et al. 2021, Lucey et al. 2021). This could allow for a more comprehensive handling of all the biological and technical interactions occurring in a system allowing for the development of robust fisheries management measures.

1.2 Challenge in the Northeast Atlantic providing tactical and strategic fisheries management advice

The International Council for the Exploration of the Sea (ICES) provides advice for over 260 fish and shellfish stocks from Greenland to the Baltic Sea, and from the Barents Sea to the Azores. The ICES strategic plan commits ICES to incorporate a wider range of scientific knowledge into its advice (ICES 2021b). Despite the mission of ICES to deliver evidence for ecosystem-based management, and a ground swell of research into ecosystem dynamics coming from across the science network, there has been no systematic mechanism, nor explicit instruction from the ICES Advisory Committee (ACOM) on how, where appropriate, ecosystem trends and variability should be incorporated. However, an explicit instruction does exist to develop advice based on "best available science" with an acknowledgement that ecosystems vary, and this variability impacts the dynamics of fish stocks. This results in some stock assessments, forecasts and MSEs incorporating relevant elements of varying productivity into tactical fisheries management advice (Skern-Mauritzen et al. 2016). However, this study overall concluded that globally fisheries management takes little account of ecosystem processes, implicitly ignoring that fish stock production is dependent on the physical and biological conditions of the ecosystem (Skern-Mauritzen et al. 2016). To obtain state-of-the-art information on the issue, and taking also into the account the methodological approach (Marshall et al. 2019), ICES carried out an audit of the inclusion of ecosystem processes and variability of ecosystem productivity in its fisheries management advice (Dickey-Collas et al. 2022).

1.3 Rationale for this study

Auditing the use of ecosystem trends and variability, while useful to ICES alone, does not provide insight into the drivers and mechanisms for inclusion of such information. This paper documents how environmental information is incorporated via environmental data, time varying biological data or time-varying model parameters, the stage in the advice system where it happens and explores the potential reasons why the information has been incorporated into fisheries advice. We tested three hypotheses to explore how the explicit instruction to use best available science has led to the implicit incorporation, i.e. without mention of it anywhere in the advice, of variability of ecosystem processes into tactical and strategic fisheries management advice. The authors were aware of the few examples of explicit incorporation of ecosystem trends, and their occurrence at the forecast and advice stage (e.g. the ICES escapement rule for short lived species (ICES 2021a) and the adjustment of target fishing mortality based on ecosystem productivity (Bentley et al. 2021)). We explored whether the characteristics of the stock, of the fishery, or of the advice process would explain the likely inclusion of ecosystem variability into the fisheries advice. We did this by selecting three proxies to represent these characteristics:

Hypothesis 1- characteristics of the stock influence incorporation;

selected proxy metric is the somatic growth coefficient K for the species.

Hypothesis 2- characteristics of the fisheries influence incorporation;

selected proxy metric is the official landings of the stock.

Hypothesis 3- characteristics of the advice process influence incorporation;

selected proxy metric is stage of the advice process where incorporation occurs.

The three hypotheses were chosen as the initial scan of the audit suggested a heterogeneous incorporation of ecosystem processes into the fisheries advice in ICES.

Changing environmental conditions affect both the spatial distribution and the productivity of fish populations (Ottersen et al. 2010). A strong link has been found between species' traits and environmental conditions in their distribution ranges with the most important structuring traits being individual growth, age-at-maturity and lifespan (Beukhof et al. 2019). It has been also established that species with rapid growth, early maturation and short lifespan dominate in warm-water areas and/or shallow depths (Beukhof et al. 2019). Further, the von Bertalanffy growth coefficient K is positively correlated with adult instantaneous natural mortality (Pauly 1980). Thus, the growth coefficient K explains some key differences among fish species in terms of spatial distribution and productivity. Hence, it might also help to explain differences in vulnerability to environmental trends and variability, which in turn could have led to differential incorporation in ICES fisheries advice.

The societal importance of exploited fish stocks can be measured by several variables (Ceriola et al. 2008, Trenkel et al. 2013). The amount landed is important in terms of food security, while generated profits (revenues less costs) and created jobs are more relevant for economic and social welfare. The list of stocks for which ICES provides management advice broadly results from the interest its member countries have in a given stock and hence their willingness to invest experts' time and finances needed for the process. Landings in tons seem therefore an appropriate and meaningful way to measure the importance of fish stocks. It also has the advantage of being available for all stocks, in contrast to landings in value.

The different stages of the ICES advice process are explained in the next section. As detailed below, the advice process becomes gradually more prescriptive, justifying the use of the stage in the advice as a proxy variable.

1.4 ICES process for advice on fishing opportunities

It is necessary to explain the ICES process that develops the fisheries advice to put the audit and the subsequent analysis into context (Figure 1). The annual or multi-annual stock assessments and forecasts are carried out by the working groups of experts. There is an annual data update. For data rich stocks, the methods used are determined by benchmarks (multi-annual) and documented in stock annexes. For data limited stocks, the methods are provided in the "Advice on fishing opportunities" (ICES 2021a). If the benchmark has agreed to include a quantitative metric of variable productivity in the stock assessment, it will be used by the working group. For some ecoregions (Greater North Sea, Celtic Seas, Bay of Biscay and the Iberian Coast) mixed fisheries analyses (also known as technical interactions) of trawl fisheries are carried out annually. In addition, fisheries and ecosystem overviews are provided by ecoregion (item overviews in Figure 1). Further, for some high-profile stocks, which are primarily targeted fisheries, MSEs have been carried out on a multi-annual basis. All of these are used to draft the advice, which is then agreed by the advisory committee (ACOM).

2. Material and methods

To carry out the audit, a questionnaire was designed covering the major categories of the ICES cycle of advice on fishing opportunities (numbered boxes in Figure 1). Additionally, the categories distributions and habitats and climate were included, which are both distributed across the advice cycle. For each category, one to five questions were asked on the implementation approach used, that is the different ways changes and variations of productivity were dealt with for a given stock (Table 1). For example, for stocks assessments the considered implementation approaches were: i) variability or change in length distribution, ii) weight-at-age, iii) maturity-at-age, iv) natural mortality and/or v) sex ratio. Variability or change in this case means either using a time series or time period specific values. For short term forecasts and management/rebuilding plans the questions covered similar approaches. For the other four categories, the implementation approaches were of a different nature, not necessarily directly linked to data or parameter values (Table 1). For example, for the category distributions and habitats, the possible approaches were accounting for i) the influence of population state, ii) habitat suitability/quality and/ iii) within-species stock mixing, in one way or another.

The scoring systems was as in Marshall et al. (2019) with four levels: i) missing/not available, ii) included in background, e.g. expert group reports, iii) qualitative, and iv) quantitative inclusion of data or information in advice (Table 2). The questionnaire was sent to 15 ICES expert groups dealing with 265 stocks and was filled in primarily in 2020 and 2021 by the group experts, covering all ICES data stock categories (Table S1). The ICES data stock categories (see ICES 2021a) run from data rich stocks with stock assessments based on population dynamics models (category 1 or 2 if the assessment is considered indicative of trends only), to more data limited stocks with reliable indicators of stock size or fishing pressure but insufficient data to develop full analytical assessment models (category 3) to stocks with only reliable catch data, landings data or negligible landings through incidental bycatch only (categories 4, 5 and 6, respectively).

The audit took three years, from consultations to designing the questionnaire, testing it with two groups covering both data rich and data poor stocks, revising questions, carrying out the main audit, and chasing missing responses. The questionnaire was set up in a manner that it covers all stocks to obtain a comprehensive overview, not targeting data rich stocks only.

Before analysis, the responses were scanned for completeness. If answers for only some questions were missing, the score 1 (missing/not available) was substituted. For each stock, the responses related to the one to five different potential implementation approaches were summarised at the category level. For this, the highest response score was retained for each category. Further, for analysing the responses related to the short term forecast category, only stocks for which these are carried out were considered (ICES data category 1). For the category management/rebuilding plans, only the 30 stocks for which such plans have been developed since 2013 were considered. ICES currently provides mixed fishery advice for stocks in the Greater North Sea, Bay of Biscay, Iberian waters and the Celtic Sea. However, the questionnaire left it open at which stage mixed fisheries issues were considered, e.g. via mixed fishery advice, in the working group report or in some other way. Therefore, we were not restrictive in terms of the stocks incorporated into analyses of the mixed fishery category questionnaire results.

To investigate hypothesis 1 that stock characteristics matter for if and how environmental variability was accounted for in the ICES fishing opportunities advice, species-specific somatic growth parameters K for fishes were taken from Beukhof et al. (2019). When available, K values from different stocks in European and North American waters were averaged to obtain a species-specific K value. For *Nephrops norvegicus* the sex-specific values in Haynes et al. (2016) were averaged. For testing hypothesis 2, fisheries characteristics matter, nominal landings (in ton) by stock came from the ICES data base and were averaged over the years 2006-2019. For analysing hypothesis 3, the stages in the advice cycle were numbered starting from stock assessments (1) and ending at advice (5) and used as continuous explanatory variable (see numbers in Figure 1). The categories distributions and habitats and climate were excluded from this analysis as they can be considered at different stages of the advice cycle.

Multinomial log-linear models were used to test the three hypotheses. For this, the highest response scores on the category levels were modelled as a function of growth parameter K, log-landings and the stage in the advice cycle, respectively. Landings were log-transformed to reduce the weight of a few large landings in model fitting. Separate models were fitted for each category. The ‘not available’ score was used as the reference score in all models and stocks with missing information were excluded. Taking the model with growth parameter K as example, the, the probability of response category “quantitative” for stock *i* is then

$$\log\left(\frac{\Pr(Y_i = \text{quantitative})}{\Pr(Y_i = \text{not available})}\right) = a_{quant} + b_{quant}\,\mathrm{K}$$

Wald tests were used for testing the significance of each of the three explanatory variables for each score level. To evaluate the degree of dependence of the tests for hypothesis 1 and 2, the Pearson correlation between the growth parameter K and log-landings was calculated.

All calculations were carried out in R and using the nnet package for the fitting multinomial log-linear models (Venables & Ripley 1999). Models were only fitted for the four process categories with sufficient stocks for which environmental variability was incorporated in one way or another: stock assessments, short term forecasts, management/rebuilding plans and distributions and habitats. Confidence intervals (95%) for estimated category membership probabilities were obtained using an empirical bootstrap randomly redrawing stocks (with replacement) for 200 resamples.

3. Results

The audit covered 265 stocks, with a response rate of 87% in terms of the number of stocks (230) and 99% in terms of total landings. For 167 stocks (73% of the stocks with replies), information on ecosystem trends and variability was included into tactical and/or strategic fisheries management advice in at least one of the advice cycle categories in at least one way. For 105 stocks (46%) this was achieved in a quantitative manner, for 9 (4%) qualitative and for 53 stocks (23%) ecosystem information was considered in the background. Responses covered data rich and data limited stocks (Supplementary Material Table S1). Among the missing 35 stocks, 12 were *Nephrops* (out of in total of 29 stocks), two cod (17), three plaice (10), three whiting (7) and all three Northern shrimp stocks.

Ecosystem trends and variability were considered for more than half of the stocks in short term forecasts and management strategy or rebuilding plan evaluations, primarily in a quantitative manner (Figure 2). Stock assessment was the category in which ecosystem information was accounted for the greatest number of stocks (Figure 2), with quantitative inclusion primarily in case of data rich stocks and consideration in the background for data poor stocks (Supplementary Material Figure S1). Quantitative inclusion of ecosystem information in stock assessments was implemented primarily via time varying length distributions and weight-at-age (Table 3, Figure 3a). In short term forecasts, implementation was also via time varying weight-at-age but also truncating recruitment time series and use of recent values or trends in maturity-at-age (Table 3, Figure 3b). Truncation of recruitment time series entails only using estimates from a recent period as basis for short term projections to account for current productivity conditions. The same three approaches (i.e. weight-at-age, truncating recruitment time series and maturity-at-age) also dominated in case of MSEs or for rebuilding plans, while environmentally driven recruitment was used for around one quarter of these stocks (Figure 3c, Table 3). Natural mortality varied or changed over time for 20% of stocks in the stock assessment and recent trends used for short term forecasts of 15% of stocks (subset of stocks). For the categories mixed fisheries, and distribution and habitats, ecosystem trends and variability were mainly considered in the background, such as expert group reports (Figure 2). For the categories advice and climate, the percentage of stocks with ecosystem considerations was low with 7% and 14%, respectively (Figure 2).

We tested the three hypotheses outlined in the introduction for explaining the audit results using multinomial log-linear models with a single explanatory variable each (model estimates in Supplementary Material tables S2, S3 and S4). It turned out that the tests of hypotheses 1 and 2 were not completely independent as growth parameter K and log-landings showed a weak but significant positive correlation (Pearson's $r=0.24$, $p\text{-value}<0.001$), which does not necessarily indicate direct causality. Further, log-landings decreased significantly with ICES data category (r=-0.6, p-value<0.001), while growth parameter K was not correlated with data category (r=-0.09, p-value=0.16) (Supplementary Material Fig. S2).

Stock characteristics significantly explained how ecosystem trends and variability was included at different stages in the ICES advice cycle, supporting thereby our hypothesis 1 (Figure 4). Quantitative incorporation of ecosystem information in both stock assessments and short-term forecasts increased significantly with species-specific growth parameter K. In contrast, for the category management/rebuilding plans, and distributions and habitats, the proportion of stocks for which ecosystem information was considered in the background increased significantly with K, while not used/available decreased significantly with K in case of all four categories.

Fisheries characteristics also significantly explained how ecosystem information was accounted for in stock assessments, short term forecasts and distributions and habitats, supporting hypothesis 2 (Figure 5). The relationship was not significant for the category management/rebuilding plans, probably because this only concerned a subset of stocks with higher landings. For distribution and habitats, both quantitative inclusion of ecosystem information and considering it in the background were more common for stocks with larger landings. In contrast, quantitative inclusion did not increase with growth rate. The shapes of the relationships were similar as for K, though slightly steeper, while confidence bands for assessments, short term forecasts, and distribution and habitats were generally tighter for landings compared to the relationships with K (Figures 5a &b vs Figures 4a & b). This indicates a relatively higher explanatory power of landings for the three categories.

The ways ecosystem trends and variability were included into the advice differed by stages of the advice cycle, thus supporting hypothesis 3 (Figure 6). The quantitative use of ecosystem information significantly decreased while not using it or using in the background only increased with advancing in the advice process (i.e. moving from the stock assessment to the advice) (Figure 6).

4. Discussion

This audit provided the first comprehensive picture of the current incorporation of ecosystem trends and variability in the ICES fishing opportunities advice. It was comprehensive both in terms of stocks, with the questionnaire designed to be applicable to all stocks, (i.e. both data limited and data rich), and in terms of stages in the advice cycle (Figure 1). The high return rate (87% of the number of stocks corresponding to 99% of landings) confirms the generality and supports the validity of the results.

The audit revealed that the explicit instruction to use "best available science" led to the implicit incorporation of variability of ecosystem processes into tactical and strategic fisheries management advice in at least one way for nearly three quarters of stocks (75% among the 230 stocks with replies). Time varying weight-at-age and length distributions were implemented for nearly half of the stocks in the assessments and more for stocks in case of management/rebuilding plans. Notably, time varying natural mortality was used for around one fifth of stocks in the stock assessment, somewhat fewer stocks for short term forecasts and in one third of management/rebuilding plan simulations. In comparison, time varying natural mortality was implemented in around one third of Canadian stock assessments with quantitative inclusion of environmental variables (Pepin et al. 2022). Both changing weight-at-age and changing natural mortality are direct effects of food web changes (Link et al. 2020), though the natural mortality is notoriously difficult to estimate (Thorpe et al. 2015). Another important result concerns recruitment. When carrying out short term forecasts, for one third of stocks historic recruitment time series were either truncated (not always recommended, ICES 2021c) or modelled with environmental drivers (11%).As a comparison, environmental drivers for predicting recruitment were found for 3% of all stock assessments in Canada, (16% among those with quantitative inclusion) (Pepin et al. 2022). The larger value in this study might indicate the degree of environmental changes and variability across the Northeast Atlantic and shelf seas (Payne et al. 2012, Worsøe Clausen et al. 2018, Bueno-Pardo et al. 2020). Distribution and habitat changes were primarily included as background information, which might be due to the ICES advice on fishing opportunities is based on single stock assessments with non-spatial approaches.

As hypothesized, the characteristics of the stocks (hypothesis 1), the fisheries (hypothesis 2) and the stage of the advice cycle (hypothesis 3) explained both the incorporation of ecosystem trends and variability, and the approach used for such incorporation. Quantitative incorporation of ecosystem trends and variability was more common for species with faster growth rates, among which are many small pelagic species with high growth rates and generally large landings (Engelhard et al. 2014). This is not surprising as the biology and ecology of pelagic species is known to be strongly influenced by environmental conditions (see review in Trenkel et al. 2014). More frequent use of environmental data for pelagic species compared to groundfish and elasmobranchs was also found in a review of Canadian stock assessments (Kulka et al. 2022, Pepin et al. 2022). This result might also be in line with the recommendations by Burgess et al. (2017) on the need to consider only processes on the same time scale as stock dynamics to avoid bias in stock assessments. The non-inclusion of ecosystem trends and variability for species with slower growth rates could indicate that recent ecosystem process changes were not on the same scale as the population changes of these species, hence reducing their influence, or simply not strong enough to be detectable or to make any difference for the advice given the inherent uncertainty in both input data and stock assessment results. Some might suggest that it could also be an artefact of not using a multispecies or ecosystem model to provide the basis of advice, but supporting information for such a paradigm is ambivalent.

However, there are deviations from such patter with one example being the eastern Baltic cod. In recent years, increased hypoxia has led to deteriorated cod body condition (Limburg & Casini 2019) and hence decreasing weight-at-age which needs to be incorporated in the assessment. Another example is the North Sea plaice for which both temporal variations in weight-at-age and sex-ratio have been observed (Kell & Bromley 2004) .

Stocks with large fisheries in terms of landings were more likely to be the subject of quantitative approaches for including ecosystem variability (hypothesis 2). These stocks are often small pelagic species, making it impossible to study completely separately the effects of stock and fisheries characteristics. However, the generally tighter confidence bands for relationships with landings could indicate that fisheries characteristics were a stronger driver than biological characteristics for the quantitative incorporating of ecosystem variability at different stages of the advice process. Assuming fisheries characteristics are important to the results, one possible explanation is that stocks with large landings are also of economic and social importance, which makes funding more accessible to collect data, explore impacts of environmental variability and invest research time to develop and apply advanced models and approaches. Indeed, the investment into basic research was identified by Pepin et al. (2022) as one of the prerequisites for the inclusion of environmental variables into stock assessments. Consequently, stocks with large landings might have more scientists working on them compared to smaller stocks. This explanation is further supported by the stocks assessed with data rich methods had generally higher landings and conversely data limited methods were used for stock with lower landings (Figure S2). Focusing process research and inclusion of environmental variability on more valuable and larger stocks could be sensible from a purely food security and economic point of view while it might be insufficient to ensure meeting biodiversity and conservation targets and addressing the concerns of small-scale fisheries and equal consideration of different stocks of the same species. Indeed, species with smaller landings might be more sensitive to overexploitation. As fisheries management becomes more ‘ecosystem approach’ focused, the rationale for monitoring priorities is changing. Thus, smaller stocks might require a greater proportion of monitoring for the delivery of assessment and advice as the general management objectives shift.

Quantitative inclusion of ecosystem variability was found to occur more often in categories occurring earlier in the advice cycle (hypothesis 3). This can be explained by the nature/role of contributors in each category (see contributors in Figure 1) and the existing opportunities in the process to include new knowledge and data. The opportunities for innovation, bringing in new science and researchers that might challenge the existing paradigms and process are largest during benchmarks. Benchmarks are the venue where new data, methods and models subsequently used for stock assessment and short-term forecasts are discussed and approved. Similarly, the process needed to set up management/rebuilding plan evaluation offers opportunities for reviewing data and knowledge on past and potential future productivity chances and including the relevant elements in simulations and scenarios. Siple et al. (2021) drawing on the literature and expert knowledge showed how to consider temporal variation in recruitment and other life-history rates, spatial structure and movement, and species interactions in management strategy evaluation for small pelagic fishes, for which such processes are common. One consequence of ecosystem variability being considered in early advice categories is that the visibility to those outside the system is reduced. Indeed, the standardised ICES advice sheets do not indicate whether and how ecosystem trends and variability and hence the wider ecosystem context as defined in this study, were included for a given stock, though this was found to be the case in at least one way for 73% of stocks in this audit. We come back to this point below.

The questionnaire underlying the audit was filled in by experts carrying out the stock assessments and short-term forecasts of the audited stocks (people in boxes 1 and 2 in figure

1). Some of them are also engaged in mixed fisheries advice and management/rebuilding plan evaluation as well as advice drafting (people in boxes 3, 4 and 5, figure 1). This is in contrast to other studies, e.g. Skern-Mauritzen et al. (2016) and Marshall et al. (2019), in which the audit was carried out by a small group of researchers, detached from the process, but similar to Kulka et al. (2022), with the main difference that they carried out additional interviews for a subset of randomly selected stocks. While involving stock experts into the audit ensures provision of the best available evidence, there might have been occasions of inconsistency of understanding of the questions during the audit and, hence, heterogeneity in the responses. Some questions were more explicit than others, e.g. accounting for "variability/change in length distribution" in assessment category compared to "specific productivity information used" in advice category (Table 1). Thus, it is conceivable that the results are impacted in addition by differences in comprehension of the questions and likely also by differences in interest in the subject.

As we were interested in general incorporation of ecosystem trends and variability in the ICES advice cycle, the scoring did not include "not relevant" criterion as a response option, which may have induced uncertainty. Such response option would have been clearly needed for stocks for which no short-term forecasts were carried out or no management/rebuilding plans developed. To correct for this we only considered stocks with model based assessments (data category 1) when analysing the results for the assessment category and only stocks with official management or rebuilding plans since 2013 for the category management/rebuilding plans. Another category is mixed fisheries for which relevance would have been important to know. ICES currently provides mixed fishery advice only for stocks in the Greater North Sea, Bay of Biscay, Iberian waters and the Celtic Sea. In these areas fisheries are generally multi-species (Bay of Biscay: Daurès et al. 2009), though there are also mixed fisheries in other regions (see ICES Fisheries overviews; https://www.ices.dk/advice/Fisheries-overviews). Further, two of the potential implementation approaches proposed for the mixed fishery category did not explicitly refer to the official mixed fisheries advice process, these were "catch and bycatch of target species" and "bycatch of non-target species". Therefore, we did not restrict the number of stocks when analysing the mixed fishery category.

Three hypotheses were formulated to explain the audit results. For testing the influence of stock characteristics on the incorporation of ecosystem variability, we used the somatic growth parameter K as a proxy variable due to its link with species geographic distributions (Beukhof et al. 2019) and its correlation with other life history traits which are expected to be impacted by environmental trends and variability (e.g. Ottersen et al. 2010). The growth parameter also has the advantage of being a continuous variable and readily available for all species, though not on a stock level. Differences in K between stocks of the same species were not considered, as these are not expected to impact the conclusions, assuming that inter-specific differences are larger than any inter-stock differences.

For testing the influence of fishery characteristics, we used mean landings in tonnes. Landings in value or profits would have been alternative options to consider, though more difficult to obtain for all stocks, in particular profits. Fishing costs depend on the fishing method, hence to estimate profits detailed fleet information is needed (e.g. Daures et al. 2013). Further, growth parameter K and landings were found to be significantly correlated, meaning the tests of the two hypotheses were not independent. However, given the shapes of the log-linear relationships differed (compare Figure 4 and 5), indicating difference in information content, we consider retaining both analyses appropriate and complementary.

Despite lacking explicit guidance contrary e.g. to Canada where the revised Fisheries Act requires taking into account environmental conditions affecting stocks (Pepin et al. 2022), information on ecosystem trends and variability, or relevant aggregators (e.g. empirically derived weights at age) have been incorporated into ICES fishing opportunities advice. This incorporation has largely gone unevaluated at the system level and thus may have remained unnoticed externally (excluding Skern-Mauritzen et al. 2016). The drive was likely “best available science”, a key requirement of the FAO code of conduct for responsible fisheries (FAO 1995). Wilson and Hegland (2005) found that the fisheries scientists in Europe were under pressure to deliver “broader science” to feed into the Common Fisheries Policy in Europe. They demonstrated that this stressed both the system and the researchers. And yet progress has been made. However, Europe has further to go on ecosystem-based fisheries management. Ballesteros et al. (2018) commented that ICES has taken a leading role in generating an Ecosystem Approach to Fisheries Management (EAFM) framework in which management decisions can operate; and while ICES can address a range of shortcomings in the current framework, bottlenecks exist on implementation. The bottlenecks demand concerted action between the advisory system and the political realm. The implementation of an EAFM requires consistency between science and management (Ballesteros et al. 2018). The distinction between the paradigms of EBFM and EAFM are not homogenously recognised by researchers nor managers across the ICES area (Link & Browman 2017) but any move to a wider management of fisheries as components of the ecosystem will require the explicit and systematic consideration of ecological, technical, and fleet interactions.

The main aim of the audit was to create an overview of current inclusion of ecosystem trends and variability in an existing formalised advice system, positioning that in a single stock approach wider ecosystem considerations can be accounted for to some degree. Because the questionnaire was set up in a manner that it covers all stocks, implementation approaches included in the questionnaire did not necessarily incorporate all possible ways ecosystem processes can be and are considered for different stocks. One of the avenues for further investigations is related to reference point estimates, given their importance for sustainable exploitation and implications of ecosystem changes for reference point estimates (O'Leary et al. 2020, Punt et al. 2021). In addition, the questionnaire did not aim to disentangle ecological processes at play. Therefore, density-dependence was not explicitly included; rather it was considered that density-dependent effects would be included in, e.g. time varying weight-at-age or truncating recruitment time series. These and potentially additional issues should be considered in future audits, incl. to be designed for data rich and data poor stocks separately, to provide more detailed information about incorporation of ecosystem information in ICES advice on fishing opportunities.

This audit should not be an end in itself. The information should be maintained and updated (after each benchmark or update of the guide to fishing opportunities advice), its visibility increased and the messaging to the users of advice strengthened. It has been highlighted that fisheries management advice in Europe is reactive, rather than proactive, and never more so than when developing approaches to address ecosystem dynamics or EBM (Ramirez-Monsalve et al. 2021). European fisheries managers should request that fisheries management advice reflects the dynamics and the state of the ecosystem. Despite this ongoing work not being highlighted in the ICES statement on EBM (ICES 2020), there is obvious benefit externally to make it more visible in the future to inform about the progress of relevant activities in ICES. Some further ideas could be taken from a US initiative, which proposes the APECS (Assessment, Profile, Ecosystem Considerations, and Socioeconomics) template for reporting stock-specific ecosystem considerations (see example in Shotwell et al. (2018)) or from the recent published tool from FAO on ecosystem approach to fisheries implementation (FAO 2021). Some expert groups in ICES have made novel advances in the incorporation of ecosystem dynamics into fishing opportunities advice (Bentley et al. 2021, Goto et al. 2022) and ICES is integrating the regional signal by publishing fisheries overviews for each ecoregion. The wider use of Surplus Production Model in Continuous Time (SPiCT; Pedersen & Berg 2017), to assess the trends in data limited stocks, offers the opportunity to increase the incorporation of aggregators for ecosystem trends and density dependent processes at high biomass into the suite of fishing opportunities advice. The need for fully documenting hypotheses and environment driven mechanisms, after rigorous and systematic evaluation of the relationship between environmental variables and stock status (biomass, abundance growth, mortality and recruitment) for all stocks has been recently highlighted (Pepin et al. 2022). Introducing systematic evaluation of environmentally and biologically driven population dynamic processes following agreed and rigorously tested standards and guidelines would represent a useful development. In addition to this implicit incorporation of ecosystem trends, ICES has supplemented with explicit adaption of advice rules, such as the annual advice for short lived species that account for annual productivity changes, and the requirements of predators, or the adaption of the pretty good yield ranges that reflect ecosystem dynamics. However, ICES should profile better these responses to variable and changing productivity, together with clearer communication of the environmentally driven changes. While ICES uses ecosystem and fisheries overviews to document these changes and associated patters, closer integration with the fishing opportunities advice is still needed.

In conclusion, we formulated three hypotheses to explain the results of the recent comprehensive audit of inclusion of trends and ecosystem variability in the ICES fishing opportunities advice. Stock characteristics (growth rate) explained well the inclusion of ecosystem information in stock assessements and short term forecasts, and to some degree also in management/rebuilding plan elaboration. We explained elevated use of ecosystem information by the large body of published work documenting environmental impacts on small pelagic species which have higher growth rates. In addition, stocks with larger landings were more likely to have quantiative inclusion of ecosystem variability in stock assessments and short term forecasts. A possible explanation is that more research effort and resources were invested to work on more valuable stocks. Stocks with larger individual growth rates and/or larger landings were also more likely to have variations in distribution and habitat being accounted for in different categories of the advice cycle. The importance of different stages of the advice cycle was further confirmed by the observation that inclusion of ecosystem information was found more likely to occur at earlier stages of the advice cycle, possibly because of the larger flexibility and room for innovation at these stages. Given the current status and dynamics of inclusion of ecosystem trends and variability into fishing opportunities advice, a move from implicit to explicit instructions with routine documentation is required to accelerate on the path to EBFM in a transparent manner.

5. Acknowledgements

We are grateful to Patrick Lynch and the following exports working groups for filling in the survey: Arctic Fisheries Working Group (AFWG), Northwestern Working Group (NWWG), Baltic Fisheries Assessment Working Group (WGBFAS), Working Group on the Bay of Biscay and Iberian Waters Ecoregion (WGBIE), Working Group on Celtic Seas Ecoregion (WGCSE), Working Group on the Assessment of Demersal Stocks in the North Sea and Skagerrak (WGNSSK), Joint NAFO/ICES Pandalus Assessment Working Group (NIPAG), Working Group on the Biology and Assessment of Deep-sea Fisheries Resources (WGDEEP), Joint EIFAAC/ICES/GFCM Working Group on Eels (WGEEL), Working Group on Elasmobranch Fishes (WGEF), Assessment Working Group on Baltic Salmon and Trout (WGBAST), Working Group on North Atlantic Salmon (WGNAS), Herring Assessment Working Group for the Area South of 62° N (HAWG), Working Group on Widely Distributed Stocks (WGWIDE), Working Group on Southern Horse Mackerel, Anchovy, and Sardine (WGHANSA). This study received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No 773713 (PANDORA). We would like to thank Pierre Pepin and one anonymous referee for insightful comments and suggestions.

6. Data availability

The questionnaire data are publicly available on the ICES website https://doi.org/10.17895/ices.data.19863214.v1.

7. References

Ballesteros M, Chapela R, Ramirez-Monsalve P, Raakjaer J, Hegland TJ, Nielsen KN, Laksa U, Degnbol P (2018) Do not shoot the messenger: ICES advice for an ecosystem approach to fisheries management in the European Union. Ices Journal of Marine Science 75:519-530

Barbeaux SJ, Holsman K, Zador S (2020) Marine heatwave stress test of ecosystem-based fisheries management in the Gulf of Alaska Pacific cod. Frontiers in Marine Science 7: 703

Bastardie F, Brown EJ, Andonegi E, Arthur R, Beukhof E, Depestele J, Doering R, Eigaard OR, Garcia-Baron I, Llope M, Mendes H, Piet G, Reid D (2021) A review characterizing 25 ecosystem challenges to be addressed by an ecosystem approach to fisheries management in Europe. Frontiers in Marine Science 7:629186

Bentley JW, Lundy MG, Howell D, Beggs SE, Bundy A, de Castro F, Fox CJ, Heymans JJ, Lynam CP, Pedreschi D, Schuchert P, Serpetti N, Woodlock J, Reid DG (2021) Refining Fisheries advice with stock-specific ecosystem information. Frontiers in Marine Science 8: 602072

Beukhof E, Frelat R, Pecuchet L, Maureaud A, Dencker TS, Solmundsson J, Punzon A, Primicerio R, Hidalgo M, Moellmann C, Lindegren M (2019) Marine fish traits follow fast-slow continuum across oceans. Scientific Reports 9: 17878

Blamey LK, Plaganyi EE, Hutton T, Deng RA, Upston J, Jarrett A (2021) Redesigning harvest strategies for sustainable fishery management in the face of extreme environmental variability. Conservation Biology 36: e13864

Bueno-Pardo J, Petitgas P, Kay S, Huret M (2020) Integration of bioenergetics in an individual-based model to hindcast anchovy dynamics in the Bay of Biscay. Ices Journal of Marine Science 77:655-667

Burgess MG, Giacomini HC, Szuwalski CS, Costello C, Gaines SD (2017) Describing ecosystem contexts with single-species models: a theoretical synthesis for fisheries. Fish and Fisheries 18:264-284

Butterworth DS, Cochrane KL, De Oliveira JAA (1997) Management procedures: a better way to manage fisheries? The South African experience. Global trends: fisheries management 20:83-90

Cao J, Chen Y, Richards RA (2017) Improving assessment of Pandalus stocks using a seasonal, size-structured assessment model with environmental variables. Part II: Model evaluation and simulation. Canadian Journal of Fisheries and Aquatic Sciences 74:363-376

Ceriola L, Accadia P, Mannini P, Massa F, Milone N, Ungaro N (2008) A bio-economic indicators suite for the appraisal of the demersal trawl fishery in the Southern Adriatic Sea (Central Mediterranean). Fisheries Research 92:255-267

Daurès F, Rochet M-J, Van Iseghem S, Trenkel VM (2009) Fishing fleet typology, economic dependence, and species landing profiles of the French fleets in the Bay of Biscay, 2000-2006. Aquatic Living Resources 22:535–547

Daures F, Trenkel VM, Guyader O (2013) Modelling the fishing costs of French commercial vessels in the Bay of Biscay. Fisheries Research 146:74-85

Dickey-Collas M, Trenkel V, Ojaveer H, Miller D (2022) ACOM sanctioned analysis of ICES productivity questionnaire (Ad Hoc). ICES Scientific Reports, https://doi.org/10.17895/ices.pub.10037 Engelhard GH, Peck MA, Rindorf A, Smout S, van Deurs M, Raab K, Andersen KH, Garthe S, Lauerburg RAM, Scott F, Brunel T, Aarts G, van Kooten T, Dickey-Collas M (2014) Forage fish, their fisheries, and their predators: who drives whom? Ices Journal of Marine Science 71:90-104

FAO (1995) FAO code of conduct for responsible fisheries. Rome. https://www.fao.org/3/v9878e/v9878e00.htm

FAO (2021) Ecosystem approach to fisheries implementation monitoring tool – A tool to monitor implementation of the ecosystem approach to fisheries (EAF) management. User manual. Rome. https://doi.org/10.4060/cb3669en

Fulton EA, Smith ADM, Smith DC, Johnson P (2014) An integrated approach is needed for ecosystem based fisheries management: Insights from ecosystem-level management strategy evaluation. PLoS ONE 9:e84242

Garcia SM, Cochrane KL (2005) Ecosystem approach to fisheries: a review of implementation guidelines. ICES Journal of Marine Science 62:311-318

Goto D, Filin AA, Howell D, Bogstad B, Kovalev Y, Gjosaeter H (2022) Tradeoffs of managing cod as a sustainable resource in fluctuating environments. Ecological Applications 32: e02498

Haynes PS, Browne P, Fullbrook L, Graham CT, Hancox L, Johnson MP, Lauria V, Power AM (2016) Growth in *Nephrops norvegicus* from a tag-recapture experiment. Scientific Reports 6:35143

Howell D, Schueller AM, Bentley JW, Buchheister A, Chagaris D, Cieri M, Drew K, Lundy MG, Pedreschi D, Reid DG, Townsend H (2021) Combining ecosystem and single-species modeling to provide ecosystem-based fisheries management advice within current management systems. Frontiers in Marine Science 7:607831

ICES (2020) ICES and Ecosystem-based management. 5 pp. https://doi.org/10.17895/ices.pub.5466.

ICES (2021a) Advice on fishing opportunities. In Report of the ICES Advisory Committee, 2021. ICES Advice 2021, section 1.1.1. 9 pp. https://doi.org/10.17895/ices.advice.7648

ICES (2021b) Strategic Plan. 18 pp. https://doi.org/10.17895/ices.pub.5466

ICES (2021c) Workshop of fisheries management reference points in a changing environment (WKRPChange, outputs from 2020 meeting). ICES Scientific Reports, Book .3 https://doi.org/10.17895/ices.pub.7660

ICES (2018) Advice basis. In Report of the ICES Advisory Committee, 2018. ICES Advice 2018, Book 1, Section 1.2. https://doi.org/10.17895/ices.pub.4503.

Kaplan IC, Gaichas SK, Stawitz CC, Lynch PD, Marshall KN, Deroba JJ, Masi M, Brodziak JKT, Aydin KY, Holsman K, Townsend H, Tommasi D, Smith JA, Koenigstein S, Weijerman M, Link J (2021) Management strategy evaluation allowing the light on the hill to illuminate more than one species. Frontiers in Marine Science 8:624355

Karp MA, Peterson JO, Lynch PD, Griffis RB, Adams CF, Arnold WS, Barnett LAK, deReynier Y, DiCosimo J, Fenske KH, Gaichas SK, Hollowed A, Holsman K, Karnauskas M, Kobayashi D, Leising A, Manderson JP, McClure M, Morrison WE, Schnettler E, Thompson A, Thorson JT, Walter JF, III, Yau AJ, Methot RD, Link JS (2019) Accounting for shifting distributions and changing productivity in the development of scientific advice for fishery management. Ices Journal of Marine Science 76:1305-1315

Kell LT, Bromley PJ (2004) Implications for current management advice for North Sea plaice (*Pleuronectes platessa* L.): Part II. Increased biological realism in recruitment, growth, density-dependent sexual maturation and the impact of sexual dimorphism and fishery discards. Journal of Sea Research 51:301-312

Kulka, DW, Thompson S, Cogliati K, Olmstead M, Austin D, Pepin P (2022) An Accounting of Integration of Environmental Variables in Fishery Stock Assessments in Canada. Canadian Technical Report of Fisheries and Aquatic Sciences, 3473: viii + 79 p. https://waves-vagues.dfo-mpo.gc.ca/Library/41060064.pdf

Limburg KE, Casini M (2019) Otolith chemistry indicates recent worsened Baltic cod condition is linked to hypoxia exposure. Biology Letters 15:20190352

Link JS, Browman HI (2017) Operationalizing and implementing ecosystem-based management. ICES Journal of Marine Science 74:379-381

Link JS, Huse G, Gaichas S, Marshak AR (2020) Changing how we approach fisheries: A first attempt at an operational framework for ecosystem approaches to fisheries management. Fish and Fisheries 21:393-434

Lucey SM, Aydin KY, Gaichas SK, Cadrin SX, Fay G, Fogarty MJ, Punt A (2021) Evaluating fishery management strategies using an ecosystem model as an operating model. Fisheries Research 234:105780

Mace PM (2004) In defence of fisheries scientists, singe-species models and other scapegoats: confronting the real problems. Marine Ecology Progress Series 274:285-291

Marshall KN, Koehn LE, Levin PS, Essington TE, Jensen OP (2019) Inclusion of ecosystem information in US fish stock assessments suggests progress toward ecosystem-based fisheries management. ICES Journal of Marine Science 76:1-9

Muffley B, Gaichas S, DePiper G, Seagraves R, Lucey S (2021) There Is no I in EAFM Adapting integrated ecosystem assessment for mid-atlantic fisheries management. Coastal Management 49:90-106

O'Leary CA, Thorson JT, Miller TJ, Nye JA (2020) Comparison of multiple approaches to calculate time-varying biological reference points in climate-linked population-dynamics models. Ices Journal of Marine Science 77:930-941

Ottersen G, Kim S, Huse G, Polovina JJ, Stenseth NC (2010) Major pathways by which climate may force marine fish populations. Journal of Marine Systems 79:343-360

Pauly D (1980) On the interrelationships between natural mortality, growth parameters, and mean environmental temperature in 175 stocks. J Cons Int Explor Mer 39:175-192

Payne MR, Egan A, Fässler SMM, Hátún H, Holst JC, Jacobsen JA, Slotte A, Loeng H (2012) The rise and fall of the NE Atlantic blue whiting. Marine Biology Research 8:475-487

Pedersen MW, Berg CW (2017) A stochastic surplus production model in continuous time. Fish and Fisheries 18:226-243

Pepin P, King J, Holt C, Smith HG, Shackell N, Hedges K, Bundy A (2022) Incorporating knowledge of changes in climatic, oceanographic and ecological conditions in Canadian stock assessments. Fish and Fisheries 23:1332-1346

Plaganyi EE, Haywood MDE, Gorton RJ, Siple MC, Deng RA (2019) Management implications of modelling fisheries recruitment. Fisheries Research 217:169-184

Punt AE, Butterworth DS, de Moor CL, De Oliveira JAA, Haddon M (2014) Management strategy evaluation: best practices. Fish and Fisheries 17: 303-334

Punt AE, Dalton MG, Cheng W, Hermann AJ, Holsman KK, Hurst TP, Ianelli JN, Kearney KA, McGilliard CR, Pilcher DJ, Veron M (2021) Evaluating the impact of climate and demographic variation on future prospects for fish stocks: An application for northern rock sole in Alaska. Deep-Sea Research Part II-Topical Studies in Oceanography 189-190:104951

Ramirez-Monsalve, P., Nielsen, K. N., Ballesteros, M., Kirkfeldt, T. S., Dickey-Collas, M., Delaney, A., Hegland, T. J., Raakjaer, J., Degnbol, P. (2021) Pulling mechanisms and pushing strategies: How to improve Ecosystem Approach Fisheries Management advice within the European Union's Common Fisheries Policy. Fisheries Research 233. doi: 10.1016/j.fishres.2020.105751

Rice J (2008) Can we manage ecosystems in a sustainable way? Journal of Sea Research 60:8-20

Rice JC (2011) Managing fisheries well: delivering the promises of an ecosystem approach. Fish and Fisheries 12:209–231

Rindorf A, Dichmont CM, Thorson J, Charles A, Clausen LW, Degnbol P, Garcia D, Hintzen NT, Kempf A, Levin P, Mace P, Maravelias C, Minto C, Mumford J, Pascoe S, Prellezo R, Punt AE, Reid DG, Rockmann C, Stephenson RL, Thebaud O, Tserpes G, Voss R (2017) Inclusion of ecological, economic, social, and institutional considerations when setting targets and limits for multispecies fisheries. ICES Journal of Marine Science 74:453-463

Shotwell SK, Fissel B, Hanselman DH (2018) Ecosystem-socioeconomic profile of the sablefish stock in Alaska. In: Hanselman DH, Rodgveller CJ, Fenske KH, Shotwell SK, Echave KB, Malecha PW, Lunsford CR (eds) Assessment of sablefish stock in Alaska Stock assessment and fishery evaluation report for the groundfish ressources of the Being Sea Aleutian Islands and Gulf of Alaska. North Pacific Fishery Management Council, Anchorage, AK,

Siple MC, Koehn LE, Johnson KF, Punt AE, Canales TM, Carpi P, de Moor CL, De Oliveira JAA, Gao J, Jacobsen NS, Lam ME, Licandeo R, Lindegren M, Ma SY, Oskarsson GJ, Sanchez-Marono S, Smolinski S, Surma S, Tian YJ, Tommasi D, Gutierrez TM, Trenkel V, Zador SG, Zimmermann F (2021) Considerations for management strategy evaluation for small pelagic fishes. Fish and Fisheries 22:1167-1186

Skern-Mauritzen M, Ottersen G, Handegard NO, Huse G, Dingsor GE, Stenseth NC, Kjesbu OS (2016) Ecosystem processes are rarely included in tactical fisheries management. Fish and Fisheries 17:165-175

Stawitz CC, Haltuch MA, Johnson KF (2019) How does growth misspecification affect management advice derived from an integrated fisheries stock assessment model? Fisheries Research 213:12-21

Stock BC, Miller TJ (2021) The Woods Hole Assessment Model (WHAM): A general state-space assessment framework that incorporates time- and age-varying processes via random effects and links to environmental covariates. Fisheries Research 240:105967

Szuwalski CS, Ianelli JN, Punt AE (2018) Reducing retrospective patterns in stock assessment and impacts on management performance. ICES Journal of Marine Science 75:596-609

Tableau A, Collie JS, Bell RJ, Minto C (2019) Decadal changes in the productivity of New England fish populations. Canadian Journal of Fisheries and Aquatic Sciences 76:1528-1540

Thorpe RB, Le Quesne WJF, Luxford F, Collie JS, Jennings S (2015) Evaluation and management implications of uncertainty in a multispecies size-structured model of population and community responses to fishing. Methods in Ecology and Evolution 6:49-58

Trenkel VM, Daures F, Rochet M-J, Lorance P (2013) Interannual variability of fisheries economic returns and energy ratios is mostly explained by gear type. PLoS ONE 8:e70165

Trenkel VM, Huse G, MacKenzie B, Alvarez P, Arrizabalaga H, Castonguay M, Goñi N, Grégoire F, Hátún H, Jansen T, Jacobsen JA, Lehodey P, Lutcavage M, Mariani P, Melvin G, Neilson JD, Nøttestad L, Óskarsson GJ, Payne M, Richardson D, Senina I, Speirs DC (2014) Comparative ecology of widely-distributed pelagic fish species in the

North Atlantic: implications for modelling climate and fisheries impacts. Progress in Oceanography 129:219-243

Venables WN, Ripley BD (1999) Modern applied statistics with S-PLUS. Springer Verlag, New York

Wilson DC, Hegland TJ (2005) An analysis of some institutional aspects of science in support of the Common Fisheries Policy. Project report for policy and knowledge in fisheries management. CEC 5th Framework Programme No Q5RS–2001-01782 Institute for Fisheries Management Publication No 126

Worsøe Clausen L, Rindorf A, van Deurs M, Dickey-Collas M, Hintzen NT (2018) Shifts in North Sea forage fish productivity and potential fisheries yield. Journal of Applied Ecology 55:1092-1101

Zhang F, Reid KB, Nudds TD (2021) The longer the better? Trade-offs in fisheries stock assessment in dynamic ecosystems. Fish and Fisheries 22:789-797

Table 1. Survey categories and implementation approaches used for accounting for time-varying processes indicating variability in productivity which were covered in the audit of stocks for which ICES provides advice (see figure 1 for categories).

Category	**Implementation approach**
Stock assessment (Ass)	-Variability/ change in length distribution -Variability/ change in weight-at-age -Variability/ change in maturity-at-age -Variability/ change in natural mortality -Variability/ change in sex ratio
Short term forecast (Fcast)	-Environmentally driven recruitment -Truncating recruitment time-series -Recent or trend in weight-at-age -Recent or trend in maturity-at-age -Recent or trend in natural mortality
Management/rebuilding plans (MSE)	-Environmentally driven recruitment -Truncating recruitment time series -Variable weight-at-age (environment or density driven)

	-Recent or trend in maturity-at-age (environment or density driven) -Dynamics in natural mortality
Advice	-Specific productivity information used (e.g. escapement rule)
Distribution and habitats (Dist)	-Influence of population state -Habitat suitability/quality -Within-species stock mixing
Mixed fisheries (Mix)	-Catch and bycatch of target species -Bycatch of non-target species -Consideration of mixed fisheries advice
Climate	-Consideration of changes due to climate variability/change

Table 2. Scoring system used for audit of the inclusion of ecosystem trends and variability in ICES advice process.

Score	**Type**	**Definition**
0	missing/not used	Information is unavailable for stock or not used, e.g. because no MSE carried out
1	considered in background	Productivity is mentioned in the working group report and/or considered in the output as background information
2	qualitatively incorporated	Applicable in two cases: i) when quantitative data/information on productivity change were included in the report, but not used in any analyses/models, or ii) explicit link between the productivity change and assessment parameters or output was established. For example, including numerical data from diet studies on the target species would receive a score of 2, as would discussing a link between sea surface temperature and recruitment predictions.
3	quantitatively incorporated	Productivity-related data was explicitly included in the assessment model through data inputs or estimated parameters.

Table 3. Percent of stocks for which a given type of variable or approach was used to account for ecosystem trends and variability (scores 1 to 3, table 2) by survey category (table 1) for stocks with replies.

Implementation approach	Stock assessment (n=230)	Short term forecast (n=102)	Management/ rebuilding plans (n=30)
Length distribution	47	-	-
Weight-at-age	45	33	62
Maturity-at-age	30	24	45
Natural mortality	20	15	31
Sex ratio	13	-	-
Truncating recruitment time series	-	22	45
Environmentally driven recruitment	-	11	24

Figures

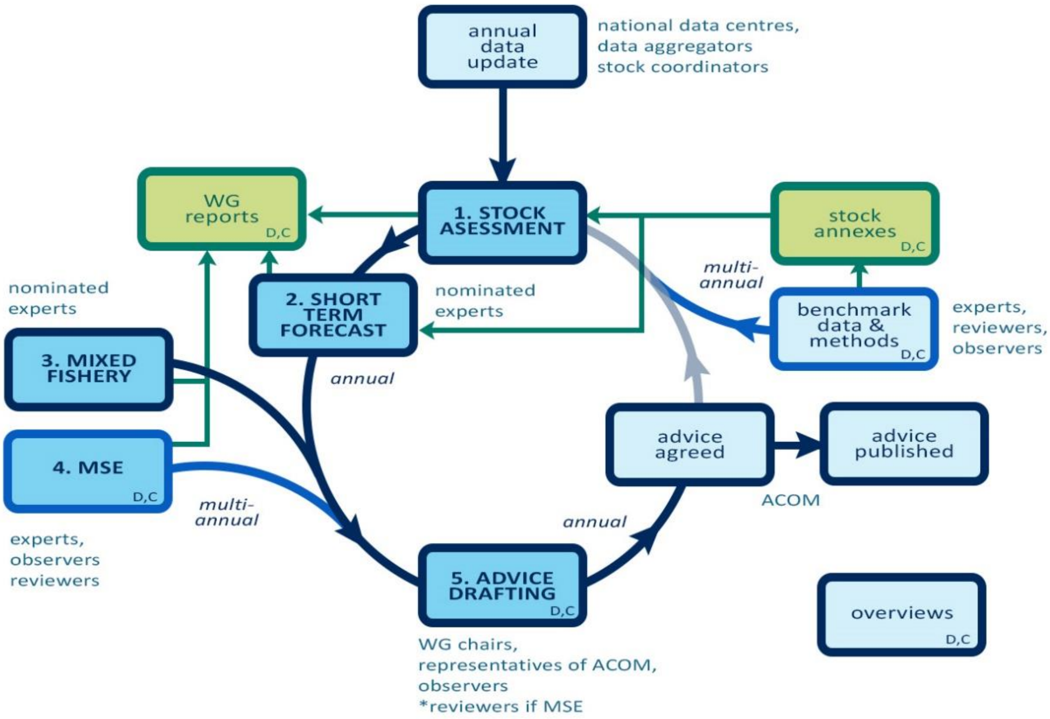


Figure 1. Schematic of the ICES cycle of advice on fishing opportunities. The categories considered in the audit are shown with numbers and bold uppercase letters, additional categories not considered in the audit are shown with lower case letters. The majority of process is annual, denoted by navy blue borders and lines, multi-annual processes denoted by royal blue borders and lines. Green denotes reporting and documentation. Dark blue border annual process; light blue border multi-annual process; blue boxes category in audit; pint boxes category not in audit; green boxes reports and documents. D.C. considerations of distribution/habitat and climate; MSE management strategy evaluation; WG working group; ACOM advisory committee. Participants in process shown in regular lowercase fonts outside

respective categories. Grey line in annual cycle represents flow of ACOM information to working groups.

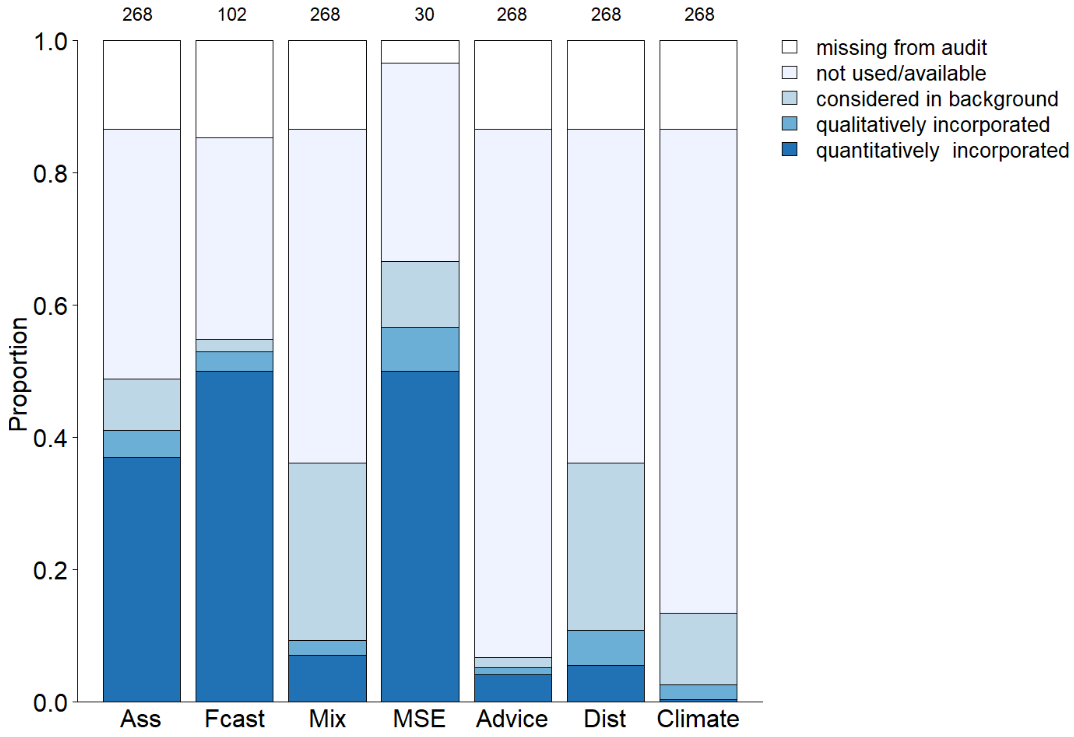
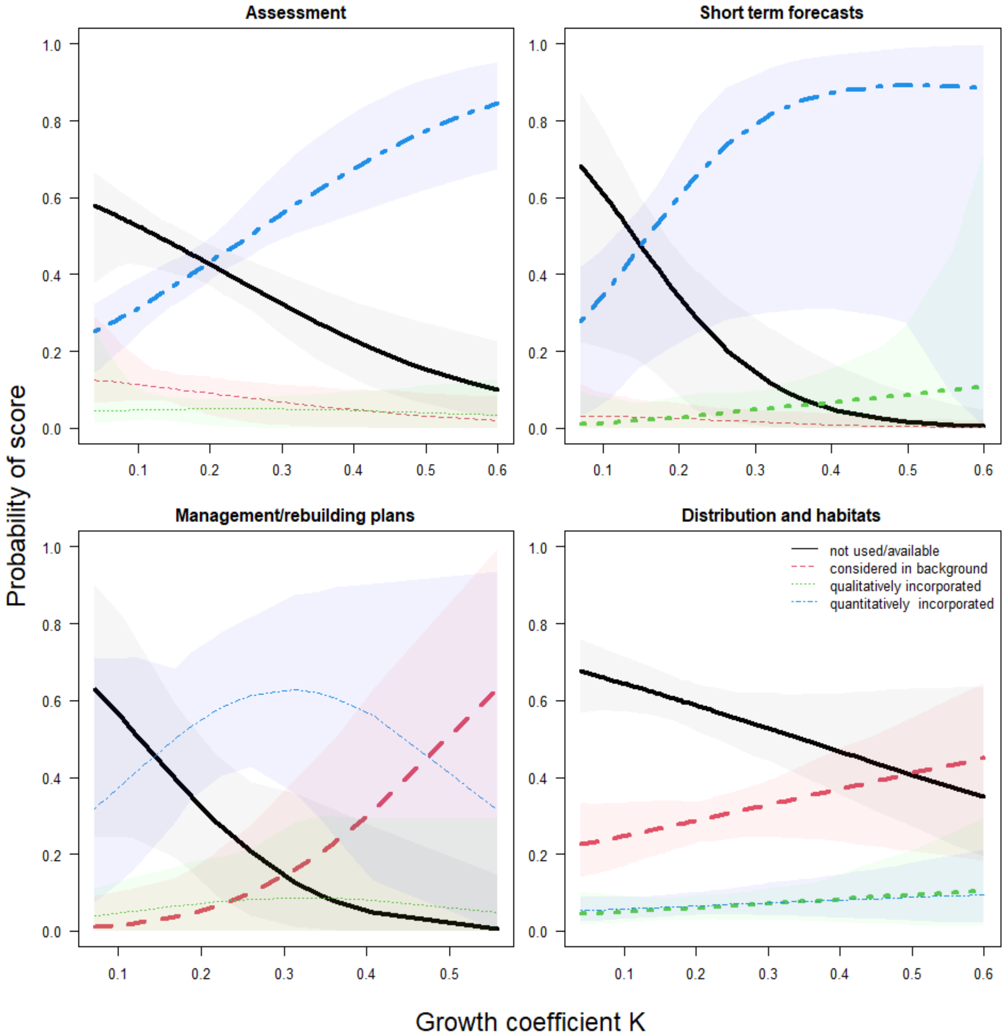


Figure 2. Proportion of stocks for which ecosystem trends and variability are accounted for in different ways in stock assessments (Ass), short term forecasts (Fcast), management plan evaluations (MSE), mixed-fisheries considerations (Mix), advice or more generally in the stock report or advice process related to distributions and habitats (Dist), or climate (see table 1) in ICES. The number of stocks considered for each category is given at the top.

Figure 3 Methods used for accounting for ecosystem trends and variability in a) stock assessments, b) short term forecasts, and c) management/rebuilding plans of fish stocks in ICES. LDist variable length distribution; WaAge variable weight-at-age; MaAge variable maturity-at-age; M dynamics in natural mortality; SR variable sex ratio; ERec.environmentally driven recruitment; TRec. truncating recruitment time-series.



Assessment
Short term forecasts
Management/rebuilding plans
Distribution and habitats
Probability of score
Growth coefficient K
not used/available
considered in background
qualitatively incorporated
quantitatively incorporated
1.0
0.8
0.6
0.4
0.2
0.0
0.1
0.2
0.3
0.4
0.5
0.6

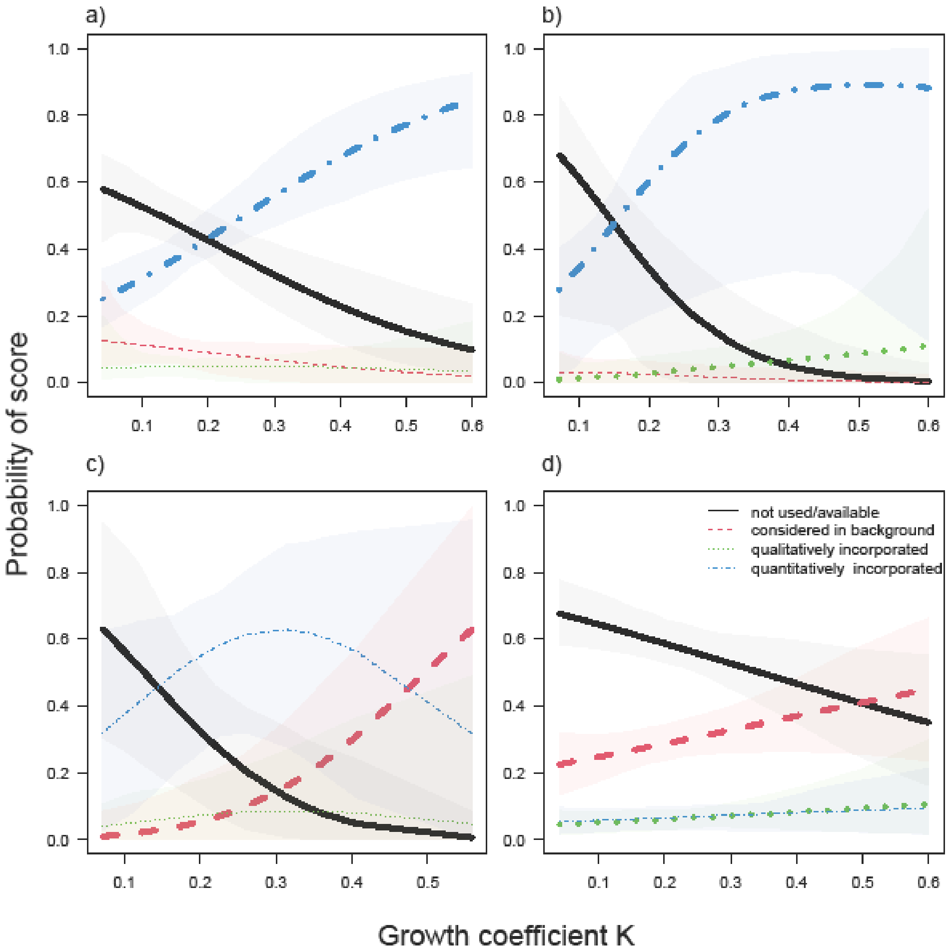
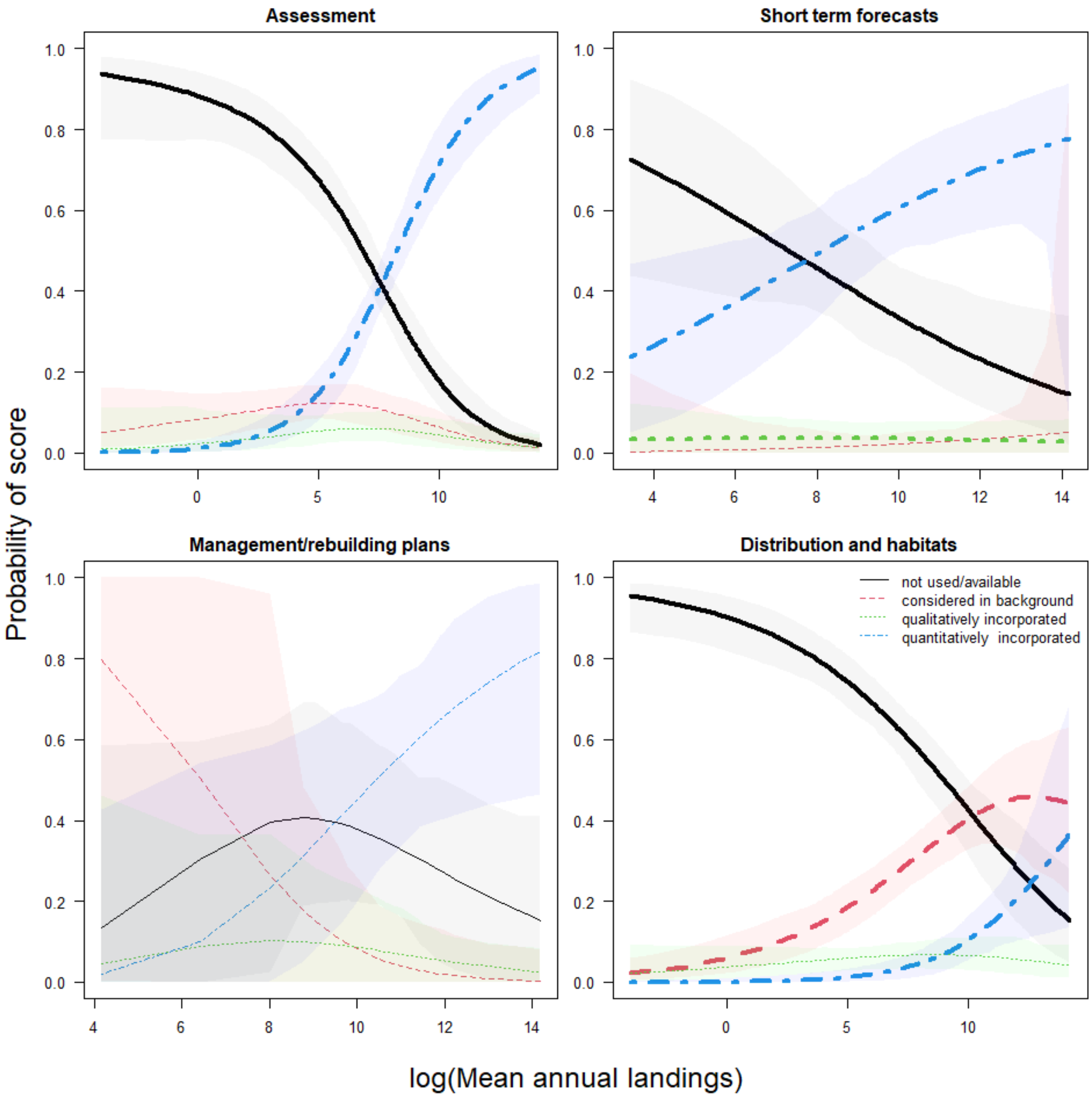


Figure 4. Estimated probabilities for different ways (scores) ecosystem trends and variability were included at the different stages in the ICES advice cycle as a function of species-specific growth parameter K (hypothesis 1). a) Assessment; b) Short term forecasts; c) Management/rebuilding plans; c) Distribution and habitats. Significant relationships are in bold (p-value<0.05).


Assessment
Short term forecasts
Management/rebuilding plans
Distribution and habitats
Probability of score
log(Mean annual landings)
not used/available
considered in background
qualitatively incorporated
quantitatively incorporated

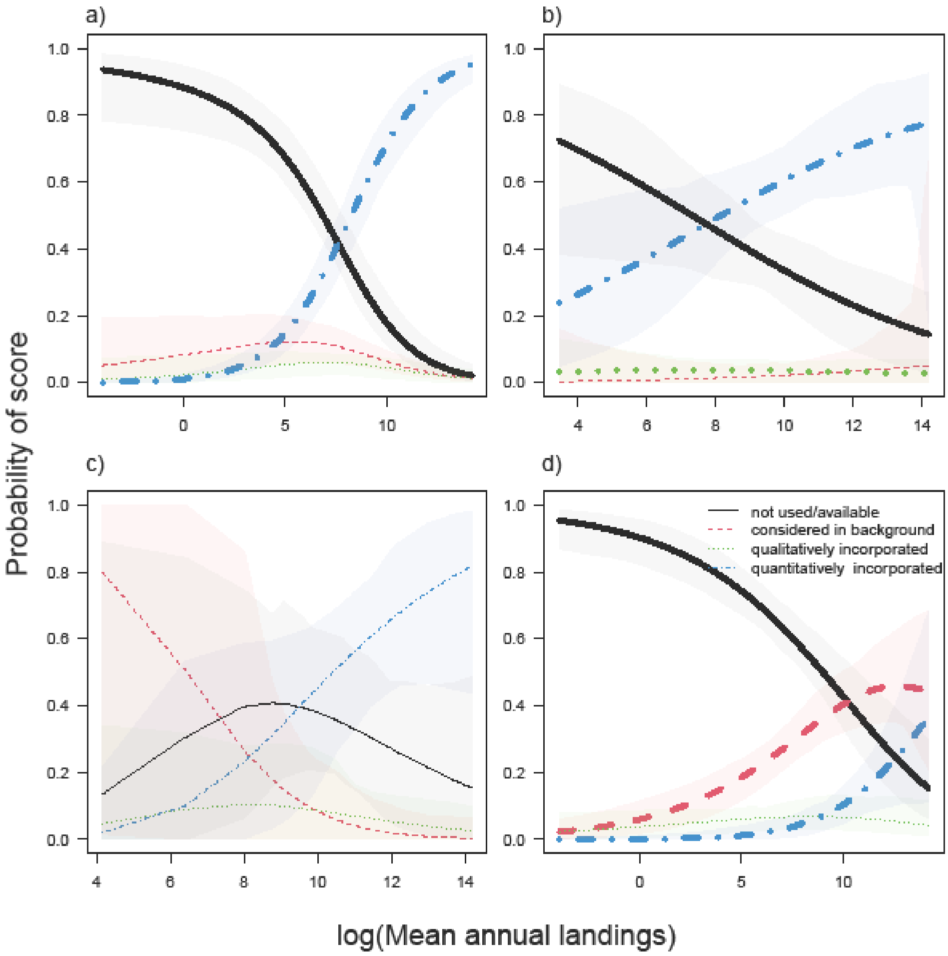


Figure 5. Estimated probabilities for different ways (scores) ecosystem trends and variability were included at the different stages in the ICES advice cycle as a function of stock-specific log-transformed mean recent landings (hypothesis 2). a) Assessment; b) Short term forecasts; c) Management/rebuilding plans; c) Distribution and habitats. Significant relationships are in bold (p-value<0.05).

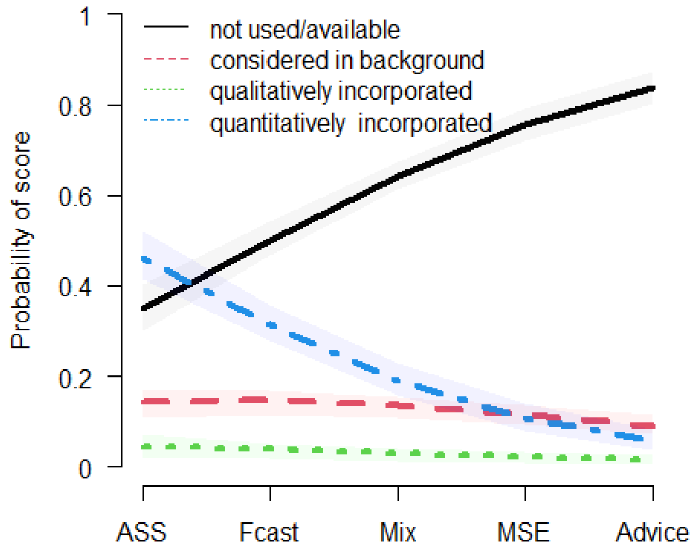


Figure 6. Estimated probabilities for different ways (scores) ecosystem trends and variability were included as a function of the stage in the ICES advice cycle (hypothesis 3). Significant relationships are in bold (p-value<0.05).