ICES Journal of Marine Science, 2023, **80**, 218–234
DOI: 10.1093/icesjms/fsac231
Advance access publication date: 30 December 2022
Original Article

ICES CIEM International Council for the Exploration of the Sea Conseil International pour l'Exploration de la Mer

Testing management scenarios for the North Sea ecosystem using qualitative and quantitative models

Erik Olsen [1,*], Maciej T. Tomczak [2,3], Christopher P. Lynam [4], Andrea Belgrano [5,6] and Andrew Kenny [4]

[1]Institute of Marine Research, PO Box 1870, N-5817 Bergen, Norway
[2]Baltic Sea Centre, Stockholm University, 106 91 Stockholm, Sweden
[3]Department of Aquatic Resources, Institute of Coastal Research, Swedish University of Agricultural Sciences, 750 07 Uppsala, Sweden
[4]Centre for Environment, Fisheries and Aquaculture Science, Lowestoft Laboratory, Pakefield Road, Lowestoft, Suffolk NR33 0HT, UK
[5]Department of Aquatic Resources, Institute of Marine Research, Swedish University of Agricultural Sciences, SE-453 30 Lysekil, Sweden
[6]Swedish Institute for the Marine Environment (SIME), University of Gothenburg, 405 30 Gothenburg, Sweden

**Corresponding author: Tel: +47 93439256;* e-mail: eriko@hi.no.

The complexities of ecosystem-based management require stepwise approaches, ideally involving stakeholders, to scope key processes, pressures, and impact in relation to sustainability and management objectives. Use of qualitative methods like Fuzzy Cognitive Mapping (FCM) with a lower skill and data threshold than traditional quantitative models afford opportunity for even untrained stakeholders to evaluate the present and future status of the marine ecosystems under varying impacts. Here, we present the results applying FCM models for subregions of the North Sea. Models for the southern North Sea, Skagerrak, Kattegat, and the Norwegian Trench were developed with varying level of stakeholder involvement. Future scenarios of increased and decreased fishing, and increased seal biomass in the Kattegat, were compared with similar scenarios run on two quantitative ecosystem model. Correspondence in response by the models to the same scenarios was lowest in the southern North Sea, which had the simplest FCM model, and highest in Norwegian Trench. The results show the potential of combining FCM and quantitative modelling approaches in integrated ecosystem assessments (IEAs) and in future ecosystem-based management advice, but to facilitate such comparisons and allow them to complement and enhance our IEAs, it is important that their components are aligned and comparable.

Keywords: ecosystem model, Fuzzy Cognitive Mapping, North Sea, qualitative modelling, stakeholders.

Introduction

With the international push towards ecosystem-based management as mandated in the Johannesburg convention (Report of the World Summit on Sustainable Development, 2002), fisheries science and management has seen a change from a single-species, single-sector approach to a broader approach, including the entire marine ecosystem and all human activities and pressures on it. Assessing the present and future state of our socio-ecological marine systems is key to any ecosystem-based approach, be it ecosystem-based-fisheries-management (Pikitch *et al*., 2004) or marine spatial planning (Douvere, 2008; Foley *et al*., 2010). National and international research and advisory bodies have therefore pushed the development of integrated ecosystem assessments (IEA, Levin *et al*., 2009; Walther and Möllmann, 2014; Dickey-Collas, 2014), to combine information on complex ecology with the human activities and management objectives (global, regional, and national). Development of IEA has also been one of the measures of broadening the participation in marine science and management, moving out of the ivory towers, including stakeholders and public in the assessments and evaluations of present and future management options (Röckmann *et al*., 2015), as transition towards more transdisciplinarity in science and management.

In the Northeast Atlantic, the International Council for the Exploration of the Seas (ICES) has led the development of IEA by a strategically establishing regional expert groups tasked with advancing the science base for and carrying out regular IEA of the marine ecosystems in the North(east) Atlantic (Dickey-Collas, 2014). At the start, these groups were mostly focused on describing the state of the ecosystems, with less attention given to understanding the causes of change induced by human activities, their pressures, and associated impacts. However, spearheaded by scientists in North America, frameworks for implementing IEAs, including the human (pressures and impacts) dimension, were developed (Levin *et al*., 2009, 2014). The most comprehensive example of applying the IEA cycle proposed by Levin *et al*. (2009) was in the ICES Working Group for the Northwest Atlantic Regional Seas (WGNARS, see ICES, 2016a). WGNARS developed a participatory qualitative IEA assessment approach built through stakeholder consultations starting at a conceptual/qualitative level (DePiper *et al*., 2017), matching the level 1 of ecological risk assessments proposed by Holsman *et al*. (2017).

The qualitative modelling approach spearheaded by WGNARS inspired the ICES Integrated Assessment Working Group for the North Sea (WGINOSE, see ICES, 2020) to improve decision support tools to support ecosystem management and advice for the 14 subregions (Figure 1), which comprise the greater North Sea Ecoregion (Walther and Möllmann, 2014). WGINOSE work on developing qualitative modelling approaches was also inspired by the development

Received: April 9, 2022. **Revised:** December 7, 2022. **Accepted:** December 8, 2022

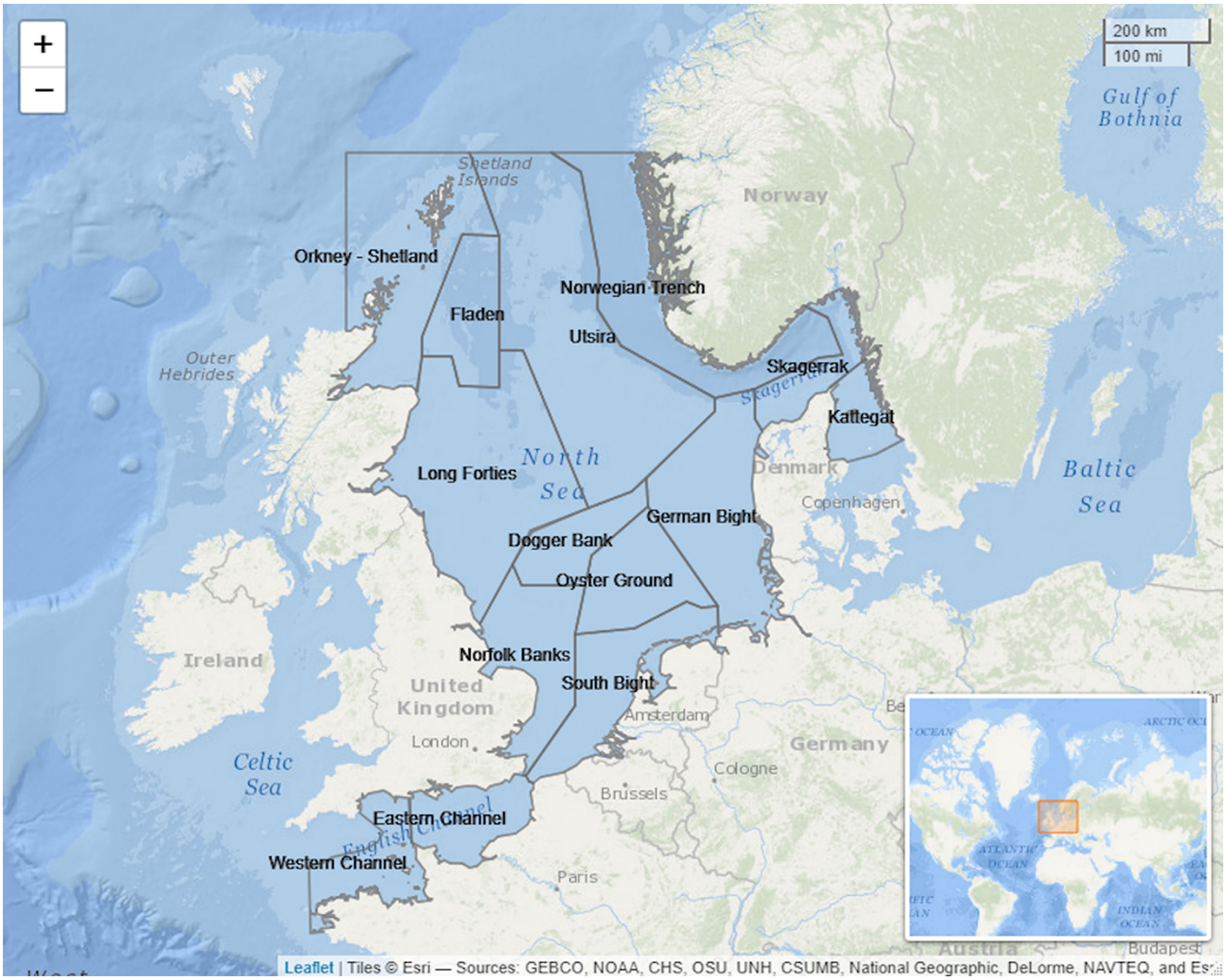

Figure 1. ICES Greater North Sea ecoregion with subregions defined by the ICES Working Group on Integrated Assessment of the North Sea (WGINOSE; ICES, 2020).

of the ICES Greater North Sea Ecosystem Overview (ICES, 2018a), which included a conceptual "wire model" linking ecosystem state with pressures and human activities. The ambition was to expand on this conceptual model to provide decision support tools that allow the evaluation of present and future management strategies of several marine sectors simultaneously. The work aimed to be participatory, allowing easy and direct access and understanding by stakeholders and the public of the key interactions of the North Sea socio-ecological system. This would allow exploring central aspects of what a future North Sea would look like under various management scenarios, identifying the key issues facing managers and stakeholders in the coming years.

A broad, qualitative approach is appropriate in a scoping phase of IEA, followed by more quantitative analyses to evaluate the magnitude and relative impact on different components of the system (Holsman *et al.*, 2017). This stepwise approach depends on the foundation that the methods employed at each step are comparable, at least so that a certain pressure elicits the same directional and relative response at all steps and levels of complexity of the analysis. If responses diverge markedly at different levels, this would indicate either differences in the components and interactions studied (e.g. structure of the methods), or fundamental uncertainties regarding our understanding of the ecosystems. An *a-priori* understanding of the structural differences between methods is necessary to understand how and when results at different levels of analytical complexity can (and should be) compared, and to identify fundamental uncertainties in ecosystem understanding.

Fuzzy Cognitive Mapping (FCM) is one such qualitative modelling technique which is seeing increased use in a wide variety of analyses and assessments of terrestrial and marine ecosystems (Papageorgiou, 2011; Gray *et al.*, 2015; Vasslides and Jensen, 2016; Stier *et al.*, 2017; Game *et al.*, 2018; van der Sluis *et al.*, 2019; Uusitalo *et al.*, 2020). FCMs are signed directed graphs showing the directional interaction between nodes (components of the modelled system), on a "fuzzy" scale from [−1 to 1] (Kosko, 1986; Özesmi and Özesmi, 2004; Jetter and Kok, 2014). Because FCMs are intuitively easy to understand and rapid to develop, they are extensively used in co-creation settings with various stakeholders (Özesmi and Özesmi, 2004; Jetter and Kok, 2014). They have proven useful to understand diverse expert opinions (Hobbs *et al.*, 2002; Stier *et al.*, 2017; Uusitalo *et al.*, 2020), but also have the capability of simulating potential future conditions or future man-

Table 1. Network and structural statistics for the four FCM (mental) models and two "EwE" models included in the present analysis.

Model type	Region	Nodes	Links	Links pr. node	H
FCM	Southern North Sea	22	47	2.14	0.059
	Skagerrak	36	117	3.25	0.030
	Kattegat	63	174	2.76	0.010
	Norwegian Trench	28	68	2.43	0.057
EwE	Kattegat	39	257	6.59	
	North Sea	80	1521	19.01	

H is the "hierarchy index" (Özesmi and Özesmi, 2004), designating the degree of hierarchy in the system from 0 to 1 (0: fully democratic, 1: fully hierarchical).

agement options (Özesmi and Özesmi, 2004; Jetter and Kok, 2014). Thus, FCMs are useful to understand possible futures, their impacts, highlighting areas of agreement and disagreement, thereby facilitating honest and open discussions about what future management strategies should be (Gabriel, 2014; Jetter and Kok, 2014).

FCM scenario modelling was therefore chosen by WGINOSE as a qualitative approaches to improve decision support tools for IEA in the Greater North Sea Ecoregion (ICES, 2020). Any form of scenario modelling, also FCM, needs to assess if the modelled behaviour is plausible (Jetter and Kok, 2014). Since the future is unknown and we therefore lack empirical observations for validation, it was decided to compare qualitative FCM scenarios with similar scenarios run on quantitative and mechanistic end-to-end ecosystem models. This is a novel and important step in the further development of model-based approaches to IEAs in the North Atlantic and globally, which can also serve as a useful starting point for developing and testing Shared Socio-economic Pathways (O'Neill *et al*., 2014; Hamon *et al*., 2021).

Material and methods

Through stakeholder workshops from 2018 to 2020, WGINOSE developed four qualitative FCM models for subregions of the greater North Sea ecoregion: southern North Sea (Southern Bight), Skagerrak, Kattegat, and the Norwegian Trench (see Figure 1) as part of a long-term process to regionalize the IEA analysis for the region (ICES, 2020). The original models and interaction matrices are available online at: https://github.com/erikjsolsen/North-Sea-model-comparison.

Many tools exist for developing FCMs, but WGINOSE choose to use the "Mental Modeler" software (MM), developed by Gray *et al.* (2013) (www.mentalmodeler.org) based on its successful application in the Northwest Atlantic (DePiper *et al*., 2017) and the Grand Banks (Wildermuth *et al*., 2017). For each of the four subregions, FCMs were developed at one-day workshops with stakeholder participation. The nodes and connections were drawn in the online application following direct input and guidance from the workshop participants. The interaction matrix ($n \times n$) of all FCM model components was exported from the application and used in further analysis.

The North Sea ecosystem has been extensively studied and there are several extant ecosystem models of the region. For the quantitative analysis, we chose to use two end-to-end ecosystem models built using the Ecopath with Ecosim (EwE) modelling framework, one for the Kattegat (ICES, 2019) and another for the North Sea (Mackinson *et al*., 2018). Similar scenarios for future human activities were run using both the FCMs and EwE models, and model results were compared based on the responses to individual model components as well as multivariate forcing. This approach allowed a comparison of the level 1 (qualitative) and level 2 (semiquantitative) assessments of the Holsman *et al.* (2017) approach to ecological risk assessment.

Qualitative FCM models

Southern North Sea (Southern Bight—Dutch sector)

The first qualitative FCM model was developed in 2018 with 10 Dutch stakeholders (mainly managers) and 11 ICES scientists at a workshop in Den Haag (Netherlands) (ICES, 2018b). The Dutch stakeholders were allowed to define the model components and structure with limited steering from the facilitators (ICES scientists), resulting in a model structure with 22 nodes and 47 links focusing on management objectives and human activities with less emphasis on the ecological components and socio-economic dimension (see Supplementary Figure S1 and Table 1).

Skagerrak

The FCM model of the Skagerrak was developed by six ICES scientists participating in the WGINOSE meeting in 2018, succeeding the Dutch stakeholder workshop where the model for the southern North Sea was developed (ICES, 2020). After evaluating the development of the southern North Sea model, it was recognized that to allow for intermodel comparison, there was a need in the future to provide the stakeholders with an *a-priori* framework for the structure FCMs, including objectives, pressures, impacts, and ecosystem components in addition to human activities. This would allow exploring the interactions between activities, pressures, and the ecosystem, as well as their relationship to overarching management objectives. A common model template would also include a common ecological structure, which together would allow for a more direct comparison with future subregional models of the North Sea. A template model structure based on the ICES Conceptual model for the Greater North Sea ecoregion (ICES, 2018a) was therefore developed in 2018 by the WGINOSE scientists (Figure 2) to be employed in all future models, first on the FCM for the Skagerrak. The Skagerrak model's 36 nodes included 19 ecological components (species and environmental forcings), 4 impacts stemming from 6 human activities (where fisheries were split into recreational, demersal, and pelagic), 6 management objectives, and 1 management action (Marine Protected Areas), connected through 117 links (see Supplementary Figure S2 and Table 1).

Norwegian Trench

The FCM model for the Norwegian Trench was developed by four Norwegian fisheries managers, four fisheries scientists,

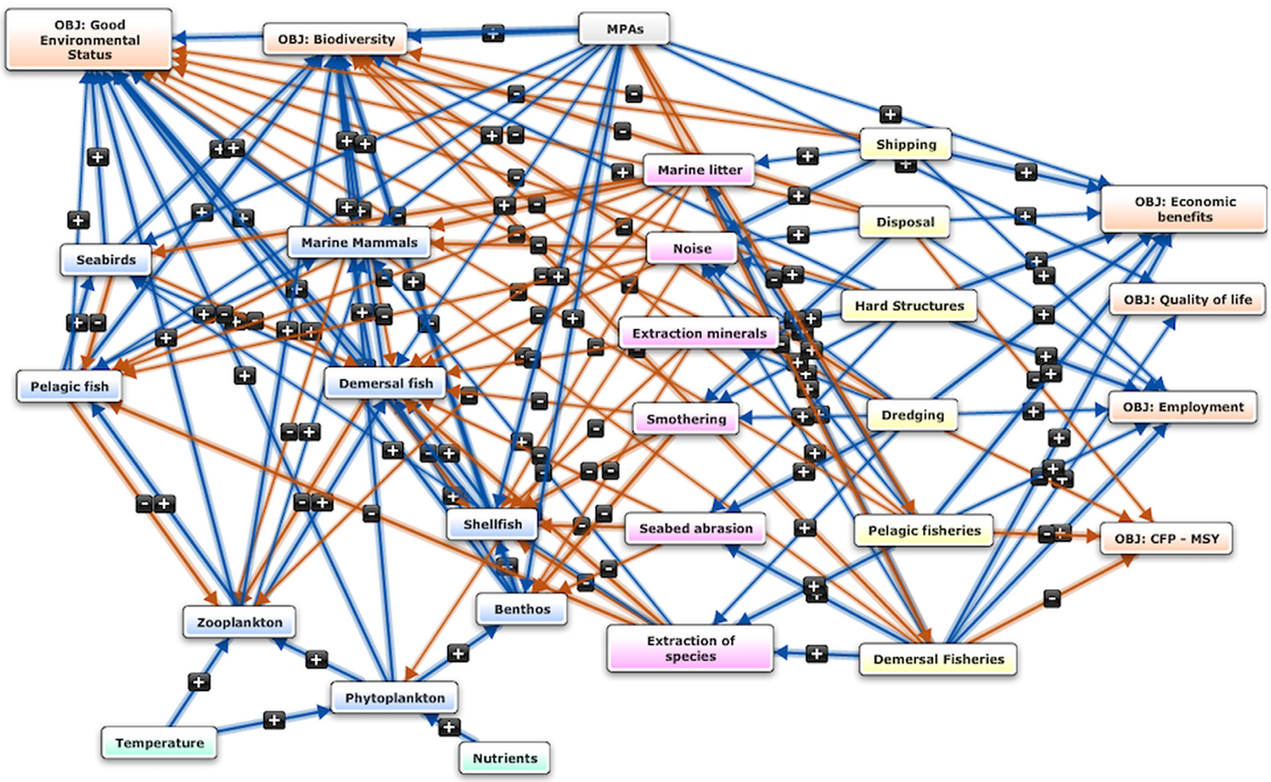

Figure 2. Template qualitative model for future North Sea regional models designed using the MM software (www.mentalmodeler.org). Orange boxes: management objectives; yellow boxes: human activities; pink boxes: pressures; blue boxes: biological species/groups; and green boxes: physical aspects. Blue lines show a positive interaction between model components in the direction of the arrow, red lines show a negative interaction between components.

and one fisher at a workshop in March 2019 (ICES, 2020). Since the Norwegian Trench is a deep-water area separating the coast of Norway from the relatively shallow North Sea basin, it differs markedly from the other subregions of the North Sea. Therefore the template FCM model structure (Figure 2) did not sufficiently fit the Norwegian Trench ecosystem, and an FCM model was hence developed from scratch, while ensuring that the main structure of the template (objectives, activities, and ecosystem state), and sufficient detail to the ecosystem were included to ensure potential for comparison with the other regional FCM model development focused on the Norwegian management objectives, the associated management actions, and how they impacted the human activities, with a clear emphasis on fisheries (see Supplementary Figure S3). The model consisted of 28 nodes with 68 connections where fisheries was split into the main subcategories: industrial, pelagic, large-mesh (trawling), and shrimp trawling. The main species caught by these fisheries were also specified in the model (e.g. hake, herring, mackerel, Norway pout, saithe, and shrimp). The workshop also opted not to use pressures as a category, instead linking the activities directly to the ecosystem components.

Kattegat

The Kattegat mental model was developed at an ICES workshop on Kattegat Ecosystem Modeling Scenarios with Stakeholder Participation (WKKEMSSP) in Gothenburg Sweden in May 2019, with nine scientists, four managers, two NGOs, and one recreational fisher (ICES, 2019). Model development followed a stepwise process by identifying

(1) key management objectives for the region;
(2) key human activities and linking these to the objectives;
(3) pressures stemming from the human activities and linking these to the activities;
(4) management actions relevant to the objectives and human activities and linking these to the activities;
(5) ecosystem components (biological and physical) and linking these to the pressures and objectives.

The workshop used the template model developed by WGINOSE (Figure 2) as a basis for development of the Kattegat model, which was further refined and amended according to the input and discussions among the stakeholders at the workshop. The workshop took the form of a brain-storming session resulting in a very expansive model with 63 components and 174 connections (see Supplementary Figure S4 and Table 1) consisting of 19 ecosystem components, 12 pressures, 12 human activities, 7 management actions, and 13 management objectives. Due to time constraints, the model was not condensed or refined in any manner.

Quantitative models

North Sea EwE model

The EwE model of the North Sea has been calibrated previously and published following quality control in accordance with guidance from ICES (2016b). The model includes 69 functional groups from phytoplankton and benthic groups at the base of the food web up to predatory sharks and seabirds.

In addition to modelling the predatory mortality between groups, the impact of 11 fishing fleets that represent the major international fleets operating in the North Sea was considered, with functional groups and fishing fleets interconnected through 1521 links [Supplementary Figure S5A and Table 1 (Mackinson *et al.*, 2018)].

The toothed whale group is composed of three species: harbour porpoise (*Phocoena phocoena*), white-beaked dolphin (*Lagenorhynchus albirostris*), and Atlantic white-sided dolphin (*Lagenorhynchus acutus*), but this group is dominated by the abundant harbour porpoise. The baleen whale group is based on data for minke whale (*Balaenoptera acutorostrata*). The seals group includes both harbour seal *Phoca vitulina* and grey seal *Halichoerus grypus*. Seabirds are grouped into either "surface-feeding seabirds" [includes species whose diet includes a significant fraction of fish (and other fauna) discarded from fisheries, e.g. gulls (*Larus* spp.), kittiwakes (*Rissa* spp.), terns (*Lari* spp.) and "diving seabirds", e.g. northern gannet (*Morus bassanus*), common guillemot (*Uria aalge*)], or razorbill (*Alca torda*). The "large piscivorous sharks" group generally represents tope (*Galeorhinus galeus*). Juvenile stages of five species only are included in multistanza: cod, haddock, whiting, saithe, and herring.

At the current stage of the model, the North-Sea Ecopath component represents biomass flows among biota groups within the food web and to fisheries in the initial model year, 1991. Ecosim was then calibrated to represent the temporal development of the food-web from 1991 to 2013.

Changes in primary production (PP) and a temperature index [Atlantic Multidecadal Oscillation, (AMO)] were applied as forcing functions in the model calibration period (ICES, 2016a). Change in consumption rates over time of adult cod, whiting, saithe, and starry rays are also driven by an inverse relationship with AMO, while mackerel were fitted with a positive relationship. In contrast, consumption rates of juvenile groups (cod, haddock, whiting, saithe, and herring) are driven by recruitment indices from stock assessment and during the calibration period this leads to a long term decrease in recruitment for each stock. Fishing mortality in the model is driven by time series of fishing mortality directly for assessed stocks. For other nonassessed species, fishing mortality is driven over time through time series of fishing effort combined with catch and effort during the base year (1991).

In the projected RCP4.5 and RCP8.5 scenarios, modelled decadal averages of temperature (both sea surface and bottom) and net PP to 2100 were downloaded for the North Sea from the US National Oceanic and Atmospheric Administration's Climate Change Web portal (https://www.esrl.noaa.gov/psd/ipcc/ocn/accessed 03 April 2020). Based on the Coupled Model Intercomparison Project (CMIP) ensemble average of models ("ENSMN"), simple linear decreases were generated and used as input time-series for Ecosim: RCP4.5 assumed an increase in AMO of 8.5% and a decrease in PP of 5% by 2199 relative to the end year of the calibration period (2013), while the RCP8.5 scenario assumed an increase in AMO of 23.2% and a decrease in PP of 8%. These environmental variables limit the production at the base of the food web and lead to decrease in the consumption rate of adult cod, whiting, saithe, and starry rays and thus an increase in mortality of these groups. Relative consumption rates of mackerel and juvenile cod, herring, saithe, and whiting were projected forward with the low levels reached at the end of the calibration period.

Kattegat EwE model

The EwE model of the Kattegat has been described in the report of the ICES Working Group on Integrated Assessment of the North Sea (ICES, 2020) and calibrated previously following quality control according to Link (2010) and Heymans et al., (2016) The EwE model of the Kattegat has 39 nodes connected through 257 links that comprises 29 biota groups representing the food web of the Kattegat marine ecosystem (Supplementary Figure S5B and Table 1). The groups are phytoplankton, benthic microalgae, perennial macroalgae (*Fucus* sp.), 2 zooplankton groups (gelatinous zooplankton and mesozooplankton), 6 benthic groups (Molluscs, Nephrops, Polychaeta, Echinodermata, and Shrimp/Mysids), 11 fish species including three of which are separated into adults and juveniles (including commercial species like cod or dab, and noncommercial species), offshore fish-feeding birds, seals, and harbour porpoise. The model also includes eight different fishing operations. At the current stage of the model, the Ecopath component represents biomass flows among biota groups within the food web and to fisheries in the initial model year, 1982. Ecosim was then calibrated to represent the temporal development of the food web from 1982 to 2008.

Changes in PP (related to nutrients input), hypoxia, and fishing pressure are currently applied as a forcing function to the model. Environmental forcing for the food-web model, as well as the future projections for climate, nutrient and chlorophyll-a concentrations are based on climate and eutrophication scenarios (Saraiva *et al.*, 2019).

Future scenarios

Strategic scoping has been advocated as a primary use of ecosystem models in IEA and ecosystem-based management (Saraiva *et al.*, 2019) and models/methods of varying complexity have their role at different steps in such scoping processes (Holsman *et al.*, 2017). To compare the performance of the FCM models and EwE models in a strategic scoping setting, the same scenarios were run on both model types for each subregion.

At the FCM modelling workshops, a range of future scenarios for changes in fishing pressure, renewable energy, marine protection, oil, and gas production to name a few, were developed and explored using the built-in scenario tool in "MM", but in the present context, we could only compare scenarios that were possible to run on both the mental models and the EwE models. Fisheries is currently the only human activity included in all the models, and therefore scenarios of changing fishing pressure were the only human impact scenarios that could be compared between the FCM models and EwE models. For the Kattegat EwE model, we also compared scenarios for increasing seal biomass—a key management issue in the region (see Table 2 for full list of scenarios). The North Sea EwE model is not regionalized, so it was the same EwE scenarios that were used in comparison with the three regional mental models (southern North Sea, Skagerrak, and Norwegian Trench). EwE models were run for the period 2020–2100 under current fishing pressure and IPCC Representative Concentration Pathways (RCP) 4.5 climate scenarios (van Vuuren *et al.*, 2011) as a base case. Climate was kept constant using the RCP 4.5 in all EwE scenarios, except the "increase fisheries + 75%" where climate scenario RCP 8.5 was used to reflect worst case scenario.

Table 2. Future scenarios for the southern North Sea, Skagerrak, Norwegian Trench, and Kattegat explored using FCMs (mental models) and EwE models.

	FCM (Mental) models				EwE models	
Scenarios	**Southern North Sea (SNS)**	**Skagerrak (SKA)**	**Norwegian Trench (NOR)**	**Kattegat (KAT)**	**North Sea (*compared with the SNS, SKA, and NOR models*)**	**Kattegat (*compared with the KAT model*)**
Increase in fisheries	*MM*: *increase* Increase all fisheries (pelagic and demersal)	*MM*: *increase* Increase all fisheries (pelagic and demersal)	*MM*: *increase* Increase all fisheries (pelagic and demersal)	*MM*: *increase* Increase all fisheries (pelagic and demersal)	(1) *EwE*: ±25% Increase bottom trawling 25% (2) *EwE*: ±75% Increase bottom trawling 75%	(1) *EwE*: ±25% Increase bottom trawling 25% (2) *EwE*: ±75% Increase bottom trawling 75%
Decrease in fisheries	*MM*: *decrease* Decrease all fisheries (pelagic and demersal)	*MM*: *decrease* Decrease all fisheries (pelagic and demersal)	*MM*: *decrease* Decrease all fisheries (pelagic and demersal)	*MM*: *decrease* Decrease all fisheries (pelagic and demersal)	(1) *EwE*: −100% Decrease bottom trawling 100% (2) *EwE*: −50% Decrease bottom trawling 50%	(1) *EwE*: −100% Decrease bottom trawling 100% (2) *EwE*: −50% Decrease bottom trawling 50%
Increase in marine mammals	n.a.	n.a.	n.a.	*MM*: *increase* Increase Seals and Porpoise groups	n.a.	(1) *EwE*: *seals* 10× Increase seal biomass 10× (2) *EwE*: *seals* 2× Increase seal biomass 2×
Decrease in marine mammals	n.a.	n.a.	n.a.	*MM*: *decrease* Decrease Seals and Porpoise groups	n.a.	n.a.

Comparing the qualitative and quantitative scenarios

For each EwE scenario, the normalized deviation of each model component from the baseline was used as the metric to measure scenario effect. To allow comparison with the MM models, components of the EwE model were aggregated to match the MM model components, with the unweighted average of the normalized deviations being used as the response for the aggregated EwE groups. To extract quantitative measures of the response of the mental models to the various scenarios, the QPRESS press-perturbation method was employed (Melbourne-Thomas *et al*., 2012). QPRESS is a Bayesian framework for evaluating the characteristics and behaviour of alternative model formulations through simulation testing. Simulation testing is based on assigning random values to the non-zero coefficients of the interaction matrix. The stability and behaviour of the model with random coefficients is evaluated based on Eigenvalues and known system properties, and only generated matrices that are stable and meet behavioural criteria [i.e. if the generated model matrix predictions are not consistent with known behaviours, (Melbourne-Thomas *et al*., 2012)] are kept and used to predict the response of the system to perturbations. This procedure was repeated 100 times in the current analysis, from which the proportion of increases or decreases in a component under a given perturbation (scenario) was calculated. The proportional outcomes (−1 to 1) from the QPRESS simulation of the mental models were compared to the normalized deviation of each component from the base case scenarios in both EwE models, both directly and with principal component analysis (PCA). Direct comparison was done at three levels by (1) calculating the average response across all model components for a given scenario and model, (2) comparing individual component responses between the two models types under the same scenario, and (3) evaluating the correspondence in directional response between the two model types under the same scenario, calculated as the average of the individual model responses >0.1 (lower response values were interpreted as no effect in terms of determining direction of the response). PCA allows for evaluating the correlation between loading factors, in this case the scenarios, casting light on how well scenarios from the mental models correspond with the EwE scenarios. Modelled variables with a high degree of correlation (for a given scenario) have low angular differences (0° indicating perfect positive correlation), opposite directions (180° differences) indicate perfect negative correlation when plotted in principal component space (e.g. PC1 vs. PC2), while 90° difference indicates no correlation.

Data analysis

Data analysis was carried out in R (version 4.0.3) using the RStudio interface (1.3.1073). All code used and data files are available on GitHub: https://github.com/erikjsolsen/North-Sea-model-comparison.

Results

Overall, 17 of the 18 FCM vs. EwE model-scenario comparisons showed weak, but similar directional average responses (Supplementary Tables S1–S4), the exception being the EwE +75% increased fishery scenario for Skagerrak (0.052 in average response) compared to −0.049 for the MM increased fisheries and −0.016 for the EwE +25% fisheries scenarios. Stronger positive responses for the "haddock" and "whiting" groups, compared to the MM and EwE +25% scenarios, were drivers for the higher (and positive) average response under this scenario (see Supplementary Table S2). All "decrease fisheries" scenarios showed a stronger absolute average response than the "increase fisheries" scenario for the same region, as expected given that "no fishing" was one of the decrease fishery scenarios.

Southern North Sea

Correspondence in directional response between the mental model and EwE scenarios were low; 33% and 0% of the model components for the decrease and increase in fisheries scenarios, respectively (Figure 3), with the highest hierarchy index (0.059) of all the models (Table 1). For the decrease in fisheries, only the biological components responded in the same direction for both model types and both EwE scenarios, while benthos and catch showed opposite responses. For the "increase in fisheries" scenarios, none of the components showed corresponding directional response between the MM and EwE scenarios (Figure 3 and Supplementary Table S1). Due to the few model components that could be used in the comparison, it was not possible to carry out a meaningful PCA.

The southern North Sea mental model is lacking essential detail associated with the biological components and fishery sector when compared to the EwE model, which results in an overly simplistic response in the MM. By contrast, the EwE model is very detailed and built on best available biological knowledge and fisheries knowledge.

Skagerrak

Compared to the southern North Sea example, there was more coherence between the MM and EwE results for the Skagerrak, with divergence for some groups, perhaps due to how EwE groups are combined. The hierarchy index for the Skagerrak model was 0.030 (Table 1). For the decreased fisheries scenarios, there was a correspondence in the direction of response for 47% and 44% of the components of the MM compared to the two EwE scenarios (−100% and −50% fisheries), while for the increased fisheries scenarios (+25% and +75%), the correspondence in directional response was 31% and 38%, respectively (Figure 4).

Haddock, seabirds, and shellfish show clear opposite responses between the MM and EwE under the decrease in fisheries scenarios, while for the increased fisheries scenarios, herring, pollock, sand eel, shellfish, sprat, and whiting show clear opposite responses (Figure 4 and Supplementary Table S2). Interestingly, sand eel and whiting also show clear opposite responses between the two EwE scenarios, indicating that the differing climate forcing (RCP 4.5 vs. RCP 8.5) may have an impact on the modelled population trends for these two fish species.

There was only a slight correlation between the corresponding mental model scenarios and EwE scenarios as determined by the angle between the different scenarios relative to the origin in PCA loadings plot of the scenarios (Figure 5). The highest degree of correlation was found between the mental model "increase fisheries" and EwE "+25% fishing" scenarios, followed by the mental model "decrease fisheries" and EwE "−50% fishing". The lowest correlation

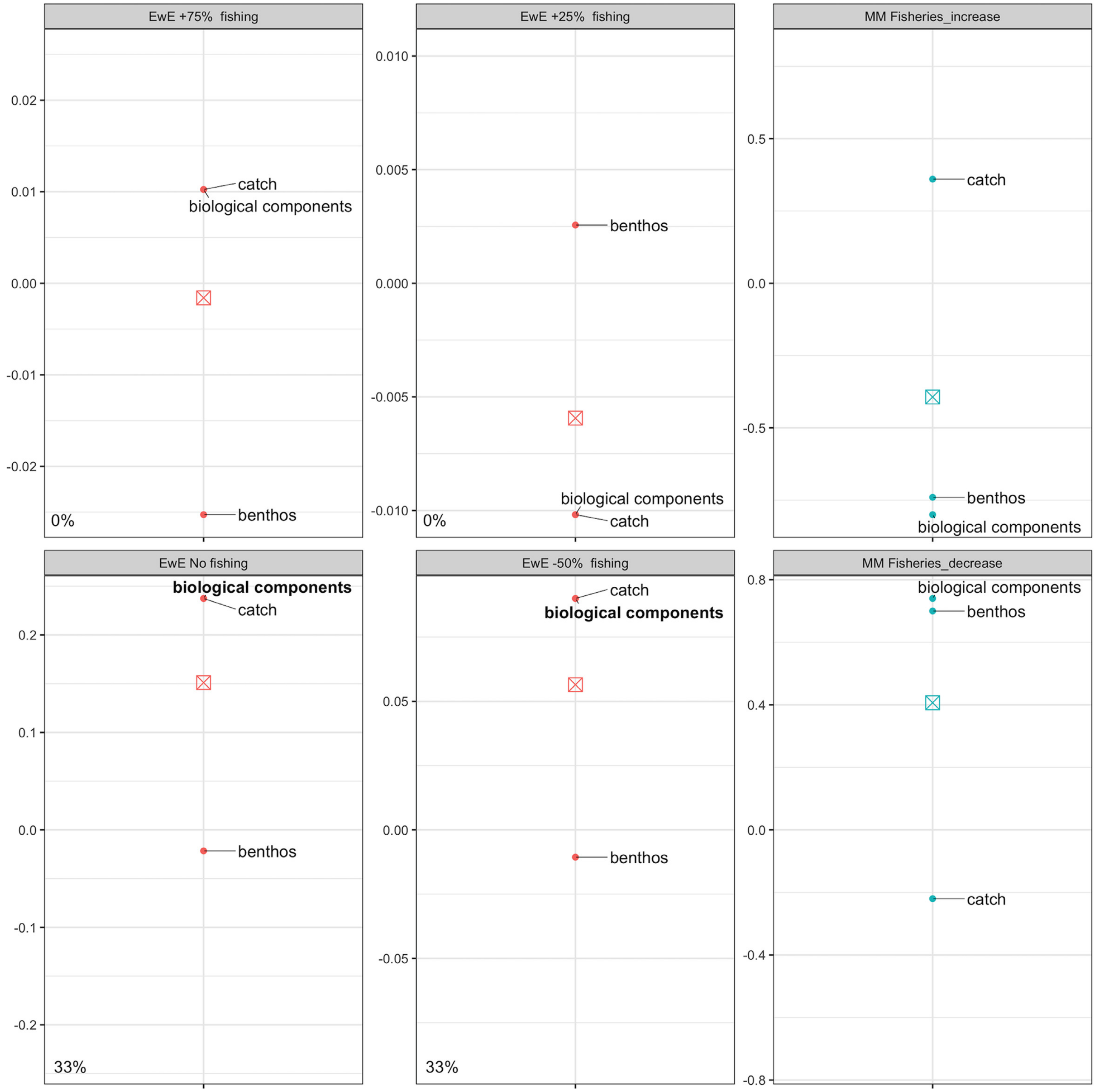

Figure 3. Panel plot of relative responses for the southern North Sea of the model components under each of the increasing and decreasing fisheries scenarios explored using FCMs (MM) and EwE models. The average response across all components in each scenario is shown by the crossed square. The relative percentage of EwE vs. FMC (MM) components having directional correspondence is printed in the bottom left of each panel. Model components of the EwE scenarios that showed a similar directional correspondence as the same component in the corresponding FCM (MM) scenarios are printed in bold.

was observed between the mental model scenarios and the "+75% fishing" and "−50% fishing" EwE scenarios. Interestingly, Figure 5 shows a very low degree of correlation between the EwE +25% and EwE +75% fishing scenarios, possibly due to the different climate forcing used in the two scenarios. For the decreased fishing EwE scenarios, there is almost perfect correlation between the "no fishing" and "−50% fishing" scenarios.

Norwegian Trench

The absolute level of responses of the components to the scenarios were lower than for the Skagerrak model (except one—hake under the EwE "−100% fisheries" scenario). For the Norwegian Trench, the mental model and EwE scenarios showed the same directional response for 58% of the components in the EwE −100% decreased fisheries scenario and 45% for the EwE −50% scenario. For the increased fisheries scenarios, coherence in directional response was lower: 17% for the EwE +25% and 18% for the EwE +75% scenarios (Figure 6). Clear divergences in responses were seen for the *Calanus finmarchicus* and shrimp components for the decreased fisheries scenarios. For the increased fisheries scenarios, divergences in responses were seen for fisheries catch and the biomass of herring, mammals, and seabirds. (Figure 6).

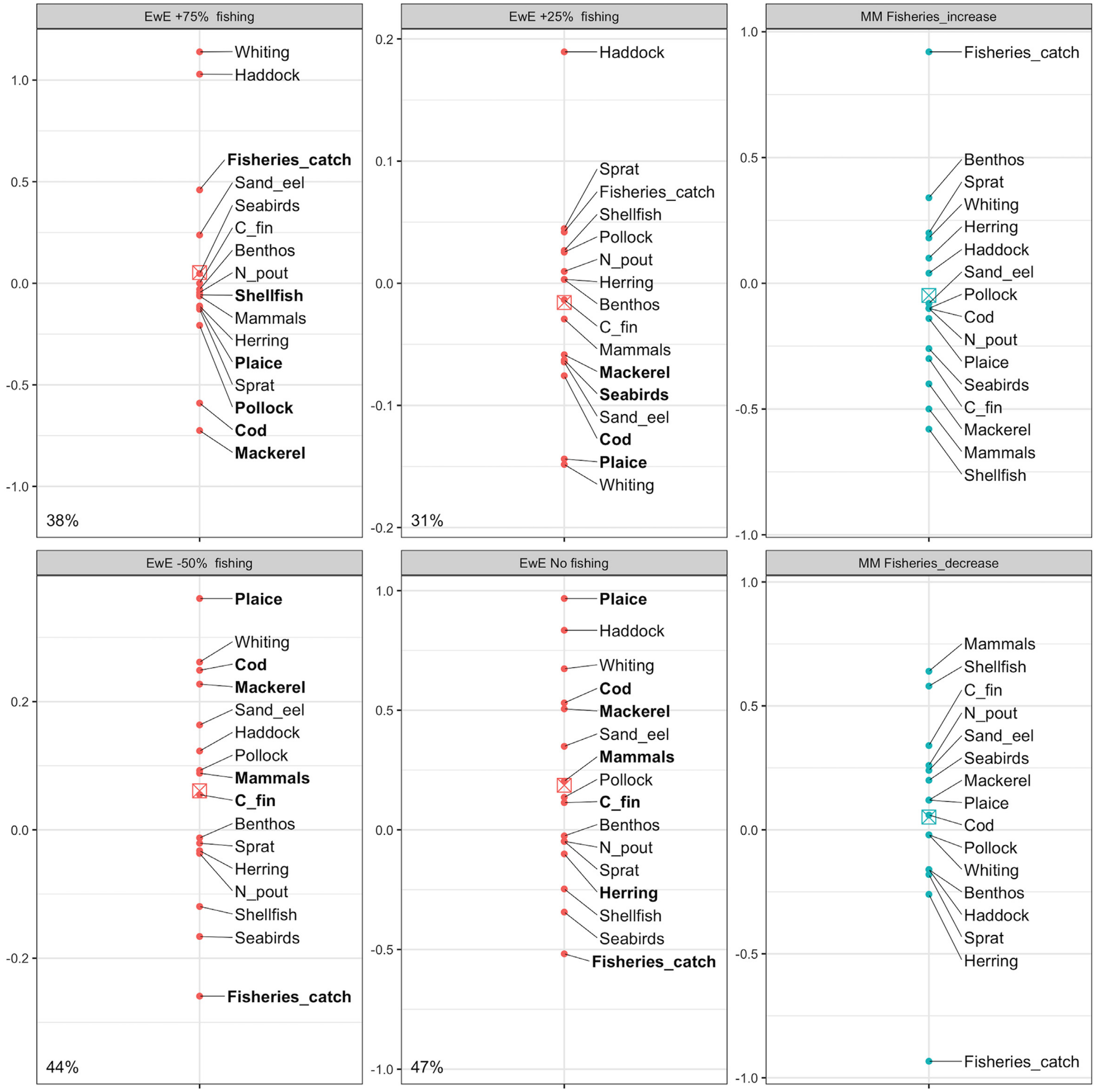

Figure 4. Panel plot of relative responses for the Skagerrak of the model components under each of the increasing and decreasing fisheries scenarios explored using FCMs (MM) and EwE models. The average response across all components in each scenario is shown by the crossed square. The relative percentage of EwE vs. FMC (MM) components having directional correspondence is printed in the bottom left of each panel. Model components of the EwE scenarios that showed a similar directional correspondence as the same component in the corresponding FCM (MM) scenarios are printed in bold.

The Norwegian Trench model had the highest (0.057) hierarchy index of all the models in the study (Table 1).

Benthos shows a clear response under both MM scenarios, but no effect (<10% change) under the EwE scenarios. Calanus responds negatively under the MM decrease in fisheries scenario, but positively under both EwE scenarios for decreased fisheries, while for the increased fishery scenarios neither MM nor EwE models show a response exceeding 10% (Figure 6 and Supplementary Table S3).

Shrimp respond positively under the MM decreased fishery scenario, but negatively under both reduced fisheries scenarios run on the EwE model, but for the increased fishery, both MM and the EwE +75% show corresponding directional response.

Seabirds respond coherently for the decrease in fisheries scenarios, while for increasing fisheries the EwE +25 shows an opposite, negative, response compared to the MM, while under the EwE +75% the seabirds show no response (<10% change). The changes in directional response between two increased fisheries scenarios run on the EwE model are most likely due to differing climatic response from the different climate forcings applied to the two scenarios (RCP 4.5 vs. RCP 8.5).

The PCA analysis shows only a slight degree of correlation between the mental model and matching EwE scenarios (Figure 7). The two mental model scenarios are almost perfectly negatively correlated with each other, while for the EwE,

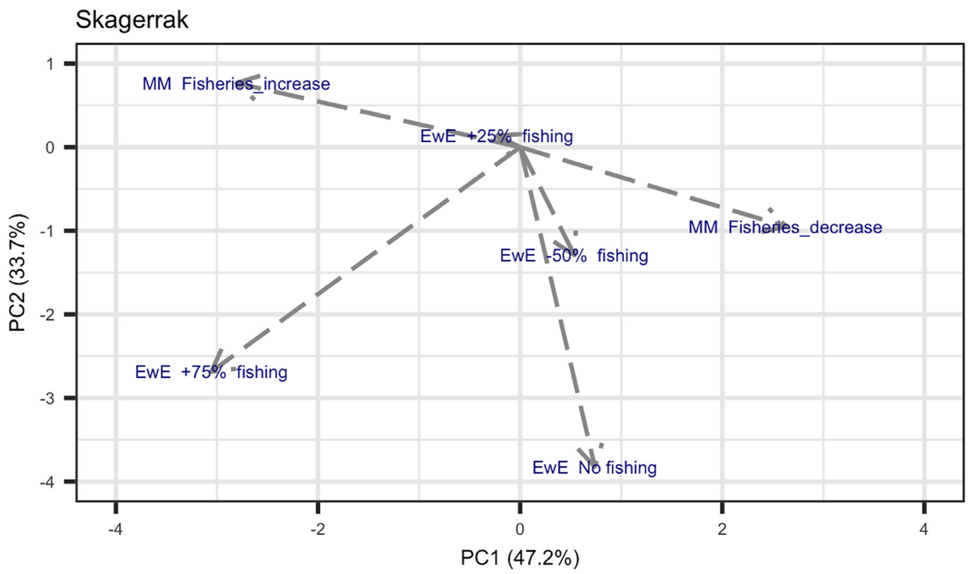

Figure 5. PCA of normalized model results from an EwE model of the North Sea with an MM of the Skagerrak. Management scenario loadings along the first and second principal component axes accounting for about 80% of the variance. Comparable scenarios exploring increased and decreased fishing were run on the two separate models. Four scenarios were run with the EwE model: "no demersal fishing", "−50% decrease in demersal fishing", "+25% increase in demersal fishing", and "+75% increase in demersal fishing", while two fisheries scenarios were run on the MM: "decrease all fisheries" and "increase all fisheries".

both increasing fishing scenarios are perfectly correlated with each other, and so are the two scenarios for decreased fishing. This corresponds to the lower level of correspondence compared to the Skagerrak as seen from Figures 4 and 5.

Kattegat

For the Kattegat, the highest absolute level of responses of all components under all models, except seals under the "seals ×10" scenario, were lower than for the Norwegian Trench or the Skagerrak models. Coherence between the matching mental model and EwE scenarios were at the same level as for the Skagerrak, with the EwE −100% decrease in fisheries scenario showing directional correspondence for 47% of the components, while the EwE −50% had a lower correspondence of 29%. The increased fisheries scenarios showed a lower correspondence of 21% and 31%, respectively, for the EwE +25% and EwE +75% scenario. For the seals scenarios, coherence was also low: 27% coherence for the EwE seals ×10 compared to the MM increased marine mammals scenario, while the EwE seals ×2 scenario only showed the same directional response for 8% of the components (Figure 8). The hierarchy index for the Kattegat model was 0.010, the lowest of all models in the present study (Table 1).

Clear divergence in responses between the MM and EwE models for the decreased fisheries scenarios was observed for the small demersal fish, flatfish, and phytoplankton groups, while for the increased fisheries scenarios, divergence was observed for the small pelagic fish group, and slight divergence for flatfish (Figure 8 and Supplementary Table S4). For the seal scenarios, clear divergences were observed for the large pelagic fish, small pelagic fish, seabirds, and zooplankton. Seabird feed mainly on small pelagics and their diet overlap with seals diet, so the observed decrease in seabird is due to competition, while the increase in zooplankton reflect the top-down trophic cascade effect from seals to pelagic fish to zooplankton.

For the scenarios of increase in marine mammals/seal, clear divergences were observed for the large pelagic fish, small pelagic fish, seabirds, and zooplankton. In the EwE model, the seabirds feed mainly on small pelagic fish (e.g. herring, sprat, and blue whiting), which overlap with the diet of seals, so the decrease in seabirds is due to increasing competition from seals. The increase in zooplankton in the EwE model is due to the top-down trophic cascade from increasing seal population increasing the predation pressure on pelagic fish (small and large), which in turn reduces the predation pressure zooplankton.

The PCA analysis of the Kattegat (Figure 9) showed no correlation between the seal and fisheries scenarios with either model. Mental model fisheries scenarios showed a correlation with the respective EwE scenarios, which in turn were almost perfectly aligned showing almost complete correlation between them. Similarly, the marine mammal increase scenario for the mental model was correlated with the EwE seal biomass ×2 scenario.

Discussion

The aim of this paper has been to compare the responses of qualitative and quantitative ecosystem models under the same future scenarios for changing fishing pressure to evaluate their combined usefulness in IEAs and ecosystem-based management. Our comparison across four subregions of the North Sea have shown that positive correspondence between mental model and EwE scenarios varied between 0%–33% for the southern North Sea, to 58% for the Norwegian Trench, with the Skagerrak and Kattegat falling between these two sets of values. The level of hierarchy of the FCM models seemed not to have any effect on the degree of correspondence between the two model type scenarios. For all regions, the decrease in fisheries scenarios showed the highest degree of correspondence between the qualitative and quantitative model.

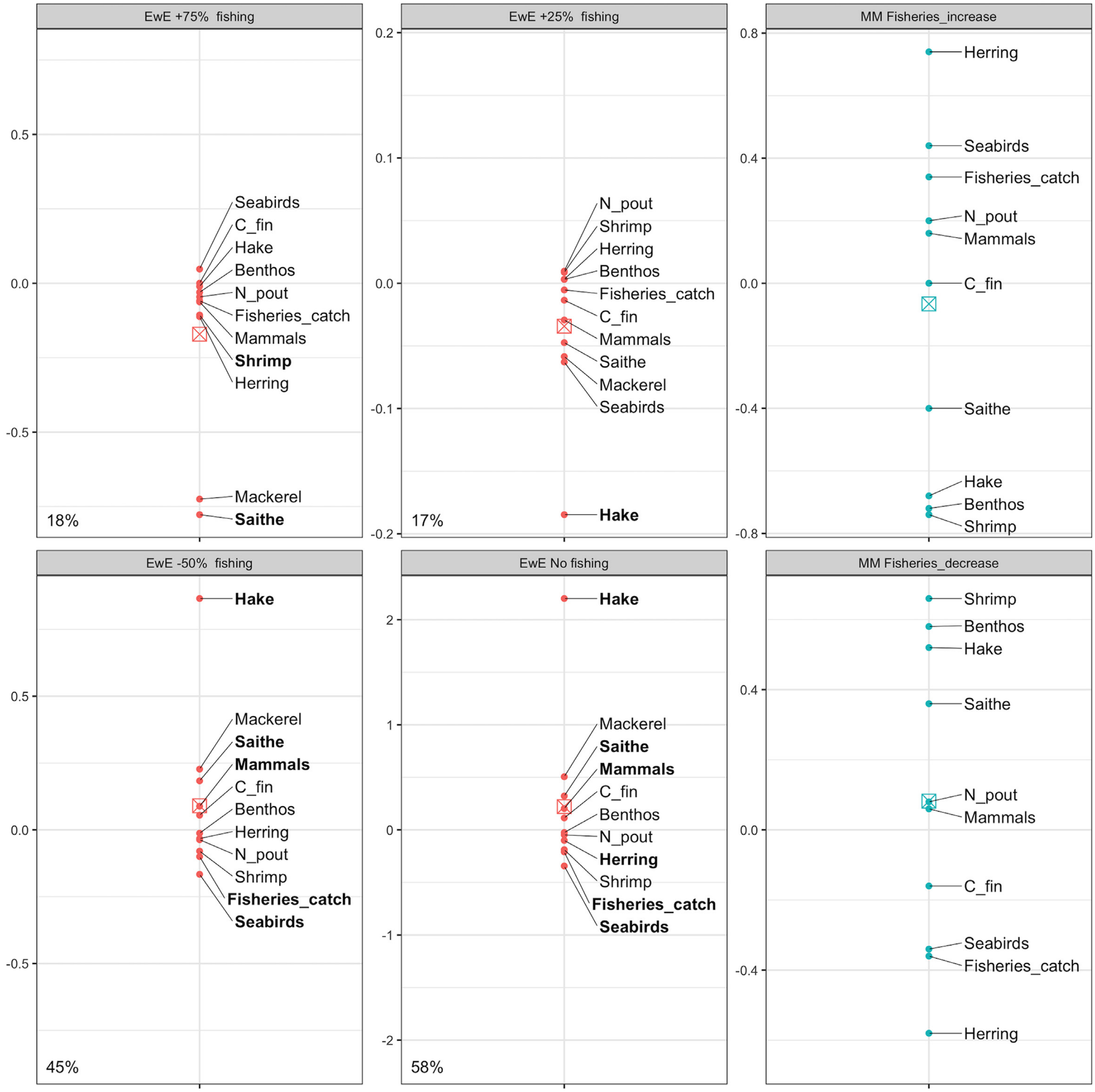

Figure 6. Panel plot of relative responses for the Norwegian Trench of the model components under each of the increasing and decreasing fisheries scenarios explored using FCMs (MM) and EwE models. The average response across all components in each scenario is shown by the crossed square. The relative percentage of EwE vs. FMC (MM) components having directional correspondence is printed in the bottom left of each panel. Model components of the EwE scenarios that showed a similar directional correspondence to the same component in the corresponding FCM (MM) scenarios are printed in bold.

The plots of PCA loadings (Figures 5, 7, and 9) supported the initial analysis of correspondence, showing how the scenarios for the Kattegat were more correlated than those for the Skagerrak and Norwegian Trench. The southern North Sea model was the simplest mental model, with the least developed biological and fisheries systems, while for the other three mental models these parts were developed based on a scientific/management understanding of the ecosystem. The EwE models are built on the best available knowledge of trophic interactions and fisheries in the North Sea and Kattegat. It is therefore not surprising that the mental models with the most advanced biological and fisheries subsystems had a better correspondence with the EwE models than that for the southern North Sea, which was developed with little focus on the biology and fisheries, and by stakeholders less knowledgeable about the ecosystems than those that took part in developing the other models.

Ecosystem EwE models developed for the North Sea and Kattegat have uncertainty coming from assumptions, structure, and parametrization specific to a given modelled ecosystem. Both applied models were checked using the PREBAL approach (Link, 2010; Heymans *et al*., 2016). The PREBAL diagnostics not only ensure confidence and quality in model design, parameterization, and implementation. These diagnos-

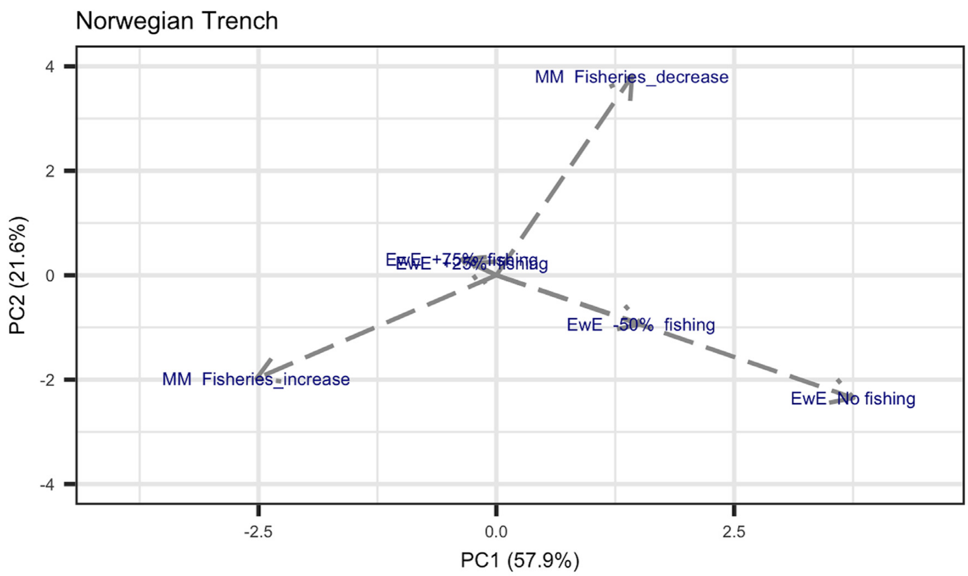

Figure 7. PCA of normalized model results from an EwE of the North Sea with a Mental Model (MM) of the Norwegian Trench. Management scenario loadings along the first and second principal component axes accounting for about 79% of the variance. Comparable scenarios exploring increased and decreased fishing were run on the two separate models. Four scenarios were run with the EwE model: "no demersal fishing", "−50% decrease in demersal fishing", "+25% increase in demersal fishing", and "+75% increase in demersal fishing", while two fisheries scenarios were run on the MM: "decrease all fisheries" and "increase all fisheries".

tics also further elucidate the understanding of key ecosystem processes that might otherwise be overlooked by proceeding to the dynamic phase of food-web modelling without pausing to rigorously evaluate these diagnostics (Link, 2010). The North Sea model was also approved by ICES (2016b) as a "key-run" and uncertainty was investigated by Mackinson *et al.* (2018). As presented by Uusitalo *et al.* (2022) for the central Baltic Sea EwE model (Bauer *et al.*, 2018), a Monte Carlo approach was used to see if model parametrization varied within reasonable limits. Here, we do not use the uncertainty ranges for simplicity of comparison, but this needs to be addressed for further research or application in management.

Nevertheless, the PCA analysis of the models for the Kattegat showed greater correspondence than those for Skagerrak or the Norwegian Trench, with one explanation being that the North Sea model is developed for the entire North Sea, not the Skagerrak or Norwegian Trench, while the Kattegat EwE model was developed specifically for the Kattegat and therefore matches the mental model area precisely. It is also worth noting that the Kattegat mental model was the most complex of the three qualitative models evaluated, indicating that increased complexity of qualitative models is not an impediment to achieve correspondence with quantitative models. Correspondence with the North Sea EwE model was higher for the Skagerrak model compared to the Norwegian Trench, possibly due to the Norwegian Trench being a deep-sea trench system, while the North Sea EwE model was developed with a focus on the shallower parts of the North Sea. Differing timeframes of mental model components (Jetter and Kok, 2014) may add explanation to the observed mismatch between the EwE and mental models. Because while all components and processes in EwE models use the same time-step, the components of the mental models may operate on different timeframes (e.g. annual temperature fluctuations vs. daily fishing activities), thus contributing to discrepancies between the model types we observed. Ideally these issues should have been dealt with through testing, calibration, and refinement of the mental models (Jetter and Kok, 2014), but due to time constraints this was not possible to achieve in the four model development workshops.

Structural uncertainty stemming from the choice of qualitative model types may also explain the discrepancies between the EwE and MM outputs. Wildermuth *et al.* (2017) showed how model complexity decreases the reliability of future scenarios, indicating that the Kattegat model, being the most complex of the models in our analysis, may be the least reliable. To overcome the structural limitations of different model types, Reum *et al.* (2021) recommended that several model types are developed in parallel for the same ecosystem. This would however require more time and resources and lead to stakeholder fatigue, so minimizing structural uncertainty by putting more effort and thought into the selection of qualitative modelling approaches as suggested by Voinov *et al.* (2018) seems as a more feasible approach to future qualitative modelling to support IEAs.

The level of detail in the bio-physical system and fisheries was much higher for the EwE models than for the mental models, with the EwE models having more biological groups, even splitting key species into adults and juveniles. This allowed for greater ecological complexity and better ability to model ecological interactions than the mental models and this may account, in large part, for the divergence we observed in individual model component responses. However, the large number of components in the EwE models can also make them prone to cascading errors, which can lead to an increase in uncertainty as scenarios are projected into the future. Nevertheless, the EwE models used here have been peer-reviewed (ICES, 2016b; Bauer *et al.*, 2018) and utilize the best available knowledge on both species interactions (including diet data), biomass (from stock assessment outputs and scientific surveys), and fishing impacts (landings and discards). Although uncertainty in the EwE models has been explored extensively

Figure 8. Panel plot of relative responses for the Kattegat of the model components under each of the increasing and decreasing fisheries scenarios explored using FCMs (MM) and EwE models. The average response across all components in each scenario is shown by the crossed square. The relative percentage of EwE vs. FMC (MM) components having directional correspondence is printed in the bottom left of each panel. Model components of the EwE scenarios that showed a similar directional correspondence as the same component in the corresponding FCM (MM) scenarios are printed in bold.

(Mackinson *et al*., 2018; Uusitalo *et al*., 2022), further development of ensemble models may provide additional confidence in projections (Spence *et al*., 2021)

Different levels of ecological complexity and complexity of the fishing fleets, especially for the North Sea EwE model compared to the FCMs could account for much of the differences observed in the components showing the largest absolute divergence between the model types (Supplementary Figures S6–S8), e.g. components that were represented by a single group in the FCM, were represented by multiple in the EwEs. Also, the FCMs lacked a detritus group, which is an important recipient node for many of the biological components in the EwE. Lacking this detritus sink may be a key explanation for the differing performance of the FCM vs. the EwE models. This is similar to what Nilsen *et al.* (2022) observed when comparing scenarios run on two ecosystem models of the Barents Sea, where the discrepancy in results between the models were attributed to weaker direct links in the most complex models in addition to the difference in taxonomic resolution, which is very similar to the present comparison of simple MM models with complex EwE models.

The present study has focused on comparing qualitative and quantitative models by evaluating their performance against comparable scenarios. Quantitative ecosystem models like EwE are typically designed with a strong focus on the biogeophysical system and fisheries, with other human activities

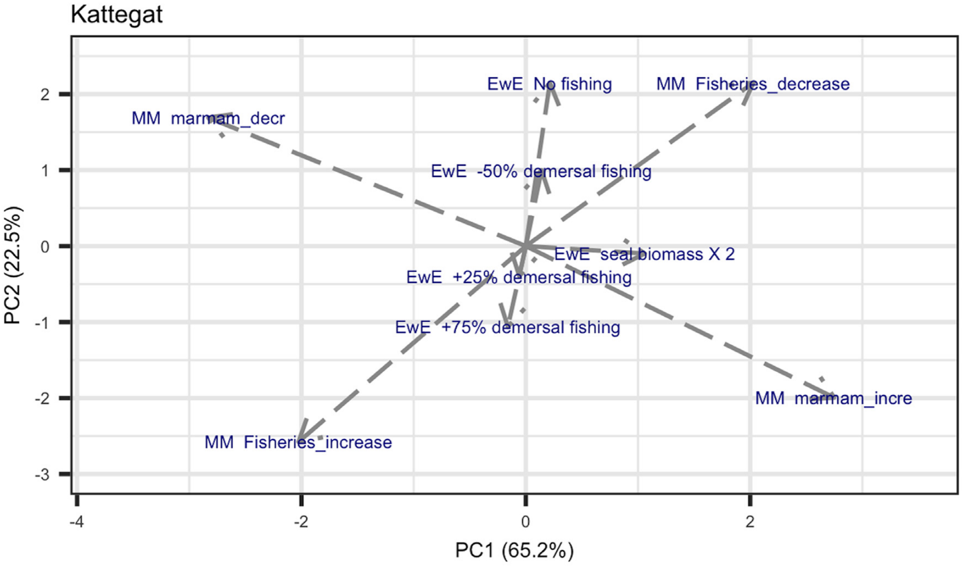

Figure 9. PCA of normalized model results from an EwE model of the Kattegat with an MM of the Kattegat. Management scenario loadings along the first and second principal axes components accounting for about 88% of the variance. Comparable scenarios exploring increased and decreased fishing were run on the two separate models. Five scenarios were run with the EwE model were included in the PCA analysis: "no demersal fishing", "−50% decrease in demersal fishing", "+25% increase in demersal fishing", "+75% increase in demersal fishing", "seal biomass ×2", while four scenarios were run on the MM: "Decrease all fisheries", "Increase all fisheries", "increase marine mammals", and "decrease marine mammals". The "seal biomass ×10" scenario was omitted from the PCA analysis as it completely dominated the principal components.

often lacking (as in the case for the Kattegat and North Sea EwE models). By contrast, the subregional mental models all include several human activities (e.g. shipping, renewable energy, oil, and gas) and as such have the potential to evaluate a wider gamut of human activities, thus being more aligned with the public concern for the human dimension of socio-ecological systems (Hobbs *et al.*, 2002). They can also easily be expanded and revised to add new activities. Therefore, qualitative models tend to have wider utility, are easier to develop and modify, which allows them to be applied to a more varied set of scenarios than quantitative ecosystem models, which must undergo lengthy development and validation to explore new human activities. Thus, the performance of qualitative models vs. quantitative models cannot be fully compared as one has wider and more adaptable capabilities than the other, whilst there are also fundamental differences in how the different modelling approaches can be validated and checked. The present analysis does, however, indicate the importance in an IEA setting to ensure that the parts of the models that are comparable are aligned (such as ensuring that the bio-physical model components represented by both sets of models are the same) for them to complement each other and enhance our understanding of potential future scenarios. Failure to do this may cause diverging results and increase uncertainty around future conditions.

Our four qualitative models were developed through guided group discussions, with a partial model presented as a starting point for Skagerrak, Kattegat, and Norwegian Trench to ensure comparability between them, but other approaches could also have been used. Development of qualitative models by groups can benefit from more structure to avoid overly complex and messy models (e.g. the Kattegat model) and more importantly ensure equal representation of all members of the group in model development (avoiding that the most vocal stakeholders dominate) (Jetter and Kok, 2014). Also, an effective strategy to ensure that critical concepts are covered and ensure comparability between models developed in different meetings is to provide stakeholders with a predetermined list of model components than must or can be included (Jetter and Kok, 2014; Uusitalo *et al.*, 2020). A predetermined list of key components has also been shown to limit the complexity of the models developed (Uusitalo *et al.*, 2020), and the predetermined concepts can also be developed (selected) by the stakeholders themselves in a screening process before building the actual model (Jetter and Kok, 2014). However, a potential, but important, pitfall is to specify objectives in a manner that restricts the input from stakeholders (Jetter and Kok, 2014)

The role of qualitative models in an IEA process therefore lies both in scoping [similar to the stage 1 of ecological risk assessment as defined by Holsman *et al.* (2017)], and in exploring future scenarios especially in situations where present quantitative tools are lacking or suboptimal, especially in processes where stakeholders are involved (Gourguet *et al.*, 2021; DePiper *et al.*, 2017). In this way, qualitative models can serve a purpose as planning tools, although by no means able to offer tactical management predictions of ecosystem state, they do provide a useful starting point for developing or refining quantitative models that can be used for tactical management purposes. Development of qualitative models are, as we have observed, very dependent on the stakeholders understanding of the studied system, and diverse stakeholder perceptions can strongly influence the perceived outcomes of future management scenarios, which can lead to diverging conclusions between stakeholders and scientists if the uncertainty stemming from diverse perceptions is not discussed in dialogue with the stakeholders (Stier *et al.*, 2017), best achieved through the co-creation of knowledge (Bentley *et al.*, 2019). The variable stakeholder involvement in the development of our four FCMs has most likely impacted the design of and output from our models, and more structured approaches in ensuring participation from relevant stakeholders, like those employed by Stier *et al.* (2017) and Uusitalo *et al.* (2020) should be employed in future FCM developments for the North Sea Ecoregion.

In the context of North Sea advice and management, there is clearly a need for both types of models. For example, quantitative EwE models are much more refined and better to explore and quantify realistic responses of the ecosystem and fisheries to perturbation (Bauer *et al.*, 2019; Piroddi *et al.*, 2021; Korpinen *et al.*, 2022; Uusitalo *et al.*, 2022) than mental models, but the mental models' ease and speed of development and almost limitless possibilities in adding any sector or objective gives them a versatility to explore other system dimensions (such as the socio-economic-management dimension) that current quantitative models tend to lack. Linking them in an IEA process while ensuring their comparability in terms of the core bio-physical parameterization at the design stage is important to ensure that FCMs can be used as relevant scoping tools in IEAs, supporting and supplementing more quantitative approaches.

As IEAs move from reporting on the present and future states of the ecosystems to a role in the management and advisory process, e.g. in the ICES Advice package—fishing opportunities together with Fisheries and Ecosystem Overviews (Ramírez-Monsalve *et al.*, 2021), it is essential to *a-priori* agree on what are acceptable levels of correspondence between qualitative and quantitative models. Traditional quantitative model skill assessment methods (Olsen *et al.*, 2016) are not directly applicable to qualitative approaches, and alternative methods should be developed, like multivariate approaches. Recent works has shown the usefulness of including ecosystem models in developing advice (Howell *et al.*, 2021) and supporting decision making process (Korpinen *et al.*, 2022; Uusitalo *et al.*, 2022), and we believe this can be further expanded with the use of qualitative models in a scoping phase to explore the full breadth of linkages between all human activities, the ecosystem, and management objectives, as exemplified for Irish waters by Pedreschi *et al.* (2019).

Through iterations between scientists and stakeholders (Howell *et al.*, 2021), qualitative approaches can be developed to both reflect the priorities of stakeholders whilst at the same time ensuring the underpinning and fundamental ecological processes and functions of the system are sufficiently and robustly described within the model, thereby resulting in a credible overall scientific understanding of the system dynamics.

Together they can specify the details where we have abundant knowledge, but also to help to identify and develop the areas of science where current understanding is lacking—the outcome of which should lead to the development of a comprehensive analytical framework enabling potential future management options to be explored. Competing activities for marine resources (biotic and abiotic) will often require "trade-offs" to be made between activities to achieve sustainable and optimal environmental, social, and economic benefits. Such a framework should result in the implementation of complex management options that can achieve humanities strategic goals, like the UN SDG that seek to balance activities to meet societal needs of achieving improvements in health and education, reducing inequality, and promoting economic growth whilst tackling climate change and working to preserve our oceans.

Supplementary material

Supplementary material is available at *ICESJMS* online.

Conflict of interest statement

The authors declare no conflicts of interest.

Funding

E.O. was funded by the IMR Research and Advisory programme for the North Sea. C.L. and M.T. were funded by the EU Horizon 2020 project FutureMARES (grant agreement No. 869300).

Data availability

The data underlying this article are available in the GitHub repository "North-Sea-model-comparison" at https://github.com/erikjsolsen/North-Sea-model-comparison and can be openly accessed.

Author contribution

E.O. conceived the idea behind the study, but all authors contributed equally to the analysis and writing of the paper.

References

Bauer, B., Horbowy, J., Rahikainen, M., Kulatska, N., Müller-Karulis, B., Tomczak, M. T., and Bartolino, V. 2019. Model uncertainty and simulated multispecies fisheries management advice in the Baltic Sea. PLoS One, 14: e0211320.

Bauer, B., Meier, H. E. M., Casini, M., Hoff, A., Margoński, P., Orio, A., Saraiva, S. *et al.* 2018. Reducing eutrophication increases spatial extent of communities supporting commercial fisheries: a model case study. ICES Journal of Marine Science, 75: 1306–1317.

Bentley, J. W, Hines, D. E., Borrett, S. R., Serpetti, N., Hernandez-Milian, G., Fox, C., Heymans, J. J. *et al.* 2019 Combining scientific and fishers' knowledge to co-create indicators of food web structure and function. ICES Journal of Marine Science, 76: 2218–2234.

DePiper, G. S., Gaichas, S. K., Lucey, S. M., Pinto da Silva, P., Anderson, M. R., Breeze, H., Bundy, A. *et al.* 2017. Operationalizing integrated ecosystem assessments within a multidisciplinary team: lessons learned from a worked example. ICES Journal of Marine Science, 74: 2076–2086.

Dickey-Collas, M. 2014. Why the complex nature of integrated ecosystem assessments requires a flexible and adaptive approach. ICES Journal of Marine Science, 71: 1174–1182.

Douvere, F. 2008. The importance of marine spatial planning in advancing ecosystem-based sea use management. Marine Policy, 32: 762–771.

Foley, M. M., Halpern, B. S., Micheli, F., Armsby, M. H., Caldwell, M. R., Crain, C. M., Prahler, E. *et al.* 2010. Guiding ecological principles for marine spatial planning. Marine Policy, 34: 955–966.

Gabriel, J. 2014. A scientific enquiry into the future. European Journal of Futures Research, 2: 1–9.

Game, E. T., Bremer, L. L., Calvache, A., Moreno, P. H., Vargas, A., Rivera, B., and Rodriguez, L. M. 2018. Fuzzy models to inform social and environmental indicator selection for conservation impact monitoring. Conservation Letters, 11: e12338.

Gourguet, S., Marzloff, M. P., Bacher, C., Boudry, P., Cugier, P., Dambacher, J. M., Desroy, N. *et al.* 2021. Participatory qualitative modeling to assess the sustainability of a coastal socio-ecological system. Frontiers in Ecology and Evolution, 9. https://www.frontier sin.org/article/10.3389/fevo.2021.635857 (last accessed 26 January 2022).

Gray, S. A., Gray, S., Cox, L. J., and Henly-Shepard, S. 2013. Mental modeler: a fuzzy-logic cognitive mapping modeling tool for adaptive environmental management. *In* 2013 46th Hawaii International Conference on System Sciences, pp. 965–973. IEEE.

Gray, S. A., Gray, S., Kok, J.-L., Helfgott, A., O'Dwyer, B., Jordan, R., and Nyaki, A. 2015. Using fuzzy cognitive mapping as a participatory approach to analyze change, preferred states, and perceived resilience of social-ecological systems. Ecology and Society, 20: 11.

Hamon, K. G., Kreiss, C. M., Pinnegar, J. K., Bartelings, H., Batsleer, J., Catalán, I. A., Damalas, D. *et al.* 2021. Future socio-political scenarios for aquatic resources in Europe: an operationalized framework for marine fisheries projections. Frontiers in Marine Science, 8. https://www.frontiersin.org/article/10.3389/fmars.2021.578516 (last accessed 11 March 2022).

Heymans, J. J., Coll, M., Link, J. S., Mackinson, S., Steenbeek, J., Walters, C., and Christensen, V. 2016. Best practice in ecopath with ecosim food-web models for ecosystem-based management. Ecological Modelling, 331: 173–184.

Hobbs, B. F., Ludsin, S. A., Knight, R. L., Ryan, P. A., Biberhofer, J., and Ciborowski, J. J. H. 2002. Fuzzy cognitive mapping as a tool to define management objectives for complex ecosystems. Ecological Applications, 12: 1548–1565.

Holsman, K., Samhouri, J., Cook, G., Hazen, E., Olsen, E., Dillard, M., Kasperski, S. *et al.* 2017. An ecosystem-based approach to marine risk assessment. Ecosystem Health and Sustainability, 3: e01256.

Howell, D., Schueller, A. M., Bentley, J. W., Buchheister, A., Chagaris, D., Cieri, M., Drew, K. *et al.* 2021. Combining ecosystem and single-species modeling to provide ecosystem-based fisheries management advice within current management systems. Frontiers in Marine Science, 7: 1163.

ICES. 2016a. Final Report of the Working Group on the Northwest Atlantic Regional Sea (WGNARS). ICES Document CM 2016/SSGIEA: 03.

ICES. 2016b. Report of the Working Group on Multispecies Assessment Methods (WGSAM). ICES Document CM 2015/SSGEPI: 20. 206pp.

ICES. 2018. Report of the ICES Advisory Committee on Greater north sea ecoregion—Ecosystem overview, 2018. ICES Advice. https://ices-library.figshare.com/articles/_/18633812 (last accessed 13 March 2022).

ICES. 2019. Workshop on Kattegat Ecosystem Modelling Scenarios with Stakeholders Participation (WKKEMSSP). http://www.ices.dk/sites/pub/PublicationReports/Forms/DispForm.aspx?ID=35541 (last accessed 27 August 2021).

ICES. 2020. Working Group on Integrated Assessments of the North Sea (WGINOSE). http://www.ices.dk/sites/pub/PublicationReports/Forms/DispForm.aspx?ID=36887 (last accessed 10 May 2021).

Jetter, A. J., and Kok, K. 2014. Fuzzy Cognitive Maps for futures studies—A methodological assessment of concepts and methods. Futures, 61: 45–57.

Korpinen, S., Uusitalo, L., Nordström, M. C., Dierking, J., Tomczak, M. T., Haldin, J., Opitz, S. *et al.* 2022. Food web assessments in the Baltic Sea: models bridging the gap between indicators and policy needs. Ambio, 51: 1687–1697. https://doi.org/10.1007/s13280-021-01692-x (last accessed 13 March 2022).

Kosko, B. 1986. Fuzzy cognitive maps. International Journal of Man-Machine Studies, 24: 65–75.

Levin, P. S., Fogarty, M. J., Murawski, S. A., and Fluharty, D. 2009. Integrated ecosystem assessments: developing the scientific basis for ecosystem-based management of the ocean. PLoS Biology, 7: e1000014.

Levin, P. S., Kelble, C. R., Shuford, R. L., Ainsworth, C., deReynier, Y., Dunsmore, R., Fogarty, M. J. *et al.* 2014. Guidance for implementation of integrated ecosystem assessments: a US perspective. ICES Journal of Marine Science, 71: 1198–1204.

Link, J. S. 2010. Adding rigor to ecological network models by evaluating a set of pre-balance diagnostics: a plea for PREBAL. Ecological Modelling, 221: 1580–1591.

Mackinson, S., Platts, M., Garcia, C., and Lynam, C. 2018. Evaluating the fishery and ecological consequences of the proposed North Sea multi-annual plan. PLoS One, 13: e0190015.

Melbourne-Thomas, J., Wotherspoon, S., Raymond, B., and Constable, A. 2012. Comprehensive evaluation of model uncertainty in qualitative network analyses. Ecological Monographs, 82: 505–519.

Nilsen, I., Hansen, C., Kaplan, I., Holmes, E., and Langangen, Ø. 2022. Exploring the role of Northeast Atlantic cod in the Barents Sea food web using a multi-model approach. Fish and Fisheries. https://onlinelibrary.wiley.com/doi/abs/10.1111/faf.12671 (last accessed 12 August 2022).

O'Neill, B. C., Kriegler, E., Riahi, K., Ebi, K. L., Hallegatte, S., Carter, T. R., Mathur, R. *et al.* 2014. A new scenario framework for climate change research: the concept of shared socioeconomic pathways. Climatic Change, 122: 387–400.

Olsen, E., Fay, G., Gaichas, S., Gamble, R., Lucey, S., and Link, J. S. 2016. Ecosystem model skill assessment. PLoS One, 11: e0146467.

Özesmi, U., and Özesmi, S. L. 2004. Ecological models based on people's knowledge: a multi-step fuzzy cognitive mapping approach. Ecological Modelling, 176: 43–64.

Papageorgiou, E. I. 2011. Review study on fuzzy cognitive maps and their applications during the last decade. *In* 2011 IEEE International Conference on Fuzzy Systems (FUZZ-IEEE 2011), pp. 828–835. IEEE.

Pedreschi, D., Bouch, P., Moriarty, M., Nixon, E., Knights, A. M., and Reid, D. G. 2019. Integrated ecosystem analysis in Irish waters; providing the context for ecosystem-based fisheries management. Fisheries Research, 209: 218–229.

Pikitch, E. K., Santora, C., Babcock, E. A., Bakun, A., Bonfil, R., Conover, D. O., Dayton, P. *et al.* 2004. Ecosystem-based Fishery Management. Science, 305: 346–347.

Piroddi, C., Akoglu, E., Andonegi, E., Bentley, J. W., Celić, I., Coll, M., Dimarchopoulou, D. *et al.* 2021. Effects of nutrient management scenarios on marine food webs: a Pan-European Assessment in support of the Marine Strategy Framework Directive. Frontiers in Marine Science, 8. https://www.frontiersin.org/articles/10.3389/fmars.2021.596797 (last accessed 16 September 2022).

Ramírez-Monsalve, P., Nielsen, K. N., Ballesteros, M., Kirkfeldt, T. S., Dickey-Collas, M., Delaney, A., Hegland, T. J. *et al.* 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: 105751.

Report of the World Summit on Sustainable Development, Johannesburg, South Africa, 26 August–4 September 2002. 2002. UN. https://digitallibrary.un.org/record/478154 (last accessed 27 August 2021).

Reum, J. C. P., Kelble, C. R., Harvey, C. J., Wildermuth, R. P., Trifonova, N., Lucey, S. M., McDonald, P. S. *et al.* 2021. Network approaches for formalizing conceptual models in ecosystem-based management. ICES Journal of Marine Science, 78: 3674–3686.

Röckmann, C., van Leeuwen, J., Goldsborough, D., Kraan, M., and Piet, G. 2015. The interaction triangle as a tool for understanding stakeholder interactions in marine ecosystem based management. Marine Policy, 52: 155–162.

Saraiva, S., Meier, H. E. M., Andersson, H., Höglund, A., Dieterich, C., Gröger, M., Hordoir, R. *et al.* 2019. Uncertainties in projections of the Baltic Sea ecosystem driven by an ensemble of global climate models. Frontiers in Earth Science, 6. https://www.frontiersin.org/articles/10.3389/feart.2018.00244 (last accessed 16 September 2022).

Spence, M. A., Griffiths, C. A., Waggitt, J. J., Bannister, H. J., Thorpe, R. B., Rossberg, A. G., and Lynam, C. P. 2021. Sustainable fishing can lead to improvements in marine ecosystem status: an ensemble-model forecast of the North Sea ecosystem. Marine Ecology Progress Series, 680: 207–221.

Stier, A. C., Samhouri, J. F., Gray, S., Martone, R. G., Mach, M. E., Halpern, B. S., Kappel, C. V. *et al.* 2017. Integrating expert perceptions into food web conservation and management. Conservation Letters, 10: 67–76.

Uusitalo, L., Blenckner, T., Puntila-Dodd, R., Skyttä, A., Jernberg, S., Voss, R., Müller-Karulis, B. *et al.* 2022. Integrating diverse model results into decision support for good environmental status and blue growth. Science of the Total Environment, 806: 150450.

Uusitalo, L., Jernberg, S., Korn, P., Puntila-Dodd, R., Skyttä, A., and Vikström, S. 2020. Fuzzy cognitive mapping of Baltic Archipelago Sea food webs reveals no cliqued views of the system structure between stakeholder groups. Socio-Environmental Systems Modelling, 2: 16343–16343.

van der Sluis, T., Arts, B., Kok, K., Bogers, M., Busck, A. G., Sepp, K., Loupa-Ramos, I. *et al.* 2019. Drivers of European landscape change: stakeholders' perspectives through fuzzy cognitive mapping. Landscape Research, 44: 458–476.

van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G. C. *et al.* 2011. The representative concentration pathways: an overview. Climatic Change, 109: 5.

Vasslides, J. M., and Jensen, O. P. 2016. Fuzzy cognitive mapping in support of integrated ecosystem assessments: developing a shared conceptual model among stakeholders. Journal of Environmental Management, 166: 348–356.

Voinov, A., Jenni, K., Gray, S., Kolagani, N., Glynn, P. D., Bommel, P., Prell, C. *et al.* 2018. Tools and methods in participatory modeling: selecting the right tool for the job. Environmental Modelling & Software, 109: 232–255.

Walther, Y. M., and Möllmann, C. 2014. Bringing integrated ecosystem assessments to real life: a scientific framework for ICES. ICES Journal of Marine Science, 71: 1183–1186.

Wildermuth, R. P., Fay, G., and Gaichas, S. 2017. Structural uncertainty in qualitative models for ecosystem-based management of Georges Bank. Canadian Journal of Fisheries and Aquatic Sciences. 75: 1635–1643.

Handling Editor: Mary Hunsicker