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Integrated ecological–economic fisheries models—Evaluation, review and challenges for implementation

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Abstract

Marine ecosystems evolve under many interconnected and area-specific pressures. To fulfil society's intensifying and diversifying needs while ensuring ecologically sustainable development, more effective marine spatial planning and broader-scope management of marine resources is necessary. Integrated ecological–economic fisheries models (IEEFMs) of marine systems are needed to evaluate impacts and sustainability of potential management actions and understand, and anticipate ecological, economic and social dynamics at a range of scales from local to national and regional. To make these models most effective, it is important to determine how model characteristics and methods of communicating results influence the model implementation, the nature of the advice that can be provided and the impact on decisions taken by managers. This article presents a global review and comparative evaluation of 35 IEEFMs applied to marine fisheries and marine ecosystem resources to identify the characteristics that determine their usefulness, effectiveness and implementation. The focus is on fully integrated models that allow for feedbacks between ecological and human processes although not all the models reviewed achieve that. Modellers must invest more time to make models user friendly and to participate in management fora where models and model results can be explained and discussed. Such involvement is beneficial to all parties, leading to improvement of models and more effective implementation of advice, but demands substantial resources which must be built into the governance process. It takes time to develop effective processes for using IEEFMs requiring a long-term commitment to integrating multidisciplinary modelling advice into management decision-making.

KEYWORDS

bio-economic models, comparative model evaluation, fisheries management advice, integrated ecological–economic fisheries models, marine spatial planning and cross-sector management, performance criteria and scales and risks, use and acceptance and implementation and communication and flexibility and complexity

1 | INTRODUCTION

There is a growing need for tools to evaluate policies and assess trade-offs in management of marine resources and provision of ecosystem services such as fishing, aquaculture, renewable energy, shipping, conservation and recreation (Cormier, Kannen, Elliott, & Hall, 2015; Degnbol & Wilson, 2008; EU 2014; Langlois, Fréon, Steyer, Delgenés, & Hélias, 2014; White et al., 2012). It is necessary to elaborate and apply common principles and broader, interdisciplinary management evaluation in the use of marine space involving several types of activities and sectors (Ramos et al., 2013; Soma et al., 2013; Stelzenmüller et al., 2013; Sundblad et al., 2014). Policymakers need to know the costs and benefits of conserving ecosystem goods and services to manage them sustainably. Moreover, according to an ecosystem-based approach to management, specific pressures, associated uncertainties and risks need to be taken into account (Douvere, 2008; Ehler & Douvere, 2009; Gilliland & Laffoley, 2008; Hicks et al., 2016; Stelzenmüller et al., 2011).

To meet these needs, there has been increasing development of Integrated Ecological–Economic Fisheries Models (IEEFMs) over the last two decades (Bjørndal, Lane, & Weintraub, 2004; Conrad, 1995; Kaplan, Holland, & Fulton, 2014; Kaplan, Horne, & Levin, 2012; Kell et al., 2007; Knowler, 2002; Mullon et al., 2009; Österblom et al., 2013; Prellezo et al., 2012; Punt et al., 2011). These models incorporate and integrate natural and human processes that have been the focus of various disciplines such as oceanography, fish ecology, fisheries economics, anthropology and sociology (Dichmont, Pascoe, Kompas, Punt, & Deng, 2010; Heal & Schlenker, 2008; Mullon, 2013; Nielsen & Limborg, 2009; Ulrich et al., 2012). Fundamentally, an IEEFM is a mathematical representation of ecological and economic systems which can also integrate social systems in some cases based on linking components, parameters and processes of each dimension (e.g. De Marchi, Funtowicz, Lo Cascio, & Munda, 2000; Österblom, Crona, Folke, Nyström, Troell 2016; Punt et al., 2010; Thébaud et al., 2013).

One of the potential benefits of IEEFMs is that one can develop a better and more comprehensive understanding of the feedback effects between human multi-actor activity, human economic structures and ecosystem dynamics. This understanding may help managers to avoid the well-documented unintended consequences of management actions that might not be predicted by simpler models that do not account for interactions and feedback processes between system components (Beddington, Agnew, & Clark, 2007; Hicks et al., 2016; Hilborn, 2007; Hilborn, 2011; Hilborn et al., 2015; Holling, 2001; Marchal et al., 2016; Ostrom, 2009; Walters 1998; Wilen et al., 2002; Worm et al., 2009). Complex feedbacks and impacts between ecosystems, exploited species and fisheries systems have been investigated and discussed extensively (Branch et al., 2010; Garcia & Cochrane, 2005; Gascuel et al., 2016; Hill et al., 2007; Howarth, Roberts, Thurstan, & Stewart, 2013; Marasco et al., 2007; Murawski et al., 2010; Neubauer, Jensen, Hutchhings, & Baum, 2013; Österblom, Jouffray, Spijkers, 2016; Pauly et al., 2013; Plagányi and Butterworth 2004; Rose et al., 2010). Comprehensive reviews of ecosystem and biological models have been conducted addressing this complexity and feedback processes (e.g. Hyder et al., 2015; Piroddi et al., 2015; Plagányi et al., 2014; Rose et al., 2010; Tedesco et al., 2016). Holistic ("end-to-end") models have been developed during the last decade including management and socio-economic modules to simulate ecosystem complexity from diverse perspectives (Christensen, Steenbeek, & Failler, 2011; Fulton, Smith, Smith, & Johnson, 2014; Fulton et al., 2011; Girardin et al., 2016; Kaplan et al., 2012, 2014) allowing both strategic (long term) and tactical (medium term) management advice on marine resources and decisions according to best practices (FAO 2008; Plagányi 2007). However, increased complexity within each dimension and greater integration of the dimensions, for example including economic dynamics in ecosystem models, may also increase the difficulty of parameterizing the models and understanding and communicating the results (e.g. Stokes et al., 1999; McAllister, Starr, Restrepo, & Kirkwood, 1999; Rochet and Rice 2009, 2010; Butterworth et al., 2010; Kraak, Kelly, Codling, & Rogan, 2010; Fulton et al., 2011, 2014; Christensen et al., 2011). There are always trade-offs involved with moving to these more complex integrated models in management advice. This is especially the case when several sectors and their markets are considered which increases complexity and accordingly limits model implementation (e.g. Hicks et al., 2016; Österblom et al., 2016).

While a variety of fisheries IEEFMs, often referred to as bio-economic models, have been developed in the past, only a small number of reviews comparing their capabilities and implementation in practice have been published. For example, Conrad (1995) and Knowler (2002) review models in which environmental influences are interlinked with economic aspects. A general introduction and overview of bio-economic models can be found already in Seijo, Defeo, and Salas (1998), but applications to specific empirical cases remain limited. Reviews of more restricted types and coverage of models include the following: Bjørndal et al., (2004), which also includes aquaculture; the review conducted by the Scientific, Technical and Economic Committee for Fisheries (STECF) of the European Union (SEC, 2006); and the review of regional economic models for fisheries management in the USA by Seung (2006). Finally, the reviews produced in Prellezo et al., (2012) and Lehuta, Girardin, Mahevas, Travers-Trolet, and Vermard (2016) focused on European operational models. The review by Lehuta et al., (2016) concentrates on methodology and model development on a subset of complex models that focus on European fisheries advice. Other types of models based on network theory such as Mullon et al., (2009) and Mullon (2013) with a global fish meal model have emerged. Individual-based and fleet-based prediction models on fuel consumption and trip planning evaluating the carbon footprint and energy consumption in fisheries have also progressed recently (e.g. Bastardie, Nielsen, Andersen, & Eigaard, 2013; Bastardie, Nielsen, & Miethe, 2014; Bastardie, Nielsen, et al., 2015; Basurko, Gabina, & Uriondo, 2013; Grimm et al., 2010; Sala et al., 2011; Trenkel et al., 2013; Waldo and Paulrud 2016). The latter enables the development of energy efficient approaches for fishing vessels (e.g. Suuronen et al., 2012) and prediction of fuel costs (Daurès, Trenkel, & Guyader, 2013).

We conduct a global comparative review and evaluation of 35 IEEFMs to provide potential users an overview of when and how IEEFMs can be and have been used worldwide and to identify the characteristics that determine their usefulness, effectiveness and implementation in fisheries advice. The review evaluates model design choices such as scope, spatial and temporal dimensions and scales, functions and processes included, level of complexity and realism, the ability to model uncertainty and stochastic process impact, and the type and robustness of advice that can be provided as well as the data and expertise needed to develop and parameterize IEEFMs. Model linking, coupling and level of integration of biological and economic and, to some extent, social components in the models are considered. This article is primarily focused on fully integrated models that allow for feedbacks between ecological and human processes although not all the models reviewed achieve that.

The review covers selected IEEFMs representing a range of approaches and perspectives rather than providing a comprehensive analysis of all existing models worldwide. The review serves to identify some common features and failings of models and hence may guide researchers in selecting existing models and further developing them rather than creating a completely new model. It also highlights modelling challenges and future directions of research especially when it comes to implementation of the models. The review demonstrates that modellers face inevitable trade-offs between complexity and comprehensiveness, flexibility and user-friendliness. Those trade-offs impact model design, performance and model acceptance and also must be considered in determining the best approach to communicate model results. No model design fits all cases and uses, but the review provides insights that may help both developers and users of models to determine the model characteristics that best suit their intended implementation, uses and how to more effectively communicate model results to ensure uptake in management advice and decisions.

The article is organized as follows: initially, the selected IEEFMs are listed with relevant references for their development. Second, the analysis methods and tools used for evaluation of the models are described. The tools are used to describe, categorize and evaluate the different type of models according to a set of specific criteria covering the above issues. This categorization and evaluation is summarized in semi-quantitative spider web plots to compare the focus and capability of the different models and what main directions of development the different models represent. The results of this meta-analysis are then discussed with a focus on use and characteristics that contribute to effective implementation. Needs for further research are identified with emphasis on specific needs for further model implementation. The specific objectives of the study are to

-Provide a set of tools and criteria to make a comparative evaluation of IEEFMs;

-Evaluate use and implementation of different types of IEEFMs through selected examples from around the world;

-Elucidate limitations and progress of IEEFM implementation and the governance process including necessary stakeholder involvement;

-Provide potential users with an overview and framework that can be used to guide in selection of the most appropriate models according to their specific needs, purpose and questions to be answered, that is providing guidelines for good practice in selection, use and communication of the models according to requirements and trade-offs.

2 | MATERIALS AND METHODS

2.1 | Surveyed models

A subset of models has been selected to provide a global perspective for the review. These models represent a wide range of different types of current and emerging IEEFMs. The 35 IEEFMs evaluated are listed in Table 1 with name and abbreviation and the model characteristics detailed in the annexes (Supplementary Material Tables S1, S2 and S3). A geographical overview of the main implementation of the different models is given in Figure 1. The models and their development are published in a comprehensive scientific literature given in Table 2.

2.2 | Meta-analysis of bio-economic models

We use three model meta-analysis tools to compare the IEEFMs on a global scale according to model type, purpose, coverage, dimensions, scales, capacity, uses and level of implementation and to evaluate trade-offs associated with complexity and flexibility. Those tools consist of a detailed Model Characteristics and Performance Evaluation Matrix (Table S1) completed by a developer of each model, a Model Categorization and Descriptors Summary Table (Table S2) also completed by a developer of each model, and a Model Use and Trade-Off Summary Table (Table S3) that compiles information about all the models. The tools and their structure as well as the details of the classification are given in the Supplementary Material Tables S1, S2 and S3, respectively. Furthermore, the results and the fourth tool of the comparative evaluation and meta-analysis are given in summary plots of the tabulations in the results section (Figures 2–7). This fourth tool is in the form of spider web plots with frequency classification of the different types of models with respect to their properties, characteristics, uses and trade-offs.

In drawing conclusions about the effectiveness of models and trade-offs faced by modellers, we also relied on discussions at workshops, working groups and special sessions organized at three scientific conferences over four years in which the meta-analysis was evaluated, several of these models were presented, and where general modelling issues were discussed by panels. Since 2011, yearly meetings were convened focusing on evaluating and comparing IEEFMs in the ICES WGIMM (International Council of Exploration of the Sea Working Group on Integrated Management Modelling, www.ices.dk 01Apr2017; e.g. ICES 2015a). The first two conference special sessions were special sessions of the International Institute for Fisheries Economics and Trade (IIFET) held in Dar es Salaam, Tanzania and Brisbane, Australia, in 2012 and 2014, respectively (Nielsen, Schmidt, et al., 2014; Thébaud et al., 2013; Thunberg, Holland, Nielsen, & Schmidt, 2013). The last was a theme session held at the ICES Annual Science Conference in Copenhagen, Denmark, in 2015 (ICES 2015b;

TABLE 1 List of tabulated models and model abbreviations used in the evaluation and for reporting results

No.	Model name	Model abbreviation
1	Crab Allowable Biological Catch Model (CRAB ABC)	CRAB ABC[a]
2	Crab Ocean Acidification Model (CRAB ACID)	
3	Multispecies Stock Production Model	MSPM
4	Ecological Modeling of Multiannual Quota (MAQ)	MAQ-ADJ[b]
5	Ecological Modeling of Multiannual Quota with Adjustment Restriction (MAD-ADJ)	
6	Economic Interpretation of ICES Advisory Committee for Fisheries Management	EIAA
7	Bio-Economic Model of European Fleets (extended EIAA)	BEMEF
8	Integrated model for Australian Torres Strait Tropical Rock Lobster	IMATSTRL
9	Bio-Economic Module Connecting Ecology and Economy	ECOb
10	Stochastic Age-Structure Optimization Model + ITQ Wealth Model	STOCH HCR
11	Individual Vessel-Based Spatial Planning and Effort Displacement	DISPLACE
12	Integration of Spatial Information for Simulation of Fisheries	ISIS-FISH
13	Baltic Coupled Fisheries Library in R and Stochastic Multi-species Model	BALTIC FLR-SMS
14	Impact Assessment Model for Fisheries Management	IAM
15	Spatial Integrated bio-economic Model for Fisheries (Wageningen University, NL)	SIMFISH
16	FISHRENT IFRO University of Copenhagen (DK)	FISHRENT[c]
17	FISHRENT TI Thunen Institute (D)	
18	Swedish Resource Rent Model for the Commercial Fisheries	SRRMCF
19	New England Coupled Lobster Model	NECLH
20	20 Baltic Sea Ecological-Economic Optimization Model	B SEA ECON-ECOL
21	Effects of Line Fishing Simulator	ELFSIM
22	Australia Northern Prawn Fishery Tiger Prawns Bio-economic Model	NPFTPBEM
23	Simplified Bio-Economic Model for the Australian Northern Prawn Fishery	NPF BIOECON
24	Mediterranean Fisheries Simulation Tool	MEFISTO
25	Bio-economic Impact Assessment using Fisheries Library in R	FLBEIA
26	Fleets and Fisheries Forecast Model Fcube	FCUBE
27	Coupled Georges bank Food Web and Computable General Equilibrium Model	GBFWCGE
28	Baltic Sea Atlantis Model	B SEA ATL
29	California Current Atlantis Model	CA CURRENT ATL
30	Southeast Australia Atlantis Model	SE AUS ATL
31	Size-spectrum bio-climate envelope model & input/output tables	SS-DBEM-IOT
32	Generic Ecosystem Model	GEM
33	Peruvian Ecopath with Ecosim Foodweb Model	PERU EwE
34	Baltic Sea Ecopath with Ecosim Foodweb Model	B SEA EwE
35	North Sea Ecopath with Ecosim and Ecospace	N SEA EwE

(Continues)

TABLE 1 (Continued)

[a]Crab Ocean Acidification (CRAB ACID) is based on the Crab ABC model so results are combined for reporting.
[b]MAQ-ADJ is based on MAQ with an added restriction on quota adjustments so results are reported only for MAQ-ADJ.
[c]FISHRENT TI and IFRO have nearly identical model characteristics and are combined for purposes of reporting.

Nielsen, Thunberg, Schmidt, Holland et al., 2015; Nielsen, Schmidt, Thunberg, Holland 2015) in which the meta-analysis of the models was presented, evaluated and discussed.

The models evaluated cover a broad range of IEEFMs covering aspects of commercial marine fisheries and associated fish stocks and ecosystems. A very broad group of model developers of the different types of integrated ecological–economic marine models were contacted through the ICES WGIMM Working Groups and IIFET Special Sessions to complete this work. All model developers filling in the meta-analysis tools were directly involved in the review. Many of the modellers also attended one or more of the workshops, working groups or conference sessions in which the models and the meta-analysis were discussed. In addition to the actual meta-analysis, we attempt to convey some of the insights gained from the evaluations and discussions at the working group meetings and conference theme sessions to help us draw some synthetic conclusions from the meta-analysis that are not readily apparent just from comparing model characteristics.

2.3 | Model Characteristics and Performance Evaluation Matrices

The Model Characteristics and Performance Evaluation Matrices given in SM Table S1 compile collective experience with and collective consensus on the models as given by the model developers including feedback to the developers from users during the model development and model implementation processes. A full compilation of Model Evaluation Matrices for all models evaluated are given in

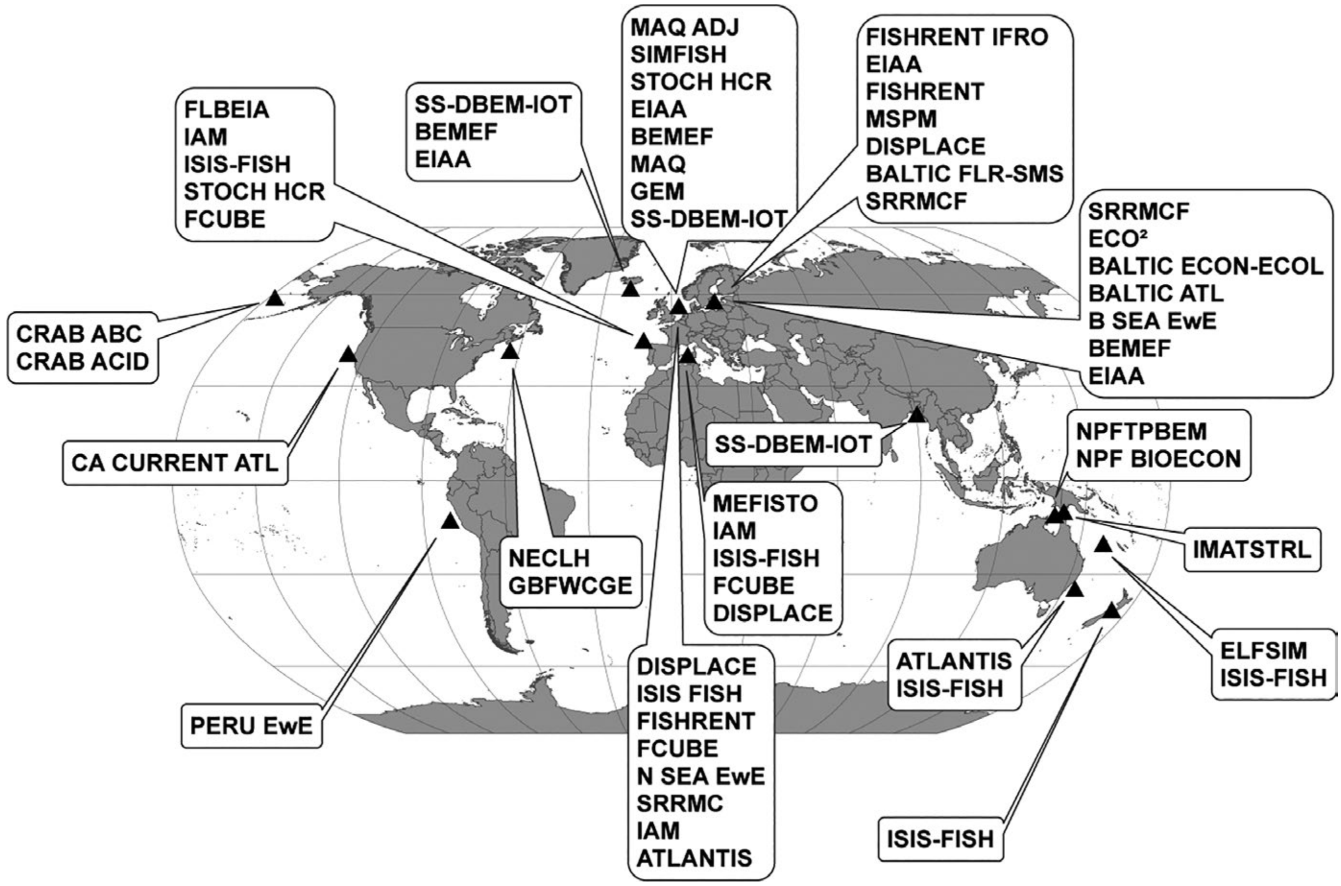

FIGURE 1 Overview of main model applications and implementation

the Supplementary Material Table S1 including the explanations of the categories herein. The Model Evaluation Matrix summarizes the following model characteristics: (i) management questions the model addressed or can address; (ii) corresponding advice (biological and economic) the model provides; (iii) institutional set-up and platforms for the model including needed partners; (iv) type of model including model linking, coupling and level of integration (linked to type of model); (v) model dimensions and model structure; (vi) usefulness of the model; (vii) focus and trade-offs (linked to usefulness above); (viii) data requirements; (ix) status of the development, application, implementation and use of the model in case studies; (x) dissemination of the model including model platform, programming language, accessibility; and (xi) format of output. For each of the above bullets, the answers could be given according to a scaling of the degree or level of the models, that is low, medium, high.

2.4 | Model Categorization and Descriptors Summary Table

Each of the above bullets is used as an axis (row or column) in a multidimensional diagram—the Model Categorization and Descriptors Summary Table shown in SM Table S2, which has been filled in for each model evaluated. Detailed descriptions of the Model Categorization and Descriptors Summary Table and an example for one model are given in the Table S2. Furthermore, the compiled material is shown in the spider web summary plots in the results section in Figures 2–6.

In the summary table, the primary-level descriptors in the rows are categorized into (i) advisory models in the short term (fisheries advice with fish stock assessment), (ii) assessment of outcomes of existing TAC or TAE (short term), (iii) management strategy evaluation (medium term, long term), (iv) strategic long-term advice and (v) broader bio-economic advice (medium-long term). The secondary-level descriptors in the columns of the table is categorized into three major model descriptors covering (i) model dimensions and structure/resolution, (ii) model complexity and flexibility and (iii) model type (see further descriptions and detailing of this in the Table S2).

2.5 | The Model Use and Trade-Off Summary Table

The Model Use and Trade-Off Summary Table given in SM Table S3 compiles the information that model developers provided in the Model Characteristics and Performance Evaluation Matrices and the Model Categorization and Descriptors Summary Table. This table notes the presence or absence of particular model characteristics and qualities in an overview form that facilitates comparison across models. There is a row for each model and with the columns indicating the model characteristics according to the primary use and types of use, as well

TABLE 2 Dissemination and publication of evaluated models

No	Model abbreviation	Model publication
1	CRAB ABC	Punt et al., 2012.
2	CRAB ACID	Punt et al., 2014; Seung et al., 2015; Punt et al., 2016.
3	MSPM	Horbowy, 1996, 2005.
4	EIAA	Frost, Levring, Hoff, & Thøgersen, 2009;.
5	BEMEF	Frost et al., 2009; Carpenter & Esteban, 2015; New Economics Foundation 2016.
6	MAQ	Van Dijk et al., 2013.
7	MAQ-ADJ	Van Dijk, Hendrix, Haijema, Groeneveld, & van Ierland, 2016.
8	IMATSTRL	van Putten et al., 2012; van Putten, Deng, et al., 2013; van Putten, Gorton, Fulton, Thebaud 2013; Plagányi et al., 2012, 2013; Pascoe, Hutton, van Putten, Dennis, Plagányi, et al., 2013; Pascoe, Hutton, van Putten, Dennis, Skewes, 2013; Hutton et al., (2016).
9	ECO²	Bethke, 2013a,b, 2015, 2016; Bethke, Bernreuther, & Tallman, 2013;.
10	STOCH HCR (ITQ WEALTH)	Da Rocha & Gutiérrez, 2011; Da-Rocha & Pujolas, 2011; Da Rocha & Mato-Amboage, 2016; Da Rocha & Sempere, 2016; Da Rocha, Cerviño, & Gutiérrez, 2010; Da Rocha, Gutiérrez, & Antelo, 2012; Da Rocha, Gutiérrez, & Cerviño, 2012; Da Rocha, Gutiérrez, Cerviño, & Antelo, 2012; Da Rocha, Gutiérrez, & Antelo, 2013; Da Rocha, Gutiérrez, Garcia-Cutrin, & Jardim, 2015; Da Rocha, Gutiérrez, Garcia-Cutrin, & Touza, 2016; Da Rocha, Gutiérrez, & Garcia-Cutrin, 2016; Da Rocha, Gutiérrez, Garcia-Cutrin, & Jardim, 2017; Arnason, 2002; Weninger and Just, 2002; Heaps, 2003; Weninger and Waters, 2003; Weninger, 2008; Kitts et al., 2011.
11	DISPLACE	Bastardie, Nielsen, Andersen, & Eigaard, 2010; Bastardie et al., 2013, 2014; Bastardie, Nielsen, Eigaard, et al., 2015; Bastardie, Nielsen, Eero, Fuga, & Rindorf, 2017; Nielsen, Kristensen, Lewy, & Bastardie, 2014; www.displace-project.org (01 Apr 2017).
12	ISIS-FISH	Mahevas & Pelletier, 2004; Pelletier et al., 2009; Drouineau, Mahévas, Pelletier, & Beliaeff, 2006; Drouineau, Mahévas, Bertignac, & Duplisea, 2010; Duplisea, 2010; Lehuta, Mahévas, Petitgas, & Pelletier, 2010; Rocklin, Pelletier, Mouillot, Tomasini, & Culioli, 2010; Lehuta, Mahévas, & Le Floc'h, 2013; Lehuta, Petitgas, et al., 2013; Lehuta, Holland, & Pershing, 2014; Lehuta, Vermard, & Marchal, 2015; Rochet & Rice, 2010; Marchal, Little, & Thebaud, 2011; Marchal, De Oliveira, Lorance, Baulier, & Pawlowski, 2013; Hussein et al., 2011a,b; Vermard et al., 2012; Gasche, Mahevas, & Marchal, 2013; Reecht et al., 2015.
13	BALTIC FLR-SMS	Bastardie et al., 2009; Bastardie, Nielsen, & Kraus, 2010; Bastardie, Vinther, Nielsen, Ulrich, & Storr-Paulsen, 2010; Bastardie, Vinther, & Nielsen, 2012; Bastardie, Nielsen, & Vinther, 2015; Bastardie & Nielsen, 2011; Nielsen et al., 2011; Feekings et al., (submitted).
14	IAM	Macher, Guyader, Talidec, & Bertignac, 2008; Macher et al., 2013; Merzéréaud, Biais, Lissardy, Bertignac, & Biseau, 2013; Merzéréaud et al., 2011; Simmonds et al., 2011; Raveau et al., 2012; Guillén et al., 2013; Guillén, Macher, Merzéréaud, Fifas, & Guyader, 2014; Guillén, Macher, Merzéréaud, Boncoeur, & Guyader, 2015; EU STECF, 2015a,b,c.
15	SIMFISH	Bartelings, Hamon, Berkenhagen, & Buisman, 2015; Kempf et al., 2016.
16	FISHRENT IFRO	Frost, Andersen, & Hoff, 2011, 2013; Lassen, Anker Pedersen, Frost, & Hoff, 2013; Thøgersen et al., 2012; Salz et al., 2010.
17	FISHRENT TI	Salz et al., 2011; Simons, Bartelings, et al., 2014; Simons, Döring, Temming 2014; Simons, Döring, & Temming, 2015a; Simons, Döring, & Temming, 2015b.
18	SRRMCF	Waldo and Paulrud 2013a,b; 2016; Paulrud & Waldo, 2011.
19	NECLH	Holland, 2011a,b; Lehuta et al., 2014;.
20	BAL. ECON-ECOL	Tahvonen, 2009; Voss, et al., 2011; Voss, Quaas, Schmidt, Hoffmann 2014; Voss, Quaas, Schmidt, Tahvonen et al., 2014; Skonhoft et al., 2012; Tahvonen et al., 2013.
21	ELFSIM	Little et al., 2007; Little, Punt, Mapstone, Begg, Goldman, Ellis 2009; Little, Punt, Mapstone, Begg, Goldman, Williams, 2009;.
22	NPFTPBEM	Dichmont, Punt, Deng, Dell, & Venables, 2003; Dichmont et al., 2010; Dichmont, Deng, Punt, Venables, & Hutton, 2012; Punt et al., 2010; 2011; Deng, Punt, Dichmont, Buckworth, & Burridge, 2015;.
23	NPF BIOECON	Gourguet et al., 2014, 2016; Dichmont et al., 2003, 2008; Punt et al., 2010, 2011.
24	MEFISTO	Lleonart et al., 1999, 2003; Maynou, Sardà, Tudela, & Demestre, 2006; Maynou, Martínez-Baños, Demestre, & Franquesa, 2014; Mattos, Maynou, & Franquesa, 2006; Merino, Karlou-Riga, Anastopoulou, Maynou, & Lleonart, 2007; Tratnik et al., 2007; Silvestri and Maynou 2009; Guillén et al., 2012; Maynou, 2014; Maouel, Maynou, & Bedrani, 2014; Maravelias, Pantazi, & Maynou, 2014;.

(Continues)

TABLE 2 (Continued)

No	Model abbreviation	Model publication
25	FLBEIA	Garcia, Santurtun, Prellezo, Sanchez, & Andres, 2012; Garcia, Urtizberra, Diez, Gil, & Marchal, 2013; García, Prellezo, et al., 2016; García, Sanchez, Prellezo, Urtizberea, Andres 2016; Jardim et al., 2013; Prellezo et al., 2016.
26	FCUBE	ICES 2006, 2014a,b; Hoff et al., 2010; Ulrich et al., 2011, 2017; Iriondo et al., 2012; Maravelias, Damalas, Ulrich, Katsanevakis, & Hoff, 2012; Jardim et al., 2013; EU STECF, 2015b; ICES 2015c,d.
27	GBFWCGE	Seung 2006; Steele et al., 2007; Pan, Failler, & Floros, 2007;.
28	BALTIC ATL	Fulton et al., 2011; Palacz et al., 2014, 2015, In Revision; Nielsen, Thunberg, et al., 2015; Nielsen et al., 2015b; Nielsen, Palacz, et al., 2015.
29	CA CURRENT ATL	Kaplan et al., 2009, 2012, 2014; Fulton et al., 2011; Kaplan & Leonard, 2012;.
30	SE AUS ATL	Fulton et al., 2011; van Putten, Gorton, Fulton, Thebaud 2013; van Putten, Deng, et al., 2013; Fulton et al., 2014;.
31	SS-DBEM-IOT	Fernandes et al., 2013; Fernandes, Kay, et al., 2016; Fernandes, Papathanasopoulou, et al., 2016; Queirós et al., 2015.
32	GEM	Ravn-Jonsen 2011; Andersen, Brander, Ravn-Jonsen 2014; Andersen, Andersen, Mardle 2014; Ravn-Jonsen et al., 2016.
33	PERU EwE	Polovina 1984; Christensen & Pauly, 1992; Christensen & Walters, 2004; Walters and Martell 2004; Walters and Christensen 2007; Walters et al., 1997, 1999, 2000; Christensen et al., 2011, 2014; Bevilacqua, Carvalho, Angelini, Steenbeek, & Christensen, In prep.
34	B SEA EwE	Polovina 1984; Christensen & Pauly, 1992; Christensen & Walters, 2004; Walters and Martell 2004; Walters and Christensen 2007; Walters et al., 1997, 1999, 2000; Tomczak et al., 2012, 2013.
35	N SEA EwE	Polovina 1984; Christensen & Pauly, 1992; Christensen & Walters, 2004; Walters and Martell 2004; Walters and Christensen 2007; Walters et al., 1997, 1999, 2000; Plagányi and Butterworth 2004; Mackinson, 2014; Mackinson & Daskalov, 2007; Mackinson, Deas, Beveridge, & Casey, 2009; Heymans, Mackinson, Sumaila, Dyck, & Little, 2011; ICES 2011; Romagnoni et al., 2015; Colléter et al., 2015.

as major trade-offs. The compiled table and descriptions to it are given in the SM Table S3. Also for this table, the compiled material is shown in the spider web summary plots in the results section in Figures 2–6.

The columns of the table categorize each model in terms of six major factors. The main uses and focus of the model are identified including: whether it is used to evaluate data needs (e.g. specific types of data or specific data collection programs); whether it has a single-stock, multispecies, mixed fishery or ecosystem orientation; and whether it provides economic and social advice (main coverage of use). Several models do include some social parameters such as employment and distribution of impacts across fishing fleets and among vessel owners and crew. Most models include only economic parameters but may be used to evaluate the implications of management changes on broader social concerns such as security of resource supply to regional or local community industry. Bio-economic models may also proxy for family status or tradition by modifications to parameters affecting fishing trip duration or fishing effort allocation. The matrix table specifies what governance body and level each model are meant to provide advice to (e.g. a specific country, ICES, EU, Australian or North American regional management bodies) and the degree to which advice from the model has been implemented (management advice). The matrix table indicates whether a paper based on the model has been published in a peer-reviewed journal or only a report or internal agency/department documents, and whether it has been frequently cited. The age of the model is shown along with the level of model development (e.g. is it only for advance users, is there a big multiuser development group, is there a website for the model?). This covers the level of model development, application and implementation. Finally, trade-offs in model use are noted according to whether the model is simple or complex, whether it is specialized or flexible, and whether the model is usable only by model developers or is open access and user friendly. In the Table S3, further details and descriptions of the different categories in the matrix table are provided.

2.6 | Spider web charts with frequency classification of the models

A set of semi-quantitative spider web plots (Figures 2–7) is produced based on the compiled model summary and descriptor tables. Here, each of the rows or columns in the summary tables is depicted in spider web plots in which the frequency of models belonging to a certain category with respect to model properties, characteristics or type of model can be summarized according to criteria used for evaluating the models. The frequency plots are used to compare the focus and capability of the different models and what main directions of development the different models represent. For example, the figures summarize the findings in terms of the level of implementation of the models according to the purpose of the models, for example whether it is for academic purposes, application in advice and management, and whether the model is fully developed and integrated or not.

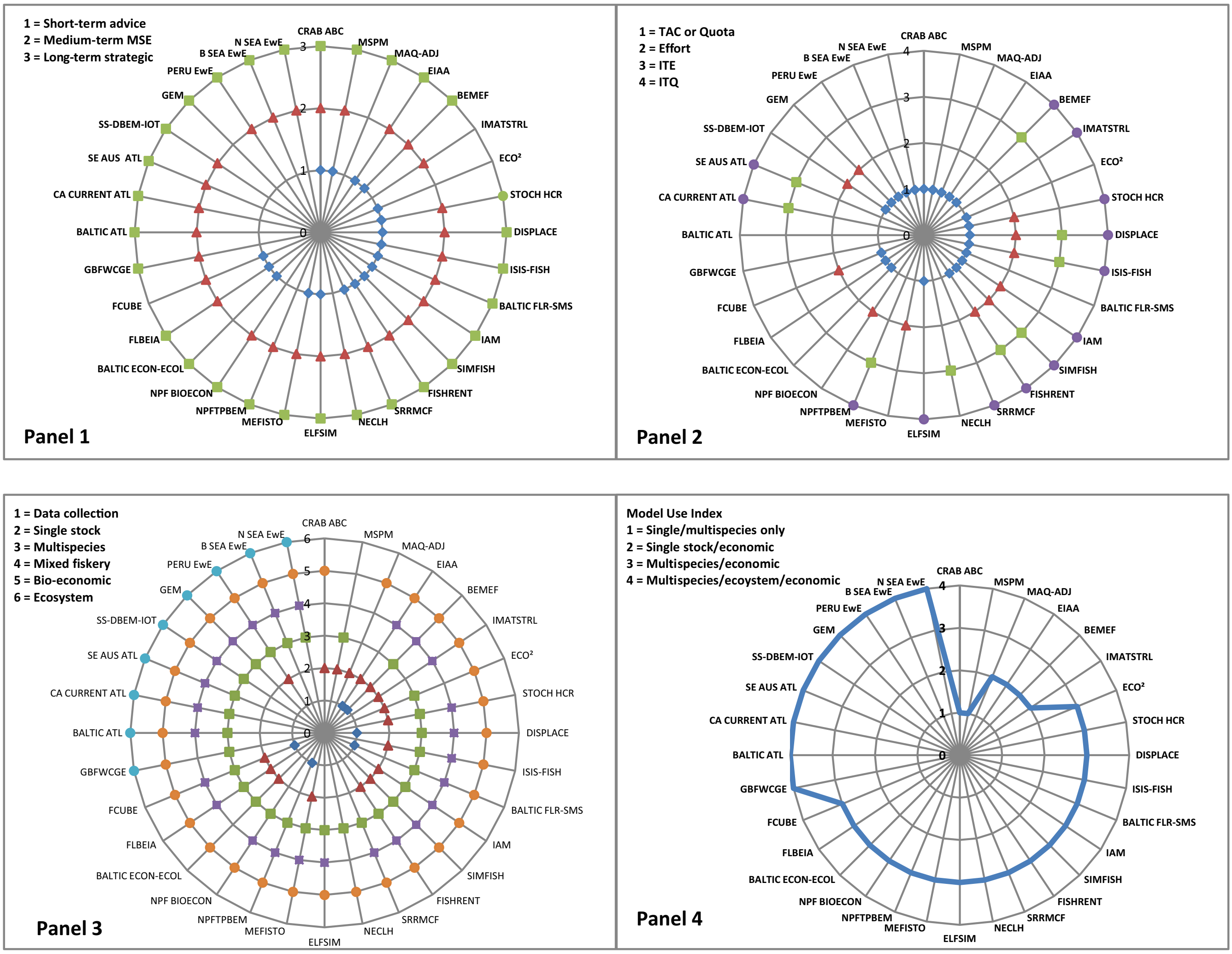

FIGURE 2 Model capabilities Panel 1—model design capabilities to provide short-term tactical, medium-term MSE or long-term strategic advice; Panel 2—model capability to provide management advice on setting TACs, effort limits, ITE and ITQ; Panel 3—model structural characteristics in terms of advice on data collection, stocks, fleets, economic and ecosystem components; Panel 4—model use index in terms of included modules and their linkages for biology (stocks), economic and ecosystems

3 | RESULTS

The results of the global review cover a comparative evaluation of 35 IEEFMs (Tables 1–2, Figure 1). The selected models represent a broad range of IEEFMs, but all address commercial fisheries and associated fish stocks. The metadata collected for each model provided information on capabilities, model structure, trade-offs and model uses. Throughout it is important to keep in mind that the evaluations of model characteristics are primarily based on self-assessments provided by the modellers themselves. In this section, we present summary information for these self-assessments across all models on each of these aforementioned dimensions. Throughout we use the model abbreviations noted in Tables 1-2. The geographical distribution of model implementation is shown in Figure 1. Several models have been widely implemented, for example Atlantis and EwE, and only a few examples of specific implementations are shown in Figure 1. Some of the 35 models analysed are included with several implementations and similar models have been clustered (Tables 1–2) resulting in 32 categories in the model meta-analysis plots in Figures 2-8. The order and sequence of the models in Tables 1–2 and accordingly in the Figures 2–8 was determined by type of advice addressed and units included in the models (data collection, single-stock, multispecies, mixed fishery, bio-economics, ecosystem; Figure 2 Panel 3) as well as according to completeness and integration of modules (biological such as single-/multispecies only, single-stock economic, multispecies economic, multispecies ecosystem/economic; Figure 2 Panel 4).

Figure 2 reports the range of capabilities in terms of type of management advice from short to long term (Panel 1) and input/output type of advice (Panel 2), structural components in terms of advice level (Panel 3) and structural modules and linkages included in the models (Panel 4).

Panel 1 shows the management advice capabilities as concentric rings where the innermost ring represents models that may be used

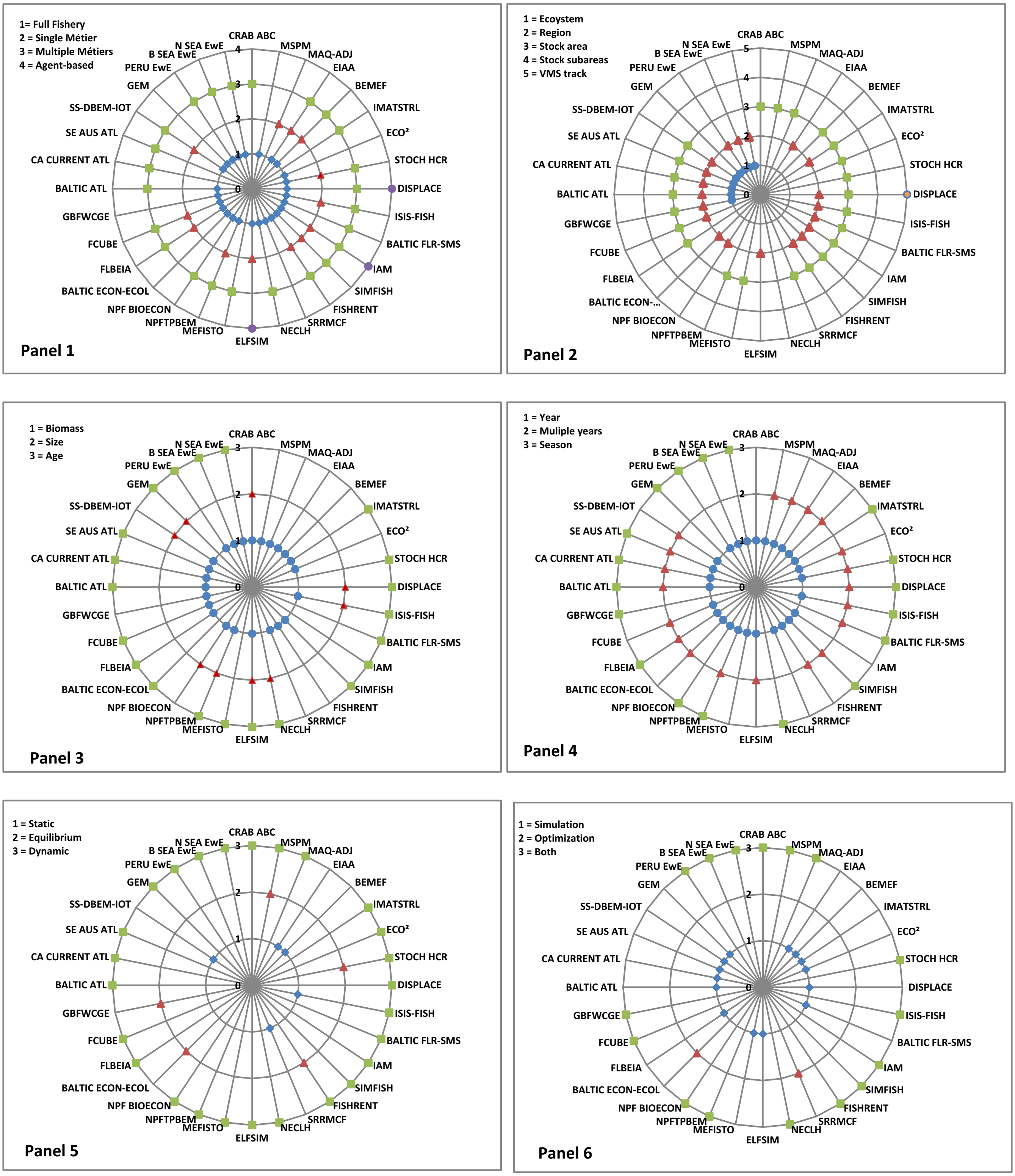

FIGURE 3 Model characteristics Panel 1—model fishing fleet characteristics (entire fishery, métiers or agent-based); Panel 2—model spatial resolution characteristics (VMS track, subarea, stock area, regions, or ecosystem); Panel 3—model biological characteristics (age-structured, size-structured, or biomass); Panel 4—model time step (season, year, multiyear); Panel 5—model characteristics in terms of static, dynamic or equilibrium with respect to coupling; Panel 6—model characteristics in terms of simulation and/or optimization algorithms

to provide short-term advice on TACs or impacts, and the outer ring represents models that are designed to provide long-term strategic advice. For any given model, the range of capabilities can be traced along the ray emanating from the origin to the model abbreviation where a marker on each ring denotes the presence of each capability (short-term tactical advice (1), medium-term MSE advice (2) and

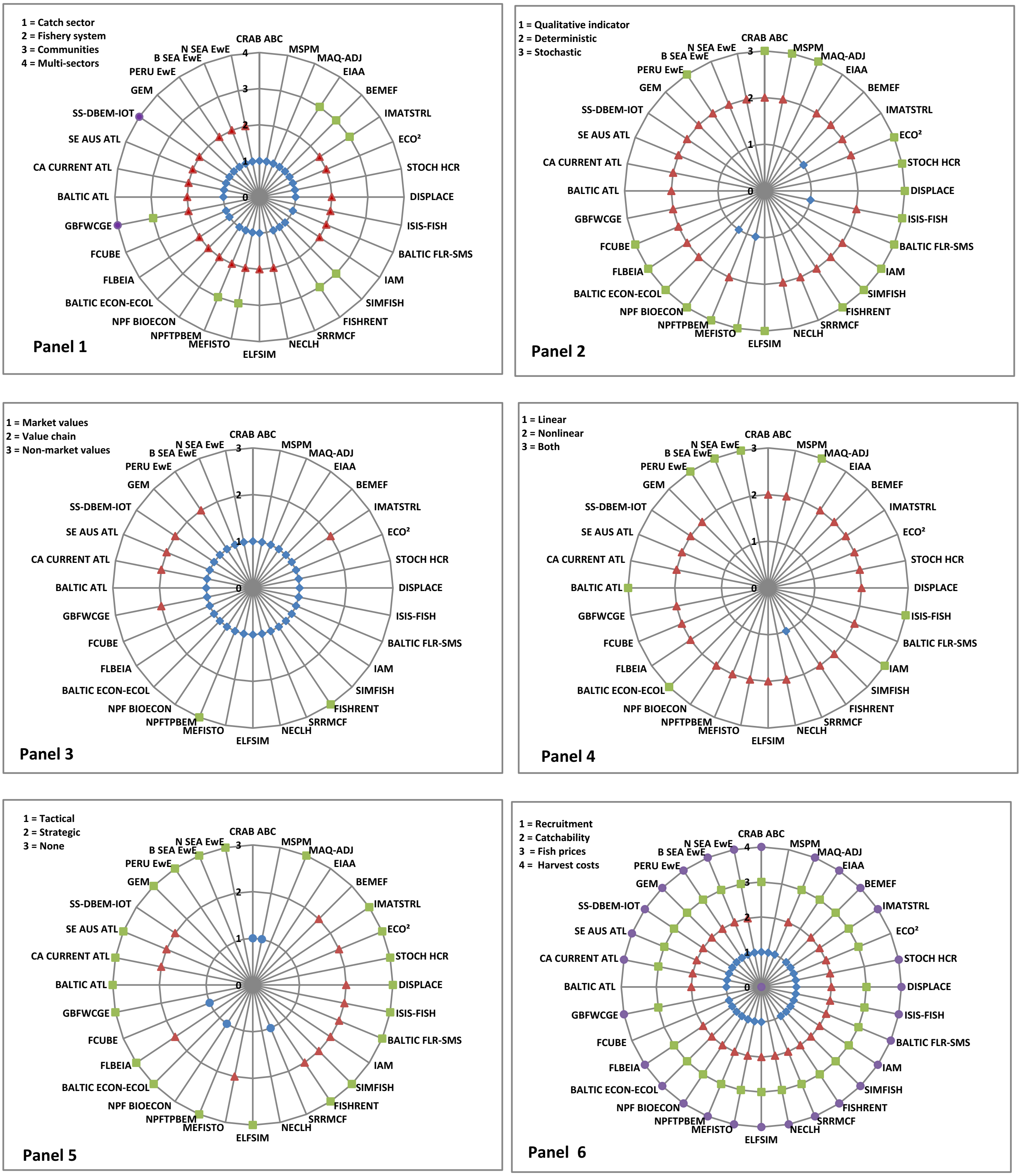

FIGURE 4 Model characteristics Panel 1—fishing sector components (catch sector, fishery system including processing and distribution, communities, and multiple sectors of a local or regional economy); Panel 2—estimation of model parameters (qualitative indicators, deterministic or stochastic parameters), Panel 3—model characteristics in terms of use of market prices, consideration of the value chain and inclusion of non-market values; Panel 4—type of embedded interactions (linear, nonlinear or both); Panel 5—nature of embedded economic behavioural model (tactical, strategic or no behavioural module); Panel 6—included functions (recruitment, catchability, fish prices and harvest costs)

long-term strategic advice (3). For example, 15 models include the capability to provide short-term, medium-term MSE and longer-term strategic advice. By contrast, MAQ-ADJ and GEM are designed only for long-term strategic advice. However, these two models are the exception as all other models are constructed to provide multiple advisory capabilities.

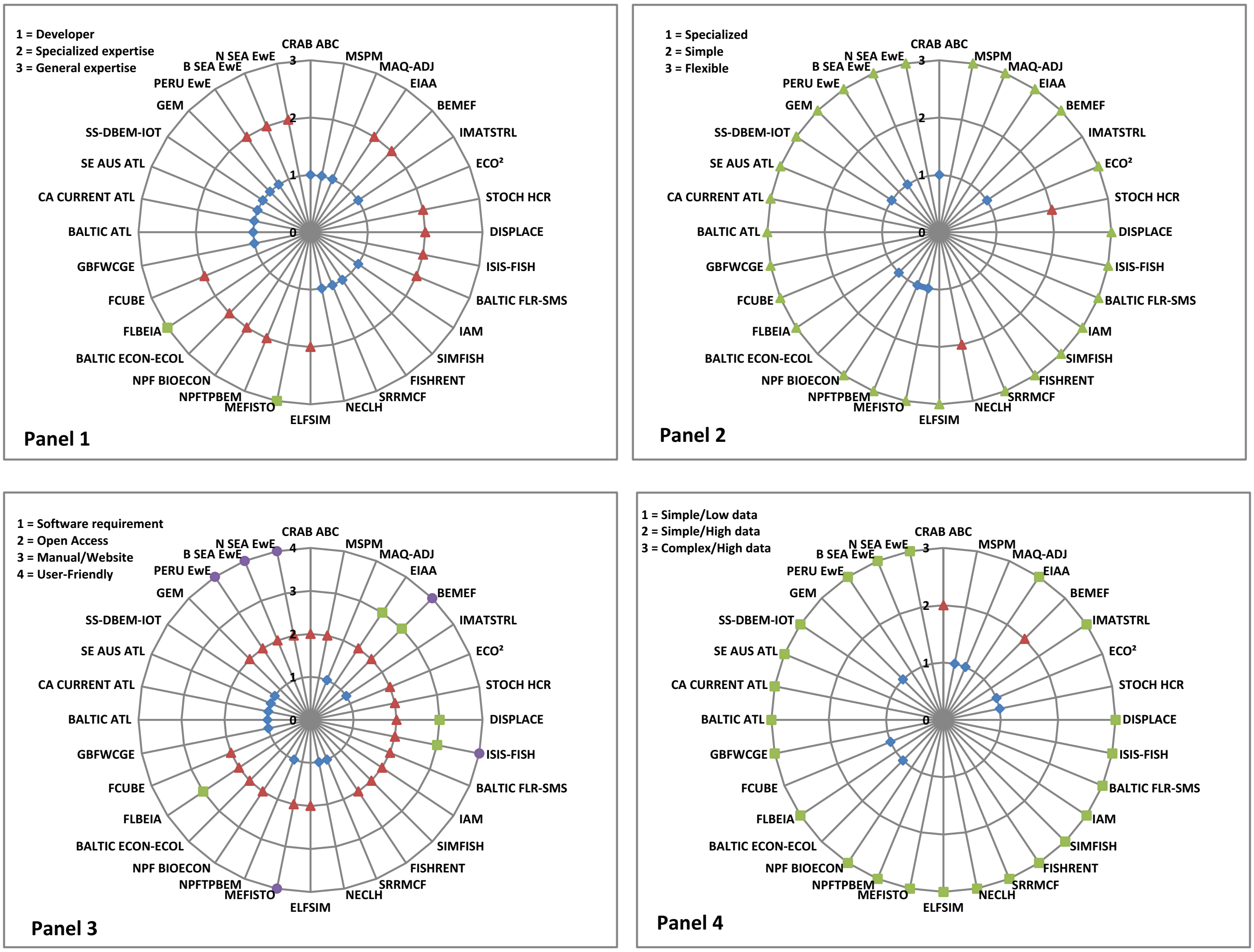

FIGURE 5 Model trade-offs Panel 1—expertise required to conduct model runs (developer, specialized expertise or training, or general expertise); Panel 2—model applications (specialized, simple or flexible); Panel 3—model accessibility to end users (software required, open access and user-friendliness); Panel 4—relationship between model complexity and data needs (simple with low data needs, simple with high data needs and complex with high data needs)

Panel 2 of Figure 2 shows structural components of the model capability with respect to type of advice provided by the model. As was the case for Panel 1, markers on each concentric ring denote the presence of each of four components such as output advice on TAC and quota (1), input effort advice (2), individual tradeable effort quota advice (3) or individual transferable quota advice (4). Most models provide TAC-Quota advice (22 models). Three models provide advice on all four levels. Another three models provide advice on three levels, while eight provide both TAC-quota and effort-based advice, but no advice relevant to individual effort or catch quotas. In total, three models provide only individual-based advice covering both output (ITQ) and input (ITE) advice, two models provide only ITQ advice, and one model provides only ITE advice. Finally, one model provides only effort-based advice.

Panel 3 of Figure 2 shows the structural components included in each model in terms of advice level. Markers on each concentric ring denote the presence of each of six components with advice on data collection level (1) single-stock level (2), multispecies level (3), mixed fishery level (4), bio-economic level (5) and ecosystem level (6). With a few exceptions, single-species models can be scaled up to multispecies, although this does not necessarily mean that the opposite is also true. In total, 28 models include multispecies, 25 include mixed fisheries, 34 include bio-economic functions or parameters, and nine include ecosystem considerations. All nine models that include ecosystems also include mixed fisheries, bio-economic and multispecies structural components except for one not including mixed fisheries. The Atlantis model does include the capacity to cover individual species and to have that in a food web with functional groups (either age or size resolved or biomass pools). The ECO^2 has the potential to formulate simple biological models at present up to full ecosystem models in future. The term multispecies here should in most cases (except for the below mentioned) be interpreted as multistock where several species single-stock assessments have been included. Only very few models include dynamic full feedback biological/trophic interactions and/or estimate fish natural mortality (mortality due to natural causes) as function of, for example, predation pressure. Such

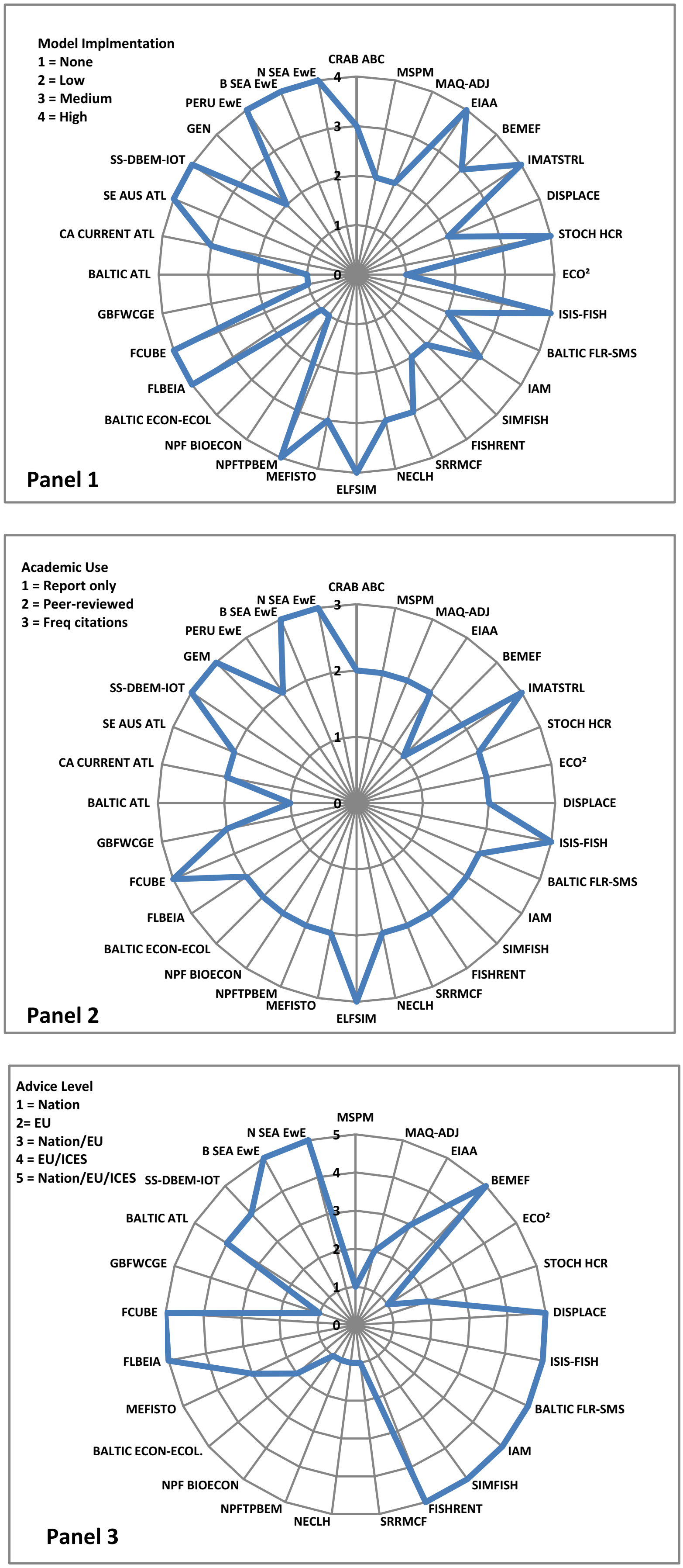

FIGURE 6 : Summary of model use Panel 1—model implementation (none, low, medium, high); Panel 2—academic use (models that only have technical reports, models that have been published in the peer-reviewed literature and models that have been widely cited), Panel 3—level of advice for models (National, EU, National and EU, EU and ICES, National, EU and ICES)

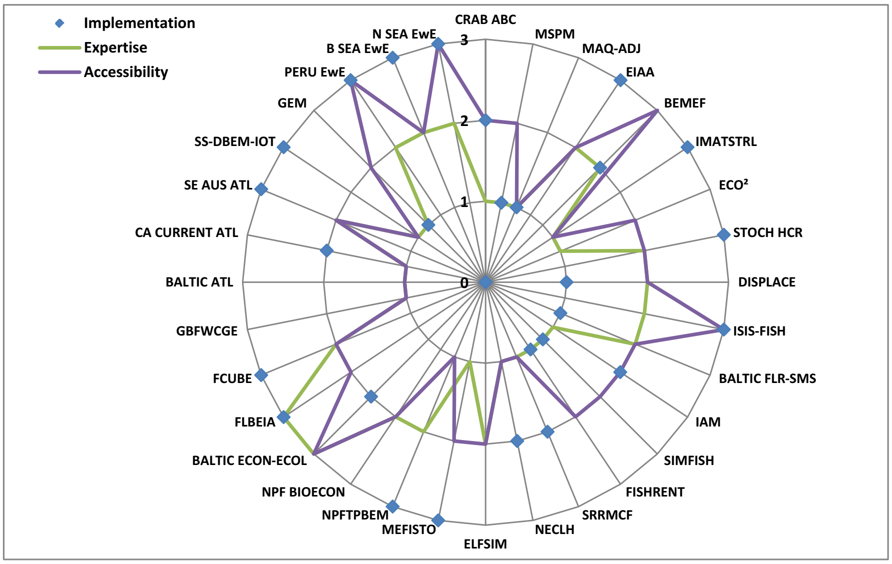

FIGURE 7 Effect of model accessibility and required expertise on model implementation

explicit modelling of biological interactions is only performed by a few ecosystem and multispecies-interaction models such as Atlantis, EwE, SS-DBEM-IOT, GBFWCGE, Baltic-FLR-SMS and the Baltic-Econ-Ecol models. The GEM explicit models a bio-energetic budget of the individual predator and thereby links somatic growth with the predation mortality inflicted on its prey.

Panel 4 of Figure 2 provides a score for structural linkages in terms of single or multispecies, bio-economics and ecosystem. In this case, the position of each model on the concentric circles is interpreted as the level of structural linkage where a score of 1 means that the model only includes single or multiple species; the model has neither bio-economic nor ecosystem linkages. A score of 2 denotes a single-species model that is linked with bio-economics. The majority of models (17) had a score of 3, which denotes models that include multi-species and bio-economics linkages. Models that include multispecies, bio-economic and ecosystem linkages (9) were scored a 4.

Model characteristics are reported in Figure 3 in terms of fishing fleet (Panel 1), spatial resolution and/or coverage of advice (Panel 2), biological characteristics (Panel 3), time step and/or coverage in advice (Panel 4), dynamics (Panel 5) and algorithm used to produce model outputs (Panel 6). In each panel, concentric rings with markers indicate the presence of a specific model characteristic.

Panel 1 of Figure 3 shows the different ways models incorporate fishing fleets where the treatment of fleets in each model can be ascertained along the ray from the origin to the model abbreviation. Nearly all models incorporate full fishing fleets, while 24 models incorporate multiple métiers and only two incorporate exclusively single métier. Only three models (DISPLACE, IAM and ELFSIM) capture fishing fleets as individual vessels.

Panel 2 of Figure 3 reports the spatial resolution and coverage in advice supported by each model where the resolution for each model (ecosystem (1), region (2), stock areas (3), stock subareas (4) and VMS track (5)) is denoted by a marker in each concentric circle. Ecosystem is a more complex but spatial coarse resolution than VMS track. Only DISPLACE includes a spatial resolution at the level of VMS track. Note that DISPLACE may also be applied at a stock area or regional spatial resolution. Twelve models have a spatial resolution needed to evaluate stock subareas, of which 11 can be scaled up to a stock area. Nine models (all Atlantis and EwE applications, GBFWCGE, SS-DBEM-IOT, GEM) support an ecosystem spatial resolution, although all but GEM and the EwE applications are scalable to a region, stock or stock area. ISIS-FISH is scalable to a region, stock or stock subarea. This classification of the models enables the user to distinguish whether the models are spatially explicit or not, that is do they only cover one area (region, or stock distribution area, or fishery area, or ecosystem) or do they contain and cover several areas and spatial units (stock subareas, ecosystem subareas, other spatial distinction such as ICES subareas, statistical rectangles) or do they follow very high spatial resolution on a haul to haul basis (or similar) or on an agent-based level when for example using VMS data.

Panel 3 of Figure 3 shows the biological characteristics (biomass, e.g., production models (1), size-based (2), and age-based, for example virtual population analysis (VPA) (3)) embedded in each model. In the majority of models (21), stock dynamics were of the age-based VPA type. Of these age-based models, 10 models (CRAB ABC, DISPLACE, ISIS-FISH, NECLH, ELFSIM, NECLH, MEFISTO; NPFTBEM, SS-DBEM-IOT and GEM) also include size-based biological considerations. It should be noted that certain ecosystem models such as the Atlantis model has emergent size-at-age, that is not a fixed growth curve, so it also takes size-based interactions into account (e.g. through gape limitation and size constrained reproduction). Whether age-based or size-based, most of these models are scalable up to an estimate of biomass. Age-based models like DISPLACE, Baltic-FLR-SMS, IAM, NECLH, MEFISTO, Baltic-Econ-Ecol and GEM certainly do include biomass estimation. Seven of the models included in this study (MSPM, MAQ-ADJ, EIAA, BEMEF, ECO^2, FISHRENT IFRO and SRRMCF) are production models, for example of the Schaeffer or Cobb–Douglas type, based solely on biomass.

Panel 4 of Figure 3 reports the time steps and time resolution and/or temporal coverage in advice for each model as seasonal (e.g.

less than an annual time step) (1), a year (2) or multiyear (3) time period, where the time step capability is indicated by a mark on each concentric circle. All but five of the IEEFMs are annually based, that is with yearly time steps and coverage, and many (20) of those operate with multiannual aspects. More than half (18) of the models are seasonally explicit as well indicating general high time resolution. Several of the models that can be run and provide advisory output for a year or multiple years have finer scale time steps/resolution in their modelling process, for example Atlantis can be run with 12- to 24-hour time steps that is then run out to year or multiple years. In total, 20 models can be run for multiple years, 27 models can be run on an annual basis and 18 on a seasonal basis. MSPM is an annual model but can be run over multiple years while FLBEIA, as well as several others (eight models), includes season, annual and multiyear modelling capabilities.

Panel 5 of Figure 3 identifies model performance in terms of whether the processes considered are static (1), equilibrium (2) or dynamic (3). The majority of models (26) incorporate dynamic processes while 3 (MSPM, STOCH HCR and FISHRENT IFRO) also incorporate processes based on equilibrium conditions. Only two models (BALTIC ECON-ECOL and GBFWCGE) have processes exclusively based on equilibrium conditions. ISIS-FISH has elements of both static and dynamic processes while EIAA, BEMEF, SS-DBEM-IOT and SRRMCF are static models.

Panel 6 of Figure 3 indicates the types of algorithms used to produce model outputs. A marker on the inner ring (1) means that the model uses a simulation algorithm. A marker on the second ring (2) denotes models that are based on an optimization algorithm, and a maker on the outer ring (3) indicates models that incorporate both, simulation and optimization algorithms. Less than half of the models (14) are simulation models, 2 are strict optimization models, while the last half (16) incorporate both types of algorithms.

Figure 4 reports additional model characteristics of the IEEFMs with focus on economic characteristics and sector coverage.

Panel 1 of Figure 4 explores fishing sector components in the model coverage categorized into catch sector (1), fishery system including processing and distribution (2), societal communities (3) and multiple sectors of a local or regional economy (4). All models address the catch sector and of those 21 also address the wider fishery system and 8 also address communities. Only two models (GBFWCGE and SS-DBEM-IOT) cover multiple sectors.

Panel 2 of Figure 4 evaluates the estimation of model parameters covering qualitative indicators (1), deterministic parameters (2) or stochastic (3). Most models (25) include deterministic parameters, while 12 of the 25 also include stochastic parameter estimation. A few models include both qualitative indicators and stochastic parameter estimation (3) or deterministic parameters (1) while only five models include exclusively stochastic parameter estimation (MAC-ADJ, STOCH HCR, DISPLACE, BALTIC FLR-SMS and ELFSIM).

Panel 3 of Figure 4 shows model characteristics in terms of use of market prices/values (1), consideration of the value chain (2) and inclusion of non-market values (3). All models, except the MSPM, include market values, while six also consider the value chain and two include both market and non-market values.

Panel 4 of Figure 4 explores the type of embedded interactions covering linear (1), nonlinear (2) or both (3). Most models (23) include nonlinear interactions, while eight include both. Only one model included only linear interactions.

Panel 5 of Figure 4 investigates the nature of the embedded economic behavioural model covering no behavioural module (1), a strategic module (2) or a tactical module (3) included. Most models include tactical modules (21) and of those nine include also strategic modules. Only four models include only strategic behaviour, and five models have no behavioural module included (Crab ABC, MSPM, SRRMCF, NPF BIOECON and FCUBE).

Panel 6 of Figure 4 explores some basic functions included in the models in relation to recruitment (1), catchability (2), fish prices (3) and the harvest costs (4). Most models include indicators and parameters for recruitment, catchability, costs and prices. Some models have those indicators included as endogenous relationships, other models use exogenous relationships for those indicators, while other models include linear or nonlinear interactions for those parameters.

Models typically require trade-offs that need to be made that can affect how the model may be applied to address a management question. Some of the key trade-offs among models that were evaluated for this study are reported in Figure 5. Some of these trade-offs include the expertise required to conduct analyses (Panel 1), range of applications and degree of specialization (Panel 2), accessibility to end users (Panel 3) and the relationship between model complexity and data needs (Panel 4).

A marker in the inner ring (1) of Figure 5, Panel 1 denotes models where analyses or model runs need to be conducted by the model developer. There are 15 models that fall into this category. A marker in the second ring (2) of Panel 1 means that analyses do not necessarily need to be conducted by the model developer but require specialized expertise or significant training before obtaining proficiency in using the model. Fourteen models require specialized expertise. The outer ring (3) denotes models that can be used with some training but can be used by individuals with general expertise. These models include FLBEIA and MEFISTO.

Panel 2 of Figure 5 reports trade-offs along a continuum from specialized to flexible in terms of possible uses and management applications the model can address. With very few exceptions, all models were self-assessed as being complex. For this reason, complexity was not included in Panel 2 since doing so would not provide any meaningful information for the purpose of model comparisons. A marker in the inner ring (1) indicates models that have been developed to address a specialized fishery or specific application for special management issues. These models (7) include CRAB ABC, IMATSTRL, BALTIC ECON-ECOL, NPFTPBEM, SS-DBEM-IOT, MEFISTO and PERU EwE. Two models (NECLH and STOCH HCR) are placed on the second ring, which denotes simple models, that is less complex models with an intermediate level of application with respect to application and management issues that can be addressed, that is between the specialized/specific application and the capability of general application addressing several management issues. All other models lie on the outer ring (3), which denotes models that may be applied in a wide range of fisheries and/or to address many different management issues.

Panel 3 of Figure 5 reports accessibility trade-offs. A marker on the inner ring (1) of Panel 3 denotes models that would require user to obtain or purchase specialized or proprietary software prior to using the model. Many models belong to this category (10). A marker on the second ring means that the model has, on the contrary, been made available as open access which is the case for 22 of the models. In a few (5) of these cases, access has been provided as a free download from a website, and sometimes there is also an elaborated user manual available at the public website. In this case, the model has a marker in the third ring (3). A marker on the outer ring (4) denotes models that also are both open access and user friendly. These models include BEMEF, ISIS-FISH, MEFISTO and the EwE applications.

Panel 4 of Figure 5 shows the relationship between model complexity and data needs where simple with low data needs are placed on the inner ring (1), simple with high data needs on the centre ring (2) and complex with high data needs situated on the outer ring (3). By far, the majority of models are highly complex with high data needs (23), while two are in the second category and seven in the first category.

An important consideration in the present model evaluation is whether and how models are used. Model use may be conditional on the stage of model implementation. In some cases, they are only used in an academic setting to further develop or improve modelling capabilities. In other cases, they are used (or intended to be used) to provide advice to different levels of management organizations. In the SM Table S3, a Model Use and Trade-Off Summary Table is given with an overview of all IEEFMs evaluated according to main use and types of use, as well as major trade-offs in relation to the use. Based among other on this table, the Figure 6 gives an overview and reports model comparisons on each of the dimensions of model use: model implementation (Panel 1), academic use (Panel 2) and management advice level and organizations (Panel 3).

Panel 1 of Figure 6 provides an ordinal rating of each model in terms of level of implementation from models that have been developed but have not been applied to any specific issue (1) to levels of low (2), medium (3) and high (4) implementation. Models that have a high level of implementation include EIAA, IMATSTRL, STOCH HCR, ISIS-FISH, ELFSIM, NPFTPBEM, FLBEIA, FCUBE, SEAUS ATL, SS-DBEM-IOT and the EwE applications (in total 13). By contrast, models that have not yet been implemented include CRAB ACID, BALTIC ECON-ECOL, NPF BIOECON, GBFWCGE and BALTIC ATL (5). All other models were rated as either a low or medium level of implementation with seven models in each of those main ratings.

Panel 2 of Figure 6 is an ordinal rating of each model in terms of academic dissemination and use. Models where a technical report has been prepared but not through the peer-reviewed literature are denoted as 1, models that have been published in peer-reviewed journals are denoted as 2, and peer-reviewed models that have been frequently cited are denoted as 3. Both BALT ATL and BEMEF provide technical reports but have not appeared in the peer-reviewed literature; however, a paper has been submitted on the first. Eight models have been frequently cited in peer-reviewed academic journals. These frequently cited models include IMATSTRL, ISIS-FISH, ELFSIM, FCUBE, SS-DBEM-IOT, GEM and EwE (8). All other models (22) have been documented in peer-reviewed literature.

Panel 3 of Figure 6 reports the advice level and types of management organizations for which each model is designed to provide advice. Here, we limit our focus to models that have been developed to provide advice to European management institutions. For reporting purposes, we assign a 1 to models that seek to provide advice to management organizations in a single nation. We assign a 2 to models that may provide advice to EU nations or management institutions. A 3 is assigned to models that address both single nation and EU advice; a 4 is assigned to models that may provide advice to both the EU and to ICES; a 5 is assigned to models that provide advice to National management bodies, the EU and ICES. Seven models (MSPM, ECO_2, SRRMCF, NECLH, NPFTPBEM, NPF BIOECON and GBFWCGE) have been designed to only provide advice to National management bodies which cover to high extent non-EU models. Three models (MAQ-ADJ, STOCH HCR and BALTIC ECON-ECOL) address EU management concerns alone, while EIAA and MEFISTO address both EU and National management institutions. The BALTIC ATL and SS-DBEM-IOT address both EU and ICES management concerns, and all other models (11) are designed to provide advice to management bodies at the National, EU and ICES levels.

The use of a model is dependent on the combinations and trade-offs in relation to model implementation (experience with the model), model expertise needed to use the model and the accessibility of the model to users. Figure 7 illustrates the integrated categorization of the models according to those three criteria and evaluates the effect of model accessibility and required expertise on model implementation. The levels of categorization of the rings in the spider web chart include 0: none, 1: low, 2: medium and 3: high. There are no strong or general trends observed; however, there is a tendency towards higher implementation when accessibility is higher and when complexity and expertise requirements are moderate. Also, there is a trade-off in model use and level of implementation with the age of the models which is analysed in Figure 8. It appears that all models with no implementation have an age of 5 years or less, and most of the models with low or medium implementation are also “young” models with an age of 5 years or less. However, a relatively high proportion of models with high implementation also have a low age of 5 years or less, but in this category, the sum of models with higher age of 6-10 and 11-15 years is higher than young models.

4 | DISCUSSION AND CONCLUSIONS

This study compares and contrasts 35 IEEFMs with a wide diversity of characteristics and uses. This diversity reflects recognition by modellers that no single model approach, structure or orientation is appropriate for all needs. This requires modellers to make trade-offs to best meet the needs of the intended uses and users for each model.

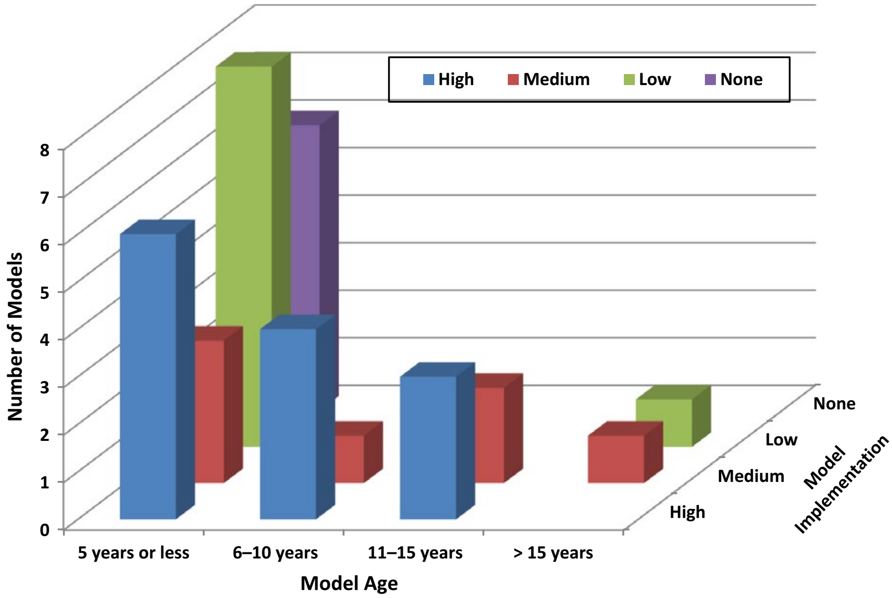

FIGURE 8 Relationship between model age and model use

Our aim is to help managers and scientists better understand how and why the characteristics of IEEFMs vary so much, what trade-offs modellers face, and what they have learned from developing and communicating these models. The documentation of the characteristics of the specific models, the development of the methods and specific tools to evaluate and categorize model characteristics, and what the model developers see as the model strengths capabilities and limitations also provide potential users and other modellers with information about how models (and modellers) may be useful to them either to provide management advice or in developing new models. Accordingly, we can help managers and scientists choosing the most appropriate models for their specific systems, advisory and management needs, and questions to be addressed. Given previous experiences and expert knowledge, we can provide methods and insights on what aspects of models to be aware of and implementation issues of the models.

This meta-analysis, based on self-assessments by model developers, compiles the experience of many different modellers. We found that it was important to collect metadata from model developers rather than just use a "standard literature review" because many of the above questions can only be answered with the insight the model developers have on their own models. However, responses compiled in the developed meta-analysis tools depend on modellers' perceived ideas and insight, for example complexity of a model depends partially on the eye of the beholder. For this reason, it is important to have the same type of people (in this case model developers) filling in the matrices and summary tables. At the same time, it has been important to have a balanced group evaluating the models with participation of economists, biologists, ecologists, theoretical people and people working with applied advice and model implementation. The present group of model developers represents such a balanced group, and it has been very useful to have group discussions during working group and conference meetings among scientists of different fields in the present evaluation.

4.1 | GENERAL CHARACTERISTICS OF THE EVALUATED IEEFMS OBTAINED FROM THE META-ANALYSIS

Most of the models reviewed are case-specific—designed or at least parameterized for specific fisheries and areas and sometimes to address specific management questions. However, a number of models are based on more generic modelling platforms but are parameterized for particular areas and fisheries and may also focus on different operating models within the more general models (e.g. various applications of the Atlantis and EwE ecosystem models). Most models reviewed provide short-term (tactical) advice and medium-term management strategy evaluation (MSE), while only about half provide both short-term and medium-term advice, as well as medium-term MSE. In many situations, adequate detailed ecosystem data and/or long-term time-series data are not available to obtain adequate precision to provide robust parameters for short-term advice with these models. This is particularly true for the more complex models with multiple species or fine-scale spatial dynamics. However, nearly all models can provide long-term strategic advice.

Most models were classified as multistock (multispecies) and mixed fisheries models having modules that also considered economics in relation to fisheries (métiers). Most of these models are actually multistock models, that is considering several stocks in a mixed fisheries context with technical interactions between fleets, but not multispecies in the sense that they integrate biological interactions, for example predation, between the different fish stocks, or ecosystem interactions. Only a few IEEFMs include biological interactions, for example actual fish multispecies prey–predator interactions, and/or trophic dynamics and interactions (the Atlantis and EwE applications, SS-DBEM-IOT, GBFWCGE, Baltic-FLR-SMS, Baltic-Econ-Ecol and the GEM models). All models contain biological–economic interactions with respect to stocks and fisheries, except the

MSPM which is an example of a stock production model where the economic module is not yet implemented, while only very few models (2) are also multisector, that is include non-fishery sectors to allow for marine spatial planning (MSP). The focus on multistock models and biological–economic interaction reflects broad interest in understanding the technical interactions that connect fisheries. This is in large part driven by concerns about by-catch and discarding that have been an important policy focus in recent years, particularly in Europe. Although the importance of understanding ecological interactions is clearly recognized, parameterizing these models accurately in a way that enables provision of tactical advice is often still not possible, and the end-to-end ecosystem models that have been developed tend to be focused on longer-term strategic advice.

In relation to model dimensions and scales, the majority of models only operate with one geographical area and unit, that is they are not spatially explicit. Some models operate with several areas such as stock or ecosystem subareas or management and advisory subregions, while only a few models are agent-based operating at very high spatial (and time) resolution. Modelling spatial dynamics at a fine scale not only greatly increases model complexity, but it also requires data on ecological and human processes that is often lacking or patchy. Management advice also still tends to focus on removals at the stock level. However, the increasing amount of use conflicts in marine areas, not just between fisheries, but between other uses such as electricity production, aquaculture and marine transport will continue to create interest in developing more spatially explicit models.

Most models are age-based or both age- and size-based, while only a very few are exclusively size-based. The broader ecosystem models usually operate with age disaggregation for the vertebrates (fish, sea mammals and birds; higher trophic levels), but not for the invertebrates and lower trophic levels. Age- and size-structure models are the standard for full analytical stock assessments, the data and information to parameterize age or size-structured models are often available, and age or size-structured bio-economic models are necessary to provide advice comparable to that of the full analytical stock assessments. Also, as management is often focused on issues of by-catch and discarding of juveniles, age and size-structure models are often necessary to address key management questions.

With respect to the types of processes (and functions) considered in the IEEFMs most models incorporate dynamic processes, while only a few were static models. Most models operate with costs, prices, catchability and recruitment as exogenous variables or functions. Only a few models include equilibrium processes. About half of the models include both simulation and optimization routines with respect to estimation of output parameters, while only very few are exclusively optimization models. The rest are pure simulation models. Among the models that include simulation and optimization routines, most optimize over fishing effort (to maximize profit or minimize costs), while ecosystem and multispecies biological interactions are simulated. This is due to the fact that the complexity of biological interactions and ecosystem dynamics does not lend itself to optimization. Most ecosystem and multispecies models are either equilibrium or simulation models where different scenarios of different factors (climate change, eutrophication pressure levels and/or fishing pressure levels on various fish species, etc.) can be evaluated through "what if" scenario evaluation.

Most models provide only deterministic quantitative estimates; however, a few provide output parameters with confidence limits and uncertainty indicated. Given their role in decision support for management, it is essential to know how the models incorporate uncertainty, for example uncertainty from a distribution range of output from multiple simulations, stochastic variables, deterministic processes or variables modelled as random processes. Communicating uncertainty is clearly important, but also a major challenge. It may increase the complexity and computational needs of models (e.g. requiring hundreds of stochastic runs). Modellers also may lack information on the correlation of stochastic processes in different model components even when they have good information on variation of individual processes. Even when modellers can provide estimates of uncertainty, users often focus on the mean or median results. It can be difficult to convey whether or how decisions should be adjusted to reflect uncertainty and doing so is often the place of the managers not the modeller.

With respect to model development, complexity, user-friendliness and flexibility, for example to what extent the models are easily used and informative for policymakers and stakeholders (i.e. industry, NGOs, other interest groups, science, managers)—nearly half of the models require analyses to be performed by the developer (due to difficulty of model use). The remainder of the models (with the exception of two models which may be operated with general expertise) could be analysed by someone other than the developer, but that person would require specialized training or expertise. Only four IEEFM models are characterized as user friendly. The majority of models were developed using open access software but a few have specific software requirements. Most IEEFMs are characterized as flexible, and only few of the models are specialized, and very few are considered to be simple. Most models have high data needs, which adds to complexity of implementation and the need for a higher level expertise to use them. This complexity and lack of user-friendliness almost certainly limits the use of many models unless modellers are able to actively engage with users of the model information. However, developing user-friendly interfaces for models can be costly and many modellers do not have those skills.

Somewhat fewer than half of the IEEFMs have achieved a high level of implementation, that is several cases of implementation and direct use in fisheries management advice. A similar proportion has a medium or low level of implementation in advice, while only a few models have no implementation at all, that is only scientific development. For many of the implemented models, the targeted advice has been broader regional, ICES or EU, while only a few models have targeted only national advice. The latter models have typically been implemented in single jurisdiction systems, such as United States, Canada or Australia. Most of the IEEFMs are published in scientific peer-reviewed journals; however, only about a fourth of the models have frequent citations. A few models have their own websites that are frequently used and sometimes involve model download.

According to the above results of the meta-analysis, there are several examples of IEEFMs that have been successful according to purpose, because the models have been used in real advice and management decision, and they have been picked up by people other than the original developer.

4.2 | MAIN CONSIDERATIONS, TRADE-OFFS AND INSIGHTS GAINED FROM DISCUSSIONS OF THE META-ANALYSES AT CONFERENCE THEME SESSIONS AND WORKING GROUP MEETINGS CONCERNING MODEL IMPLEMENTATION AND USE

The above meta-analysis suggests a number of factors that determine the usefulness of models in providing management advice and consequently the degree to which model advice informs and influences management decisions. Some of these suggest trade-offs for modellers to consider.

In general, it is important to determine and assess the context of the use of the model in order to have a well-defined problem before designing and/or implementing a model, that is what management objectives, purposes and decisions are to be addressed and informed in the application of the model, or whether the model only intended for theoretical (academic) use. Here, there is a trade-off between successful implementation of a model and the previous effort put into analysis of the context the model should be used in. The efforts needed for application of the model and the expected outcomes need to be considered and balanced with the political and management advisory needs and economic importance of the advice in order to be cost efficient because implementation of models is very resource demanding. Similarly, it is necessary to define and formulate quantifiable objectives and make these a priority which the IEEFMs directly can address. The key to dissemination and transmission has often been advisory working groups and bodies, larger research projects and dedicated training courses where a broader range of model experts have participated. In most cases, the developers are involved in providing technical support and in the formal use of the model. Expanded use of model websites and platforms show that model developers can more efficiently communicate their work and models through cooperation with visual communications experts and graphic designers and by participating in communications trainings.

More complex models may be able to account for interconnected ecological and economic processes and provide more nuanced advice, but unless the modeller is involved in the management process and can tailor the outputs and model scenarios to meet managers' needs, the model may only be used to provide general strategic advice rather than informing specific decisions. A simpler, user-friendly model may provide less nuanced advice, but if managers and stakeholders can use it themselves, it may have more influence on decisions. Consequently, there is a trade-off between the use and extent of inclusion of ecosystem or economic or social complexity in the IEEFMs which gives more nuances but also has the risk of reducing likelihood of use.

There is a trade-off between the model projection period, that is the time scale, in the advice or management evaluation it informs and the precision of the model output and advice. The data needed, the precision of the data, the tools used, as well as the output produced vary depending on whether the model deals with a strategic (what should be done in the long-run), versus a tactical approach (what can be done in the short-run). Models that provide useful tactical advice may need to incorporate single-species biological models comparable to stock assessment models and may need to incorporate technical interactions in fisheries. Models useful for strategic advice need to consider how ecological and economic and social processes may change and interact over time, but these processes may be hard to parameterize in ways that provide both accurate short-term predictions and longer-term insights. For example, a statistically fitted stock assessment model may provide accurate short-term predictions, while an ecosystem model may be more useful for considering how the fishery system will react to changes in the environment over time. This orientation towards tactical vs. strategic advice is particularly relevant with respect to human behavioural and social processes. Modellers face important choices about whether to try to simulate observed behaviour with statistically fitted models, use theoretically based models or specify behaviour in the model to achieve some objective (e.g. set effort or catch to maximize profits or to follow historical patterns of effort allocation). Generally, the former is most useful for models to be used for tactical advice, while models aimed at providing strategic advice and long-term insights may also take the latter approaches. The choice is also dependent on the management context. For example, does the model assume an open pool resource, effort limitations, individual transferable quotas, or communal management, or some other representation. Modelling behaviour in ITQ or communal management regimes may require modelling strategic behaviour of fishermen and group dynamics, while modelling behaviour in a common pool, particularly one observed for some time, may be simpler. If the model is expected to make predictions when the management regime is fundamentally changed, statistically fitted behavioural models based on prior observed behaviour are likely to do a poor job of predicting behaviour in a new management regime, and it may be necessary to either specify behaviour or incorporate a theoretically based behavioural model.

It is important to use an appropriate spatial scale to match the biological scale and the scale of key human processes. For example, the management areas and units addressed in a model ideally should match the resource distribution areas, that is distribution of the fish stocks to be managed. If the management area and the model domain only cover parts of the stocks distribution areas, important ecological parameters and population dynamics may not be captured and taken fully into account in the models (e.g. migrations, growth and recruitment in relation to spawning or feeding areas) which will bias their output. On the other hand, boundaries must be drawn at some point and enlarging them will necessarily add complexity. Modellers must ultimately decide whether processes external to the model domain are consequential enough to require modelling or can be specified rather than modelled directly (e.g. a certain catch or natural mortality applied outside the model domain).

The uptake and use of models may depend on how flexible they are. While models built from scratch tailored to specific purposes may provide more accurate answers to the specific questions they were designed for, models that enable users to modify assumptions and processes may ultimately be more useful and can provide users the ability to determine the sensitivity of results to assumptions or explore questions not originally envisioned by the model developer. Models that have been around longer and are more familiar to managers are probably more likely to be used because they are more likely to have been reviewed and people have some basis for deciding whether they provide useful and accurate advice. The number of times the model has previously been implemented or brought to a policy institution as a decision support tool, the more likely the advice will be used because policymakers are comfortable with it and perhaps have had a chance to see whether prior advice was useful. Thus, there may be a trade-off between introducing a new model, even if it is an improvement, and sticking with or adapting an existing model.

4.3 | GLOBAL EXPERIENCES IN IMPLEMENTATION AND USE OF IEEFMS—ADDITIONAL INSIGHTS FROM THE CONFERENCE THEME SESSION AND WORKING GROUP DISCUSSIONS

The effective integration of IEEFMs into the provision of management advice can be driven by and depend on having advisory and/or management bodies and fora (institutional set-up) where the models can be used in cooperation with stakeholders. It can take time for building trust in these fora, for the bodies to develop and for participants to learn to use models effectively. For example, in the Australian fisheries management and advisory system, the participatory management and advice between many stakeholders has been the main driver of the implementation of the models (Smith et al., 1999, 2001, 2014; Sainsbury et al., 2000; Rayns 2007). Such a system requires the establishment of appropriate facilitating legislation and comanagement bodies which can be a long process (5–10 years). Importantly, the comanagement structure or adaptive management process needs to be cross-sector involving a number of parties, including, conservation and recreational fishery sectors along with the commercial. Such a long-term, cross-sectoral view has been taken in the contested environment on the Great Barrier Reef (Mapstone et al., 2008).

Effectively using IEEFMs to provide management advice can be enhanced by simulation tests of management plans to evaluate trade-offs and robustness to uncertainty, and it is important to involve stakeholders in this process. In Australia, formal methods of the management strategy evaluation have been used to assess impacts of alternative sets of measures aimed to meet a variety of management goals (Fulton et al., 2014). Involving stakeholders directly in management and/or advice is important because it creates incentives for involvement in advance and drives the need for adequate management strategy evaluation tools to address complex questions involving many stakeholders and both ecological and economic aspects of management and advice. Thus, it is important that governance structures are in place for establishing processes that enable stakeholders to participate in management strategy evaluations (see, e.g. Fulton et al., 2011, 2014).

The preeminent management objectives mandated by legislation can be important in determining whether and how IEEFMs are used to provide management advice, particularly for tactical management decisions such as set TACs each year? For example, while management of fisheries in Australia is supported through the application of bio-economic models, these play virtually no role in fisheries management in New Zealand (Pascoe et al., 2016). This discrepancy is a direct result of the differing emphasis on how economic objectives are achieved, with Australia targeting maximum economic yield (MEY), while New Zealand targets maximum sustainable yield (MSY) (Pascoe et al., 2016). Similar to New Zealand, fisheries management in Europe and USA tends to be driven primarily by biological targets and reference points related to MSY. Economic and social factors enter mostly in allocation decisions and designing management approaches to achieve desired catch levels. In contrast, when MEY is the objective, it becomes necessary to integrate human behaviour, economics and perhaps social factors into integrated models that can identify what MEY is and how it can be achieved.

When integrating models into comanagement structures and processes, model flexibility, transparency, portability, build-up time, expert knowledge of the system to model and the model interface available can be critical determinants of success. It seems necessary to concentrate more on making models flexible, more understandable to stakeholders, portable and more user friendly to increase the level of implementation and use by stakeholders in general. Here, it should be noted that flexibility to be implemented in different cases does not necessarily come with greater complexity.

Involvement of stakeholders and establishing suitable advisory and management structures to enhance implementation of IEEFMs may be particularly challenging in the EU which consists of a variety of member countries bound together with several supra-national institutions (Marchal et al., 2016). The scientific management advice in the EU and Iceland for conservation and utilization of the resources is mainly conducted by scientists using IEEFMs for providing advice although there are informal consultations in decision-making. In contrast, there are mandatory and formalized consultations with stakeholders both in scientific advice and in decision-making in Australia, USA and New Zealand allowing IEEFMs to be used in an interactive and integrative way for providing commonly agreed advice for management. (Marchal et al., 2016). In USA, there have been some problems with insufficient trust in the management institutions or processes or a lack of trust between different stakeholders; in this case, integrated models will not evolve and not be used. It takes a long time to build up trust in the management structures and between the user groups in order to cooperate on IEEFM approaches. In a review on implementation of ecosystem models, Hyder et al., (2015) conclude that it is necessary to establish a stronger link to social and economic systems to increase the range of policy-related questions that the models can address, and it is also important to improve communication between policy and modelling communities so there is a shared understanding of the strengths and limitations in the use of ecosystem models.

The EU and member states have invested considerable resources to develop various multispecies and ecosystem models for different marine ecosystems and regional seas and, in parallel, to conduct field programs advancing process knowledge on biological and trophodynamic interactions and the response of food webs to anthropogenic changes in environmental conditions. Strong evidence has accumulated across all EU waters for the importance of accounting for the dynamics of species interactions when attempting to understand and predict the response of fisheries resources to ecosystem change. As a result, multispecies and ecosystem models exist for all regions. For every proposal of a new EU fisheries regulation, the European Commission is required to provide an assessment of ecological, economic and social impacts of the regulation. Over the last decade, several impact assessments have been undertaken applying the available bio-economic models. In particular, in EU research projects, the models for this have been further developed and implemented to be able to provide the necessary tools for the assessments (see Supplementary Material S4 for details of implementation of various IEEFMs through a row of extensive projects).

ICES has in its latest Strategic Plan (www.ices.dk;05Apr2017) explicitly requested integrated fisheries management advice and defined advisory needs for IEEFMs. It seems that adequate methods and relevant advanced IEEFMs are already developed and in place to meet these advisory demands according to the management types used in ICES context. Also, relevant model developer expertise exists on national basis within the ICES member countries besides the global experiences and methods for model evaluation outlined in this paper which can be directly used in ICES context. Given the model evaluation methods developed and the experiences outlined above it will, however, be necessary to formally establish integrated ICES working groups where economists, biologists and sociologists can interact. It will also be important to allow for and promote involvement of stakeholders in using IEEFMs for management advice.

4.4 | CONCLUSIONS

Managers of marine resources must balance diverse and often competing interests and must make decisions about highly complex systems with limited and imprecise knowledge. IEEFMs are playing an increasingly important role in supporting this challenging task. They can provide managers with a better and more explicit understanding of how natural and human processes interact to influence outcomes. IEEFMs can provide a means to quantify the trade-offs between different management objectives and how benefits and costs for different groups of stakeholders are affected by management decisions. If model results can be effectively conveyed to stakeholders, or preferably if stakeholder can be involved in development and use of IEEFMs, this can generate greater acceptance of management actions and facilitate more effective implementation.

IEEFMs represent complex systems, and modellers face trade-offs when attempting to limit complexity to make models more tractable and easier for managers and stakeholders to use. Our review suggests that modellers are sometimes reticent to make these trade-offs. Many of the models reviewed are extremely complex and are designed to provide both short-term tactical and long-term strategic advice on a range of management decisions. Many attempt to model multiple species, sometimes with both technical and ecological interactions. This complexity may often be justified, but it places much greater demands on the modellers and the managers to use the models effectively. Modellers need to be willing to invest time into making models user friendly or be prepared to participate directly, and probably repeatedly, in management fora where models and model results can be explained and discussed. This involvement can be beneficial to all parties, leading both to improvement of models and more effective implementation of advice, but can demand substantial time and resources which must be built into the governance process. It may also take time to develop effective processes for using IEEFMs requiring a long-term commitment to integrating multidisciplinary modelling advice into management decision-making. Given the mismatch between the time required for a model to become mature (6 or more years) and the funding duration typically available (3–4 years), there is a need for new funding schemes that support development of models with good documentation and user-friendly, open-source platforms that enable replicability and continuing development and adaptation of the models.

This article is a step towards developing methods and specific tools to evaluate model characteristics and applying a categorization system for these complex models. Future studies should standardize and detail those tools more, for example by quantifying and detailing further the ranges of the different categorizations in the classes, for example level of implementation and the time ranges for short-, medium- or long-term management advice. The evaluation, discussion and feedback on the meta-analysis conducted in the working group, workshop and conference meetings in ICES and IIFET context have led to a more standardized way for model developers to conduct self-assessments of their models.

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SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

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