



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

J. Rasmus Nielsen, Eric Thunberg, Daniel S. Holland, Jorn O. Schmidt, Elizabeth A. Fulton, François Bastardie, André E. Punt, Icarus Allen, Heleen Bartelings, Michel Bertignac, et al.

► To cite this version:

J. Rasmus Nielsen, Eric Thunberg, Daniel S. Holland, Jorn O. Schmidt, Elizabeth A. Fulton, et al.. Integrated ecological–economic fisheries models-Evaluation, review and challenges for implementation. Fish and Fisheries, 2018, 19 (1), pp.1-29. 10.1111/faf.12232 . hal-01561007

HAL Id: hal-01561007

<https://institut-agro-rennes-angers.hal.science/hal-01561007>

Submitted on 12 Jul 2017

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

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

J Rasmus Nielsen^{1,¶}  | Eric Thunberg^{2,¶} | Daniel S Holland^{3,¶} | Jorn O Schmidt^{4,¶} | Elizabeth A Fulton^{5,#} | Francois Bastardie^{1,#} | Andre E Punt^{6,#} | Icarus Allen^{7,*} | Heleen Bartelings^{8,*} | Michel Bertignac^{9,*} | Eckhard Bethke^{10,*} | Sieme Bossier^{1,*} | Rik Buckworth^{11,*} | Griffin Carpenter^{12,*} | Asbjørn Christensen^{1,*} | Villy Christensen^{13,*} | José M Da-Rocha^{14,*} | Roy Deng^{11,*} | Catherine Dichmont^{11,*} | Ralf Doering^{10,*} | Aniol Esteban^{12,*} | Jose A. Fernandes^{7,*} | Hans Frost^{15,*} | Dorleta Garcia^{16,*} | Loic Gasche^{17,*} | Didier Gascuel^{18,*}  | Sophie Gourguet^{19,*} | Rolf A Groeneveld^{20,*} | Jordi Guillén^{21,*} | Olivier Guyader^{19,*} | Katell G Hamon^{8,*} | Ayoe Hoff^{15,*} | Jan Horbowy^{22,*} | Trevor Hutton^{11,*} | Sigrid Lehuta^{17,*} | L Richard Little^{5,*} | Jordi Leonart^{21,*} | Claire Macher^{19,*} | Steven Mackinson^{23,*} | Stephanie Mahevas^{17,*} | Paul Marchal^{24,*} | Rosa Mato-Amboage^{14,*} | Bruce Mapstone^{5,*} | Francesc Maynou^{21,*} | Mathieu Merzéréaud^{19,*} | Artur Palacz^{1,*} | Sean Pascoe^{11,*} | Anton Paulrud^{25,*} | Eva Plaganyi^{11,*} | Raul Prellezo^{16,*} | Elizabeth I vanPutten^{5,*} | Martin Quaas^{4,*} | Lars Ravn-Jensen^{26,*}  | Sonia Sanchez^{27,*} | Sarah Simons^{10,*} | Olivier Thébaud^{19,*} | Maciej T Tomczak^{28,*} | Clara Ulrich^{1,*} | Diana vanDijk^{29,*} | Youen Vermard^{17,*} | Rudi Voss^{4,*} | Staffan Waldo^{30,*}

¹Technical University of Denmark, National Institute of Aquatic Resources, Kgs. Lyngby, Denmark

²Social Sciences Branch, Northeast Fisheries Science Center, NOAA Fisheries Office of Science and Technology, Woods Hole, MA, USA

³Conservation Biology Division, Northwest Fisheries Science Center, NMFS, NOAA Fisheries Office of Science and Technology, Seattle, WA, USA

⁴Department of Economics, Christian-Albrechts-Universität zu Kiel, Kiel, Germany

⁵CSIRO Oceans and Atmosphere, Marine Laboratories, Hobart, TAS, Australia

⁶School of Aquatic and Fishery Sciences, University of Washington, Seattle, WA, USA

⁷Plymouth Marine Laboratory (Sea and Society) Prospect Place, Plymouth, UK

⁸Wageningen Economic Research, Wageningen University, WUR, The Hague, The Netherlands

⁹Unité Science et Technologies Halieutique, STH French Research Institute for Exploitation of the Sea, Ifremer, Plouzané, France

¹⁰Thünen Institute of Sea Fisheries, Hamburg, Germany

¹¹CSIRO Oceans and Atmosphere, Queensland Biosciences Precinct, St Lucia, QLD, Australia

¹²New Economics Foundation, London, UK

¹³The University of British Columbia, Institute for the Oceans and Fisheries, Vancouver, BC, Canada

[¶]Authorship equal for these lead authors.

[#]Authorship equal for these authors.

^{*}Authorship equal for these authors.

This is an open access article under the terms of the Creative Commons Attribution-NonCommercial-NoDerivs License, which permits use and distribution in any medium, provided the original work is properly cited, the use is non-commercial and no modifications or adaptations are made.

© 2017 The Authors. *Fish and Fisheries* Published by John Wiley & Sons Ltd.

¹⁴Escuela de Comercio, Universidade de Vigo, Vigo, Spain

¹⁵Department of Food and Resource Economics, University of Copenhagen, Copenhagen, Denmark

¹⁶AZTI, Txatxarramendi Ugarteia z/g, Sukarrieta, Spain

¹⁷Unité Ecologie et Modèles pour l'Halieutiques, EMH French Research Institute for Exploitation of the Sea, Ifremer, Nantes, France

¹⁸UMR Ecology and Ecosystem Health (ESE), Université Bretagne Loire (UBL), Rennes, France

¹⁹Unité d'Economie Maritime, AMURE French Research Institute for Exploitation of the Sea, Ifremer, Plouzané, France

²⁰Environmental Economics and Natural Resources Group, Wageningen University WUR, Wageningen, The Netherlands

²¹Spanish National Research Council, Institut de Ciències del Mar, CSIC, Barcelona, Spain

²²National Marine Fisheries Research Institute, Gdynia, Poland

²³Scottish Pelagic Fishermen's Association, Fraserburgh, UK

²⁴Unité Halieutique de Manche Mer du Nord, HMMM, IURHF French Research Institute for Exploitation of the Sea, Ifremer, Boulogne-sur-Mer, France

²⁵Swedish Agency for Marine Water Management, Göteborg, Sweden

²⁶Department of Environmental and Business Economics, University of Southern Denmark, Esbjerg, Denmark

²⁷AZTI, Herrera Kaia – Portualdea z/g, Pasaia, Spain

²⁸Baltic Sea Centre, Stockholm University, Stockholm, Sweden

²⁹Swiss Federal Institute of Aquatic Science and Technology, Dübendorf, Switzerland

³⁰Department of Economics, Swedish University of Agricultural Sciences, Lund, Sweden

Correspondence

J Rasmus Nielsen, Technical University of Denmark, National Institute of Aquatic Resources, Kgs. Lyngby, Denmark.
Email: rn@aqu.dtu.dk

Present addresses

Rik Buckworth, Charles Darwin University,
PO Box 304, NT 0815, Australia.

Cathy M Dichmont, Cathy Dichmont
Consulting, 47 Pioneer Road, Sheldon, QLD,
Australia.

Artur Palacz, Institute of Oceanology of the
Polish Academy of Sciences, Powstańców
Warszawy 55, 81-712 Sopot, Poland.

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; Mullan 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; Mullan, 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, Hutchings, & 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 Mullan et al., (2009) and Mullan (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	NPFTPBM
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

(Continues)

TABLE 1 (Continued)

No.	Model name	Model abbreviation
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

^aCrab Ocean Acidification (CRAB ACID) is based on the Crab ABC model so results are combined for reporting.

^bMAQ-ADJ is based on MAQ with an added restriction on quota adjustments so results are reported only for MAQ-ADJ.

^cFISHRENT 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

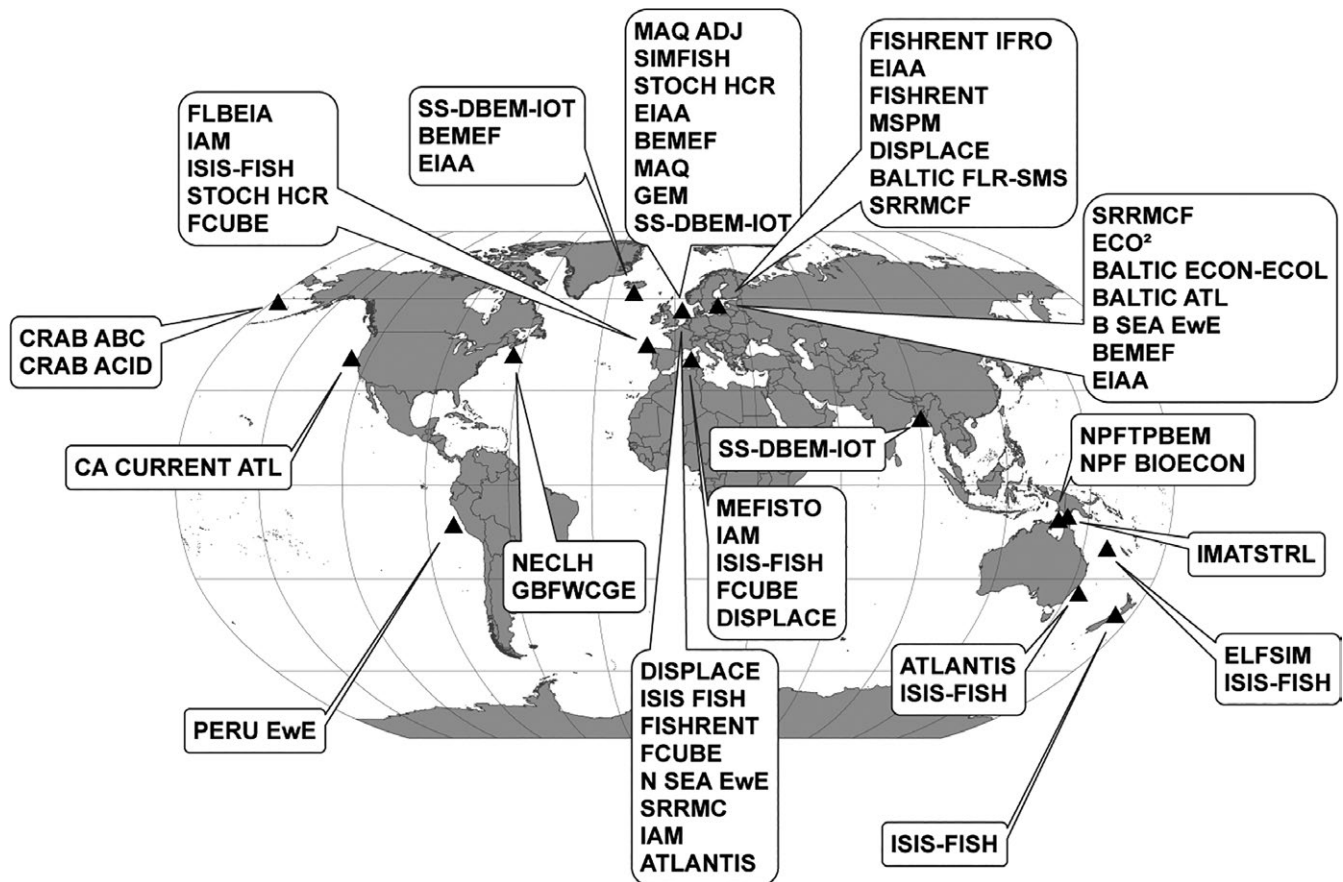


FIGURE 1 Overview of main model applications and implementation

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	ECO ²	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, Lorange, 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; Skonhøft 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	NPFTPBE	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, Urtizberra, 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.

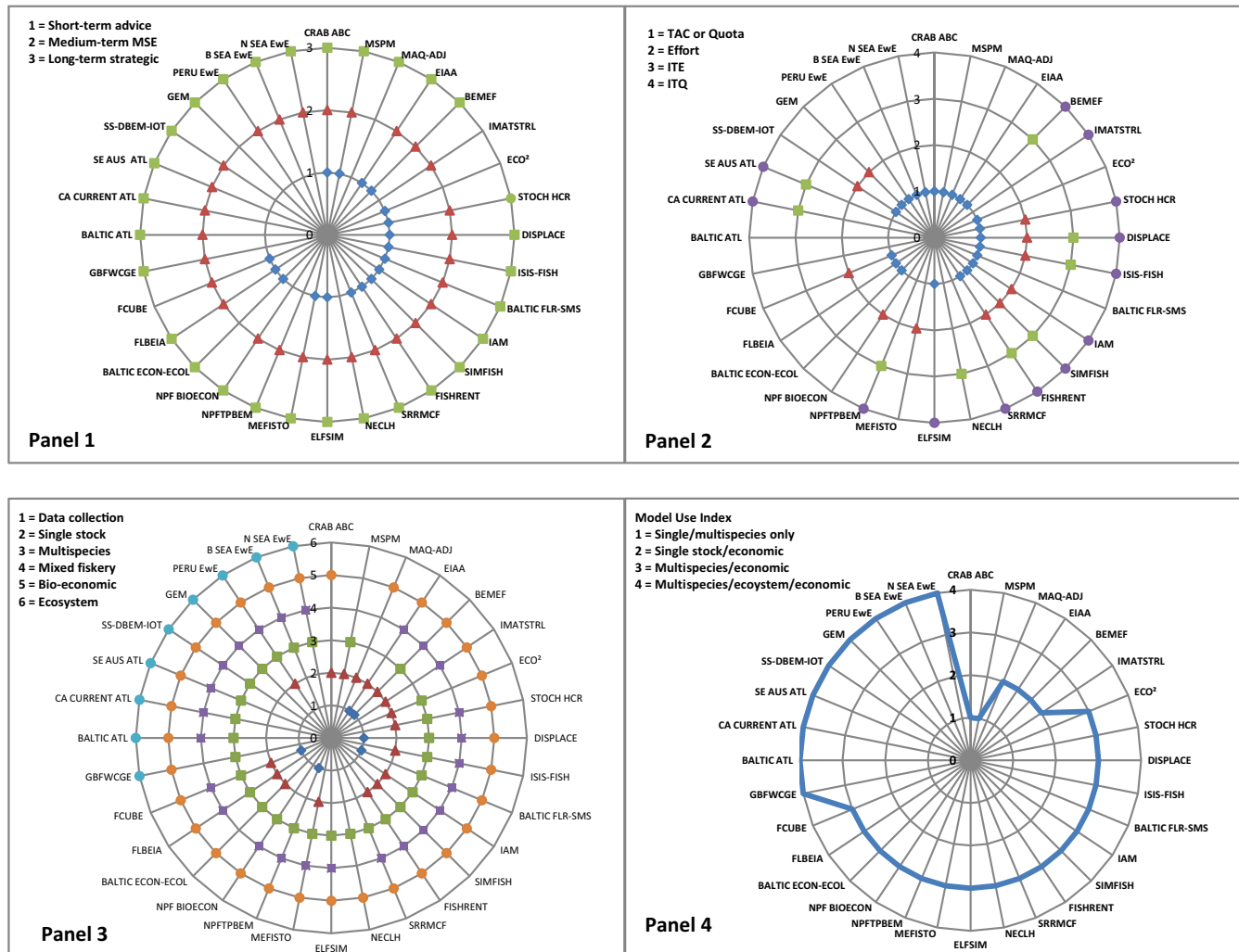


FIGURE 2 Model capabilities Panel 1—model design capabilities to provide short-term tactical, medium-term MSE or long-term strategic advice; Panel 2—model capability to provide management advice on setting TACs, effort limits, ITE and ITQ; Panel 3—model structural characteristics in terms of advice on 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

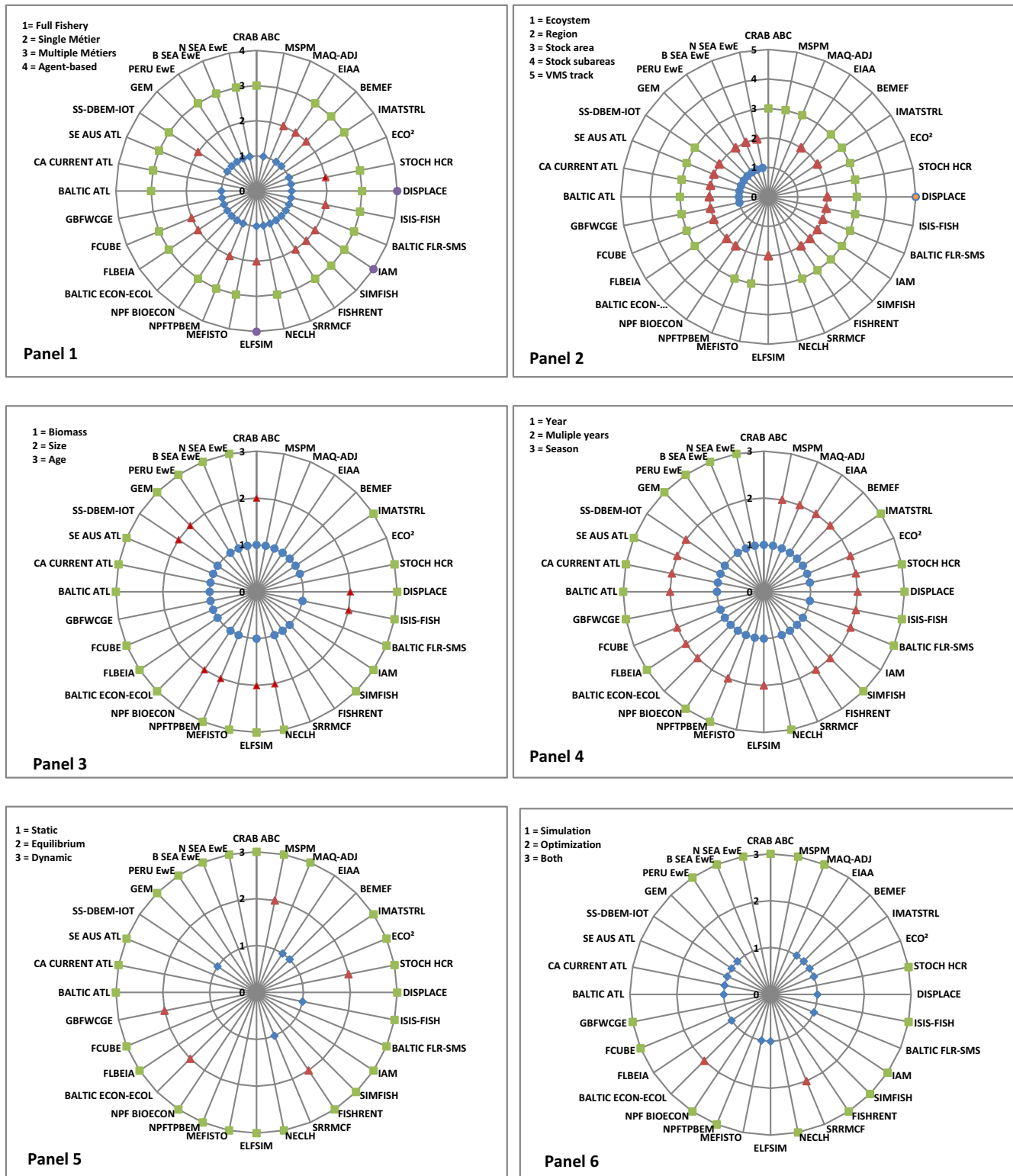


FIGURE 3 Model characteristics Panel 1—model fishing fleet characteristics (entire fishery, métiers or agent-based); Panel 2—model spatial resolution characteristics (VMS track, subarea, stock area, regions, or ecosystem); Panel 3—model biological characteristics (age-structured, size-structured, or 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

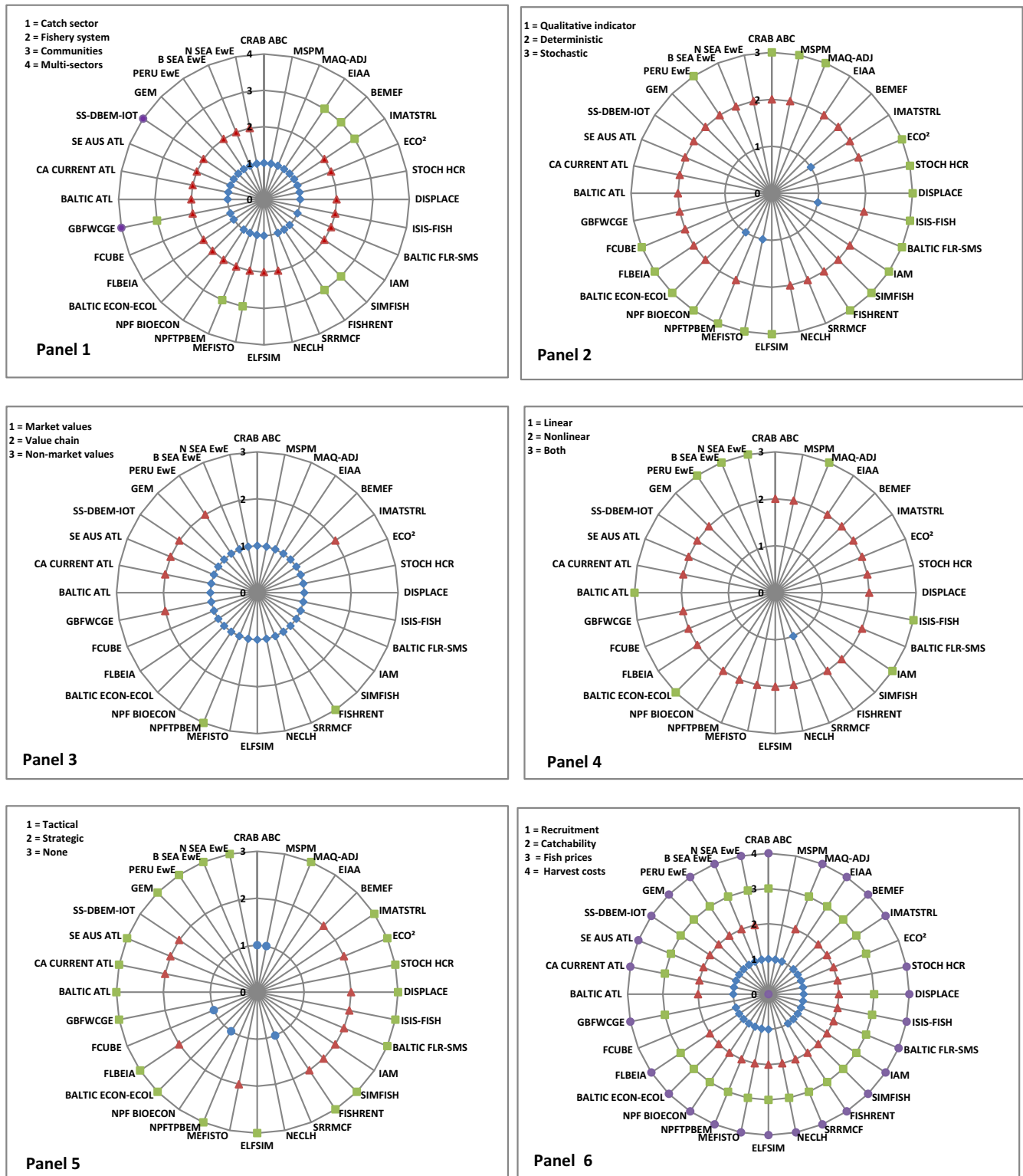


FIGURE 4 Model characteristics Panel 1—fishing sector components (catch sector, fishery system including processing and distribution, communities, and multiple sectors of a local or regional economy); Panel 2—estimation of model parameters (qualitative indicators, deterministic or stochastic parameters), 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.

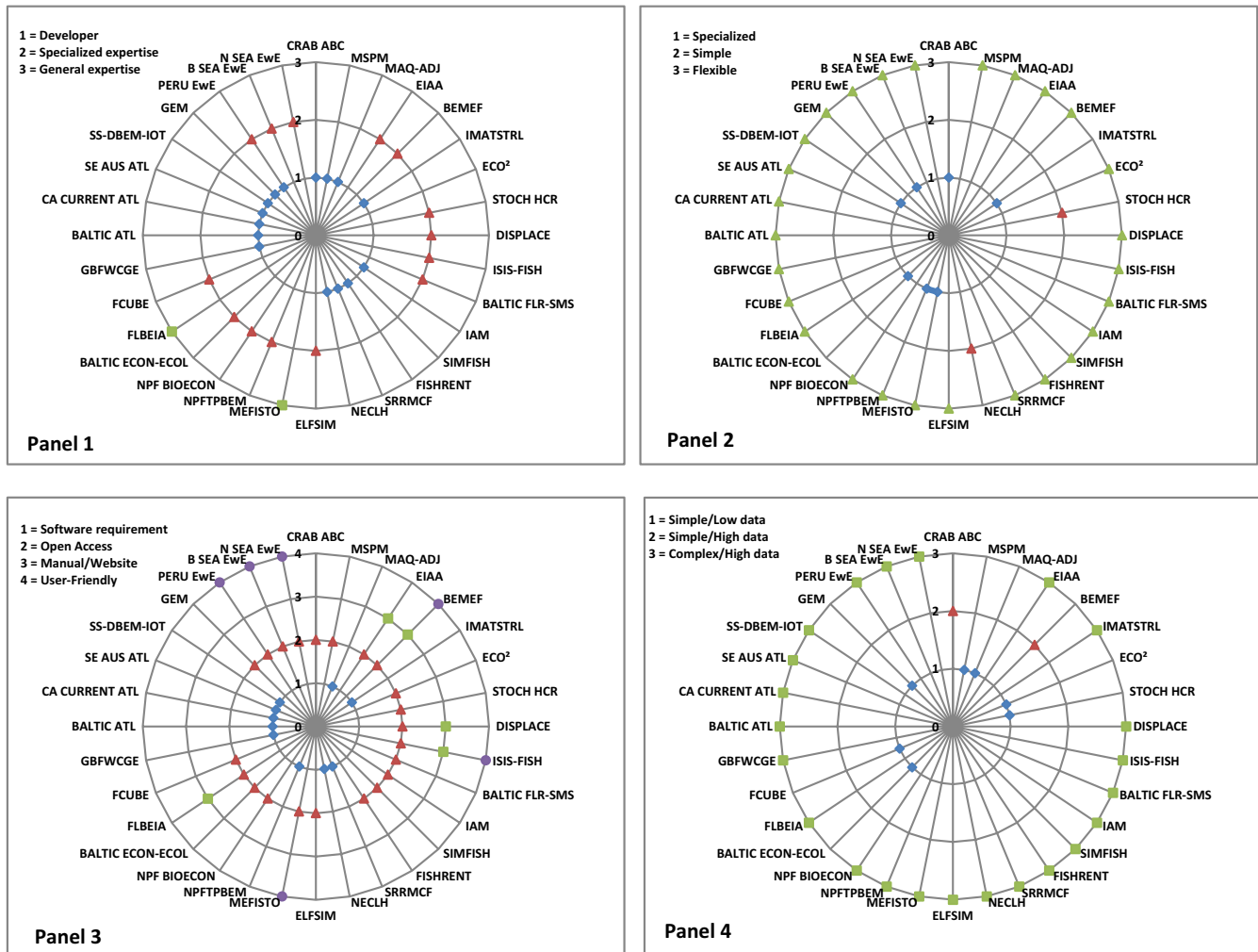


FIGURE 5 Model trade-offs Panel 1—expertise required to conduct model runs (developer, specialized expertise or training, or general expertise); Panel 2—model applications (specialized, simple or flexible); Panel 3—model accessibility to end users (software required, open access and user-friendliness); 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 ECO² 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

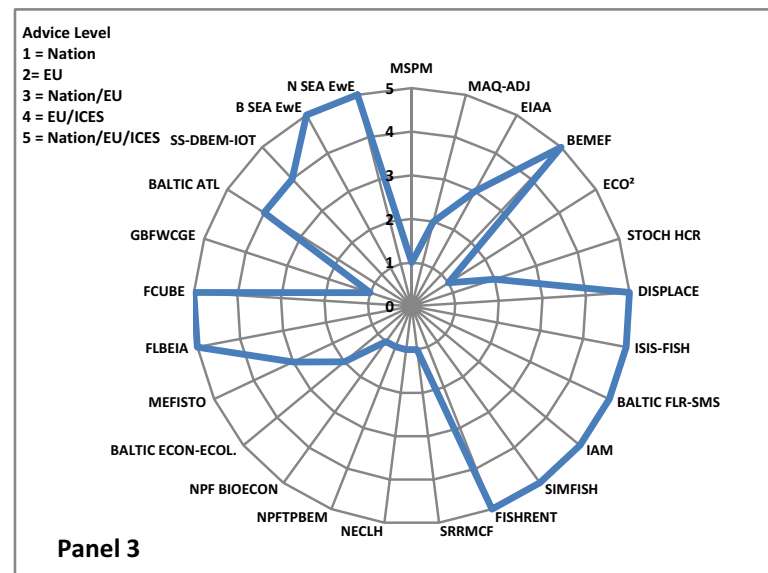
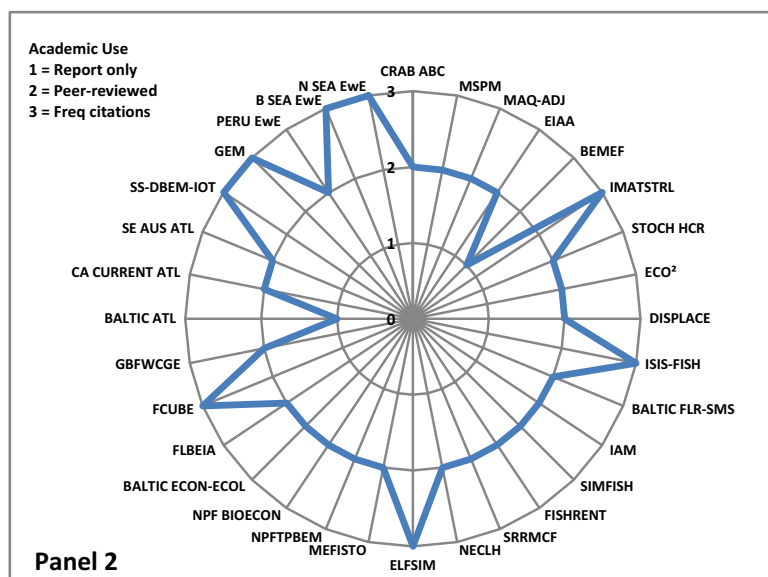
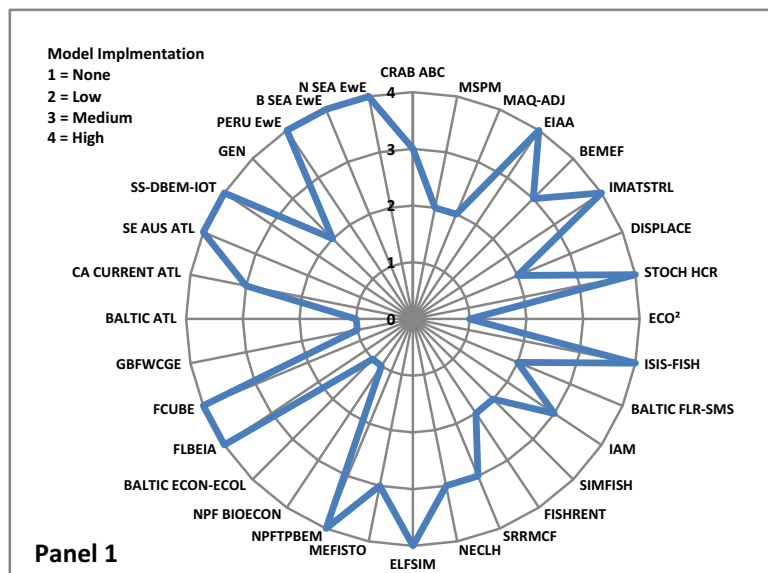


FIGURE 6 : Summary of model use
 Panel 1—model implementation (none, low, medium, high); Panel 2—academic use (models that only have technical reports, models that have been published in the peer-reviewed literature and models that have been widely cited), Panel 3—level of advice for models (National,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

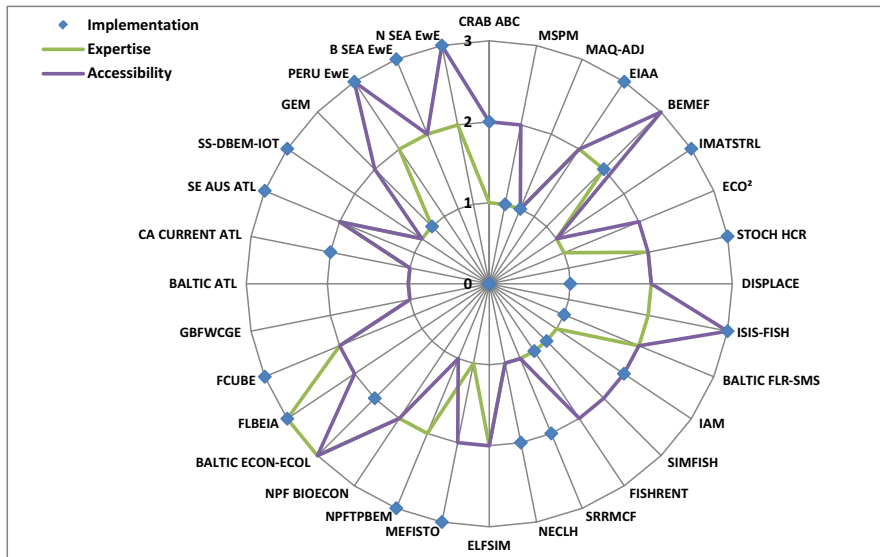


FIGURE 7 Effect of model accessibility and required expertise on model implementation

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 multispecies 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, ECO², 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 marker 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, NPFTPBEIM, 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, NPFTPBE, 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, ECO₂, SRRMCF, NECLH, NPFTPBE, 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.

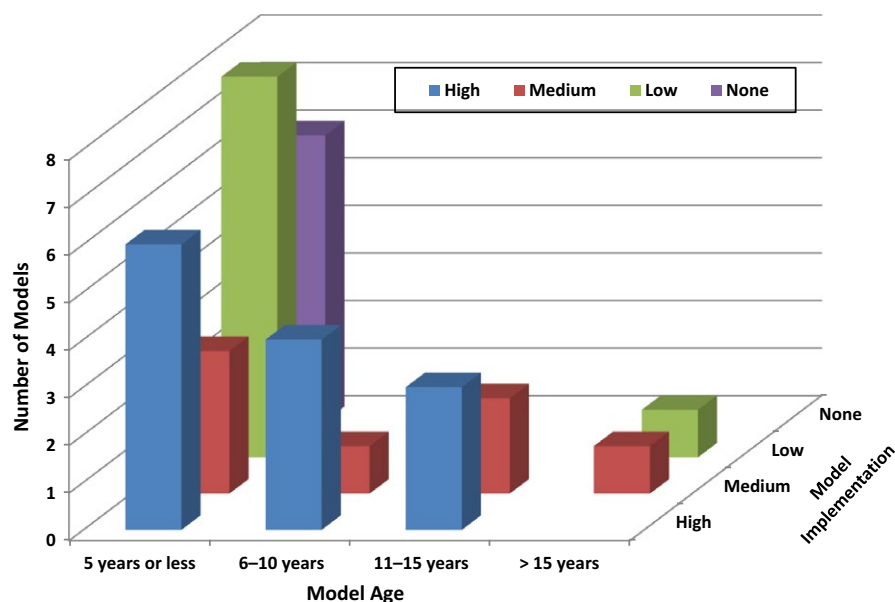


FIGURE 8 Relationship between model age and model use

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 modelers 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.

ACKNOWLEDGEMENTS

This work has been conducted partly under the ICES Working Group for Integrated Management Modelling (ICES WGIMM).

REFERENCES

- Andersen, P., Andersen, J. L., & Mardle, S. (2014). *What's going to happen with the EU's discard policy? IIFET 2014 Australia Conference Proceedings*. Available at: <http://ir.library.oregonstate.edu/xmlui/bitstream/handle/1957/54625/Mardle%20333.pdf?sequence=4>
- Andersen, K. H., Brander, K., & Ravn-Jonsen, L. J. (2014). Trade-offs between objectives for ecosystem management of fisheries. *Ecological Applications*, 25, 390–1396.
- Arnason, R. (2002). *A review of international experiences with ITQs: An annex to Future options for UK fish quota management*. CEMARE Rep. 58, 64p.
- Bartelings, H., Hamon, K. G., Berkenhagen, J., & Buisman, F. C. (2015). Bio-economic modelling for marine spatial planning application in North Sea shrimp and flatfish fisheries. *Environmental Modelling & Software*, 74, 156–172.

- Bastardie, F., Baudron, A., Bilocca, R., Boje, J., Bult, T. P., Garcia, D., ... Ulrich, C. (2009). Evaluating biological robustness of innovative management alternatives. In K. H. Hauge, & D. C. Wilson (Eds.), *Comparative evaluations of innovative fisheries management: Global experiences and European prospects*. Dordrecht, The Netherlands: Springer Publishing, Dordrecht.
- Bastardie, F., Nielsen, J. R., Andersen, B. S., & Eigaard, O. (2010). Effects of fishing effort allocation scenarios on energy efficiency and profitability: An individual-based model applied to Danish fisheries. *Fisheries Research*, 106, 501–516.
- Bastardie, F., Nielsen, J. R., Andersen, B. S., & Eigaard, O. (2013). Integrating individual trip planning in energy efficiency – Building decision tree models for Danish fisheries. *Fisheries Research*, 143, 119–130.
- Bastardie, F., Nielsen, J. R., Eero, M., Fuga, F., & Rindorf, A. (2017). Impacts of changes in stock productivity and mixing on stock sustainability and fishery economic viability. *ICES Journal of Marine Science*, 74(2), 535–551.
- Bastardie, F., Nielsen, J. R., Eigaard, O., Fock, O. H., Jonsson, P., & Bartolino, V. (2015). Competition for marine space: Modelling the Baltic Sea fisheries and effort displacement under spatial restrictions. *ICES Journal of Marine Science*, 72(3), 824–840.
- Bastardie, F., Nielsen, J. R., & Kraus, G. (2010). Management strategy evaluation framework for the Eastern Baltic cod fishery to test robustness of management against environmental conditions and fleet response scenarios. *ICES Journal of Marine Science*, 67, 71–86.
- Bastardie, F., Nielsen, J. R., & Mithé, T. (2014). Displace: A dynamic, individual-based model for spatial fishing planning and effort displacement – Integrating underlying fish population models. *Canadian Journal of Fisheries and Aquatic Science*, 71, 1–21.
- Bastardie, F., Nielsen, J. R., & Vinther, M. (2015). *Causes and consequences of technical, biological and spatial interactions in fisheries management modelled from the individual distribution of fishing effort*. CM 2015/M:03.
- Bastardie, F., & Nielsen, J. R. (2011). *Stock-based and fleet-based evaluation of the multi-annual management plan for the cod stocks in the Baltic Sea with respect to cod stock mixing and TAC vs. effort regulation under different constraints and stock conditions*. Work. Doc., 40 pp. In: Simmonds et al. (eds). 2011. Report of the Sub Group on Impact Assessment of Baltic cod multi-annual plans. EU STECF EWG-11-07a. Hamburg (D), 20–24 June 2011. Luxembourg: Publications Office of the European Union, 2011. ISSN 1018-5593 (print).
- Bastardie, F., Vinther, M., & Nielsen, J. R. (2012). *Impact assessment (IA) of alternative HCRs to the current multiannual Baltic Sea plan on the bio-economy of fleets – Coupling the SMS model to the FLR Baltic model*. Working Document, 36 pp. Appendix 3. In: Multi-Species Management Plans for the Baltic (Simmonds and Jardim eds). EU-EWG-12-02 Rostock March 2012 STECF 12-06 Report, March 2012. Luxembourg: Publications Office of the European Union. ISSN 1831-9424 (print).
- Bastardie, F., Vinther, M., Nielsen, J. R., Ulrich, C., & Storr-Paulsen, M. (2010). Stock-based vs. fleet-based evaluation of the multi-annual management plan for the cod stocks in the Baltic Sea. *Fisheries Research*, 101, 188–202.
- Basurko, O. C., Gabina, G., & Uriondo, Z. (2013). Energy performance of fishing vessels and potential savings. *Journal of Cleaner Production*, 54, 30–40.
- Beddington, J. R., Agnew, D. J., & Clark, C. W. (2007). Current problems in the management of marine fisheries. *Science*, 316(5832), 1713–1716.
- Bethke, E. (2013a). *The Eco² model – A basic bio-economic module for the description of the dynamics of cohort biomass on exploitation (July 12, 2013)*. Available at: SSRN: <http://ssrn.com/abstract=2309280> or <https://doi.org/10.2139/ssrn.2309280> (01 Nov 2016).
- Bethke, E. (2013b). *Beverton and Holt reloaded – Incorporating variable growth into a yield per recruit model*. Available at: SSRN: <http://ssrn.com/abstract=2310545> (01 Nov 2016) or <https://doi.org/10.2139/ssrn.2310545> (01 Nov 2016).
- Bethke, E. (2015). *Maximum feeding rations and maximum growth rates as a function of temperature – Derived by using a traditional feeding chart for rainbow trout (Oncorhynchus mykiss)*. Available at: SSRN: <http://ssrn.com/abstract=2634000> (01 Nov 2016) or <https://doi.org/10.2139/ssrn.2634000> (01 Nov 2016).
- Bethke, E. (2016). *A simple age- and growth-dependent sequential selectivity function for trawls – An additional module for the Eco²-model*. Available at: SSRN, <http://ssrn.com/abstract=2737823> (01 Nov 2016) or <https://doi.org/10.2139/ssrn.2737823> (01 Nov 2016).
- Bethke, E., Bernreuther, M., & Tallman, R. F. (2013). *Feed efficiency versus feed conversion ratio – Demonstrated on feeding experiments with Juvenile Cod (Gadus Morhua)*. Available at: SSRN, <http://ssrn.com/abstract=2313137> or <https://doi.org/10.2139/ssrn.2313137> (01 Nov 2016).
- Bevilacqua, A. H., Carvalho, A. R., Angelini, R., Steenbeek, J., & Christensen, V. (In Prep). Value chain analysis of income distribution in a small-scale fishery. *Ecological Economics* (MS in Prep).
- Bjørndal, T., Lane, D. E., & Weintraub, A. (2004). Operational research models and the management of fisheries and aquaculture: A review. *European Journal of Operational Research*, 156, 533–540.
- Branch, T. A., Watson, R., Fulton, E. A., Jennings, S., McGilliard, C. R., Pablico, G. T., ... Tracey, S. R. (2010). The trophic fingerprint of marine fisheries. *Nature*, 468, 431–435.
- Butterworth, D. S., Bentley, N., De Oliveira, J. A. A., Donovan, G. P., Kell, L. T., Parma, A. M., ... Stokes, T. K. (2010). Purported flaws in management strategy evaluation: Basic problems or misinterpretations? *ICES Journal of Marine Science*, 67, 567–574.
- Carpenter, G., & Esteban, A. (2015). *Managing EU fisheries in the public interest*. New Economics Foundation Available at: http://b3cdn.net/nefoundation/e2a0356a6c69ec0cc6_ygm6bznj3.pdf
- Christensen, V., De la Puente, S., Sueiro, J. C., Steenbeek, J., & Majluf, P. (2014). Valuing seafood: The Peruvian fisheries sector. *Marine Policy*, 44, 302–311.
- Christensen, V., & Pauly, D. (1992). ECOPATH II – A software for balancing steady-state ecosystem models and calculating network characteristics. *Ecological Modelling*, 61, 169–185.
- Christensen, V., Steenbeek, J., & Failler, P. (2011). A combined ecosystem and value chain modeling approach for evaluating societal cost and benefit of fishing. *Ecological Modelling*, 222, 857–864.
- Christensen, V., & Walters, C. J. (2004). Ecopath with Ecosim: Methods, capabilities and limitations. *Ecological Modelling*, 172, 109–139.
- Colléter, M., Valls, A., Guitton, J., Gascuel, D., Pauly, P., & Christensen, V. (2015). Global overview of the applications of the Ecopath with Ecosim modelling approach using the EcoBase models repository. *Ecological Modelling*, 302, 42–53.
- Conrad, J. (1995). Bioeconomic models of the fishery. In: D. Bromley (Ed.), *Handbook of environmental Economics* (pp. 405–432). Oxford, UK: Blackwell.
- Cormier, R., Kannen, A., Elliott, M., & Hall, P. (2015). *Marine spatial planning quality management system*. ICES Cooperative Research Report No. 327, 106 pp.
- Da-Rocha, J. M., Cerviño, S., & Gutiérrez, M. J. (2010). An endogenous bio-economic optimization algorithm to evaluate recovery plans: An application to Southern Hake. *ICES Journal of Marine Science*, 67(9), 1957–1962.
- Da-Rocha, J. M., & Gutiérrez, M. J. (2011). Lessons from the northern hake long-term management plan: Could the economic assessment have accepted it? *ICES Journal of Marine Science*, 68(9), 1937–1941.
- Da-Rocha, J. M., Gutiérrez, M. J., & Antelo, L. T. (2012). Pulse vs. optimal stationary fishing: The Northern stock of hake. *Fisheries Research*, 121–122, 51–62.
- Da-Rocha, J. M., Gutiérrez, M. J., & Antelo, L. T. (2013). Selectivity, pulse fishing and endogenous lifespan in Beverton-Holt models. *Environmental Resource Economics*, 54(1), 139–154.
- Da-Rocha, J. M., Gutiérrez, M. J., & Cerviño, S. (2012). Reference points based on dynamic optimisation: A versatile algorithm for mixed fishery

- management with bio-economic age-structured models. *ICES Journal of Marine Science*, 69(4), 660–669.
- Da-Rocha, J. M., Gutiérrez, M. J., Cerviño, S., & Antelo, L. T. (2012). "logMSY" and optimal harvesting control rules: New tools for the implementation of the European Common Fisheries Policy. *Ocean Coastal Management*, 70, 48–53.
- Da-Rocha, J. M., Gutiérrez, M. J., & García-Cutrin, J. (2016). *Harvesting Control Rules that deals with Scientific Uncertainty WP*. Available at: https://www.researchgate.net/publication/301887234_Harvesting_Control_Rules_that_deal_with_Scientific_Uncertainty (01Mar2017).
- Da-Rocha, J. M., Gutiérrez, M. J., García-Cutrin, J., & Jardim, E. (2015). Fleet behaviour, management plans and endogenous fishing mortalities fluctuations. In: E. Jardim & I. Mosqueira (Eds.), *Multiannual management plans SWW and NWW*, STECF-15-08 EUR – Scientific and Technical Research series. ISSN 1831-9424 (online); ISSN 1018-5593 (print).
- Da-Rocha, J. M., Gutiérrez, M. J., García-Cutrin, J., & Jardim, E. (2017). Endogenous fishing mortalities: A state-space bioeconomic model. *ICES Journal of Marine Science*. <https://doi.org/10.1093/icesjms/fsx067>
- Da-Rocha, J. M., Gutiérrez, M. J., García-Cutrin, J., & Touza, J. (2016). Reconciling yield stability with international fisheries agencies precautionary preferences: The role of non constant discount factors in age structured models. *Fisheries Research*, 173, 282–293.
- Da-Rocha, J. M., & Mato-Amboage, R. (2016). On the benefits of including age-structure in Harvest control rule. *Environmental and Resource Economics*, 64(4), 619–641.
- Da-Rocha, J. M., & Sempere, J. (2016). ITQs, firm dynamics and wealth distribution: Does full tradability increase inequality? *Environmental and Resource Economics*. Available at: <https://doi.org/10.1007/s10640-016-0017-3> (01Mar2017).
- Da-Rocha, J. M., & Pujolas, P. (2011). Vessel dynamics, itq's and endogenous vessels distributions. In: J. Simmons et al. (Eds.), *Impact Assessment of multi-annual plans for Southern hake, angler fish and Nephrops*. STECF-11-06 EUR – Scientific and Technical Research series ISSN 1831-9424 (online), ISSN 1018-5593 (print).
- Daurès, F., Trenkel, V. M., & Guyader, O. (2013). Modelling the fishing costs of French commercial vessels in the Bay of Biscay. *Fisheries Research*, 146, 74–85.
- De Marchi, B., Funtowicz, S. O., Lo Cascio, S., & Munda, G. (2000). Combining participative and institutional approaches with multicriteria evaluation. An empirical study for water issues in Troina. *Sicily. Ecological Economics*, 34, 267–282.
- Degnbol, D., & Wilson, D. C. (2008). Spatial planning on the North Sea: A case of cross-scale linkages. *Marine Policy*, 32, 189–200.
- Deng, R. A., Punt, A. E., Dichmont, C. M., Buckworth, R. C., & Burrige, C. Y. (2015). Improving catch prediction for tiger prawns in the Australian northern prawn fishery. *ICES Journal of Marine Science*, 72(1), 117–129.
- Dichmont, C., Deng, A., Punt, A. E., Ellis, N., Venables, W., Kompas, T., ... Bishop, J. (2008). Beyond biological performance measures in management strategy evaluation: Bringing in economics and the effects of trawling on the benthos. *Fisheries Research*, 94, 238–250.
- Dichmont, C. M., Deng, R. A., Punt, A. E., Venables, W. N., & Hutton, T. (2012). From input to output controls in a short-lived species: The case of Australia's Northern Prawn Fishery. *Marine and Freshwater Research*, 63(8), 727–739.
- Dichmont, C. M., Pascoe, S., Kompas, T., Punt, A. E., & Deng, R. (2010). On implementing maximum economic yield in commercial fisheries. *Proceedings of the National Academy of Sciences*, 107(1), 16–21.
- Dichmont, C. M., Punt, A. E., Deng, A., Dell, Q., & Venables, W. (2003). Application of a weekly delay-difference model to commercial catch and effort data for tiger prawns in Australia's Northern Prawn Fishery. *Fisheries Research*, 65, 335–350.
- DISPLACE Model Website. Available at: www.displace-project.org (01Apr 2017).
- Douvere, F. (2008). The importance of marine spatial planning in advancing ecosystem-based sea use management. *Marine Policy*, 32, 762–771.
- Drouineau, H., Mahévas, S., Bertignac, M., & Duplisea, D. (2010). A length-structured spatially explicit model for estimating hake growth and migration rates. *ICES Journal of Marine Science*, 67(8), 1697–1709.
- Drouineau, H., Mahévas, S., Pelletier, D., & Beliaeff, B. (2006). Assessing the impact of different management options using ISIS-Fish: The French Merluccius merluccius–Nephrops norvegicus mixed fishery of the Bay of Biscay. *Aquatic Living Resources*, 19(1), 15–29.
- Duplisea, D. (2010). A length-structured spatially explicit model for estimating hake growth and migration rates. *ICES Journal of Marine Science*, 67(8), 1697–1709.
- Ehler, C., & Douvère, F. (2009). *Marine spatial planning: A step-by-step approach toward ecosystem-based management*. Intergovernmental Oceanographic Commission and Man and the Biosphere Programme. IOC Manuals and Guidelines No 53. ICAM Dossier No 6, UNESCO, Paris, 98 pp.
- EU. (2014). *Directive 2014/89/EU OF THE European Parliament and of the Council of 23 July 2014 establishing a framework for maritime spatial planning*. Publications Office of the European Union, Luxembourg OJ L157. 28.8.2014, p. 135.
- EU STECF. (2015a). *Scientific, Technical and Economic Committee for Fisheries (STECF) Multiannual management plans SWW and NWW*. Publications Office of the European Union, Luxembourg STECF-15-08 EUR 27406 EN, JRC 96964, 82 pp.
- EU STECF. (2015b). *Scientific, Technical and Economic Committee for Fisheries (STECF) – Evaluation of management plans: Evaluation of the multi-annual plan for the North Sea demersal stock*. Publications Office of the European Union, Luxembourg STECF-15-02, 152 pp.
- EU STECF. (2015c). *Scientific, Technical and Economic Committee for Fisheries. Evaluation of management plans. Evaluation of the multi-annual plan for the North Sea demersal stocks*. Publications Office of the European Union, Luxembourg STECF-15-04.
- FAO. (2008). *Best practices in ecosystem modelling for informing an ecosystem approach to fisheries*. FAO Fisheries Technical Guidelines for Responsible Fisheries No. 4, Suppl. 2, Add. 1, Rome, FAO, 1–78.
- Feekings, J. P., Bastardie, F., Nielsen, J. R., Lund, H., & Frandsen, R.. *Can changing the MLS for Norway Lobster (Nephrops norvegicus) improve the biological and economic performance of the Skagerrak and Kattegat demersal trawl fisheries? A bio-economic analysis of consequences under both landings and catch quota management systems*. (Submitted).
- Fernandes, J. A., Cheung, W. W., Jennings, S., Butenschön, M., de Mora, L. Frölicher, T. L., ... Grant, A., (2013). Modelling the effects of climate change on the distribution and production of marine fishes: Accounting for trophic interactions in a dynamic bioclimate envelope model. *Global Change Biology*, 19, 2596–2607.
- Fernandes, J. A., Kay, S., Hossain, M. A. R., Ahmed, M., Cheung, W. W. L., Lazar, A. N., & Barange, M. (2016). Projecting marine fish production and catch potential in Bangladesh in the 21st century under long-term environmental change and management scenarios. *ICES Journal of Marine Science*, <https://doi.org/10.1093/icesjms/fsv217>.
- Fernandes, J. A., Papathanasopoulou, E., Queirós, A. M., Cheung, W. W. W., Yool, A., Artioli, Y., ... Barange, M. (2016). Estimating the ecological, economic and social impacts of ocean acidification and warming on UK fisheries. *Fish and Fisheries*, <https://doi.org/10.1111/faf.12183>.
- Frost, H. S., Andersen, P., & Hoff, A. (2011). An application of fisheries economics theory: 100 years after Warming's paper: "Rent of fishing grounds. *Nationaløkonomisk Tidsskrift*, 149(1–3), 55–84.
- Frost, H., Andersen, P., & Hoff, A. (2013). Management of complex fisheries: Lessons learned from a simulation model. *Canadian Journal of Agricultural Economics*, 61(2), 283–307.
- Frost, H., Levring, J. A., Hoff, A., & Thøgersen, T. (2009). *The EIAA model: Methodology, definitions and model outline*. Institute of Food and Resource Economics, University of Copenhagen FOI Report No. 200. Available at: https://curis.ku.dk/portal/files/44693774/Report_200.pdf
- Fulton, E. A., Link, J. S., Kaplan, I. C., Savina-Rolland, M., Johnson, P., Ainsworth, C., ... Smith, D. C. (2011). Lessons in modelling and

- management of marine ecosystems: The Atlantis experience. *Fish and Fisheries*, 12(2), 171–188.
- Fulton, E. A., Smith, A. D. M., Smith, D. C., & Johnson, P. (2014). An integrated approach is needed for ecosystem based fisheries management: Insights from ecosystem-level management strategy evaluation. *PLoS ONE*, 9, e84242.
- García, S. M., & Cochrane, K. L. (2005). Ecosystem approach to fisheries: A review of implementation guidelines. *ICES Journal of Marine Science*, 62, 311–318.
- García, D., Prellezo, R., Sampedro, P., Da-Rocha, J. M., Castro, J., Cerviño, S., ... Gutiérrez, M.-J. (2016). Bioeconomic multistock reference points as a tool for overcoming the drawbacks of the landing obligation. *ICES Journal of Marine Science*, <https://doi.org/10.1093/icesjms/fsw030>.
- García, D., Urtizborea, A., Diez, G., Gil, J., & Marchal, P. (2013). Bio-economic management strategy evaluation of deep water stocks using FLBEIA model. *Aquatic Living Resources*, 26, 365–379.
- García, D., Sanchez, S., Prellezo, R., Urtizborea, A., & Andres, M. (2016). *FLBEIA: A toolbox to conduct Bio-Economic Impact Assessment of fisheries management strategies*. SoftwareX (Under review).
- García, D., Santurtun, M., Prellezo, R., Sanchez, S., & Andres, M. (2012). *FLBEIA: A toolbox for bioeconomic impact assessment of fisheries management strategies*. ICES Annual Science Conference Bergen ICES CM 2012/K:01.
- Gasche, L., Mahevas, S., & Marchal, P. (2013). Supporting Fisheries Management by Means of Complex Models: Can We Point out Isles of Robustness in a Sea of Uncertainty? *PLoS ONE*, 8(10).
- Gascuel, D., Coll, M., Fox, C., Guénette, S., Guitton, J., Kenny, A., ... Shephard, S. (2016). Fishing impact and environmental status in European seas: A diagnosis from stock assessments and ecosystem indicators. *Fish and Fisheries*, 17, 31–55.
- Gilliland, P. M., & Laffoley, D. (2008). Key elements and steps in the process of developing ecosystem-based marine spatial planning. *Marine Policy*, 32, 787–796.
- Girardin, R., Fulton, E. A., Lehuta, S., Savina-Rolland, M., Thébaud, O., Travers-Trolet, M., ... Marchal, P. (2016). Identification of the main processes underlying ecosystem functioning in the Eastern English Channel, with a focus on flatfish species, as revealed through the application of the Atlantis end-to-end model. *Estuarine and Coastal Shelf Science*, <https://doi.org/10.1016/j.ecss.2016.10.016>.
- Gourguet, S., Thébaud, O., Dichmont, C., Jennings, S., Little, L. R., Pascoe, S., ... Doyen, L. (2014). Risk versus economic performance in a mixed fishery. *Ecological Economics*, 99, 110–120.
- Gourguet, S., Thébaud, O., Jennings, S., Little, L. R., Dichmont, C., Pascoe, S., ... Doyen, L. (2016). The cost of co-viability in the Australian Northern Prawn Fishery. *Environmental Modeling & Assessment*, 21(3), 371–389.
- Grimm, V., Berger, U., DeAngelis, D. L., Polhill, J. G., Giske, J., & Railsback, S. F. (2010). The ODD protocol: A review and first update. *Ecological Modelling*, 221, 2760–2768.
- Guillén, J., Macher, C., Merzéréaud, M., Bertignac, M., Fifas, S., & Guyader, O. (2013). Estimating MSY and MEY in multi-species and multi-fleet fisheries, consequences and limits: An application to the Bay of Biscay mixed fishery. *Marine Policy*, 40, 64–74.
- Guillén, J., Macher, C., Merzéréaud, M., Boncoeur, J., & Guyader, O. (2015). Effects of the Share Remuneration System on Fisheries Management Targets and Rent Distribution. *Marine Resource Economics*, 30(2), 123–138.
- Guillén, J., Macher, C., Merzéréaud, M., Fifas, S., & Guyader, O. (2014). The effect of discards and survival rate on the Maximum Sustainable Yield estimation based on landings or catches maximisation: Application to the nephrops fishery in the Bay of Biscay. *Marine Policy*, 50, 207–214.
- Guillén, J., Maynou, F., Floros, C., Sampson, D., Conides, A., & Kostas, K. (2012). A bio-economic evaluation of the potential for establishing a commercial fishery on two newly developed stocks: The Ionian red shrimps fishery. *Scientia Marina*, 76(3), 597–605.
- Heal, G., & Schlenker, W. (2008). Economics: Sustainable fisheries. *Nature*, 455, 1044–1045.
- Heaps, T. (2003). The effects on welfare of the imposition of individual transferable quotas on a heterogeneous fishing industry. *Journal of Environmental Economics and Management*, 46, 557–576.
- Heymans, J. J., Mackinson, S., Sumaila, U. R., Dyck, A., & Little, A. (2011). The impact of subsidies on the ecological sustainability and future profits from North Sea fisheries. *PLoS ONE*, 6(5), e20239.
- Hicks, C. C., Levine, A., Agrawal, A., Basurto, X., Breslow, S. J., Carothers, C., ... Levin, P. S. (2016). Engage key social concepts for sustainability. Social indicators, both mature and emerging, are underused. *Science*, 352, 38–40.
- Hilborn, R. (2007). Managing fisheries is managing people: What has been learned? *Fish and Fisheries*, 8, 285–296.
- Hilborn, R. (2011). Future directions in ecosystem based fisheries management: A personal perspective. *Fisheries Research*, 108, 235–239.
- Hilborn, R., Fulton, E. A., Green, B. S., Hartmann, K., Tracey, S. R., & Watson, R. A. (2015). When is a fishery sustainable? *Canadian Journal of Fisheries and Aquatic Science*, 72, 1433–1441.
- Hill, S. L., Watters, G. M., Punt, A. E., McAllister, M. K., Le Quére, C., & Turner, J. (2007). Model uncertainty in the ecosystem approach to fisheries. *Fish and Fisheries*, 8, 315–336.
- Hoff, A., Frost, H., Ulrich, C., Damalas, D., Maravelias, C. D., Goti, L., & Santurtún, M. (2010). Economic effort management in multispecies fisheries: The FcubEcon model. *ICES Journal of Marine Science*, 67, 1802–1810.
- Holland, D. S. (2011a). Optimal intra-annual exploitation of the Maine Lobster Fishery. *Land Economics*, 87(4), 699–711.
- Holland, D. S. (2011b). Planning for Changing Productivity and Catchability in the Maine Lobster Fishery. *Fisheries Research*, 110(1), 47–58.
- Holling, C. S. (2001). Understanding the complexity of economic, ecological and social systems. *Ecosystems*, 4, 390–405.
- Horbowy, J. (1996). The dynamics of Baltic fish stocks on the basis of a multispecies stock-production model. *Canadian Journal Fisheries Aquatic Sciences*, 53, 2115–2125.
- Horbowy, J. (2005). The dynamics of Baltic fish stocks based of a multi-species stock production model. *Journal of Applied Ichthyology*, 21, 198–204.
- Howarth, L. M., Roberts, C. M., Thurstan, R. H., & Stewart, B. D. (2013). The unintended consequences of simplifying the sea: Making the case for complexity. *Fish and Fisheries*, 15(4), 690–711.
- Hussein, C., Verdoit-Jarraya, M., Pastor, J., Ibrahim, A., Saragoni, G., Pelletier, D., ... Lenfant, P. (2011a). Assessing the impact of artisanal and recreational fishing and protection on a white seabream (*Diplodus sargus sargus*) population in the north-western Mediterranean Sea using a simulation model. Part2: Sensitivity analysis and management measures. *Fisheries Research*, 108(1), 174–183.
- Hussein, C., Verdoit-Jarraya, M., Pastor, J., Ibrahim, A., Saragoni, G., Pelletier, D., ... Lenfant, P. (2011). Assessing the impact of artisanal and recreational fishing and protection on a white seabream (*Diplodus sargus sargus*) population in the north-western Mediterranean Sea using a simulation model. Part 1: Parameterization and simulations. *Fisheries Research*, 108(1), 163–173.
- Hutton, T., Putten, I. V., Pascoe, S., Deng, R., Plagányi, E., & Dennis, D. (2016). Trade-offs in transitions between indigenous and commercial fishing sectors: The Torres Strait Tropical Rock Lobster Fishery. *Fisheries Management and Ecology*, 23, 463–477.
- Hyder, K., Rossberg, A. G., Allen, I., Austen, M. C., Barciela, R. M., Bannister, H. J., ... Paterson, D. M. (2015). Making modelling count increasing the contribution of shelf-seas community and ecosystem models to policy development and Management. *Marine Policy*, 61, 291–302.
- ICES. (2006). *Report of the Working Group on Workshop on Simple Mixed Fisheries Management Models*. ICES CM 2006/ACFM:14
- ICES. (2011). *Annex 5 Report on Key Run for the North Sea Ecopath with Ecosim Ecosystem Model, 1991–2007*. in ICES. 2012. Report of the

- Working Group on Multispecies Assessment Methods (WGSAM), 10–14 October 2011, Woods Hole, USA. ICES CM 2011/SSGSUE:10, 229 pp.
- ICES. (2014a). *Report of the Working Group on Mixed Fisheries Advice for the North Sea (WGMIXFISH-NS)*, 26–30 May 2014, ICES HQ, Copenhagen, Denmark. ICES CM 2014/ACOM:22, 95 pp.
- ICES. (2014b). *Report of the Working Group on Mixed Fisheries Methods (WGMIXFISH-METH)*, 20–24 October 2014, Nobel House, London, United Kingdom. ICES CM 2014/ACOM:23, 79 pp.
- ICES. (2015a). *First Interim Report of the Working Group on Integrating Ecological and Economic Models (ICES WGIMM)*. ICES CM 2015/SSGIEA:05, 15 pp.
- ICES. (2015b). *ICES ASC Theme Session M 2015*. In: Nielsen, J.R., Schmidt, J., Thunberg, E., and Holland D. 2015. Social, economic, and ecological impact assessment across marine sectors. ICES CM 2015/Theme Session M Summary, 3 pp. Available at: www.ices.dk (05Apr2017).
- ICES. (2015c). *Report of the Working Group on Mixed Fisheries Advice Methodology (WGMIXFISH-METH)*, 5–9 October 2015, DTU-Aqua, Charlottenlund, Denmark. ICES CM 2015/ACOM:22, 51 pp.
- ICES. (2015d). *Report of the Working Group on Mixed Fisheries Advice (WGMIXFISH-ADVICE)*, 25–29 May 2015, ICES HQ, Copenhagen, Denmark. ICES CM 2015/ACOM:21, 171 pp.
- Iriondo, A., García, D., Santurtún, M., Castro, J., Quincoces, I., Lehuta, S., ... Ulrich, C. (2012). Managing mixed fisheries in the European western waters: Application of Fcube methodology. *Fisheries Research*, 134–136, 6–16.
- Jardim, E., Urtizberea, A., Motova, A., Osio, C., Ulrich, C., Millar, C., ... Holmes, S.. (2013). *Bioeconomic modelling applied to fisheries with R/FLR/FLBEIA*. JRC Scientific and Policy Report EUR 25823 EN JRC79217.
- Kaplan, I. C., Holland, D. S., & Fulton, E. A. (2014). Finding the accelerator and brake in an individual quota fishery: Linking ecology, economics, and fleet dynamics of US West Coast trawl fisheries. *ICES Journal of Marine Science*, 71, 308–319.
- Kaplan, I. C., Horne, P., & Levin, P. S. (2009). *Ecosystem-based management of what? An emerging approach for balancing conflicting objectives in marine resource management*. The Future of Fisheries Science in North America, Springer, pp. 77–95.
- Kaplan, I. C., Horne, P. J., & Levin, P. S. (2012). Screening California Current Fishery Management Scenarios using the Atlantis End-to-End Ecosystem Model. *Progress In Oceanography*, 102, 5–18.
- Kaplan, I. C., & Leonard, J. (2012). From krill to convenience stores: Forecasting the economic and ecological effects of fisheries management on the US West Coast. *Marine Policy*, 36, 947–954.
- Kell, L. T., Mosquera, I., Grosjean, P., Fromentin, J.-M., Garcia, D., Hillary, R., ... Scott, R. D. (2007). FLR: An open-source framework for the evaluation and development of management strategies. *ICES Journal of Marine Science*, 64, 640–646.
- Kempf, A., Mumford, J., Levontin, P., Leach, A., Hoff, A., Hamon, K. G., ... Rindorf, A. (2016). The MSY concept in a multi-objective fisheries environment – Lessons from the North Sea. *Marine Policy*, 69, 146–158.
- Kitts, A., Bing-Sawyer, E., Walden, J., Demarest, C., McPherson, M., Christman, P., ... Clay, P. (2011). *Final Report on the Performance of the Northeast Multispecies (Groundfish) Fishery (May 2010; April 2011)*. US Department of Commerce, Northeast Fisheries Science Centre, Ref Doc. 11-19, 97 pp.
- Knowler, D. (2002). A Review of Selected Bioeconomic Models with Environmental Influences in Fisheries. *Journal of Bioeconomics*, 4, 163–181.
- Kraak, S. B. M., Kelly, C. J., Codling, E. A., & Rogan, E. (2010). On scientists' discomfort in fisheries advisory science: The example of simulation-based fisheries management-strategy evaluations. *Fish and Fisheries*, 11, 119–132.
- Langlois, J., Fréon, P., Steyer, J.-P., Delgenés, J.-P., & Hélias, A. (2014). Sea-use impact category in life cycle assessment: State of the art and perspectives. *International Journal Life Cycle Assessment*, 19, 994–1006.
- Lassen, H., Anker Pedersen, S., Frost, H., & Hoff, A. (2013). Fishery management advice with ecosystem considerations. *ICES Journal of Marine Science*, 70(2), 471–479.
- Lehuta, S., Girardin, R., Mahevas, S., Travers-Trolet, M., & Vermard, Y. (2016). Reconciling complex system models and fisheries advice: Practical examples and leads. *Aquatic Living Resources*, 29(208), 1–20.
- Lehuta, S., Holland, D. S., & Pershing, A. J. (2014). Investigating interconnected fisheries: A coupled model of the lobster and herring fisheries in the Northeast US. *Canadian Journal of Fisheries and Aquatic Sciences*, 71(2), 272–289.
- Lehuta, S., Mahévas, S., & Le Floch, P. (2013). Simulation-based bio-economic indicators of management impact: Assessing relevance and robustness for the pelagic fishery of the Bay of Biscay. *Canadian Journal of Fisheries and Aquatic Sciences*, 70(12), 1741–1756.
- Lehuta, S., Mahévas, S., Petitgas, P., & Pelletier, D. (2010). Combining sensitivity and uncertainty analysis to evaluate the impact of management measures with ISIS-Fish: Marine Protected Areas for the Anchovy (*Engraulis encrasicolus* L.) fishery in the Bay of Biscay. *ICES Journal of Marine Science*, 67, 1063–1075.
- Lehuta, S., Petitgas, P., Mahévas, S., Vermard, Y., Huret, M., Uriarte, A., & Record, N. R. (2013). Selection and validation of a complex fishery model using an uncertainty hierarchy. *Fisheries Research*, 143, 57–66.
- Lehuta, S., Vermard, Y., & Marchal, P. (2015). *A spatial model of the mixed demersal fisheries in the Eastern Channel*. In Marine Productivity: Perturbations and Resilience of Socio-Ecosystems. Proceedings 15th French-Japan Oceanographic Symposium 187–95.
- Little, L. R., Punt, A. E., Mapstone, B. D., Begg, G. A., Goldman, B., & Ellis, N. (2009). Different responses to area closures and effort controls for sedentary and migratory harvested species in a multispecies coral reef line fishery. *ICES Journal of Marine Science*, 66, 1931–1941.
- Little, L. R., Punt, A. E., Mapstone, B. D., Begg, G. A., Goldman, B., & Williams, A. J. (2009). An agent-based model for simulating trading of multi-species fisheries quota. *Ecological Modelling*, 220, 3404–3412.
- Little, L. R., Punt, A. E., Mapstone, B. D., Pantus, F., Smith, A. D. M., Davies, C. R., & McDonald, A. D. (2007). ELFSim – A Model for Evaluating Management Options for Spatially-Structured Reef Fish Populations: An Illustration of the “Larval Subsidy” Effect. *Ecological Modelling*, 205, 381–396.
- Leonart, J., Maynou, F., & Franquesa, R. (1999). A bioeconomic model for Mediterranean fisheries. *Fisheries Economy Newsletter*, 48, 1–16.
- Leonart, J., Maynou, F., Recasens, L., & Franquesa, R. (2003). A bioeconomic model for Mediterranean Fisheries, the hake off Catalonia (Western Mediterranean) as a case study. *Scientia Marina*, 67(suppl. 1), 337–351.
- Macher, C., Guyader, O., Talidec, C., & Bertignac, M. (2008). A cost-benefit analysis of improving trawl selectivity in the case of discards: The Nephrops norvegicus fishery in the Bay of Biscay. *Fisheries Research*, 92(1), 76–89.
- Macher, C., Merzéréaud, M., Guyader, O., Lagiere, R., Larabi, Z., Le Grand, C., & Morin, L. (2013). Governance system of fisheries quota: A bio-economic approach in the case of the bay of Biscay sole fishery. ESEE 2013 Conference: Ecological Economics and Institutional Dynamics. 10th biennial conference of the European Society for Ecological Economics, 18–21 Jun 2013, Lille (France).
- Mackinson, S. (2014). Combined analyses reveal environmentally driven changes in the North Sea ecosystem and raise questions regarding what makes an ecosystem model's performance credible? *Canadian Journal of Fisheries and Aquatic Science*, 71, 31–46.
- Mackinson, S., & Daskalov, G. (2007). *An ecosystem model of the North Sea to support an ecosystem approach to fisheries management: Description and parameterisation*. Scientific Series Technical Report, Cefas Lowestoft 142, 196 pp.
- Mackinson, S., Deas, B., Beveridge, D., & Casey, J. (2009). Mixed-fishery or Ecosystem conundrum? Multi-species considerations inform thinking on long-term management of North Sea demersal stocks. *Canadian Journal of Fisheries and Aquatic Science*, 66, 1107–1129.

- Mahevas, S., & Pelletier, D. (2004). ISIS-Fish, a generic and spatially explicit simulation tool for evaluating the impact of management measures on fisheries dynamics. *Ecological Modelling*, 171(1–2), 65–84.
- Maouel, D., Maynou, F., & Bedrani, S. (2014). Bioeconomic analysis of small pelagic fishery in Central Algeria. *Turkish Journal of Fisheries and Aquatic Sciences*, 14, 1–8.
- Mapstone, B. D., Little, L. R., Punt, A. E., Davies, C. R., Smith, A. D. M., Pantus, F., ... Jones, A. (2008). Management Strategy Evaluations for line fishing in the Great Barrier Reef: Balancing conservation and multi-sector fishery objectives. *Fisheries Research*, 94, 315–329.
- Marasco, R. J., Goodman, D., Grimes, C. B., Lawson, P. W., Punt, A. E., Quinn, T. J. II (2007). Ecosystem-based fisheries management: Some practical suggestions. *Canadian Journal of Fisheries and Aquatic Sciences*, 64, 928–939.
- Maravelias, C., Damalas, D., Ulrich, C., Katsanevakis, S., & Hoff, A. (2012). Multispecies fisheries management in the Mediterranean Sea: Application of the Fcube methodology. *Fisheries Management and Ecology*, 19(3), 189–199.
- Maravelias, C., Pantazi, M., & Maynou, F. (2014). Fisheries management scenarios: Trade-offs between economic and biological objectives. *Fisheries Management and Ecology*, 21(3), 186–195.
- Marchal, P., Andersen, J. L., Aranda, M., Fitzpatrick, M. J. L., Goti, L., Guyader, O., ... Ulrich, C. (2016). A comparative review of fisheries management experiences in the European Union and other countries worldwide: Iceland, Australia, New Zealand. *Fish and Fisheries*, 17, 803–824.
- Marchal, P., De Oliveira, J., Lorange, P., Baulier, L., & Pawlowski, L. (2013). What is the added value of including fleet dynamics processes in fisheries models? *Canadian Journal of Fisheries and Aquatic Sciences*, 70, 992–1010.
- Marchal, P., Little, L. R., & Thebaud, O. (2011). Quota allocation in mixed fisheries: A bioeconomic modelling approach applied to the Channel flatfish fisheries. *ICES Journal of Marine Science*, 68(7), 1580–1591.
- Mattos, S. M. G., Maynou, F., & Franquesa, R. (2006). A bio-economic analysis of the hand-line and gillnet coastal fisheries of Pernambuco State, north-eastern Brazil. *Scientia Marina*, 70(2), 335–346.
- Maynou, F. (2014). Co-viability analysis of Western Mediterranean fisheries under MSY scenarios for 2020. *ICES Journal of Marine Science*, 71(7), 1563–1571.
- Maynou, F., Martínez-Baños, P., Demestre, M., & Franquesa, R. (2014). Bio-economic analysis of the Mar Menor (Murcia, SE Spain) small-scale lagoon fishery. *Journal of Applied Ichthyology*, 30(5), 978–985.
- Maynou, F., Sardà, F., Tudela, S., & Demestre, M. (2006). Management strategies for red shrimp (*Aristeus antennatus*) fisheries in the Catalan sea (NW Mediterranean) based on bioeconomic simulation analysis. *Aquatic Living Resources*, 19(2), 161–171.
- McAllister, M. K., Starr, P. J., Restrepo, V. R., & Kirkwood, G. P. (1999). Formulating quantitative methods to evaluate fishery-management systems: What fishery processes should be modelled and what trade-offs should be made? *ICES Journal of Marine Science*, 56, 900–916.
- Merino, G., Karlou-Riga, C., Anastopoulou, I., Maynou, F., & Lleornart, J. (2007). Bioeconomic simulation analysis of hake and red mullet fisheries in the Gulf of Saronikos (Greece). *Scientia Marina*, 71(3), 525–535.
- Merzéréaud, M., Biais, G., Lissardy, M., Bertignac, M., & Biseau, A. (2013). Evaluation of proposed harvest control rules for Bay of Biscay sole. *ICES CM 2013/ACOM:75*, 18p.
- Merzéréaud, M., Macher, C., Bertignac, M., Frésard, M., Le Grand, C., Guyader, O., ... Fifas, S. (2011). Description of the impact assessment bio-economic model for fisheries management (IAM). Amure Electronic Publications, Working Papers Series D-29-2011, 19 p.
- Mullon, C. (2013). *Network economics of marine ecosystems and their exploitation*. CRC Press.
- Mullon, C., Mittaine, J.-F., Thébaud, O., Péron, G., Merino, G., & Barange, M. (2009). Modeling the global fishmeal and fish oil markets. *Natural Resource Modeling*, 22(4), 564–609.
- Murawski, S. A., Steele, J. H., Taylor, P., Fogarty, M. J., Sissenwine, M. P., Ford, M., & Suchman, C. (2010). Why compare marine ecosystems? *ICES Journal of Marine Science*, 67, 1–9.
- Neubauer, P., Jensen, O. P., Hutchings, J. A., & Baum, J. K. (2013). Resilience and recovery of overexploited marine populations. *Science*, 340, 347–349.
- New Economics Foundation (2016). *Bio-economic model of European fleet, documentation*. Available at: <http://fisheriesmodel.org/documentation> (01 Nov 2016)
- Nielsen, J. R., Bastardie, F., Egekvist, J., Jantzen, K., Raid, T., Goldmanis, E., ... Eero, M. (2011). Evaluation of Effort and TAC Quota Uptake and Capacity Use by Country as well as efficiency of effort measures according to fishing mortality and fishing power in the Western and Eastern Baltic Cod Fishery during 2005–2010 in relation to the multi-annual cod management plan. Working Document, 70 pp. In: Simmonds et al. (eds). 2011. Report of the Sub Group on Impact Assessment of Baltic cod multi-annual plans. EU STECF EWG-11-07a. Hamburg (D), 20–24 June 2011. Luxembourg: Publications Office of the European Union, 2011. ISSN 1018-5593 (print). ICES WKROUND ACOM 2011/ACOM: 55, 67 pp.
- Nielsen, J. R., Kristensen, K., Lewy, P., & Bastardie, F. (2014). A statistical model for estimation of fish density including correlation in size, space, time and between species from research survey data. *PLoS ONE*, 9(6), e99151. p. 1–15.
- Nielsen, J. R., & Limborg, M. (2009). Managing fleets and fisheries rather than single stocks – conceptual change in European fisheries management advice. *World Fishing*, 58(1), 8–9.
- Nielsen, J. R., Palacz, A., Christensen, A., Bastardie, F., Maar, M., Hoff, A., ... Fulton, B. (2015). A Baltic Management Evaluation Framework: Ecosystem End2End ATLANTIS & Bio-Economic FISHRENT & DISPLACE Models – Models, Linkages, Scenarios, Initial Results. W.&A. de Nottbeck Foundation and KONEEN SÄÄTIÖ International Symposium on “Baltic Sea Ecosystem Models and their Application for Management” Tvärminne, SF, 13–16 Sept. 2015. Available at: [http://www.helsinki.fi/science/fem/workshop/\(01 Nov 2016\)](http://www.helsinki.fi/science/fem/workshop/(01%20Nov%202016)).
- Nielsen, J. R., Schmidt, J. O., Holland, D., Thunberg, E., Amboage, R. M., Bastardie, F., ... Waldo, S. (2014). Evaluation of integrated ecological-economic models – What are they used for? IIFET Conference, July 7–11, Brisbane Australia Extended Abstract and Oral Presentation ID 494
- Nielsen, J. R., Schmidt, J., Thunberg, E., & Holland, D. (2015). Social, economic, and ecological impact assessment across marine sectors. *ICES CM 2015/Theme Session M Report*, 3 pp.
- Nielsen, J. R., Thunberg, E., Schmidt, J. O., Holland, D., Bastardie, F., Andersen, J. L., ... Buckworth, R. (2015). Evaluation of integrated ecological-economic models – Review and challenges for implementation. *ICES ASC CM 2015/M:10*.
- Österblom, H., Crona, B. I., Folke, C., Nyström, M., & Troell, M. (2016). Marine ecosystem science on an intertwined planet. *Ecosystems*, <https://doi.org/10.1007/s10021-016-9998-6> (01 Nov 2016).
- Österblom, H., Jouffray, J.-B., & Spijkers, J. (2016). Where and how to prioritize fishery reform? *Proceedings of the National Academy of Sciences*, <https://doi.org/10.1073/pnas.1605723113> (01 Nov 2016).
- Österblom, H., Merrie, A., Metian, M., Boonstra, W. J., Blenckner, T., Watson, J. R., ... Folke, C. (2013). Modeling Social-Ecological Scenarios in Marine Systems. *BioScience*, 63(9), 735–744.
- Ostrom, E. (2009). A general framework for analyzing sustainability of social-ecological systems. *Science*, 325, 419–422.
- Palacz, A. P., Nielsen, J. R., Christensen, A., Hoff, A., Frost, H., Gislason, H., ... Fulton, E. A. (2015). An integrated end-to-end modelling framework for testing ecosystem-wide effects of human-induced pressures in the Baltic Sea. *ICES ASC CM 2015/M:12*
- Palacz, A. P., Nielsen, J. R., Christensen, A., Hoff, A., Maar, M., Frost, H., ... Fulton, E. A. (In Revision). An integrated end-to-end modelling framework for testing ecosystem-wide effects of human-induced pressures in the Kattegat and Western Baltic Sea region. *PLoS ONE* (in revision).

- Palcz, A., Nielsen, J. R., Christensen, A., Gislason, H., Bastardie, F., Geitner, K., ... Fulton, E. (2014). *The Baltic Atlantis model: Implementing a holistic framework to evaluate ecosystem wide responses to changes in climate and anthropogenic forcing*. EU-FP7-VECTORS Symposium, La Grande Motte, France, 18–20 Nov. 2014
- Pan, H., Failler, P., & Floros, C. (2007). *A regional computable general equilibrium model for fisheries*. CEMARE Research Paper No. 163. Portsmouth, UK.
- Pascoe, S., Hutton, T., vanPutten, E. I., Dennis, D., Plagányi, É., & Deng, R. (2013). Implications of quota reallocation in the Torres Strait Tropical Rock Lobster Fishery. *Canadian Journal of Agricultural Economics* 61(2), 335–352.
- Pascoe, S., Hutton, T., van Putten, E. I., Dennis, D., Skewes, T., Plagányi, É., & Deng, R. (2013). DEA-based predictors for estimating fleet size changes when modelling the introduction of rights-based management. *European Journal of Operational Research*, 230(3), 681–687.
- Pascoe, S., Kahui, V., Hutton, T., & Dichmont, C. (2016). Experiences with the use of bioeconomic models in the management of Australian and New Zealand fisheries. *Fisheries Research*, 183, 539–548.
- Paulrud, A., & Waldo, S. (2011). *Mot nya vatten – vart leder individuella överförbara fiskekvoter?* Rapport till Expertgruppen för miljöstudier, Swedish Government 2011: 4. ISBN 978-91-38-23597-3.
- Pauly, D., Hilborn, R., & Branch, T. A. (2013). Does catch reflect abundance? *Nature*, 494, 303–306.
- Pelletier, D., Mahevas, S., Drouineau, H., Vermard, Y., Thebaud, O., Guyader, O., & Poussind, B. (2009). Evaluation of the bioeconomic sustainability of multi-species multi-fleet fisheries under a wide range of policy options using ISIS-Fish. *Ecological Modelling*, 220(7), 1013–1033.
- Piroddi, C., Teixeira, H., Lynam, C. P., Smith, C., Alvarez, M. C., Mazik, K., ... Uyarra, M. C. (2015). Using ecological models to assess ecosystem status in support of the European Marine Strategy Framework Directive. *Ecological Indicators*, 58, 175–191.
- Plagányi, É. E. (2007). *Models for an ecosystem approach to fisheries*. FAO Fisheries Technical Paper No. 477. Rome, FAO, 108p.
- Plagányi, É. E., & Butterworth, D. S. (2004). A critical look at the potential of Ecopath with Ecosim to assist in practical fisheries management. *African Journal of Marine Science*, 26, 261–288.
- Plagányi, É. E., Deng, R., Dennis, D., Hutton, T., Pascoe, S., van Putten, E. I., & Skewes, T. (2012). *An integrated Management Strategy Evaluation (MSE) for the Torres Strait tropical rock lobster Panulirus ornatus fishery*. CSIRO/AFMA Final Project Report AFMA Project number 2009/839. ISBN 978 0 643 10887 5.
- Plagányi, É. E., Punt, A. E., Hillary, R., Morello, E. B., Thébaud, O., Hutton, T., ... Rothlisberg, P. C. (2014). Multispecies fisheries management and conservation: Tactical applications using models of intermediate complexity. *Fish and Fisheries*, 15(1), 1–22.
- Plagányi, E., van Putten, E. I., Hutton, T., Deng, R., Dennis, D., Pascoe, S., ... Campbell, R. (2013). Integrating indigenous livelihood and lifestyle objectives in managing a natural resource. *Proceedings of the National Academy of Sciences*, 110(9), 3639–3644.
- Polovina, J. J. (1984). Model of a coral reef ecosystem I. The ECOPATH model and its applications to French Frigate Shoals. *Coral Reefs*, 3, 1–11.
- Prellezo, R., Accadia, P., Andersen, J. L., Andersen, B. S., Buisman, E., Little, A., ... Röckmann, C. (2012). A review of EU bio-economic models for fisheries: The value of a diversity of model. *Marine Policy*, 36, 423–431.
- Prellezo, R., Carmona, I., & Garcia, D. (2016). The bad, the good and the very good of the landing obligation implementation in the Bay of Biscay: A case study of Basque trawlers. *Fisheries Research*, 181, 172–185.
- Punt, A. E., Deng, R. A., Dichmont, C. M., Kompas, T., Venables, W. N., Zhou, S., ... Van der Velde, T. (2010). Integrating size-structured assessment and bioeconomic management advice in Australia's northern prawn fishery. *ICES Journal of Marine Science*, 67(8), 1785–1801.
- Punt, A. E., Deng, R., Pascoe, S., Dichmont, C. M., Zhou, S., Plagányi, E. E., ... van der Velde, T. (2011). Calculating optimal effort and catch trajectories for multiple species modelled using a mix of size-structured, delay-difference and biomass dynamics models. *Fisheries Research*, 109(1), 201–211.
- Punt, A. E., Foy, R. J., Dalton, M. G., Long, W. C., & Swiney, K. M. (2016). Effects of long-term exposure to ocean acidification conditions on future southern Tanner crab (*Chionoecetes bairdi*) fisheries management. *ICES Journal of Marine Science*, 73, 849–864.
- Punt, A. E., Poljak, D., Dalton, M. G., & Foy, R. J. (2014). Evaluating the impact of ocean acidification on fishery yields and profits: The example of red king crab in Bristol Bay. *Ecological Modelling*, 285, 39–53.
- Punt, A. E., Siddeek, M. S. M., Garber-Yonts, B., Dalton, M., Rugolo, L., Stram, D., ... Zheng, J. (2012). Evaluating the impact of buffers to account for scientific uncertainty when setting TACs: Application to red king crab in Bristol Bay, Alaska. *ICES Journal of Marine Science*, 69, 624–634.
- Queirós, A. M., Fernandes, J. A., Faulwetter, S., Nunes, J., Rastrick, S. P., Mieszkowska, N., ... Widdicombe, S. (2015). Scaling up experimental ocean acidification and warming research: From individuals to the ecosystem. *Global Change Biology*, 21, 130–143.
- Ramos, J., Soma, K., Bergh, Ø., Schulze, T., Gimpel, A., Stelzenmüller, V., ... Gault, J. (2013). Multiple interests across European coastal waters: The importance of a common language. *ICES Journal of Marine Science*, <https://doi.org/10.1093/icesjms/fsu095>.
- Raveau, A., Macher, C., Méhault, S., Merzéréau, M., Le Grand, C., Guyader, O., ... Guillén, J. (2012). A bio-economic analysis of experimental selective devices in the Norway lobster (*Nephrops norvegicus*) fishery in the Bay of Biscay. *Aquatic Living Resources*, 25(3), 215–229.
- Ravn-Jensen, L. J. (2011). Intertemporal Choice of Marine Ecosystem Exploitation. *Ecological Economics*, 70, 1726–1734.
- Ravn-Jensen, L. J., Andersen, K. H., & Vestergaard, N. (2016). An Indicator For Ecosystem Externalities In Fishing. *Natural Resource Modeling*, <https://doi.org/10.1111/nrm.12094>.
- Rayns, N. (2007). The Australian government's harvest strategy policy. *ICES Journal of Marine Science*, 64, 596–598.
- Reecht, Y., Gasche, L., Lehuta, S., Vaz, S., Smith, R., Mahévas, S., & Marchal, P. (2015). Toward a dynamical approach for systematic conservation planning of Eastern English Channel fisheries. In: H. J. Ceccaldi, Y. Hénocque, Y. Koike, T. Komatsu, G. Stora, & M.-H. Tusseau-Vuillemin (Eds.), *Marine productivity: Perturbations and resilience of socio-ecosystems*. Proceedings of the 15th French-Japanese Oceanography Symposium, 175–85.
- Rochet, M.-J., & Rice, J. C. (2009). Simulation-based management strategy evaluation: Ignorance disguised as mathematics? *ICES Journal of Marine Science*, 66, 754–762.
- Rochet, M.-J., & Rice, J. C. (2010). Comment on “Purported flaws in management strategy evaluation: Basic problems or misinterpretations?” by Butterworth et al. *ICES Journal of Marine Science* 67, 575–576.
- Rocklin, D., Pelletier, D., Mouillot, D., Tomasini, J. A., & Culioli, J. M. (2010). *Simulating management scenarios for the spiny lobster fishery in a Mediterranean MPA using ISIS-Fish*. Oral communication – International Marine Conservation Congress, Washington DC, 19–24 May 2010.
- Romagnoni, G., Mackinson, S., Hong, J., & Eikeset, A. M. (2015). The ecospace model applied to the North Sea: Evaluating spatial predictions with fish biomass and fishing effort data. *Ecological Modelling* 300, 50–60.
- Rose, K. A., Allen, J. I., Artioli, Y., Barange, M., Blackford, J., Carlotti, F., ... Flynn, K. (2010). End-to-end models for the analysis of marine ecosystems: challenges, issues, and next steps. *Marine Coastal Fisheries*, 2, 115–130.
- Sainsbury, K. J., Punt, A. E., & Smith, A. D. M. (2000). Design of operational management strategies for achieving fishery ecosystem objectives. *ICES Journal of Marine Science*, 57, 731–741.
- Sala, A., De Carlo, F., Buglioni, G., & Lucchetti, A. (2011). Energy performance evaluation of fishing vessels by fuel mass flow measuring system. *Ocean Engineering*, 38, 804–809.
- Salz, P., Buisman, E., Soma, K., Frost, H., Accadia, P., & Prellezo, R. (2010). *Study on the remuneration of spawning stock biomass*. MARE/2008/11.

- Call for Tenders MARE/2008/11 – Lot 3. Available at: http://ec.europa.eu/fisheries/documentation/studies/remuneration_of_the_spawning_stock_biomass_en.pdf (01 Nov 2016), 298 p.
- Salz, P., Buisman, E., Soma, K., Frost, H., Accadia, P., & Prellezo, R. (2011). *FISHRENT. Bio-economic simulation and optimisation model for fisheries*. LEI-Report 2011-024.
- Seijo, J. C., Defeo, O., & Salas, S. (1998). *Fisheries Bioeconomics. Theory, Modelling and Management*. FAO Fisheries Technical Paper No. 368.
- Seung, C. K. (2006). A Review of Regional Economic Models for Fisheries Management in the U.S. *Marine Resource Economics*, 21, 101–124.
- Seung, C. K., Dalton, M. G., Punt, A. E., Poljak, D., & Foy, R. (2015). Economic impacts of changes in an Alaska crab fishery from ocean acidification. *Climate Change Economics*, 6(4), 1550017. <https://doi.org/10.1142/S2010007815500177>
- Silvestri, S., & Maynou, F. (2009). Application of a bioeconomic model for supporting the management process of the small pelagic fishery in the Veneto Region, northern Adriatic Sea. *Italy. Scientia Marina*, 73(3), 563–572.
- Simmonds, J., Biais, G., Bertignac, M., Macher, C., Merzéréaud, M., Scott, R., & Vanhee, W. (2011). *Impact Assessment of Bay of Biscay sole (STECF-11-01)*. Prepared in Copenhagen February 2011, adopted by the EU STECF during its 36th plenary meeting held from 11–15 April, 2011 in Barza, Italy. 41 pp.
- Simons, S. L., Bartelings, H., Hamon, K. G., Kempf, A., Döring, R., & Temming, A. (2014). Integrating stochastic age-structured population dynamics into complex fisheries economic models for management evaluations: The North Sea saithe fishery as a case study. *ICES Journal of Marine Science: Journal du Conseil*, 71(7), 1638–1652.
- Simons, S. L., Döring, R., & Temming, A. (2014). Modelling the spatio-temporal interplay between North Sea saithe (*Pollachius virens*) and multiple fleet segments for management evaluation. *Aquatic Living Resources*, 27(01), 1–16.
- Simons, S. L., Döring, R., & Temming, A. (2015a). Modelling fishers' response to discard prevention strategies: The case of the North Sea saithe fishery. *ICES Journal of Marine Science*, 72(5), 1530–1544.
- Simons, S. L., Döring, R., & Temming, A. (2015b). Combining area closures with catch regulations in fisheries with spatio-temporal variation: Bio-economic implications for the North Sea saithe fishery. *Marine Policy*, 51(1), 281–292.
- Skonhoft, A., Vestergaard, N., & Quaas, M. F. (2012). Optimal harvest in an age structured model with different fishing selectivity. *Environmental and Resource Economics*, 51(4), 525–544.
- Smith, A. D. M., Sainsbury, K. J., & Stevens, R. A. (1999). Implementing effective fisheries-management systems – management strategy evaluation and the Australian partnership approach. *ICES Journal of Marine Science*, 56, 967–979.
- Smith, A. D. M., Smith, D. C., Haddon, M., Knuckey, I., Sainsbury, K. J., & Sloan, S. (2014). Implementing harvest strategies in Australia: 5 years on. *ICES Journal of Marine Science*, 71, 195–203.
- Smith, D. C., Smith, A. D. M., & Punt, A. E. (2001). Approach and process for stock assessment in the South East Fishery: A perspective. *Marine and Freshwater Research*, 52, 671–681.
- Soma, K., Ramos, J., Bergh, Ø., Schulze, T., van Oostenbrugge, H., van Duijn, A. P., ... Buisman, E. (2013). The “mapping out” approach: Effectiveness of marine spatial management options in European coastal waters. *ICES Journal of Marine Science*, 71, 2630–2642. <https://doi.org/10.1093/icesjms/fst193>
- Steele, J. H., Collie, J. S., Bisagni, J. J., Gifford, D. J., Fogarty, M. J., Link, J. S., ... Stockhausen, W. T. (2007). Balancing end-to-end budgets of the Georges Bank ecosystem. *Progress in Oceanography*, 74, 423–448.
- Stelzenmüller, V., Breen, P., Stamford, T., Thomsen, F., Badalamenti, F., Borj, A., Buhl-Mortensen, L., et al. (2013). Monitoring and evaluation of spatially managed areas: A generic framework for implementation of ecosystem based marine management and its application. *Marine Policy*, 37, 149–164.
- Stelzenmüller, V., Schulze, T., Fock, H. O., & Berkenhagen, J. (2011). Integrated modelling tools to support risk-based decision-making in marine spatial management. *Marine Ecology Progress Series*, 441, 197–212.
- Stokes, T. K., Butterworth, D. S., Stephenson, R. L., & Payne, A. I. L. (1999). Confronting uncertainty in the evaluation and implementation of fisheries-management systems. *ICES Journal of Marine Science*, 56, 795–796.
- Sundblad, E.-L., Grimvall, A., Gipperth, L., & Morf, A. (2014). Structuring social data for the Marine Strategy Framework Directive. *Marine Policy*, 45, 1–8.
- Suuronen, P., Chopin, F., Glass, C., Løkkeborg, S., Matsushita, Y., Queirolo, D., & Rihan, D. (2012). Low impact and fuel efficient fishing—Looking beyond the horizon. *Fisheries Research*, 119–120, 135–146.
- Tahvonen, O. (2009). Economics of Harvesting Age-Structured Fish Populations. *Journal of Environmental Economics and Management*, 58, 281–299.
- Tahvonen, O., Quaas, M. F., Schmidt, J. O., & Voss, R. (2013). Optimal harvesting of an age-structured schooling fishery. *Environmental and Resource Economics*, 54(1), 21–39.
- Tedesco, L., Piroddi, C., Kämäri, M., & Lynam, C. (2016). Capabilities of Baltic Sea models to assess environmental status for marine biodiversity. *Marine Policy*, 70, 1–12.
- Thébaud, O., Doyen, L., Lample, M., Mahévas, S., Mullon, C., Planque, B., ... Vermard, Y. (2013). Building ecological-economic models and scenarios of marine resource systems: Workshop report. *Marine Policy*, <https://doi.org/doi.org/10.1016/j.marpol.2013.05.010>.
- Thunberg, E., Holland, D., Nielsen, J. R., & Schmidt, J. (2013). *Coupled Economic-Ecological Models for Ecosystem-Based Fishery Management: Exploration of Trade-offs Between Model Complexity and Management Needs*. Proceedings of the Sixteenth Biennial Conference of the International Institute of Fisheries Economics & Trade (IIFET), July 2012, Dar-Es-Salaam, Tanzania: Economics of Fish Resources and Aquatic Ecosystems: Balancing Uses, Balancing Costs, 2013, International Institute of Fisheries Economics & Trade, Corvallis, OR. Also orally presented at IIFET 2012.
- Thøgersen, T. T., Hoff, A., & Frost, H. (2012). Linking effort and fishing mortality in a mixed fisheries model: Comparing linear versus non-linear assumptions. *Fisheries Research*, 127–128, 9–17.
- Tomczak, M. T., Heymans, J. J., Yletyinen, J., Niiranen, S., Otto, S. A., & Blenckner, T. (2013). Ecological Network Indicators of Ecosystem Status and Change in the Baltic Sea. *PLoS ONE*, 8(10), e75439.
- Tomczak, M. T., Niiranen, S., Hjerne, O., & Blenckner, T. (2012). Ecosystem flow dynamics in the Baltic Proper-Using a multi-trophic dataset as a basis for food-web modelling. *Ecological Modelling*, 230, 123–147.
- Tratnik, M., Radinović, S., & Pedišić, P. (2007). *Upravljanje fondom srdele u Hrvatskom dijelu jadranskog mora. Managing stocks of sardines in the Croatian part of the Adriatic Sea*. Agronomski Glasnik 1/2007. ISSN 0002-1954.
- Trenkel, V. M., Daurès, F., Rochet, M.-J., & Lorange, P. (2013). Interannual Variability of Fisheries Economic Returns and Energy Ratios Is Mostly Explained by Gear Type. *PLoS ONE*, <https://doi.org/doi.org/10.1371/journal.pone.0070165>.
- Ulrich, C., Reeves, S. A., Vermard, Y., Holmes, S., & Vanhee, W. (2011). Reconciling single-species TACs in the North Sea demersal fisheries using the Fcube mixed-fisheries advice framework. *ICES Journal of Marine Science*, 68, 1535–1547.
- Ulrich, C., Vermard, Y., Dolder, P. J., Brunel, T., Jardim, E., Holmes, S. J., ... Rindorf, A. (2017). Achieving maximum sustainable yield in mixed fisheries: A management approach for the North Sea demersal fisheries. *ICES Journal of Marine Science*, <https://doi.org/10.1093/icesjms/fsw126>.
- Ulrich, C., Wilson, D. C., Nielsen, J. R., Bastardie, F., Reeves, S., Andersen, B. S., & Eigaard, O. R. (2012). Challenges and opportunities for fleet- and métier-based approaches for fisheries management under the

- European Common Fishery Policy. *Ocean & Coastal Management*, 70, 38–47.
- Van Dijk, D., Haijema, R., Hendrix, E. M. T., Groeneveld, R. A., & van Ierland, E. C. (2013). Fluctuating quota and management costs under multianual adjustment of fish quota. *Ecological Modelling*, 265, 230–238.
- Van Dijk, D., Hendrix, E. M. T., Haijema, R., Groeneveld, R. A., & van Ierland, E. C. (2016). An adjustment restriction on fish quota: Resource rents, overcapacity and recovery of fish stock. *Environmental & Resource Economics*, <https://doi.org/10.1007/s10640-015-9983-0>.
- van Putten, E. I., Deng, R., Dennis, D., Hutton, T., Pascoe, S., Plagányi, É., & Skewes, T. (2013). The quandary of quota management in the Torres Strait rock lobster fishery. *Fisheries Management and Ecology*, 20(4), 326–337.
- van Putten, I. E., Gorton, R. J., Fulton, E. A., & Thebaud, O. (2013). The role of behavioural flexibility in a whole of ecosystem model. *ICES Journal Marine Science*, 70, 150–163.
- van Putten, E. I., Lalancette, A., Bayliss, P., Dennis, D., Hutton, T., Norman-López, A., ... Skewes, T. (2012). A Bayesian model of factors influencing indigenous participation in the Torres Strait tropical rock lobster fishery. *Marine Policy Special Issue*, 37, 96–105.
- Vermard, Y., Lehuta, S., Mahevas, S., Thebaud, O., Marchal, P., & Gascuel, D. (2012). *Combining fleet dynamics and population dynamics for a volatile fishery: the example of the anchovy fishery of the Bay of Biscay*. IFREMER Report, 25pp Available at: [http://archimer.ifremer.fr/doc/00107/21858/\(01 Nov 2016\)](http://archimer.ifremer.fr/doc/00107/21858/(01 Nov 2016))
- Voss, R., Hinrichsen, H.-H., Quaas, M. F., Schmidt, J. O., & Tahvonen, O. (2011). Temperature change and Baltic sprat: From observations to ecological-economic modelling. *ICES Journal of Marine Science*, 68(6), 1244–1256.
- Voss, R., Quaas, M. F., Schmidt, J. O., & Hoffmann, J. (2014). Regional trade-offs from multispecies maximum sustainable yield (MMSY) management options. *Marine Ecology Progress Series*, 498, 1–12.
- Voss, R., Quaas, M. F., Schmidt, J. O., Tahvonen, O., Lindegren, M., & Möllman, C. (2014). Assessing social-ecological trade-offs to advance ecosystem-based fisheries management. *PLoS ONE*, 9(9), e107811.
- Waldo, S., & Paulrud, A. (2013a). ITQs in Swedish demersal fisheries. *ICES Journal of Marine Science*, 70(1), 68–77.
- Waldo, S., & Paulrud, A. (2013b). *The Swedish Resource Rent Model for the Commercial Fishery, SRRMCF*. AgriFood Working Paper 2013: 1.
- Waldo, S., & Paulrud, A. (2016). Reducing Greenhouse Gas Emissions in Fisheries: The Case of Multiple Regulatory Instruments in Sweden. *Environmental and Resource Economics*, <https://doi.org/10.1007/s10640-016-0018-2>.
- Walters, C. J. (1998). Designing fisheries management systems that do not depend upon accurate stock assessment. In: T. J. Pitcher, P. J. B. Hart & D. Pauly (Eds.), *Reinventing fisheries management* (pp. 279–288). London: Chapman & Hall.
- Walters, C., & Christensen, V. (2007). Adding realism to foraging arena predictions of trophic flow rates in Ecosim ecosystem models: Shared foraging arenas and bout feeding. *Ecological Modelling*, 209, 342–350.
- Walters, C., Christensen, V., & Pauly, D. (1997). Structuring dynamic models of exploited ecosystems from trophic mass-balance assessments. *Reviews in Fish Biology and Fisheries*, 7, 139–172.
- Walters, C., & Martell, S. J. D. (2004). *Fisheries Ecology and Management*. NJ, USA: Princeton University Press. 448 pp.
- Walters, C., Pauly, D., & Christensen, V. (1999). Ecospace: Prediction of mesoscale spatial patterns in trophic relationships of exploited ecosystems, with emphasis on the impacts of marine protected areas. *Ecosystems*, 2, 539–554.
- Walters, C., Pauly, D., Christensen, V., & Kitchell, J. F. (2000). Representing density dependent consequences of life history strategies in aquatic ecosystems: EcoSim II. *Ecosystems*, 3, 70–83.
- Weninger, Q. (2008). Economic Benefits of Management Reform in the Gulf of Mexico Grouper Fishery: A Semi-Parametric Analysis. *Environmental and Resource Economics*, 41, 479–497.
- Weninger, Q., & Just, R. E. (2002). Firm Dynamics with Tradable Output Prices. *American Journal of Agricultural Economics*, 84, 562–584.
- Weninger, Q., & Waters, J. R. (2003). Economic benefits of management reform in the northern Gulf of Mexico reef fish fishery. *Journal of Environmental Economics and Management*, 46(2), 207–230.
- White, C., Halpern, B. S., & Kappel, C. V. (2012). Ecosystem service tradeoff analysis reveals the value of marine spatial planning for multiple ocean uses. *Proceedings of the National Academy of Sciences*, 109(12), 4696–4701.
- Wilén, J. E., Smith, M. D., Lockwood, D., & Botsford, L. W. (2002). Avoiding surprises: Incorporating fisherman behavior into management models. *Bulletin of Marine Science*, 70(2), 553–575.
- Worm, B., Hilborn, R., Baum, J. K., Branch, T. A., Collie, J. S., Costello, C., ... Zeller, D. (2009). Rebuilding Global Fisheries. *Science*, 325, 578–585.

SUPPORTING INFORMATION

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

How to cite this article: Nielsen JR, Thunberg E, Holland DS, et al. Integrated ecological–economic fisheries models—Evaluation, review and challenges for implementation. *Fish Fish*. 2017;00:1–29. <https://doi.org/10.1111/faf.12232>