Rev Fish Biol Fisheries (2015) 25:413–424
DOI 10.1007/s11160-015-9386-x

REPORT

Modelling dynamic ecosystems: venturing beyond boundaries with the Ecopath approach

M. Coll · E. Akoglu · F. Arreguín-Sánchez · E. A. Fulton · D. Gascuel · J. J. Heymans · S. Libralato · S. Mackinson · I. Palomera · C. Piroddi · L. J. Shannon · J. Steenbeek · S. Villasante · V. Christensen

Received: 19 December 2014 / Accepted: 25 April 2015 / Published online: 5 May 2015

Abstract Thirty years of progress using the Ecopath with Ecosim (EwE) approach in different fields such as ecosystem impacts of fishing and climate change, emergent ecosystem dynamics, ecosystem-based management, and marine conservation and spatial planning were showcased November 2014 at the conference "Ecopath 30 years-modelling dynamic ecosystems: beyond boundaries with EwE". Exciting new developments include temporal-spatial and end-to-end modelling, as well as novel applications to environmental impact analyses, in both aquatic and terrestrial domains. A wide range of plug-ins have been added to extend the diagnostic capabilities of EwE, and the scientific community is applying EwE to a diversified range of topics besides fishing impact assessments, such as the development of scientific advice for management, the analysis of conservation issues, and the evaluation of cumulative impacts of environmental and human activities in marine food webs (including habitat modification and the invasion of alien species). Especially promising is the new potential to include the EwE model in integrated assessments with other models such as those related to climate change research. However, there are still many challenges, including the communication of scientific results in management procedures. In addition, other

M. Coll (✉)
Institut de Recherche pour le Développement, Sète, France
e-mail: marta.coll@ird.fr

M. Coll · I. Palomera · J. Steenbeek
Ecopath International Initiative Research Association, Barcelona, Spain

E. Akoglu · S. Libralato
Instituto Nazionale di Oceanografia e di Geofisica Sperimentale, Trieste, Italy

F. Arreguín-Sánchez
Instituto Politécnico Nacional, Centro Interdisciplinario de Ciencias Marinas, La Paz, Baja California Sur, Mexico

E. A. Fulton
CSIRO Marine and Atmospheric Research, Hobart, Australia

D. Gascuel
Agrocampus Ouest, Université Européenne de Bretagne, Rennes, France

J. J. Heymans
Scottish Association for Marine Science, Oban, Scotland, UK

S. Mackinson
Centre for Environment, Fisheries and Aquaculture Science, Lowestoft, UK

I. Palomera · C. Piroddi
Institute of Marine Science, Spanish Research Council, Barcelona, Spain

C. Piroddi
Joint Research Centre, European Commission, Ispra, Italy

important scientific issues are how to improve model result validation and perform model quality control. During the conference, the Ecopath International Research and Development Consortium was presented as a way for the EwE user community to become involved in the long-term sustainability of the EwE approach. Overall, exciting times are facing the ecosystem modelling scientific community, and as illustrated by the conference: synergistic cooperation is the future path for the EwE approach.

Keywords Ecopath with Ecosim · Ecospace · Ecosystem modelling · Ecosystem-based management · End-to-end modelling · Environmental impact assessment · Fishing impacts · Conservation · Cumulative impacts

Background

In 1984, Dr. Jeffrey Polovina and colleagues at the National Marine Fisheries Service, Honolulu Laboratory, developed an innovative marine ecosystem model aptly named Ecopath (Polovina 1984). Ecopath was one of the first models to apply 'path analysis' statistics to the field of marine ecology. The simplicity of the Ecopath model and its ability to accurately identify ecological relationships revolutionized the ability of scientists to understand complex marine ecosystems (Christensen 2013).

In the 30 years since its conception, the Ecopath approach has grown into the modelling suite "Ecopath with Ecosim and Ecospace", or the EwE toolbox (Steenbeek et al. Submitted), which integrates the original Ecopath model (Polovina 1984; Christensen and Pauly 1992, 1993) with the temporal dynamic and temporal–spatial dynamic modules Ecosim and Ecospace, respectively (Walters et al. 1997, 1999; Christensen and Walters 2004; Pauly et al. 2000). This approach was the first ecosystem-level simulation model to be freely accessible, which in combination with its user-friendly interface, has contributed to its global uptake and its popularity as a key tool for the ecosystem-approach to fisheries and marine resources (Christensen and Maclean 2011; Christensen 2013). In acknowledgement of this success, in 2010, the US National Oceanographic and Atmospheric Administration (NOAA) formally recognized Ecopath as one of the ten biggest scientific breakthroughs in the organization's 200 year history (http://celebrating200years.noaa.gov/breakthroughs/ecopath/).

Currently, more than 400 ecosystem models using the EwE approach have been published (Colléter et al. 2015). A search using the Web of Science shows that EwE is described in more than 500 available publications, which are referenced by more than 700 citations per year, on average over the last decade (Fig. 1). This makes EwE an important modelling approach to explore ecosystem related questions in predominantly aquatic ecosystems.

The first EwE conference, "Ecopath 25 years: conference and workshops", took place in 2009 at the Fisheries Centre of the University of British Columbia in Vancouver, Canada (http://conference.ecopath.org/). This conference provided an overview of 25 years of progress using the EwE approach in different fields (Palomares et al. 2009). Due to its positive impact on the EwE community, this event was repeated in 2014, jointly with the 30th anniversary of the approach. The conference "Ecopath 30 years—modelling dynamic ecosystems: beyond boundaries with EwE" was held at the Institute of Marine Science (ICM-CSIC) in Barcelona, Spain, from 10 to 12 November 2014 (http://ewe30.ecopathinternational.org/). A series of very successful introductory and advanced workshops on EwE tools preceded the conference.

Conference "Ecopath 30 years: modelling dynamic ecosystems: beyond boundaries with EwE"

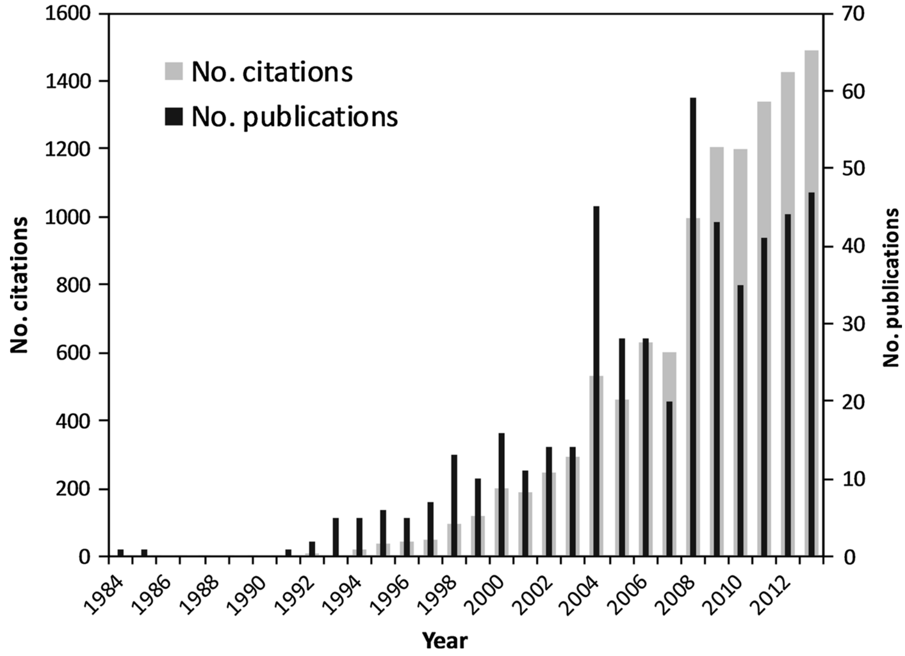
This second Ecopath conference brought together leading ecosystem modelers and model developers from 28 countries in Africa, Asia, Australia, Europe, and North and South America (Fig. 2) to share scientific work, modelling experiences and ideas for

L. J. Shannon
Marine Research Institute, University of Cape Town, Cape Town, South Africa

S. Villasante
University of Santiago de Compostela, Santiago de Compostela, Spain

V. Christensen
University of British Columbia, Vancouver, Canada

Fig. 1 Number of citations and publications using Ecopath, Ecosim or Ecospace (1984–2013) (*Source*: Web of Science ™, query 21/11/2014)



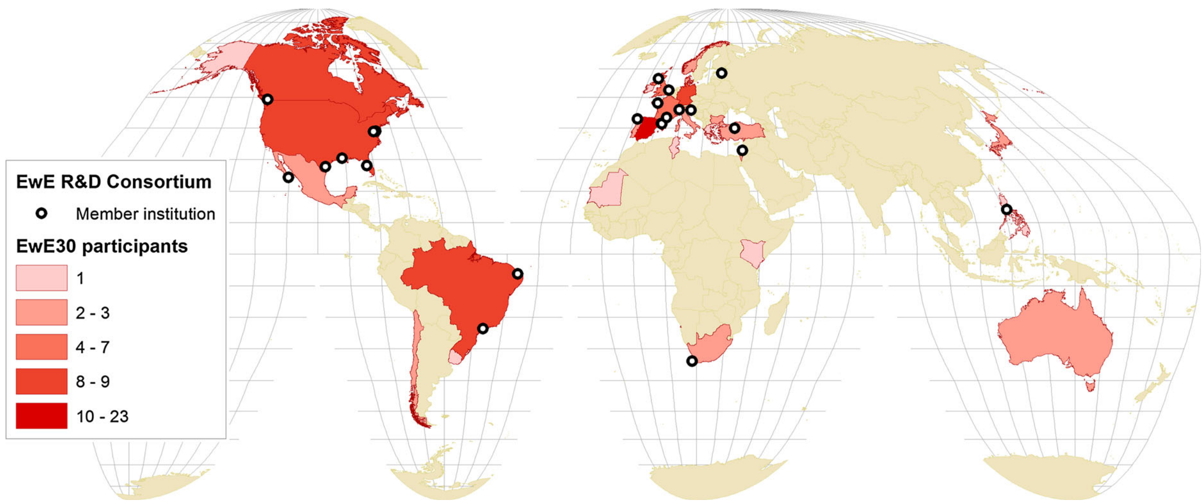


Fig. 2 Origin of participants to the conference “Ecopath 30 years—modelling dynamic ecosystems: beyond boundaries with EwE” in 2014 and location of the 23 members of the Ecopath International Research and Development Consortium

new developments of the EwE approach. The event was organised in six sessions reporting the use of EwE for: (1) providing scientific advice for management; (2) informing and planning marine conservation; (3) incorporating ecosystem evolution and challenges for management, (4) modelling cumulative ecosystem dynamics; (5) developing end-to-end models, and (6) “What Next?”. Below we summarize the main topics presented during the event, discussions raised during the conference, and novel ideas proposed by and to the scientific community (all the contributions can be freely accessed through the proceedings, Steenbeek et al. 2014).

This conference also highlighted the transition of the EwE software from a tool developed and provided by a single-institute, to a peer-reviewed, open source toolbox developed by and for the scientific community. During the conference, a sustainable basis for the long-term sustenance and growth of the EwE modelling approach and software was discussed.

Scientific advice for management: from research to advisory tools

The implementation of the ecosystem-based approach to fisheries (Pikitch et al. 2004; Link 2011) requires that ecosystem models are designed so that their output is made relevant and useful for managers. The EwE approach has been frequently used to explore the ecosystem impacts of fishing with the aim to inform on ecosystem-based issues and impact management processes (Christensen and Walters 2011). The first session of the conference posed several important questions along this theme, including: (1) what are the research areas where ecosystem models have most to contribute to provide management advice?; (2) what can EwE offer to managers in terms of advice on ecosystem-based fisheries management?; (3) what does it take to provide managers with the confidence they need to use outputs from tools like EwE models?; and (4) what does it take to move from exploratory research tools to giving advice, and is the EwE community ready for that responsibility? Presentations in this session and following discussion aimed to partially answer these questions by providing examples related to: (1) applications to management and lessons learned; (2) processes, procedures and methods for quality control; (3) model validation, sensitivity and performance testing; and (4) critical evaluation of the usefulness of EwE for providing advice and reflections on what it takes to do better.

Several presentations showcased EwE modelling activities relevant to managers, including the development of analysis to respond to new scientific targets linked to new legislation contexts, such as the Marine Strategy Framework Directive in Europe in a multi-species context with mixed fisheries. For example, good opportunities for fishing were identified for several stocks close to fishing mortality (F) at Maximum Sustainable Yield (MSY) (Fmsy) in the North sea (Staebler et al. 2014). A few EwE applications were actually applied to provide formal management advice such as the case of Australia (Bulman et al. 2014), where EwE models have been applied extensively to analyse the ecosystem impacts of fishing. Examples in Europe showed a current emphasis on achieving the quality assurance (quality control, validation, performance testing, and evaluation of uncertainties) needed to provide managers with the confidence for using EwE models for advice (Mackinson 2014). Other examples included managing fisheries in Lake Kinneret (Israel) (Ofir et al. 2014) and the impacts of prawn trawling effort after closure of an MPA in Australia (Fondo et al. 2014). Interactions between industrial and small scale fisheries were analysed in the context of developing countries using the EcoTroph approach and plug-in (Meissa et al. 2014).

However, this session indicated that the uptake of ecosystem modelling analyses for fisheries management is still low. Two reasons for this remain prevalent: (1) researchers do not see or notice a ‘demand’ directly coming from managers for ecosystem model-derived advice; and (2) modelers fail to communicate the value and relevance of their work to management advisors. During the session it was discussed whether this was a matter of communication, confidence, or both. In the case of low confidence the discussion pointed out that this can be alleviated by putting effort into quality assurance of input and output data and results, which should boost the confidence of both the researcher and the manager in model results and evaluations. During the session it was also highlighted that even if the ecosystem-based approach to fisheries management is recognized worldwide as a necessity, it remains still poorly implemented. In practice almost all fisheries regulations are still based on the single-species approach, and in most countries no formalized scientific advice system on the ecosystem-based approach has been set up.

Informing and planning marine conservation

By exploring direct and indirect interactions among both exploited and non-exploited species within marine ecosystems, ecosystem modelling can be used in a variety of ways for marine conservation by investigating implications of different management strategies and spatial and temporal ecosystem changes (Christensen 2013; Shannon et al. 2010). The key question addressed during the second session of this conference was how EwE applications can be fed into decision making for informing and planning marine conservation.

Novel contributions were presented, illustrating where EwE can be used as a tool to examine implications of, challenges around, and trade-offs involved in balancing marine conservation (of single species or whole communities). For example, EwE can be used to calculate biodiversity and conservation-based indicators useful to support policy decisions (Coll and Steenbeek 2014) and inform the implementation of MPAs (Pitcher et al. 2014). The importance of considering multiple drivers (fishing and climate) when assessing the effectiveness of reducing fishing pressure was highlighted by Taylor and Wolff (2014).

Several case studies in this session highlighted the importance and value of active and two-way dialogue between modelers and stakeholders (decision makers, managers, lawyers, conservationists, etc.). Studies indicated that communication with stakeholders, particularly decision makers, should be encouraged before and during model development to ensure that ecosystem modelling work is tailored (1) to address relevant management objectives, questions and issues on the table, and (2) to facilitate the necessary buy-in and investment by decision makers into the process of producing scientific results for advising management. In this context, an interesting example was presented of how dialogue with the Port-Cross National Park (NW Mediterranean Sea) MPA managers is initiating improvements in terms of monitoring of key groups in MPA and stimulating keen interest and buy-in from the MPA managers (Prato et al. 2014). Another example was provided in the context of management of marine resources in the Azores (Morato et al. 2014), where managers obtained buy-in from fishers after they saw the improved catches due to closures for research purposes. A new approach to identify keystone species was proposed (Valls et al. 2015), showing that commonly used keystones indices may lead to misidentification of keystone species.

A particular highlight of this session was the presentation by Fretzer (2014) show-casing the application of the new habitat suitability modelling capabilities of EwE (Christensen et al. 2014) to a Natura 2000 terrestrial forest/cultivated ecosystem for direct input to a legally required Ecosystem Impact Assessment in Germany. This study represented an application of EwE to the terrestrial domain. EwE was used to assess environmental impacts in an agricultural case and showed how the modelling approach could play an influential role in supporting legal action in response to development of land and the ecosystem impacts thereof.

Ecosystem evolution and challenges for management

Conventional fisheries management is supported by population dynamics models that are usually based on a limited number of constant parameters, such as natural mortalities. Such models thus implicitly assume a stable state of ecosystems (Hilborn and Walters 1992). Presently it is recognized that such assumptions are rarely valid: ecosystems change over time, and attributes such as organization, resilience, and vulnerability, among others, evolve (Link 2011). Management strategies, in practice, must take trophic interactions into account, as well as environmental patterns, and deal with ecosystem evolution and dynamics. Thus, knowledge of how ecosystems change becomes highly significant to formulate adaptive strategies for sustainably exploited ecosystems over time. Implementation of tools that consider these dynamics for ecosystem-based management is a critical challenge in modern fisheries management (Arreguín-Sánchez et al. 2014). This challenge includes improving the understanding of the direct and indirect impacts of fisheries and other anthropogenic pressures on marine ecosystems under an interconnected and changing world.

During the third session of the conference, time-changes, evolving ecosystem processes and their consequences in structure, organization and management were highlighted. New concepts and ideas were presented, and discussion centred around addressing different relevant research questions and policy challenges including: (1) how can EwE help to scientifically simplify the complexity of marine food webs and analyse ecosystem evolution?; (2) what progress has been made in implementing ecosystem-based management under a changing environment?, (3) how can EwE provide scientific motivation for increasing resilience and adaptability of marine ecosystems and fishers under surprising changes and marine regime shifts?; (4) how do fisheries management policies respond to ecosystem evolution at spatial and temporal scales?; and (5) what is the role of different types of data when addressing conflicting fisheries management and management-plans?

The keynote lecture of the session highlighted how size-based models can be used in order to investigate ecosystem functioning and to provide new insights on trophic cascade effects, and especially addressed challenges for different (and often conflicting) objectives of fisheries management (Andersen 2014). Papers presented represent different type of problems within the complexity of ecosystems, including how such problems must be faced when evolving over time. Examples involve a wide range of regions such as

Europe, Latin America, the Mediterranean, and North America, and demonstrate the diversity and complexity of potential applications of EwE for the different purposes and end-users. Some presentations focused on modelling marine ecosystems and their trophic interactions, reporting creative ways to represent specific ecological dynamic processes, such as changes induced in the food web by invasive species (Kumar et al. 2014) and by changes in the abundance of marine mammals and krill production (Surma et al. 2014). In addition, relevant topics such as adaptability, complexity, and regime shifts were addressed in order to increase the scientific evidence on multiple-stability domains and thresholds of marine ecosystems (Heymans and Tomczak 2014).

Two topics were of special interest because their relevance for potential use of EwE models for management purposes, or better understanding of ecosystem processes and patterns. For example, some contributions emphasized the role of local and qualitative data from fisher's knowledge (Bevilacqua et al. 2014), which can complement data from scientific surveys, in particular in the context of developing countries. Moreover, the new EcoBase global database of EwE models was introduced in the context of its potential use to extract global patterns of ecosystem structure and functioning (Colléter et al. 2014). Additional discussions between participants in this session highlighted the importance to take into account socio-economic factors and effects when developing EwE empirical applications to provide a comprehensive assessment to the scientific community, industry and society in general.

Modelling cumulative ecosystem dynamics

In the last decade, the scientific community has made substantial progress in the identification and quantification of multiple human threats that impact marine diversity, habitats, and ecosystems (Jackson et al. 2001). The way these stressors may interact and combine to affect productivity patterns of marine ecosystems is not well known (Crain et al. 2008; Darling and Côté 2008). Multiple stressors are spatially and temporally distributed in heterogeneous ways, and their interactions do not occur the same way everywhere, affecting productivity differently (Halpern et al. 2008; Lotze et al. 2006). Future changes of current human activities (such as climate change, fishing or the invasion of new species), and the appearance and spread of new activities (such as deep seas exploitation), will likely challenge our current understanding of anthropogenic impacts. To tackle some of these scientific challenges, there is a growing need to develop novel methodologies of data integration, assimilation and modelling at different scales, taking into account uncertainties in data and processes.

The fourth session of the conference was dedicated to novel studies and technical developments on how the scientific community can make progress to model these cumulative effects and assess their interacting and cumulative impacts on marine food webs using the EwE approach. Interesting studies on how to model interacting stressors, such as fishing and invasive species (Pedersen et al. 2014), fishing and climate change (Tecchio et al. 2014), and climate, fishing and invasive species (Caccin et al. 2014), mainly using the Ecopath and Ecosim modules, were presented. In addition, new developments on how to model interacting stressors with temporal–spatial variability were introduced with the new habitat foraging capacity model (HFCM) framework within Ecospace (Christensen et al. 2014). This new approach, especially linked to the recently developed spatial–temporal data framework (Steenbeek et al. 2013), offers many exciting possibilities for future research directions by merging species distribution and spatial ecosystem models capabilities. Applications of this new algorithm to Mediterranean ecosystems were presented during the session (Piroddi et al. 2014; Coll et al. 2014).

Limitations encountered while modelling cumulative impacts were also identified and discussed. For example, a limiting factor of EwE in defining functional responses to link stressors to impacted organisms has been overcome by using the HFCM and linking laboratory experiments, field work and statistical modelling results with EwE. Other limitations included how to consider impacts directly linked to socio-economic drivers; address spatial validation of results; and communicate complex results from cumulative effects assessments. The scientific community is actively working to address these issues, and an exponential increase in spatial–temporal studies is predicted to emerge, illustrating how to advance in modelling ecosystem dynamics considering cumulative effects. It is foreseen that in this field the EwE approach will see major developments in the near future.

End-to-end modelling

Current societal challenges for the sustainable use of aquatic ecosystems require integrated approaches "from physics to fishermen" that explicitly and directly account for environmental, biological, social and economic interactions and feedbacks (Fulton 2010). EwE can be a cornerstone in the development of such end-to-end models and approaches that can represent important tools for the development of ecosystem-based management approaches. This session was the ideal forum for presenting and discussing experiences in integrating EwE philosophy with other complex processes and dynamic models (hydrodynamic, biogeochemical, climatic, socio-economic, etc.). During the session, technical issues and limitations were highlighted, but also solutions and advantages in using EwE for setting up end-to-end descriptions for aquatic ecosystems.

The keynote presentation illustrated EwE integration into a multi-model approach. It showed experiences gained from two decades of use of EwE for fisheries management in the Alaska region (Aydin 2014), where different types of models have interfaced (off-line or on-line) with the EwE toolbox to influence ongoing management policy. In addition, other presentations highlighted the widespread need and promising results in integrating EwE models with other models or results to include drivers such as climatic processes and changes (temperature, acidification), physical processes, recycling and nutrient dynamics, and low trophic level dynamics (Christensen et al. 2014; Guénette et al. 2014; Taylor and Wolff 2014).

Furthermore, a couple of end-to-end applications presented in this session consisted of two-way coupling of models that are needed in end-to-end modelling approaches (Akoglu et al. 2015; Ruzicka et al. 2014). These examples showed the importance of representing bi-directional feedback between processes in ecosystems because they can help to safely bound predicted future changes and to account for trade-offs (Link 2011). Therefore, assessment/quantification of bi-directional feedback of models should be pursued as much as possible. Related to this issue, the spatial–temporal data framework, a major recent improvement in EwE, was presented (Steenbeek 2013). This new capability enables linking of the EwE approach with external spatial–temporal explicit datasets and models, facilitating one-way or two-way directional exchange of geographically referenced information in and out of EwE, while separating scientific and technical challenges to such linkages.

The new forthcoming versions of Ecopath and Ecosim in FORTRAN (Akoglu et al. 2015) and Ecopath in R (Lucey et al. 2014) were introduced. Discussion of how these developments should further facilitate applications and integrations of EwE philosophy with other models followed. Given that models are constructed with specific scopes and assumptions in mind, their integration and coupling should include careful consideration of any important simplifications, aggregations and parameterization choices. Integrating different models necessitates clear evaluation of the "usability" of each original model, and requires a good understanding of the mathematics of the individual models. On the basis of the experiences discussed during this session, EwE could be used as the core of operational complex integrated models (de Young et al. 2004) in novel ways, which may include new links to spatial lower trophic level models, multispecies stock assessment models, bioenergetics models, individual-based models, and/or high-resolution climate-earth modelling. In this context, the discussion highlighted some under-represented topic in the end-to-end session, such as aquaculture activities and socio-economic dynamics. Aquaculture is representing a growing scientific issue, and a challenge for the next future would be the linking of the EwE approach to detailed and sophisticated aquaculture models to help better represent the ecological effects of aquaculture and to provide a basis for management spatial planning. Finally, real end-to-end approach should integrate also socio-economic drivers and dynamics, thus it is envisaged that future integrated approaches should include also socio-economic models in order to better serve society and its needs.

What next?

The last session of the conference provided an opportunity for the EwE community to highlight impending scientific challenges and to identify what capabilities are missing in the EwE toolbox, what are needed, and what would be exciting extensions to the EwE approach. Discussion centred on how the EwE scientific community can contribute to the continued application and growth of the EwE approach in the immediate and long-term future. This session promoted an "all in" discussion about the future of EwE, encouraging a group discussion about where the software and approach should go.

One of the key points of this session was that the applications of the EwE toolbox have matured enormously beyond an exclusive focus on fisheries issues. In fact, they have diversified to address other environmental issues such as climate change, habitat modification, and the impact of other human effects on ecosystems, such as the invasion of alien species. The EwE community has been widening its scope to a broader horizon, expanding its activities to new areas, for example applying the EwE toolbox to environmental impact assessments in both aquatic and terrestrial ecosystems. During the "What next" session an exciting discussion emerged around how to move towards providing practical management advice to a diversity of environmental management processes and possibilities to adapt to global (including climate) change. The community agreed this would be a step forward towards a professional application of the toolbox. However, the EwE community also recognized that there are many challenges to communicate scientific results to management procedures and that much more research effort is needed in this regard.

Other important scientific issues arose during the general discussion, such as how to improve model result validation and perform model quality control. This stresses the need to improve the use of uncertainty when developing and presenting EwE models, and to advance in multi-model ensemble predictions connecting models, with a special emphasis on the connections with socio-economic models.

During this session, participants also discussed how the broad EwE community can become involved in the long-term sustainability of the EwE approach, and participate in the activities stimulated by the Ecopath International Research and Development Consortium (www.ecopath.org/consortium, or Consortium). The Consortium is a supporting, cooperative network of institutions focused on the research, development and sustainability of the EwE approach and software. It was established in 2011 as a non-commercial activity that is operated on a not-for-profit basis, aimed at distributing the core EwE software and its source code freely, and to practice open-source software development through peer collaboration and production. The Consortium undertakes several EwE-related activities, such as: (1) maintaining and developing the EwE software; (2) providing user support and organizing co-development; (3) organizing training courses and conferences; (4) developing and evaluating professional standards and best practices for EwE applications, and (5) facilitating the distribution of EwE publications and models through online repositories.

Currently, the Consortium is composed of 23 institutional members from throughout the world (Fig. 2). Establishment of the Consortium was motivated by the fact that until 2010 the EwE approach was financially supported by the University of British Columbia (Canada) through research projects that provided budget dedicated to maintain the EwE approach. This changed in 2010, when a four-year Lenfest Future Oceans-funded project to modernize the EwE approach came to an end. Through the Lenfest project, EwE version 6 was released, recast into a modular model creation toolbox, and designed for extensibility and model interoperability. Since 2010, EwE has been maintained without core funding, and with the Consortium a new strategy was found to continue the EwE approach via active involvement of its users.

During the Ecopath 30 years conference, ways to fund the future of EwE were discussed. Future funding of the development of EwE could be supported through the continuation of the already implemented user support and co-development programmes, which have been working since 2012 with good results for the user community. Collaborative research projects, crowd source funding, and the creation of an additional professional version of EwE were discussed as future complementary options. In addition to the features available in the free version of EwE, this professional version could offer specific features needed for professional modelling applications in academic, governmental and private purposes.

Conclusions

The conference "Ecopath 30 years—modelling dynamic ecosystems: beyond boundaries with EwE" held in Barcelona, Spain, from 10 to 12 November 2014 highlighted the major developments and modelling capabilities of the EwE toolbox over the last 5 years. The highlights of the conference on "venturing beyond boundaries" can be summarized in six points: (1) the new habitat foraging capacity model, which utilizes the spatial–temporal data framework, (2) the momentum to apply EwE to the terrestrial domain, (3) the development of EwE in other formats such as R and FORTRAN, (4) the EcoBase global database, and (5) the fact that there is no longer core funding for EwE, which encourages the EwE community to work together to continue maintaining and adapting the approach.

Moving from the academic, fisheries-focused applications to broader applications poses a series of scientific challenges. Fisheries management, as a rule, is rather reactively focused on tactical issues instead of requiring pro-active forecasts such as needed for ecosystem-based management and impact assessments. Here, models can contribute most strongly by addressing mid-term strategic forecasts about ecosystem changes and associated trade-offs for management. Ecosystem-based methods have a strong role to play for management, and while major progress on this front has been made in notably Europe and Australia, there is still a long way to go.

The "Ecopath 30 years" conference highlighted that the EwE approach is providing the tools required for ecosystem-based management and impact assessments in many areas of application, and presentations and discussions during the conference will serve as an important milestone for ecosystem modelling. Contributions presented at the conference covered a wide range of topics, starting off with scientific advice for management, on to marine conservation, ecosystem evolution, cumulative dynamics, and end-to-end modelling. Overall, this showed the versatility of the approach, and even more importantly, how the diversity of scientists that cooperate on moving toward ecosystem-based management can jointly contribute to a scientific development that is bigger than what any scientist can accomplish individually.

Acknowledgments We thank all contributors to the conference "Ecopath 30 years—modelling dynamic ecosystems: beyond boundaries with EwE" for their active participation in the event and for presenting their work with much enthusiasm and high quality standards. We thank the Institute of Marine Science (ICM-CSIC) in Barcelona (Spain) for hosting the conference. MC was partially supported by a Marie Curie CIG grant to BIOWEB project.

References

Akoglu E, Libralato S, Salihoglu B, Oguz T, Solidoro C (2015) EwE-F 1.0: an implementation of Ecopath with Ecosim in Fortran 95/2003 for coupling. Geosci Model Dev Discuss 8(2):1511–1537

Andersen KH (2014) Conflicting objectives for ecosystem based fisheries management. In: Steenbeek J, Piroddi C, Coll M, Heymans JJ, Villasante S, Christensen V (eds) Ecopath 30 years conference proceedings fisheries: extended abstracts., Fisheries Centre Research Reports 22(3) [ISSN 1198-6727]. 237 p Fisheries Centre, University of British Columbia, Vancouver, pp 77–78

Arreguín-Sánchez F, Del Monte-Luna P, Zetina-Rejón MJ (2014) Ecosystem change, "ecosystem limit reference level", and adaptability for sustainable fisheries: the Campeche Bank Mexico as study case. In: Steenbeek J, Piroddi C, Coll M, Heymans JJ, Villasante S, Christensen V (eds) Ecopath 30 years conference proceedings: extended abstracts., Fisheries Centre Research Reports 22(3) [ISSN 1198-6727]. 237 p Fisheries Centre University of British Columbia, Vancouver, pp 101–102

Aydin K (2014) Ecopath and Ecosim in fisheries management: notes from three decades on the front lines. In: Steenbeek J, Piroddi C, Coll M, Heymans JJ, Villasante S, Christensen V (eds) Ecopath 30 years conference proceedings: extended abstracts., Fisheries Centre Research Reports 22(3) [ISSN 1198-6727]. 237 p Fisheries Centre, University of British Columbia, Vancouver, p 175

Bevilacqua A, Carvalho A, Lopes P, Angelini R (2014) Beyond anecdotal information: the use of fisherś knowledge to model fisheries. In: Steenbeek J, Piroddi C, Coll M, Heymans JJ, Villasante S, Christensen V (eds) Ecopath 30 years conference proceedings: extended abstracts., Fisheries Centre Research Reports 22(3) [ISSN 1198-6727]. 237 p Fisheries Centre, University of British Columbia, Vancouver, pp 79–81

Bulman C, Fulton E, Smith A, Johnson P, Lozano-Montes H, Griffiths S, Bustamante R (2014) EwE models in Australia. In: Steenbeek J, Piroddi C, Coll M, Heymans JJ, Villasante S, Christensen V (eds) Ecopath 30 years conference proceedings: extended abstracts., Fisheries Centre Research Reports 22(3) [ISSN 1198-6727]. 237 p Fisheries Centre, University of British Columbia, Vancouver, pp 190–192

Caccin A, Anelli Monti M, Libralato S, Pranovi F (2014) Marine food webs and warming scenarios: modelling a thermophilic species invasion. In: Steenbeek J, Piroddi C, Coll M, Heymans JJ, Villasante S, Christensen V (eds) Ecopath 30 years conference proceedings: extended abstracts., Fisheries Centre Research Reports 22(3) [ISSN 1198-6727]. 237 p Fisheries Centre, University of British Columbia, Vancouver, pp 137–139

Christensen V (2013) Ecological networks in fisheries: predicting the future? Fisheries 38(2):76–81

Christensen V, Maclean J (2011) Ecosystem approaches to fisheries: a global perspective. Cambridge University Press, Cambridge

Christensen V, Pauly D (1992) ECOPATH II—a software for balancing steady-state ecosystem models and calculating network characteristics. Ecol Model 61:169–185

Christensen V, Pauly D (1993) Trophic models of aquatic ecosystems, vol 26. ICLARM conference proceedings, p 390

Christensen V, Walters C (2004) Ecopath with Ecosim: methods, capabilities and limitations. Ecol Model 72:109–139

Christensen V, Walters CJ (2011) Progress in the use of ecosystem models for fisheries management. In: Christensen V, Maclean J (eds) Ecosystem approaches to fisheries: a global perspective. Cambridge University Press, Cambridge, pp 189–205

Christensen V, Coll M, Steenbeek J, Buszowski J, Chagaris D, Walters CJ (2014) Representing variable habitat quality in a spatial food web model. Ecosystems 17(8):1397–1412

Coll M, Steenbeek J (2014) New software plug-into calculate biodiversity and conservation-based indicators from EwE food web models. In: Steenbeek J, Piroddi C, Coll M, Heymans JJ, Villasante S, Christensen V (eds) Ecopath 30 years conference proceedings: extended abstracts., Fisheries Centre Research Reports 22(3) [ISSN 1198-6727]. 237 p Fisheries Centre, University of British Columbia, Vancouver, pp 67–68

Coll M, Steenbeek J, Palomera I, Sole J, Christensen V (2014) Cumulative effects of environmental and human activities in the Southern Catalan Sea ecosystem (NW Mediterranean) associated with the Ebro Delta River. In: Steenbeek J, Piroddi C, Coll M, Heymans JJ, Villasante S, Christensen V (eds) Ecopath 30 years conference proceedings: extended abstracts., Fisheries Centre Research Reports 22(3) [ISSN 1198-6727]. 237 p Fisheries Centre, University of British Columbia, Vancouver, pp 169–171

Colléter M, Gascuel D, Pauly D (2014) A meta-analysis of ecosystems' trophic functioning: identification of typical trophic behaviour and associated responses to fishing impact. In: Steenbeek J, Piroddi C, Coll M, Heymans JJ, Villasante S, Christensen V (eds) Ecopath 30 years conference proceedings: extended abstracts., Fisheries Centre Research Reports 22(3) [ISSN 1198-6727]. 237 p Fisheries Centre, University of British Columbia, Vancouver, pp 93–94

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. Ecol Model 302:42–53

Crain CM, Kroeker K, Halpern BS (2008) Interactive and cumulative effects of multiple human stressors in marine systems. Ecol Lett 11(12):1304–1315. doi:10.1111/j.1461-0248.2008.01253.x

Darling ES, Côté IM (2008) Quantifying the evidence for ecological synergies. Ecol Lett 11(12):1278–1286

de Young B, Heath M, Werner F, Chai F, Megrey B, Monfray P (2004) Challenges of modeling ocean basin ecosystems. Science 304(5676):1463–1466

Fondo E, Skilleter G, Chaloupka M (2014) The impacts of changes in prawn trawling effort on trophic structure after establishment of a marine park. In: Steenbeek J, Piroddi C, Coll M, Heymans JJ, Villasante S, Christensen V (eds) Ecopath 30 years conference proceedings: extended abstracts., Fisheries Centre Research Reports 22(3) [ISSN 1198-6727]. 237 p Fisheries Centre, University of British Columbia, Vancouver, pp 20–21

Fretzer S (2014) Implementing the habitats directive in Germany: case conventions versus Ecopath, Ecosim & Ecospace. In: Steenbeek J, Piroddi C, Coll M, Heymans JJ, Villasante S, Christensen V (eds) Ecopath 30 years conference proceedings: extended abstracts., Fisheries Centre Research Reports 22(3) [ISSN 1198-6727]. 237 p Fisheries Centre, University of British Columbia, Vancouver, pp 63–64

Fulton EA (2010) Approaches to end-to-end ecosystem models. J Mar Syst 81:171–183

Guénette S, Araújo J, Bundy A (2014) Exploring the potential effects of climate change on the Western Scotian Shelf ecosystem, Canada. J Mar Syst 134:89–100

Halpern BS, Walbridge S, Selkoe KA, Kappel CV, Micheli F, D'Agrosa C, Bruno JF, Casey KS, Ebert C, Fox HE, Fujita R, Heinemann D, Lenihan HS, Madin EMP, Perry MT, Selig ER, Spalding M, Steneck R, Watson R (2008) A global map of human impact on marine ecosystems. Science 319(5865):948–952. doi:10.1126/science.1149345

Heymans JJ, Tomczak MT (2014) Regime shifts in the Northern Benguela: challenge for management. In: Steenbeek J, Piroddi C, Coll M, Heymans JJ, Villasante S, Christensen V (eds) Ecopath 30 years conference proceedings: extended abstracts., Fisheries Centre Research Reports 22(3) [ISSN 1198-6727] 237 p Fisheries Centre, University of British Columbia, Vancouver, pp 88–89

Hilborn R, Walters C (1992) Quantitative fisheries stock assessment. Choice, dynamics and uncertainty. Kluwer Academic Publishers, New York

Jackson JBC, Kirby MX, Berger WH, Bjorndal KA, Botsford LW, Bourque BJ, Bradbury RH, Cooke R, Erlandson J, Estes JA, Hughes TP, Kidwell S, Lange CB, Lenihan HS, Pandolfi JM, Peterson CH, Steneck RS, Tegner MJ, Warner RR (2001) Historical overfishing and the recent collapse of coastal ecosystems. Science 293(5530):629–638

Kumar R, Varkey D, Pitcher TJ (2014) Simulation of zebra mussel invasion and evaluation of impacts on the Mille Lacs Lake, Minnesota: an ecosystem model. In: Steenbeek J, Piroddi C, Coll M, Heymans JJ, Villasante S, Christensen V (eds) Ecopath 30 years conference proceedings: extended abstracts., Fisheries Centre Research Reports 22(3) [ISSN 1198-6727]. 237 p Fisheries Centre, University of British Columbia, Vancouver, p 85

Link J (2011) Ecosystem-based fisheries management: confronting tradeoffs. Cambridge University Press, Cambridge

Lotze HK, Lenihan HS, Bourque BJ, Bradbury RH, Cooke RG, Kay MC, Kidwell SM, Kirby MX, Peterson CH, Jackson JBC (2006) Depletion, degradation, and recovery potential of estuaries and coastal seas. Science 312(5781):1806–1809. doi:10.1126/science.1128035

Lucey S, Aydin K, Gaichas S, Fogarty M, Hyun S-Y, Cadrin S (2014) Improving the EBFM toolbox with an open source mass balance model. In: Steenbeek J, Piroddi C, Coll M, Heymans JJ, Villasante S, Christensen V (eds) Ecopath 30 years conference proceedings: extended abstracts., Fisheries Centre Research Reports 22(3) [ISSN 1198-6727]. 237 p Fisheries Centre, University of British Columbia, Vancouver, pp 205–206

Mackinson S (2014) A European perspective on modelling to support an ecosystem approach to management. In: Steenbeek J, Piroddi C, Coll M, Heymans JJ, Villasante S, Christensen V (eds) Ecopath 30 years conference proceedings: extended abstracts., Fisheries Centre Research Reports 22(3) [ISSN 1198-6727]. 237 p Fisheries Centre, University of British Columbia, Vancouver, p 15

Meissa B, Gascuel D, Guénette S (2014) Diagnosis of the ecosystem impact of fishing and trophic interactions between fleets: a Mauritanian application. In: Steenbeek J, Piroddi C, Coll M, Heymans JJ, Villasante S, Christensen

V (eds) Ecopath 30 years conference proceedings: extended abstracts. Fisheries Centre, University of British Columbia, Vancouver, pp 26–27

Morato T, Giacomello E, Bon-de-Sousa J, Heymans J, Menezes G, Pitcher T (2014) Deep-sea ecosystem model of the Condor seamount. In: Steenbeek J, Piroddi C, Coll M, Heymans JJ, Villasante S, Christensen V (eds) Ecopath 30 years conference proceedings: extended abstracts., Fisheries Centre Research Reports 22(3) [ISSN 1198-6727]. 237 p Fisheries Centre, University of British Columbia, Vancouver, p 62

Ofir E, Gal G, Shapiro J (2014) Managing lake ecosystem by using a food-web model: Lake Kinneret as a case study. In: Steenbeek J, Piroddi C, Coll M, Heymans JJ, Villasante S, Christensen V (eds) Ecopath 30 years conference proceedings: extended abstracts., Fisheries Centre Research Reports 22(3) [ISSN 1198-6727]. 237 p Fisheries Centre, University of British Columbia, Vancouver, pp 195–196

Palomares MLD, Morissette L, Cisneros-Montemayor A, Varkey S, Coll M, Piroddi C (2009) Ecopath 25 years conference: extended abstracts. Fish Centre Res Rep 17(3):171

Pauly D, Christensen V, Walters C (2000) Ecopath, Ecosim, and Ecospace as tools for evaluating ecosystem impact of fisheries. ICES J Mar Sci 57(3):697–706

Pedersen T, Fuhrmann M, Lindstrøm U, Nilssen E, Ivarjord T, Ramasco V, Jørgensen L, Sundet J, Sivertsen K, Källgren E, Michaelsen C, Systad G, Svenning M (2014) Ecopath modelling of a subarctic Norwegian fjord after a decline in the coastal cod (Gadus morhua) stock and invasion of red king crab (*Paralithodes camtschaticus*). In: Steenbeek J, Piroddi C, Coll M, Heymans JJ, Villasante S, Christensen V (eds) Ecopath 30 years conference proceedings: extended abstracts., Fisheries Centre Research Reports 22(3) [ISSN 1198-6727]. 237 p Fisheries Centre, University of British Columbia, Vancouver, pp 128–130

Pikitch EK, Santora C, Babcock EA, Bakun A, Bonfil R, Conover DO, Dayton P, Doukakis P, Fluharty D, Heneman B, Houde ED, Link J, Livingston PA, Mangel M, McAllister MK, Pope J, Sainsbury KJ (2004) Ecosystem-based fishery management. Science 305(5682):346–347

Piroddi C, Steenbeek J, Liquete C, Coll M, Macias Moy D, Giannoulaki M (2014) Advances of modelling spatial–temporal ecosystem dynamics in the Mediterranean Sea. In: Steenbeek J, Piroddi C, Coll M, Heymans JJ, Villasante S, Christensen V (eds) Ecopath 30 years conference proceedings: extended abstracts., Fisheries Centre Research Reports 22(3) [ISSN 1198-6727]. 237 p Fisheries Centre, University of British Columbia, Vancouver, pp 142–143

Pitcher TJ, Kumar R, Varkey D, Surma S, Lam ME (2014) Marine protected areas in the Haida Gwaii ecosystem: modelling and policy issues. In: Steenbeek J, Piroddi C, Coll M, Heymans JJ, Villasante S, Christensen V (eds) Ecopath 30 years conference proceedings: extended abstracts., Fisheries Centre Research Reports 22(3) [ISSN 1198-6727]. 237 p Fisheries Centre, University of British Columbia, Vancouver, p 49

Polovina JJ (1984) Model of a coral-reef ecosystem. 1. the Ecopath model and its application to french frigate shoals. Coral Reefs 3(1):1–11

Prato G, Gascuel D, Valls A, Francour P (2014) Balancing complexity and feasibility in Mediterranean coastal food-web models: uncertainty and constraints. Mar Ecol Prog Ser 512:71–88

Ruzicka JJ, Brink KH, Gifford DJ, Bahr F, Peterson WT (2014) An intermediate complexity, physically coupled end-to-end model platform for coastal ecosystems. In: Steenbeek J, Piroddi C, Coll M, Heymans JJ, Villasante S, Christensen V (eds) Ecopath 30 years conference proceedings: extended abstracts., Fisheries Centre Research Reports 22(3) [ISSN 1198-6727]. 237 p Fisheries Centre, University of British Columbia, Vancouver, pp 185–187

Shannon LJ, Jarre AC, Petersen SL (2010) Developing a science base for implementation of the ecosystem approach to fisheries in South Africa. Prog Oceanogr 87:289–303

Staebler M, Kempf A, Temming A (2014) Potatoes of opportunity for fishing in the Southern North Sea. In: Steenbeek J, Piroddi C, Coll M, Heymans JJ, Villasante S, Christensen V (eds) Ecopath 30 years conference proceedings: extended abstracts., Fisheries Centre Research Reports 22(3) [ISSN 1198-6727]. 237 p Fisheries Centre, University of British Columbia, Vancouver, p 29

Steenbeek J (2012) Bridging the gap between ecosystem modelling tools using geographic information systems, vol 20. Fisheries Centre Research Report, University of British Columbia, Fisheries Centre, p 131

Steenbeek J, Buszowski J, Christensen V, Akoglu E, Aydin K, Ellis N, Felinto D, Guitton J, Lucey S, Kearney K, Mackinson S, Pan M, Platts M, Walters C (Submitted) Ecopath with Ecosim as a model-building toolbox: source code capabilities, extensions, and variations. Ecol Model

Steenbeek J, Coll M, Gurney L, Melin F, Hoepffner N, Buszowski J, Christensen V (2013) Bridging the gap between ecosystem modeling tools and geographic information systems: driving a food web model with external spatial–temporal data. Ecol Model 263:139–151

Steenbeek J, Piroddi C, Coll M, Heymans JJ, Villasante S, Christensen V (2014) Ecopath 30 years conference proceedings: extended abstracts. In: Conference EY (ed) Fisheries Centre Research Reports, Barcelona, Spain, 2014. vol 3. Fisheries Centre, University of British Columbia [ISSN 1198-6727], pp 237, Accessed from http://ewe230.ecopathinternational.org/proceedings/

Surma S, Pakhomov E, Pitcher T (2014) Effects of whaling on the structure of the southern ocean food web: insights on the "Krill Surplus" from ecosystem modelling. PLoS One. doi:10.1371/journal.pone.0114978

Taylor MH, Wolff M (2014) Towards an ecosystem approach to fisheries in the Northern Humboldt Current System. In: Steenbeek J, Piroddi C, Coll M, Heymans JJ, Villasante S, Christensen V (eds) Ecopath 30 years conference proceedings: extended abstracts., Fisheries Centre Research Reports 22(3) [ISSN 1198-6727]. 237 p Fisheries Centre, University of British Columbia, Vancouver, pp 197–198

Tecchio S, Coll M, Sarda F (2014) Comparative ecological analysis of Mediterranean deep-sea ecosystems and simulations of global change. In: Steenbeek J, Piroddi C, Coll M, Heymans JJ, Villasante S, Christensen V (eds) Ecopath 30 years conference proceedings: extended abstracts., Fisheries Centre Research Reports 22(3) [ISSN 1198-6727]. 237 p Fisheries Centre, University of British Columbia, Vancouver, pp 135–136

Valls A, Coll M, Christensen V (2015) Keystone species: towards an operational concept for marine biodiversity conservation. Ecol Monogr 85:29–47

Walters C, Christensen V, Pauly D (1997) Structuring dynamic models of exploited ecosystems from trophic mass-balance assessments. Rev Fish Biol Fish 7(2):139–172

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