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Editorial

Modelling marine ecosystems using the Ecopath with Ecosim food web approach: New insights to address complex dynamics after 30 years of developments

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ABSTRACT

Marine and coastal ecosystems provide multiple benefits that are fundamental to human wellbeing, but human actions are disrupting and impacting the Earth's ecosystems at an alarming rate. The Ecopath approach was designed to understand the impact of the wide range of anthropogenic pressures that are exerted on the oceans, and of management options for countering these, and it has over the last thirty years grown into a complex and capable modelling framework: "Ecopath with Ecosim" – with Ecospace added on. Exciting new developments of the approach are contributing to address critical and complex issues related to the health of marine ecosystems such as invasion of species, illegal fishing activities, climate change and the development of new activities (e.g., aquaculture and infrastructure development) in coastal areas.

This Special Issue presents new findings from selected case studies around the world using advanced features of Ecopath with Ecosim that were presented at the International Conference "Ecopath 30 Years-Modelling ecosystem dynamics: beyond boundaries with EwE" (November 2014, Barcelona, Spain). These contributions showcase new capabilities and findings of Ecopath with Ecosim models applications. Together these papers show that a range of diverse ecological, economic, social and governance drivers are often interacting at dynamic and temporal scales to modify marine resources, which underlines that managing marine ecosystems needs a continuous effort to integrate multiple processes.

1. Introduction

During the last thirty years, the Ecopath approach has grown into the modelling suite "Ecopath with Ecosim", or the EwE toolbox (Steenbeek et al., 2016), which integrates the original Ecopath model (Polovina, 1984; Christensen and Pauly, 1992; Christensen and Pauly, 1993) with the temporal dynamic and temporal–spatial dynamic modules Ecosim and Ecospace, respectively (Walters et al., 1997, 1999, 2010; Christensen and Walters, 2004). This approach was among the first ecosystem-level simulation model to be freely accessible and user friendly, which contributed to its worldwide uptake and popularity as a key tool for the ecosystem-approach to fisheries and marine resources. In acknowledgement of this impact, 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/).

Up to now, more than 500 ecosystem models using the EwE approach have been published which are referenced by more than 700 citations per year, on average over the last decade (Colléter et al., 2013, 2015); and EwE is also described in more than 668 available publications (searched on 19th April 2016).

This Special Issue is one of the scientific outcomes of the International Conference entitled "Ecopath 30 Years-Modelling ecosystem dynamics: beyond boundaries with EwE" hosted by the Institute of Marine Science (ICM-CSIC) held in Barcelona (Spain) from 10 to 12 November 2014 (http://ewe30.ecopathinternational.org/) (Coll et al., 2015). The Special Issue is comprised of 15 papers dealing with ecological and socio-economic impacts of environmental change and human activities and (such as fisheries, aquaculture, marine renewable energy installations) in a wide range of marine ecosystems. The papers include both general studies about the application of EwE and specific case studies that examine local and regional issues impacting marine food webs. Simple to complex environmental and human drivers such as illegal fishing, regime shifts, climate change as well as how to tackle these drivers with different conservation and fisheries management strategies to ensure the health of marine ecosystems are investigated.

We have organized the content of the Special Issue in four thematic areas that illustrate the use of EwE to address diverse research topics: (i) modelling the ecosystem impact of fishing and aquaculture activities; (ii) modelling marine ecosystems under anthropogenic pressures such as invasive species, oil spills and climate change; (iii) modelling spatial–temporal complex dynamics

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of marine ecosystems; and (iv) general applications and guidelines for best practices when using EwE models.

2. Ecopath with Ecosim 30 years Special Issue

2.1. Ecosystem impact of fishing and aquaculture activities

The first thematic area of this Special Issue includes five papers. In the first paper, Bacalso et al. (2016) use an Ecosim dynamic simulation model to analyse the potential biological and socio-economic effects of a hypothetical successful ban on the illegal fisheries in the Central Visayas islands of the Philippines under "*with*" and "*without*" fishing effort reallocation scenarios. The authors find that the elimination of illegal fisheries can be a profitable strategy without necessarily having to reduce fisheries employment through a reallocation of displaced illegal fishers to the legal fisheries. Effort reallocation without job losses presents an attractive scenario for stakeholders in subsistence fisheries where alternative livelihoods are limited. The results also show that the weighted average per capita net profit income in the studied municipal fisheries could increase substantially (38%) compared to the current status quo.

In the second paper, Stäbler et al. (2016) develop a food web model of the southern North Sea to investigate the potential achievement of a multispecies maximum sustainable yield (MSY) and good environmental status at the same time. The study also quantifies interactions between species and fisheries that lead to trade-offs between fisheries policy goals and marine conservation strategies. The paper concludes that it is impossible to achieve good yields of all scope species simultaneously – in line with the findings of Walters et al. (2005). In fact, long-term projections carried out in this contribution highlights multiple fishing regimes that lead to catches of at least 30% of all focal single species MSYs at the same time.

The third paper in this thematic area is by Ocampo Reinaldo et al. (2016) who developed the first comprehensive dynamic EwE model of the San Matias Gulf food web in Argentina. The authors investigate the effect of a growing South American sea lion (*Otaria flavescens*) population on the Argentine hake (*Merluccius hubbsi*) in the gulf. The analyses show that over four decades the increase in sea lion biomass has not generated a significant increase in the predation mortality of Argentinean hake. They also find that an increase and subsequent variation in the fishing mortality of large Argentine hake seems to be related with long-term changes in abundance of large individuals and a decrease in medium-sized, constraining the cannibalism mortality. In spite of further research and refinement of the food web model still being needed (e.g., filling of information gaps), the approach establishes an important basis for future hypothesis testing on synergistic activities over the San Matias Gulf food web.

The fourth paper by Izquierdo-Gómez et al. (2016) develop an EwE model to shed light on the population dynamic of aquaculture escapees in the wild and on the effects of recapture by a local fishery in the Mediterranean Sea. During the last thirty years, the number of fish farms has increased dramatically in coastal waters, releasing a substantial amount of organic matter, modifying the habitat and communities beneath cages and changing the spatial–temporal distribution of species. Under different simulated scenarios of escaped biomass, the authors find an increase of fishing effort enhancing the capture per unit of effort of the fleet and also a minimization of net expenses. They also conclude that fleets benefit from escapees in terms of yield, but revenues usually depend on how escapees affect the value of the catches, be it positively or negatively.

Finally, Kluger et al. (2016) use an EwE model to analyze the expansion of the Peruvian bay scallop (*Argopecten purpuratus*) in the Sechura Bay (North of Peru), where overstocking of scallops combined with important environmental changes may cause mass mortalities and have severe consequences for the marine ecosystem. The results of the model indicate that the further expansion of scallop culture generally caused total system biomass to increase and induced a change in community structure due to the bottom-up effect of scallop on its predators. The study also shows that exceeding a threshold scallop biomass levels of 458 $t\,km^{-2}$ may cause other functional groups biomasses to decrease below the 10% threshold of their original standing stock, potentially threatening ecosystem functioning. Overall, the work is highlighting the necessity for an ecosystem-based approach to establish the ecological carrying capacity of the system.

2.2. Impact of invasive species, oil spills and climate change

The second thematic area of this Special Issue contains four contributions to this Special Issue. In the first paper, Kumar et al. (2016) develop an EwE model for Mille Lacs Lake Central Minnesota (USA) with the aim to study the food-web dynamics of the lake, especially as a consequence of establishment of zebra mussels (*Dreissena polymorpha*) in the system. Model predictions are in close-agreement with the field-data for many species when compared for the years 2006–2012. The simulation results show system-wide collapse of major predators including walleye due to the bottom-up trophic control as zebra mussels efficiently filter out the phytoplankton from the system. The model predicts severe declines in phytoplankton and zooplankton densities followed by a system-wide collapse of forage fish and top predators including walleye. The model also suggests increases in species such as shiners, minnows and sunfish which depend on periphyton.

In the second paper of this thematic area, Larsen et al. (2016) address the potential negative impacts expected from oil spills through severe mortality events for marine organisms in the Pechora Sea (South Eastern Barents Sea). The authors use the contaminant tracer module Ecotracer included in the EwE suite, to model the spread of Polycyclic Aromatic Hydrocarbons from a fictitious spill of marine diesel oil. Ecotracer predicts that pollution in the mussels would spread throughout the food-web, especially to the top predators of mussels, king eider (*Somateria spectabilis*) and Atlantic walrus (*Odobenus rosmarus rosmarus*), and also from snow crab (*Chionoecetes opilio*) to seals and toothed whales. Despite some data limitations, the paper shows that a food web influenced by a single accidental event can be modelled, and the spread of contaminants addressed by applying Ecotracer.

This thematic area includes the paper from Ruzicka et al. (2016), who describe a theoretical framework for the construction of an intermediate complexity, physically coupled end-to-end (E2E) model built upon traditional Ecopath food web models applied to the Northern California Current upwelling ecosystem. The model is run under alternative physical driver scenarios to evaluate the effects of changing upwelling characteristics on the production and spatial distribution of functional groups across all trophic levels included in the study. As the duration of individual upwelling events tends to increase which implies some climate change induced effects, model simulations predict an overall reduction of productivity at all trophic levels and a shift in the size composition of the phytoplankton community, especially within the nearshore region.

2.3. Modelling spatial–temporal complex dynamics

The third theme of this Special Issue deals with the spatial–temporal applications of EwE models. In the first paper, Coll et al. (2016) use Ecospace to drive a spatially explicit marine food web model representing the Southern Catalan Sea (NW Mediterranean Sea, Spain) with various environmental drivers and fishing.

Three commercial species, European hake (*Merluccius merluccius*), anchovy (*Engraulis encrasicolus*) and sardine (*Sardina pilchardus*) are used to evaluate results. The paper compares the outcomes of the original Ecospace model that used habitats (Walters et al., 1999) with the new habitat capacity modelling approach, which is a combination of niche modelling and food web modelling (Christensen et al., 2014). The study shows that the new Ecospace approach predicts more realistic results and that the effects of environmental conditions and fishing tend to accumulate in a synergistic or antagonistic way, where the sum of individual contributions does not result in the overall contribution when factors are included in the simulations together. Fishing has the highest impact on spatial modelling results for anchovy, sardine and hake, while the spatial distribution of primary producers and depth follows in importance as relevant drivers. The study helps provide a baseline to further develop spatial–temporal analyses and move forward with the evaluation of future scenarios of global change in the Western Mediterranean Sea, including the impact of climate variability and regional change.

In the second paper Alexander et al. (2016) analyse the utility Ecospace to study two plausible benefits (the 'artificial reef effect' and the 'exclusion zone effect') of marine renewable energy device installations to mitigate the potential loss of access for the fishing industry on the West coast of Scotland (United Kingdom). The model results suggest that it is currently not possible to definitively point out whether the positive effects of marine renewable energy device installations would mitigate any loss of access to fishing areas caused by them. Further research is still needed to validate the spatial distribution of species biomass using the habitat capacity module of Ecospace (Christensen et al., 2014).

Lewis et al. (2016) present the third paper under this topic. The study uses the habitat capacity module of Ecospace and the spatial–temporal data framework (Steenbeek et al., 2013) to determine, under different modelling scenarios, if a suitable response mechanism between estuarine organisms and marsh edge distance could be developed in the Barataria Bay, Louisiana (USA). The model effort reveals that, while species-specific responses to marsh edge, the association between nekton and marsh edge may not be as tightly coupled in coastal Louisiana as once thought. Taking into account that marsh edge and marsh area have both decreased over the 10 year period of the model run, coupled with the fact that the modeled edge curves do not notably improve model fits when incorporated in Ecospace, they find that estuarine nekton may not be as dependent on marsh edge as once thought. The authors conclude that a possible explanation for the resilience observed in many estuarine species could be derived from their adaptive capacity to dynamic deltaic ecosystems over thousands of years.

This thematic area ends with a paper by Mutsert et al. (2016) who develop an EwE model to analyse the net effects of hypoxia on fish biomass and fisheries landings in the Northern Gulf of Mexico (USA) using the habitat capacity module of Ecospace and the spatial–temporal data framework. The study suggests that reductions in landings and biomass due to hypoxia are an order of magnitude lower than increases seen due to the nutrient enrichment, which is, in turn, the main cause of hypoxia. In terms of fisheries management, the model simulations indicate that policy makers need not consider the hypoxic zone into account in fisheries management plans, as the occurrence of seasonal hypoxia in combination with fishing does not necessarily lead to unsustainable biomass reductions.

2.4. General applications and guidelines

The last thematic area of the Special Issue includes three studies. In the first paper, Heymans and Tomczak (2016) use an EwE model to analyse the impacts that fishing activities and climate change have on the structure of the Northern Benguela ecosystem. This study introduces a general analysis on how to detect regime shifts using results from Ecopath with Ecosim models. Ecological Network Analysis indices and Integrated Trend Assessment of the input data and model outputs are used to describe changes in the ecosystem over the last 50 years. The results show that the system has moved from a regime with high redundancy and lower internal structure into a system with higher internal structure and less resilience due to high fishing pressure and two specific catastrophic events in form of Benguela Niños that occurred in the early 1970s and the early 1980s.

In the second paper, Fretzer (2016) investigates the impacts of an industrial area, construction of a road and a wind power generator that might negatively affect a Natura 2000 site in Germany by using the Ecospace habitat capacity model. This study is the first application of the habitat capacity model in a terrestrial environment and with the objective to contribute to a formal environmental impact assessment application in mind. To ensure that project or plans that cause habitat loss do not negatively affect a Natura 2000 site (Article 6.3 of the Habitats Directive; 92/43/EEC) clearly specifies the assessment procedure. This study quantifies the ecological damage and indicates effective compensation measures, as well as appropriate monitoring programs. The author illustrates that the Ecopath modelling is the most appropriate tool for environmental management in the European Union.

Finally, the Special Issue concludes with the paper from Heymans et al. (2016) that provides a suite of best practices for creating EwE models. The authors describe diagnostics to check for thermodynamic and ecological principles when building and balancing a model. They highlight the potential pitfalls when comparing Ecopath models using Ecological Network Analysis indices and they present the state of the art in calibrating models to data using a formal fitting procedure and statistical goodness of fit. Finally, uncertainty in input parameters can be addressed and how to best use these models in the management context, specifically using the concept of 'key runs' for ecosystem-based management. These best practices will help with the uptake and utilization of model outputs and increase the credibility of EwE models for wider application.

Combined, the contributions in this Special Issue illustrate that the EwE approach is coming of age – thirty is a respectable age – and that it is capable of contributing to a wide variety of ecological studies ranging from basic to applied research, and notably related to fisheries management and environmental impact assessment. We find the recent developments in spatial modelling techniques especially encouraging, and we do expect that this is an area that will see rapid development in the years to come.

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