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Best practice in Ecopath with Ecosim food-web models for ecosystem-based management

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ABSTRACT

Ecopath with Ecosim (EwE) models are easier to construct and use compared to most other ecosystem modelling techniques and are therefore more widely used by more scientists and managers. This, however, creates a problem with quality assurance; to address this we provide an overview of best practices for creating Ecopath models. We describe the diagnostics that can be used to check for thermodynamic and ecological principles, and highlight principles that should be used for balancing a model. We then highlight the pitfalls when comparing Ecopath models using Ecological Network Analysis indices. For dynamic simulations in Ecosim we show the state of the art in calibrating the model by fitting it to time series using a formal fitting procedure and statistical goodness of fit. Finally, we show how Monte Carlo simulations can be used to address uncertainty in input parameters, and we discuss the use of models in a management context, specifically using the concept of 'key runs' for ecosystem-based management. This novel list of best practices for EwE models will enable ecosystem managers to evaluate the goodness of fit of the given EwE model to the ecosystem management question.

1. Introduction

Ecopath with Ecosim (EwE) is a modelling complex that has been used to create mass balanced models of marine and aquatic ecosystems since the 1980s, when the first Ecopath model of the French Frigate Shoals was created by Jeff Polovina (1984). The software and techniques have been improved to include methods of comparing ecosystems using Ecological Network Analysis (Christensen and Pauly, 1992), to model dynamic changes using Ecosim (Walters et al., 1997), to model spatial changes using Ecospace (Walters et al., 1999) and to model both temporal and spatial dynamics using the spatial-temporal-framework and the habitat foraging capacity model (Christensen et al., 2014).

EwE is the most applied tool for modelling marine and aquatic ecosystems globally, with over 400 models published to date (Colléter et al., 2013). Ecopath was recognized as one of NOAA's top ten scientific breakthroughs (http://celebrating200years.noaa.gov/breakthroughs/ecopath/welcome.html) in its 200 year history, and the 30th anniversary of the approach was recently celebrated with an international conference (Steenbeek et al., 2014; Coll et al., 2015). The EwE approach is able to address many of the questions asked by managers on marine policy issues such as natural variability and monitoring, management measures, ecosystem goods and services, "Good Environmental Status" targets for the EU Marine Strategy Framework Directive, and environmental change and climate adaptation (Steenbeek et al., 2014; Hyder et al., 2015). It has also been partially re-coded in different programming languages (Steenbeek et al., 2015) including Fortran (Akoglu et al., 2015), Matlab (Kearney et al., 2013), and R (Lucey et al., 2014). However, of the 105 models used for comparative analyses by Heymans et al.

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(2014) few have been fitted to historical data using Ecosim (27/105) and even fewer (13/105) were actually calibrated by fitting to time series data (Table S1 in Heymans et al., 2014). Additionally, very few models have actually been used in a management context. A noteworthy exception is the model of the North Sea (Mackinson et al., 2009b), which has recently been used to establish a "key run" (see Section 8 below for a description of key runs) for the ICES Working Group on Multispecies Assessment Methods, WGSAM http://www.ices.dk/community/groups/Pages/WGSAM.aspx (ICES, 2013), and used to evaluate EU Commission proposals for multi-annual plans in the North Sea (STECF, 2015). Models have also been used in the Gulf of Alaska and Bering Sea (Aydin et al., 2007; Gaichas et al., 2011) and the Western Scotian Shelf (Araújo and Bundy, 2012), where those outputs informed the management process by evaluating previously unexplained mortality.

Because of its ease of use, both the construction and comparison of EwE models can be easily misused by inexperienced users. Ecopath models are easy to construct, with very few automatic checks, but instead requiring the understanding and application of ecological knowledge by users. Ecological Network Analysis (ENA) comparisons are similarly easily undertaken without checking the thermodynamic and mathematical rules behind the analyses (but this is true for all ecological analyses). EwE models, once balanced (whether sensibly or not) can then be used to describe dynamics in the ecosystem without forced calibrations, which again can be used for management without proper verification and validation. This easy access, with limited quality control, may have contributed to the limited utilization of EwE models for management applications.

In order for EwE models to be accepted as being rigorous and consistent enough to be used for management, guidelines are needed to establish best practices in creating and using the models. These guidelines need to take into consideration the thermodynamics and ecological rules available to users, recommended approaches to balance an Ecopath model, the best tools to fit models to time series data, and how to evaluate uncertainty. In addition, we need best practices for comparing ecosystem models of different ecosystems or different models of the same ecosystem via standardized indicators, descriptors, etc. Here, we provide an overview of the best practices for creating Ecopath models, fitting Ecosim models to time series, evaluating uncertainty, and comparing models. The contents herein can serve as guidelines for testing and reviewing EwE models, especially if they are to be used for management purposes.

2. Why and how to create an Ecopath model

The FAO have suggested best practices for developing models for an ecosystem approach to fisheries, including considerations for model aggregation, spatial consideration, etc. However, in this paper we are providing the best practices specifically with respect to creating, balancing, fitting and using an EwE model, after one has followed the more generalized best practice guidelines of FAO (2008).

2.1. Why this model?

The choice of modelling technique should always depend on the policy or research question that is to be addressed. The model has to be constructed with the policy or research questions clearly formulated, which will lead to using the correct modelling framework. The FAO report on models used for an ecosystem approach to fisheries (Plagányi, 2007) gives a flow chart that summarizes the models explained and where they are best used. This is a very handy way of making sure the model one uses is able to answer the question being asked. However, it is important that the newest descriptors of the techniques are used when making that decision, as the 2007 report describes the capacity of modelling techniques at that time. According to the report, EwE can be selected to: identify and quantify major energy flows in an ecosystem, describe the ecosystem resources and their interactions among species, evaluate the ecosystem effects of fishing or environmental changes, explore management policy options by incorporating economic, social and ecological considerations of fisheries, evaluate the placement and impact of marine protected areas, or predict the bioaccumulation of persistent pollutants. EwE models are also useful for testing ecosystem theories on resilience, stability and regime shifts (Pérez-España and Arreguín-Sánchez, 2001; Tomczak et al., 2013; Arreguín-Sánchez and Ruiz-Barreiro, 2014; Heymans and Tomczak, 2015).

2.2. Creating an Ecopath model

A EwE model must represent the main species and trophic levels that are present in the modelled ecosystem and are of relevance for the policy or research question that is to be addressed. The time frame and spatial extent of the EwE model depends on the questions that are to be addressed, as well as data availability. The modelled ecosystem should, as a rule, include the whole habitat area of the main species of concern. If for instance the role of a migratory species on a smaller ecosystem needs to be studied, the biomass of that migratory species would have to be forced in the model. The model will not be able to predict its biomass without information of dynamics outwith the system. The baseline Ecopath models are usually based on average parameters for a given baseline year, and thus typically average over seasonal changes in the ecosystem, although daily (Orr, 2013) and seasonal (Heymans et al., 2002) models have also been developed. To use a EwE model for ecosystem-based management, time series fitting is required to incorporate density-dependence, which best is done by evaluating how the EwE model can reproduce historical dynamics. It follows that sufficiently long time series are required to provide contrast, and the baseline Ecopath model should thus be based on the earliest time where data is available. Temporal extents have ranged among EwE models from 10 to >50 years, depending on the degree of available data. Alternatively, a model can be constructed for the year where most data is available, and then adapted to an earlier timeframe where time series data started, as was done in several examples such as for Central North Pacific (Cox et al., 2002), the Aleutian Islands (Heymans, 2005), Newfoundland (Pitcher and Heymans, 2002), the North Sea (Mackinson and Daskalov, 2007), and the north-western Mediterranean (Coll et al., 2008). It is important, however, to consider the choice of time frame in relation to changes in ecosystem structure that should be accounted for in the dynamic behaviour of the ecosystem model. For example the behaviour might be different in one climate regime than in another. In some cases it is possible to model this change, such as was done in the Baltic Sea (Tomczak et al., 2013), the Gulf of Alaska (Heymans et al., 2007), and the northern Benguela (Heymans and Tomczak, 2015). However, it might not be possible to model this behavioural change, which will severely limit the given model's long-term predictive capabilities.

EwE models must contain at least one detritus group and one consumer group, while there in practice is no upper limits to the number of groups that can be included. Primary producers, while most often included, are not required. As an example, in deep sea models (Tecchio et al., 2013) primary producers may not be present and more than 1 detritus group might be needed to describe the system adequately, for example incorporating marine snow. Often, a combination of functionality and lack of data will require aggregation of several species into 'functional groups' to describe the ecosystem. Functional groups can be individual species or groups

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