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A combined ecosystem and value chain modeling approach for evaluating societal cost and benefit of fishing☆

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ABSTRACT

We describe a combined ecological and economic approach aimed at giving more equal emphasis to both disciplines, while being integrated so that design, analysis, data entry and storage, and result capabilities are developed with emphasis on deriving a user-friendly, easily accessible tool. We have thus developed the approach as an integrated module of the freely available Ecopath with Ecosim scientific software; the world's most widely applied ecological modeling tool. We link the trophic ecosystem model to a value-chain approach where we explicitly and in considerable detail keep track of the flow (amounts, revenue, and costs) of fish products from sea through to the end consumer. We also describe the social aspects of the fish production and trade, by evaluating employment and income diagnostics. This is done with emphasis on distribution income while accounting for social aspects of the fishing sector. From a management perspective, one of the interesting aspects of the approach we introduce here, is that it opens for direct evaluation of what impact management interventions, e.g., quota settings, effort regulation, or area closures, may have on the ecosystem, the economy and the social setting, as well as on food availability for the consumer.

1. Introduction

There is an increasing tendency for contemporary studies in fisheries research to strive for interdisciplinarity, and such is almost certainly a requirement if we are to live up to the ambitious agreement of the Johannesburg Plan directing management of fisheries so as to allow ecosystems to be restored by 2015 (United Nations, 2002). As researchers, we tend, however, to build our tools of analysis around what we know best, adding complexity where we from experience know it is required, while giving other areas and disciplines but cursory treatment. We all stand 'guilty as charged' in this respect; we have for instance as ecologists when developing the Ecopath with Ecosim (EwE) approach and software limited the economical aspects to simple ex-vessel cost and benefit considerations (Christensen and Walters, 2004a), even if policy optimization tools with an economic perspective have been added on (Christensen and Walters, 2004b). Similarly, many bioeconomic models have ignored ecological aspects such as caused by trophic interactions (fish eat fish!), and have typically just applied a simple population growth function to capture fish stock dynamics (e.g., Failler and Pan, 2007).

In this contribution, we describe a combined ecological and economic approach aimed at giving more equal emphasis to both disciplines, while being integrated so that design, analysis, data entry and storage, and result capabilities are developed with emphasis on deriving a user-friendly, easily accessible tool.

We build on the EwE approach, which is implemented as the world's most widely applied ecological modeling software, and which has been recognized as a flexible and capable tool (Plaganyi, 2007), as expressed by its recognition by the US National and Atmospheric Administration as one of the 10 biggest scientific breakthroughs in the organization's 200-year history.

The approach has the Ecopath mass-balance approach as its starting point (Polovina, 1984; Christensen and Pauly, 1992), and involves description and evaluation of the key resources and their trophic interactions as well as of their exploitation. Following, time-dynamics are modeled using the Ecosim model (Walters et al., 1997, 2000), involving a comprehensive scheme for tuning to time-series data in order to replicate time trends in the ecosystem while evaluating fisheries and environmental impact (Christensen and Walters, 2005).

The Ecopath model describes what happens in the oceans with particular emphasis on the food web and on human exploitation. It ends, however, when the ship reaches the port. We have not gone beyond ex-vessel prices when describing bio-economical aspects.

☆ *Software availability*: The value chain module is distributed as an optional module with the Ecopath with Ecosim software, version 6, freely available from www.ecopath.org. The source code is available on request from the corresponding author.

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Here, we link the trophic model to a value-chain approach where we explicitly and in considerable detail keep track of the flow of fish products from sea through to the end consumer.

The supply chain approach was developed to assess the contribution made by both foreign and domestic fleets operating in West African EEZs to the supply of fish for the local population in countries such as Mauritania, Senegal, Guinea and Guinea Bissau where fish plays an important role in the daily diet (Failler, 2001; Failler et al., 2005). It gives, in a simple manner, a panoramic vision of the fishery sector and the path followed by the fish from its capture to its consumption. Since then the fish chain approach has been used by FAO (Failler, 2006) and UNEP (Failler, 2007, 2009) to show how international trade is one of the main driving factors behind fisheries exploitation. The strong link between fish trade and marine ecosystems is currently being used – following the supply chain approach – in the international cooperation research project ECOST (www.ecostproject.org) of the European Commission.

We also describe the social aspects of the fish production and trade, by evaluating employment and income diagnostics. This is done with emphasis on distribution income while accounting for gender aspects of the fishing sector, including for dependents.

From a management perspective, one of the interesting aspects of the approach we introduce here, is that it opens for direct evaluation of what impact management interventions, e.g., quota settings, effort regulation, or area closures, may have on the ecosystem, the economy and the social setting, as well as on food availability for the consumer. Likewise the approach, given its capability to evaluate environmental impact (Christensen and Walters, 2005), opens for quantification of how climate impact may impact future harvest from the sea. In this paper, we describe the extended value chain approach, and we demonstrate its use through a hypothetical case study.

We expect that applications of the approach generally will fall in two categories. The first is detailed case studies of the value chain in a given area, typically with focus on fine-scale economical and social indicators, and possibly describing only part of the fishing sector. The second type will be more general descriptions, e.g., at the country-level, used to evaluate the contribution of fisheries overall, e.g., to the Gross Domestic Product and to national employment or for estimation of potential loss through overexploitation (Arnason et al., 2009).

2. Methods

2.1. The ecosystem model

Ecopath is a mass-balance model, originally developed to describe the trophic flows in the French Frigate Shoals ecosystem in the Northwestern Hawaiian Islands, with emphasis on describing all trophic levels in the system and on evaluating how demand by predators could be balanced by production of prey (Polovina, 1984). The approach has been under development for more than 25 years. The computational aspects of the modeling are described in many other publications to which we refer for details (e.g., Christensen and Walters, 2004a).

The key aspect of the ecological model is that for each functional group (i) in the system we describe the production (P_i),

$$P_i = B_i \cdot (F_i + M0_i + NM_i + \Delta B_i) + \sum_j Q_j \cdot DC_{ji} \qquad (1)$$

where B_i is the biomass of (i) F_i is the fishing mortality rate (catch/biomass), $M0_i$ is the unexplained mortality rate, NM_i is the net migration rate (immigration–emigration), ΔB_i is the biomass accumulation rate, and where the last term describes the predation mortality rate, obtained from summing for all predators (j), the consumption rate (Q) times the proportion (DC) the prey contributes to the predator diet.

We further estimate the consumption (Q) for the group as,

$$Q_i = P_i + X_i + R_i \qquad (2)$$

where X_i is the combined excretion and egestion rate, and R_i is the respiration rate. When parameterizing the model, we typically estimate $M0_i$ in Eq. (1), and R_i in Eq. (2) in order to balance the resulting two sets of linear equations. This leaves the total mortality (Z_i or P_i/B_i), biomass, catches, migration, biomass accumulation, diets, consumption, and excretion/egestion as the parameters for input, all group-specific.

The Ecopath model provides a static description of the ecosystem, with ability to describe the food web in detail as desired. Functional groups may thus consist of multiple species, or they may be detailed age groupings of individual species, depending on what is opportunistic in the individual case (Walters et al., 2008). Fishing operations may similarly be described in details as required.

The time-dynamics are modeled using the Ecosim model (Walters et al., 1997, 2000), which is based on the same equations as above, while estimating time-varying production rates based on changes in predation, prey availability, fishing pressure, and environmental productivity. From a parameterization standpoint, the Ecosim model only requires few additional parameters beyond what is required for the underlying Ecopath model, yet, facilitates modeling of more complex relations such as, e.g., life-history dynamics (Walters et al., 2008), mediation, prey switching, and density-dependent catchability (Walters and Martell, 2004).

For the Ecosim modeling, the most important question is how density-dependence impacts population trends: how may the consumption by a group change when its abundance changes? Should the population double; will it be able to double its food consumption? We model this through a 'vulnerability' parameter, which expresses the maximum factor the predation mortality can increase for a prey given a large increase in the given predator's biomass. The vulnerabilities cannot be estimated directly from observations, and our best approach for estimation involves non-linear fitting to time series data (Christensen and Walters, 2005).

Through the ecosystem modeling we obtain a quantified description of how the fisheries catches change over time, in the past, present as well as into the future through evaluation of alternative management and climate change scenarios (Brown et al., 2010).

2.2. Value chain modeling

In the value chain modeling (or product flow analysis) we distinguish between producers, processors, distributors, sellers, and consumers, and we describe the flows between these, summing up to estimate overall flow of products, values, and services. We have implemented the value chain approach using an object-oriented programming (OOP) approach in which the enterprises (i.e. excluding the consumers) listed above inherit a suite of joint properties for all enterprises.

We have listed the production and revenue-related parameters in Table 1, the cost parameters in Table 2, and the parameters relating to social aspects in Table 3. A characteristic of the OOP implementation is that it is straightforward to change the parameter structure, including addition of more parameters when this is warranted.

2.2.1. Producers

We start the analysis with the producers, and have defined two alternative starting points, both parameterized from the underlying ecosystem model. We can describe fisheries landings by 'métier', i.e. by fishing fleet and by species or functional group, or we can, for