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Exploring conflicting management objectives in rebuilding of multi-stock fisheries

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ABSTRACT

Rebuilding depleted fish stocks and preventing the collapse of fisheries are major challenges for most coastal countries. In addition to human-induced factors, interactions between fish stocks within a food web add further complexity to the task of stock rebuilding. In this study we use a stylized bioeconomic model of a multi-stock fishery to study how different management objectives are affected by the nature of stock interactions and to identify potential trade-offs between multiple objectives in stock rebuilding. The results show that the type and strength of stock interactions determine directly the trade-offs between the biological and economic objectives of the fishery as well as the short-term and long-term objectives in stock rebuilding. Compared to a single species perspective, the opportunity cost of hastening the speed of stock rebuilding by reducing the fishing capacity is lower when the depleted stocks have a competitive relationship and higher when the interdependence between the stocks is predatory-prey or mutually beneficial. Our model results further show that stock interactions directly influence whether full or partial rebuilding of depleted stocks is achieved and whether the biomass of rebuilt stocks remains above the management target over time. Even a simple form of competitive or predator-prey interaction can prolong the duration of the rebuilding process and reverse initial rebuilding success or prevent it entirely, underlying the importance of stock interactions for the rebuilding of fisheries.

1. Introduction

Rebuilding of depleted fish stocks towards ecological, social and economic goals has been long recognized as a key challenge for fisheries management (May et al., 1979; Gulland and Garcia, 1984). Although stock recovery plans have been implemented globally and the significant benefits of rebuilding depleted fisheries have been demonstrated (Arnason et al., 2009; Costello et al., 2012; Sumaila et al., 2012), the success of rebuilding efforts is mixed (Caddy and Agnew, 2004; Murawski, 2010; Ye et al., 2013). Almost 90% of global fish stocks are classified as either overfished or fully fished while in only 10% of the fisheries the harvest has remained below maximum sustainable level (Worm et al., 2006; Burgess et al., 2013; FAO, 2016).

Human drivers of overexploitation in fisheries and major obstacles for rebuilding efforts include a lack of incentives for fishers to take into account the full impact of their harvesting practices on fisheries (Grafton et al., 2006), overcapitalized fleets and non-malleability of fishing capital (Clark, 2010), fleet capacity moving from one fishery to the next in response to changes in management systems (Asche et al., 2007; Cunningham et al., 2016), and myopic political objectives in fisheries management (Hilborn, 2007). Moreover, interactions among fish stocks introduce additional complexity to the task of stock rebuilding and may even impede recovery or result in poor economic returns from fisheries. For example, given a stock recovery plan, the difference in the productivity of stocks and interactions between them determine the time frames required to rebuild the stocks to target levels and the maximum fishing pressure that can be applied. The varying time frames required for rebuilding different stocks can complicate the planning and regulatory decision-making as well as the cost of management. Interactions between stocks can also lead to changes in the dynamics of fishing fleets, resulting in policy outcomes that may differ from those expected (Fulton et al., 2011).

Different fish stocks and their fisheries are linked through

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various forms of stock interactions. Direct and evident interactions have classically been the main focus of attention, in particular the relationship between predator and prey, and occasionally direct competition between species (Nicholson and Bailey, 1935; May et al., 1979; Clark, 2010). Within food webs, however, the abundance of one stock can affect another stock positively or negatively, through direct or indirect effects of predation or competition for common resources. Positive effects can occur when, for instance, one stock preys on a direct competitor of another stock (Jennings et al., 2009). Furthermore, different life stages of stocks are found on different trophic levels and can both compete with and feed on each other over the course of their life span, as illustrated by several commercially important pelagic stocks in the Northeast Atlantic Ocean (Cabral and Murta, 2002; Sætre et al., 2002; ICES, 2014).

Incorporating social and economic considerations into stock rebuilding can further complicate the design of effective recovery plans. This particular dimension in rebuilding of multi-stock fisheries requires understanding of trade-offs between potentially conflicting management objectives and how they are affected by alternative stock recovery paths and by the nature of stock interactions. For example, achieving the objective of rebuilding depleted stocks for a given time frame might be prohibitively expensive because of trade-offs associated with the short to medium-term economic and social returns to society from the use of resources. The importance of identifying such conflicts in different management objectives is increasingly recognized in the literature (Hilborn, 2007; Dichmont et al., 2010; Péreau et al., 2012). Furthermore, differences in the relative importance of alternative objectives among various stakeholder groups have increasingly been incorporated in fisheries management and institutional policies (Pascoe et al., 2009, 2016). For successful rebuilding, therefore, major food web interactions among overfished stocks require particular consideration, together with the understanding of potential trade-offs between multiple objectives in stock rebuilding (Murawski, 2010; OECD, 2010).

The importance of incorporating the multi-stock nature of resource dynamics in fisheries management has been acknowledged in the literature for a long time (Anderson, 1975; May et al., 1979; Wilson, 1982) and has received increasing attention in recent years, as accounting for trophic interactions is a keystone of the ecosystem approach to fisheries (Garcia and Cochrane, 2005; Jennings, 2005; Morishita, 2008) or, more recently, balanced harvesting (Garcia et al., 2012; Law et al., 2012). However, ecosystem drivers and ecological interaction have been included for only two percent of fish stocks globally in their tactical management advice such as stock assessment models or harvest control rules (Skern-Mauritzen et al., 2016). This gap between theory and management is caused by a number of factors, including the complexity of ecosystems, scientific uncertainty and unpredictability of many ecosystem processes, and institutional and technological constraints (Fulton et al., 2003; Planque, 2016). As one possible resolution, it has been suggested to focus on those interactions between stocks that are most relevant for commercial fisheries, and thus to explore how they influence management strategies and cause potentially conflicting objectives within tractable models of controllable simplicity.

There are two diverging approaches to incorporate interactions between stocks into models: i) analytical multi-stock models and ii) simulation models that encompass entire food webs or ecosystems.[1] Ecosystem models are commonly based on mass-balance approaches that simulate food web interactions by tracking energy and nutrient flows and often integrate biogeographical, oceanographic or anthropogenic submodels. Common tools include Ecopath/Ecosim (Pauly et al., 2000) and ATLANTIS (Fulton, 2004), which have been applied to various systems (Link et al., 2010; Kaplan et al., 2013; Colléter et al., 2015). Existing analytical models, on the other hand, focus typically on one type of stock interactions at one point in time, particularly predator-prey systems (Hannesson, 1983) or competition (Flaaten, 1991). These models are, therefore, unable to assess how the outcomes of fisheries management is affected by different forms of stock interactions. Furthermore, multispecies analytical models commonly focus on fisheries where access is unrestricted, partially restricted, or where the harvest is optimally controlled (Poudel et al., 2012); yet, there are few insights developed specifically for rebuilding of multi-stock fisheries. One exception is Agar and Sutinen (2004) who developed a stylized model of a fishery to investigate the role of technical control (i.e., control of the catchability coefficient) in rebuilding multi-species fisheries, which, however, only considered a predator-prey interaction.

The contribution of this study is to explore the role of food web interactions in general for rebuilding, filling a gap in the literature on bioeconomics and fisheries management. We focus on direct interactions between stocks within a stylized dynamic model to explore the rebuilding of an interacting multi-stock system and to identify potential conflicts among multiple objectives in the process of stock rebuilding. Using a parameterized version of the model, we examine the performance of rebuilding a multi-stock fishery under different stock recovery paths and how the outcomes of stock rebuilding are affected by the types and strengths of interactions among depleted fish stocks. The performance of stock rebuilding is reported against four performance indicators. Two indicators correspond to the economic and conservation objectives of stock rebuilding, while the other two indicators correspond to the long-term objectives of fisheries management. Evaluating the outcomes of alternative stock recovery paths against different performance indicators allows us to study potential trade-offs between indicators, and hence, to identify conflicting objectives in an attempt to rebuild the fish stock.

2. Model description

2.1. Population dynamics

A conceptual diagram of the model is presented in Fig. 1. Our model considers a system in which there are N stocks. Let $x_{i,t}$ and K_i respectively denote the population biomass and carrying capacity of stocks $i = 1,2 \ldots,N$. To describe population dynamics of each stock over time, we use a generalized Lotka-Volterra type model in which each stock has an intrinsic growth rate, $r_i > 0$, and the change in population biomass of stock i is linearly related to stock j, such that:

$$x_{i,t+1} = x_{i,t} + r_i x_{i,t}(1 - x_{i,t}/K_i) - \sum_{i \neq j} \alpha_{ij} x_{j,t} x_{i,t} - h_{i,t} \tag{1}$$

where $i,j = 1,2,\ldots,N, i \neq j$ for discrete annual time steps t. The last term on the right hand side of equation (1), denoted by $h_{i,t}$, is the harvest of stock i in year t. The second term on the right hand side of the equation is the natural growth of stock i and the third term is the interaction of stocks i and j with the interaction parameter $\alpha_{ij} \in \mathbb{R}$, which determines the nature and strength of interactions between the stocks. We standardize each population biomass by setting $K_i = 1$ so that $x_{i,t}$ is bounded between zero and one, and hence it represents the density of stock i. The Lotka-Volterra model has a long-history in modelling the dynamic process of interacting

[1] See Whipple et al. (2000), Fulton et al. (2003) and Collie et al. (2016) for reviews of different ecosystem modelling approaches in the aquatic environment and a discussion on the use of ecosystem models in fisheries management.