Ecological Economics 70 (2011) 1726–1734

Contents lists available at ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon

Analysis

Intertemporal choice of marine ecosystem exploitation

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ARTICLE INFO

Article history:
Received 30 June 2009
Received in revised form 25 January 2011
Accepted 14 April 2011

Keywords:
Marin ecosystem model
Bioeconomics
Fishery
Ecosystem management
Size-based model

ABSTRACT

Exploitation of the marine ecosystem brings with it an intertemporal choice: there is a choice of catching the fish today, or restrain from fishing with the option of an increase in the benefit from future harvest. In a marine ecosystem under common pool management regime the contribution margin from catching the fish belongs to the fisher, while the benefit from the investment of leaving the fish in the sea will be shared in the common pool. The intertemporal choice therefore creates a driver for short sighted use of the ecosystem. The intertemporal balance of the exploitation is analyzed by applying capital theory to a size-based ecosystem model. The model reveals a need for intertemporal balance with respect to both fish size and harvest volume. The management therefore is, at an ecosystem level, to set target and regulate not only harvest volume but also size.

1. Introduction

The marine ecosystem seems to be degenerating; Pauly et al.(1998) found a decline in the mean trophic level of global landings reported to FAO in the period 1950–1994. The term they used for the gradual transition in the composition of these landings from long-lived, high trophic piscovorous fish to short-lived, low trophic level invertebrate and planktivorous fish was “Fishing Down Marine Food Webs.” Based on their models, Christensen et al.(2003) established that catches of predator fish in the North Atlantic increased in the late 1960s from 2.4 to 4.7 million tonnes annually but then declined to below 2 million tonnes annually in the late 1990s. The biomass of high trophic fish in the North Atlantic declined by two-thirds during the last 50 years and is now a ninth of the size it was a century ago. In addition to this decline in the biomass of high trophic fish, other unintended consequences of fishing, such as habitat destruction, incidental mortality of non-target species, evolutionary shifts in population demographics, and changes in the function and structure of ecosystems, are becoming increasingly recognized (Pikitch et al., 2004). To address the degrading of the marine ecosystem, a management of the marine ecosystem in a broader perspective, Ecosystem-Based Fishery Management, is recommended by Pikitch et al.(2004) and seven quoted references.

Recently Worm et al.(2009) analyzed several marine ecosystem models and found that for some systems the exploitation rate seems to have declined and a few have started to recover: the paper then raises a hope that, if exploitation rates are reduced sustainably, the ecosystem can recover. Further Worm et al.(2009), in ten systems, analyzed the management tools and found that in order for management to succeed, depending on local context, a variety of tools is needed. The analysis of the management tools looks on input, the management tools, and output, the state of the ecosystem, without explaining the functionality of the fishery system. From a management point of view, in order to select the proper tools, it must be important to understand the forces that drive the degeneration of the ecosystem. The present article attempts to analyze the economics of marine ecosystem exploitation in order to give insight in some driving forces of marine ecosystem degeneration.

A prerequisite for successful Ecosystem-Based Fishery Management is the ability to create a quantifiable link from the strategic level, the ecosystem, to the level of operation where fish are caught at an aggregated level not bigger than a shoal. To evaluate costs and benefits economic is essential and ecosystem models suitable for economic analyses are therefore needed. Most of the analyses in Worm et al.(2009) are performed on Ecopath, Ecosim and Atlantis models, which all are multispecies mass balance models, whereas the figure ((Worm et al., 2009), Fig. 2) where the concept of multispecies maximum sustainable yield (MMSY) is explained, is based on a sized structured model (Hall et al., 2006). As size is a good proxy for ecological functionality it makes sense to include size as a dimension in the model. However, to make economical analyses with traceable conclusion the model has to be transparent. This can be achieved by including the most important functionality, yet make the model as simple as possible. The present paper adopts the idea of size as the most important dimension in predator–prey interaction in marine ecosystem, combined with the principle of mass balance in the predator–prey interaction and the principle of somatic growth determined by the consumption of prey. To make the model as

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doi:10.1016/j.ecolecon.2011.04.011

simple as possible, size is the only dimension in the model, that is, there are no species. The model of Benoît and Rochet(2004) possesses these properties and is in this paper extended with economics and numerics.

Exploiting the ecosystem brings with it an intertemporal choice: there is a choice of catching the fish to day, or restrain from fishing with the option of an increase in future harvest. If the value of the increased harvest in the future is larger than the value of the forgone harvest today, the restrain from fishing is an investment and the exploitation calls for an intertemporal balancing of the exploitation. Capital theory was first applied in fishery by Clark and Munro(1975) to understand how probably to balance present exploitation of a stock with the future exploitation. In this article capital theory is applied to investigate the intertemporal choice of marine ecosystem exploitation.

If the resource, as in the case of the marine ecosystem, is a common pool,[1] the contribution margin from catching the fish belongs to the fisher, while the benefit from the investment of leaving the fish in the sea will be shared in the common pool. Therefore, if the choice between exploitation and investment in the marine ecosystem is left to the fisher only, the right intertemporal balance will not be attained and the system will be exploited for short sighted gain. As capital theory investigates this intertemporal choice, it gives insight into this driver for short sighted exploitation and the derived risk of degeneration of the resource.

The capital approach of Clark and Munro(1975) has been extended from the single stock model into cohort models (e.g. (Botsford, 1981; Tahvonen, 2009)), and two species models (e.g. (Hannesson, 1983; Ragozin and Brown, 1985)) and three species models (e.g. Flaaten, 1988). Cohort models give insight into economic aspects related to somatic growth and recruitment, and multispecies models give insight in economic aspects related to predation and competition. However, if ecosystem is used in the sense of Tansley(1935), Lindeman(1942) and O'Neill et al.(1986), an ecosystem model must model a system in the sense of physics and build on an understanding of physical processes. None of the mentioned models are physical systems, and they treat the predominant physical aspects of the system, predation and growth, as either external or empirical estimated relations. Regardless of whether the models do model ecological features, the models can in my opinion not qualify as ecosystem models.

Few other attempts to build ecosystem models suitable for economic analysis exist. Ecopath, the model behind both Pauly et al. (1998), Christensen et al.(2003) and Worm et al.(2009) are probably too complicated for capital theoretic analyses. The same applies to the extension Ecosim and for Atlantis. There is to my knowledge no attempt to make capital theoretical analysis on these models. Two other examples are Finnoff and Tschirhart(2003), where general equilibrium theory is applied to the predator–prey interaction in a species community model, and Sanchirico et al.(2008), where portfolio investment theory is applied to the stocks of populations. Both of these are attempts to apply economic models to ecosystem components. The Finnoff and Tschirhart(2003) general equilibrium model is built on the concept of an input–output matrix in the predator–prey interaction and in this way takes a production view of the ecosystem. There do not, however, seem to have been any attempts to apply capital theory to the model. The model of Sanchirico et al.(2008) treats the different populations as investment portfolio objects. The model does not, however, build on a theory of production in the ecosystem.

[1] A common pool can involve different management regimes, defined as the set of rules, cultural or social norms, etc. that regulate the operation. Such span from open access, where there are no or few rules, to ITQ systems where fishers have a tradeable exploitation permit to a specific part of the resource.

The purpose of this article is twofold. First, the intertemporal balancing of the exploitation of the marine ecosystem is analyzed in the context of the trophic level of exploitation. Second, the details behind the economics are analyzed with the purpose of obtaining a better understanding of the driving forces behind the degrading of marine ecosystem. The structure of the paper is as follows. The size-based ecosystem model, the capital theory, the applied method and the results are presented in Section 2. Only the main feature of the model is described in the section; the more technical details of the model are given as supplementary material. In Section 3, the results and their consequences are discussed along with an attempt to explain some forces that drive the degrading of marine ecosystem.

2. Methods and Results

2.1. The Size-based Ecosystem Model

The marine ecosystem has as its atomic production unit the individual fish,[2] and the production itself is the somatic growth of the fish. In order to produce, the fish has to consume other organisms like, for example, other fish. The fish is then a product as well; it can be caught by humans or be internally distributed between other production units. Thus the atomic product of marine ecosystem is the individual fish, and this product may be internally allocated by a predator–prey interaction, or it may be caught by humans as an outlet from the ecosystem. This duality, the fish as both the product and production unit, is a common feature of renewable resources.

It is impossible to model every single organism in an ecosystem, and the fish has to be stratified appropriately. When the fish is stratified, the internal allocation between production units can be described as an input–output matrix with the stratas as both row and column name. Stratified *appropriately* then means stratified in a manner such that the predator–prey interaction matrix is predictable. This predictability can be expected if the fish is stratified according to its function in the trophic system. In the marine ecosystem, the function of the individual fish, as seen in a trophic context, is closely related to the size of the fish. Two fish of the same size but of different species are more alike with respect to food preferences and predator risk than, for example, two fish of the same species but of different sizes (Jennings et al., 2001; Scharf et al., 2000). Furthermore, the predators in the marine ecosystem are generally considerably larger than their prey, and body size is therefore a rough indicator of trophic level (Borgmann, 1987). In other words, the distribution of individuals with respect to size can be seen as a mapping of the trophic system.

Consequently, the organisms in the sea are stratified in the model according to their body mass m, referred to as their size. The strata, or bins, are made infinitesimally small, transmuting the strata into a continuum of m. The model's state variable is concerned with the number of fish in the sea of a given size. The state variable $N(t,m)$ gives the density of fish of size m at time t and is referred to as the spectrum. Strictly speaking, density refers to both volume and mass. The density with respect to volume just signifies that the model reflects one representative cubic meter of water, and its unit therefore is per cubic meter of sea. The density with respect to mass signifies that in order to know the number of fish in a size interval between, for example, m_1 and m_2, the density has to be integrated: $\int_{m_1}^{m_2} N \mathrm{d}m$.

In Fig. 1 the processes of the model are illustrated. The diagram illustrates the population spectrum with size as the abscissa and the density as ordinate; the bold black line then illustrates $N(m)$, and the gray illustrates that the N is a density and that to know the distribution of the fish, N has to be integrated, hence the area under the curve. The N is drawn as a line; if the two axis are both logarithmic,

[2] The model do not distinguish according to phylogeny, so that a fish can be any organism.