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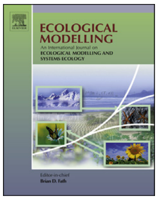

Dynamic patterns of overexploitation in fisheries

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ABSTRACT

Understanding overfishing and regulating fishing quotas is a major global challenge for the 21st Century both in terms of providing food for humankind and to preserve the oceans' ecosystems. However, fishing is a complex economic activity, affected not just by overfishing but also by such factors as pollution, technology, financial factors and more. For this reason, it is often difficult to state with complete certainty that overfishing is the cause of the decline of a fishery. In this study, we developed a simple dynamic model specifically designed to isolate and to study the role of depletion on production. The model is based on the well-known Lotka-Volterra model, or Prey-Predator mechanism, assuming that the fish stock and the fishing industry are coupled variables that dynamically affect each other. In the model, the fishing industry acts as the "predator" and the fish stock as the "prey". If the model can fit historical data, in particular relative to the productive decline of specific fisheries, then we have a strong indication that the decline of the fish stock is driving the decline of the fishery production. The model doesn't pretend to be a general description of the fishing industry in all its varied forms; however, the data reported here show that the model can describe several historical cases of fisheries whose production decreased and collapsed, indicating that the overexploitation of the fish stocks is an important factor in the decline of fisheries.

1. Introduction

Many of the world's fisheries are showing a decline in the fishing yield, a phenomenon that's clearly important for the global economy and which is often interpreted in terms of the overexploitation of the fish stock (Pauly, 2009): the fishing industry is consistently depleting the fish stock at a rate higher than the capability of the system to replenish it, as a result of biological reproduction (Lotze and Worm, 2009), (Bailey, 2016). This subject is complex and it was explored first in some early studies by Scott Gordon (Gordon, 1954) and Milner Schaefer (Schaefer, 1957). In the general field of resource overexploitation, an important influence was the work by Garrett Hardin (Hardin, 1968), known under the name of "The Tragedy of the Commons." Hardin's model was only qualitative, but it established the patterns of overexploitation of any resource that's exploited at a rate faster than it can reform (Roopnarine, 2013). In more recent times, fisheries have been extensively modeled, normally with considerably complex models (Schoener, 1976) and as reviewed, for instance, by Worm et al. (Worm et al., 2009).

Of course, in modeling fisheries, several factors must be taken into consideration in addition to overfishing including, e.g. the climate change (Perry et al., 2005) and that the models based on trophic chains may be over simplified (Polis and Strong, 1996). The problem, here, is to establish exactly which factors are the most important ones in generating the decline of fisheries. This is a crucial issue in the management of fisheries; overexploitation can be fought by establishing fishing quotas but we need to quantify whether there are other factors affecting yield declines. Although there appears to be a general agreement that overexploitation is an important cause of the decline of many fisheries, its extent is sometimes debated.

In the present paper, we aim at providing further evidence that overexploitation plays a central role in the collapse of at least some fisheries. We demonstrate this point by using a simple system dynamics model that takes into account the coupling of the fish stock and the fishing effort of the industry. The fact that the model

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can provide a good fitting with the historical data is a clear indication that the two factors influence each other in a classic feedback relationship that sees the depletion of the stock being enhanced by the effort of the industry to maintain its production rate.

The model utilized here is based on the well-known Lotka-Volterra or “prey-predator” model. Alfred Lotka (Lotka, 1925) and, independently, Vito Volterra (Volterra, 1928), (Volterra, 1931) were the first to use differential equations in order to describe the dynamics of the predator/prey interaction in biological systems and the structure of the model can be seen as an ancestor of modern “system dynamics” (Forrester, 1989). George Gause (Gause, 1932) was probably the first to seek for experimental validation of the Lotka-Volterra (LV) model and he found it, but only for very simple biological systems in the form of two species of yeasts in laboratory conditions. In general, the behavior of real biological systems turned out being too complex to be captured by the simple LV model (Hall, 1988). However, the model had been originally proposed by Vito Volterra as describing the behavior of human fisheries rather than biological systems, even though, at that time, suitable mathematical tools to fit experimental data were not available (D’Ancona, 1942). On the basis of this early idea by Volterra, we developed a simplified version of the model assuming that the fish stock behaves as a non-renewable resource when it is exploited so fast that the reproduction rate becomes a negligible parameter in the system. Some data on this approach had been reported in an earlier paper (Bardi et al., 2011) in regard to the mining industry. Even though the model we developed does not claim to be able to describe all the complex ecosystem and economics interactions that occur in a fishery, we can report several cases in which it is possible to use the model to describe the historical production patterns of fisheries. We believe that this approach can play an important role in helping people to understand the basic mechanisms of fishery management, and in particular of overexploitation. Further studies might lead to the model being usable in order to determine the carrying capacity of the system and help in the sustainable management of fisheries.

2. Methods

The model utilized here is based on the following couple of differential equations

$$R' = -k_1 CR$$

$$C' = k_2 CR - k_3 C$$

where “R” stands for the resource stock while “C” stands for the capital stock. The three constants of the model describe how efficiently fish is caught (k_1), how efficiently the fish stock is transformed into capital (k_2) and how rapidly capital is dissipated (k_3). The dimensions of the constants depend on the units used for the capital and resource stocks.

This model is the same as the well-known Lotka-Volterra, predator-prey model, except in the fact that it lacks the term for the reproduction of the prey (named the resource) in the first equation.

In the original Lotka Volterra model, the prey is assumed to have an unlimited food supply and to reproduce exponentially unless subject to predation; this exponential growth is represented by a term $k_0 R$ in the first equation. We will show later this term can be neglected in the study of the historical cases reported here, but see also the ‘fleet dynamic model’ reported in the work by Hilborn and Walters (Hilborn and Walters, 1992).

In the present study, the “resource stock” (or the “prey”) is the fish stock while the “capital stock” (or the “predator”) is a parameter proportional to the capital of the fishing industry in terms of vessels and other resources (including human resources). The rate of predation, R', is assumed to be proportional to the abundance of both the stocks; this is represented above by $-k_1 CR$, where the efficiency of the fighting process is described by the k_1 coefficient.

In the second equation, C' indicates the variation of the capital stock as a function of time or the ‘capital flow’. k_2 is a constant that describes the rate of growth of the Capital stock, also proportional to the abundance of both the fish and the capital stocks; k_3 is a third constant that describes the decline of the capital stock due to asset depreciation.

The model was implemented using MATLAB® computing language and the associated Simulink toolbox. Typical results are reported in Fig. 1.

In comparing the results of the model to the historical data, the three constants (k_1, k_2 and k_3) were allowed to vary until the best fitting was obtained. All the fittings reported here were generated using the unconstrained nonlinear optimization method based on the Nelder-Mead algorithm (termed “fminsearch” in Matlab). The objective is to minimize the sum of the square of the residuals (SSE, the sum of squared errors of prediction) generated by the deviations of the LV predicted data from actual empirical values of data. The fitting procedure was found to be very sensitive to the initial values of the k_1, k_2 and k_3 parameters, as well as to the initial values of the stocks (R_o and C_o). The initial guesses for these parameters were provided by the Parameter Estimation tool available in the Simulink® Design Optimization™ toolbox (Fig. 2). The Goodness of fit (GOF) was calculated by as the Normalized Mean Square Errors (NMSE) function which measures the discrepancy between the real values and the estimated ones and it was calculated by means of the Matlab Curve Fitting Toolbox. An NMSE equal to 1 represents the

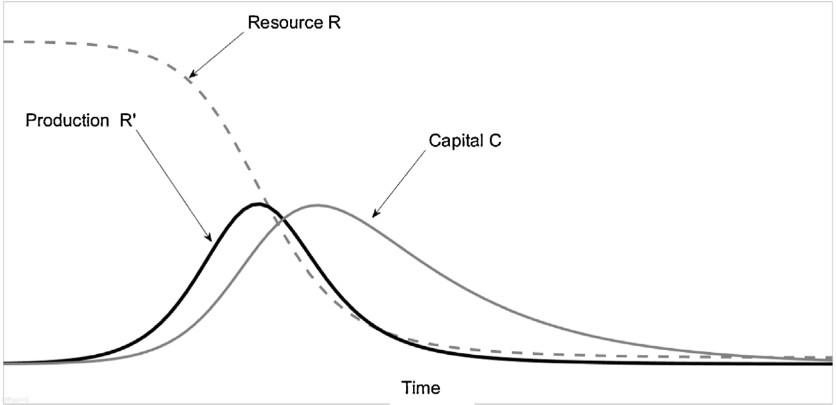

Fig. 1. Qualitative solutions of the model. Neglecting the rate of prey reproduction imposing $k_0 = 0$, the prey-predator dynamic experiences a single oscillation, showing a definitive depletion of the prey stock and the subsequent collapse of predators’ stock.