The decline of fisheries in Japan described by a simple dynamic model

Ilaria Perissi(1), Alessandro Lavacchi (2), Toufic el Asmar(3), Ugo Bardi (1, 4)

1. Consorzio Interuniversitario Nazionale per la scienza e la tecnologia dei Materiali (INSTM); at Università di Firenze, Chemistry Department, Via della Lastruccia 3, Sesto Fiorentino, Italy, tel. +390554573119; email: ilariaperissi@gmail.com

2. Consiglio Nazionale delle Ricerche, CNR-ICCOM; Via Madonna del Piano 10, 50019 Sesto Fiorentino, Italy; tel. +390555225250; email: alessandro.lavacchi@cnr.it

3. Food and Agriculture Organization, FAO; Roma, Italy, Tel. +390657055739, Fax. +390657053057, email: toufic.elasmar@fao.org

4. Dipartimento di Scienze della Terra, Università di Firenze; at Chemistry Department, Via della Lastruccia 3, 50019 sesto Fiorentino, Italy; tel +390554573118, fax:+390554573120; email: ugo.bardi@unifi.it

Keywords: overfishing, exploitation, Lotka-Volterra, system dynamics

Abstract

Fisheries have been a historical playground for dynamic models involving depletion and resource overexploitation, inspiring Vito Volterra in the development of what was probably the first system dynamic model of resource depletion. The model is known today as the Lotka-Volterra (LV) model. In the present paper, we examine the specific case of the Japanese fisheries by means of a simple dynamic system based on the original LV model. We assume that the prey is the fish stock and the predator is an aggregated parameter that takes into account the capital stock of the fishing industry, introducing in the model innovative elements beyond the populations of predators and prey. The results confirm those of earlier work (Ugo Bardi & Lavacchi, 2009) on the behavior of the 19th century whale fishery and show that the LV model can be used for the quantitative description of a real-world model.

Introduction

The overexploitation of the world's fisheries is a much debated problem in view of the depletion of many fish stocks (Myers & Worm, 2003), (Worm et al., 2009), (Lotze & Worm, 2009), (Pauly, 2009) (Watson et al., 2013). The question is obviously complex and the yields of fisheries depend on a variety of physical and economic factors which may be difficult to disentangle from each other. In the present paper we wish to contribute to the understanding of the problem by presenting evidence that, at least in some cases, the behavior of fisheries can be quantitatively understood by means of a simple dynamic model that assumes that overfishing is the main parameter involved in the decline of the fish stock and, as a consequence, of the fishery yield.

The model we are using is derived from the well known "Lotka-Volterra" (LV) (Alfred J. Lotka, 1925) (Volterra, 1926) model (also know as the "Foxes and Rabbits" model). It is based on two coupled partial differential equations that describe the behavior of the simplest possible trophic chain in biological systems: a predator and a prey. The structure of this simple model can be seen as the ancestor of modern "system dynamics" (Forrester, 1989) a method of simulation of complex systems also based on coupled differential equations. The LV model was found to perform poorly for real biological systems (Hall, 1988) but we can show here that it can be used to describe the historical data for at least some cases of a well known economic system: fisheries. We assume that the prey is the fish stock and the predator is an aggregated parameter that takes into account the capital stock of the fishing industry. We report here an example of this approach for the case of the Japanese fishing industry, where we observed that the model can provide a good fit with the historical data. We do not claim that this model is of general validity for the world's fishing industry. However, the fact that it can provide a good insight for at least some cases show that overexploitation is an important parameter that needs to be taken into account when studying the economics of fisheries .

Model outline

The two equations that form the Lotka-Volterra model are well known and can be written as follows:

$$R' = k_o R - k_1 CR$$
$$C' = k_2 CR - k_3 C$$

In this model, *R* is an exploitable 'resource stock' (the prey) and *C* is the 'capital stock' (the predator). We define as *R'* and *C'* as the flow (the variation as a function of time) of the stocks of resources and capital. Further parameters of the model are the initial stocks of resource (R_o) and of capital (C_o). The model depends on four constants, namely: how fast the resource renews itself (k_0), how efficiently the resource is extracted or produced (k_1), how efficiently the resource is transformed into capital (k_2) and how rapidly capital depreciates (k_3). The dimensions of these constants depend on the units used for the capital and resource stocks.

It is well known that this version of the LV model generates infinite oscillations in the amount of both stocks. In the examination of the historical behavior of fisheries, there are examples of multiple cycles of oscillations that may be related to this behavior. However, in this study we have examined systems where a single cycle is observed in the historical record and where, therefore, the reproduction coefficient (k_0) can be considered as close to zero. In other words, in these systems, the reproduction of the stock is so slow that the system behaves as if the stock were not renewable.

In this form, the model generates a declining sigmoid curve for the R stock, that behaves as if it were a non renewable resource. As a consequence, the flow of the stock, R' (the first derivative of the stock amount) appears as a sigmoid curve. Also the capital parameter follows a bell shaped curve, but shifted forward in time with respect to the flow of the resource stock. These two latter parameters, R' and C, are especially important when using the model to describe historical cases, since they can be estimated by means of suitable proxies, whereas the actual stock, R, is usually not an easily available datum. In the model, R' is normally taken as the "landings", that is the fishery yield, whereas the capital, it could be represented by the labor force (in number of person or in salary) employed in the fishery, the number of fishing vessels, the tonnage of the fishing fleet; and, in recent statistics, also data of investment in currency or expressed by economic indexes are available.

This is the model that was used in the present study, details about the fitting procedure and the calculation of the goodness of fit are reported in the appendix.

Model testing and discussion

The LV model described in the previous section was tested in several cases of historical fisheries. Here, we report the case of the fishery sector of Japan. This is an important fishery that ranks as the 6th in the world in terms of productivity, harvesting more than 3.6 million metric tons of fish in 2012, according to the Food and Agriculture Organization (FAO).

Here we report the evolution of the Japanese total fish catch and the national Disbursement of Fishery, from 1962 to 2000 (Source: Statistics Bureau, Ministry of Internal Affairs and Communications, website http://www.stat.go.jp/).
The catch data are expressed as the quantity, in weight, of fish. The disbursement is expressed in currency and it includes expenses for the fisheries' in terms of wages, fuel, fishing boats capital and replacement and equipment, thus, it is a direct measurement of the capital investment in the sector. As shown in the figure, the historical data show a decline in the fishery yield starting with approximately 1980. The capital expenditure peaks approximately with the peak yield, but it declines less rapidly afterward.

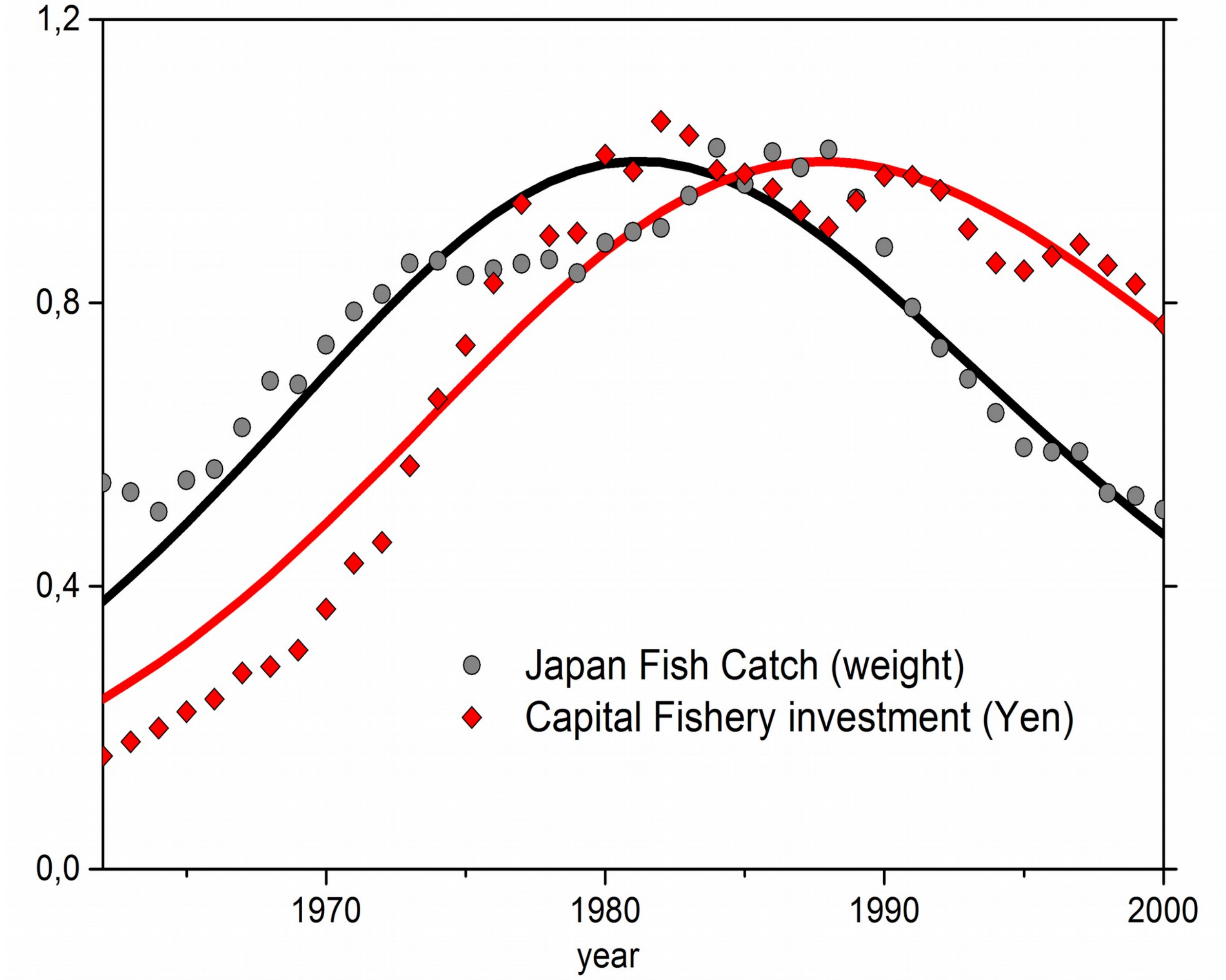

Fig. 1. Lotka Volterra modeling of Japanese total Catch (production-prey) and the Disbursement of Fishery (capital-predator) from 1962 to 2000. Normalizing factors: catch 1.26 10^7 Tons, disbursement 1.35 10^8 Yen. Data Source: Statistics Bureau, Ministry of Internal Affairs and Communications (http://www.stat.go.jp/). The goodness of fit (GOF) is obtained by calculating the normalized means square errors (NMSE) function (see supplemental data). For the fitted data: NMSE Catch fit: 0.81; NMSE Disbursement fit: 0.92.

The LV model can describe these trends reasonably well; indicating that the fish stock and the capital stock relate to each other in a prey/predator relationship where the yield of the fishery depends on the product of the remaining resource stock times the available capital stock. As the fish stock declines, the profits of the industry decline, too, and less resources are available for replacing the obsolescence of the fishing capital, which therefore declines as well. This is a typical behavior of these predator/prey systems.
Recent data from the Statistical Handbook of Japan 2015 (OECD, 2015) show that, since 2000, the Japanese fish production trend is still declining. The value of the catch is decreasing with a rate of 25% from 2000 to 2014. For the same period, the Statistical Handbook of Japan 2015 also reports the number of Enterprises and the number of workers engaged in the Fishery sector. The values of such entities, even thought they are not expressed in currency, can be reasonable assumed proportional to the capital effort invested in the sector. The data show that the trend, for both, is declining: in particular, from 2000 to 2014, the number of enterprises is reduced by 39%, while the number of

workers is reduced by 33%.

Conclusion

The history of fisheries tells us of how the yield of the system is determined as the result of an intensive 'fish extraction' effort. Fishes are a renewable resources, and this is undoubtedly true, as long as the velocity of the resource reproduction is faster respect to the velocity of depletion. But in fact, in particular after the II world war, the rapid growth of the economy ,the development of the open access market economy, the ‘velocity of fishing’ (power fishing) in several different kind of fish supply chain, experienced a fast speed up respect to the ‘velocity of the fish stock rebuilding’ that remained almost invariant or even lowered, because more and more younger spawns were caught or trapped to satisfy the growing fish demand. Thus, in such a situation, a net resource outflow depletes the fish stock and this flow can not be balanced by the inflow due to the biological renewability of the resource itself.

Therefore, it is clear that fish can behave as a non-renewable resource, as shown by another historical case, the collapse of the US whaling industry collapse (Starbuck, 1989). (U Bardi, 2007), which was also found to fit the Lotka_Volterra model (Ugo Bardi & Lavacchi, 2009b). There are several other cases of collapsing fish stocks also indicating that these stocks may behave as non-renewable resources, for instance the Californian pacific sardina in the 1950s (Wolf, 1992),

With this example, we show that the prey-predator dynamic can describe the behavior of an economic system: the whole fishing sector of a country operating in a global open market framework. The innovative approach of this model is that it is a quantitative application of system dynamics that emphasizes the role of depletion and the feedback relationships of the various parameters of the models. The reasonably good fitting of the model with the historical data does not mean that depletion is the only forcing that affects the system, but it invites to consider depletion as an important parameter even in systems that are normally defined as “renewable”.

Acknowledgement

This work was partially supported by the MEDEAS project, funded by the European Union’s Horizon 2020 research and innovation program under grant agreement No 691287. The opinion expressed in the present work are those of the author's only and are not to be attributed to any organ of the European Union

References

Alfred J. Lotka. (1925). *Elements of Physical Biology. Williams and Wilkins Company.* http://doi.org/10.2105/AJPH.15.9.812-b

Bailey, J. (2016). Adventures in cross-disciplinary studies: Grand strategy and fisheries management. *Marine Policy*, *63*, 18–27. http://doi.org/10.1016/j.marpol.2015.09.013

Bardi, U. (2013). Mind Sized World Models. *Sustainability*, *5*(3), 896–911. http://doi.org/10.3390/su5030896

Bardi, U., & Lavacchi, A. (2009). A simple interpretation of Hubbert's model of resource exploitation. *Energies*, *2*(3), 646–661. http://doi.org/10.3390/en20300646

Forrester, J. (1989). *The beginning of system dynamics Banquet Talk at the international meeting of the System Dynamics Society. McKinsey Quarterly*. Stuttgart, Germany.

Lotze, H. K., & Worm, B. (2009). Historical baselines for large marine animals. *Trends in Ecology & Evolution*, *24*(5), 254–62. http://doi.org/10.1016/j.tree.2008.12.004

OECD. (2015). Japan 2015. *OECD Economic Surveys*. Retrieved from http://dx.doi.org/10.1787/eco_surveys-jpn-2015-en

Papert, S. (1980). *Mindstorms: Computers, children, and powerful ideas*. *NY: Basic Books*. NY: Basic books.

Radovich, J. (1982). The Collapse of the California Sardine Fishery What Have We learned ? *CalCOFI Reports*, *XXIII*, 56–78.

Starbuck, A. (1989). *History of the American Whale Fishery*. Castle. Retrieved from https://books.google.it/books?id=zGYRAAAAYAAJ

The World Bank. (2013). FISH TO 2030 Prospects for Fisheries and Aquaculture, (83177), 102. http://doi.org/83177-GLB

Thurstan, R. H., Brockington, S., & Roberts, C. M. (2010). The effects of 118 years of industrial fishing on UK bottom trawl fisheries. *Nature Communications*, *1*(2), 1–6. http://doi.org/10.1038/ncomms1013

Tower, W. S. (1907). *A History of the American Whale Fishery*. Pub. for the University. Retrieved from https://books.google.it/books?id=du4JAAAAIAAJ

Volterra, V. (1928). Variations and fluctuations of the number of individuals in animal species living together. *Journal Du Conseil Permanent International Pour L' Exploration de La Mer*, *3*(1), 3–51. http://doi.org/10.1093/icesjms/3.1.3

Watson, R. A., Cheung, W. W. L., Anticamara, J. A., Sumaila, R. U., Zeller, D., & Pauly, D. (2013). Global marine yield halved as fishing intensity redoubles. *Fish and Fisheries*, *14*(4), 493–503. http://doi.org/10.1111/j.1467-2979.2012.00483.x

Wolf, P. (1992). Recovery of the pacific sardine and the california sardine fishery. *CalCOFI Rep*, *33*, 76–86. Retrieved from http://www.calcofi.org/publications/calcofireports/v33/Vol_33_Wolf.pdf

Supplemental information on the model

The model was implemented using MATLAB&Simulink as shown in figure 2.

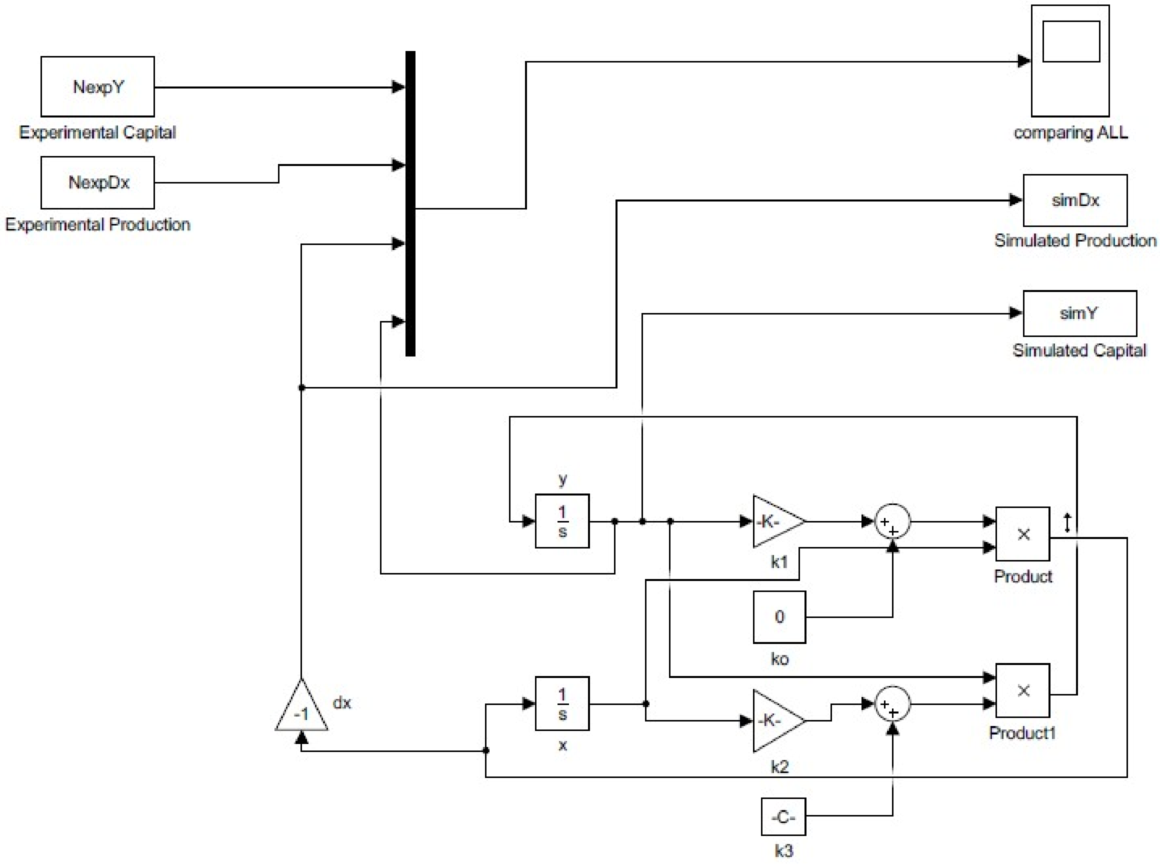

Fig. 2. Simulink blocks' model to obtain the graphical solution of the Lotka Volterra equations adapted for the study of the fishery dynamics. NexpDx and NexpY are respectively the production and the capital available data. SimDx and SimY are the simulated production and capital: they correspond to the fitting curves.

In the implementation of the model, because data of R' and data of C can be very different in order of magnitude, we normalized each data series. The fitting procedure is very sensitive on the initial value of the k1, k2 and k3. Thanks to the graphic solution of LV with Simulink (fig. 2), we can obtain a set of initial guesses for such constants that are successively optimized with Matlab employing a nonlinear least squares routine, using as objective function the sum of the square of residuals (SSE, sum of squared errors of prediction) here represented by the deviations of the LV predicted data from actual empirical values of data. All the fitting are provided using the unconstrained nonlinear optimization method based the Nelder-Mead algorithm. The goodness of fit is generated by calculating the normalized mean square errors (NMSE) function. NMSE measure the discrepance between the historical data and the model estimated value. The NMSE value is calculated by the Matlab toolbox facilities 'goodnessoffit': NMSE equal to 1 represents the perfect fit, NMSE equal to zero means that real data are no better than a straight line at matching the model.