SIMULATION MODEL EVALUATION OF SOME FISHERIES BALANCE INDICATORS

David Sampson, Joint Research Center, david.sampson@jrc.ec.europa.eu
Robert Scott, Joint Research Center, robert.scott@jrc.ec.europa.eu

ABSTRACT

Chronic overcapacity has been identified as a major cause of the overfishing of Europe's fish stocks and the poor economic performance of the European fishing fleets. Mechanisms are needed to ensure that the capacity of European fishing fleets remain proportionate to available fish stocks. To that end, the European Commission developed "Guidelines for an improved analysis of the balance between fishing capacity and fishing opportunities", which specify a minimum set of fleet-based technical, biological, economic, and social indicators that purportedly measure the balance between fishing fleets and fish resources. A bioeconomic simulation model was developed to assist in the evaluation of some of these balance indicators. The model is age-structured, like standard single-species stock assessment models, but accommodates multiple independent fish stocks that are harvested by multiple independent fishing fleets. The fish stocks occupy multiple spatial regions with diffusion of fish between regions. The fishing fleets choose where and how to fish based on anticipated profits. Randomness is included in the simulated system in the annual fish recruitments and their spatial distribution. The model was used to generate a series of balance indicators that were then compared against the true conditions in the simulated fisheries to evaluate whether the indicators provide accurate signals of system status. The simulations showed that randomness in recruitment propagates directly into randomness in the balance indicators implying that it will be difficult to detect meaningful signals from any short time series of balance indicator values.

Keywords: bioeconomic simulation model; capacity / balance indicators; fleet / effort dynamics.

INTRODUCTION

Overcapacity of the world's fishing fleets has become a great concern to fishery managers to such an extent that the Food and Agriculture Organization (FAO) of the United Nations (UN) developed guidelines on managing fishing capacity in support of implementing the UN Code of Conduct for Responsible Fisheries (FAO 2008). Underlying these guidelines is the notion that excess fishing capacity is the cause of overfishing. There are too many fishing vessels relative to the biological productivity of the fish stocks. That idle fishing boats do not catch fish and therefore do not contribute to overfishing is a fact that seemingly has been lost in the discussion. The purpose of this paper, however, is not to debate whether overcapacity is a cause of overfishing or rather a symptom that arises from a lack of property rights. Instead we explore certain practical issues related to the measurement of overcapacity.

A technical consultation by the FAO defined fishing capacity as "… the maximum amount of fish over a period of time (year, season) that can be produced by a fishing fleet if fully utilized, given the biomass and age structure of the fish stock and the present state of the technology" (FAO 2000). Measuring fishing capacity however remains fraught with difficulties, not least of which is the availability of suitable data. Some of the technical consultants to FAO proposed that fishing capacity could be measured using the Data Envelope Analysis (DEA) approach, which uses the concept of a production possibility frontier to measure the relative ability of different fishing vessels to produce catches given variable inputs such as vessel size, engine horsepower, and crew size (Kirkley and Squires 1999). There are several issues with the DEA approach that make it a problematic tool for measuring capacity. DEA measures the relative productivity of different fishing vessels and identifies vessels whose productivity is less than the full potential, but the analysis is based on the assumption that the fish stock biomass is fixed. The DEA capacity measurements are short-run and may change with variations in the fish biomass or with changes in the number of vessels in the fleet. The DEA provides no absolute scale or long-run target. Also, if the fishing vessels are collectively constrained by total allowable catches then the most productive fishing vessels as measured by the DEA may be the ones who are best at racing for fish rather than being the most efficient producers.

The term overcapacity is often associated with the idea of a fishery in which there are too many vessels chasing after too few fish. Ward et al. (2004) define it as follows.

> *Overcapacity can be considered the generic term for excessive levels of capacity in the longer term and relates to some long-term desirable level of capacity (the target capacity). This may be either some long-term target sustainable yield, or some long-term target level of capital employed in the fishery*.

In contrast to the FAO definition of capacity, which is a short-run concept based on fixed stock biomass, this definition of overcapacity incorporates the notion of long-term sustainable yields. To make this definition operational for managing a fishery requires both a feasible technique for measuring fishing capacity and a clear specification of the desired target level of fishing capacity. For many fishery management agencies achieving the maximum sustainable yield (MSY) is the stated policy goal for the management of individual fish stocks, but for multi-stock fisheries it is generally understood that simultaneously achieving MSY for all stocks is probably impossible. Thus multi-stock fisheries require special consideration in defining a biologically based target for fishing capacity. Also, because most fish stocks have highly variable annual recruitment one would expect capacity utilization to vary from year to year, with greater use of capacity during periods of strong recruitment abundance and lesser use of capacity during periods of weak recruitment. That there are idle fishing vessels during some years does not mean that these vessels will not be needed during other years. It would be silly for a city manager to conclude that his city has an overcapacity of storm drains because they are rarely fully utilized. Similarly it would be silly to scrap a fishing vessel one year only to have to build a replacement vessel a few years later when fishing conditions have improved.

In Europe the Green Paper on the Reform of the Common Fisheries Policy (CFP) identified fleet overcapacity as the fundamental problem of the current CFP (EC 2009) and stated that "the future CFP must have in-built mechanisms to ensure that the size of European fishing fleets is adapted and remains proportionate to available fish stocks." The Green Paper also blamed failings of the current CFP on "imprecise policy objectives resulting in insufficient guidance for decisions and implementation" and stating that there are "no clear indicators and yardsticks that could provide more concrete guidance or to help measure policy achievements". In 2008 the European Commission's Directorate General for Fisheries and Maritime Affairs published guidelines for the routine calculation by Member States of a set of "balance indicators" for the regular monitoring of the balance between fishing capacity and fishing opportunities (DG MARE 2008). These balance indicators were to be based on data that the Member States collect annually as part of the Data Collection Regulation, which was in force through 2009, and subsequently the Data Collection Framework, which became operational in 2010. The objective of the exercise is to facilitate monitoring the performance of Member States in fulfilling their obligation to achieve a stable and enduring balance between their fishing capacities and fishing opportunities. Whether or not these balance indicators are adequate for achieving this goal is the subject of our study.

In recognition that there are multiple dimensions whereby society might value fishing activities, the guidelines developed by the European Commission's Scientific, Technical and Economic Committee for Fisheries and subsequently published by DG MARE include biological indicators, economic indicators, social indicators and technical indicators. For our study we chose to explore the behavior of one biological indicator,

$$\text{Biol.Ind} = \text{current.F} / \text{F.MSY},$$

and one economic indicator,

$$\text{Econ.Ind} = (\text{ Income} - \text{Variable.Costs }) / \text{Fixed.Costs} .$$

In the biological indicator the denominator (F.MSY) is the theoretical rate of fishing mortality that results in the long-term maximum yield and thus represents an upper bound on the long-run revenue flow that can be taken from the stock. Hence if the value of this indicator is greater than one then the fishery could achieve increased long-run yield by reducing the rate of fishing.

In the economic indicator the numerator is the portion of revenue that is left after paying the operating costs, which is the money available to pay the fixed costs of owning a fishing vessel. If the indicator is greater than one then the fleet is generating super-normal profits; if the indicator is less than one the fleet is making less than a normal return on investment.

Although it seems very clear how these indicators should behave in the long term (at equilibrium), it is not clear that the short-term behavior of these indicators will provide reliable signals of the status of a set of fisheries. With this issue in mind the objectives of this study are: (1) to evaluate the performance of capacity indicators relative to the known status of the fishery system using a bioeconomic simulation model; (2) to help clarify our thinking about capacity and over-capacity and the role they play in fisheries; and (3) to advance the art of modeling fishing fleet and effort dynamics.

BIOECONOMIC FISHERY SIMULATION MODEL

In part for this study, but more generally because we perceived that a tool was needed for evaluating the performance of different approaches to fishery management, we developed a generalized bioeconomic simulation model with the following features. The model is flexible in how it can be configured and in the types of fishery systems that it can mimic. In general the model can have multiple fish stocks that are harvested by multiple fishing fleets within the framework of a set of spatial regions. The fish stock components are age-structured and the model uses the standard equations of fishery science to model the fundamental biological processes of survival, growth and reproduction. The fish stocks and fishing fleets are indexed to the spatial regions, with movements of fish and the redistribution of fishing occurring instantaneously at the end of each annual time step. Fish catches are age-structured and occur independently within each region based on the fishing effort applied in that region. The dynamics of fishing effort for each year are driven by the maximization of expected profits; the entry / exit of fishing boats from each fleet are driven by realized profits. The fishing boats within each fishing fleet are treated as having homogeneous characteristics. There is randomness in the system in the annual recruitment events for each fish stock and in the spatial distributions of this recruitment. The model is written in R (R Development Core Team 2009) and uses the data structures and programming features of the FLR package (Kell et al. 2007).

We take a standard approach for modeling the biological dynamics of the fish stock. For each fish stock there is a Beverton and Holt equation defining the relationship between the expected age-1 recruitment produced annually by the parental spawning stock biomass. The random recruitment that is actually produced each year follows a lognormal distribution and this recruitment is randomly distributed each year to the spatial regions, with each region receiving on average a given proportion of the recruitment. Each fish stock suffers a fixed rate of natural mortality and there are no biological interactions between the different stocks (no predation or competition). Growth of individual fish within each stock conforms to the von Bertalanffy growth model and the proportion mature-at-age is determined by a logistic function. The equations governing the fishing process assume that within each region each fleet generates age-specific rates of fishing mortality that are the product of a set of selectivity coefficients (age-specific but time-invariant) and a fishing mortality coefficient (age independent but time-dependent). The fishing mortality coefficient generated by a given fleet is the product of a time-invariant catchability coefficient (no technological change) and the fishing effort (fishing-days) expended by the fleet in that region. The overall harvest of a fish stock from a given region is determined using the standard catch equation based on the additivity of the fleet-specific rates of age-specific fishing mortality.

The amounts of fishing effort generated by the fleets each year and the spatial distribution of this effort are determined using the system of catch equations and solving for the equilibrium levels of effort that maximize the profits of all the fleets. A game-theoretic approach must be used because the catch taken from a region by one fleet depends on the amount of fishing conducted in that region by all the competing fleets. However, for any individual fleet one can calculate the fishing effort needed to maximize net revenue (gross revenue minus variable costs) given the fishing effort levels of the other fleets (Fig. 1). The set of effort levels across all fleets that simultaneously satisfy these maximum net revenue functions is the Nash equilibrium for the system (Fig. 2) and represents the expected amounts of fishing effort under the assumption that all the fleets operate to achieve maximum profits.

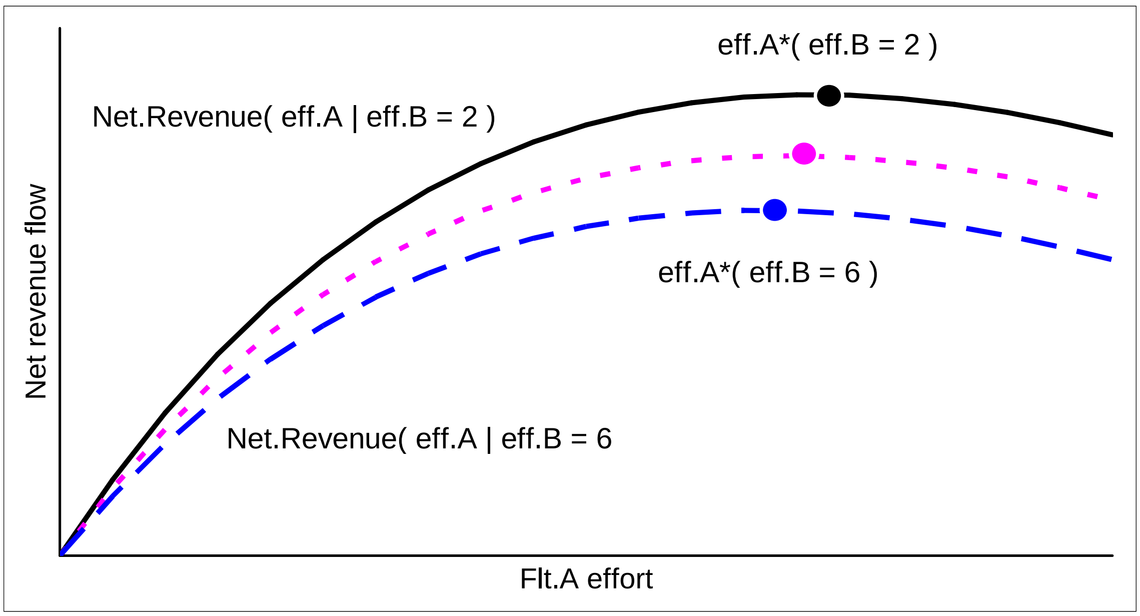

Figure 1. Net revenue flow to fleet A given its own and the competition's levels of fishing effort.

If the vessels in a fleet are generating sufficient gross revenues to cover both their variable costs (operating expenditures) and the annualized flow of their fixed costs (e.g., normal return on investment, insurance, dockage fees), then one would expect that the existence of these super-normal profits signal an investment opportunity that would entice new fishing vessels to join the fleet. Conversely if the vessels in a fleet fail to cover their costs then one would expect vessels to exit from the fishery. Consistent with these assumptions, the simulation model uses the following function of profit flow to mimic the process of vessel entry and exit from a fleet,

$$\text{N.Vessels}_{y+1} = \text{N.Vessels}_{y} * \exp(\ \alpha \cdot \text{Profit.flow}_{y} / \text{Fixed.cost.flow}_{y}\ )\ .$$

The coefficient α controls how rapidly the fleet grows from one year to the next given any fixed non-zero level of profits. If flow of profits is equal to the flow of fixed costs then the relative increase in fleet size is roughly equal to α.

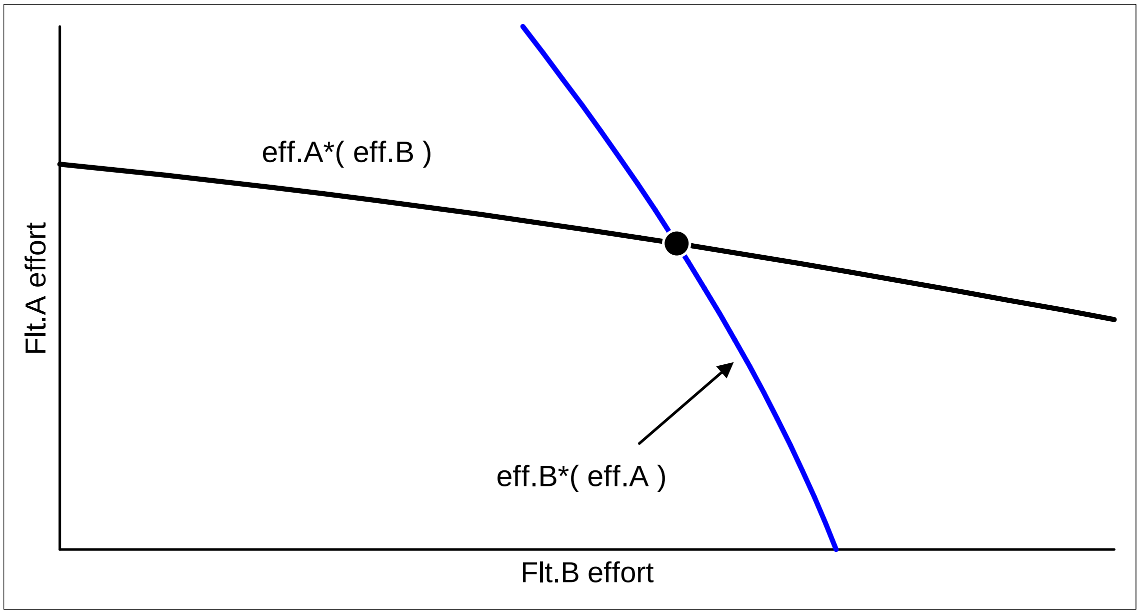

Figure 2. The equilibrium levels of fishing effort jointly maximize the net revenue flows of all the fleets.

HYPOTHETICAL FISHERY SYSTEM

We simulated the behavior of two fishery balance indicators (Biol.Ind, Econ.Ind) for a simple hypothetical fishery system in which there were two fish stocks residing in three geographic regions and exploited by two fishing fleets, with parameters as specified in Table 1. These particular parameter values were chosen for convenience and were not intended to be representative of any existing fishery. The two fish stocks differed in the overall stock productivity (Fig. 3) and in the growth of individuals (Fig. 4) with stock 1 being less productive but longer lived and achieving larger weights-at-age. The two fleets differed in the fishing power of their vessels and in their operating and fixed costs. The vessels in fleet B had larger catchability coefficients and had higher variable and fixed costs. The regional variation in the variable costs is consistent with the idea that region 1 is closest to the homeport of fleet A and farthest from the homeport of fleet B, whereas region 3 is closest to the homeport of fleet B and farthest from the homeport of fleet A; region 2 is intermediate between the two homeports.

We used a trial and error approach to determine a set of initial conditions for fishing effort (fishing days) by fleet and region that would result in the system being in equilibrium given that there was no variability in the annual recruitment to the fish stocks or in the spatial distribution of this recruitment. Changing any of the parameter values in Table 1 will result in different equilibrium values. Given limited experiments with perturbations from these initial conditions it appeared that this system was stable. These equilibrium conditions provided a baseline against which we subsequently compared results from simulated systems that had variability in the annual recruitment. For the initial equilibrium conditions the fleet A effort levels were 101.5 fishing-days in region 1, 58.7 days in region 2, and zero days in region 3, and the fleet B effort levels were zero days in region 1, 72.1 days in region 2, and 96.7 days in region 3. Under these equilibrium conditions both fish stocks were heavily over-fished (Fig. 5) in the sense that a reduction in the amount of fishing would result in an increase in the long-term yield. Under the equilibrium conditions the spawning stock biomass for stock 1 was depleted to 4.9% of the unfished level and the spawning stock biomass for stock 2 was depleted to 14.1% of the unfished level.

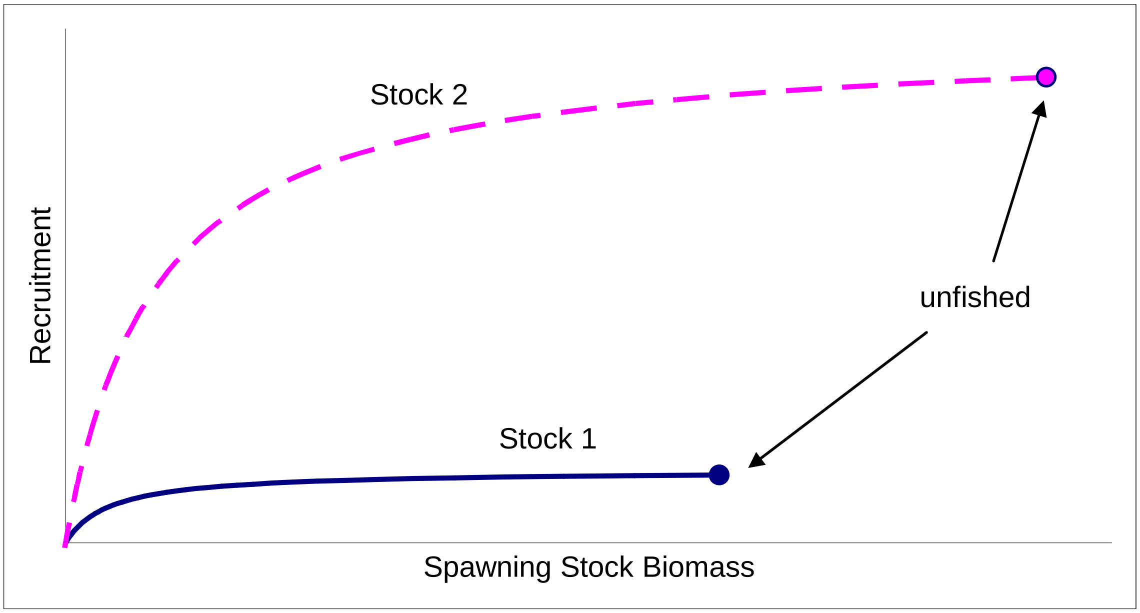

Figure 3. The Beverton and Holt recruitment versus stock relationships for the two simulated fish stocks.

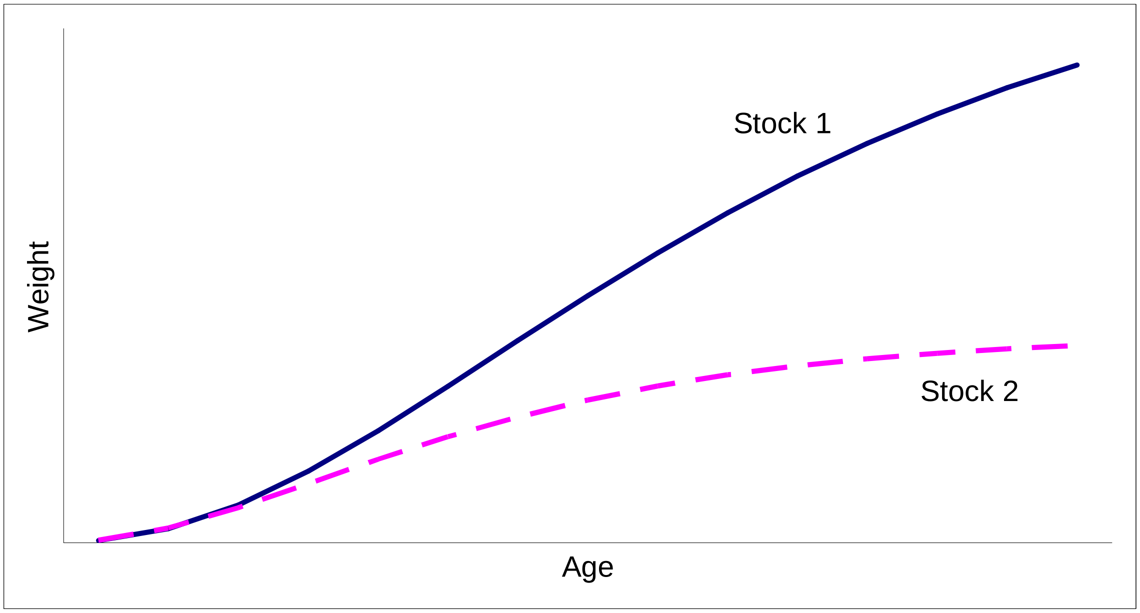

Figure 4. The growth in weight functions for the two simulated fish stocks.

To evaluate how randomness in recruitment propagates into the biological and economic indicators, we conducted a set of 30-year simulations that began in year 1 with the system at the equilibrium conditions described above. Starting in year 2 the recruitment values for each stock were lognormal random variates with log-scale standard deviations of 0.35 for stock 1 and 0.25 for stock 2 (corresponding to arithmetic-scale coefficients of variation of 36.1% and 25.4%). We conducted 20 random trials of the fishery system and graphically explored the resulting time series of balance indicator values.

Table 1. Some of the parameters defining the hypothetical fishery used for the simulations.

		Region-specific values		
Parameter	Value	Region 1	Region 2	Region 3
Stock 1				
Natural mortality (/yr)	0.25			
Recruitment CV	36.1%			
Recruitment distribution		25%	50%	25%
Stock 2				
Natural mortality	0.40			
Recruitment CV	25.4%			
Recruitment distribution		30%	40%	30%
Fleet A				
Catchability for stock 1	0.0055			
Catchability for stock 2	0.0060			
Price for stock 1 (/t)	2600			
Price for stock 2 (/t)	3200			
Fixed cost flow (/yr)	37465			
Variable cost (/day)		1000	1200	1400
Fleet B				
Catchability for stock 1	0.0065			
Catchability for stock 2	0.0070			
Price for stock 1 (/t)	2800			
Price for stock 2 (/t)	3400			
Fixed cost flow (/yr)	53335			
Variable cost (/day)		1500	1300	1100

SIMULATION RESULTS

The stochastic levels of recruitment in the two fish stocks, and their initial spatial distributions, altered the levels and spatial distributions of fishing effort needed to produce the maximum net revenue flows for the two fleets. The short-run revenue and cost flows of the two fleets deviated from the long-run equilibrium conditions. Fig. 6 provides an example from one simulation run in which lower than average recruitment events during the initial years caused negative profit flows and a consequent shrinkage of the fishing fleets, followed subsequently by above average recruitment, positive profit flows and growth of the fishing fleets.

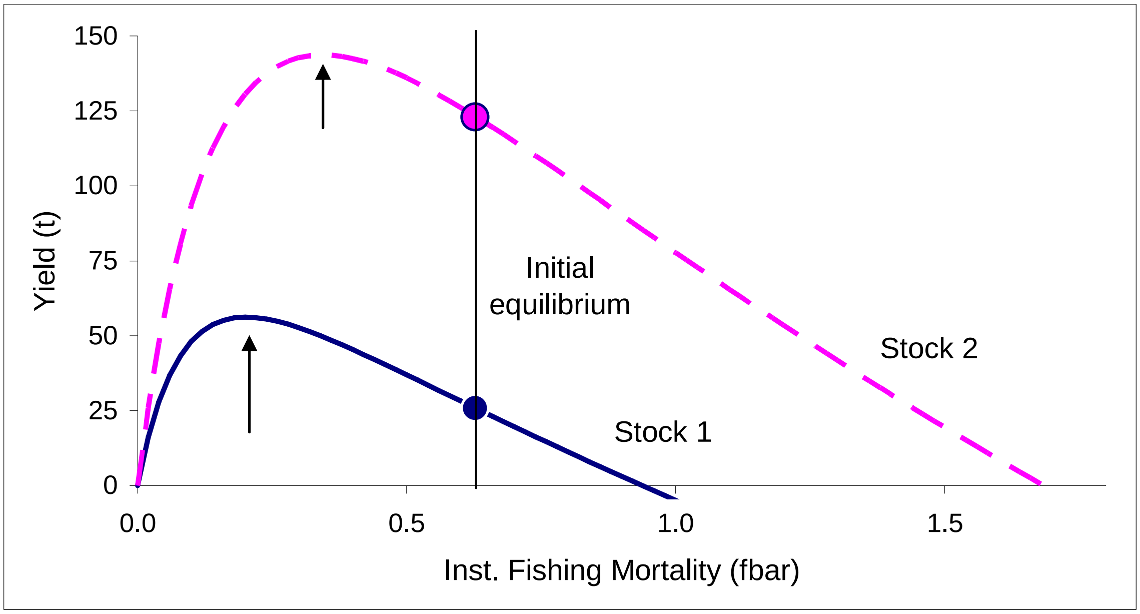

Figure 5. Long-term yields versus instantaneous fishing mortality for the two simulated fish stocks. The arrows indicate the fishing mortality levels needed to take the MSY for each stock.

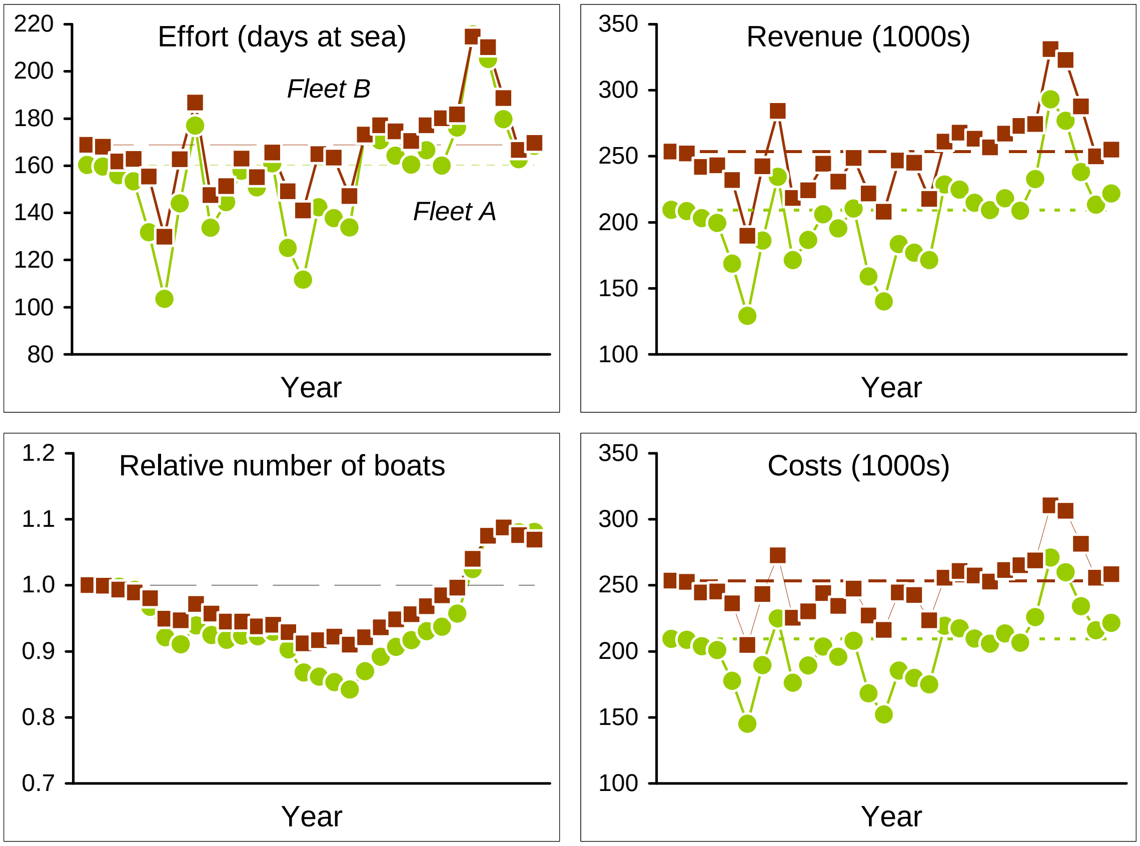

Figure 6. Example of the short-run dynamics of fishing effort and revenues and costs for the two simulated fishing fleets (circles = fleet A; squares = fleet B). The horizontal lines indicate the equilibrium levels.

The randomness in the annual recruitment propagates directly into the biological and economic balance indicators. The upper panels of Fig. 7 show the biological (on the left) and economic (on the right) indicators for the same example simulation run used for Fig. 6. The lower panels of Fig. 7 show the indicator values averaged across the 20 independent stochastic simulations and the minimum and maximum values. The average values are approximately equal to the long-run equilibrium values but in any given year the indicators can deviate substantially from the long-run equilibrium values. The average coefficients of variation for the annual indicator values were 11.4% (stock 1) and 11.6% (stock 2) for the biological indicators and 18.8% (fleet 1) and 14.3% (fleet 2) for the economic indicators.

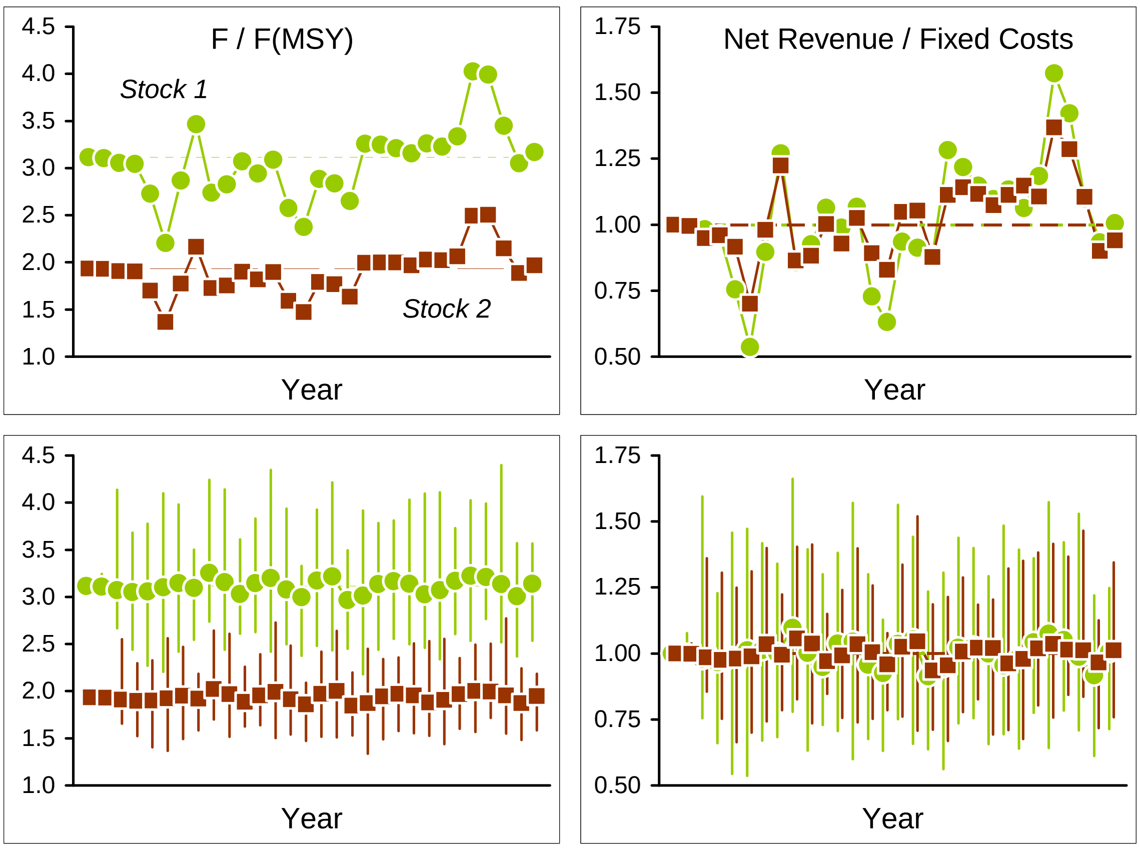

Figure 7. Examples of the short-run dynamics of the biological (on the left) and economic (on the right) indicators. The upper panels correspond to the same simulation as used to produce Fig. 6. The lower panels correspond to the yearly average values and ranges taken across all 20 independent random simulations. In the economic indicators the circles mark the values for fleet A and the squares mark the values for fleet A

DISCUSSION, CONCLUSIONS AND NEXT STEPS

The fishery simulation model proved to be an easy-to-use tool for exploring the behavior of two simple balance indicators that have been proposed for the routine monitoring of fishing fleets and the fish stocks that support these fleets. The simple demonstrations conducted for this study clearly indicated that these balance indicators are sensitive to recruitment variability. We note, however, that the fishery system did not simply transfer recruitment variation to the indicators. Whereas the input levels of recruitment variation were 36% and 25%, the coefficients of variation (CV) for the biological indicators were only about 11% for both stocks, implying that there is important damping in this particular system. We have not yet explored the behavior of systems with higher and more realistic levels of recruitment variability. Hennemuth et al. (1980) calculated and reported annual recruitment CV values for a number of commercially important fish stocks. The recruitment CV was 0.59 for North Sea saithe, 0.63 for North Sea cod, and 1.42 for North Sea haddock.

In the fishery simulator we used a unique approach for modeling the dynamics of fishing effort. The published literature on fishing effort dynamics and fishing location choice describes three general methods for modeling the allocation of fishing effort to spatial regions: one is based on the so-called Ideal Free Distribution model from foraging theory (Gillis et al. 1993); the second method is based on the so-called gravity model (Walters and Bonfil 1999); and the third method uses the so-called random utility model (Holland and Sutinen 1999). All three methods have the same objective of specifying the spatial distribution of fishing effort based on the attractiveness or profitability of different fishing locations but they differ in their underlying theory and in the mathematical details. None of the methods, however, address the basic issue of how much overall fishing effort will be deployed. In our simulator we use the basic catch equation to solve for the levels of fishing effort that should be distributed to all spatial regions based on the assumption of profit-maximizing behavior by the competing fishing fleets.

If fishery capacity indicators are to provide feedback to fishery managers on the success of management actions, it will be important to establish the conditions under which the indicators provide reliable signals. For the simple system that we explored the two fish stocks were drastically depleted and the biological indicators gave quite obvious indications of this situation despite the noise caused by the recruitment variability. The economic indicators however simply measured whether the fleets were making short-run profits or losses, without regard to any long-term target. The simulations demonstrated that there can be drastic year-to-year changes in profitability with the economic balance indicator varying from low to high by a factor of three or more. How one might use such information for management purposes is unclear.

The variability in these balance indicators was due entirely to variability in recruitment. A real fishery system would also have year-to-year variability in other processes (e.g., natural mortality, growth, catchability) and additionally would have measurement error associated with the indicators. Given more realistic levels of variability it remains an open question whether the balance indicators would provide useful information. We intend to extend the fishery simulator to include randomness in additional processes and to include various forms of measurement error, with the long-term goal of being able to use the simulator to conduct evaluations of how balance indicators or other metrics could be used for constructing fishery management strategies that are robust to uncertainties. Other important extensions to the model are to allow the dynamics of fishing effort to be constrained by direct quotas on fishing effort or by indirect quotas on catch or landed catch.

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