FISHSIM:

A Generalized Fishery Simulation Model

MICHAEL KING

Abstract

This paper describes a general bioeconomic model, FISHSIM, which uses traditional equations and submodels to represent the biological parameters of a fish stock, and simple financial equations to represent the profitability of the fishery.

FISHSIM allows the user to enter the biological and economic parameters of a fishery, or to see the program run with built-in parameters. The model simulates a fishery over a 50-year period, during which the user may stop the run (for policy intervention), and alter fishing effort and age at first capture. The output of the model includes graphs of annual recruitment, fishing effort and catch weight. The full executable version of FISHSIM is available from the author's institution.

Introduction

Modeling, the application of mathematics to quantify processes, has been used to describe the dynamics of fish stocks since the beginning of the century, when Baranov (1918) described the numbers of fish in a catch as a function of stock size, natural mortality and fishing mortality. A model presenting a wider view of a fish stock as a whole, by describing the opposing effects of growth and mortality on a fish stock, was proposed in the 1930s by Russell (1931). By the end of the 1950s, an analytical model which estimated yield per recruit in terms of a species growth, weight, mortality and age at first capture was developed by Beverton and Holt (1957).

The use of analytical models, such as yield-per-recruit analyses, allows the description of events in powerful mathematical terms. However, ecological and biological factors which influence fish stocks, and additional factors including economics which are involved in fisheries, result in a total system which is far too complex for analytical treatment. More detailed models which mimic or simulate how fish stocks behave under various levels of exploitation became possible only with the widespread use of microcomputers in the 1960s. In simulation models, the complex equations of analytical models are replaced by a much larger number of simple arithmetic steps, which must be solved repeatedly for different age classes and successive time periods. Collectively, the sequence of equations and submodels simulate the behavior of a complex system in more realistic ecological terms at the expense of mathematical power.

Computer simulation models can readily be made stochastic, and therefore more realistic, by including the possibility of chance variation or random catastrophic events in their components. This is a distinct advantage in modeling biological systems, which are notoriously variable. Variability is usually assumed to be related to environmental effects, and although the causes of variation may not be known, the degree of variation often is. The relative variation in recruitment from year to year, for example, may often be inferred from catch data, and can be incorporated into stochastic models as random fluctuations about an average or predicted value.

Fisheries scientists were among the first to use simulation models (Grant 1986), and some interactive models have been used as tools for examining natural resource systems since the 1960s (e.g., Paulik 1969; Walters 1969). In the 1980s, Deriso's (1980) simulation model, or Schnute's improvement of it, which include some of the characteristics of both surplus yield and dynamic pool models, were predicted to replace the more simplistic classical models as standard tools for stock analysis (Walters 1980). Adaptive management, in which the uncertainties of renewable resource management are dealt with in an adaptive and experimental manner (Walters 1986), appears to be a particularly fruitful area of application for simulation models, which can be used to predict the possible outcomes of alternative management strategies.

Most simulation models have been purpose-built to predict the outcomes of varying fishing pressure on particular fish stocks. Perhaps because of this specificity, very few single simulation models have been widely used, or are easily adaptable for application to other species. This paper describes a more generalized simulation model, FISHSIM, which makes use of well-tested and conventional equations and submodels to represent the biological parameters of a fish stock, and simple financial equations (revenue minus fishing costs) to represent the profitability or otherwise of the fishery.

There are at least two phases in building a simulation model. The first involves the development of a conceptual model, and the second involves the quantification of the component steps. Further phases include the validation and use of the model (Grant 1986).

Formulating a conceptual model involves defining the limits of the system of interest, and identifying relationships between its components. Conceptualization may be in the form of a flow diagram, such as the one representing FISHSIM shown in Fig. 1. In this case, the fishery is the system, and its biological components are recruitment and growth which increase stock biomass, and natural mortality and fishing mortality which decrease biomass. The financial parameters included are those relating to the costs of, and returns from, commercial fishing.

The second phase involves quantifying the qualitative conceptual model by substituting data and equations for, and establishing mathematical relationships between, each of the components. Several texts provide details of model construction (e.g., Grant 1980; Walters 1986), and standard texts may be consulted regarding the quantification of biological comof biological components (e.g., King 1995). Quantification, in relation to the simulation model described in this paper, is presented in the following section.

As representations of complex systems, simulation models are always approximations to, and simplifications of, reality. For these reasons, models should be validated. In some cases, where historic catch and effort records exist for a fishery, it is possible to compare simulated results with actual catch records, thereby providing a check of the model, and some verification of the parameters used in its construction. In the gummy shark (*Mustelus antarcticus*), fishery, for example, data have been collected since the 1920s, allowing a simulation model to be evaluated by comparing the predicted results with long-term catch records from the fishery (Walker 1992).

Description of the Model

FISHSIM is a stochastic, bioeconomic, simulation model, which allows the user either to enter the biological and financial parameters of a fishery, or to see the program run with built-in parameters from a hypothetical fishery. The model simulates a fishery over a 50-year period, during which the user may stop the run for policy intervention, and alter input parameters such as fishing effort and age at first capture.

The following generalized mathematical description of FISHSIM applies to events which occur in each single year of the 50-year run built into the model. The recruited stock size, S, is the sum of the numbers of fish in all age classes from the age at recruitment t_r, to some maximum age, t_{max};

$$S = \sum_{t=t_r}^{t_{max}} N_t$$

where N_t is the number of fish in age class t. As natural mortality M is assumed to be constant after the age at recruitment, the number of fish in each successive year class in the unexploited stock is estimated as

$$N_{t+1} = N_t \exp[-M]$$

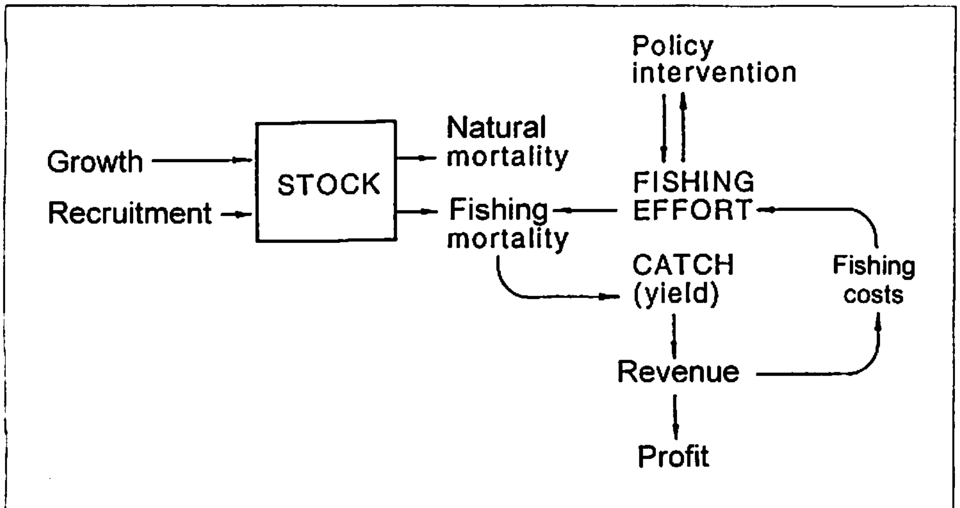

Fig 1. The conceptual model of the bioeconomic fisheries simulation model, FISHSIM, showing input and output components; policy intervention allows the alteration and fishing effort and age at first capture.

Recruitment is assumed to occur at the beginning of each year of the run. In the case of the built-in parameters of FISHSIM, recruitment is predicted by the Ricker stock recruitment relationship (Ricker 1975)

$$R = a\, S_m \exp(-bS_m)$$

where R is recruitment, S_m is the number of sexually mature fish in the stock (age classes above the age at sexual maturity t_m), and a and b are the constants in the relationships. In the case where stock parameters are entered by the user (in the full version), recruitment is estimated as the level required to replace numbers lost by natural mortality. Under exploited conditions, recruitment fluctuates around this mean level unless the spawning stock falls below a minimum percentage (entered by the user) of its size before exploitation. At stock levels below this minimum, recruitment decreases according to a linear relationship between recruitment and stock size.

Fishing effort or f is defined in terms of boat days per year, q is the catchability coefficient per vessel per day, and fishing mortality or F is calculated as

$$F = qf$$

The mean weight of fish at the midpoint of age t is calculated as W_t from the von Bertalanffy growth formula:

$$W_t = W_\infty(1-\exp[-K(t + 0.5 - t_0)])^3$$

where K is the growth coefficient, W is the asymptotic weight, and t is the age at zero length.

The annual catch in terms of weight (Y) is estimated from the catch equation as the sum of catches from all age classes between the age at first capture, t_c, and the maximum age t_{max};

$$Y = \sum_{t=t_c}^{t_{max}} Wt\,(F/(F+M))\,Nt\,(1-\exp[-(F+M)])$$

where W_t is the mean weight at age t, and N_t is the number of individuals surviving at age t.

If P represents fish price per kg, the annual total catch value, V, is given by

$$V = PY$$

If C_r is the running cost per boat per day, C_f is the annual fixed cost per boat, and B is the number of boats, the total fishing costs (C_t)for the fleet is

$$C_t = (C_r f)+(C_f B)$$

Profit per year (P) is therefore calculated as:

$$P = V - C_t$$

During each year of the 50-year run, graphs of recruitment, fishing effort and catch weight are updated and shown in three windows on the computer screen. A fourth window shows the current year, number of boats, and annual catch details (Fig. 2, top). At the end of each year, the numbers in all age classes are decreased according to the rate of total mortality Z:

$$S = \sum_{t=t_r}^{t_{max}} N_t \exp[-Z]$$

where N_t is the number of individuals at age t, and total mortality, Z = M+F in all exploited age classes, and Z = M in unexploited age classes (those below the age at first capture, t_c). Finally, each age class is advanced by one year of age before the program loops back to repeat the calculations for the following year. The sexually mature part of the total stock then becomes the stock from which a new recruitment is estimated.

At the end of a 50-year run, the program shows the mean annual catch and the mean annual profit, and (in the full version) the user is given an option which, if chosen, re-runs the simulation with incremental increases in fishing effort, and provides deterministic graphs of profit and yield by effort (Fig. 2, bottom).

A simulation model written as suggested in the above is deterministic. The most direct way of introducing stochasticity is to allow parameter values to vary randomly with equal probability between extremes obtained from field observations or noted from the past history of the fishery. In this case, the parameter has a range within which annual values vary randomly around a mean or predicted value.

An often more realistic alternative is where the probability of values occurring close to the mean or predicted value is higher than the probability of values being further away from the mean. In this case, values may be allowed to vary randomly according to a normally distributed probability curve centered around the mean or predicted value. A random variate, x, from a normal distribution with a mean, χ, and a standard deviation, s, is given by

$$x = \chi + sN$$

where N is a standard normal random variate (a random number from a standard normal distribution). A value for N may be obtained from

$$N = \sum_{i=1}^{12} U_i - 6$$

where U represents twelve uniform random variates selected from random number tables (Hastings and Peacock 1975). In programming, this formula can be easily adapted to make use of built-in random number generators, such as RND in BASIC.

In FISHSIM, the value of recruitment is allowed to vary randomly according to a normally distributed probability curve centered around the predicted value. Catchability and fish prices are allowed to vary randomly within a certain percentage (entered by the user) either above or below the entered mean value.

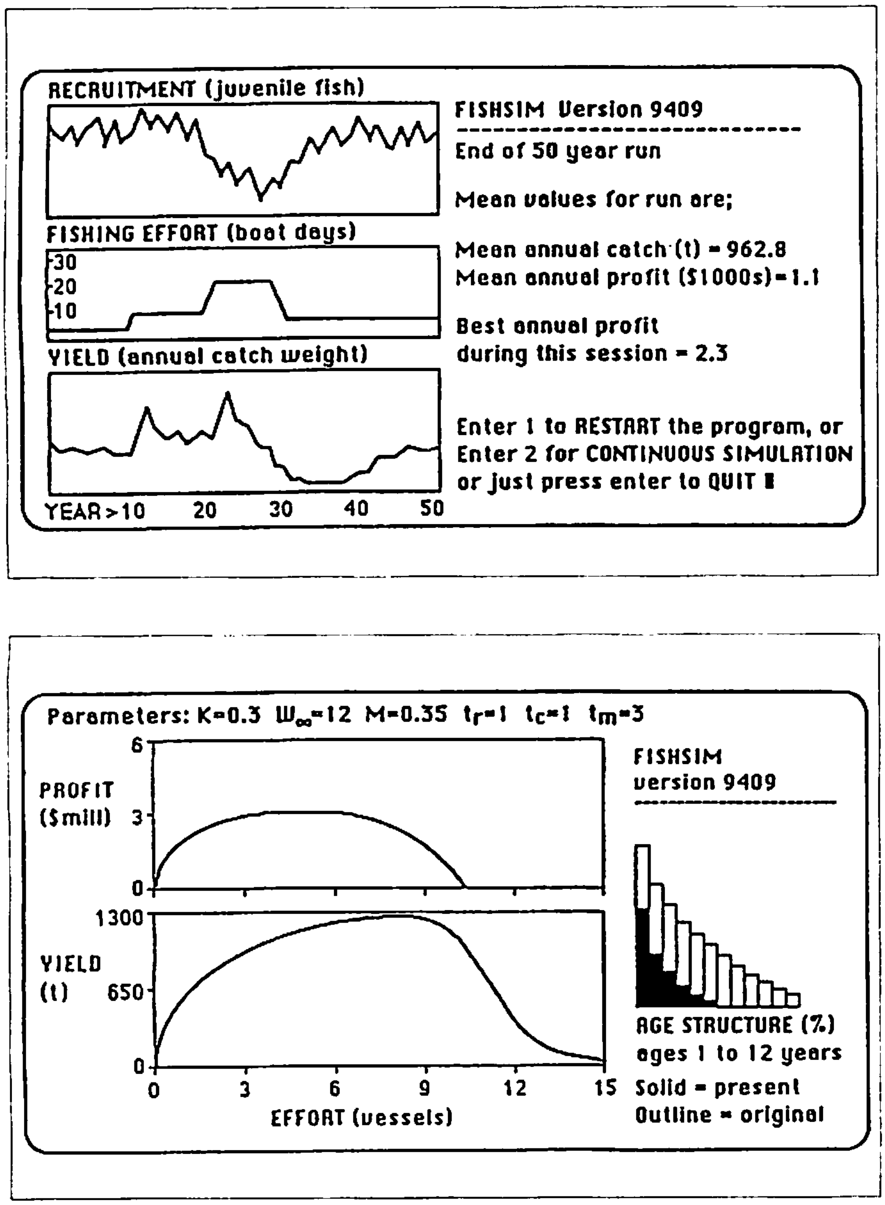

Fig. 2. Screen outputs from the fishery simulation model FISHSIM. Top: graphs of recruitment, fishing effort, and catch weight, at the end of a 50-year run (note that the user has altered fishing effort several times over the run), and, bottom: deterministic graphs of simulated profit and yield against incremental increases in fishing effort.

Discussion

Extensive use of the simulation model described in this paper with fishing industry representatives, policymakers, researchers and fisheries students has suggested several benefits in the use of such a model:

- Simulation models allow an increased awareness of how population parameters influence the total dynamic system of a fish stock. Many parameters (growth and mortality rates, for example) have antagonistic effects on outputs such as biomass and yield, and the result of different combinations of these may not be readily apparent. Simulation models allow biologists, economists and managers to visualize how a complex system, such as a natural resource, responds to the many components of the system.
- Running a simulation model with a range of different components allows researchers to determine the sensitivity of the output of interest to these components. The output of interest, yield for example, is said to be sensitive to a particular input parameter if small variations in the input value causes large variations in yield values. Results of such analyses may be used to suggest that research effort should be directed towards obtaining more precise estimates of those parameters to which the output is most sensitive. Using a simulation model to mimic the past history of a fishery allows a comparison of predicted results with actual catch records, and not only provides a check of the model, but some verification of the parameters used in its construction.
- By escaping the steady-state assumptions of the classical models, and by including recruitment estimates, models can be used to simulate the future behavior of the fishery under different rates of exploitation. The use of stochastic simulation models results in advice which may be given, most sensibly, in terms of probabilities, e.g., a 90% probability that yield will be within a certain range for a particular level of fishing effort.

  However, because simulation models are usually stochastic, the resulting yield curve (if produced) is unlikely to resemble the smooth, but often misleading, deterministic yield curve often expected by fisheries managers. There may also be some reluctance to accept advice on the basis of a simulation, which is often regarded as a "black box" approach to fishery assessment. While it is true that a model is only as good as its inherent assumptions and input parameters, it should be noted that many of the caveats which apply to simulation models also apply to other assessment tools such as production and yield-per-recruit models.
- Simulation models allow fisheries researchers and managers to "try out" various levels of fishing effort and different management strategies on the modeled fish stock. Simulations may be run repeatedly not only to estimate the probability of obtaining desirable outcomes, but the risk of undesirable ones. For example, the desired objective of managing a fishery may be to ensure that there is less than a 10% chance that the stock will be reduced below 25% of the virgin biomass; repeated runs of a simulation program will estimate the probabilities of a particular management strategy, reducing the biomass below the minimum reference point.
- Simulation models, particularly if they include pictorial representations of outputs, provide a convenient way of communicating the results of stock assessment, and the likely outcomes of alternative management strategies to managers and the fishing industry. However, the ease with which results can be presented in a visually pleasing and interactive simulation program, may result in simulation models being misused as vehicles to "sell" inadequate or bad science. Simulation models should be transparent enough for others to be aware of the component parameters and submodels, and the assumptions used in their construction. Indeed, one of the benefits of such a transparent model is that it allows industry, policymakers and modelers to exchange information and identify inadequacies in the model.

In summary, this paper describes a bioeconomic simulation model, FISHSIM, which uses conventional equations and submodels to represent a fishery. The model is sufficiently generalized to be easily adaptable for different target species groups and fishery management requirements. The model may be used as an aid in understanding complex natural systems, in determining the sensitivity of outputs to various input parameters, in the analysis of fish stocks, in the assessment of risks associated with different management strategies, and in the communication of results of fisheries assessment.

References

Baranov, F.I. 1918. On the question of the biological basis of fisheries. Nauch. Issled. Ikhtiol. Inst. Izvest. 1:81-128. [In Russian]

Beverton, R.J.H. and S.J. Holt. 1957. On the dynamics of exploited fish populations. MAF (UK) Fish. Invest. Ser. 2(19), 533 p.

Deriso, R.E. 1980. Harvesting strategies and parameter estimation for an age-structured model. Can. J. Fish. Aquat. Sci. 377:268-282.

Grant, W.E. 1986. Systems analysis and simulation in wildlife and fisheries sciences. John Wiley and Sons, New York. 338 p.

Hastings, N.A.J. and J.B. Peacock. 1975. Statistical distributions. Butterworth, London.

King, M.G. 1995. Fisheries biology, assessment, and management. Fishing News Books/Blackwell Scientific, Oxford, UK. 357 p.

Paulik, G.J. 1969. Computer simulation models for fisheries research, management and teaching. Trans. Am. Fish. Soc. 98:551-559.

Ricker, W.E. 1975. Computation and interpretation of biological statistics of fish populations. Fish. Res. Board Can. Bull. 191, 382 p.

Russell, E.S. 1931. Some theoretical considerations on the over-fishing problem. J. Cons. CIEM 6: 23-26.

Walker, T.I. 1992. Fishery simulation model for sharks applied to the gummy shark, *Mustelus antarcticus* Gunther, from Southern Australian waters. Aust. J. Mar. Freshwat. Res. 5:54-104.

Walters, C.J. 1969. A generalized computer simulation model for fish population studies. Trans. Am. Fish. Soc. 98:505-512.

Walters, C.J. 1980. Comment on Deriso's delay-difference population model. Can. J. Fish. Aquat. Sci. 37:23-65.

Walters, C.J. 1986. Adaptive management of renewable resources. Macmillan Publishing Co., New York. 374 p.

M. King is from the Australian Maritime College, Tasmania, Australia. His present address is Fisheries Division, PO Box 1874, Apia, Western Samoa.