FLR: an open-source framework for the evaluation and development of management strategies

L. T. Kell[1], I. Mosqueira[2], P. Grosjean[4], J-M. Fromentin[5], D. Garcia[3], R. Hillary[6], E. Jardim[7], S. Mardle[8], M. A. Pastoors[9], J. J. Poos[9], F. Scott[1] and R. D. Scott[1]

[1] Cefas, Lowestoft Laboratory, Pakefield Road, Lowestoft, Suffolk NR33 0HT, UK
[2] AZTI Tecnalia, Marine Research Division, Txatxarramendi ugartea z/g, 48395 Sukarrieta, Bizkaia, Spain
[3] AZTI Tecnalia, Marine Research Division, Txatxarramendi ugartea z/g, 48395 Sukarrieta, Bizkaia, Spain
[4] Ecologie Numérique des Milieux Aquatiques, Mons-Hainaut University 8, av du Champ de Mars, 7000 Mons, Belgium
[5] IFREMER, Centre de Recherche Halieutique Méditerranéen et Tropical, BP 171, 34203 Sète Cedex, France
[6] Department of Biology, Imperial College, London SW7 2BP, UK
[7] IPIMAR, Av. De Brasilla, 1449-006 Lisboa, Portugal
[8] Centre for the Economics and Management of Aquatic Resources (CEMARE), University of Portsmouth, Boathouse 6, College Road, HM Naval Base, Portsmouth, Hants PO1 3LJ, UK
[9] Wageningen IMARES, PO Box 68, 1970 AB IJmuiden, The Netherlands

Correspondence to L. T. Kell: tel: +44 1502 524572; fax: +44 1502 524511; e-mail: laurence.kell@cefas.co.uk

Abstract:

The FLR framework (Fisheries Library for R) is a development effort directed towards the evaluation of fisheries management strategies. The overall goal is to develop a common framework to facilitate collaboration within and across disciplines (e.g. biological, ecological, statistical, mathematical, economic, and social) and, in particular, to ensure that new modelling methods and software are more easily validated and evaluated, as well as becoming widely available once developed. Specifically, the framework details how to implement and link a variety of fishery, biological, and economic software packages so that alternative management strategies and procedures can be evaluated for their robustness to uncertainty before implementation. The design of the framework, including the adoption of object-orientated programming, its feasibility to be extended to new processes, and its application to new management approaches (e.g. ecosystem affects of fishing), is discussed. The importance of open source for promoting transparency and allowing technology transfer between disciplines and researchers is stressed.

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L. T. Kell, F. Scott, and R. D. Scott: Cefas, Lowestoft Laboratory, Pakefield Road, Lowestoft, Suffolk, NR33 0HT, UK. I. Mosqueira and D. Garcia: AZTI Tecnalia, Marine Research Division, Txatxarramendi ugartea z/g, 48395 Sukarrieta, Bizkaia, Spain. P. Grosjean: Ecologie Numérique des Milieux Aquatiques, Mons-Hainaut University 8, av du Champ de Mars, 7000 Mons, Belgium. J-M. Fromentin: IFREMER, Centre de Recherche Halieutique Méditerranéen et Tropical, BP 171, 34203 Sète Cedex, France. R. Hillary: Imperial College, Department of Biology, Imperial College London, SW7 2BP, UK. E. Jardim: IPIMAR, Av. De Brasilla, 1449-006, Lisboa, Portugal. S. Mardle: Centre for the Economics and Management of Aquatic Resources (CEMARE), University of Portsmouth, Boathouse 6, College Road, HM Naval Base, Portsmouth, Hants. PO1 3LJ. UK. M. Pastoors and J. J. Poos: Wageningen IMARES, PO Box 68, 1970 AB IJmuiden, Netherlands. Correspondence to L. T. Kell: tel: +44 1502 524572; fax: +44 1502 524511; e-mail: laurence.kell@cefas.co.uk.

Introduction

The management of fisheries increasingly embodies multiple and conflicting biological, ecological, economic, and social objectives. However, despite constant efforts to regulate fisheries by regional management bodies and national governments, fishing capacity often

remains above that necessary to ensure the sustainable exploitation of marine resources, especially in developed countries. This failure has been analysed in depth during the past decade by the scientific community, which has repeatedly recommended substantial changes in incentives and governance, as well as adjustments in the way that fisheries research and monitoring are conducted and expertise is deployed (Bosford *et al*., 1997; Gislason *et al*., 2000; Pauly *et al*., 2002; Sinclair *et al*., 2002; Garcia and de Leiva Moreno, 2003; Hilborn *et al*., 2004; Jennings, 2004; Sissenwine and Murawski, 2004; Grafton *et al*., 2006).

Although the need to develop alternative novel management strategies is widely recognized, it is almost impossible to develop these by conducting large-scale experiments on fish stocks, with the notable exception of that reported by Sainsbury *et al*. (1997). There has therefore been a trend towards the use of computer simulation to develop robust management strategies that can meet multiple objectives. This approach was pioneered by the Scientific Committee of the International Whaling Commission (IWC; Hammond and Donovan, in press), and is now being used in fisheries management, particularly in South Africa (Butterworth and Bergh, 1993; Butterworth *et al*., 1997; Cochrane *et al*., 1998; Geromont *et al*., 1999; De Oliveira and Butterworth, 2004; Johnston and Butterworth, 2005) and Australia (Punt and Smith, 1999; Tuck *et al*., 2003; Campbell and Dowling, 2005; Dichmont *et al*., 2005; Punt *et al*., 2005).

A major failing of conventional management advice has been that it does not explicitly incorporate important sources of uncertainty. For example, it is generally assumed that (i) input data are appropriate and not biased, (ii) stock assessment models accurately reflect both population and fisheries dynamics, and (iii) management measures are perfectly implemented (Cotter *et al*., 2004; Peterman, 2004; Punt, in press). In others words, the robustness of the advice to uncertainty with respect to both the intrinsic properties of natural systems and our ability to understand, monitor, and control them is largely ignored.

Following Rosenberg and Restrepo (1994), Francis and Shotton (1997), and Kell *et al*. (2005a, 2005b, 2006), uncertainties in fish stock assessment and management can be categorized as:

- Process error – caused by disregarding variability, temporal and spatial, in dynamic population and fisheries processes;
- Observation error – sampling error and measurement error;
- Estimation error – arising when estimating parameters of the models used in the assessment procedure;
- Model error – related to the ability of the model structure to capture the core of the system dynamics;
- Implementation error – where the effects of management actions may differ from those intended.

Simulation is an important tool that can be used to generate data, conditional on a set of assumptions about the dynamics, then to evaluate the accuracy and precision of estimates derived from stock assessment models, the robustness of those models to mis-specification, and their sensitivity to changes in the input data.

In reality, however, many of these error types are interdependent, and the total uncertainty cannot always be decomposed in the constituting types. It is therefore not sufficient to identify the sources of error; their complex interactive relationships need to be understood as well. While the statistical models of Fournier *et al*. (1998), Methot (2005), Michielsens *et al*. (2006), and Porch *et al*. (2006) can integrate several sources of uncertainty (e.g. observation and process error), stock assessment models alone cannot rigorously test the robustness of a management strategy (i.e. control rules to implement specific management measures in order to achieve a particular set of objectives) to a wide range of uncertainties.

Traditionally, stock assessment requires a time-consuming re-evaluation of data and the running of increasingly complex models to produce advice that may deviate considerably from one year to the next. Hilborn (2003) forecasts the end of such a treadmill and the increased use of Management Strategy Evaluation (MSE), in which complex models are used primarily to test the robustness of simpler assessment/management rules before implementation, by conducting computer-based experiments that embody how the whole

system reacts to a variety of possible management actions. Population and fleet dynamics are deduced from a range of plausible hypotheses and available data sets, rather than being based on a singular set of assumptions, because the objective is to develop strategies that are robust to our uncertainty about the "true" dynamics and hence to meet the requirements of the precautionary approach to fisheries management adopted by FAO (1996). Therefore, there has been a trend towards MSE that allows the data-collection regimes, assessment procedures and rules for decision making, e.g. harvest control rules (HCRs), to be evaluated either in the form of a Management Procedure (MP; Butterworth *et al*., 1997), in which all elements are pre-specified, or alternatively to draw conclusions about individual components of a management strategy so that even if implementation differs from that actually tested, the results are still applicable.

However, Butterworth and Punt (1999) noted that the absence of any general software package was a major impediment to the wider use of MSE. Therefore the FLR (Fisheries Library in R) open-source framework was developed, to provide an integrated suite of software that allows data exploration, conditioning of models (the estimation of parameters consistent with the data, and hypotheses about how these were generated), implementation of management procedures (e.g. methods for stock assessments and forecasts), and the testing of management strategies and economic impact assessments to be conducted within a common environment. The use of open source is important in that it facilitates better collaboration and the transfer of knowledge within and between disciplines.

Conceptual framework

The MSE approach requires mathematical representations of two systems: a "true" system and an "observed" one. The true system is represented by the operating model (OM) that simulates the real world. It does so by attempting to capture all existing knowledge and data, and in some cases presumptions and opinion about the real world (Hammond and Donovan, in press), including the full dynamics of the exploited populations, fishers behaviour in response to management actions (an implementation model), and environmental conditions (external driving forces), as well as interactions between all its components. The OM will often contain a greater level of complexity and knowledge than that used within stock assessment models. It should also allow the evaluation of the consequences of contrasting hypotheses about the real dynamics.

In contrast, the observed system represents the conventional management procedure (MP), from data collection through stock assessment to management implementation. The MP may be based on current or alternative stock assessment methods and management strategies and includes (i) an observation model that simulates data collection from the true population in the OM, (ii) an assessment model to derive estimates of stock status from the simulated observations, and (iii) a predefined set of management actions according to some specified rules (e.g. a HCR) that takes into account the outcome of the assessment.

The observed system will further act on the real system through feedback of the management options. For example, the main management instrument of the EU Common Fisheries Policy to control fishing mortality is to set the total allowable catch (TAC). However, reported catches are also one of the main sources of data for providing scientific advice, meaning that bias, particularly where there is potential for fisheries to fool the inspection, in the assessment process can be driven by management advice, which in turn is based upon the assessment process.

Software framework

The EU project FEMS (Framework for the Evaluation of Management Strategies, contract Q5RS–2002–01824) proposed, and initially developed, a generic framework that is now the core of the FLR initiative (http://www.flr-project.org). FLR is developed using R (R Development Core Team, 2006), an environment and computer language for statistical computing and graphics that is highly extensible. It includes effective data handling and storage facilities, mathematical operators including those for matrices, and a large, coherent,

integrated collection of statistical, mathematical, and graphical tools for data analysis. The term "environment" is intended to characterize R as a fully planned and coherent system, rather than an incremental accretion of specific, inflexible, and rigid tools, as is frequently the case with other data-analysis software (and fisheries software in particular). This environment is designed around a computer language, and allows users to add additional functionality by defining new functions or developing new libraries. FLR takes advantage of these features and extends them to fisheries modelling.

FLR allows exploratory data analyses to be conducted, alternative stock assessment methods to be implemented (including the incorporation of existing methods written in Fortran and C/C++), management procedures to be developed (including testing of HCR for working groups; ICES, 2006a, 2006b, 2006c, 2006d) and the conditioning of operating models on a variety of data and hypotheses. Economic and ecosystem models are also currently being incorporated to allow better evaluation of management strategies for mixed and multispecies fisheries.

FLR, like R, is an open-source project licensed under the GNU General Public License (www.gnu.org/licenses/licenses.html#GPL). The source code is freely available, allowing scientists to check and to validate the implementation of methods, computations carried out, and assumptions made, which constitutes an implicit peer-review process. Code-sharing also speeds up the scientific process, and because R already has a broad set of tools for data analysis, practitioners can focus on the real issues instead of rewriting specific software already developed by someone else.

FLR is implemented using object-orientated programming (OOP). The essence of OOP is to treat data, and the procedures that act upon data, as a single object. These objects are of particular types or classes and represent the different elements of a system (S4 classes within R; Chambers, 2000). Using this approach, different elements of fisheries systems (stocks, fleets, assessment methods, etc.) are represented as core classes, and the framework is extendable by adding new classes (e.g. to implement economic and ecosystem models). Further information about the structure and use of these classes can be found in the documentation and tutorials (http://www.flr-project.org/doku.php?id=courses:tyflr).

The basic component of FLR classes is the FLQuant class, which is essentially an array used to store data of one particular type (e.g. observations such as catch data or parameters such as natural mortality). Using a standard class makes it easier to implement methods to summarize them and operate them. FLQuant has five dimensions in version 1, and six in versions 2.0 and later. However, often one or more of the dimensions will be not be used, and their existence is transparent to the user. The quantity represented by the first dimension can be set by the user. For example, it could correspond to age, length, or vessel class. The next four dimensions are, in order, year, unit, season, and area; "unit" is open to any sort of division that might be of use, e.g. sub-stocks, or male/female, and "season" and "area" allow for time and space subdivisions. The sixth dimension, "iter" is used to store different iterations when conducting Monte Carlo simulations, e.g. when bootstrapping or running Bayesian estimation methods.

Although the vast majority of programming is in R, code written in other languages such as Fortran or C++ can also be included. For example, solving non-linear equations is computationally intensive, and fast C++ routines using automatic differentiation can be called from R. Existing stock assessment methods, e.g. ICA (Patterson and Melvin, 1996) and XSA (Shepherd, 1999), have also been integrated using the original source code. Even when classes have additional code written in other languages, R is still the front end of the FLR framework, and the user is unaware of their use. Non-R code is also distributed under the GPL license, so its use does not detract from the peer-review process.

Operating and management models

Figure 1 shows the conceptual framework and its implementation in the FLR classes. In the Operating Model, the true population is represented by an object of class FLBiol; additional classes are used to model particular processes, e.g. the stock-recruitment relationship is via

the FLSR class. The population interacts with fishing fleets, a single fleet represented by the FLFleet. The MSE may be based on several stocks combined using the class FLBiols, which is essentially a collection of FLBiol objects. Multiple fleets can also be accommodated using a similar mechanism.
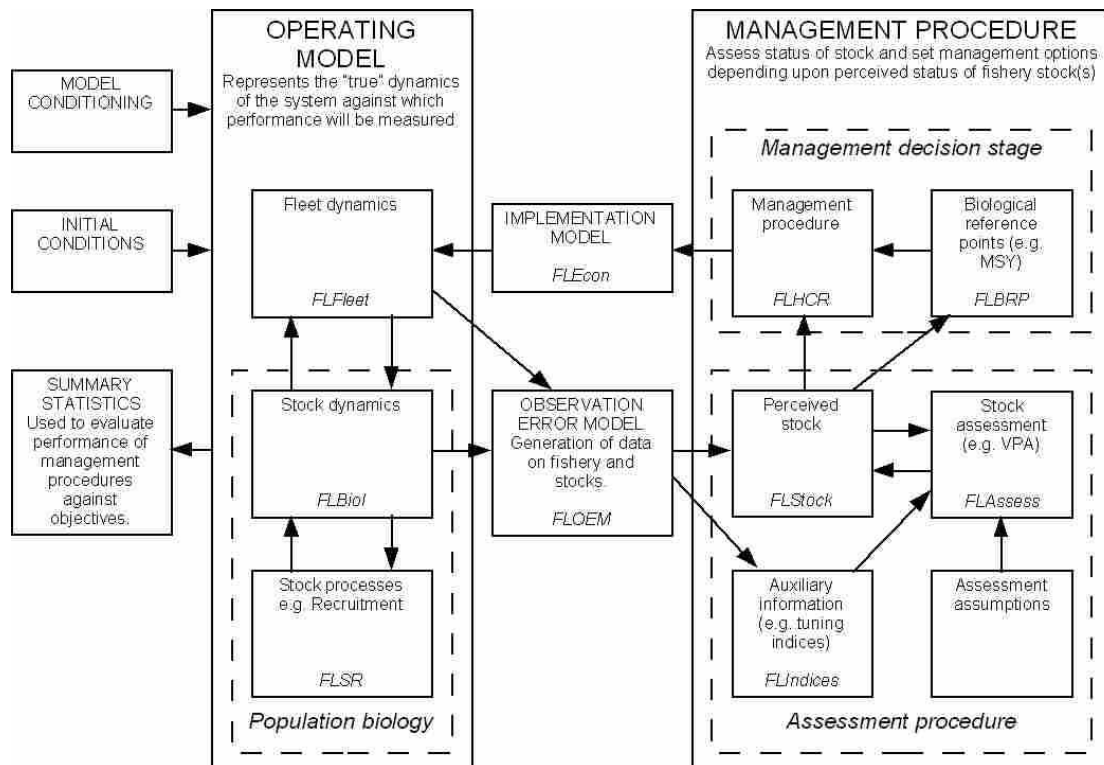

Figure 1. The conceptual framework and how it is mapped into FLR classes.

Full details of FLR packages can be found on the FLR website (http://www.flr-project.org/), this list will be continually updated with latest information and links to documentation and examples.

As the world can only be seen through the data that we collect, observations are sampled from the OM for use in the MP. Observation error is implemented using the FLOE class, which is the link between the OM and the MP. Observations are generated from the variables simulated in the OM (both biological and human), and are used, directly or indirectly, in the MP to ascertain stock status. The MP uses the FLStock class to calculate stock data (catches, weights-at-age, etc), based on the observations modified by FLOE, and the FLIndex class to model indices of abundance (e.g., catch per unit effort [cpue] from fleets or surveys). Stock assessment is carried out using the FLAssess package, which provides classes for data input, diagnostics inspection, and stock status estimation, and is intended to allow for the implementation of a variety of stock assessment methods.

Estimates of stock status obtained from stock assessment are used in the decision model (e.g., a HCR), which attempts to affect the behaviour of the human elements in the OM (e.g., through the use of TACs) to achieve specific goals within prescribed constraints. Alternatively, the data could be used directly to set management regulations, in which case the data generated by the observation error model would be used directly by the HCR. Several classes are available to assist in implementing a HCR, including one class for performing a short-term forecast (FLSTF) and one to calculate biological reference points (FLBRP). The results of the HCR are fed back into the OM. In the real world, however, management actions are never implemented perfectly, and within FLR, implementation error can be modelled in a variety of ways (e.g., by modelling the relationship between fleet capacity, effort, and fishing

mortality). This should take into account factors that may cause the effects of management to differ from the goals of the decision model, such as limitations imposed by bycatch. FLFleet therefore has attributes that record true catches, landings, and discards from different biological populations.

The behaviour of a fleet, and hence compliance with regulations, might differ from that assumed by a HCR because of fleet adaptation, learning, or as a response to economic constraints. Such responses are motivated by economic factors (i.e. profits), so consideration of economic incentives provides a means of estimating how fishers may respond to changes in the natural, economic, and regulatory environment within which they operate. An economic package FLEcon is therefore being developed that allows economic indicators to be calculated and the response of fishers, and hence compliance with regulations, to be modelled. This includes dynamics relating to fleet mobility (effort allocation), fleet adaptation, and the effects of prices and costs (e.g., of fuel).

Conditioning operating models on data

An OM is a simulation model that represents plausible hypotheses about stock dynamics and the behaviour of fleets, and is intended to test the robustness of management strategies to what we do not know and cannot control, as well as to what we know and can control. Components of the OM, biological, economic, or bio-economic, must be conditioned on available data, so that model predictions and data are consistent (Zeh and Punt, 2005). Alternative OMs should be constructed on the basis of structurally different models so that the robustness of candidate management strategies can be tested. These might include less obvious, but still plausible, hypotheses about the dynamics.

Kell *et al*. (2006) identified four different approaches for developing OMs, which were expressed mostly in a Bayesian context, but are equally relevant within a frequentist philosophy. The amount of knowledge, data requirements, and complexity of implementation differ quite markedly among these approaches. Depending on the situation, FLR allows the implementation of all types, but the complexity and demands on the analyst varies between types:

(i)   The OM mimics the current stock assessment model, implying that the assessment model describes the true dynamics almost perfectly. This approach has arguably the least demand for knowledge and data.

(ii)   The OM represents all available (and valid) data, and its parameter estimates depend almost exclusively on the data (including maximum-likelihood estimation or a Bayesian analysis with non-informative priors). The OM does not need to be identical to the assessment model used in the MP. The strong and often unrealistic assumption in this case is that future developments will be similar to what happened in the past.

(iii)   As for (ii), except that in a Bayesian modelling approach, informative priors (from meta-analytic or Monte Carlo methods) describe in a formal probabilistic way *a priori* degrees of belief in parameters and processes based on expert judgement. Data from other sources other than a specific fishery have an impact when conditioning the OM.

(iv)   As for (iii), except that the emphasis is on *a priori* information and expert beliefs about the processes that may affect the management system in future (i.e. the focus is on the future, not on fitting historical data). Consequently, the OM must be flexible so that a range of factors can be addressed.

Although standard statistical techniques allow performance to be assessed, the Bayesian approach allows one also to assign prior degrees of belief in parameters, processes, and models for which there is information, be it expert or derived from meta-analyses. Therefore, the FLBayes package is being developed, intended as a generic tool for Bayesian estimation, and will implement a class specific to storage and basic analysis of the parameter Markov chains coming from Monte Carlo estimation procedures. This is compatible with all the FLBayes estimation routines, and also allows those who wish to do so to import such Markov chains from other external estimation schemes (e.g., BUGS) for use in management

simulations. The sixth dimension in the FLQuant is where the Monte Carlo samples resulting from the simulations are stored, allowing inferences to be drawn on important stock and fishery quantities. In future it is envisaged that, for as many methods as is feasible, using both Bayesian and frequentist estimation schemes will be possible.

Discussion

A major challenge for fisheries science is to develop a framework for scientific advice that comprehensively accounts for key uncertainties and risks while supporting the sustainable exploitation of marine living resources and maintaining an economically viable fishing industry. An important principle when developing such a framework is robustness to uncertainty because, although it is seldom possible to predict the response of fish populations to management with any degree of accuracy, it is possible to assess which strategies will on average work best, i.e. which management option is more robust.

Scientists involved in stock assessment working groups are experiencing morale problems rooted in a feeling that too often all they are doing is "turning the crank" on assessments (Wilson and Hegland, 2005), and would prefer a greater scientific focus and combinations of reforms such as the development of management strategies that incorporate alternative measures, fleet-, fisheries-, and ecosystem-based approaches, and more interaction about advice with managers. FLR will hopefully help by providing tools for stock assessors, managers, and others for use in the advisory process, and allow strategic decisions to be made. For example, they should allow "what if" questions to be answered.

Using R and adopting an open-source license and development model, FLR is intended to improve transparency and scientific review, to encourage active participation, and to blur the distinction between developers and users by allowing participation in the development process. This is important: management of fisheries requires collaboration between disciplines, e.g. biological and economic, because if two policies have the same biological impact but different ones in economic terms, then an economic impact analysis can help derive a preferred option. For example, a reduction in fishing mortality implemented as an effort reduction may have the same biological effect regardless of whether it is implemented by limiting days at sea or reducing fleet size. However, the economic consequences and hence fishers' response to these two alternative management measures would be very different. Notably, if such a policy makes a fleet bankrupt, then it is unlikely to get implemented in law or practice as a consequence respectively of political pressure or non-compliance.

Enforcement costs are also important, because the benefits of a policy may not outweigh the costs. There is therefore increasing need to build bio-economic models to perform cost/benefit analyses of enforcement schemes and to conduct impact analyses, in order to decide upon the best way to implement management objectives. The cost of computer simulation is much less than the cost of collecting data or the value of foregone yield through bad management. This approach has successfully been used for small stocks, e.g. the Blackwater herring (Roel *et al.*, 2004), which allowed assessment and management costs to be reduced and still allowed the stock to maintain Marine Stewardship Council certification (www.msc.org).

There are two main areas where FLR is or is intended to be applied within an ecosystem context: (i) testing the robustness of simple assessment/management rules given that species interactions are occurring, and (ii) to help develop indicator-based management systems to assess the impacts of fishing on ecosystems.

Aydin and Gaichas (2006) noted three important sources of uncertainty in multispecies models: (i) structural uncertainty, e.g. aggregation in the foodweb, (ii) functional uncertainty in predator/prey relationships, and (iii) data uncertainty. There are often insufficient data to decide upon the main interactions between species or to describe the response of individual species to management, but even when data are available, limited knowledge of the functional form and precise dynamics of the relationships among species jeopardizes our ability to use them in models to provide management advice directly. Therefore, it is important to allow for

a range of alternative operating models, with different assumptions, to be developed. Only in that way will it be possible to ensure that the full uncertainty is captured.

Aydin and Gaichas (2006) also pointed out that there are two basic approaches to multispecies modelling:

- "Minimum Realistic Modelling" (Punt and Butterworth, 1995), e.g. adding complexity in a piecemeal fashion to improve fits to the data. An example is Multi-Species Virtual Population Analysis (MSVPA; Sparre 1991), which extended single-species VPA by including predator/prey interactions to estimate natural mortality.
- "Big Picture"; i.e. models of "the whole ecosystem" or, in a predator/prey context, the whole foodweb, for example Ecopath with Ecosim (Christensen *et al*., 2005).

Distinction should be made between the uses of "Minimum Realistic" and "Big Picture" models. The main use of models such as MSVPA has been to improve existing single-species evaluations, while "Big Picture" models have been used mainly to explore or evaluate hypotheses. It is envisaged that, in future, "Big Picture" models will be used to evaluate the minimum level of realism needed when providing management advice, i.e. to evaluate the benefits of adding complexity, rather than adding complexity for complexity's sake. For example, multispecies models may also be used to test the robustness of simpler assessment/management rules before implementation, in particular for species and fisheries in which there are important interactions but insufficient data to provide traditional advice.

MSE is increasingly being used to design management strategies for achieving fishery ecosystem objectives (Sainsbury *et al*., 2000), and in particular to help develop indicator-based management systems to assess the impacts of fishing on ecosystems. For example, Fulton *et al*. (2004a, 2004b, 2005) have applied MSE to evaluate the performance of state indicators in an Australian fishery, using a relatively complex deterministic model to describe ecosystem dynamics. Those authors then used a sampling model to generate data with realistic measurement uncertainty (bias and variance) for a given sampling design (location and timing), to produce the data required to calculate state indicators. Simulated data were collected for different levels of fishing, and for fishing combined with other activities. The performance of the indicators derived from the data was then assessed in terms of the indicators' capacities to track properties of interest. Indicator performance can be measured as the ability of indicators to detect or to predict trends in attributes, where the true values are known from the models.

A similar system is to be evaluated using FLR, in order to develop an environmental assessment (EA) of the North Sea. It will benefit from a relatively good understanding of biological processes and the variety of models already developed in FLR. This could therefore be an ideal system in which to test the implementation of an EA based on indicators. It may also allow us to assess how effectively management can be applied in data-poor circumstances by comparing the performance of management systems based on suites of linked pressure-state and response indicators with those based solely on routine monitoring of pressure and infrequent monitoring of some aspects of state.

Although MSE is a powerful tool, the aim ultimately is to improve the quality of management. Importantly, the MSE approach is intended to do so not by making the analysis more complex, but by helping in the development of a robust management framework that can handle the often conflicting and poorly defined management objectives, account for many of the uncertainties that are often ignored in the conventional approach, and aid in strategic decision-making.

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