

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

L. T. Kell, I. Mosqueira, P. Grosjean, J-M. Fromentin, D. Garcia, R. Hillary, E. Jardim, S. Mardle, M. A. Pastoors, J. J. Poos, F. Scott, and R. D. Scott

Kell, L. T., Mosqueira, I., Grosjean, P., Fromentin, J-M., Garcia, D., Hillary, R., Jardim, E., Mardle, S., Pastoors, M. A., Poos, J. J., Scott, F., and Scott, R. D. 2007. FLR: an open-source framework for the evaluation and development of management strategies. – *ICES Journal of Marine Science*, 64: 640–646.

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 effects of fishing), is discussed. The importance of open source for promoting transparency and allowing technology transfer between disciplines and researchers is stressed.

**Keywords:** bio-economic modelling, management strategy evaluation, open source, precautionary approach, simulation framework, software, stock assessment, uncertainty.

Received 30 June 2006; accepted 2 January 2007; advance access publication 29 March 2007.

L. T. Kell, F. Scott, and R. D. Scott: Cefas, Lowestoft Laboratory, Pakefield Road, Lowestoft, Suffolk NR33 0HT, UK. I. Mosqueira: AZTI Tecnalia, Marine Research Division, Txatxarramendi ugarte a z/g, 48395 Sukarrieta, Bizkaia, Spain (current address Cefas, Lowestoft Laboratory, Pakefield Road, Lowestoft, Suffolk NR33 0HT, UK). D. Garcia: AZTI Tecnalia, Marine Research Division, Txatxarramendi ugarte a 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: 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. A. Pastoors and J. J. Poos: 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

### 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 the level 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 to incentives and governance, as well as adjustments to the way that fisheries research and monitoring are conducted and expertise is deployed (Botsford *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 novel alternative management strategies is widely recognized, it is almost impossible to develop these by conducting large-scale experiments on fish stocks,

except that reported by Sainsbury *et al.* (1997). Therefore, there has 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 (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, 2006). In other 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, b, 2006b), uncertainties in fish stock assessment and management can be categorized as follows:

- 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; to evaluate the accuracy and precision of estimates derived from stock assessment models, the robustness of those models to misspecification, 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 into the constituting types. It is not sufficient, therefore, to identify the sources of error; their complex interactive relationships need to be understood as well. Although 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 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), either to be evaluated 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 MPs (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, fisher 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 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. an HCR), which 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 in the assessment process, particularly where there is potential for fisheries to fool the inspection, 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, which 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++), MPs to be developed (including testing of HCR for working groups; ICES, 2006a–d), and the conditioning of OMs on a variety of data and hypotheses. Currently, economic and ecosystem models are also 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](http://www.gnu.org/licenses/licenses.html#GPL)). The source code is freely available, allowing scientists to check and validate the implementation of methods, computations carried out, and assumptions made, which implicitly constitutes a 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, and so on.) 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 and operate them. FLQuant has five dimensions in version 1, and six in versions 2.0 and later. Often, however, one or more of the dimensions will 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 most 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 FLR classes. In the OM, the true population is represented by an object of class FLBiol; additional classes are used to model

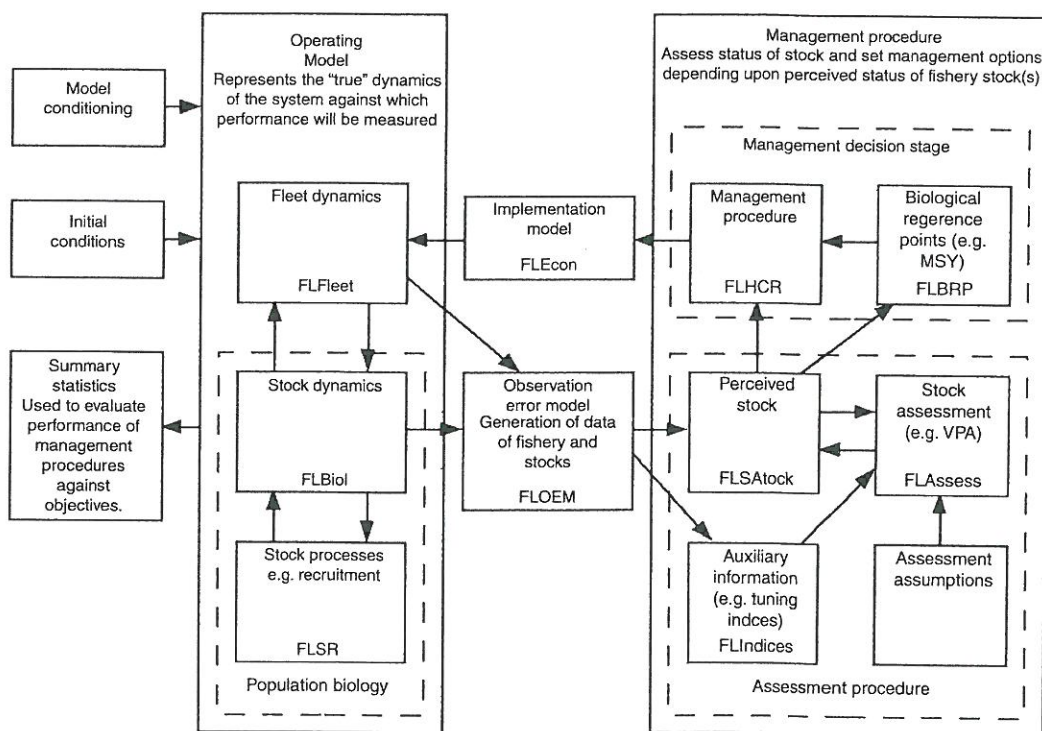


Figure 1. The conceptual framework and how it is mapped into FLR classes.

particular processes, e.g. the stock-recruitment relationship is via the FLSR class. The population interacts with fishing fleets, a single fleet represented by 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.

Full details of FLR packages can be found on the FLR website (<http://www.flr-project.org/>); this list will be continually updated with the 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, weight-at-age, and so on), on the basis of observations modified by FLOE, and the FLIndex class to model indices of abundance [e.g. catch per unit of 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. an 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 an 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 an 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. As a result, FLEcon, an economic package, is being developed, which 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 OMs 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.* (2006a) identified four different approaches to 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 vary between types:

- (i) The OM mimics the current stock assessment model, implying that the assessment model describes the true dynamics almost perfectly. Arguably, this approach is the least demanding of 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-analytical or Monte Carlo methods) describe in a formal probabilistic way *a priori* degrees of belief in parameters and processes on the basis of expert judgement. Data from 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 the assignment of 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 as a generic tool for the Bayesian estimation, and it 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 FLBayes estimation routines and also allows the import of such Markov chains from other external estimation schemes (e.g. BUGS) for use in management simulations. The sixth dimension in FLQuant is where Monte Carlo samples resulting from the simulations are stored, allowing inferences to be drawn on important stock and fishery quantities. It is envisaged that, in the future and 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. It is hoped that FLR will 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, encourage active participation, and 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 differ 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 be implemented in law or practice as a consequence of, respectively, political pressure or non-compliance.

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

There are two main areas where FLR is applied or is intended to be applied within an ecosystem context: (i) testing the robustness of simple assessment-management rules given species interactions and (ii) helping develop indicator-based management systems to assess the impact 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 too few data to identify 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 develop a range of alternative OMs, with different assumptions. Only in this 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 multispecies 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, Ecosim with Ecosim (Christensen *et al.*, 2005).

A 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, whereas 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 too few data to provide traditional advice.

Increasingly, MSE is 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 impact of fishing on ecosystems. For example, Fulton *et al.* (2004a, b, 2005) 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 predict trends in attributes, where the true values are known from the models.

To develop an environmental assessment (EA) of the North Sea, a similar system is to be evaluated using FLR. It will benefit from a relatively good understanding of biological processes and the variety of models already developed in FLR. For these reasons, this could 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 ultimate aim 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 to develop 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.

## Acknowledgements

FLR is an open-source initiative, so has been improved by the contributions of many parties. It was initially proposed and developed by the FEMS project (Framework for Evaluation of Management Strategies; contract Q5RS-2002-01824) funded by the European Commission Research Directorate, the UK's Department for the Environment, Food and Rural Affairs (under contract M0322 "Fisheries Interactions"), and the Basque Government (under contract RP2003021). Subsequent development of FLR has been supported by various projects, including projects partially funded by the EU: COMMIT, EFIMAS, FISBOAT, UNCOVER, and NeoMav (QCA3/MARE-FEDER). The authors also thank the reviewers André Punt and Hajo Rätz, editor-in-chief of the ICES Journal Andrew Payne, and guest editor Niels Daan for many comments that greatly improved the initial draft.

## References

- Aydin, K. Y., and Gaichas, S. K. 2006. In defence of complexity: towards a representation of uncertainty in multispecies models. International Whaling Commission, Scientific Committee Paper, SC/58/E48.
- Botsford, L. W., Castilla, J. C., and Peterson, C. H. 1997. The management of fisheries and marine ecosystems. *Science*, 277: 509–515.
- Butterworth, D. S., and Bergh, M. O. 1993. The development of a management procedure for the South African anchovy resource. *In Risk Evaluation and Biological Reference Points for Fisheries Management*, pp. 83–99. Ed. by S. J. Smith, J. J. Hunt, and D. Rivard. Canadian Special Publication of Fisheries and Aquatic Sciences, 120.
- Butterworth, D. S., Cochrane, K. L., and De Oliveira, J. A. A. 1997. Management procedures: a better way to manage fisheries? The South African experience. *In Global Trends: Fisheries Management*, pp. 83–90. Ed. by E. K. Pikitch, D. D. Huppert, and M. P. Sissenwine. American Fisheries Society Symposium, 20.
- Butterworth, D. S., and Punt, A. E. 1999. Experiences in the evaluation and interpretation of management procedures. *ICES Journal of Marine Science*, 56: 985–998.
- Campbell, R. A., and Dowling, N. A. 2005. Evaluating harvest strategies for a rapidly expanding fishery: the Australian broadbill swordfish fishery. *In Fisheries Assessment and Management in Data-Limited Situations*, pp. 509–532. Ed. by G. H. Kruse, V. F. Gallucci, D. E. Hay, R. I. Perry, R. M. Peterman, T. C. Shirley, P. D. Spencer *et al.* Alaska Sea Grant College Program Report, 05–02. University of Alaska, Fairbanks.
- Chambers, J. M. 2000. *Programming with Data*. Wiley, New York.
- Christensen, V., Walters, C., and Pauly, D. 2005. *Ecopath with Ecosim: a User's Guide*, November 2005 edn. 154 pp. Fisheries Centre, University of British Columbia, Vancouver. at [www.ecopath.org](http://www.ecopath.org).
- Cochrane, K. L., Butterworth, D. S., De Oliveira, J. A. A., and Roel, B. A. 1998. Management procedures in a fishery based on highly variable stocks and with conflicting objectives: experiences in the South African pelagic fishery. *Reviews in Fish Biology and Fisheries*, 8: 177–214.
- Cotter, A. J. R., Burt, L., Paxton, C. G. M., Fernandez, C., Buckland, S. T., and Pan, J.-X. 2004. Are stock assessment methods too complicated? *Fish and Fisheries*, 5: 235–254.
- De Oliveira, J. A. A., and Butterworth, D. S. 2004. Developing and refining a joint management procedure for the multispecies South African pelagic fishery. *ICES Journal of Marine Science*, 61: 1432–1442.
- Dichmont, C. M., Deng, A. R., Venables, W. N., Punt, A. E., Haddon, M., and Tattersall, K. 2005. A new approach to assessment in the NPF: spatial models in a management strategy environment that includes uncertainty. Report of the Fisheries Research and Development Corporation, 2001/002, CSIRO Marine Research, Hobart. 165 pp.
- FAO. 1996. Precautionary approach to capture fisheries and species introductions. FAO Technical Guidelines for Responsible Fisheries, 2. FAO, Rome. <http://www.fao.org/DOCREP/003/W3592E/W3592E00.HTM>; (accessed 8 December 2006).
- Fournier, D. A., Hampton, J., and Sibert, J. R. 1998. MULTIFAN-CL: a length-based, age-structured model for fisheries stock assessment, with application to south Pacific albacore, *Thunnus alalunga*. *Canadian Journal of Fisheries and Aquatic Sciences*, 55: 2105–2116.
- Francis, R. I. C. C., and Shotton, R. 1997. "Risk" in fisheries management: a review. *Canadian Journal of Fisheries and Aquatic Sciences*, 54: 1699–1715.
- Fulton, E. A., Fuller, M., Smith, A. D. M., and Punt, A. 2004b. Ecological indicators of the ecosystem effects of fishing: final report. Australian Fisheries Management Authority Final Research Report R99/1546. 239 pp.
- Fulton, E. A., Smith, A. D. M., and Punt, A. E. 2005. Which ecological indicators can robustly detect effects of fishing? *ICES Journal of Marine Science*, 62: 540–551.
- Fulton, E. A., Smith, A. D. M., Webb, H., and Slater, J. 2004a. Ecological indicators for the impacts of fishing on non-target species, communities and ecosystems: review of potential indicators. Australian Fisheries Management Authority Final Research Report, R99/1546. 116 pp.
- Garcia, S., and de Leiva Moreno, I. 2003. Global overview of marine fisheries. *In Responsible Fisheries in the Marine Ecosystem*, pp. 1–24. Ed. by M. Sinclair, and G. Valdimarsson. FAO Rome, and CABI Publishing, Wallingford, UK.
- Geromont, H. F., De Oliveira, J. A. A., Johnston, S. J., and Cunningham, C. L. 1999. Development and application of management procedures for fisheries in Southern Africa. *ICES Journal of Marine Science*, 56: 952–966.
- Gislason, H., Sinclair, M., Sainsbury, K., and O'Boyle, R. 2000. Symposium overview: incorporating ecosystem objectives within fisheries management. *ICES Journal of Marine Science*, 57: 468–475.
- Grafton, R. Q., Arnason, R., Bjørndal, T., Campbell, D., Campbell, H. F., Clark, C. W., Connor, R. *et al.* 2006. Incentive-based approaches to sustainable fisheries. *Canadian Journal of Fisheries and Aquatic Sciences*, 63: 699–710.
- Hammond, P. S., and Donovan, G. P. Development of the IWC Revised Management Procedure. *Journal of Cetacean Research and Management*, Special Edition 4, in press.
- Hilborn, R. 2003. The state of the art in stock assessment: where we are and where we are going. *Scientia Marina*, 67(Suppl. 1): 15–21.
- Hilborn, R., Punt, A. E., and Orensanz, J. 2004. Beyond band-aids in fisheries management: fixing world fisheries. *Bulletin of Marine Science*, 74: 493–507.

- ICES. 2006a. Working Group on the Assessment of Demersal Stocks in the North Sea and Skagerrak (WGNSSK). ICES Document CM 2006/ACFM: 09.
- ICES. 2006b. Report of the Working Group on the Assessment of Southern Shelf Stocks of Hake, Monk and Megrin (WGHMM). ICES Document CM 2006/ACFM: 29.
- ICES. 2006c. Report of the Working Group on the Assessment of Northern Shelf Demersal Stocks (WGNSSD). ICES Document CM 2006/ACFM: 30.
- ICES. 2006d. Workshop on Biological Reference Points for Northeast Arctic Haddock. ICES Document CM 2006/ACFM: 19.
- Jennings, S. 2004. The ecosystem approach to fishery management: a significant step towards sustainable use of the marine environment? *Marine Ecology Progress Series*, 274: 279–282.
- Johnston, S. J., and Butterworth, D. S. 2005. The evolution of operational management procedures for the South African west coast rock lobster fishery. *New Zealand Journal of Marine and Freshwater Research*, 39: 687–702.
- Kell, L. T., De Oliveira, J. A. A., Punt, A. E., McAllister, M. K., and Kuikka, S. 2006a. Operational Management Procedures: an introduction to the use of evaluation frameworks. *In* *The Knowledge Base for Fisheries Management*, pp. 379–407. Ed. by L. Motos, and D. C. Wilson. Elsevier, Amsterdam.
- Kell, L. T., Pastoors, M. A., Scott, R. D., Smith, M. T., Van Beek, F. A., O'Brien, C. M., and Pilling, G. M. 2005a. Evaluation of multiple management objectives for Northeast Atlantic flatfish stocks: sustainability vs. stability of yield. *ICES Journal of Marine Science*, 62: 1104–1117.
- Kell, L. T., Pilling, G. M., Kirkwood, G. P., Pastoors, M., Mesnil, B., Korsbrekke, K., Abaunza, P. *et al.* 2005b. An evaluation of the implicit management procedure used for some ICES roundfish stocks. *ICES Journal of Marine Science*, 62: 750–759.
- Kell, L. T., Pilling, G. M., Kirkwood, G. P., Pastoors, M. A., Mesnil, B., Korsbrekke, K., Abaunza, P. *et al.* 2006b. An evaluation of multi-annual management strategies for ICES roundfish stocks. *ICES Journal of Marine Science*, 63: 12–24.
- Method, R. 2005. User manual for the assessment program Stock Synthesis 2: Model Version 1.19. NOAA Fisheries, Northwest Fisheries Science Center, Seattle, WA, 47 pp.
- Michielsens, C. G. J., McAllister, M. K., Kuikka, S., Pakarinen, T., Karlsson, L., Romakkaniemi, A., Perä, I. *et al.* 2006. A Bayesian state-space mark-recapture model to estimate fishing mortality rates within a mixed stock fishery. *Canadian Journal of Fisheries and Aquatic Sciences*, 63: 321–334.
- Patterson, K. R., and Melvin, G. D. 1996. Integrated catch at age analysis, Version 1.2. *Scottish Fisheries Research Report*, 58. 60 pp.
- Pauly, D., Christensen, V., Guénette, S., Pitcher, T. J., Sumaila, U. R., Walters, C. J., Watson, R. *et al.* 2002. Towards sustainability in world fisheries. *Nature*, 418: 689–695.
- Peterman, R. M. 2004. Possible solutions to some challenges facing fisheries scientists and managers. *ICES Journal of Marine Science*, 61: 1331–1343.
- Porch, C. E., Eklund, A.-M., and Scott, G. P. 2006. A catch-free stock assessment model with application to goliath grouper (*Epinephelus itajara*) off southern Florida. *Fishery Bulletin US*, 104: 89–101.
- Punt, A. E. 2006. The FAO Precautionary Approach after almost 10 years: have we progressed towards implementing simulation-tested feedback-control management systems for fisheries management? *Natural Resource Modeling*, 19: 441–464.
- Punt, A. E., and Butterworth, D. S. 1995. The effects of future consumption by the Cape fur seal on catches and catch rates of the Cape hakes. 4. Modelling the biological interaction between Cape fur seals (*Arctocephalus pusillus pusillus*) and Cape hakes (*Merluccius capensis* and *M. paradoxus*). *South African Journal of Marine Science*, 16: 255–285.
- Punt, A. E., and Smith, A. D. M. 1999. Harvest strategy evaluation for the eastern stock of gemfish (*Rexea solandri*). *ICES Journal of Marine Science*, 56: 860–875.
- Punt, A. E., Pribac, F., Taylor, B. L., and Walker, T. I. 2005. Harvest strategy evaluation for school and gummy shark. *Journal of Northwest Atlantic Fisheries Science* (Online) 35, art. 18: 22 <<http://journal.nafo.int/35/18-punt.html>> (Accessed 6 January 2006).
- R Development Core Team. 2006. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. <http://www.r-project.org/>.
- Roel, B. A., O'Brien, C. M., and Basson, M. 2004. Management options for the Blackwater herring, a local spring-spawning stock in the Thames Estuary. *ICES Journal of Marine Science*, 61: 297–307.
- Rosenberg, A. A., and Restrepo, V. R. 1994. Uncertainty and risk evaluation in stock assessment advice for US marine fisheries. *Canadian Journal of Fisheries and Aquatic Sciences*, 51: 2715–2720.
- Sainsbury, K. J., Campbell, R. A., Lindholm, R., and Whitelaw, A. W. 1997. Experimental management of an Australian multispecies fishery: examining the possibility of trawl-induced habitat modification. *In* *Global Trends: Fisheries Management*, pp. 107–112. Ed. by E. K. Pikitch, D. D. Huppert, and M. P. Sissenwine. American Fisheries Society Symposium, 20.
- Sainsbury, K. J., Punt, A. E., and Smith, A. D. M. 2000. Design of operational management strategies for achieving fishery ecosystem objectives. *ICES Journal of Marine Science*, 57: 731–741.
- Shepherd, J. G. 1999. Extended survivors analysis: an improved method for the analysis of catch-at-age data and abundance indices. *ICES Journal of Marine Science*, 56: 584–591.
- Sinclair, M., Arnason, R., Csirke, J., Karnicki, Z., Sigurjonasson, J., Skjoldal, H. R., and Valdimarsson, G. 2002. Responsible fisheries in the marine ecosystem. *Fisheries Research*, 58: 255–265.
- Sissenwine, M. P., and Murawski, S. 2004. Moving beyond “intelligent tinkering”: advancing an ecosystem approach to fisheries. *Marine Ecology Progress Series*, 274: 291–295.
- Sparre, P. 1991. Introduction to multispecies virtual population analysis. *ICES Marine Science Symposia*, 193: 12–21.
- Tuck, G. N., Sainsbury, K., and Williams, R. 2003. Abundance estimation and TAC setting for Patagonian toothfish (*Dissostichus eleginoides*) at Macquarie Island: a synopsis. Unpublished Paper presented to 1 May 2003 meeting of the Sub-Antarctic Fisheries Assessment Group, SAFAG17, Agenda 5. 16 pp.
- Wilson, D. C., and Hegland, T. J. 2005. An Analysis of Some Institutional Aspects of Science in Support of the Common Fisheries Policy. Project Report for Policy and Knowledge in Fisheries Management. CEC 5th Framework Programme No. Q5RS-2001-01782. Institute for Fisheries Management, Publication, 126.
- Zeh, J. E., and Punt, A. E. 2005. Updated 1978–2001 abundance estimates and their correlations for the Bering–Chukchi–Beaufort Seas stock of bowhead whales. *Journal of Cetacean Research and Management*, 7: 169–175.