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

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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 is more easily validated and evaluated, as well as becoming widely available once developed. In particular, the framework details how to implement and link a variety of fishery, biological and economic software 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 extensibility 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.

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

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## Introduction

Management of fisheries increasingly embodies multiple and often conflicting biological, ecological, economic and social objectives and despite constant efforts to regulate fisheries by regional management bodies and national governments, fishing capacity often remains above that necessary to sustainably exploit marine resources, especially in developed countries. This failure has been

analysed in depth during the last 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). However, while the need to develop alternative novel management strategies is widely recognised, it is almost impossible to develop these by conducting large-scale experiments on fish stocks, with the notable exception 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 International Whaling Commission (IWC; Hammond and Donovan, in press; Kirkwood) and is also 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; Campbell and Dowling, 2005; Tuck *et al.*, 2003; Punt *et al.*, 2005; Dichmont *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, b, 2006), uncertainties in fish stock assessment and management can be categorised 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 - arises when estimating parameters of the various 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 - because the effects of management actions may differ from those intended.

In reality many of these error types are interdependent and the total uncertainty cannot always be decomposed in the constituting types. It is therefore not enough to identify the sources of error; their complex interactive relationships should be understood as well and for which simulation is an important tool. Simulation can be used to generate data, conditional on a given model or models, for use by an estimation procedure to evaluate the accuracy and precision of model estimates and to determine robustness to model misspecification and sensitivity to changes in the input data. 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 can not 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 also 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 another. Hilborn (2003) forecasts the end of such a treadmill and the increased use of Management Strategy Evaluation (MSE) where instead 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, since the objective is to develop strategies that are robust to our uncertainty about the "true" dynamics and hence meet the requirements of the precautionary approach to fisheries management adopted by FAO (1996). Therefore there has been a trend towards Management Strategy Evaluation (MSE) which 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<sup>1</sup>, Butterworth *et al.*, 1997) where 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 which was actually tested the results are still applicable.

However, Butterworth and Punt (1999) noted that the lack of any general software packages was a major impediment to the wider use of MSE. Therefore the FLR (Fisheries Library in R) open source framework was developed, in order 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, the 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 higher 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 the data collection through stock assessment to the management implementation. The MP may be based on the 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, (iii) a predefined set of management actions according to some specified rules (e.g., harvest control rule or HCR) that take 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 European Union's Common Fisheries Policy is to set the total allowable catch (TAC) to control fishing mortality. However reported catches are also one of the main sources of data for providing scientific advice, this means 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, a large, coherent, integrated collection of statistical, mathematical and graphical tools for data analysis. The term "environment" is intended to characterise 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 is intended to allow exploratory data analyses, implement alternative stock assessment methods (including the incorporation of existing methods written in Fortran and C/C++) and management

procedures (including testing of HCR for working groups; ICES, 2006abcd) and develop and condition operating models on a variety of data and hypotheses. Economic and ecosystem models are currently being incorporated into the framework to allow the better evaluation of management strategies for mixed multi-species fisheries.

FLR like R is an open-source project licensed under the GNU General Public License (<http://www.gnu.org/licenses/licenses.html#GPL>). The source code is freely available and scientists can check and validate the implementation of methods, the computations carried out and assumptions made; which constitutes an implicit peers' review process. Code sharing also speeds up the scientific process. Sharing a wide set of tools for data analysis, scientists can focus on the real issues instead of "reinventing the wheel", i.e. rewriting specific software which was already developed by someone else.

The FLR framework is implemented using object-oriented 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 representing 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 summarise and operate on them. FLQuant has five dimensions

in version 1 and six in versions 2.0 and greater. 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, vessel class etc. 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 male/female etc. while *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 like 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 how 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 *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.

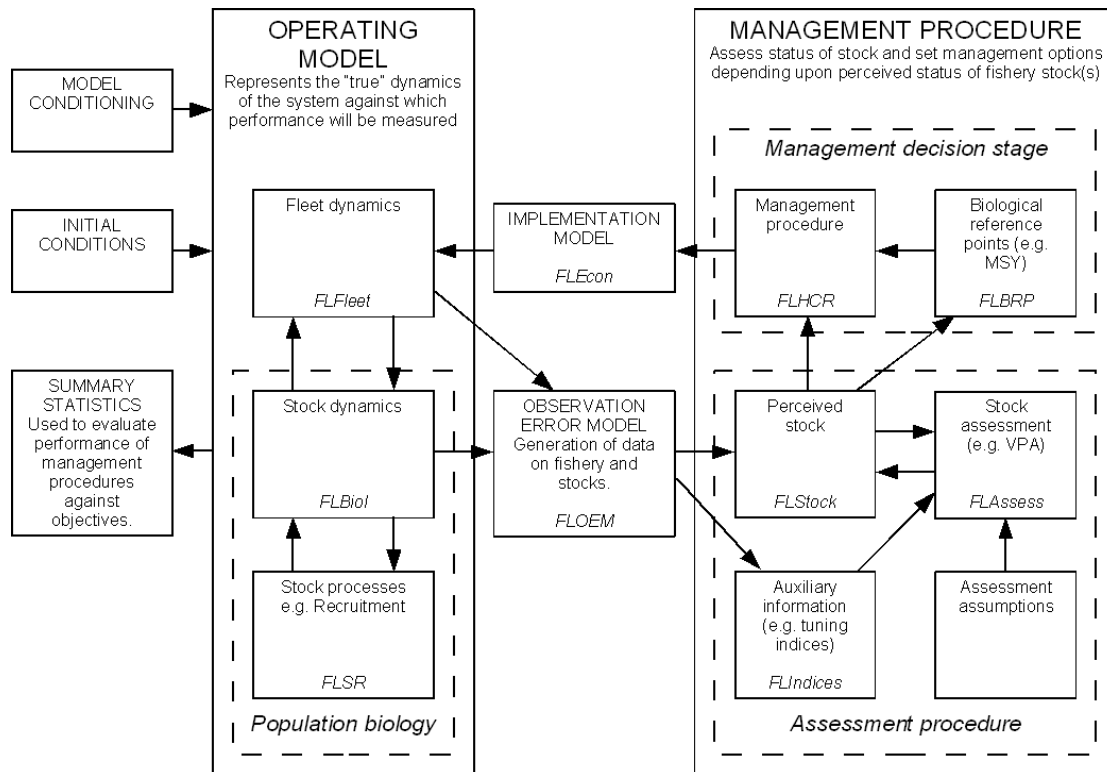


Figure 1. The conceptual framework and how it is mapped into FLR classes

Full details of FLR packages can be found on the FLR web site (<http://www.flr-project.org/>), this list will be continually updated with latest information and links to documentation and examples. As we can only see the world through the data that we collect, observations 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 as modified by FLOE, and the FLIndex class to model indices of abundance (e.g., cpue from fleets or surveys). Stock assessment is carried out using the FLAssess package, which provides classes for data input, diagnostic 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 data generated by the observation error model would be used directly by the HCR. Several classes are available to assist in implementing a harvest control rule, including a class for performing a short-term forecast (FLSTF) and a class to calculate biological reference points (FLBRP). The results of the HCR are fed back into the OM. However, in the real world 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 which 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 due to fleet adaptation, learning or as a response to economic constraints. Such responses are motivated by economic factors (i.e. profits) and therefore considering economic incentives provide a means of estimating how fishers may respond to changes in the natural,

economic and regulatory environment that they operate within. 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 as well as the effects of prices and costs (e.g. 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 the available data so that model predictions and the data are consistent (Zeh and Punt, 2005). Alternative OMs should be constructed based upon 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 differs 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 the types.

I. The OM mimicks the current stock assessment model, implying that the assessment model describes the "true" dynamics almost perfectly. This approach has arguably the lowest demands for knowledge and data.

II. The OM represents all of the 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 needs not 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 upon 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 *a priori* information and expert beliefs about the processes that may affect the management system in the future (i.e. the focus is on the future, not on fitting historical data). Consequently, the OM must be flexible so that they can deal with a range of factors.

Although standard statistical techniques allow one to assess performance, the Bayesian approach allows us to also assign prior degrees of belief in parameters, processes and models for which we have information, be it expert or derived from meta-analyses. Therefore the FLBayes package is being developed, which is intended to be a generic tool for Bayesian estimation, and implements a class specific to the storing 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 people to import such Markov chains from other external estimation schemes, BUGS for example, for use in management simulations. The sixth dimension in the FLQuant is where the Monte Carlo samples resulting from the simulations are stored, allowing us to make inference on important stock and fishery quantities. In the 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 since, although it is seldom possible to predict the response of fish populations to management with any great degree of accuracy, it is possible to work out, what strategies will on average work best, i.e. what 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 management measures, fleet, fisheries-based 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 allow "what if" questions to be answered.

By using R and adopting an open source license and development model, FLR is intended to improve transparency, scientific review and encourage active participation and to blur the distinction between developers and users by allowing participation in the development process.

This is important since management of fisheries requires collaboration between disciplines, e.g. biological and economic since 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 on 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 the two alternative management measure would be very different. Particularly since if a policy sends a fleet bankrupt, then it is unlikely to get implemented in law or practice due respectively to political pressure or non-compliance.

Enforcement costs are also significant and so the benefits of a policy may not outweigh the costs. There is therefore an increasing need to build bio-economic models to perform both 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 and the value of forgone yield due to bad management. This approach has success fully been used for small stocks, for example, the Blackwater herring (Roel et al ?), which enabled assessment and management costs to be reduced and for the stock to achieve Marine Stewardship Council certification ([www.msc.org](http://www.msc.org)).

There are two main areas where FLR is or is intended to be applied within an ecosystem context a) testing the robustness of simple assessment/management rules given that species interactions are occurring and b) 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 multi-species models i) structural uncertainty e.g. aggregation in the food web; 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 describe the response of individual species to management, and even when data are available, our knowledge of the functional form and precise dynamics of the relationships among species limits our ability to use them in models to provide management advice directly. Therefore the importance of such models will allow 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 multi-species modelling i.e.

- "Minimum Realistic Modeling" (Punt and Butterworth 1995), e.g. adding complexity in a piece meal 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 food web, 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 used to improve existing single-species models, while

"Big Picture" type models have been used mainly for the exploration or evaluation of hypotheses. It is envisaged that in the 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 complexities sake.

For example Multi-species models may also be used to test the robustness of simpler assessment/management rules before implementation, in particular for species and fisheries where 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 MSE has been applied to evaluate the performance of state indicators in an Australian fishery, where Fulton et al. (2004a, b and 2005) used a relatively complex deterministic model to describe ecosystem dynamics. They 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 fishing combined with other activities. The performance of indicators derived from the data was assessed in terms of the indicators capacity 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.

A similar system is to be evaluated using FLR in order to develop an EA in the North Sea which will benefit from a relatively good understanding of biological processes and a variety of models

already developed in FLR. This is therefore thought to be an ideal system in which to test the implementation of an EA based on indicator systems. It will also allow us to assess how effectively management could 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, ultimately the aim is to improve the quality of management. Importantly, the MSE approach is intended to do so, not by making it 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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#### References

Economic Assessment of European Fisheries. 2006. Economic Performance of Selected Fishing Fleets. Annual Report 2005. STECF, SGECA, European Commission. 306 pp. (available online <http://stecf.jrc.cec.eu.int/sgeca/eaef/2005-final.pdf>)

Aydin, K. Y., and Gaichas, S. K. 2006. In defense of complexity: Towards a representation of uncertainty in multispecies models. International Whaling Commission, Scientific Committee Paper No. SC/58/E48.

Bosford, 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*. Ed. by Smith, S.J., Hunt, J.J. and Rivard, D. Canadian Special Publication of Fisheries and Aquatic Sciences, 120: 83-99.

Butterworth, D. S., and Punt, A. E. 1999. Experiences in the evaluation and interpretation of MPs. In *Confronting Uncertainty in the Evaluation and Implementation of Fisheries-Management Systems*. Ed. by A.I.L. Payne. *ICES Journal of Marine Science*, 56: 985-998.

Butterworth, D. S., Cochrane, K. L., and De Oliveira, J. A. A. 1997. MPs: a better way to manage fisheries? The South African experience. In *Global Trends: Fisheries Management*. Ed. by E. K. Pikitch, D. D. Huppert, and M. P. Sissenwine. *American Fisheries Society Symposia*, 20: 83-90.

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. Ed. by Kruse, G. H., Gallucci, V. F., Hay, D. E., Perry, R. I., Peterman, R. M., Shirley, T. C., Spencer, P. D., Wilson, B. and Woodby, D. Alaska Sea Grant College Program Report No. 05-02, pp. 509-532. University of Alaska, Fairbanks.

Chambers, J. M. 2000. Programming with data. Wiley, New York.

Christensen, V., Walters, C., and Pauly, D. 2005. Ecopath with Eco-sim: A User's Guide. Fisheries Centre, University of British Columbia, Vancouver. November 2005 edition, 154 pp. (available online 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, 165pp.

FAO. 1996. Precautionary approach to capture fisheries and species introductions. *FAO Technical Guidelines for Responsible Fisheries*. No.2. FAO, Rome. (available online <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 fo fisheries stock assessment, with application to south Pacific albacore, *Thunnus alalunga*. *Canadian Journal of Fisheries and Aquatic Science*, 55: 2105-2116.

Francis, R. I. C. C., and Shotton, R. 1997. 'Risk' in fisheries management: a review. *Canadian Journal of Fisheries and Aquatic Science*, 54: 1699-1715.

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.

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.

Garcia, S., and de Leiva Moreno, I. 2003. Global overview of marine fisheries. In Responsible fisheries in the marine ecosystem. Ed. by M. Sinclair and G. Valdimarsson. FAO, Rome & CABI publishing, Wallingford, UK, pp. 1-24.

Geromont, H. F., De Oliveira, J. A. A., Johnston, S. J. and Cunningham, C. L. 1999. Development and application of MPs 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. et al. 2006. Incentive-based approaches to sustainable fisheries. Canadian Journal of Fisheries and Aquatic Science, 63: 699-710.

Hammond, P. S., and Donovan, G. P. In press. Development of the IWC Revised Management Procedure. *Journal of Cetacean Research and Management*, Special Edition 4.

Hilborn, R. 2003. The state of the art in stock assessment: where we are and where we are going. *Scientia Marina*, 67 (Supplement 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. 2004. Report of the Working Group on Methods of Fish Stock Assessments. ICES Document CM 2004/D:03 Ref. G, ACFM

ICES. 2006a. Working Group on the Assessment of Demersal Stocks in the North Sea and Skagerrak (WGNSSK). ICES 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 CM 2006/ACFM:29

ICES. 2006c. Report of the Working Group on the Assessment of Northern Shelf Demersal Stocks (WGNSSD). ICES CM 2006/ACFM:30

ICES. 2006d. Workshop on Biological Reference Points for Northeast Arctic Haddock. ICES 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., 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., Aps, R., Biseau, A., Kunzlik, P., Needle, C., Roel, B. A., and Ulrich-Rescan, C. 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., Mesnil, B., Korsbrekke, K., Abaunza, P., Aps, R., Biseau, A., Kunzlik, P., Needle, C., Roel, B. A., and Ulrich-Rescan, C. 2006. An evaluation of multi-annual management strategies for ICES roundfish stocks. *ICES Journal of Marine Science*, 63: 12-24.

Kell, L. T., De Oliveira, J. A., Punt, A., McAllister, M., and Kuikka, S. 2006. Chapter 15 - Operational Management Procedures: An Introduction to the Use of Evaluation Frameworks. In *The Knowledge Base for Fisheries Management*. Ed. by L. Motos and D. C. Wilson. Amsterdam: Elsevier.

Kirkwood, G. P., and Smith, A. D. M. 1996. Assessing the precautionary nature of fishery management strategies. In *Precautionary Approach to Fisheries, Part 2: Scientific Papers*. FAO Fisheries Technical Paper 350/2: 141-158.

McAllister, M. K., Starr, P. J., Restrepo, V. R. and Kirkwood, G. P. 1999. Formulating quantitative methods to evaluate fishery-management systems: what fishery processes should be modelled and what trade-offs should be made? In *Confronting Uncertainty in the Evaluation and Implementation of Fisheries-Management Systems*. Ed. by A. I. L. Payne. ICES Journal of Marine Science, 56: 900-916.

Methot, 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., and Mäntyniemi, S. 2006. A Bayesian state-space mark-recapture model to estimate fishing mortal-

ity rates within a mixed stock fishery. *Can. J. Fish. Aquat. Sci.*, 63: 321-334.

Pascoe, S., Koundouri, P., and Bjorndal, T. 2006. Estimating targeting ability in multi-species fisheries: a primal multi-output distance function approach. [To appear:] *Land Economics*.

Pastors, M., Poos, J. J., and Machiels, M. 2006. Evaluation of a proposed management plan for Northsea flatfish. FLR Project, RIVO, NL. (available online <http://flr-project.org/doku.php?id=appl:nsrac>) [accessed 08 December 2006]

Patterson, K. R., and Melvin, G. D. 1996. Integrated catch at age analysis, Version 1.2. Scottish Fisheries Research Report No. 58, 60 pp.

Pauly, D., Christensen, V., Guénette, S., Pitcher, T. J., Sumaila, U. R., Walters, C. J., Watson, R., and Zeller, D. 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*, 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.

R Development Core Team. 2006. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing. Vienna, Austria. (available online <http://www.r-project.org/>)

Ravier, C., and Fromentin, J-M. 2001. Long-term fluctuations in the eastern Atlantic and Mediterranean bluefin tuna population. ICES Journal of Marine Science, 58: 1299-1317.

Ravier, C., and Fromentin, J-M. 2004. Are the long-term fluctuations in Atlantic bluefin tuna (*Thunnus thynnus*) population related to environmental changes? Fisheries Oceanography, 13: 145-160.

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 U.S. marine fisheries. Canadian Journal of Fisheries and Aquatic Science, 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. Ed. by E. K. Pikitch, D. D. Huppert, and M. P. Sissenwine. American Fisheries Society Symposia, 20: 107-112.

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: 584e591.

Sinclair, M., Arnason, R., Csirke, J. et al. 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 multi-species virtual population analysis. *ICES Marine Science Symposia*, 193: 12-21.

Ulrich, C., Andersen, B. S., Sparre P. J., and Nielsen, J. R. 2005. TEMAS - A fleet based bioeconomic simulation software for management strategies accounting for fishers behaviour. DIFRES, Denmark.

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, 16pp.

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 No. 126.

