

A BRIEF INTRODUCTION TO SOME APPROACHES TO MULTISPECIES/ECOSYSTEM MODELLING IN THE CONTEXT OF THEIR POSSIBLE APPLICATION IN THE MANAGEMENT OF SOUTH AFRICAN FISHERIES

*D. S. BUTTERWORTH** and *É. E. PLAGÁNYI**

Aspects of the potential application of multispecies/ecosystem modelling to advise the management of South African fisheries are discussed. In general, reliable predictive ability from such models is likely to be achieved sooner for top predators, because relatively fewer links need to be modelled. Accordingly, discussion concentrates on the deliberations of scientific workshops on modelling marine mammal – fisheries interactions held by two international marine mammal commissions during 2002. Five questions are posed, and some responses suggested, relating to the development of a framework for multispecies/ecosystem modelling to contribute to South African fisheries management: (1) should such models be used for testing or making decisions; (2) do they appreciably reduce uncertainties associated with single-species models; (3) are whole ecosystem or minimum realistic models more appropriate; (4) what computer software is best suited to implement such approaches; (5) what are the overall cost implications? Caution is expressed that general scientific acceptance of predictive reliability for such models (as required for their use for management) is unlikely in the short term, and will probably require considerable data collection and complex analysis at not insubstantial cost.

Key words: ecosystem, fisheries, management, minimum realistic model, multispecies, OMP, operating model

The workshop on ecosystems modelling approaches for South African fisheries management, at which this paper was first presented, had two objectives (Shannon *et al.* 2004a):

- (1) to introduce the concept of ecosystem-based fisheries management to South African fisheries scientists and to present modelling tools to achieve this, in particular the ECOPATH/ECOSIM (Polovina 1984, Christensen and Pauly 1992, Walters *et al.* 1997, 1999) approach; and
- (2) to propose a framework of practical ways in which the incorporation of ecosystem considerations (potentially using information from ECOPATH/ECOSIM and other approaches to multispecies modelling) into current Operational Management Procedures (OMPs) and other management strategies for South Africa's marine resources could be attempted.

By way of explanation, an OMP is the combination of a prescribed set of data to be collected and the analysis procedure to be applied to such data, to provide a scientific recommendation for a management measure, such as a Total Allowable Catch (TAC), for a resource (Butterworth *et al.* 1997, Butterworth and Punt 1999, Cooke 1999). A key aspect of the OMP approach

is that the analysis procedure has been tested across a wide range of scenarios for the underlying dynamics of the resource using computer simulation. This is to ensure that the likely performance of the OMP, in terms of attributes such as (high) expected catch and (low) risk of unintended depletion, is reasonably robust to the primary uncertainties about such dynamics. This approach is used at present to manage South Africa's three most valuable fisheries: those for Cape hake *Merluccius capensis* and *M. paradoxus*, for sardine *Sardinops sagax* and anchovy *Engraulis encrasicolus*, and for West Coast rock lobster *Jasus lalandii* (Germont *et al.* 1999).

This paper seeks to provide an introduction to Objective 1 above. It begins by clarifying the different roles played by models in the OMP approach, and raises questions about the costs of the data collection (in particular) needed to apply a multispecies modelling approach in South African fisheries management. It then summarizes the deliberations of workshops held by the Scientific Committees of two international marine mammal commissions during 2002 on the subject of applying multispecies/ecosystem approaches to provide management advice (North Atlantic Marine Mammal Commission 2003, International Whaling Commission 2004a). This leads to the identification of

* MARAM (Marine Resource Assessment and Management Group), Department of Mathematics and Applied Mathematics, University of Cape Town, Rondebosch 7701, South Africa. E-mail: dll@maths.uct.ac.za

five questions relating to the framework envisaged in Objective 2 above to incorporate ecosystem considerations in the management of South African fisheries.

ROLES FOR MODELS IN OMPs: TESTING vs DECISION

Models play two very different roles in the process of developing and implementing OMPs.

“*Decision Models*” essentially integrate information available from monitoring a resource (e.g. *cpue*, survey indices of abundance) together with a control rule to provide a scientific recommendation for management such as a *TAC*. Typically, these are simple population models, fitted to data that indicate trends in abundance, which seek to provide “feedback correction” (e.g. if future data indicate a downward trend in abundance, the *TAC* is reduced to attempt to arrest and reverse this trend). Some decision models are even simpler than this. For example, the annual *TAC* for the South African directed sardine fishery is set as a fixed proportion of the hydroacoustic estimate of abundance forthcoming from an annual spawning biomass survey, where computer simulation testing was used to advise the choice of the specific proportion set (De Oliveira *et al.* 1998, Geromont *et al.* 1999).

Decision models are not intended necessarily to provide an accurate representation of the possible underlying resource dynamics. Rather, the basis for their choice is that computer simulation tests show them to be likely to provide robust achievement of the objectives sought by the management authority.

In contrast, “*Testing Models*” (which are often termed “*Operating Models*”) do seek to reflect accurately alternative possibilities for the true underlying dynamics of the resource or resources under consideration. They may seek a high degree of realism, and hence may be quite complex (e.g. International Whaling Commission 2003). The role of these testing models is to provide the basis for computer simulations to project resource trends into the future to test how well alternative candidate decision models achieve the objectives sought by the management authority.

What potential role do multispecies/ecosystem models have as decision and as testing models? We suspect that it will be many years before such models might be used as decision models for OMPs, primarily because of the uncertainty surrounding appropriate choices for the numerous parameter values and the functional forms to describe species interactions, as discussed below. Rather it seems that testing models are the more appropriate level at which multispecies/ecosystem models might first be used under the

OMP approach. To date, such implementation in OMP evaluation exercises generally has been implicit only. For example, in the computer simulation testing of its Revised Management Procedure, the Scientific Committee of the International Whaling Commission (IWC) did not develop testing models with multiple interacting species; instead it allowed for time-dependence in the intrinsic growth rate and carrying capacity parameters of the testing model for the population under harvest, to mimic the typical impacts on that population of changing levels of other predator and prey species (International Whaling Commission 1989).

COSTS

Some caution is appropriate before decisions might be taken to advocate greatly enhanced multispecies/ecosystem modelling efforts to contribute to South African fisheries management. Single-species models rely primarily on time-series of catches and abundance indices for the population concerned. Multispecies models require in addition not only dietary information for that population, but also abundance and dietary data for its major predators and prey. This can add substantially to research and monitoring costs, and this needs to be justified by likely resultant improvements to management advice.

A review of stock assessment needs for fisheries in the USA (NMFS 2001) provides some figures that assist in placing this aspect in perspective. By way of background, in 1999 a US National Marine Fisheries Service Report to Congress on the Status of Fisheries (NMFS 1999) listed 904 marine stocks, but information sufficient to assess status is available for only some 40% of these. Only 119 of these US stocks are routinely assessed at the state-of-the-art single-species level, although this group does include most species of high value, volume or profile.

NMFS (2001) identify further research vessel surveys and observer programmes as the two most important needs to enhance scientific advice for fisheries management in the USA. For a balanced overall approach, they group the areas requiring further resources into three categories, with the following increases required to the present US fisheries research budget:

- (i) improve stock assessments using existing data – 11%;
- (ii) elevate stock assessments to new national standards of excellence – 32%;
- (iii) next generation assessments – 25%.

Such an overall 68% budget increase corresponds to

some US \$90 million per year¹. It is only the “next generation” assessments that are envisaged to “explicitly incorporate ecosystem considerations such as multispecies interactions and environmental effects, fisheries oceanography, and spatial and seasonal analyses” (NMFS 2001, p. 2). The budget estimates above assume that this would be attempted only for “core species” – of the order of 20–40 stocks for the USA as a whole.

Coarsely comparing South African to US fisheries, one would be dealing with approaching an order of magnitude fewer stocks, and costs are lower. However, even taking these factors into account, the figures above suggest that full incorporation of ecosystem considerations into the assessment and management of, for example, the half dozen or so most important South African fisheries could entail additional annual research costs of the order of a few tens of millions of Rands, the local currency worth around US\$6.5 in 2004.

Clearly, therefore, research priorities in this area need to be carefully and realistically chosen, and weighed against other research needs, such as the extra research vessel surveys and enhanced observer programmes stressed by NMFS (2001), for improved management of South African fisheries. Nevertheless, these priorities also need to be assessed in the light of various policy obligations, by South Africa and other nations, to broaden the current focus on target stocks to include consideration of the ecosystem effects of fishing (Gislason *et al.* 2000).

POINTERS FROM MARINE MAMMAL COMMISSION WORKSHOPS

Why the current focus on marine mammals?

Two international marine mammal Commissions held workshops on multispecies/ecosystem modelling during 2002 (see National Atlantic Marine Mammal Commission 2003, International Whaling Commission 2004a). These were not the first scientific meetings that have been held to consider how multispecies modelling might inform fisheries management advice concerning marine mammal–fisheries interactions. For example, earlier meetings were held to discuss interactions between fur seals *Arctocephalus pusillus pusillus* and fisheries off South Africa (Butterworth and Harwood

1991), and between harp seals *Phoca groenlandica* and fisheries off eastern Canada (Anon. 1997). The question needs to be asked: why this seemingly sudden rekindling of interest in this topic? Two reasons spring to mind, though there are likely others. The first is estimates by Tamura (2003) that annual prey consumption by cetaceans worldwide is about 3–5 times the ± 80 million ton annual harvest by marine capture fisheries. The trend in this harvest has levelled over recent years, whereas demand for fish products is projected to grow (FAO 2002). As a result, some fisheries managers have raised the issue of appropriate management strategies for marine mammal populations (and specifically their abundances) if these animals are in effect in competition with fishers and hence limiting potential sustainable harvests from fisheries. Such issues can be addressed only with reliable multispecies models.

The second obvious reason is a widespread call for more account to be taken of ecosystem aspects in the formulation of recommendations for fisheries management (see FAO 2003). Multispecies/ecosystem models with reliable predictive ability are one key requirement for achieving this goal (as far as taking appropriate account of biological interactions between species is concerned), and such ability seems likely to be achieved sooner for top predators than for species intermediate in the food chain, because of the lesser number of linkages that apply to the former (Butterworth and Punt 2003). Stated another way: until scientists’ abilities have developed sufficiently to provide quantitatively reliable predictive multispecies models for marine mammal–fisheries interactions, can one realistically expect such ability to be achieved for more general multispecies interaction scenarios in fisheries?

Characterization of approaches

Both workshops mentioned above reviewed the variety of approaches that have been used for multispecies/ecosystem modelling. These may be conveniently separated into two groups.

WHOLE ECOSYSTEM MODELS

Such approaches attempt to take all trophic levels in the ecosystem into account, from primary producers to top predators. Quite sweeping simplifications and assumptions may need to be made in this process. An example is the ECOPATH with ECOSIM (EwE) framework, which is usually applied in this manner. Details of EwE may be found in Walters *et al.* (1997, 1999) and Christensen and Walters (2000, 2004).

¹ These figures relate to staffing and minor associated infrastructure needs only. If other costs such as vessel time and major infrastructure are added, the US\$90 million quoted virtually doubles (P. Mace, National Marine Fisheries Service, pers. comm.)

Table I: Important issues in the further consideration of ecosystem interactions between fish stocks and cetaceans, as identified by an IWC Workshop held in July 2002 (International Whaling Commission 2004a)

-
-
- All of the modelling approaches available thus far (and developed in the future) must explicitly allow for uncertainty in all aspects of their use, including model specification and assumptions
 - Existing models should be used to determine data requirements in terms of quality and quantity
 - The simulation approaches in terms of accounting for uncertainty used in the Revised Management Procedure/Aboriginal Whaling Management Procedure development should be considered
 - Modelling approaches should include consideration of how they might be validated
 - Consideration should be given to the possibility of establishing a relatively complex “virtual” ecosystem for testing approaches
 - Modelling approaches should try taking into account the effects of short-, medium- and long-term ecosystem changes
 - Models must be flexible/expanded to take into account the nature of competition, functional responses, etc.
 - Fisheries must be modelled realistically, particularly in taking into account uncertainty in data; the level of detail and realism required for reasonable single-species management may be insufficient for multispecies analyses
 - Further work on field methodology is required to improve data quality and availability for all aspects of systems, including abundance/production of species that are not fishery targets, etc.; links between models and data requirements should be followed up in terms of sensitivity, power analysis, etc.
 - Attention should be focused on specific areas/systems where there is most chance of success
-

MINIMUM REALISTIC MODELS

The Minimum Realistic Model (MRM) terminology was coined at a workshop held in Cape Town in 1991 to develop a basis to evaluate fur seal–fishery interactions off the west coast of South Africa (Butterworth and Harwood 1991). The underlying concept is to restrict the model developed to those species most likely to have important interactions with the species of interest. In this case, concern centred on the potential effect of seals on the Cape hake resource (commercially South Africa’s most valuable). The model that was subsequently implemented (Punt and Butterworth 1995) was restricted to the two species constituting the hake resource, seals, a grouped category of large predatory fish, and the Cape hake fishery. Together these were estimated to account for more than 90% of all mortality of Cape hake.

The MULTSPEC model of the major fish and marine mammal species in the Barents Sea (Bogstad *et al.* 1997) is also of the MRM type, as is multispecies virtual population analysis (MSVPA; Sparre 1991, Magnusson 1995), which has been widely applied to species in the North Sea in particular, and its derivatives that project into the future (e.g. Vinther 2001). MSVPA is an extension of VPA, which assesses historical population size by summing catches made from different cohorts (year-classes), while making allowance for losses to natural mortality M , usually under the assumption that M is constant. The extension to MSVPA accounts for estimated levels of consumption by major predators in computing these losses to natural mortality, and has led to the important insight that M is typically much higher during the earliest years of a fish’s life (Pope 1991).

The specification of an MRM raises the important question: what is the optimal level of complexity for multispecies models? Reducing the number of species considered, or aggregating similar species into groups, reduces the number of inter-species links that need to be modelled, but consequently also reduces the number of weak links included in the model. Yodzis (1998) used a foodweb model of the Benguela ecosystem to show that the exclusion of feeding links representing <10% of consumption both by and of any species had minimal effect on model predictions, but that above this threshold for linkage strength, the model predictions start to become unreliable.

Summary views

Table I provides a list of issues considered important for further work on cetacean–fisheries interactions by the IWC Workshop. Table II enumerates desirable features of multispecies modelling approaches as identified by the National Atlantic Marine Mammal Commission (NAMMCO) Workshop in 2002.

Important common concerns evident are:

- The need to pay more attention to the implications of uncertainties (including bias and imprecision) in available data and model structure assumptions.
- More specifically, the need to examine the implications of alternative ways of modelling the interactions between species.

Both workshops stressed that those implementing multispecies/ecosystem models need to have a good understanding of the assumptions underlying their models. This is because it is important to assess

Table II: Desirable general features of multispecies modelling approaches for analysing marine mammal–fisheries interactions, as identified by a NAMMCO Workshop held in September, 2002 (North Atlantic Marine Mammal Commission 2003)

- Flexibility of functions for prey selection that can be manipulated by the modeller
- Flexibility of age-structuring, from fully age-structured to fully aggregated
- Accessible source code and transparency of operation – the model must not be a “black box”
- Able to be tailored to the area and species of interest, rather than generic
- Model interactions accounting for most of the natural mortality of the fish species of concern
- Spatial and temporal resolution tailored to the target species, with flexibility for changing resolution
- Uncertainty in data and model structure is reflected in the results

whether the assumptions of a model are appropriate to the case under consideration. Different assumptions (concerning interactions in particular) can frequently yield appreciably different predictions of future resource trends under a particular management strategy. Research then needs to be focused on discriminating between those assumptions that give rise to the greatest differences.

As an example of the potential importance of how multispecies interaction terms are modelled, contrast the assumptions of the MSVPA (and its associated derivatives that provide projections) and ECOSIM approaches, which may be categorized as “efficient predator models” and “hungry predator models” respectively. MSVPA assumes that a predator is always able to consume its desired daily ration of food. If N_j is the number of predators of species j , and the number of their prey species i (N_i) is kept fixed, then Figure 1a shows the implication of the MSVPA assumption for how the total consumption rate Q_{ij} of prey i by predator j grows as the number of predators increases: linear proportionality.

ECOSIM on the other hand is based upon the foraging arena model (Walters *et al.* 1997), whereby a predator competes with others of the same species for a limited proportion of the prey population that are “vulnerable” to be consumed. This leads to the form of relationship between total consumption rate Q_{ij} and the number of predators N_j shown in Figure 1b: the rate saturates at a constant level for high numbers of predators.

This different functional form for interactions in the foraging arena model (*per capita* consumption by a predator decreases with the overall abundance of that

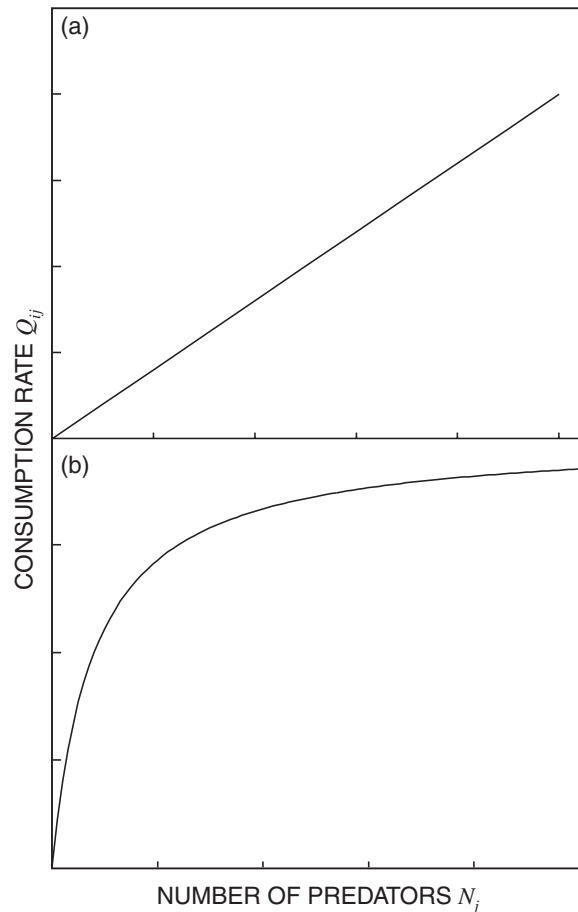


Fig. 1: Schematic showing how the total consumption rate Q_{ij} of prey species i by predator species j grows as the number of predators increase for the two contrasted cases – (a) MSVPA (and its derivatives providing projections) showing a linear proportionality relationship, (b) ECOSIM’s foraging arena-based model in which the total rate saturates at a constant level for high numbers of predators

predator) compared with the constant ration model (*per capita* consumption is set equal to the predator’s required daily ration) for predator feeding has important implications for model behaviour and predictions. The foraging arena model tends (desirably) to dampen the large amplitude oscillations in population size frequently predicted by multispecies models (e.g. Mori and Butterworth 2004). More problematically, however, if predator numbers are initially high and then

for example halved, the total consumption rate by those predators will hardly change, so the consumption rate per predator doubles, leading to questionable model behaviour, as discussed further in Plagányi and Butterworth (2004). Furthermore, the predicted implications for a fishery on prey species i of a cull of (say) half the predators will clearly be very different for the two models. For the foraging arena model, the predators remaining consume virtually all the prey that the predators removed would have eaten; furthermore the increased *per capita* consumption will likely lead to enhanced reproduction and increasing predator numbers in time, so that there is hardly any scope for the fishery to benefit. However, under the constant ration model, predator consumption of prey is halved, and (in the simplest situation) the fishery can harvest the other half of what the predators previously consumed while the predators remain stable at their reduced level. Walters *et al.* (2000) advance two arguments to support the foraging arena over the constant ration model, but there appears to be little observational evidence to distinguish the two, and the International Whaling Commission (2004a) describes the biological underpinnings of the foraging arena model as “controversial and uncertain”. Clearly, therefore, evaluations to provide advice on the impact of, say, a predator cull on fisheries for prey species cannot be based on the foraging arena model alone as a representation of species interactions; rather the robustness of results across a range of plausible functional forms needs to be considered.

A further difficult issue in multispecies modelling that was raised at both workshops is that of estimating prey suitability. “Suitability” expresses the relative preference of a predator for consuming one prey species rather than another, when both prey are present in equal densities. Experimental estimates of suitability often refer only to the microscale, but multispecies models require parameter values that reflect effective responses at a macroscale level (Lindstrøm and Haug 2001). Reliable integration of microscale estimates of suitabilities over the spatiotemporal distributions for both predators and prey to provide macroscale parameter values is likely a realistic objective for the long term only; in the short term, regression approaches will probably be needed to attempt to relate macroscale changes in diet to variations in prey abundance.

Recommendations and future work

The agreed conclusion of the IWC’s Scientific Committee following discussion of the report of its work-

shop states: “for no system at present are we in the position, in terms of data availability and model development, to provide quantitative management advice on the impact of cetaceans on fisheries, or of fisheries on cetaceans. However, this does not rule out the possibility of providing qualitative advice if a number of different approaches yield qualitatively similar results” (International Whaling Commission 2004b, p. 30) Although agreeing that consideration of ecosystem interactions between fish stocks and cetaceans is a potentially important research topic, the committee disagreed whether further pursuit of the matter was likely to be helpful in providing advice to the Whaling Commission regarding the management of whale populations (International Whaling Commission 2004b). The priority of further work on the issues listed in Table I was accordingly seen to be conditional on how the Commission viewed the matter.

The conclusions of the NAMMCO Workshop (North Atlantic Marine Mammal Commission 2003) were formulated somewhat more positively. While acknowledging that lack of information on certain effects would render predictions from models subject to considerable uncertainty, the workshop nevertheless recommended further work on a MRM for the Barents Sea encompassing cod *Gadus morhua*, herring *Clupea harengus*, capelin *Mallotus villosus*, minke whales *Balaenoptera acutorostrata* and harp seals *Pagophilus groenlandicus*. Future development of this model would make use of the GADGET (Globally Applicable Area-Disaggregated Generic Ecosystem Evaluation Tool) modelling approach (<http://www.hafro.is/dst2/report2/>). Although the output from such a model was not expected to be able to predict all aspects of future states of the ecosystem, the model had potential utility for management through testing scenarios where abundances of target species are manipulated. In addition, the workshop recommended the development of a generic (or “template”) North Atlantic model, based on GADGET, and including major fish and marine mammal species. The main use of such a model was seen to be to identify the inputs that had the greatest effect on model predictions, and hence to guide research priorities in different regions, each subject to different deficiencies in data.

A FRAMEWORK FOR SOUTH AFRICA

Objective 2 of the workshop was to develop a framework to incorporate multispecies/ecosystem modelling research in South African fisheries management (particularly in an OMP context).

Arising from the issues discussed above, five questions that need to be addressed in this development are offered, together with brief associated commentary.

- (1) *In an OMP context, is the immediate role for multi-species/ecosystem models as “testing” or “decision” models?* As elaborated above, we argue that this role is as testing (operating) models.
- (2) *Do mass-balance constraints appreciably reduce uncertainty about current single-species management model estimates of abundance and productivity?* While predictive multispecies population models may have limited management impact in the short term, if only because of considerations of lack of data, model complexity and uncertainty, and research costs, there are some initiatives that might be pursued with the information that is to hand. The mass-balance relationships of the ECOPATH approach (Christensen and Pauly 1992) provide some information beyond that conventionally incorporated in single-species assessments, and do so essentially independent of concerns about how best to model the functional forms of species interactions. Considerable work in implementing ECOPATH has already been carried out for the southern African region (e.g. Shannon *et al.* 2000, 2003, 2004b, Shannon and Moloney 2004) and has been successful in identifying some data gaps and inconsistencies. Approaches based on the ECORANGER (Pauly *et al.* 2000) adjunct to ECOPATH, which takes account of imprecision in inputs to ECOPATH, could be used to determine the quantitative extent by which the precision of single-species assessment estimates might be improved through taking account of mass-balance constraints. However, care will need to be taken to reflect current estimates of imprecision in the inputs to any such analyses accurately.
- (3) *What immediate relative emphasis should be placed on Whole Ecosystem vs Minimum Realistic Model analyses?* Our view is that, until whole ecosystem approaches have been shown to demonstrate adequate robustness in their predictions to uncertainties in input data and alternative plausible choices for the functional forms of interactions between species, they should have lower priority than the development of MRMs given an aim of providing inputs to local fisheries management advice. At the very least, MRMs would seem the obvious first step to take in the process of moving from single-species models to the extremely ambitious and demanding aim of a reliable predictive model for all major ecosystem components. Given the dominance of Cape hake among local demersal

species, and the high value of the South African hake fishery, an immediate candidate for such an MRM study is hake cannibalism and interspecies predation, taking account of considerable further data that have become available since the earlier analyses of Punt and Butterworth (1995).

- (4) *What are the most appropriate analysis platforms for such exercises?* The selection here seems to lie between EwE, GADGET and *ab initio* coding. The first, which could also be tailored to implement MRMs, is readily available and has been widely applied. The appropriate choice would likely depend on the specific question being addressed, but particular weight must be given to the importance of being readily able to investigate the sensitivity of results to alternative functional forms for interactions between species. The ideal (if not always practical) scenario is one in which a plurality of approaches is applied, so that there is an opportunity for the comparative and confirmatory use of multiple MRMs (Fulton *et al.* 2003).
- (5) *What are the cost implications for data collection and analysis?* The cost estimates for multispecies assessments provided by the US study by NMFS (2001) discussed above are sobering. Clearly, costs depend on the extent of the activities proposed. However, given that population projections will likely prove highly sensitive to the functional forms chosen for species interactions, it is difficult to imagine how alternative models might be discriminated without recourse to regular dietary data-collection exercises. This is so as to be able to check how diet changes in response to changes in the relative abundances of prey species (cf the ICES “years of the stomach” for the North Sea; Rice *et al.* 1991). Such activities will not be cheap. What seems important is that careful cost estimates are made for data-collection and analysis exercises as part of the planning of research programmes to address management questions that have a multispecies/ecosystem context, so that these can be contrasted with the likely resultant improvements in management.

CONCLUDING REMARKS

Multispecies/ecosystem modelling that aims to advise fisheries management decisions is an interesting and challenging activity which needs to be pursued. However, we caution against unrealistic expectations of substantial progress towards this aim in the short and even medium term. Arguments that reliable pre-

dictive ability is most likely to first be achieved for top predators are noted above. Recent international scientific discussions of the marine mammal–fisheries interaction issue summarized above may not reflect a full spectrum of scientific views, because of the necessarily limited participation at these events; nevertheless they do make clear that there is still a long road to travel before many interested and affected parties are likely to accept that such reliability has been satisfactorily demonstrated. Considerable data collection and complex analysis over a period of several years will likely be necessary to achieve such reliability, and the associated costs will not be insubstantial.

ACKNOWLEDGEMENTS

Support for this work by the Marine & Coastal Management branch of the Department of Environmental Affairs and Tourism, and the National Antarctic Programme is gratefully acknowledged. Comments by John Harwood and Tony Smith on an earlier version of this document are gratefully acknowledged, as are clarifications from Pamela Mace concerning the NMFS Stock Assessment Improvement Plan referenced.

LITERATURE CITED

- ANON. 1997 — Harp seal–fishery interactions in the Northwest Atlantic; toward research and management actions. *International Scientific Workshop, St Johns, Newfoundland, February 1997*. Canadian Centre for Fisheries Innovation, Memorial University of Newfoundland: 41 pp.
- BOGSTAD, B., HAUGE, K. H. and Ø. ULLTANG 1997 — MULTSPEC – A multispecies model for fish and marine mammals in the Barents Sea. *J. North Atl. Fish. Sci.* **22**: 317–341.
- BUTTERWORTH, D. S., COCHRANE, K. L. and J. A. A. DE OLIVEIRA 1997 — Management procedures: a better way to manage fisheries? The South African experience. In *Global Trends: Fisheries Management*. Pikitch, E. K., Huppert, D. D. and M. P. Sissenwine (Eds). *Am. Fish. Soc. Symp.* **20**: 83–90.
- BUTTERWORTH, D. S. and J. HARWOOD (Rapps) 1991 — Report on the Benguela Ecology Programme workshop on seal–fishery biological interactions. *Rep. Benguela Ecol. Progm. S. Afr.* **22**: 65 pp.
- BUTTERWORTH, D. S. and A. E. PUNT 1999 — Experiences in the evaluation and implementation of management procedures. *ICES J. mar. Sci.* **56**: 985–998.
- BUTTERWORTH, D. S. and A. E. PUNT 2003 — The role of harvest control laws, risk and uncertainty and the precautionary approach in ecosystem-based management. In *Responsible Fisheries in the Marine Ecosystem*. Sinclair, M. and G. Valdimarsson (Eds). Rome; FAO and CABI Publishing: 311–319.
- CHRISTENSEN, V. and D. PAULY 1992 — ECOPATH II – A software for balancing steady-state models and calculating network characteristics. *Ecol. Model.* **61**: 169–185.
- CHRISTENSEN, V. and C. J. WALTERS 2000 — ECOPATH with ECOSIM: methods capabilities and limitations. In *Methods for Assessing the Impact of Fisheries on Marine Ecosystems of the North Atlantic*. Pauly, D. and T. J. Pitcher (Eds). *Fish. Centre Res. Rep.* **8**(2): 79–105.
- CHRISTENSEN, V. and C. J. WALTERS 2004 — ECOPATH with ECOSIM: methods, capabilities and limitations. *Ecol. Model.* **172**: 109–139.
- COOKE, J. G. 1999 — Improvement of fishery-management advice through simulation testing of harvest algorithms. *ICES J. mar. Sci.* **56**: 797–810.
- DE OLIVEIRA, J. A. A., BUTTERWORTH, D. S., ROEL, B. A., COCHRANE, K. L. and J. P. BROWN 1998 — The application of a management procedure to regulate the directed and bycatch fishery of South African sardine *Sardinops sagax*. In *Benguela Dynamics: Impacts of Variability on Shelf-Sea Environments and their Living Resources*. Pillar, S. C., Moloney, C. L., Payne, A. I. L. and F. A. Shillington (Eds). *S. Afr. J. mar. Sci.* **19**: 449–469.
- FAO 2002 — The state of world fisheries and aquaculture. Rome; FAO Fisheries Department: 149 pp.
- FAO 2003 — The ecosystem approach to fisheries. *FAO Technical Guidelines for Responsible Fisheries*. Rome, FAO **4**(2): 112 pp.
- FULTON, E. A., SMITH, A. D. M. and C. R. JOHNSON 2003 — Effect of complexity on marine ecosystem models. *Mar. Ecol. Prog. Ser.* **253**: 1–16.
- GEROMONT, H. F., DE OLIVEIRA, J. A. A., JOHNSTON, S. J. and C. L. CUNNINGHAM 1999 — Development and application of management procedures for fisheries in southern Africa. *ICES J. mar. Sci.* **56**: 952–966.
- GISLASON, H., SINCLAIR, M., SAINSBURY, K. and R. O'BOYLE 2000 — Symposium overview: incorporating ecosystem objectives within fisheries management. *ICES J. mar. Sci.* **57**: 468–475.
- INTERNATIONAL WHALING COMMISSION 1989 — Report of the Comprehensive Assessment Workshop on Management Procedures, Lowestoft, U.K., February 1989. *Rep. int. Whal. Commn Special Issue 11*: 29–44.
- INTERNATIONAL WHALING COMMISSION 2003 — Significations of the North Pacific minke whaling trials. *J. Cetacean Res. Mgmt* **5** (Suppl.): 133–149.
- INTERNATIONAL WHALING COMMISSION 2004a — Report of the modelling workshop on cetacean – fishery competition, La Jolla, June 2002. *J. Cetacean Res. Mgmt* **6** (Suppl.): 413–426.
- INTERNATIONAL WHALING COMMISSION 2004b — Report of the Scientific Committee. *J. Cetacean Res. Mgmt* **6** (Suppl.): 1–60.
- LINDSTRØM, U. and T. HAUG 2001 — Feeding strategy and prey selectivity in common minke whales (*Balaenoptera acutorostrata*) foraging in the southern Barents Sea during early summer. *J. Cetacean Res. Mgmt* **3**: 239–249.
- MAGNUSSON, K. G. 1995 — An overview of the multispecies VPA – theory and applications. *Revs Fish Biol. Fish.* **5**(2): 195–212.
- MORI, M. and D. S. BUTTERWORTH 2004 — Consideration of multispecies interactions in the Antarctic: a preliminary model of the minke whale – blue whale – krill interaction. In *Ecosystem Approaches to Fisheries in the Southern Benguela*. Shannon, L. J., Cochrane, K. L. and S. C. Pillar (Eds). *Afr. J. mar. Sci.* **26**: 245–259.
- NORTH ATLANTIC MARINE MAMMAL COMMISSION 2003 — Report of the NAMMCO Scientific Committee Working Group on Modelling Marine Mammal Fisheries Interactions in the North Atlantic. Annex 2, Report of the 10th Meeting of the Scientific Committee. In *Annual Report 2003*. Tromsø;

- NAMMCO: 259–281.
- NMFS 1999 — Report to Congress on the Status of Fisheries of the United States. National Marine Fisheries Service, NOAA, Department of Commerce. Silver Spring, Maryland: 112 pp.
- NMFS 2001 — Marine fisheries stock assessment improvement plan. Report of the National Marine Fisheries Service national task force for improving fish stock assessments. *NOAA tech. Memo. NMFS-F/SPO-56*: 69 pp. + 25 Appendices.
- PAULY, D., CHRISTENSEN, V. and C. [J.] WALTERS 2000 — ECOPATH, ECOSIM and ECOSPACE as tools for evaluating the impact of fisheries. *ICES J. mar. Sci.* **57**: 697–706.
- PLAGÁNYI, É. E. and D. S. BUTTERWORTH 2004 — A critical look at the potential of ECOPATH with ECOSIM to assist in practical fisheries management. In *Ecosystem Approaches to Fisheries in the Southern Benguela*. Shannon, L. J., Cochrane, K. L. and S. C. Pillar (Eds). *Afr. J. mar. Sci.* **26**: 261–287.
- POLOVINA, J. J. 1984 — Model of a coral reef ecosystem. 1. The ECOPATH model and its application to French Frigate Shoals. *Coral Reefs* **3**(1): 1–11.
- POPE, J. G. 1991 — The ICES Multispecies Assessment Working Group: evolution, insights, and future problems. *ICES mar. Sci. Symp.* **193**: 22–33.
- PUNT, A. E. and D. S. BUTTERWORTH 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 the Cape hakes *Merluccius capensis* and *M. paradoxus*. *S. Afr. J. mar. Sci.* **16**: 255–285.
- RICE, J. C., DAAN, N., POPE, J. G. and H. GISLASON 1991 — The stability of estimates of suitabilities in MSVPA, over four years of data from predator stomachs. *ICES mar. Sci. Symp.* **193**: 34–45.
- SHANNON, L. J., CHRISTENSEN, V. and C. J. WALTERS 2004b — Modelling stock dynamics in the southern Benguela ecosystem for the period 1978–2002. In *Ecosystem Approaches to Fisheries in the Southern Benguela*. Shannon, L. J., Cochrane, K. L. and S. C. Pillar (Eds). *Afr. J. mar. Sci.* **26**: 179–196.
- SHANNON, L. J., COCHRANE, K. L., MOLONEY, C. L. and P. FRÉON 2004 — Ecosystem approach to fisheries management in the southern Benguela: a workshop overview. In *Ecosystem Approaches to Fisheries in the Southern Benguela*. Shannon, L. J., Cochrane, K. L. and S. C. Pillar (Eds). *Afr. J. mar. Sci.* **26**: 1–8.
- SHANNON, L. J., CURY, P. M. and A. JARRE 2000 — Modelling effects of fishing in the southern Benguela ecosystem. *ICES J. mar. Sci.* **57**: 720–722.
- SHANNON, L. J. and C. L. MOLONEY 2004 — An ecosystem framework for fisheries management in the southern Benguela upwelling system. In *Ecosystem Approaches to Fisheries in the Southern Benguela*. Shannon, L. J., Cochrane, K. L. and S. C. Pillar (Eds). *Afr. J. mar. Sci.* **26**: 63–77.
- SHANNON, L. J., MOLONEY, C. L., JARRE, A. and J. G. FIELD 2003 — Trophic flows in the southern Benguela during the 1980s and 1990s. *J. mar. Syst.* **39**: 83–116.
- SPARRE, P. 1991 — Introduction to multispecies virtual population analysis. *ICES mar. Sci. Symp.* **193**: 12–21.
- TAMURA, T. 2003 — Regional assessments of prey consumption and competition by marine cetaceans in the world. In *Responsible Fisheries in the Marine Ecosystem*. Sinclair, M. and G. Valdimarsson (Eds). Rome; FAO and CABI Publishing: 143–170.
- VINTHER, M. 2001 — *Ad hoc* multispecies VPA tuning applied for the Baltic and North Sea fish stocks. *ICES J. mar. Sci.* **58**: 311–320.
- WALTERS, C., CHRISTENSEN, V. and D. PAULY 1997 — Structuring dynamic models of exploited ecosystems from trophic mass-balance assessments. *Revs Fish Biol. Fish.* **7**: 139–172.
- WALTERS, C. J., PAULY, D. and V. CHRISTENSEN 1999 — ECOSPACE: prediction of mesoscale spatial patterns in trophic relationships of exploited ecosystems, with emphasis on the impacts of marine protected areas. *Ecosystems* **2**: 539–554.
- WALTERS, C. J., PAULY, D., CHRISTENSEN, V. and J. F. KITCHELL 2000 — Representing density-dependent consequences of life history strategies in aquatic ecosystems: ECOSIM II. *Ecosystems* **3**: 70–83.
- YODZIS, P. 1998 — Local trophodynamics and the interaction of marine mammals and fisheries in the Benguela ecosystem. *J. Anim. Ecol.* **67**: 635–658.