Scientific tools to support the practical implementation of ecosystem-based fisheries management

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Ecosystem-based fisheries management (EBFM) has emerged during the past 5 y as an alternative approach to single-species fishery management. To date, policy development has generally outstripped application and implementation. The EBFM approach has been broadly adopted at a policy level within Australia through a variety of instruments including fisheries legislation, environmental legislation, and a national policy on integrated oceans management. The speed of policy adoption has necessitated equally rapid development of scientific and management tools to support practical implementation. We discuss some of the scientific tools that have been developed to meet this need. These tools include extension of the management strategy evaluation (MSE) approach to evaluate broader ecosystem-based fishery management strategies (using the Atlantis modelling framework), development of new approaches to ecological risk assessment (ERA) for evaluating the ecological impacts of fishing, and development of a harvest strategy framework (HSF) and policy that forms the basis for a broader EBFM strategy. The practical application of these tools (MSE, ERA, and HSF) is illustrated for the southern and eastern fisheries of Australia.

Keywords: Atlantis, ecological risk assessment, ecosystem-based fishery management, harvest strategy framework, management strategy evaluation.

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Introduction

The past decade has seen a gradual evolution in fisheries management from a primary focus on sustainability of target species and resources to a much wider focus on ecosystems, and the impacts of fisheries on them. This new approach has come to be called ecosystem-based fisheries management (EBFM), or alternatively the ecosystem approach to fisheries (Garcia *et al.*, 2003; Pikkitch *et al.*, 2004). Pikkitch *et al.* (2004) outlined the main elements of EBFM, including (i) avoiding the degradation of ecosystems; (ii) minimizing the risk of irreversible change; (iii) obtaining long-term socio-economic benefits from fishing; and (iv) adopting a precautionary approach to uncertainty.

Moves towards EBFM have also evolved in Australian fisheries during the past decade, driven by a number of policy directions and initiatives. These include: (i) a national, government-wide approach to ecologically sustainable development, released in 1991; (ii) development of fisheries legislation that incorporates explicit reference to wider ecological impacts of fishing (e.g. the Fisheries Management Act 1991); (iii) new environmental legislation that assesses fisheries against environmental standards (e.g. the Environmental Protection and Biodiversity Conservation Act 1999); and (iv) Australia's Oceans Policy, which adopts an explicit ecosystem-based approach to management, with explicit requirements for regional ocean planning for all uses and users of the marine environment. More recently, the Australian Fishery Managers Forum (incorporating heads of all federal, state, and territory fishery management agencies) adopted EBFM as the approach to future management.

Although fishery scientists played important roles in these policy developments towards EBFM, in almost all respects the policy has been running ahead of the development of the knowledge and scientific tools to support its implementation. As a consequence, the scientists had to "catch up" with the policy, and spent a great deal of effort in developing the tools, which were usually implemented immediately. This rapid development has had both benefits and costs, but has resulted in considerable progress in the practical implementation of EBFM approaches.

We offer a conceptual framework for tool development in support of EFBM and illustrate this with three examples, all within the federal level of fisheries management jurisdiction. No attempt is made to review the broader international developments in the field, and we present only a subset of the developments currently taking place within Australia.

A framework for tool development

Many of the analytical scientific tools developed are extensions of tools already in use in fisheries assessment and management, including methods for stock assessment as well as management strategy evaluation (MSE). It is helpful to think of the various tools as supporting different elements in the adaptive management cycle that characterizes fisheries management. The key steps in the cycle requiring scientific support include monitoring, assessment, and decision-making. In addition, the evaluation of the entire management cycle via MSE requires scientific input.

As noted above, EBFM has increased the scope of fisheries management. In particular, the ecological focus has broadened from concerns about target species and resources to concerns about non-target species, including protected species, habitats, and ecological communities – broadly, to ecosystems. Despite this broadening of ecological focus, socio-economic concerns are also important. Different tools may be needed to support these different elements.

The scientific tools may adopt a variety of approaches or methods. They may be broadly classified on a spectrum from qualitative to quantitative methods, although in practice the distinctions are not always clear cut. In particular, the methods may be based on expert judgement (an informal or formal, qualitative method that reflects the predominant opinion within a group of well-informed people); they may be largely empirical; or they may be based on quantitative models, although these categories are not exhaustive.

Figure 1 illustrates the different aspects in a schematic framework, defining a three-dimensional space for tool development. The elements of the adaptive management cycle are listed along the tools axis. The focus of the tool is on the scope axis, and the approach to be used is on the method axis. For example, traditional quantitative stock assessment would be found at the node consisting of population (scope), assessment (tool), and model (method), whereas the MSE for a single-species harvest strategy would be at the population, MSE, model node. Some tools may span multiple elements in a single axis, as will become clear below.

Ecological risk assessment for effects of fishing

Considerable work has gone into developing ecological risk assessment (ERA) methods for fisheries during the past 5 y. In general, the methods have been based either on expert judgement (Fletcher *et al.*, 2002; Fletcher, 2005) or empirical (Milton, 2001; Stobutzki *et al.*, 2001; Griffiths *et al.*, 2006). Here, we describe briefly a hierarchical framework for ERA for effects of fishing (ERAEF; for technical detail, see Hobday *et al.*, 2006), including a scoping stage and then up to three levels of assessment, spanning expert-based (Level 1), through semi-quantitative or empirical (Level 2), to fully quantitative methods (Level 3), with explicit links between them (Figure 2).

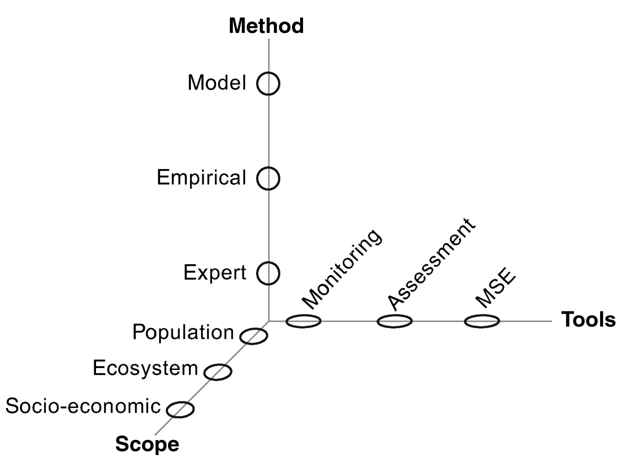

Figure 1. Framework for EBFM tool development.

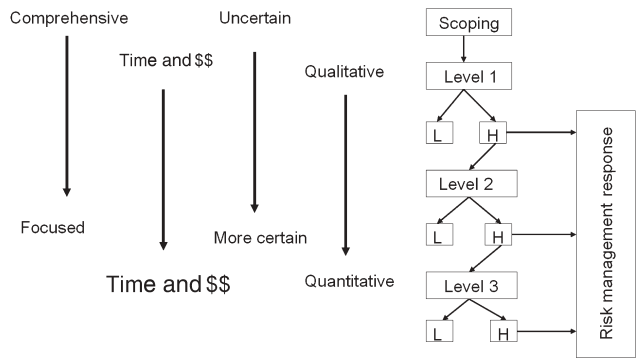

Figure 2. Hierarchical structure of ERAEF, illustrating the three levels of assessment, resulting in identification of low (L) and high (H) risk, at which point assessment moves to a higher level or to a risk management response. Qualifiers to the left indicate differences in specificity, costs, certainty, and quantification of the assessment.

ERAEF is based on an exposure–effects approach, rather than a likelihood–consequence approach, because most fishing activities are common and deliberate rather than rare and accidental. The different levels of assessment provide a series of filters to screen out low risks efficiently, with the assessment extending to the next level only if the risk is judged to be above a determined threshold. A cost-effective alternative to moving to the next level of analysis may be to instigate risk-management actions to mitigate the identified risk.

The scoping stage includes four aspects: fishery description, detailed objectives, list of activities (potential hazards), and identification of units of analysis (lists of species, habitats, and communities). The fishery description includes identification of subfisheries or fleets (mainly designated by fishing method), historical development, current status, and current management arrangements. This step identifies information available to support assessment at the subsequent levels. The hazards relevant to the specific fleet are identified from a specified list of 26 activities associated with fishing, as well as six external activities that could also have impacts on the ecological system. Impacts are assessed against five ecological components representing the ecosystem: target species; by-product and bycatch species; threatened, endangered, and protected (TEP) species; habitats; and communities. For each component, the relevant units of analysis are identified, comprising either a list of species, habitats, or communities. Benthic habitats are classified based on geomorphology, sediment, and faunal cover, most often using photographic images. Communities are classified using nationally agreed bioregions and biotic provinces, combined with depth classification. Depending on the nature and scale of the fishery under assessment, the units of analysis may be hundreds of species and habitat types, and tens of community types.

The Level 1 assessment uses a scale, intensity, consequence analysis (SICA) method that involves assessing the impact of each activity on each component using expert judgement and a six-point scale from negligible to catastrophic. The potential amount of analysis required at this qualitative level is limited by taking a "plausible worst case" approach that selects the unit of analysis identified by stakeholders (including fishers, managers, environmental agencies, and NGOs) to be most vulnerable to each activity. The maximum number of scenarios required is 160 (32 activities by five components). Each scenario is carefully documented, and only activity/component combinations (hazards) for which the risk score is >2 (moderate or above) are assessed at the next level. In practice, most hazards are eliminated at Level 1. In some cases, entire components are assessed to present low risk (e.g. habitats for pelagic longline fisheries), and excluded from further assessment at higher, more costly levels.

Level 2 assessments are based on a productivity–susceptibility analysis (PSA) approach derived from Stobutzki *et al.* (2001). All units of analysis are assessed for any component not screened out at Level 1. Given that there may be up to 500 bycatch species in a tropical prawn fishery, an efficient screening process is required. This is achieved by compiling a list of attributes for each unit of analysis that bear either on productivity (ability of the unit to recover from impact; $\approx$ resilience) or susceptibility (exposure of the unit to impact; $\approx$ vulnerability). The productivity attributes are averaged, but a multiplicative approach is used for susceptibility (Walker, 2005). The overall risk score for each unit is the Euclidean distance from the origin on a two-dimensional plot of productivity and susceptibility (Figure 3), with low productivity and high susceptibility corresponding to high risk. The PSA approach has also been developed to assess habitats, but the Level 2 assessments for communities are still under development.

No new methods have been developed for Level 3 assessments, because existing methods were considered suitable. These include quantitative stock assessment for target and by-product (retained, non-target) species, population viability analysis for TEP species, and potentially methods such as Ecopath/Ecosim for community analyses.

Several other features of ERAEF are worth describing briefly. First, the three levels of assessment are formally linked by a common underlying theoretical basis that is loosely founded around a commonly used "impact model" described by the equation

$$\frac{dB}{dt} = rB\left(1 - \frac{B}{K}\right) - qEB,$$

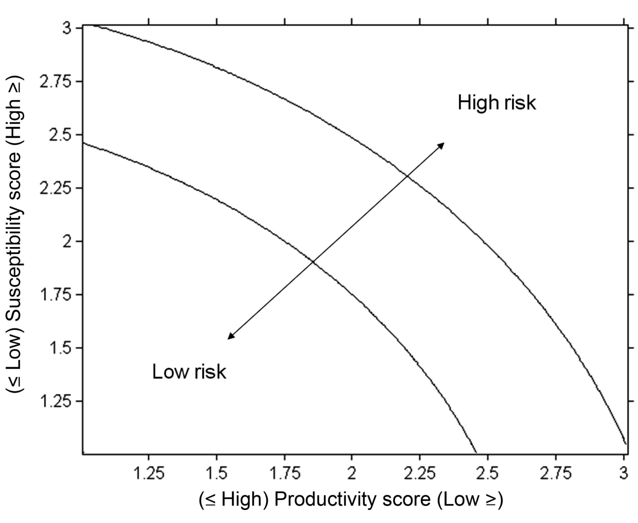

Figure 3. PSA plot: the two axes define the risk involved for each unit of analysis. See text for further explanation.

where B is biomass or numbers (or other appropriate measures of the unit of interest), r the intrinsic rate of increase, K the carrying capacity, q the catchability, and E is the fishing effort. At a population level, this represents the familiar Schaefer model, where qEB is the catch equation, but it can also be applied to habitat impacts and potentially to certain aspects of community impact (under development). The Level 1 assessment attempts to estimate the impacts qualitatively (i.e. the direction of change dB/dt), whereas Level 2 provides proxies for r (productivity) and q (susceptibility). Level 3 solves the full equation (or its equivalent).

ERAEF also has an explicit and formal treatment of uncertainty. As already noted, the Level 1 assessment is based on a "plausible worst case" treatment of impact, and the Level 2 assessment uses a default scoring (in the absence of better information) that leads to a high risk. Therefore, the method provides the correct incentive to acquire better information to reduce risk.

Overall, the hierarchical approach leads to a cost-effective means of screening hazards, Level 1 allowing for rapid assessment with minimal information requirements, and successive levels requiring more time, resources, and information, but only being called upon if needed (Figure 2).

ERAEF has been applied recently to all fisheries currently managed by the Australian Fisheries Management Authority (AFMA), amounting to >30 subfisheries. This has demonstrated its utility and flexibility, and the consistency of the approach is leading to improved selection of research priorities, both within and between fisheries. To date, >1800 species have been screened using the PSA method, together with several hundred habitat types. AFMA is in the process of developing sets of risk management responses to the results, and intends to build ERAEF into an ongoing adaptive environmental management system with reassessment at intervals of 3–5 y.

Management strategy evaluation

MSE methods have seen wide application in fisheries during the past decade or more. Most applications have been concerned with developing harvest strategies for single species, or occasionally for multispecies fisheries, either dealing with technical (Punt *et al.*, 2002) or trophic interactions (Punt and Butterworth, 1995; Sainsbury *et al.*, 2000).

There are few instances where MSE methods have been applied at the level of a whole fisheries management plan. One such instance is the "alternative management strategies" project, currently being used to assess a broad range of management options for the southern and eastern scalefish and shark fishery (SESSF), an amalgamation of separate fisheries in southeastern Australia using different gears, including otter trawl, Danish seine, gillnet, trap, longline, and dropline. It extends over 24° latitude and 52° longitude, from the subtropics to the Subantarctic, and from the coast out to depths of 1500 m. The fishery is currently managed by a combination of input and output controls, including a quota management system (Smith and Smith, 2001).

The "alternative management strategies" project arose because of concerns about the rapidly deteriorating ecological status of the stocks and economic status of the fishery. Its brief was to rethink the whole basis for managing the fishery, to identify management options that would lead to better ecological and economic outcomes, and to bring stakeholders along in the process. The project was developed in two stages, both involving an MSE approach. Stage 1 involved undertaking a "qualitative" MSE, where the usual operating model used to test alternative strategies was replaced by projections based on expert judgement. The experts were a group of government and industry scientists, two economists, and a manager with (collectively) >150 y experience in the SESSF. The group was guided by a steering committee of stakeholders from all sectors of the fishing industry, an environmental NGO, managers, and representatives of two key funding agencies. The stage 1 report evaluated four different management scenarios, against >20 performance measures consisting of a combination of ecological, economic, and social objectives. Only the most radical management scenario (involving a balanced combination of quota management, gear controls, spatial management, and effort control) led to acceptable longer-term outcomes, but at the expense of severe short-term economic dislocation for most sectors of industry. However, the report was instrumental in helping industry confront a range of systemic problems and issues in the fishery, and was used in part as the basis for a successful call for assistance in restructuring the fishery to achieve the changes that were identified as needed.

The project is currently in stage 2, which involves a full quantitative MSE of a refined set of management options, based around stage 1, but further informed by recent developments in federal fishery management (http://www.deh.gov.au/minister/env/2005/mr23nov205.html). The operating model for the quantitative MSE is a version of the Atlantis model (Fulton *et al.*, 2005a) developed specifically for the project. It comprises a biophysical model, an economics model, and a management model. The biophysical model captures the spatial and temporal dynamics of the sets of ecosystems present within the SESSF, including the population structure by age or size of selected vertebrate species and groups (of particular management interest), and biomass pools of the invertebrate parts of the food chain. It is driven by physical processes, including current movements and upwelling, varying across a range of temporal scales from tidal to seasonal to annual and decadal. The biological dynamics include such processes as habitat and food chain mediation. The management model includes the ability to deploy a wide range and combination of management tools or levers, including quota, harvest strategies, seasonal and spatial closures, gear controls, trip limits, and days at sea. It can also simulate the collection of both fishery-dependent and -independent data, as well as the application of a range of stock assessment and other analytical methods to such data. The economics model captures the dynamics of exploitation and fleet deployment, including multiple fleets, deployment and impacts of different types of gear, impacts of discarding and habitat modification, effort allocation, response to quota mix, spatial management, and compliance.

To date, the biophysical model has been tuned to capture historical changes in the fishery and ecosystems from 1900 to 1990, with the economics model tuned to more recent data from 1990 to 2004. Initial projections of the model to 2020 have been undertaken, to capture the expected changes in performance indicators for the management scenarios from stage 1. Figure 4 provides an overview of some of the changes to ecosystem structure within a restricted area hindcast by the model over the exploitation period 1900–1990. Of particular interest are the substantial changes to the age and size structure of most exploited vertebrate populations (except baleen whales), and the apparent ecological "release" from predation of small pelagic fish, squid, and jellyfish, owing to declines in their predators caused by fishing. These changes are consistent with what is known about historical changes in populations and communities. Changes to other parts of the ecological system are less substantial.

Further tuning is required before the tests of different management strategies can be finalized. A formal uncertainty analysis will also be undertaken to attempt to capture the major uncertainties in the biophysical and economics models. Results to date do suggest, however, that MSE evaluation at the level of entire and complex fisheries is not beyond the means of current tool development, although the robustness of conclusions drawn from such analyses has yet to be validated.

Harvest strategy framework

Management procedures and formal use of harvest control rules (HCRs) have been developed in several parts of the world (Butterworth and Punt, 1999), but infrequently so in Australia, notwithstanding the considerable effort put into MSE (Punt *et al.*, 2001). However, a formal harvest strategy framework (HSF) for quota species in the SESSF was developed and applied during 2005, drawing on experience from elsewhere.

This HSF adopts a tiered approach to deal with the broad range of information available for the 34 stocks managed by quota. Currently, there are four tiers, tier 1 being used if a robust and recent quantitative stock assessment is available, and tier 2 corresponding to a more uncertain, preliminary, or less recent quantitative assessment. Tier 3 is based on estimates of fishing mortality derived from catch curves, and tier 4 on recent trends in commercial catch per unit effort. HCRs are applied at each tier level to calculate a recommended biological catch (RBC) to be used as the basis for setting a total allowable catch (TAC). AFMA has determined that very strong justification is required for a TAC to be set above the RBC.

Several aspects of the HSF are designed to ensure that the overall approach will be precautionary. First, the HCRs associated with the first three tier levels are designed such that the RBC will be reduced successively as the tier level increases, corresponding to an increase in the uncertainty about stock status. Tier 4 currently may give a higher RBC than previous ones, a deficiency that is in the process of being corrected. Other precautionary elements built into the HSF are that exploitation rates (not just catch levels) are reduced as stocks drop below target levels, and for tiers 1 and 2, that a biomass limit (B_{lim}) is established below which targeted exploitation ceases (Figure 5). In the current implementation of the HSF, the target biomass for tier 1 is 40% of unfished biomass B_0, and B_{lim} is set at 20% B_0. For tier 3, where biomass cannot be estimated directly, there is an upper value of fishing mortality ($F = 2M$, where M is the rate of natural mortality) above which exploitation ceases.

One of the features is that, as with the ERAEF approach to precaution, the HSF provides an incentive structure for investment in research and monitoring to reduce uncertainty. This is an important feature within the Australian fisheries management system, where most of the management costs (including assessment) are recovered directly from the fishing industry. Industry is confronted directly with the trade-off between investment in research and monitoring, and lower TACs if stocks remain at higher tier levels. The overall management aim is that the risks to the stock should be comparable, no matter the tier level at which it is managed. A project is under way to formally evaluate the tier rules and strategies against this aim and other performance criteria.

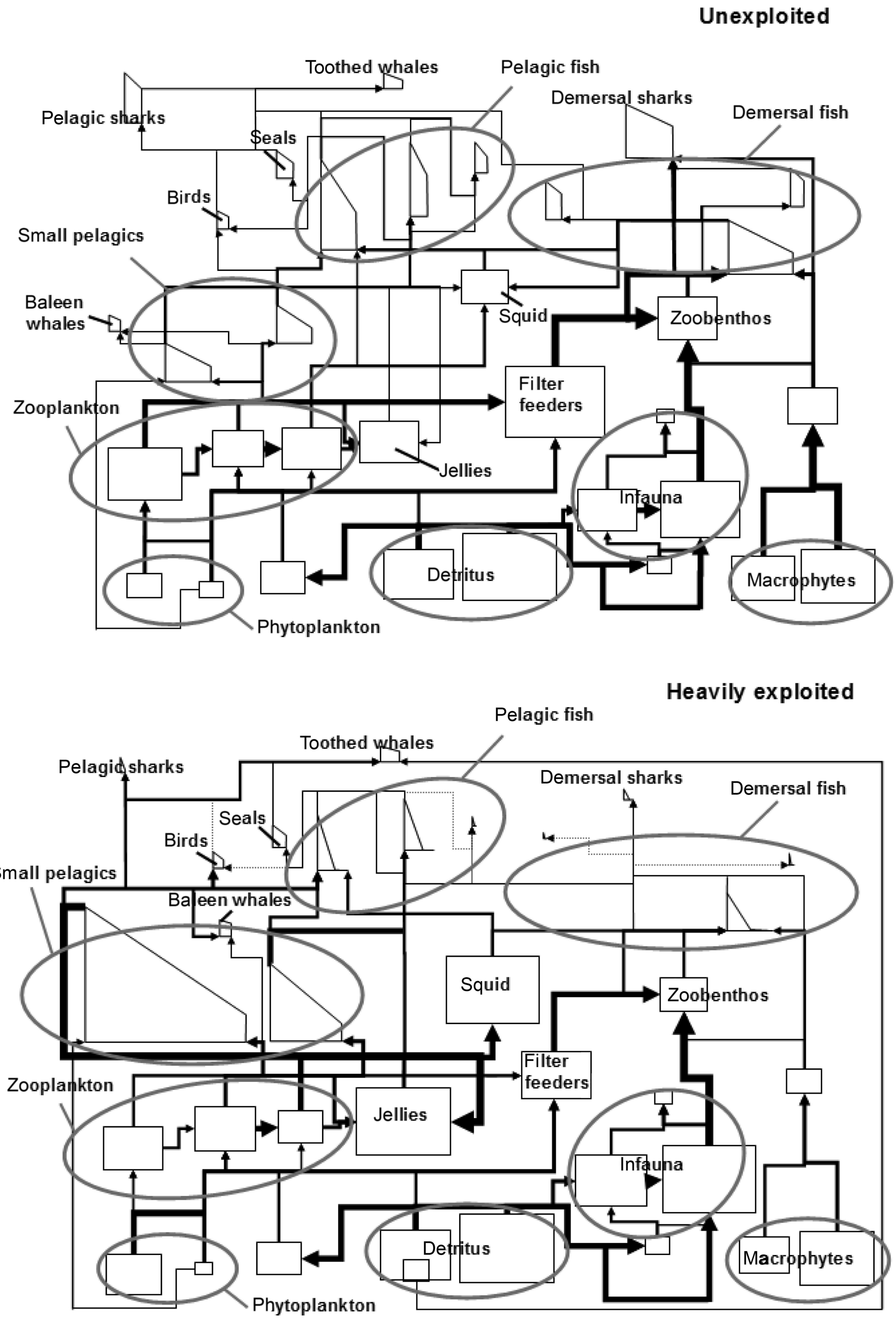

Figure 4. Schematic representation of the Atlantis model for Australia's Southeast Fishery, showing trophic structure before and after heavy exploitation. For groups represented as biomass pools, the size of the box corresponds to the size of the pool. For vertebrate species, size or age distributions of populations are indicated by the downward sloping lines on the boxes.

The HSF for the SESSF has been used as a starting point for developing a new harvest strategy policy to apply to all federally managed fisheries in Australia from 2008.

Discussion

The three examples discussed above represent only a subset of the tools currently under development at a federal fishery

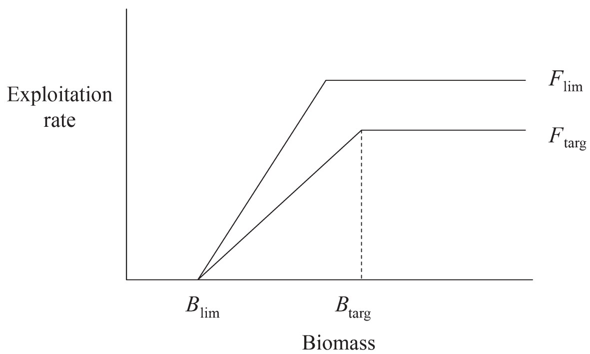

Figure 5. Basic HCR for tier 1 for the SESSF. The breakpoint in target fishing mortality (F_{targ}) occurs at the target biomass (B_{targ}) with the default value being at 40% of unfished biomass (B_0). B_{lim} is set at half B_{targ}.

management level within the comprehensive EBFM tools framework (Figure 1). ERAEF is an assessment tool spanning both population and ecological (but not socio-economic) assessment, whose methods cover the full range from expert-judgement-based assessment (Level 1 SICA) through empirical (Level 2 PSA) to model-based assessment (Level 3). The "alternative management strategies" project illustrates that the MSE approach can span the full scope of EBFM, from population through ecological to socio-economic objectives and issues. It also illustrates that MSE approaches need not necessarily rely only on model-intensive quantitative methods, and that a qualitative MSE is both feasible and useful. The HSF for the SESSF shows that assessments at a population level can be model-based, but also empirical. No mention has been made of the monitoring element of the tools axis, although previous work has helped to identify robust ecological indicators that use both empirical and model-based methods (Fulton *et al.*, 2005b). Also little attention has been paid to assessment tools that deal with socio-economic considerations.

The tools framework provides a helpful conceptual and planning framework in at least two respects. First, it suggests ways in which elements of separate tools might be usefully combined. For example, some effort has already gone into extending the PSA analysis to include a third "management" dimension. This would not only allow a more explicit inclusion of the impacts of management and mitigation measures, but would also provide an explicit link of ERAEF to MSE, and potentially an "empirical" level approach to MSE (something that has been missing so far). The framework also suggests ways of combining the HSF and ERAEF approaches. For example, the level 2 species assessments might be used as the basis for a "tier 5" harvest strategy, allowing development of explicit HCRs for bycatch species, as well as the existing target and by-product species.

Second, the tools framework can be used to identify missing tools in the toolbox. It is our contention that, sooner or later, tools corresponding to all elements in the three-dimensional framework will be required. This is clearly the case for the scope and tools axes, and arguably the case for the methods axis, because circumstances frequently arise where restrictions of time, resources, and data will limit ability to develop the (preferred) model-based approaches, and where expert-based and empirical methods, provided they are well founded, can still provide valid scientific advice in support of EBFM.

Although considerable progress has been made in developing and applying a range of scientific tools in support of EBFM, not all problems have been addressed or solved. The tools described are still evolving, not least in response to problems arising during their application. ERAEF is currently in its seventh version, and further modifications are being undertaken to address an at times unacceptably high rate of false positives (species assessed at high risk that are not) in the Level 2 screening process. Although the qualitative MSE proved to be of practical use in expanding the range of management options considered for the SESSF, the quantitative phase is not yet complete, and the characterization of uncertainty in the Atlantis model regarding the ecosystem dynamics (and even more so regarding human behaviour and socio-economic dynamics) is challenging, to say the least. The SESSF HSF has been applied, and each time problems and issues have arisen, and practical modifications have been required. We predict that each of these tools, and others currently in development, will continue to evolve as they face the test of application in real fisheries. However, it will be some time before the toolbox is well enough developed to say that we are achieving EBFM as outlined in the vision of Pikkitch *et al.* (2004).

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