Ralf Yorque Symposium and Ecopath with Ecosim Training Course

E.A. Fulton

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Abbreviations

EwE – Ecopath with Ecosim (ecosystem modelling software based on food web connections and fishing)

EBFM – Ecosystem based fisheries management

Executive Summary

This report summarises the outcome of a Ralf Yorque symposium – a small fairly informal series of workshops aimed at providing the big picture thinking space needed to underpin multi-year, multi-project research programs that incrementally piece together the necessary components of a pragmatic, practical and effective means of delivering sustainable fisheries – across ecosystems, for data poor and data rich species alike, in the context of climate and other cumulative pressures on Australian and global ecosystems.

Such an exercise is not a trivial undertaking and benefited from synthesizing current understanding, drawing insights from the last 40-50 years of the development of adaptive management and to scope what would be required of the design of a self-learning adaptive management approach for developing fisheries or fisheries with limited access to data.

The workshop(s) – held in March 2016 – focused on the ecological problems involved in managing multi-species fisheries in an ecosystem context (both practical and theoretical). While the workshop canvassed some of the institutional, social and political problems involved in fisheries and resource management, the majority of the discussion focused on EBFM and underlying ecological problems, including:

- understanding the ecological basis of fisheries production;
- the implications of the interplay of fisheries production and ecosystem dynamics for management of single-species fisheries;
- the management of regional multi-species fisheries; and
- the management of bycatch, especially bycatch of species of high conservation value.

An Ecopath with Ecosim training workshop was held on the back of the symposium to capitalise on the presence of the key developers of the tool being in Australia and thereby build capacity with these tools in Australian agencies and research bodies.

This intensive expert driven style of workshop was championed in the early 1970s in the International Institute for Applied Systems Analysis (IIASA) and the University of British Columbia. The original Ralf Yorque meetings were a key launch point for many of the foundational ideas of modern resource management, including the very concept of adaptive management (Holling 1978). Indeed many of the topics under consideration were also of interest back then – including how to deal with multispecies, multifleet fisheries (Getz et al 1985). Seminal work by Holling (1978), Schnute (1985), Mangel (1985) and Walters (1986) are all examples of work that have come from previous Ralf Yorque symposia.

The warning given by Donald Ludwig in his review of the Proceedings of the Second Ralf Yorque Workshop (held in Ashland, Oregon, July 23 - 25, 1984) remain particularly pertinent "… The difficulties in the field go much deeper than this: there is no agreement upon objectives or optimal policies, and there is no politically or economically feasible way to resolve basic scientific issues, as is witnessed by Walters' contribution. Why then should anybody concern himself with such a mess? There are many reasons. Chief among them is that the problems are important ones and they cannot safely be ignored. Resource management problems are representative of a host of other problems that involve environmental, social, political and biological issues. Their resolution will undoubtedly require development of entirely new methods of cooperation and analysis." (Ludwig 1987, *Mathematical Bioscience* 83: 231-233).

Keywords

ecosystem based management, ecosystem models, multispecies fisheries, data poor assessments, adaptive management

Introduction

Workshops

Australian Government and industry have many objectives for Australia's natural resources. Amongst their highest priorities are the sustainable use of Australian resources. This has seen significant effort of the past 50 years has seen the tools available for established, often high value, fisheries become increasingly robust and transparent. The combination of Ecological Risk Assessments of the Effects of Fishing (Hobday et al 2011), tiered Harvest Strategies (Smith et al 2008, Butterworth et al 2010, Smith et al 2013, Dichmont et al 2015, 2017) and ecosystem-based assessment models and tools (Smith et al 2007, Fulton et al 2011) becoming global standards and placing Australia amongst the leading nations of fisheries science. However, much remains to be done at a multi-species and ecosystem level (e.g. finding practical means of tactically managing fisheries at this level).

Reassuring the public that all Australia resources are being sustainably managed is difficult, however, as many of Australia's resources are poorly known. In 2014, even 18% of primary target species were of unknown stock status (Georgeson et al 2014) – only dropping to 14% by 2017 (Patterson et al 2017). This means that new and developing sectors, attempting to exploit resources in a new way, or targeting species that have not previously been considered main target species can come under considerable stakeholder scrutiny and public debate (as seen in the Commonwealth Small Pelagic Fishery). Such situations will not ease under climate change, as ecosystem restructuring will mean the mix of target species will need to shift, making the most of new opportunities, if Australian fisheries are to remain sustainable (Fulton and Gorton 2014, Fulton et al 2018).

The rapidly changing nature of marine systems under global change presents new challenges and opportunities for fisheries; driving home the realization that well-intentioned single species oriented harvest approaches may compromise ecosystem integrity and ultimately undermining the intent of regulatory actions taken with the aim of achieving and maintaining sustainable fisheries (Zhou et al 2010, Garcia et al 2012). In addition, at the time of the workshops described in this report there was also significant efforts required for low-value, small-scale and developing fisheries where information availability can be less than ideal, both within Australia and more broadly around the globe. This coincides with significant effort being put into data poor methods (Dowling et al 2015a, 2015b), which has only grown since (Dowling et al 2016, https://fishpath.org), which has helped ameliorate the issue, though even now data poor fisheries management remains a pressing issue globally.

Management approaches and harvest rules that support responsible fisheries management of multispecies fisheries as well as developing fisheries or small-scale, data-constrained fisheries are an important new tool needed to achieve Australian objectives for sustainable fisheries. Such a scheme will require the development of management approaches that more effectively incorporate the diverse and potentially conflicting needs and effects across all sectors accessing Australian stocks. It is already understood that management will need to more explicitly acknowledge the role of ecosystem integrity in delivering sustainable stocks and that new multispecies harvesting regimes will be required (Zhou et al 2010, Garcia et al 2012). However, the true form of such harvesting remains uncertain and any approach will need to allow for adaptive learning. Consequently, there is a need to design multispecies harvesting schemes and self-learning adaptive management approaches.

While new approaches to dealing with multispecies fisheries questions are being posed, scientific debate around the "balanced harvest" concept shows that it is unlikely to be a plausible solution as a sustainable multispecies harvesting approach (Jacobsen et al 2014, Froese et al 2015, Garcia et al 2015). Nevertheless, multispecies harvesting schemes will be required if sustainable stocks and ecosystem objectives are to be met. The vast majority of the species in marine ecosystems, even in countries such as Australia, are poorly known and simple extension of existing methods designed for primary target species are likely to be too data and resource intensive to simply extend across entire ecosystems (Dichmont et al 2017). A new approach is needed, one that is cognizant not only of ecosystem structure and function, but also of the challenging data status of most small-scale and developing fisheries. Such an approach would not only benefit countries like Australia that struggle to manage hundreds of species across multiple jurisdictions, aiming for ecosystem based management principles, but would also be useful for developing nations which do not have the resources to adopt the approaches routinely employed in the developed world. This problem is now widely recognized by regional management authorities but also NGOs (such as the Lenfest Oceans Program), who have come to appreciate that neither spatial management nor catch shares can act as a "silver bullet" to reform fisheries management in the developing world. The tools developed by countries such as Australia and the United States may have the potential, in combination with multispecies harvesting regimes, to address both food security and conservation concerns. However, these would need to be used in the right combination, which almost certainly depends significantly on the local situation. The same holds true for small-scale and data-poor fisheries in Australian jurisdictions (and even well-developed Australian fisheries, such as the Southern and Eastern Scalefish and Shark Fishery (SESSF), struggling under the weight of monitoring and managing multiple species). The key is to design fisheries reform that automatically learns "what works" as it progresses, maintaining (or recovering) ecosystem structure and function so that it provides the maximum flow of benefits to the community, region or country.

Designing and testing such an approach is a non-trivial exercise. In fact, these workshops marked the start of a multi-year, multi-project research program that is incrementally piecing together the needed components in a cost effective and practical form. As the true scope of such a program was unclear at the time of the workshops the workshops aimed to bring together experienced fisheries scientists to take the first step and synthesize current understanding, draw insights from the last 40-50 years of the development of adaptive management and to scope what would be required of the design of a self-learning adaptive management approach for developing fisheries or fisheries with limited access to data. This approach, of intensive expert driven "Ralf Yorque"[1] style workshops, was a key launch point for many of the foundational ideas of modern fisheries management, including the very concept of adaptive management (Holling 1978).

Training Course

In addition to new approaches, a broader set of the management and fisheries science community needs to be at ease with ecosystem oriented tools, such as Ecopath with Ecosim (EwE). Training in the latest versions of the software by those most intimately associated with it is a key step in improving the jurisdictional capacity of fisheries agencies in Australia in terms of ecosystem based management. Consequently, the second component of this project was a training course on the widely used (and ever evolving) Ecopath with Ecosim software (Christensen and Walters 2004). The week long training course was run by the key scientists and coders who developed the software and covered the software from its most basic components to new and extended features – such as fine scale spatial habitat representations, coupling with hydrodynamic and primary production drivers and full management strategy evaluation options.

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[1] http://www.iiasa.ac.at/web/home/about/alumni/Buzz_Holling.html

Objectives

The objectives of the project were as follows

1. Draw together some of the worlds most experienced fisheries and ecosystem scientists to provide insight into forms of multi-species harvesting (including of forage fish species) that are sustainable, account for the production-biodiversity trade-offs, and allow for adaptive learning.
2. Scope issues to do with assessment tools for adaptive management for data poor and developing fisheries
3. Provide a training course on Ecopath with Ecosim (one of the world's most widely used ecosystem model), thereby maximizing the benefit of having Carl Walters and Villy Christensen visiting Australia and expanding the capacity of fisheries management and research bodies in Australia to use the EwE software.
4. Provide hands on experience around how to test ecosystem-based fisheries management approaches, using EwE, and to synthesis existing understanding and test management concepts using the MSE approach.

Method

The project has two parts – (i) a set of expert meetings on hot-spot fisheries topics (specifically sustainable and ecosystem-based management; and data poor methods for fisheries assessments); and (ii) an Ecopath with Ecosim (EwE) training workshop.

Expert Workshops

The project team and invited experts participated in a set of expert workshops held in early March 2016. These workshops focused on fisheries and sustainability, particularly for data constrained (also known as data poor) and developing fisheries.

The intention of the first workshop was to follow the format of the highly successful series of Ralf Yorque meetings held by the University of British Columbia fisheries group in the 1970s and 1980s. These meetings (and many of the participants of the current meeting) led to the genesis of adaptive management (Holling 1978, Walters 1986), systems-based simulation approaches for exploring sustainability (Holling 1974) and the basis of concepts like resilience theory (Holling 1973). The theories were not formulated in a complete sense during the course of a single meeting, but the core ideas were laid down within the meetings. It is in this spirit that the workshop explored the topic of sustainable fisheries, ecosystem approaches to fisheries management and designing a self-learning adaptive management approaches that are robust in data poor and developing fisheries. For example, issues around multi-species harvesting (including of forage fish species, which are the focus on many developing fisheries in both the developed and developing world) were discussed at link, with an effort to account for the production-biodiversity trade-off issues.

The second workshop focused explicitly on assessment approaches for data poor and developing fisheries, with the express intent of considering how best to tackle the broad range of species reported on via the Status of Australian Fish Stocks (www.fish.gov.au).

Training Course

Members of the project team led a one-week training course on Ecopath with Ecosim (EwE), which was attended by fisheries scientists from jurisdictional agencies, researchers and graduate students from Tasmania, South Australia, Victoria and New South Wales. The course also featured expert instructors from the EwE consortium – Drs Jeroen Steenbeek (Barcelona Ocean), Marta Coll (Institut de Ciències del Mar - Consejo Superior de Investigaciones Científicas; ICM-CSIC), Villy Christen and Carl Walters (both from UBC).

Discussion of the Outcomes

Ralf Yorque Symposium

This Ralf Yorque Symposium was held in honour of the retirement of Dr Tony Smith (CSIRO) and follows on in the tradition of a group of key quantitative ecological scientists who interacted at the University of British Columbia and IIASA (and elsewhere), particularly during the 1970s and 1980s. The discussions held at those early Ralf Yorque symposia shaped concepts that have become central to sustainable management and fisheries – such as the formulation of adaptive management (Holling 1978, Walters 1986). Given a number of the symposium participants were key members of those early meetings it seemed a fitting way to reflect on lessons from more than 40 years of research and to try to extract lessons for continuing issues around ecosystem approaches, particularly in data poor settings.

Overall Summary

The workshop focused on the ecological problems involved in managing multi-species fisheries in an ecosystem context (both practical and theoretical). While the workshop canvassed some of the institutional, social and political problems involved in fisheries and resource management, the majority of the discussion focused on Ecosystem Based Fisheries Management (EBFM) and underlying ecological problems, including:

- understanding the ecological basis of fisheries production;
- the implications of the interplay of fisheries production and ecosystem dynamics for management of single-species fisheries;
- the management of regional multi-species fisheries; and
- the management of bycatch, especially bycatch of species of high conservation value.

Despite more than three decades of investment in ecosystem modelling packages (e.g. EwE, the earliest instance of which was used by Polovina 1984) and ecosystem field studies, most practical fisheries management is still based on single species (stock) concepts and assessments. The majority of multi-species fisheries are still managed via piece-meal addition of independent population models applied at a stock level. Where "interactions" are considered, it is chiefly in the form of technical interactions (Ono et al 2017) or key predator-prey dependencies (Agnew 1997).

While global stock status is mixed, with many stocks below sustainable levels (Costello et al 2016, Worm 2016, Hilborn and Costello 2018). Under many circumstances sound population level management and modelling can maintain key parts of the system (the target stocks) in reasonable health or support their rebuilding (NRC 1999, Fulton et al 2018). This is in part because in uncertain systems, with limited data, simple rules and simple models can often out-perform both free for all no-management situations (Holden and Ellner 2016) and highly complex models (Ludwig and Walters 1986). It is also because (in the most successful locations, such as Australia) they are used as part of a broader package of management measures – including spatial and other management levers intended to protect key ecosystem components such as habitats, but also adaptive feedback harvest strategies that are as robust as possible to errors and uncertainties.

Ecologically, the degree of success of single species approaches is surprising, as it assumes all the effect of the dynamic ecological interactions and broader environmental drivers can be subsumed into population parameters to do with recruitment, growth and "natural" mortality. Moreover, for statistical reasons (given limited available data) the latter two processes are parameterised using constants, rather than dynamic variables even though it is well known by ecologists that these processes do indeed vary through time and space on management relevant scales. This means the bulk of the dynamic nature of stocks is captured only in recruitment parameters. These parameters are often treated stochastically, or with serial autocorrelation, due to their high degree of variability and the difficulty of identifying meaningful stock-recruit relationships. The compound nature of what the recruitment parameters (deviates) are really representing (i.e. recruitment as well as interactions with other species, such as predators, prey, competitors and habitats) is likely why both autocorrelation and variability can be high and why failure to recognise 'regime shifts' can produce such strongly sub-optimal outcomes.

Nevertheless, there is sufficient evidence that single species approaches are insufficient when used in isolation (Walters et al 2005, Costello et al 2016, Fulton et al 2018). For example, the under caught quotas and failure of a number of overfish stocks in the SESSF to recover are potentially a symptom of attempting to manage a complex socioecological system (with multiple interacting environmental, social and economic drivers) based on a largely single species reference point paradigm. Gaichas et al (2017) have also shown that in multi-species or multi-stock fisheries, where gears are not sufficiently selective, it is generally impossible to efficiently exploit all stocks – either some are over exploited (if optimising for more productive stocks) or under exploited (if mandated to avoid all overfishing, as is the case in the US). Even within single stock management the compound nature of recruitment parameterisations means environmental shifts are easily confounded with strong dependence of recruitment on biomass, which can lead to diametrically opposing management recommendations.

Garcia et al (2012, 2015), Gaines et al (2018) and Hilborn and Costello (2018) are all part of a broader discussion on how to achieve close to maximum economic yields and to address food security issues, with some food web distortion, but no loss of species. This discussion has grown from managing bycatch of species of conservation concern, to habitats, fish stocks and even ecosystem structure and function. However, agencies are now struggling around how to deliver such management in a cost-effective way, as costs of gathering adequate data and assessing stock (or system) status do not typically vary with stock size or catch, and so effective management approaches for low value and generally data deficient fisheries remains a high interest but largely unresolved issue.

A first step to gaining clarity on this issue is to understand the benefits at stock and ecosystem level of different forms of management – from single species through to full ecosystem-based management. This was a topic of much discussion at the workshop and has subsequently been addressed by the work of Fulton et al (2016), Dichmont et al (2017) and Fulton et al (2018) – which shows both that (i) while single species management can be effective, but that ecosystem based approaches outperform them for many management objectives and (ii) that the opportunity costs associated with going with lower cost (data-poor) assessment methods can be substantial (Dichmont et al 2017). It has also led to the development of a project to define effective but pragmatic multispecies harvest strategies (FRDC project number 2018-021).

The next step is to understand what ecosystems are robust or sensitive to and what actually effects system structure. Evidence from around the world is that many ecosystems are relatively robust to a wide range of exploitation levels. This has led to the discussions around the benefits and pitfalls associated with different approaches to multispecies fisheries and exploiting ecosystems. Examples were presented that showed similar biomass yields could be sustained under a wide range of fishing efforts, but that depending on the pattern of fishing there could be quite different outcomes in terms of stock biomass and size structure. These discussions indicate a high degree of system specificity – with some systems showing a high degree of within species density dependent compensation and relatively weak ecological interactions and interdependencies (e.g. where top predators population shifts had little effect on ecosystem structure), while other systems underwent regime shifts after the removal of key predators or ecosystem engineers (e.g. the NW Atlantic cod collapse, or the rock lobster-urchin-kelp regime switches).

The sharp end of this debate over appropriate multispecies harvest strategies has been focused on the discussion of the 'balanced harvest' fishing strategy (Garcia et al 2012), where fishing effort is distributed across species in proportion to their productivity. Proponents point to the capacity of the approach to maintain ecosystem structure and function (by avoiding selective practices and maintaining relative size and species compositions and protecting network structure) and minimise wasteful discarding (Garcia et al 2015). Those critical of the approach state that: (i) the level of biological knowledge required is infeasible; (ii) it is impossible to achieve balanced harvest with current fishing technologies and system state; and (iii) if it could technically be done that effective control is unlikely and so the approach will devolve into a free-for-all - with systems fished in this way seen to be far from healthy (Froese et al 2015). Moreover, while the concept may be a worthwhile "theoretical" proposition, the approach is not actually practicably possible, and even if it were, we are not starting from a clean slate and a transition from the current state to the ideal balanced harvest state would have to be found. While not necessarily a fruitful option in and of itself, the 'balanced harvest' debate has acted to exercise the community with more and more researchers stirred into action to find feasible multispecies harvest strategies (e.g. Gachias et al 2017). Significant time was put into the discussion of these ideas during the symposium. One of the resulting suggested strategies, which attempts to design a practical mixed set of fishing methods (building on the fisheries métier concept) that could steer ecosystems in desired directions is one of the strategies being considered in the multispecies harvest strategies project (FRDC project number 2018-021).

Ecosystem models are taking a prominent role in these considerations of multispecies fisheries and ecosystems. Structural uncertainty is a significant source of divergence between their predictions under certain conditions – with quite different predictions of the potential sensitivity of ecosystem composition and function coming from the different kinds of models. A paper written as a direct result of the discussion of these topics at the symposium shows that even in simple predator-prey differences in process representation (e.g. of predator functional responses) can produce substantial differences in the response of the modelled populations to changes in stressors (Walters et al 2016).

Summary of Specific Discussions

Successful management options

Key concepts in successful ecosystem approaches have married together two scientific principles:

I. Using effective quantitative methods (e.g. stochastic control theory, stability isocline analysis. kalman filters) to underlie ecological understanding, systems thinking and decision analysis.

II. Successful adaptive management is dependent on key people and long-term relationships/engagement with regulators/industry (to build trust and confidence so can impart scientific ideas and get uptake)

Key Fisheries Issues in Australia

The last 10 years has seen the universal adoption of ecosystem-based fisheries management (EBFM) in Australia – at both federal and state levels – as well as the introduction and review of harvest strategy policy. This has been highly successful, with overfishing falling to zero at the federal level (as of 2017, Patterson et al 2017) and the number of overfished stocks falling to historic lows (Patterson et al 2017). In contrast, the step to integrated management of all marine sectors – ecosystem-based management (EBM) – has not ultimately been embraced and existing legislation can be contradictory and requires harmonisation (e.g. between the EPBC and Fisheries Acts).

Social licence (the level of social approval that exists in relation to the development or use of common pool resources for private or public purposes; Moffat et al. 2016), or public opinion, is having an increasing influence on the execution of Australian fisheries (Tracey et al 2013). In turn, this is putting pressure on AFMA and other management authorities to justify their management decisions (e.g. the Fisheries department of Western Australia put all stocks through MSC pre-certification to proactively and publicly illustrate their sustainable status) and to find new technological solutions to monitoring and assessment (e.g. close-kin, Bravington et al 2016) that are robust to the fact that Australian fisheries are data poor. The low volume of Australian fisheries (and the low value of some individual finfish species) means that careful attention must be given to the ratio of the value of the fishery to the cost of research and management (meaning blind application of methods used in the United States or

Europe is not advisable). This will require finding and exploiting new technological (and likely analytical) solutions that drastically expand monitoring and assessment potential while reducing unit costs – such as what is beginning to be possible with close-kin genetic analyses (Hillary et al 2018).

A failure to recognise the multispecies nature of Australian fisheries has also led to a number of management associated issues – specifically undercaught TACs and a failure to promote recovery in some fish stocks. Since the time of the symposium a dedicated project has been initiated on this topic (FRDC project number 2016-146; http://frdc.com.au/project/2016-146), which has gone into much greater depth on potential causes and so we will refrain from providing partial commentary here.

Equally the multifaceted nature of Australian fisheries has not always been recognised, with species treated in different ways in different jurisdictions or with differential data availability across different fisheries types (e.g. commercial in comparison to recreational). Again, since the time of the symposium this imbalance is being more formally recognised via requirements of AFMA to explicitly include consideration of indigenous and recreational aspects rather than focusing solely on commercial implications and effects.

The issue of broader considerations will only grow with an expanding blue economy, which will push beyond EBFM to EBM across all sectors (Smith et al 2017) – including: tourism, ports, energy, mining, conservation etc. This begs the question of how to achieve (i) formalised enviro standards and (ii) operationalised objectives across industries. The need to consider objectives and performance measures in this context will likely reignite the need to explicitly discuss what constitutes acceptable impacts, something all stakeholders (including society at large) has dodged to date. Indeed, the failure to engage the public in meaningful communication of Australian fisheries issues has contributed to the decline in social licence for the industry and its management. Available information and engagement channels mean most Australians do not access locally appropriate knowledge when forming an opinion of fisheries, instead defaulting to global messages of poor exploitative and management practices. This may be due to barriers to easily accessing relevant/accurate information or a cultural disconnect (as few Australians have commercial fishing in their heritage or as a key cultural component, despite many seeing recreational fishing as a core cultural identity; Griffiths et al 2014). It was generally agreed that a strategy for transparently (but effectively) communicating the true state of Australian fisheries is required going forward.

Barriers to advancing good fisheries management

The hurdles to effective multispecies fisheries management has highlighted ongoing pitfalls with traditional fisheries management and assessment approaches. Keith Sainsbury led a discussion of lessons learnt from decades of accumulated experience of fisheries management. This experience clearly showed that any form of structured management was more effective than unstructured decision making (Holden and Ellner 2016), and that single species methods are very effective when dealing with a truly isolated species, or a set of species that are acting in parallel with no/little interaction (either trophic or technical via being caught by the same gear). For mixed species fisheries, where species are caught together but do not trophically interact, single species concepts or even optimisations across species can be effective, though typically they do require some adaptation (typically to do with managing for the choke species, by easing requirements so that there is no target reference point, but still demand no species drops below their limit reference point). The greatest challenges are associated with multispecies fisheries where there is both biological and technological interactions; these fisheries are bedevilling science the world over and likely require the development of new methods (see further discussion of this in the next section).

This discussion also highlighted inertia in assessment processed. It has been recognised for decades that single species concepts and models are not realistic in terms of some of their fundamental assumptions – such as changing recruitment or natural mortality. For a long time, this was accepted as there was a significant body of work indicating that managing a complex system using a simple model was often more effective than using a more complicated approach (Ludwig and Walters 1985).

Nevertheless, more recent work has shown that there is significant danger to this approach where there is a trending change to system parameters – as can occur due to climate change (e.g. Brown et al 2012). While fisheries scientists recognise this threat they have still been conservative in terms of changes to assessment procedures (perhaps a case of preferring the "devil you know", similarly to the reluctance to move away from linear economic models assumptions in other disciplines).

While there was general agreement that models of some form have a strong place in fisheries management advice, there was acknowledgement of jurisdictions (e.g. South Australia) that have instead opted for empirical harvest control rules. The general observation was, however, that such approaches often grow to be quite complicated, relying on multiple empirical indicators. In reality, such approaches can be quite resource and time consuming and require more assumptions than using well specified models (as models can aggregate information, allowing for identification of trends and break points and supporting the use of simple adaptive rules, such as "broken stick" harvest strategies; Smith et al 2008). Such discussions will be ever more pressing into the future as certain data-oriented research fields put forward the line that brute force pattern recognition will be sufficient (somewhat like relying on intuition by less quantitative people). This ignores the great benefit that can be garnered from explicitly laying out assumptions, as it reduces the likelihood of being trapped by psychological fallacies such as confirmation bias. Such clear expression of assumptions in data rich situations can actually aid the development of heuristic rules for use in data poor situations. For example, it has been found using ecosystem models that the sustainable ratio of fishing (F):natural (M) mortality levels shifts with position in the food web (trophic level), meaning rather than assume $F_{sustainable}$~M, a more precautionary assumption of $F_{sustainable}$~0.5M is more robust.

The broad ranging discussion also summarised experience with the efficacy of different fisheries management approaches. Put simply, input controls are harder to manage well (especially across gears and species), but output controls are more expensive to execute and require more monitoring-based information. Moreover, output controls can prove to be very challenging in mixed and multispecies fishery circumstances. So neither approach is a perfect standalone solution.

Multispecies Harvesting

The work led by Garcia et al (2012) on balanced harvesting originally neglected the economic aspects. Although this has since been rectified by dedicated papers – e.g. Charles et al (2015). These state that the use of balanced harvest could avoid costs (financial and perception based) associated with the extirpation of species, food security can be improved, though whether this improves net revenue is unclear due to potential barriers involving costs of management and finding suitable markets.

Using the output of the models that underlies the work by Garcia et al (2012), the matching economic plot was created (Figure 1). This showed that far from a simple decline in value – whether with selective, unselective or balanced harvesting – the value curves were highly non-linear. The value of landings could be quite variable across systems under unselective harvesting – with potential value differing by as much as 90% and mean values remaining at about 20% of the maximum. Balanced harvesting performed strongly, with values typically 40-70% of the maximum seen. Selective fishing followed a quite complex pattern, first decreasing (matching classical expectations of fishing down the foodweb), before rising and dropping again (as the forage fish are depleted) and rising again as high value invertebrates come to dominate the catches.

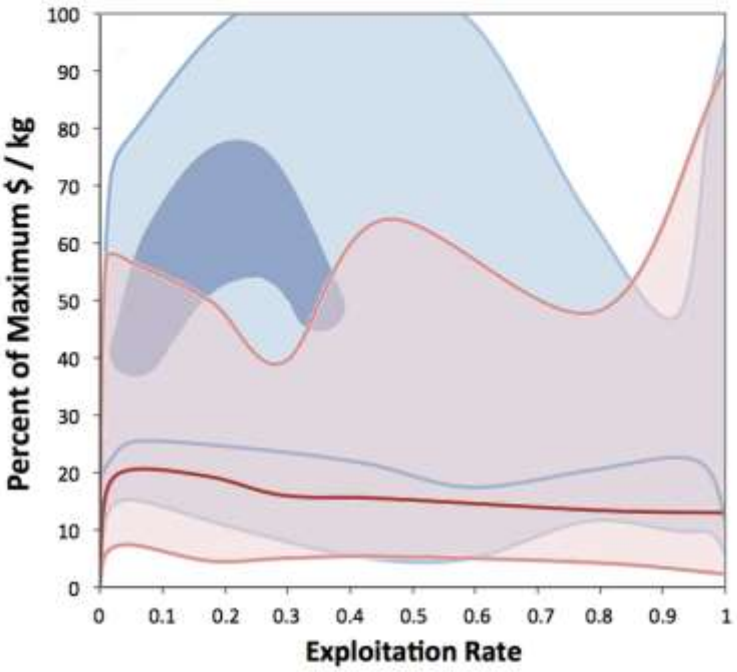

Figure 1: *Effects of increasing exploitation rate (defined as instantaneous total catch / total available biomass in the system) on 36 ecosystem models from 30 systems with fishing preferentially concentrated on large and valuable groups and age/size classes (red) or spread more broadly over all fish groups and sizes (blue). Averaged results of simulations are displayed for landings value as a percentage of the maximum value. All values are plotted against the maximum across both selective and unselective fishing strategies. The shaded areas mark one standard error from the mean. Note that balanced harvesting is only a subset of more broadly spread (blue) fishing cases and is shown by the dark blue patch.*

Even within the ecological aspects of fished ecosystems there is much to learn when shifting from single species paradigms to consideration of the dynamics of multiple species or the structure of the ecosystem. What is ‘acceptable’ for ecosystem structure and function is an ongoing scientific and cultural discussions. As demonstrated by the activities of SE Asian fishing nations, it is possible to put intense pressure on an ecosystem and have high yields over extended periods – transforming rather than collapsing an ecosystem. In those instances, reducing pressure does not necessarily lead to higher catches (at least not in ecosystem models, though single species models would suggest an increase in catch is possible; Hilborn and Costello 2018), simply less employment, which may not be a socially desirable outcome. The ecosystem models used by Garcia et al (2012) suggest that when fishing across taxa, as done in SE Asia, under high fishing pressure the yield curve is flat for a broad range of effort levels, although ultimately the system does decline overall. This later state may have been reached in some SE Asian locations (e.g. Myanmar) where there has been an across the board reduction in fish stocks of >75% since the 1970s, with even fast growing species such as Leiognathids effected.

While modelling has been at the heart of many studies considering multispecies harvesting, not all those have been ecosystem models. Moreover, the questions are not new ones. For example, Hilborn and Walters (1989) dealt with optimal fishing exploitation patterns across multiple species, finding it is possible to find optima where fishing pressure is high enough that weak stocks go extinct, even if the stronger stocks are being fished sustainably.

Simply defaulting to avoiding the overexploitation of weaker stocks might not be a feasible option either. For example, work done in the California Current has shown that a significant volume of catch is given up when fishing so as to avoid the extirpation of all species (Hilborn et al 2012). This work also showed that it is possible to maximise profit without collapsing any stock, but some stocks will nonetheless have to be overfished.

Across the developed world there has been significant effort put into fisheries management reform over the past decade. For example, looking at east coast US fish stocks in the RAM legacy database shows that the stocks were heavily depleted into the early 1990s, but that subsequent management efforts have seen decreases in fishing pressure and notable increases in biomass, with stock sizes now approaching or around target levels (Hilborn and Ovando 2014). Despite theory indicating that healthier stocks can support larger catches by volume than a heavily depleted stocks, in reality catches have not increased alongside biomasses. Instead fleet size has decreased, while the regulatory burden has increased. While some stocks have shown improved CPUE and profitability, total catch has not risen, raising old arguments around potential benefits of recovery. This is not to say that recovery should not be sought, but rather a call to understand why stock rebuilding does not automatically translate into higher catches.

In searching for these answers, a number of topic areas were touched on – such as changes in underlying system productivity. Most discussion, however, went into dynamics of human behaviour – such as how the dynamics of quota trading markets can help or hinder fishing operations. For example, fishers often hold on to more quota of byproduct (or secondary and tertiary) species than they actually need in anticipation of a potential (though often unmet) need. This behaviour, in turn, prevents access to quota of those fishers who do catch these species thereby preventing fishing of target species. This makes the bycatch species choke species, whose quota limits the capacity to fish even if they are not in themselves the major target species. A failure to share information (and thereby avoid undesirable bycatch) can lead to similar situations and there is a strong contrast in this mechanic off the east and west coasts of the US; in the west the fleet quickly displayed cooperative behaviour and learning to avoid bycatch blockages (Branch et al 2006). While in the east there has traditionally been little information sharing so bycatch could severely hamper the dynamics of some fleets, this has recently been rectified by a combination of near real time reporting and predictive modelling (Hobday et al 2018).

Model structures

Models have played a significant role in fisheries science and will continue to do so. The form of these models must receive careful attention as the shape of the functional responses used within models does have qualitative effects on their predictions (e.g. changing the direction and form of responses to fishing pressure).

Two fundamental assumptions at the heart of most ecologically based fisheries models (conceptual, qualitative or quantitative) is that biomass decreases as increasing fishing pressure; and that total mortality increases as fishing mortality increases. If these assumptions do not hold then fishing would not detrimentally effect populations and ecosystems even at high levels. The assumption can legitimately breakdown if trophic interactions mediate the assumed dynamics. For instance, if a fishery targets young fish (recruits) and there is density dependent compensation in recruitment then there would be no effects of fishing observed until fishing mortalities were excessively high. Another possibility is that if natural mortality is the dominant component of total mortality and it drops as fishing mortality levels increase then total mortality may remain roughly constant. Examples of where this has been observed in reality include:

- the African lakes system (Kolding and van Zwieten 2014) where the slope of the biomass size spectra (which reflects total mortality) has remained constant even as fishing pressure has risen;
- the Anchoveta Fishery where size-based data indicated natural mortality dropped as the fishery intensity grew (Hilborn pers comm)
- Crab species where size distributions have shown little change even as fishing mortality rises steeply

Classical predator-prey models (e.g. Lotka-Volterra) are well characterised and their equilibrium behaviour has been well researched and summarised – e.g. Gotelli (2001). In this model fishing mortality substitutes for natural mortality and so the ultimate effect of fishing the forage species is to depress the predator abundance that can be supported, until the predators are totally excluded from the system – at that point total mortality increases in direct proportion to fishing mortality. Elaboration of the model by Bazykin (1976) and others has shown that this simple behaviour breaks down with the introduction of elaborations such as predator interference (competition), density dependent limitation of the predator (e.g. via a stock recruit relationship) etc. Under these circumstances the drop in natural mortality is non-existent (or at best small) so total mortality increases with fishing pressure. Predator responses are also sharper, showing little movement until their threshold needs are passed (at quite low levels of forage biomass) and then dropping rapidly. There is evidence of such dynamics in some forage fish systems (see panel 29 and 32 in Hilborn et al 2017).

The sensitivity of models is always of keen interest to users. Inter-model comparisons undertaken over the last 20 years have suggested differential responsiveness between platforms such as Atlantis and EwE – with EwE often showing more production anomaly amplification – where a small shift in primary production leads to larger shifts up through the food web than Atlantis (e.g. Fulton and Smith 2004; Forrest et al 2015). However, this is not always the case, as seen for the Benguela (Smith et al 2015), where Atlantis proved more responsive to shifts in fisheries pressure than Ecosim. One of the reasons for these differences are the stabilising mechanisms included in the respective models – such as quadratic mortality and stock-recruit relationships in Atlantis (Audzijonyte et al 2017) and foraging arenas in Ecosim (Walters et al 2000). Comparing the model responses indicates that system structure influences model responses – whether it amplifies or suppresses direct and indirect effects (predation and competition together) – in particular by strongly influencing the contribution of individual processes that introduce delays and buffer ecosystems. These include the stabilising mechanisms, but also age and stage structure, reproductive delays, gape-limited predation and diet switching.

While modellers are unified in their position that model behaviour should not be prescribed and that multiple stable states (regime shifts) should not be artificially constrained in models (Shin et al 2010), finding sufficient data on real world mechanisms that lead to such dynamics is difficult (meaning those mechanisms are often omitted from models). The most common such mechanism is allowing for ontogenetic prey-predator reversal (e.g. herring versus cod; Gårdmark et al 2015). There is also some evidence of predators holding prey at low levels, with resulting ‘explosions’ in prey biomass once predators are depleted (e.g. as happened for crustaceans on the east coast of North America with the depletion of cod; Frank et al 2005).

Given the desire to capture nonlinearities in simulated system dynamics, and the desire to expand assessment models to embrace the “minimum realistic model” or “model of intermediate complexity” (MICE) ethic – where assessment-type models are expanded to include a short list of additional key system components such as a prey or predator group, or a climate associated driver etc. – a discussion was help on what are minimum model requirements. It was agreed that models should include:

- Compensatory foraging (e.g. Holling type II feeding functional response, or satisificing – where foraging time changes with prey availability – as most fields observations support the existence of this mechanism)
- Early life history compensatory mortality (either via inclusion of explicit larval dynamics or stock-recruit relationships to reflect density dependency in restricted nursery habitats etc.)
- Habitat dependency (especially for demersal systems)
- Forage arenas (whether in the form of that included in Ecosim or simply by recognising that behaviours such as diel vertical migration can squeeze predator and prey populations into small areas with high overlaps, where intense bouts of feeding can occur)
- Contraction of spawning areas with contraction of stock size (so density of eggs m^{-2} can remain high, but in contracting areas with concomitant effective contraction in carrying capacity)
- Inclusion of depensatory dynamics in some instances (e.g. Holling Type III functional response or spatial constraints and ‘storage effects’ (Chessson 2017) – where pulse in/out of a refugia areas as the population expands/contracts – are needed to reproduce the kind of ‘outbreak dynamics’ seen in some species)

Regime Shifts

The existence of multiple stable states in even the simplest of models suggests that regime shifts are likely to be real world phenomena, even if rarely experienced in the fisheries world to date. This is supported by the long list of entries in the global regime shifts database (http://www.regimeshifts.org/). Given the potential for regional scale regime shifts being predicted by Australian marine ecosystem models forced with potential climate change scenarios, management would be wise to consider how it will deal with such situations. Work in the Benguela and California Current systems, where changes in forage fish biomass levels (regimes) have been observed historically, indicates that management schemes that recognise regime shifts do see variable catches, but that variability is not as high as when the management scheme ignores the regime state (in this instance management typically ends up shutting the fishery for decades at a time during lower productivity system states) (Punt et al 2016).

Summary of Data Poor Methods

The other major topic of discussion at the symposium was data poor methods. A lot has happened in this area in the intervening years since the meeting took place. This is an active and rapidly expanding research area (e.g. Carruthers et al 2014, Dowling et al 2015a, 2015b, 2016) with extensive literature discussion of data-poor assessment methods, but less on appropriate harvest strategies (Dowling et al 2014, 2015a). Dowling et al (2014 and 2016) outline a process that begins with compiling and reviewing available information; identifying possibly indicators and reference points; identifying appropriate assessment approaches (e.g. as summarised in Carruthers et al (2014) or Dowling et al 2016) and then selecting appropriate harvest strategy and decision rules (ideally testing them before implementation). The development of tools such as FishPath (Dowling et al 2016) should be a significant step forward in facilitating selection of appropriate approaches, by providing users with a systematic tool for characterising a fishery in terms of (i) available data; (ii) life history and biological attributes of the key species; (iii) operational properties of the fishery; (iv) socioeconomic characteristics; (v) governance context. This characterisation then allows FishPath to assist users in identifying the subset of management strategy options that are appropriate for the fishery given all its constraints.

The expanding body of work on data poor methods includes many useful approaches. For example, stochastic stock reduction analysis (Walters et al 2006) is a relatively easy method to implement, which uses a fully age structured approach that allows for: catch curve derived relative level of depletion; stochastic recruitment (with anomalies derived from historical time series); and consideration of uncertainty around exploitation and biomass levels at maximum sustainable yield using Bayesian Markov Chain Monte Carlo procedures. This approach is used as a basis for approximately 50% of the 170 quotas set for fished species on the US west coast; where there is insufficient data for this approach Depletion-Corrected Average Catch (DCAC) approaches are used (MacCall 2009). In reviews of data poor methods, Carruthers et al (2014) found most data poor approaches depend mostly on catch data. While methods relying only on historical catches often had poor performance (worse than simply maintaining current fishing levels), the addition of information regarding stock depletion, historical fishing effort and current abundance greatly expanded the value of the assessments.

The group of experts gathered for the symposium did highlight that recruitment trends are far more reliable option than abundance trends for data poor fisheries – with inshore surveys, bycatch tracking and the like being much cheaper than dedicated adult independent surveys (which can also be affected by statistical power issues). Moreover, they provided advice on the kinds of issues summarised by Carruthers et al (2014). In particular, they underlined the need to appropriately correct available catch data and catch curves (e.g. length-based catch curves) to adjust for potential bias. For example, growth curve corrections are required as faster growers are caught first so observed growth curves do not actually match the true underlying growth curve. This then undermines the fishing mortality estimate.

In addition, strong selective pressure occurs on the population (with slower growers being the ones left to reproduce), which can be expressed as a declining size at age for oldest ages, which further impacts the proficiency of the methods being used.

There has been so much interest in data poor methods over the last few years (before and after the symposium discussion) that dedicated tool boxes have been developed. For example Carruthers and Hordyk (2018) have developed the Data-Limited Methods Toolkit (DLMtool available from https://www.datalimitedtoolkit.org/), which is an R package that consolidates a large number of existing data-limited management procedures and allows for rapid management strategy evaluation testing of them and other new approaches. The experts agreed that access to these tools and FishPath guidance is important as there is no generalised method guaranteed to work in every system, as each data limited system has its own idiosyncrasies in terms of function and how data limited the system is. This requires a tailoring of the approach taken. The Marine Stewardship Council and NGOs (e.g. the Nature Conservancy) are making significant investments in this arena as it is seen as an important route to sustainability for a many of the lower value or 'small-scale' fisheries globally.

While data poor methods are all that is possible for many stocks in Australia, the experts felt it was important that it was recognised that data poor methods can be ambiguous and therefore there are implications for assessment of stock status. Rectifying this situation would require investing more in both data collection and assessment. Indeed, there was a strong recommendation to collect as much data as possible regardless of the assessment used so that the data could be 'banked' for future use, should there be the need for more data intensive methods in the future (if a reduction in uncertainty became critical or increased exploitation meant the species needed to be moved into a data rich category). The most useful data types (in order of priority): are size composition (to estimate fishing mortality levels), age composition (these also allow for estimation of fishing mortality levels), catch history (though care must be taken given the constraints and potential biases), recruitment indices.

Finally, all the experts present unanimously stressed the need to avoid fixating on assessment methods (as these can prove to be quite biased for data poor methods) and instead focusing on the need to move to harvest strategies that are robust to uncertainty.

Ecopath with Ecosim (EwE) Training

The Ecopath with Ecosim (EwE) training course was run at CSIRO Oceans and Atmosphere Hobart (Castray Esplanade) laboratories from 7 to 11th March 2016. The program for the course can be found in Appendix 3 and much of the general content (summarised here) is available from https://ecopath.org/support/.

EwE is a free trophic interaction-based ecosystem modelling platform, with three main components:

- Ecopath – a static, mass-balanced snapshot of the system (summarising energy or biomass flows between food web components and fisheries; Christensen and Walters 2004);
- Ecosim – a time dynamic simulation (initialised using Ecopath values), which tracks overall system evolution through time and can be used to explore fisheries policy implications (Walters et al 2000); and
- Ecospace – a spatial implementation of Ecosim, which was initially designed for exploring impact and placement of protected areas (Pauly et al 2000, Steenbeek et al 2013).

EwE is an ecological modelling software suite for personal computers that was built and extended on for almost twenty years, with applications widespread throughout the world. As of January 2018, EwE has an estimated 8000 users in over 170 different countries, with over 800 publications in the ISI Web of Knowledge using the software. EwE is an important modelling approach to explore ecosystem related questions in marine science, which can be used to:

- Facilitate end-to-end trophic ecosystem model construction;

- Address ecological understanding pertaining to foodweb structure and function;
- Evaluate ecosystem effects of fishing;
- Explore management policy options;
- Model the effect of environmental or production changes;
- Explore the impact and placement of marine protected areas; and
- Through modules extend the platform to consider new and novel aspects of systems – such as predict the transfer and accumulation of contaminants (Ecotracer; Christensen and Walters 2004, Tierney et al 2018), or consider fisheries supply chains.

The development of the software is centred at the Ecopath International Initiative, a non-profit research association established to secure the long-term development of EwE.

Ecopath

A summary of the Ecopath approach, its methods, capabilities and pitfalls are described in detail by Christensen and Walters (2004), Ainsworth and Walters (2015), Heymans et al (2016) and Steenbeek et al (2016). A brief overview of the course content is reproduced below.

Ecopath is the foundation of EwE. The structure of an EwE model is made up of biomass pools that consist of a single species, or species groups representing ecological guilds. These biomass pools may be split into ontogenetically linked stanzas – e.g. larvae, juveniles (say ages 1-2), and spawners (say age 3+).

The final parameterization of an Ecopath model is based on satisfying two ‘master’ equations. The first equation describes the how the production term for each group can be divided:

$$\begin{aligned} Production = {} & Catch + Predation + Net\ migration + Biomass\ accumulation \\ & + Other\ (unexplained)\ mortality \end{aligned}$$

While the aim of the Ecopath model is to describe all mortality factors, this is not always explicitly possible and so the ‘other mortality’ term is needed to cover factors not explicitly captured in the model (such as disease or senescence).

The second ‘master’ equation is based on the principle of conservation of matter for each biomass pool:

$$Production = Consumption - Respiration - Unassimilated\ food$$

These equations (one set per biomass pool) are combined to form a set of simultaneous equations (which are solved assuming mass balance). It is then a simple requirement to input three of the following four parameters for each biomass pool (to allow for the simultaneous equations to be solved): biomass, production/biomass ratio (equivalent to total mortality), consumption/biomass ratio, and ecotrophic efficiency. The ecotrophic efficiency term of EwE expresses the proportion of the production that is explicitly used in the system, (i.e. it incorporates production, net migration, biomass accumulation and predation, but not ‘other mortality’). Typically, either biomass or ecotrophic efficiency is estimated by the model (preferably ecotrophic efficiency). In the rare cases where all four basic parameters are available for a group, the program can instead estimate either biomass accumulation or net migration.

This approach means Ecopath data requirements are relatively simple, with the data used to populate the spreadsheet involves: biomass estimates, total mortality estimates, consumption estimates, diet compositions, and fishery catches. These values capture what is needed for the simultaneous equations and are often readily available from stock assessments and ecological (literature) studies.

Constructing an Ecopath model is a valuable exercise in itself, as it provides an explicit synthesis of understanding of the system (simultaneously identifying existing data gaps), drawing together work from many researchers and organisations.

Once the Ecopath model is developed there is an extensive list of inbuilt tools for exploring the structure of the food web and its flows.

Ecosim

Ecosim provides a time dynamic simulation at the ecosystem level. It is initialised using the ecosystem state summarised by the Ecopath model and uses differential equations to express biomass flux rates among pools resulting from feeding and harvesting (see Walters et al 2000 for more details of the specific equations). Key scientific and computational aspects of Ecosim include:

- Variable speed splitting to allow for efficient numerical handling of the dynamics of both ‘fast’ (phytoplankton) and ‘slow’ groups (whales);
- Effects of micro-scale behaviours on macro-scale rates: top-down vs. bottom-up control incorporated explicitly via a foraging arena (predator-prey interactions are moderated by prey behavior to limit exposure to predation, the parameterization of this allowing for representation of both top-down and bottom-up control).
- Includes biomass and size structure dynamics for key ecosystem groups, using a mix of differential and difference equations. This involves tracking biomasses via delay-difference equations and for multi-stanza groups this involves tracking monthly cohorts, as well as density- and risk-dependent growth;

The emergent dynamics of the model can capture real world phenomena, such as stock-recruitment relationships (which are an ‘emergent’ property of competition/predation interactions of juveniles).

Ecosim biomasses can be formally fit to historical time series (of relative or absolute abundance, catches, effort, fishing rates or mortality estimates) using routines within the software that estimate a statistical measure of goodness of fit measure (using weighted sum of squared deviations of log biomasses from log predicted biomasses). These time series are often available from single species stock assessments. In this way Ecosim (like Ecopath) builds on – and complements – traditional stock assessment approaches. This handling of the fitting of Ecosim allows the researcher to:

i. Determine the sensitivity of the fit to critical Ecosim parameters (e.g. vulnerability);
ii. Search for vulnerability estimates that provide the best ‘fits’ of Ecosim to the available time series data (with the user able to constrain the search to sensible bounds); and
iii. Search for patterns of change in annual relative primary productivity (which provide hypotheses regarding historical productivity ‘regime shifts’ impacting the ecosystem).

As for Ecopath, Ecosim contains a range of inbuilt tools. The best known of these tools are to do with management policies. These policies can either literally ‘sketched in’ using the interface (say in discussion with system users) to play out options being considered, or a formal policy optimisation can be run. The later employs user defined objective functions (which identify what criteria the policy must fulfil in terms of economic returns, employment and ecosystem structure) to explore policy options, finding the combination of fishing levels per fleet and through time that best match the defined ecosystem-level criteria. These policy results provide insight about how high the fishing mortality rates should be, and how they should be varied over time (at least during fishery development or during a recovery phase to allow for rebuilding from past overfishing).

These two policy exploration approaches can best be used in combination – performing a formal optimization search then ‘reshaping’ the resulting fishing rates per fleet in order to meet other objectives (which cannot be formally captured in the search’s objective function, such as social, safety or cultural wellbeing considerations).

Ecospace

Ecospace is the spatially dynamic version of Ecosim (Walters et al. 1999) that uses a regular grid to capture a two dimensional representation of the modelled domain (with land, sea, habitat, marine reserves and other features defined by the user when constructing the map). The model assumes symmetrical movements from a cell to its four adjacent cells based on a “gravity” assumption (i.e. rates of movement are higher towards areas of ‘preferred habitat’). Fish migration and advection can be modelled explicitly and predation risk and effects on feeding rates in non-preferred habitats can also be parameterised.

A simple effort allocation model is used to implement fishing pressure, with a level of fishing effort applied to each cell that is proportional to the overall profitability of fishing in that cell (the distribution can also be made sensitive to costs, such as those that increase with distance from port).

Given its structure, Ecospace has primarily been used to explore the potential role of Marine Protected Areas (MPAs) as an ecosystem-based management tool (e.g. Walters et al 1999). Spatial optimisation functions have been built in to the Ecosim software to aid in site selection for spatial management zones within the model domain (i.e. they optimize the placement of protected areas). These optimisation tools are based on maximising an objective function that incorporates ecological, social, and economic criteria. Two different optimisation methods are available: one iteratively trials the growth of protected areas from seed locations (evaluating whether the addition of adjacent cells improves the optimisation score); while the other approach uses a Marxan-like likelihood sampling procedure based on weighted importance layers of conservation interest (Christensen et al 2009).

Implications

While these meetings have not directly informed industry and consumers, they have considerably benefited the researchers who support management and have gone on to shape the path of many subsequent projects that are now benefiting all stakeholders. Projects that have resulted from the workshops, or directly benefited, include:

- Development and evaluation of multi-species harvest strategies in the SESSF (FRDC project number 2018-021)
- Understanding factors influencing under-caught TACs, declining catch rates and failure to recover for many quota species in the Southern and Eastern Scalefish and Shark Fishery (FRDC project number 2016-146)
- Drafting of the new harvest strategy policy (HSP) guidelines
- Adaptation of Commonwealth fisheries management to climate change (FRDC project number 2016-059)
- Cumulative impacts across fisheries in Australia's marine environment (FRDC project number 2018-020)
- An appreciation that continuing to rely on biological parameters long out of date carries significant risks for management and industry.

Research insights gained during the workshops address practical fisheries management issues (with policy implications). The outcome of the discussions has directly benefited subsequent projects, their recommendations and system understanding, and the management advice stemming from that knowledge. In addition, the training course has increased the ecosystem modelling and EBFM capacity of Australian fisheries agencies and research bodies.

Further development

The project does not resolve management issues in its own right, but instead has provided information that can (i) guide prioritisation of ongoing and research to support industry and (ii) highlights where management changes may be needed to address:

- Data poor stocks
- Impacts and opportunities associated with systems shifting under climate change
- Cumulative impacts
- Successful and cost-effective implementation of ecosystem-based fisheries management

The work laid considerable ground work, maximising the efficiency of broad scale fisheries oriented projects funded by FRDC (as listed above) and seeing additional beneficial fisheries oriented work funded by CSIRO, The Nature Conservancy and the Lenfest Ocean Program – such as the FishPath work and the Lenfest-CSIRO expert working group on Benchmarks under EBFM.

Extension and Adoption

The academic nature of the working groups meant that there was no direct communication of the workshop content to the general user, but the workshop findings were reflected back to fisheries scientists and agency personnel in a number of ways:

- Materials provided to all participants in the EwE training course
- A summary of workshop findings and discussions that were then drawn upon in shaping up subsequent dedicated projects (as listed above)
- Briefing notes taken by participants to discussions (with FRDC and other bodies) around data poor methods, their development and support
- Inspiration for papers such as Dowling et al (2015) – which directly addresses the need for guidance on the implementation of data poor methods
- The original paper by Walters et al (2016) that was derived from material discussed at the expert workshops
- Contributions to the final design of the simulation experiments in Fulton et al (2018), which uses the methods developed for the FRDC project 2012-202 *Operationalising the risk cost catch trade-off* to explore the implications of different kinds of management (single species, multispecies and ecosystem based) for management performance against key system-level objectives.

Project materials developed

As outlined above, there were a number of informal products created during the workshops. The only formal product was the paper (https://doi.org/10.1016/j.ecolmodel.2016.07.014):

Walters, C., Christensen, V., Fulton, E.A., Smith, A.D.M., Hilborn, R., 2016. Predictions from simple predator-prey theory about impacts of harvesting forage fishes. Ecological Modelling 337: 272–280.

Appendices

Appendix 1 – List of Researchers Involved in the Symposium and Training Course

Workshop attendees were amongst the leading thinkers in fisheries science and adaptive management, including:

- Professor Carl Walters (University of British Columbia)
- Professor Ray Hilborn (University of Washington)
- Professor Andre Punt (University of Washington, CSIRO)
- Professor Villy Christensen (University of British Columbia)
- Dr Tony Smith (CSIRO)
- Dr David Smith (CSIRO)
- Dr John Parslow (CSIRO)
- Professor Keith Sainsbury (University of Tasmania)
- Dr Ana Parma (Centro Nacional Patagonico (CONICET), Argentina) participated for part of the workshop, providing guidance on links to single species approaches and Management Strategy Evaluation.
- Dr Beth Fulton (CSIRO).

The training course (which had approximately 20 people in attendance) was led by Professor Carl Walters (University of British Columbia) and Professor Villy Christensen (University of British Columbia), with support from two of the other chief developers of the software – Dr Jeroen Steenbeek and Dr Marta Coll who leads the Ecopath Consortium in Europe.

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Appendix 3 - EwE Training Workshop Program Plan

7 March - day 1

Morning

- Welcome/housekeeping
- Introduction of teachers and participants
- Introduction to Ecological Modelling and the Ecopath Research and Development Consortium
- Introduction to Ecopath, Ecosim, Ecospace
- The Ecopath model: general principles and data needed

Afternoon

- Introduction to Ecopath, Ecosim and Ecospace applications in Australia
- Practice session - Presentations of participants' models and questions
- Exploration time (time to 'play' with the modelling software, explore its options and see how they can be used to deliver specific system configurations)

8 March - day 2

Morning

- Balancing Ecopath models
- Advanced features of Ecopath model, including the use of online databases and the EwE pedigree routine

Afternoon (practice sessions –some participants may want to team up if no models of their own)

- Practice session - Exercise 1: Parameterization of Ecopath models
- Practice session - Exercise 2: Balancing Ecopath models
- Exploration time (time to 'play' with the modelling software, explore its options and see how they can be used to analyse network structure, system flows and indicators)

9 March - day 3

Morning

- Introduction to Ecosim
- Fitting models to time series of data in Ecosim

Afternoon

- Practice session - Exercise 3: Ecosim model
- Practice session - Exercise 4: Fitting a model to time series
- Exploration time (time to 'play' with the modelling software, explore its options and see how to perform system-level fisheries policy optimisation searches)

10 March - day 4

Morning

- More advanced feature of Ecosim-supply chain, MSE
- More Ecosim play
- Introduction to the original Ecospace model

Afternoon

- Introduction to the habitat foraging capacity model
- Introduction to the spatial-temporal data framework
- Practice session - Exercise 5: Developing an Ecospace model
- Practice session - Exercise 6: Connecting with online databases to parameterize EwE models
- Exploration time (time to 'play' with the modelling software, explore its options for spatial management placement searches)

11 March - day 5

Morning

- Practice session - Exercise 7: Developing an Ecospace model habitat foraging capacity model
- Practice session - Exercise 8: Developing spatial-temporal data framework

Afternoon

- Intro to programming
- General questions session