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Cumulative impacts across fisheries in Australia's marine environment

Final Report

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We would also like to thank the project steering committee for their insightful comments regarding the form of useful content for decision making.

Abbreviations

EIA: Environmental Impact Assessment

ERA: Ecological Risk Assessment

CEA: Cumulative Effects Assessment

Executive Summary

Report topic

The world is changing more rapidly than any one individual can track. The Environment Protection and Biodiversity Conservation Act 1999 (1999) (EPBC Act) requires for all human activities, such as fisheries, to be sustainable not only in isolation but in combination with other anthropogenic activities and the general state of the environment. It is difficult for fishery managers and operators to comply with this requirement without appropriate assessment methods. In addition, trying to understand the complete state of an ecosystem and all its interacting parts is a substantial and challenging task, especially for a nation with national waters as large and diverse as Australia's.

In response researchers from the CSIRO and the University of Adelaide set about reviewing existing tools used to undertake Ecological Risk Assessments (ERAs) or Cumulative Effects Assessments (CEAs). This information then formed the basis for developing a new Cumulative Effects Assessment framework which was applied to 409 species around Australia to understand what the cumulative effects of fisheries are on Australia's marine systems. This understanding and the recommendations made around strengthening existing assessment methods used by the Australian Fisheries Management Authority (AFMA) and other fisheries regulatory agencies will place Australia in a better place to ensure it is not only meeting regulatory requirements, but supporting sustainable industries and helping to coordinate across government agencies to safeguard healthy marine ecosystems into Australia's future.

Background

More and more human activities are moving into the oceans, with multiple fisheries operating in overlapping areas just one example of this. Increasing awareness of the footprints of the different activities, crowding, climate change disturbance and observed changes to the distribution and abundance of marine species has created concern about marine ecosystems and increased awareness around the risk of unforeseen impacts and environmental degradation that could threaten existing activities and benefits. Over the past two decades concerned government agencies and society have both increasingly pushed for clearer approaches for describing cumulative pressures so that managing oceans could be evidence-based, thereby responding directly to conflict and stress potentially accruing among the increasingly complex mix of ocean uses.

Aims/objectives

This project aimed to (i) review the state of the science around ERA and CEA methods nationally and internationally, (ii) use that knowledge to develop a CEA framework that could be applied in Australian fisheries and (iii) perform an Australia-wide assessment that accounts for commercial, recreational and customary fisheries for species spanning State and Commonwealth jurisdictions.

Methods

The two reviews followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRIMSA) protocol, to ensure they were as transparent and reproducible as possible. This structured approach uncovered 221 ERA-relevant documents and 65 documents on CEAs. Insights and recommendations from these reviews led to eight critical CEA steps which in turn became the basis of a hierarchical CEA framework which was applied to Australian species. This framework was intentionally built to be consistent with ERA methods already used by the AFMA and a CEA method used to inform Parks Australia around general pressure levels in Australian waters. Stage 1 of the analysis created maps of cumulative fishing pressure on 409 species around Australia, assuming those pressures were additive. Stage 2 of the analysis draws on ecosystem model output to characterise more complex, non-additive responses which are then used to create updated non-linear cumulative effects maps. The complexity and uncertainty associated with this model-based approach meant that it was applied as a proof-of-concept-only in this report.

Disruption caused by the COVID-19 pandemic meant close collaboration with operators and representatives of customary fisheries was not possible, so this work was restricted to analytical approaches only. The inclusion of customary fisheries would involve follow-up of future work.

Results/key findings

The review of ERA methods found that the approach used for Australia's approaches to Ecological Risk Assessment for the Effects of Fishing (ERAEF) remains relatively competitive as best-practice internationally, but there is potential for refinement. In particular, the method could: adopt more taxon-specific traits in the assessment (learning from what has been done for sharks, rays, seabirds, turtles and marine mammals in ERAs applied in New Zealand, RFMOs and elsewhere); include habitat and trophic dependencies; and account for the influence of climate, making the approach proactive not just retrospective.

The review of CEAs highlighted that CEAs undertaken by proponents (as part of project-related environmental impact assessments), or by government agencies (federal and state) as part of strategic or regional assessments have been of mixed content and quality. While Australia provides some laudable examples there is a good deal of heterogeneity of approach and many approaches have data requirements that are currently unavailable for many species that interact with Commonwealth fisheries. It was clear that map-based methods are a very effective means of conveying information, but methods are needed that not only highlight additive pressure but non-linear and indirect effects (where cumulative effects may be amplifying or mediated by trophic or habitat connections) as well, as they are common in ecological systems.

These factors have been accounted for via a hierarchical CEA framework, developed as part of this project, that builds off Australian ERAs to generate relative cumulative additive fishing pressure maps in the first instance, moving to non-linear absolute maps where there is demand for such products and resources to support the more complex modelling tools needed to generate them. Applying this framework to 409 species from around Australia highlighted that while most species are under light pressure over most of their distribution, pressure hotspots exist and 15-26% of species appear to be under heavy cumulative pressure and require more in-depth management consideration (59 species require attention due to Commonwealth fisheries alone, but the number increased to 107 when the influence of State fisheries is also considered).

The analysis of non-additive pressure found that some species could be benefiting from fisheries activities, with lower to mid trophic level groups such as cardinal fish, euphausids, Jack Mackerel (*Trachurus declivis*), Cucumberfish (*Chlorophthalmus nigripinnis*) and Redbait (*Emmelichthys nitidus*) likely seeing the strongest combined benefits off Victoria and deeper waters off New South Wales. In contrast, demersal sharks, macrobenthos (such as crabs and lobster), shelf dwelling predatory fish may be feeling some of the strongest combined direct and indirect negative effects of fishing. Mesopelagics seems to be under strong food web mediated negative effects. Tuna and bill fish, flathead and redfish are the most strongly negatively affected main target species considered in the Stage II analysis.

Implications for relevant stakeholders

Through its history the Australian ERAEF process has proven to be an effective means of demonstrating that AFMA (and other fisheries nationally and internationally) are meeting their EPBC (or equivalent) sustainability requirements and has been adopted as part of the Marine Stewardship Council guidelines (Marine Stewardship Council 2013). The potential for CEAs is just as large. While this project has focussed on method development, preliminary assessments and proof-of-concept applications, the potential implications for industry and management could be more significant (especially if the trajectory on requirement of CEA for regional planning or regulatory access matches what is being seen in the northern hemisphere (e.g. Hammar et al 2020)).

Recommendations

Due to the challenging nature of the topic being tackled and the constraints imposed by the COVID-19 pandemic, this project did not completely achieve the objectives originally set out. A number of follow-up steps would usefully extend the research, extending the reach of the approach to the originally envisaged scope or to verify the veracity of the method or refine it so that results are less uncertain. In particular: working with First Nations fishers to appropriately include customary fisheries in the CEA framework; refining and extending nonlinear analyses applied as proof-of-concept in this report; implementation of the method into online tools to allow maximum access to automated forms of the methods – making its use as resource light as possible and facilitating the potential for its seamless integration into existing management processes.

Keywords

Fisheries, cumulative effects, Ecological Risk Assessment, Cumulative Effects Assessment

Introduction

Background

Information, methods, and estimates of cumulative effects are needed to allow marine managers such as fisheries managers, to understand both the effects and risk associated with multiple activities (past and present) and environmental stressors occurring in a region. Nationally and globally there has been both a policy and a societal push for development of these approaches, as use of ocean spaces have increased leading to potential for conflict among sectors (Stelzenmüller et al., 2018). The increasing footprints of the different activities, the crowding occurring in some locations, and the observable changes to marine ecosystems, habitats and species occurring due to climate change and increasing ocean use has led to a realisation that there is the risk of unforeseen impacts and degradation that could threaten existing activities and benefits (Halpern et al., 2015). Cumulative Effects Assessments (CEAs) are now commonly used in European waters for regional planning and for assessing the pressure being applied to vulnerable species and regional ecosystems (ICES, 2019).

The scientific capacity to deliver the required tools to assess cumulative impacts has been dependent on the availability of requisite data sets and computing power. To date these efforts have been insufficient to routinely address the interacting and dynamic nature of systems and the resulting non-additive interactions between pressures and non-linear responses (Crain et al., 2008; Côté et al., 2016).

When are effects cumulative?

Cumulative effects result from interacting activities – these may overlap spatially or occur via sequential or overlapping activities in a single location through time, where the effect of one activity has not dissipated before another activity occurs. Cumulative effects can be of many forms (Figure 1), but can be simply classified as additive or nonlinear. Additive effects are most often seen in physical systems (MacDonald 2000), but effects are often more complex in ecological systems, meaning nonlinear outcomes are more common (Crain et al., 2008; Piggott et al., 2015; Côté et al., 2016). Nonlinear effects occur when the outcome does not match what would occur if the effects of each individual pressure were simply added together. Instead, nonlinear effects may see one pressure dominate (mask) others; or pressures may buffer (work against) each other so that the final outcome is less than the sum of the individual effects (known as antagonistic effects); or the combined effect may be greater than the sum of the individual effects as the interacting activities amplifying any changes to the system (known as a synergistic effect). The form of the cumulative effects is important for directing management interventions, as synergistic effects represent the potential for cost effective intervention (larger outcomes than for the same spend for additive cases), while antagonistic will need careful handling over the long term as intervention will likely require multiple steps and can see things become worse before they improve (Brown et al., 2013).

(A)

	Single Pressure	Multiple Pressures
Occurring Once	Not Cumulative	Potential cumulative effects overlapping in space
Occurring Multiple Times	Potential cumulative effect through time	Potential cumulative effect overlapping in space and time.

(B)

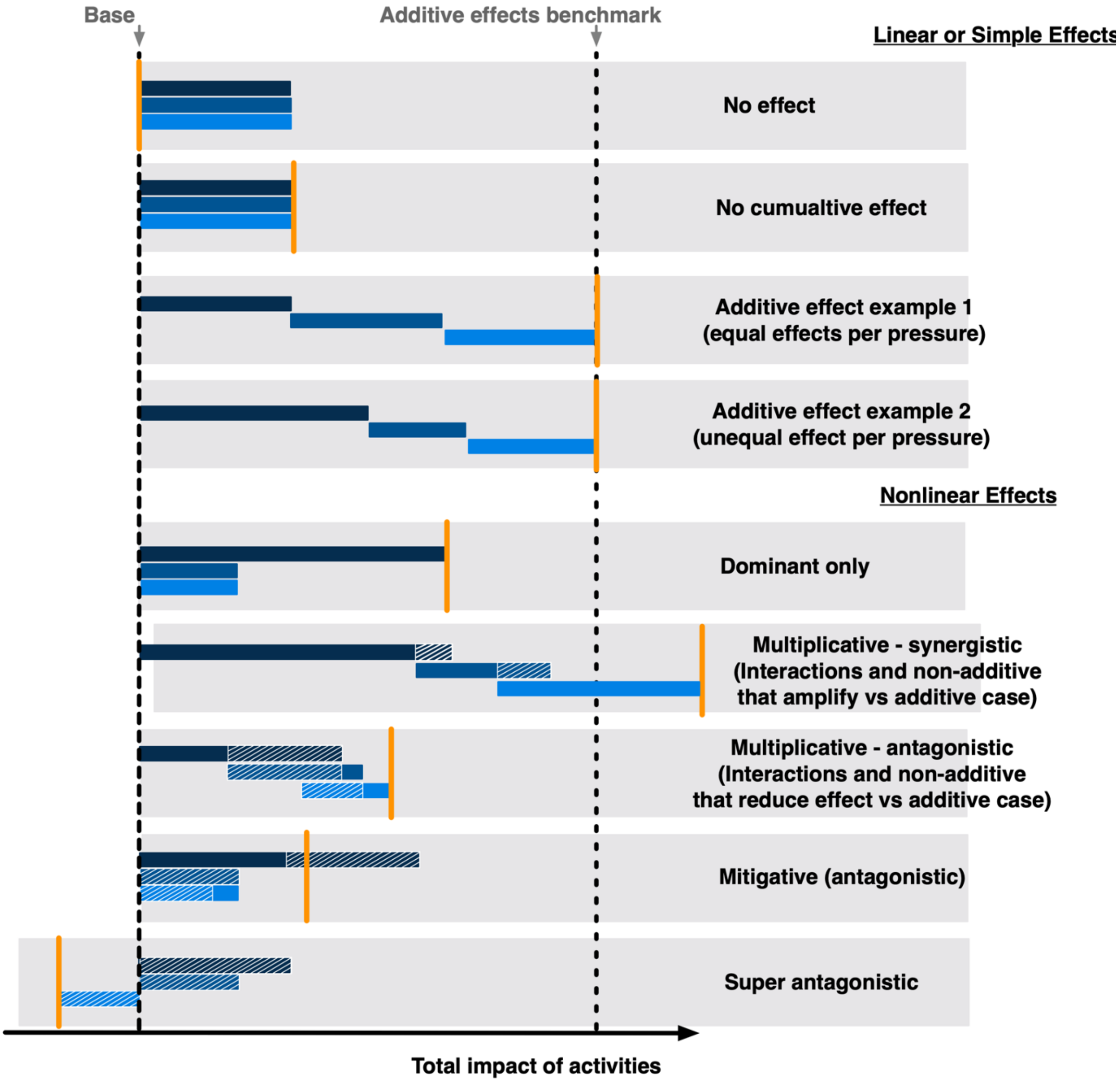


Figure 1: Reproduced from Fulton et al 2021. (A) Matrix of conditions leading to cumulative effects; (B) schematic showing different types of effects – non-cumulative and cumulative (additive and non-linear). Non-linear effects are marked by interactions (hashed areas on each bar) meaning the outcomes do not simply add up to the linear sum of the individual effects (the base of no effect and the benchmark of additive effects are shown as vertical black dotted lines so the levels resulting from other effects are clearer). Panel B is modified from Halpern et al (2008)

Need

The need for Cumulative Effects Assessment (CEA) is increasingly being recognised as a pressing priority for environmental management nationally and internationally (Halpern et al., 2008; Korpinen and Andersen, 2016; Stelzenmüller et al., 2018; Treblico et al., 2021). The development process for Australia's Harvest and Bycatch Policies, and their associated guidelines have reinforced the need for assessment of cumulative effects, and the Environment Protection and Biodiversity Conservation Act 1999 EPBC Act has also explicitly required consideration of cumulative impacts, and successive State of the Environment Reports have identified better accounting for and management of cumulative impact as a key need for supporting ongoing sustainability of Australia's environment (Cresswell et al 2021, Jackson et al 2016).

The focus of this project was the development of methods to estimate the cumulative effects of multiple fisheries and sectors (commercial and recreational) on individual species, habitats and communities. The assessment framework is scalable both in terms of spatial extent, but also to allow for the effects of other sectors (e.g. customary fisheries) and non-fishing activities (e.g. coastal development, habitat loss) in future as required.

Where multiple activities occur or are planned, an understanding of their combined effects on the environment is necessary to address policy requirements and achieve sustainability (Halpern et al., 2008). The concept of cumulative effects assessment is not new – indeed cumulative assessment has been recognized since 1983 (NRC, 1983), though ecological rather than toxicological assessments did not really begin before the 1990s and the release of the USA Environmental Protection Agency (EPA) "Red Book" in 2003 (Suter et al., 2003). Interest in CEAs rose sharply from 2000 onwards, especially in marine systems, with the release of the US EPA's revised guidelines (US EPA 2003), the "Silver Book" (NRC, 2009) and the work by Astles et al., (2006), Halpern et al., (2008) and others (e.g. Samhouri and Levin, 2012) that began to address the need for more holistic approaches that had the capacity to assess the combined effects of cumulative exposure to multiple stressors (of multiple types) from multiple sources, acting via multiple and potentially interacting pathways.

A range of methods have been proposed around the globe (Callahan and Sexton, 2007; Stelzenmüller et al., 2018; Hammar et al., 2020). However, no single method for undertaking cumulative assessments has been accepted nationally or globally. Within fisheries there is a need to consider the effects across all fishing sectors (commercial, recreational, indigenous, as required by recent changes to the Fisheries Administration Act 1991) and all jurisdictions. Taking a systemic view, there is also an increasing need to consider other users of marine resources and coastal waters (e.g. renewable energy, shipping etc.,), especially given the expanding use of ocean and coastal waters (McCauley et al., 2015; AIMS, 2020; Future Earth Australia, 2021;). Allowing for such an expansion of scope in future, without a substantial revision of the approach proposed for fisheries was an important consideration underlying the method developed in this project.

Target species stock assessments typically consider the species of interest as well as other sources of fishing mortality (e.g. discards), but they do not usually consider their effects on other fisheries sectors, or the effects of other sectors on the focal fishery. CEA methods therefore need to consider both direct and indirect effects. To date, direct effects are often viewed as additive (simple linear addition of one impact to another) with little consideration given to synergistic, antagonistic or non-linear effects, and indirect effects are generally not considered. While the ERAEF toolbox used for assessment of byproduct, bycatch and protected species has some potential options for cumulative impacts (e.g. eSAFE method; Zhou et al. 2016), at this stage they are insufficient for moving to the scales and complexities attributable across multiple fishing sectors and fisheries. Thus, sustainable fisheries management requires a new approach that considers all sectors and all fisheries and how they impact the environment.

Project Context – COVID-19

The project was originally developed in consultation with AFMA, Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES), and several Australian state fisheries and environmental departments, and operators in multiple commercial fishing sectors. At the outset of the project the intent was to continue that close consultation through the life of the project, including working with customary fishers to include their sector in this initial assessment. Unfortunately, close to the completion of the review of the approaches to Ecological Risk Assessment for the Effects of Fishing (ERAEF), which formed a foundational stage of the work, the SARS-CoV-2 (COVID-19) pandemic began. This meant it was impossible to engage with First Nation or fishing communities directly and the research had to become purely analytical.

Objectives

1. Undertake a two-part review. This first part being to review existing cumulative impacts literature on methods applied elsewhere in the world, to produce design principles for a scalable cumulative impacts approach; and a synthesis of current benchmark methods and gaps in methods that must be filled to deliver Australian needs. And the second part being a global Ecological Risk Assessment (ERA) review to identify cumulative impacts seen in other fisheries, with the specific focus of this review as specified by the AFMA led ERA/ERM working group – including looking: at the assessment methods used elsewhere; their information needs and context; the strengths and weaknesses of the different approaches; synergies and efficiencies that can be adopted; and recommend cost-effect ERA/ERM integration of additional methods that have been found to be appropriate given an AFMA context.

2. Characterise cumulative issues complicating cumulative impact assessments and, via a methods scan, deliver a list of options for addressing these issues.

3. Develop a cumulative impacts framework that structures the sequence of analyses done for each assessment based on the characteristics of the sectors and ecological components involved – key commercial, byproduct, bycatch and protected species, and habitats and ecological communities.

4. Perform an Australia-wide cumulative impacts assessment, with fishery-specific results, for (i) Commonwealth fisheries across ecological components, (ii) indigenous and recreational sectors that interact with Commonwealth fisheries for these components and (iii) and state and recreational fisheries where they overlap with Commonwealth fisheries.

Method

Reviews

The reviews of available ERA and CEA methods deliver on Objective 1 of the project. Both reviews followed the PRIMSA protocol.

This ERA review built on the work of Holsman et al., (2017) and others and synthesised the large number of publicly available documents (papers and reports) regarding ERA applications around the world. We did not attempt to review in detail the many Level 3 (fully quantitative) assessment models as reviews already existed for those assessment methods (e.g. for single species, ecosystems and data poor) (Quinn and Deriso, 1999; Plagányi, 2007; Travers et al., 2008; Fulton, 2010; ICES, 2012; Fulton and Link, 2014; Chrysafi and Kuparinen, 2016; Dowling et al., 2016; Carruthers and Hordyk, 2018; Aeberhard et al., 2018).To canvas the ERA assessments within scope a document search was performed on May 5th 2019 using the Web of Science database, google scholar (https://scholar.google.com/), semantic scholar (https://www.semanticscholar.org/) and google more generally. The search terms were "fisheries AND 'ecological risk assessment'" as well as "ecological AND risk AND assessment AND fisheries". The papers secured from this first search were reviewed. Any relevant papers/reports referred to in the papers from this first search were also retrieved and reviewed. A total of 221 ERA-relevant documents were reviewed with respect to:

- Geographic location
- Objectives of the specific study being reported in the document
- ERA method used (including dimensions or criteria, if noted)
- Strengths and weaknesses of the specific approach
- Other relevant commentary on content or messages from the paper.

For the CEA review a document search was undertaken on the 7th of January and again on the 19th of November 2020 using the Web of Science, Google Scholar (https://scholar.google.com/) and Semantic Scholar (https://www.semanticscholar.org/) based on the search phrases; (cumulat* OR compound* OR combin*) AND (effect* OR impact*) AND assess* and for the entire time period available. While this set of search terms went beyond the marine and environmental sectors it provided useful insight into historical precedent, motivation and grounding of more recent methods. Once that foundation was summarised, the body of the review focused on marine and coastal CEAs (on the assumption that this would include assessments directly relevant to fisheries or could be extended to fisheries easily). This stage of the review was constrained to publications from 2000 onwards, as this coincided with the initiation of increasing interest in the marine sphere, as well as a review and refinement of methods used in many of the disciplines using CEAs. In total more than 65 papers were reviewed in drawing together material for the CEA review.

Cumulative Effects Assessment

The output of the CEA review, results of which are summarised and can be found in full in Fulton et al., (2021), formed the basis of a method scan in that it allowed for the derivation of the CEA approach applied in the remainder of the project**. This work delivered on Objective 2.**

The review recommended a staged approach but also envisaged a collaborative science-policy process that was beyond the scope of what was possible once COVID-19 began. Consequently, a purely analytical approach was undertaken following the steps outlined in Figure 2 (and detailed further below) and drawing on the system structural state categorisations in Figure 3 and the assessment structuring questions given in Table 1.

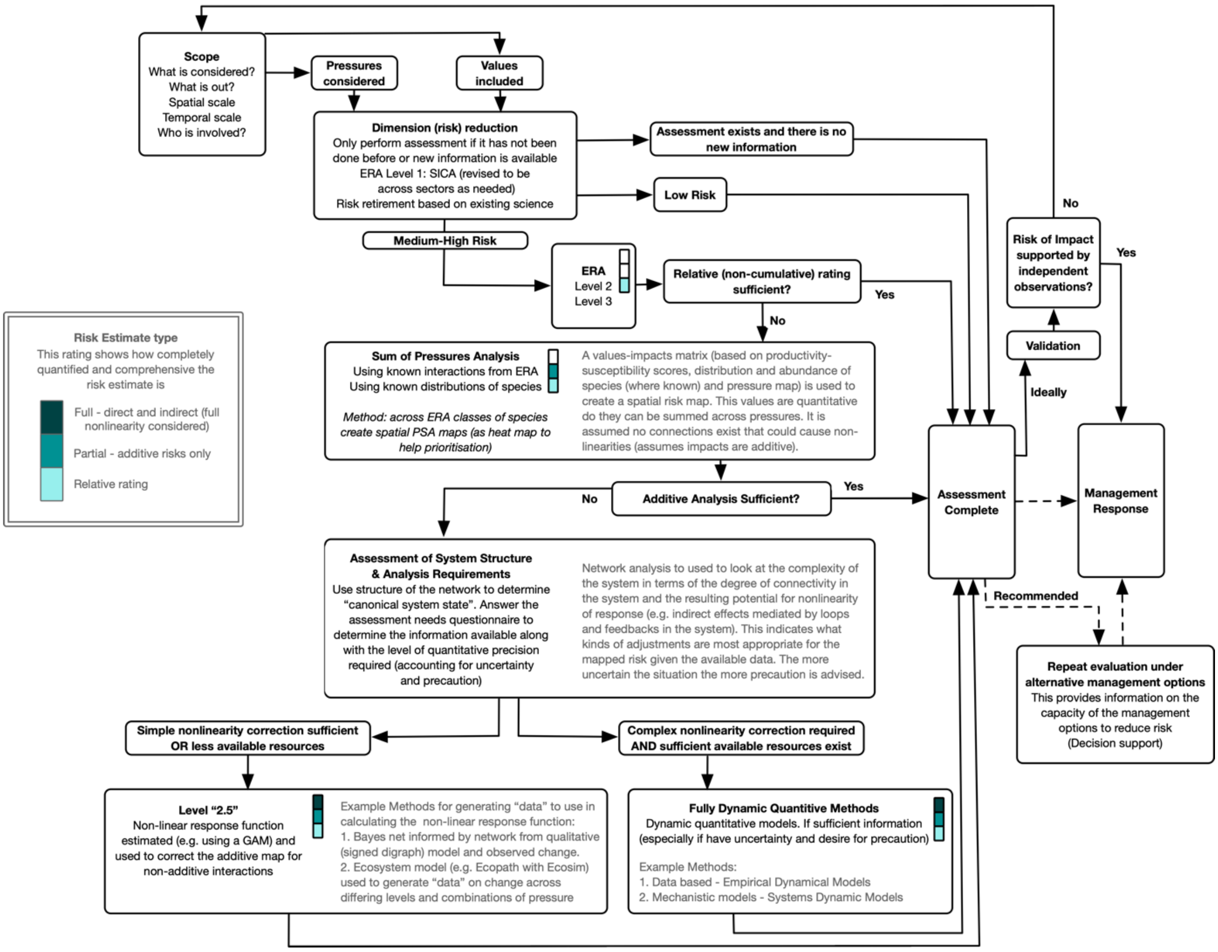


Figure 2: Flow diagram of cumulative assessment steps used in this project – derived based on a horizon scan of available approaches. There is a focus on the analytical steps here as more participatory approaches were precluded by COVID-19. Ideally these steps would form the analytical steps of a science-regulatory-policy participatory process as outlined in Fulton et al., (2021).

The analysis framework provided by Figures 2 and 3 and Table 1 delivers on Objective 3, as the analyses provide a means of calculating the cumulative effects of recreational, state and commonwealth fisheries for key commercial, byproduct, bycatch and protected species. The COVID-19 pandemic precluded the inclusion of customary fisheries as the level of in person engagement and collaboration required to include those fisheries in detail was not possible; consequently, delivering on that part of the objective was not possible.

The same method can be used for habitats. For example, via a pressure overlay on the habitat definitions of Pitcher et al (2016). Ecosystem considerations can be directly generated from the network analysis or modelling work undertaken as part of the "Level 2.5" or "Fully Dynamic Quantitative Methods". It would be straightforward to extend the analysis to non-fisheries sectors in future.

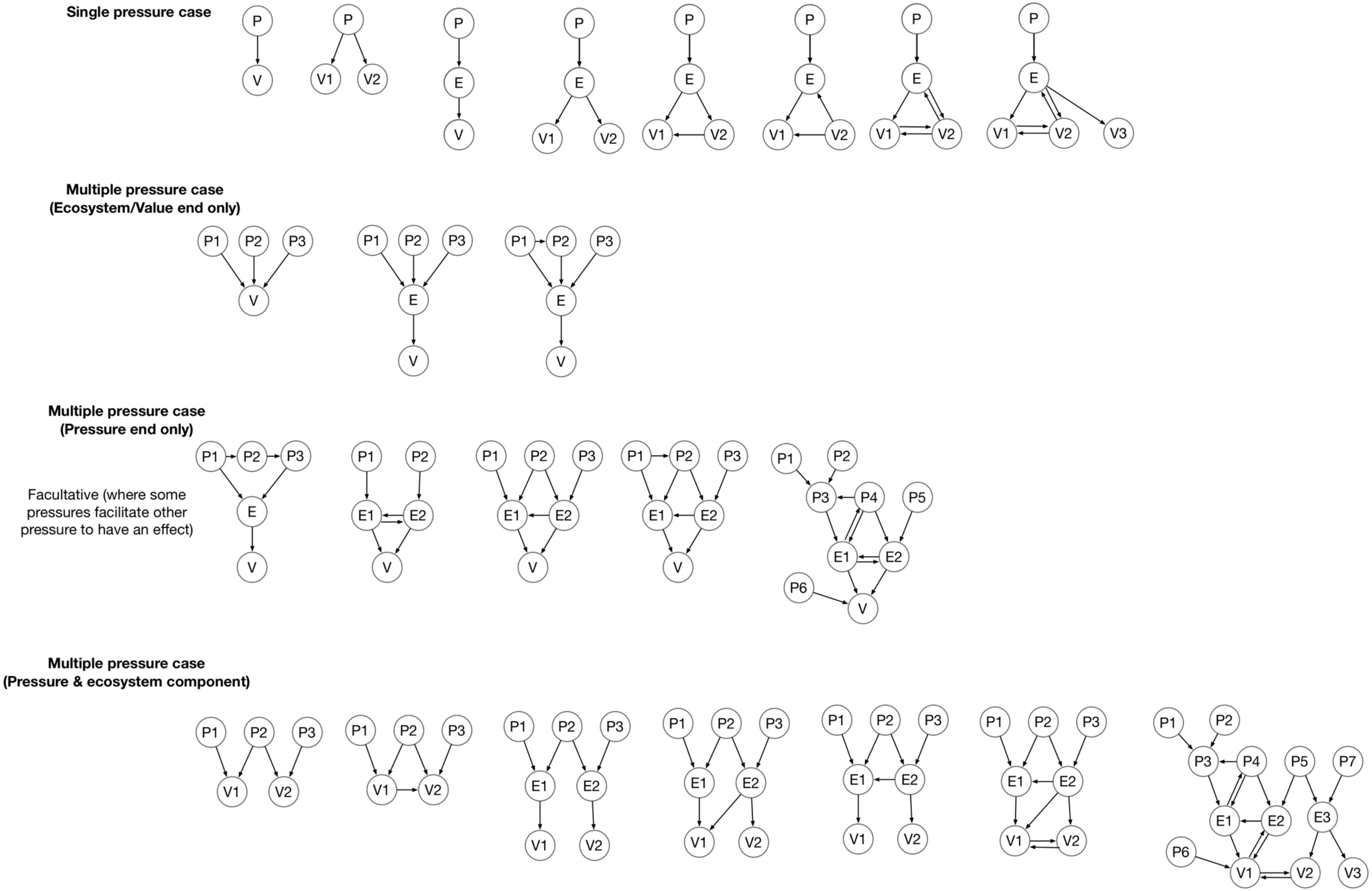


Figure 3: Different general forms of system structural state – P is for pressure, E is for effect type and V is for system value (in this case species or habitat; ecosystem effects are emergent from the combined set of values). Structural complexity increases top to bottom and left to right. Some methods are better able to cope with certain types of complexity

Table 1: Analysis Requirements – the table entries show which tools are appropriate. Note that machine learning and artificial intelligence are included in responses for statistical models.

Key				
	□ No capability	▒ Partial	■ Full	▨ With Modification

	System Structure					
	Single Pressure		**Multiple independent pressures**		**Multiple interacting pressures**	
Analysis requirements*	**Independent values**	**Interacting values**	**Independent values**	**Interacting values**	**Independent values**	**Interacting values**
Spatial distribution of cumulative effects	▨ Expert information ■ Overlays □ Signed diagraphs ■ Statistical Models ▨ Bayes Nets ■ Dyn. Systems Model	▨ Expert information ■ Overlays □ Signed diagraphs ■ Statistical Models ▨ Bayes Nets ■ Dyn. Systems Model	▨ Expert information ■ Overlays □ Signed diagraphs ■ Statistical Models ▨ Bayes Nets ■ Dyn. Systems Model	▨ Expert information ■ Overlays □ Signed diagraphs ■ Statistical Models ▨ Bayes Nets ■ Dyn. Systems Model	□ Expert information □ Overlays □ Signed diagraphs ■ Statistical Models ▨ Bayes Nets ■ Dyn. Systems Model	□ Expert information □ Overlays □ Signed diagraphs ■ Statistical Models ▨ Bayes Nets ■ Dyn. Systems Model
Identification of altered ecosystem processes	▒ Expert information □ Overlays ▒ Signed diagraphs ■ Statistical Models ■ Bayes Nets ■ Dyn. Systems Model	▨ Expert information □ Overlays ▒ Signed diagraphs ■ Statistical Models ▨ Bayes Nets ■ Dyn. Systems Model	▒ Expert information □ Overlays ▒ Signed diagraphs ■ Statistical Models ■ Bayes Nets ■ Dyn. Systems Model	▒ Expert information □ Overlays ▒ Signed diagraphs ■ Statistical Models ▨ Bayes Nets ■ Dyn. Systems Model	□ Expert information □ Overlays ▒ Signed diagraphs ■ Statistical Models ▨ Bayes Nets ■ Dyn. Systems Model	□ Expert information □ Overlays ▒ Signed diagraphs ■ Statistical Models ▨ Bayes Nets ■ Dyn. Systems Model
Explicit link between pressures or values	■ Expert information ■ Overlays ■ Signed diagraphs ■ Statistical Models ■ Bayes Nets ■ Dyn. Systems Model	■ Expert information ■ Overlays ■ Signed diagraphs ■ Statistical Models ■ Bayes Nets ■ Dyn. Systems Model	■ Expert information ■ Overlays ■ Signed diagraphs ■ Statistical Models ■ Bayes Nets ■ Dyn. Systems Model	▒ Expert information ■ Overlays ■ Signed diagraphs ■ Statistical Models ■ Bayes Nets ■ Dyn. Systems Model	□ Expert information □ Overlays ■ Signed diagraphs ■ Statistical Models ■ Bayes Nets ■ Dyn. Systems Model	□ Expert information □ Overlays ■ Signed diagraphs ■ Statistical Models ■ Bayes Nets ■ Dyn. Systems Model
Non-linear effects between pressures and values need to be represented	□ Expert information □ Overlays ▒ Signed diagraphs ■ Statistical Models ▒ Bayes Nets ■ Dyn. Systems Model	□ Expert information □ Overlays ▒ Signed diagraphs ■ Statistical Models ▒ Bayes Nets ■ Dyn. Systems Model	□ Expert information □ Overlays ▒ Signed diagraphs ■ Statistical Models ▒ Bayes Nets ■ Dyn. Systems Model	□ Expert information □ Overlays ▒ Signed diagraphs ■ Statistical Models ▒ Bayes Nets ■ Dyn. Systems Model	□ Expert information □ Overlays ▒ Signed diagraphs ■ Statistical Models ▒ Bayes Nets ■ Dyn. Systems Model	□ Expert information □ Overlays ▒ Signed diagraphs ■ Statistical Models ▒ Bayes Nets ■ Dyn. Systems Model
Indirect effects need to be incorporated	□ Expert information □ Overlays ■ Signed diagraphs ■ Statistical Models ▒ Bayes Nets ■ Dyn. Systems Model	□ Expert information □ Overlays ■ Signed diagraphs ■ Statistical Models ▒ Bayes Nets ■ Dyn. Systems Model	□ Expert information □ Overlays ■ Signed diagraphs ■ Statistical Models ▒ Bayes Nets ■ Dyn. Systems Model	□ Expert information □ Overlays ■ Signed diagraphs ■ Statistical Models ▒ Bayes Nets ■ Dyn. Systems Model	□ Expert information □ Overlays ■ Signed diagraphs ■ Statistical Models ▒ Bayes Nets ■ Dyn. Systems Model	□ Expert information □ Overlays ■ Signed diagraphs ■ Statistical Models ▒ Bayes Nets ■ Dyn. Systems Model

	System Structure					
	Single Pressure		Multiple independent pressures		Multiple interacting pressures	
Analysis requirements*	**Independent values**	**Interacting values**	**Independent values**	**Interacting values**	**Independent values**	**Interacting values**
Masking, antagonistic, additive and synergistic effects need to be distinguished	□ Expert information	□ Expert information	□ Expert information	□ Expert information	□ Expert information	□ Expert information
	□ Overlays	□ Overlays	□ Overlays	□ Overlays	□ Overlays	□ Overlays
	▒ Signed diagraphs	▒ Signed diagraphs	▒ Signed diagraphs	▒ Signed diagraphs	▒ Signed diagraphs	▒ Signed diagraphs
	■ Statistical Models	■ Statistical Models	■ Statistical Models	■ Statistical Models	■ Statistical Models	■ Statistical Models
	■ Bayes Nets	▒ Bayes Nets	■ Bayes Nets	▒ Bayes Nets	▒ Bayes Nets	▒ Bayes Nets
	■ Dyn. Systems Model	■ Dyn. Systems Model	■ Dyn. Systems Model	■ Dyn. Systems Model	■ Dyn. Systems Model	■ Dyn. Systems Model
“Gateway pressures” (pressures that cause change that facilitates further effect) need to be identified	▒ Expert information	▒ Expert information	▒ Expert information	▒ Expert information	□ Expert information	□ Expert information
	□ Overlays	□ Overlays	□ Overlays	□ Overlays	□ Overlays	□ Overlays
	□ Signed diagraphs	□ Signed diagraphs	□ Signed diagraphs	□ Signed diagraphs	□ Signed diagraphs	□ Signed diagraphs
	□ Statistical Models	□ Statistical Models	□ Statistical Models	□ Statistical Models	□ Statistical Models	□ Statistical Models
	□ Bayes Nets	□ Bayes Nets	□ Bayes Nets	□ Bayes Nets	□ Bayes Nets	□ Bayes Nets
	■ Dyn. Systems Model	■ Dyn. Systems Model	■ Dyn. Systems Model	■ Dyn. Systems Model	■ Dyn. Systems Model	■ Dyn. Systems Model
The impacts of multiple pressures acting simultaneously or sequentially need to be incorporated	▒ Expert information	▒ Expert information	▒ Expert information	▒ Expert information	▒ Expert information	▒ Expert information
	▒ Overlays	▒ Overlays	▒ Overlays	▒ Overlays	▒ Overlays	▒ Overlays
	▒ Signed diagraphs	▒ Signed diagraphs	▒ Signed diagraphs	▒ Signed diagraphs	▒ Signed diagraphs	▒ Signed diagraphs
	▒ Statistical Models	▒ Statistical Models	▒ Statistical Models	▒ Statistical Models	▒ Statistical Models	▒ Statistical Models
	▒ Bayes Nets	▒ Bayes Nets	▒ Bayes Nets	▒ Bayes Nets	▒ Bayes Nets	▒ Bayes Nets
	■ Dyn. Systems Model	■ Dyn. Systems Model	■ Dyn. Systems Model	■ Dyn. Systems Model	■ Dyn. Systems Model	■ Dyn. Systems Model
Temporal variation or time lags need to be included	▒ Expert information	▒ Expert information	▒ Expert information	▒ Expert information	▒ Expert information	▒ Expert information
	□ Overlays	□ Overlays	□ Overlays	□ Overlays	□ Overlays	□ Overlays
	▨ Signed diagraphs	▨ Signed diagraphs	▨ Signed diagraphs	▨ Signed diagraphs	▨ Signed diagraphs	▨ Signed diagraphs
	■ Statistical Models	■ Statistical Models	■ Statistical Models	■ Statistical Models	■ Statistical Models	■ Statistical Models
	▨ Bayes Nets	▨ Bayes Nets	▨ Bayes Nets	▨ Bayes Nets	▨ Bayes Nets	▨ Bayes Nets
	■ Dyn. Systems Model	■ Dyn. Systems Model	■ Dyn. Systems Model	■ Dyn. Systems Model	■ Dyn. Systems Model	■ Dyn. Systems Model
Future effects need to be predicted	▒ Expert information	▒ Expert information	▒ Expert information	▒ Expert information	▒ Expert information	▒ Expert information
	□ Overlays	□ Overlays	□ Overlays	□ Overlays	□ Overlays	□ Overlays
	▒ Signed diagraphs	▒ Signed diagraphs	▒ Signed diagraphs	▒ Signed diagraphs	▒ Signed diagraphs	▒ Signed diagraphs
	▒ Statistical Models	▒ Statistical Models	▒ Statistical Models	▒ Statistical Models	▒ Statistical Models	▒ Statistical Models
	■ Bayes Nets	■ Bayes Nets	■ Bayes Nets	■ Bayes Nets	▒ Bayes Nets	▒ Bayes Nets
	■ Dyn. Systems Model	■ Dyn. Systems Model	■ Dyn. Systems Model	■ Dyn. Systems Model	■ Dyn. Systems Model	■ Dyn. Systems Model
Changes in system structure or function need to be captured	▒ Expert information	▒ Expert information	▒ Expert information	▒ Expert information	▒ Expert information	▒ Expert information
	□ Overlays	□ Overlays	□ Overlays	□ Overlays	□ Overlays	□ Overlays
	▒ Signed diagraphs	▒ Signed diagraphs	▒ Signed diagraphs	▒ Signed diagraphs	▒ Signed diagraphs	▒ Signed diagraphs
	▒ Statistical Models	▒ Statistical Models	▒ Statistical Models	▒ Statistical Models	▒ Statistical Models	▒ Statistical Models
	▒ Bayes Nets	▒ Bayes Nets	▒ Bayes Nets	▒ Bayes Nets	▒ Bayes Nets	▒ Bayes Nets
	■ Dyn. Systems Model	■ Dyn. Systems Model	■ Dyn. Systems Model	■ Dyn. Systems Model	■ Dyn. Systems Model	■ Dyn. Systems Model

	System Structure											
	Single Pressure				Multiple independent pressures				Multiple interacting pressures			
Analysis requirements*	**Independent values**		**Interacting values**		**Independent values**		**Interacting values**		**Independent values**		**Interacting values**	
The method needs to provide new system understanding	□	Expert information	□	Expert information	□	Expert information	□	Expert information	□	Expert information	□	Expert information
	□	Overlays	□	Overlays	□	Overlays	□	Overlays	□	Overlays	□	Overlays
	■	Signed diagraphs	■	Signed diagraphs	■	Signed diagraphs	■	Signed diagraphs	**	Signed diagraphs	**	Signed diagraphs
	▒	Statistical Models	▒	Statistical Models	▒	Statistical Models	▒	Statistical Models	▒	Statistical Models	▒	Statistical Models
	■	Bayes Nets	■	Bayes Nets	■	Bayes Nets	■	Bayes Nets	■	Bayes Nets	■	Bayes Nets
	■	Dyn. Systems Model	■	Dyn. Systems Model	■	Dyn. Systems Model	■	Dyn. Systems Model	■	Dyn. Systems Model	■	Dyn. Systems Model
Uncertainty estimates	▨	Expert information	▨	Expert information	▨	Expert information	▨	Expert information	▨	Expert information	▨	Expert information
	▨	Overlays	▨	Overlays	▨	Overlays	▨	Overlays	▨	Overlays	▨	Overlays
	▒	Signed diagraphs	▒	Signed diagraphs	▒	Signed diagraphs	▒	Signed diagraphs	▒	Signed diagraphs	▒	Signed diagraphs
	■	Statistical Models	■	Statistical Models	■	Statistical Models	■	Statistical Models	■	Statistical Models	■	Statistical Models
	■	Bayes Nets	■	Bayes Nets	■	Bayes Nets	■	Bayes Nets	■	Bayes Nets	■	Bayes Nets
	▒	Dyn. Systems Model	▒	Dyn. Systems Model	▒	Dyn. Systems Model	▒	Dyn. Systems Model	▒	Dyn. Systems Model	▒	Dyn. Systems Model
The method can deal with the absence of information	▒	Expert information	▒	Expert information	▒	Expert information	▒	Expert information	▒	Expert information	▒	Expert information
	□	Overlays	□	Overlays	□	Overlays	□	Overlays	□	Overlays	□	Overlays
	▒	Signed diagraphs	▒	Signed diagraphs	▒	Signed diagraphs	▒	Signed diagraphs	▒	Signed diagraphs	▒	Signed diagraphs
	▒	Statistical Models	▒	Statistical Models	▒	Statistical Models	▒	Statistical Models	▒	Statistical Models	▒	Statistical Models
	▒	Bayes Nets	▒	Bayes Nets	▒	Bayes Nets	▒	Bayes Nets	▒	Bayes Nets	▒	Bayes Nets
	▒	Dyn. Systems Model	▒	Dyn. Systems Model	▒	Dyn. Systems Model	▒	Dyn. Systems Model	▒	Dyn. Systems Model	▒	Dyn. Systems Model
The method needs to sit within an adaptive management cycle	▒	Expert information	▒	Expert information	▒	Expert information	▒	Expert information	▒	Expert information	▒	Expert information
	▒	Overlays	▒	Overlays	▒	Overlays	▒	Overlays	▒	Overlays	▒	Overlays
	▒	Signed diagraphs	▒	Signed diagraphs	▒	Signed diagraphs	▒	Signed diagraphs	▒	Signed diagraphs	▒	Signed diagraphs
	■	Statistical Models	■	Statistical Models	■	Statistical Models	■	Statistical Models	■	Statistical Models	■	Statistical Models
	■	Bayes Nets	■	Bayes Nets	■	Bayes Nets	■	Bayes Nets	■	Bayes Nets	■	Bayes Nets
	■	Dyn. Systems Model	■	Dyn. Systems Model	■	Dyn. Systems Model	■	Dyn. Systems Model	■	Dyn. Systems Model	■	Dyn. Systems Model
The method is suitable when there is limited resources	■	Expert information	■	Expert information	■	Expert information	■	Expert information	■	Expert information	■	Expert information
	■	Overlays	■	Overlays	■	Overlays	■	Overlays	■	Overlays	■	Overlays
	■	Signed diagraphs	■	Signed diagraphs	■	Signed diagraphs	■	Signed diagraphs	■	Signed diagraphs	■	Signed diagraphs
	▒	Statistical Models	▒	Statistical Models	▒	Statistical Models	▒	Statistical Models	▒	Statistical Models	▒	Statistical Models
	▒	Bayes Nets	▒	Bayes Nets	▒	Bayes Nets	▒	Bayes Nets	▒	Bayes Nets	▒	Bayes Nets
	▒	Dyn. Systems Model	▒	Dyn. Systems Model	▒	Dyn. Systems Model	▒	Dyn. Systems Model	▒	Dyn. Systems Model	▒	Dyn. Systems Model

* Additional constraints may exist depend on the risk profile of the decision maker

** Constrained by the number of components the analysis can include before it struggles with convergence

The highly variable nature of the distribution of fisheries around Australia, along with international best practice recommendations on the use of spatial maps for communicating cumulative effects, means qualitative non-spatial assessments were not undertaken here (nor are they being recommended, though Table 1 includes them for completeness).

Stage I steps through the framework from scoping to the "Sum of Pressure Analysis" step. The output of that analysis provides an indicative additive estimate of cumulative effects for individual species and overall. While eSAFE (Zhou et al., 2019) also provides for cumulative effects of fishing, we intentionally expanded the form of assessment tools here to allow for easy inclusion of pressures beyond fisheries in the future and expanded the range of species for which the methods used could be straightforwardly applied. This allows for consistency with what is being done in other federal management agencies, such as Parks Australia.

A demonstration of how this could be extended to non-linear interactions ("Level 2.5") is given for Stage II. This non-additive estimate is predicated on having diet and fisheries catch composition data and, where possible, a verified ecosystem model such as Ecopath with Ecosim (Christensen and Walters 2004; Bulman et al., 2006). Given those constraints, Stage II analyses were only carried out for species in south-eastern Australia to demonstrate the method and allow comparison with the additive (Stage I) approach to judge the value added by inclusion of the non-additive components. This location was selected as it has the most robustly fit ecosystem models and because levels of activity in this region mark the area out as the highest priority for understanding the magnitude of cumulative effects. While ecosystem models do exist for many other locations around Australia, some gaps exist (especially in south western Australia) and it would be important to fill these gaps and build confidence in these models (e.g. by verifying model dynamics and content versus more recent fisheries data from the relevant jurisdictions) before attempting an Australia-wide application. Moreover, the results from the proof-of-concept application in south-eastern Australia show wide uncertainty bands, highlighting the need for validation for there to be confidence in the reliability of results. Consequently, rolling out this approach at a national level seemed premature. Additional consideration of other model types would be needed if the approach was expanded to include other sectors.

Stage I Analysis

Scope

As directed by the original project need statement, the assessment was conducted for species listed in AFMA ERA documents that interact with state, Commonwealth and recreational fisheries. The temporal period considered was constrained to 2011-2015 as spatial records of effort for state fisheries were only available for that time. Consequently, the results will only be indicative of effects of more recent effects levels. If longer or more spatially resolved fisheries time series were available across jurisdictions, the analysis could be straightforwardly updated using existing R scripts created to undertake each step of the analysis. Alternatively, individual jurisdictions could apply the method (using the R-scripts) within the agency to consider results in more detail.

Values

Distribution of the species listed in ERA assessments were obtained from existing data (the current species distributions used in ERA) where available. This identifies where a species occurs (a value of 1) or is absent (a value of 0).

Potential future extensions could include model-based analysis using a variety of potential methods such as Poission Point models (Warton & Shepherd 2010). This approach could be flexibly applied to a number of different distributions (eg Negative Binomial; Zhou 2013), the generalised additive model (GAM) of Zhou et al (2019) and machine learning methods could be applied where appropriate (eg MAXENT; Steven et al 2006).

Pressures

Fisheries data from AFMA fisheries was extracted for the years 2011 to 2015. This corresponds with the dates that were used to obtain data on state fisheries and corresponds with the data sets publicly released at https://marlin.csiro.au/geonetwork/srv/eng/catalog.search#/metadata/aa53a4df-7fe6-46d1-93b7-2d3732f4883e . Full metadata for state fisheries is given in Dunstan et al (2023). For this analysis, the effort for Queensland, NSW, Victoria, Tasmania, South Australia and Western Australia were used. Data from Norther Territory was assessed as not compatible with this analysis due to the extremely large grid size used and the fisheries gears. Fisheries data for all fisheries were aggregated by gear type at a 0.1 degree grid resolution – this was done as the spatial resolution of the effort data varies across jurisdictions. Standardised fisheries effort across all fleets was calculated using the number of operations in each grid cell, scaled so that the maximum recorded effort is for each fishery 1.

Assumed recreational fishing effort applied per grid cell was calculated from Navarro et al (2021) who used a random utility model to estimate recreational fishing effort nationally.

As gear efficiencies were not directly available for State fisheries, the potential availability of each species to state gear was based on: (i) the gears it interacts with in Commonwealth waters; (ii) reporting in any documents accessible on the websites of the various state fisheries agencies – including annual reports, assessment reports, risk assessments etc. Laying the fisheries out in this way meant a mapping was possible between State and Commonwealth fisheries so that gear efficiencies from Commonwealth fisheries could be applied to state gears as a first approximation (this can be replaced in future should more direct estimates be available).

Dimension Reduction

This was inferred from the SICA available in the existing ERA documents.

Sum of Pressure Analysis

The eSAFE method of Zhou et al (2019) is an additive risk approach and could be used in full at this set step of the analysis. However, as noted by Zhou et al (2019) it can be challenging for particularly data poor species. Consequently, we explore an approach based on the ERA PSA scores, which utilises existing information. While bSAFE also presents a potential spatial method providing semi-quantitative indicators of the distribution of cumulative effects, we made the decision to use the method/data for the distribution of the values, as outlined below, as it aligns this approach with methods being used to inform Parks Australia regarding cumulative pressure (Hayes et al 2021, Dunstan et al 2023). Achieving consistency across departments and sectors will be an important outcome for managing future cumulative effect at a whole of seascape scale.

The Productivity-Susceptibility Analysis (PSA) steps were reproduced in R (and verified against CSIRO's automated ERA analysis products). Then for each 0.1 degree cell, for species (s) across all F fisheries (gears), the cumulative score is calculated as:

$$CumScore = \sum_{f=1}^{f=F} PSA_{sf} \cdot Effort_f \cdot \alpha_s \cdot Zoning_f$$

where α_s is the weighting due to the species distribution. In the simplest form of analysis, as shown here, will be 1 if present, 0 if absent. However, relative abundance could be used instead to capture a more graduated representation of population level exposure and risk; similarly fishing efficiency for the species-gear combination (e.g. as calculated in Zhou et al., 2013, 2019 for species with data on absences or Warton & Shepherd (2010) where only presences are known) could be used in place of the susceptibility aspect of the PSA score to provide a more resolved representation of exposure to the pressure. Given available information across species we used the PSA_{sf} score for each combination of species (s) and fishery (f) and a simple presence-absence weighting (α_s). Moreover, we assume that any post catch mortality or survival is already captured in the PSA score. If this is not the case then a survivorship term should be included in the equation, as done in Zhou et al., (2019).

The scalar $Zoning_f$ per fleet (f) was set to 1.0 when looking at total potential cumulative risk. To look at residual risk the cumulative score was then calculated with the zoning scalar set to 0 in any regions where effort by that fishery (gear type) was excluded through sector specific fisheries closures or Australian Marine Parks (as in Hayes et al 2021, Dunstan et al 2023). The total cumulative risk to Australia's marine species can be calculated from these scores by summing across all S species. Maps showing the difference between the total potential and residual cumulative risk can also be generated. The R-script to complete this analysis is available at https://github.com/eafulton/RmapCEA.git (species names and distributions are provided but not the fishing data, as that is subject to jurisdiction imposed restrictions on sharing, and the final effects maps are too large to store on that site, please contact the authors if that data is required).

Note that cumulative effects scores are negative if the species is detrimentally affected – so the larger the negative number, the more heavily impacted. The project team debated reversing the sign to ease communication, but as Stage II scores can have a beneficial effect, due to interaction effects, in the end it was decided a detrimental effect would be indicated by a negative score and beneficial effects with positive scores.

Stage II

Assessment of System Structure & Analysis Requirements

The COVID-19 pandemic meant that the relevant stakeholders required to define aspects of the Fully Dynamic Quantitative Assessment were unavailable which precluded providing an example of this kind of assessment. However, such an assessment would involve the spatial applications of a detailed Ecospace, Atlantis (e.g. Fulton et al., 2014, Coll et al., 2016) or similarly detailed social-ecological systems model that included the full food web, all fisheries sectors and detailed reconstructions of historical and current fishing.

"Level 2.5" Analysis

An updated version of the Ecopath with Ecosim (EwE) model of Bulman et al., (2006) was used to generate the information used to characterise the response function per modelled group. So that fishing pressure by fleet i for iteration j was given by:

$$Fishing\_Pressure_{i,j} = Baseline\_pressure_i \cdot \delta_j$$

$$\delta_j \sim \begin{cases} (0.2, 0.4, \dots, 4.8, 5.0) \text{ incrementing by } 0.2, \delta_j \leq 5 \\ (5.5, 6, \dots, 9.5, 10) \text{ incrementing by } 0.5, 5 \leq \delta_j \leq 10 \end{cases}$$

This iteration of fishing pressure was first done for one fleet at a time (holding all other fleets at baseline historical levels), and then for combinations of fleets changing together. It was too computationally prohibitive to consider every possible combination of fleet changes given the 11 different fleets in the model, but a full combinatoric set was considered for 2 through to 5 fleets changing together as well as 10 and 11 fleets changing together. This bookended the space of possible outcomes and represented 8506 individual simulations (executed using the EwE software's batch processing capability). Each simulation was run for 50 years, as the groups had reached equilibrium under the scaled fishing pressure by this point. The change in effort level per fleet as well as the end point changes in biomass and catch for each species or functional group, and the change in biodiversity (calculated using Kempton's Q; Ainsworth and Pitcher 2006) were stored for each run.

The normalised relative effort level in each simulation ($\acute{E}$) and the change in biomass (as an index of cumulative effect) under each fishing pressure iteration for each modelled species or functional group (ΔB_s) was then used as input to a GAM (using the mgcv package in R; Wood 2017) of the form:

$$\Delta B_s = f_1(\acute{E}) + f_2(\acute{E}, N)$$

Where f_1 and f_2 are thin plate regression splines and N is the number of fisheries in each simulation. This GAM was used to predict the response of each species/group for different combinations of effort and fleet number, based on the observed effort and fleet characteristics in each cell. The relative effort was the same as used for the PSA level 1 analysis. This approach allows us to predict the combined effects (including any non-linearities or indirect effects) of the fisheries active there given the fisheries (gear types) active. As there was a range of responses across the different combinations of fleets for each effort level a confidence interval was created by taking the mean, upper and lower bound of the GAM and using each in turn to generate the cumulative effects map. This reflects the range in responses for different combinations of fisheries. Ultimately, an approach that combined knowledge of the ecosystem dynamics and the spatial distribution of species/ecosystems and fisheries effort is needed.

An alternative to using the GAM would be to parameterise a Bayes Net per cell using the step PSA (or equivalent) score from the Sum of Pressure Analysis step to parameterise the strength of any direct interactions and then the output of a loop analysis and observed change (e.g. see Dambacher et al 2009) or ecosystem model output (as done above) to parameterise the strength of the nonlinear (including indirect) effects stemming from the ecosystem structure.

The R-scripts used to complete this analysis is available at https://github.com/eafulton/RmapCEA.git.

Results

The outputs of the reviews deliver on Objective 1 and 2. The framework used to generate the results for the Stage I and II analyses delivers on Objective 3 and the outputs of the Stage I and II analyses deliver on Objective 4.

ERA Review

The full ERA review can be found in Fulton et al (2019), reproduced in Appendix 3.

In summary, the review (which encompassed 221 papers or reports) highlighted that the ecosystem approach to fisheries management (EAFM) necessitates consideration of the status and hazards facing species that interact with fisheries beyond just target species. Ecological Risk Assessment for the Effects of Fishing (ERAEF) is a pragmatic approach to providing this consideration. The method originally developed by Hobday et al. (2007) had been expanded upon in the years since the original methodological publication, as the approach had been adopted in a number of jurisdictions. The review discussed how the method had been modified in subsequent implementations, with the intent of identifying any advances that could be applied in Australia.

The resulting recommended extensions to the methods used in Australian fisheries prioritised re-consideration of biological traits and Level 2 (PSA and SAFE) analyses to capture more taxon-specific traits and points of risk that may be missed with a more generalised set of attributes (as shown in Figure 4). For example: exposure or sensitivity of individual life history stages (when strong ontogenetic changes exist); cryptic mortalities (e.g. for seabirds); habitat and trophic dependencies; climate and how that adds stress or modifies the attribute values of each species, or how it changes spatial distributions and thereby exposure to fishing, or even which species should be included in the assessment; “predictability” of stocks (i.e. the influence of environmental variability); and for communities, review and update the indicators used. These modifications could be straightforwardly implemented via taxon-specific filtering of the traits used in online assessment tool used for ERAEF assessments for AFMA.

These changes and further automation of other aspects of the ERAEF would also make it easily extensible to consideration of absolute risk (and thereby cumulative effects) and proactive preparation for future effects and sustainability, rather than simply past or present fishery interactions and status. This would also allow for more direct links to tactical multi-species management and allow for expansion of the ERAEF approach to ecosystem scales (e.g. as part of multispecies harvest strategies).

Other ecosystem-oriented aspects should also be considered in any future revision of the approach applied by AFMA, such as: species interactions and indirect effects (e.g. trophic dependency); system dependency on that species (which could be assessed using the SURF or Hub network indices); ecosystem system structure and function (which will become easier as ecosystem metrics are more widely used in general); inter-annual variability and regime shifts (which may change attribute scores, outcomes of residual risk analyses, or even the species considered). In addition, the attributes and the scoring criteria used in Level 1 and 2 analyses should be periodically reviewed, as climate and exploitation can change susceptibility. The frequency of any such review should be tailored to the magnitude and rate of change of the environment or exploitation; with reviews occurring more frequently at higher rates of change, where there is higher sensitivity to mis-specification of traits and levels of exposure.

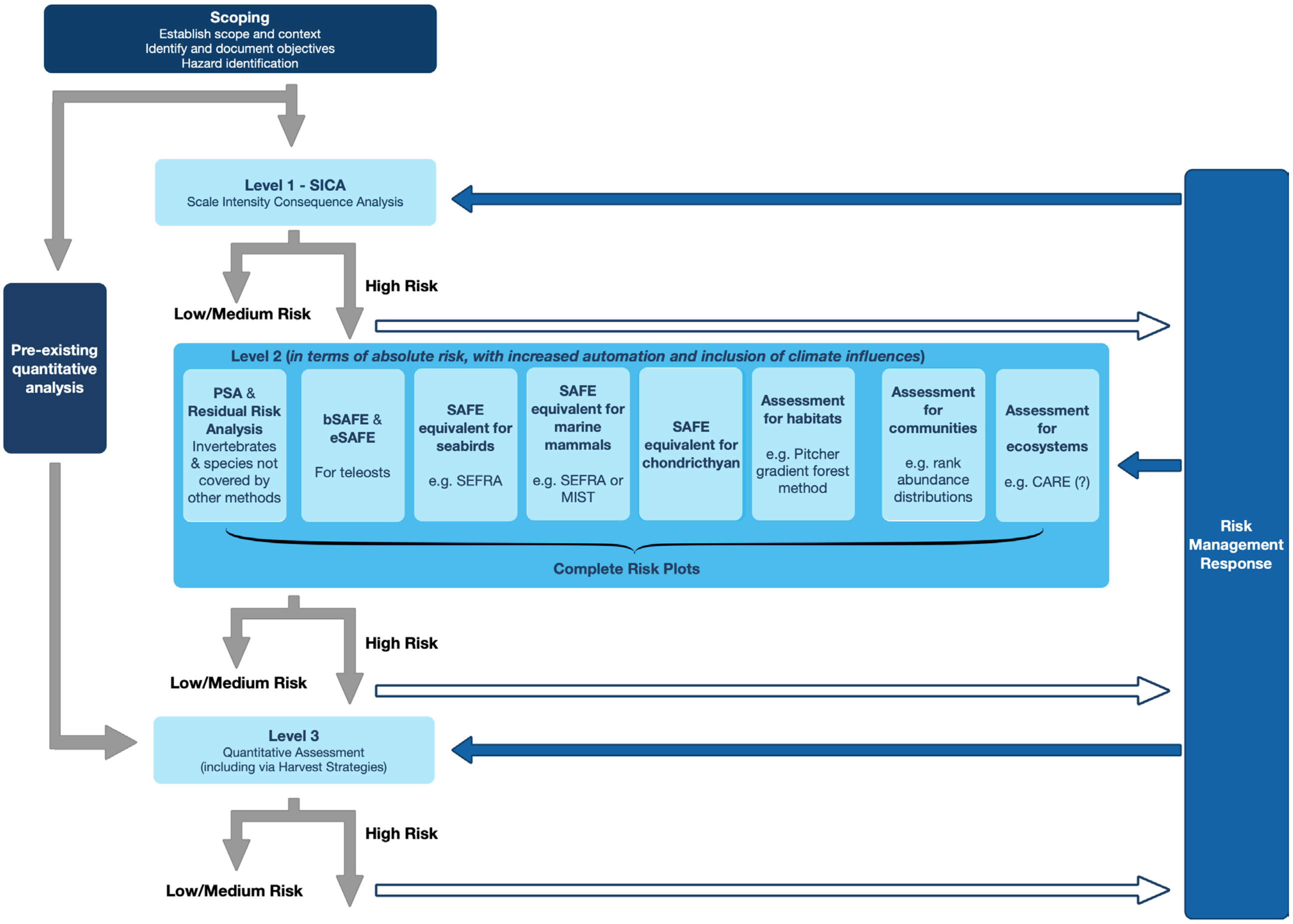


Figure 4: Recommended updated ERAEF workflow from Fulton et al (2019). Note that the use of absolute risk removes the need for Residual Risk Assessments. Also note that if a substantial number of species continue to be assessed using Productivity-Susceptibility Analysis (PSA), then inclusion of target stocks in the PSA is a valuable means of facilitating interpretation of the vulnerability of non-target stocks.

CEA Review

The full CEA review can be found in Fulton et al (2021), reproduced in Appendix 4.

The review of 65 relevant documents identified 14 different methods for completing a CEA, summarising (in Table 1 of that report) their individual approaches, scale, the forms of interactions and response types (additive or nonlinear) accounted for by the assessment, along with the system values considered (geochemical/physical, species, habitat, economic, social, cultural), specific data demands, uncertainty handling and whether it is possible to update or validate the assessment outputs and whether future predictions or attribution of effects is possible. The history of CEAs and common steps in these assessments were also discussed before outlining the following recommended approach:

1. Define the scope – both the geographic extent and the values (ecosystem components, whether ecological, social, economic or cultural) and activities/stressors to be considered
2. Mapping the spatiotemporal extent of the stressors
3. Mapping the spatiotemporal extent of the values of interest
4. Simple prioritisation – combine the outputs of the pressure and values mapping process through simple overlays, or via weighted maps based on the sensitivity of ecosystem components to stressors, to provide a prioritisation map that represents the area of highest overlap

5. Consideration of nonlinear CEA via development of conceptual models of system structure, zone of influence and use of ecosystem models to quantify non-linear response functions
6. Assess risk and associated uncertainty
7. Validation – where possible, the networks of interactions, maps of risk and cumulative effects should be empirically tested
8. Evaluation of management options/performance.

This approach became the foundation of the method applied here to assess cumulative effects on fished species around Australia. The validation and evaluation of alternative management strategies was not possible for the assessment undertaken here but would be recommended in any future work as best practice.

The following sections provide a summary of the two stages of the analysis. To help interpretation a complete worked example with interpretation will be presented in plain English first before going into the results in more depth.

Box 1: Simple description of the cumulative effects assessment steps and interpretation

Stage I

The ERAEF method is used in fisheries (especially AFMA managed fisheries) to judge how vulnerable species might be to fishing pressure per fishery. Stage 1 of this CEA builds off those vulnerability ratings and effort of fishery activities to create spatial maps of potential vulnerability.

It does this by creating a simple score of cumulative pressure on a species using existing information on catch (including as bycatch/byproduct to identify if a particular fishery or gear catches the species), effort maps, maps of marine parks and fisheries closures (which may affect the level of local effort) and the species PSA score from the ERAEF method (which shows its relative vulnerability to fishing). Per fishery (or gear if there are multiple gears within a fishery) the method creates a map of pressure, with more negative scores if the species is more vulnerable and where effort is higher in fisheries that catch that species. The final score is then created by summing up across all the fisheries. The way to interpret the final map is (i) to look at the spatial distribution of scores – are there areas with stronger (more negative scores?) and (ii) to look at the peak score (the strongest score seen in any one spot). Based on comparison with other methods, such as the eSAFE methods used in ERAEF's, if a score is stronger than -5 than the species needs extra management consideration to make sure actions are being taken to try to mitigate the pressure or reduce its impact overall and in the specific hotspot locations (e.g. via gear modifications, rules around local depletion etc).

This approach has the advantage of using existing information and being straightforward to apply with GIS tools. The assumptions sitting behind the method are imperfect (we explain why in the following few paragraphs), but it still provides a straightforward means of indicating the relative size of the pressure a species is under. If the marine parks and fishing closures are not included, the method shows maximum potential cumulative effect, but if zones are overlaid zeroing out any effort of gears excluded by that zone then the resulting "residual plots" show what cumulative effect is left (from historical pressure) after that kind of management has been included. Other forms of management could be included via using a gear selectivity estimate (if available) to weight the effort.

The maps are most reliable when comparing across spatial locations within the same map (i.e. within the map for a species). It can be used to some extent to compare across species, but such a comparison needs to be used with some caution as the PSA scores are not absolute risk, but only a semi-quantitative index (so useful in a "fuzzy" relative way to say whether things are high or low etc, but not cast-iron in the sense of a fully quantitative statistical estimate). Similarly, while it is possible to look at the contributions per fishery to a species' map, the semi-quantitative nature of the fishery specific PSA score again means comparing contributions per fishery should only be done with caution (acceptable if no other information is available, but better if multiple lines of evidence can be drawn upon).

All current analyses of cumulative effects assume that pressures can be added. This is a tractable first step assumption used widely around the world, meaning it is an acceptable method, especially if no other information is available, or if resources for doing an assessment are limiting. However, scientific understanding is that species and the ecosystems they sit in often do not respond to pressure in an additive way. This motivated the Stage II preliminary analysis.

Stage II

This stage of the analysis steps to more explicitly quantitative values and beyond simple additive layers. Ecosytem model simulations are used to characterise patterns of how species respond to different fishing pressure patterns across multiple fisheries (gears); to explore how these pressures interact and whether the response is larger or smaller than you would expect if simply adding pressures together. Direct observational information around this topic are rare and hard to do, which is why this project relies on model simulations to look at the interactions – both direct effects of multiple fishing operations on a species, but also how effects are mediated through food web and habitat links. These simulations show that the response of species to different patterns of fishing is highly non-linear. It is not additive. Under some combinations of gears and specific intensity of fishing some species are more heavily effected than they would be under an additive assumption, but other species actually show a positive effect (benefit) from fishing.

Non-linear cumulative effects maps are created by taking the same effort maps as used in Stage I and putting the effort per spatial cell through the model-derived relationship (between pressure level and effect) to get the final non-linear cumulative effects scire for that cell – generating a map of potential responses. Because the shape of the response itself is uncertain (has a wide range of possible values across the specific fishing combinations) three maps are created for each species - the “weakest possible”, “mean (or middle of the road)” and “strongest possible” effects. These maps show how variable the effects can be across different fishing patterns and across space. Where maps consistently show pressure is higher (across maps for a species or across species) are places where extra attention is needed to make sure it is not having undue effects on the local ecosystem and the species that live there or pass through. While uncertain, this is likely to be the most accurate representation of the complexity of how cumulative effects are actually felt in real world systems. Unfortunately, it was not possible to extend this analysis beyond the SE region within this project and an Australia-wide application would be a good topic for a future project.

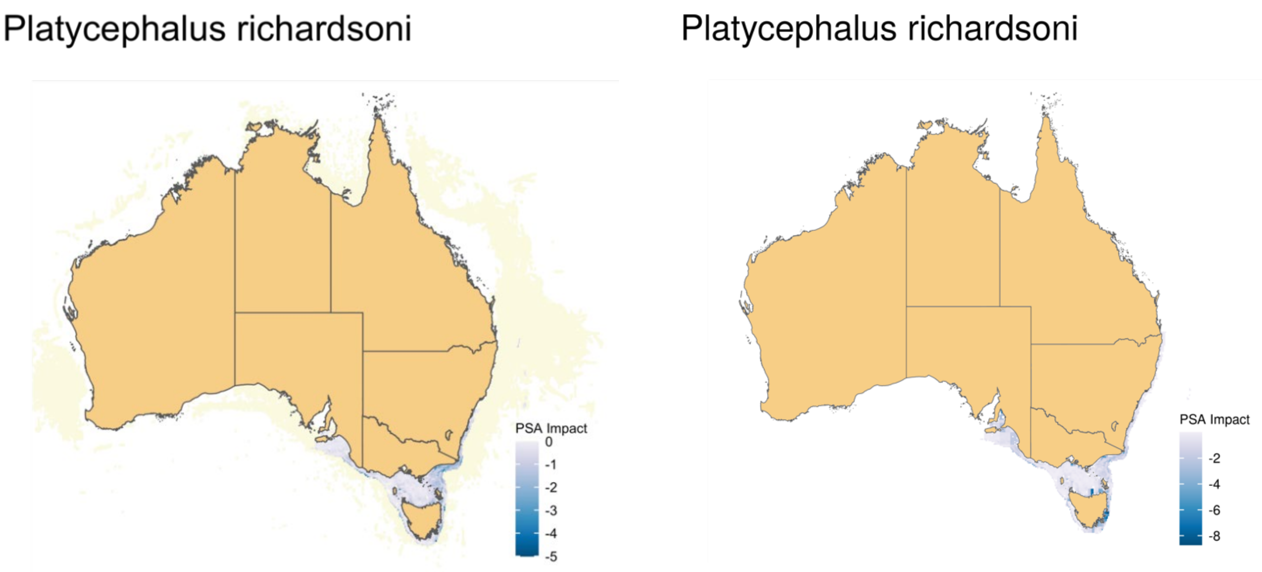
Final Method Considerations

The results presented here mean that Stage I should be considered a useful first step, which: (i) is in line with approaches Parks Australia is using and with what is being done in other jurisdictions internationally; (ii) is indicative of which spatial regions are under extra pressure and (iii) can provide a preliminary list of species that might be at risk. However, where possible ecosystem models (or suitable observational data if available) should be used to characterise the non-linear response to ecosystem components to combined fishing pressure so that non-linear cumulative effects maps (which will be more accurate in terms of realised pressure) can be generated.

Stage I

Appendix 5 provides the individual species maps of the Stage I cumulative PSA based score. Figure 5 provides an example of the kinds of output possible from this form of analysis, in this case for the Tiger Flathead (*Platycephalus richardsoni*). Figure 5(a) shows the case for where their interaction is with AFMA managed fisheries only, but the map includes where historical interactions (total catch of the species and/or effort from relevant fisheries) are zero but interactions are possible due to the distribution of the species. In Figure 5(b) interactions with both State and Commonwealth fisheries are shown, but only locations of non-zero interactions are shown (anywhere where there was no take or effort during the period of the data have been blanked), this includes cells in areas fished historically but now zoned closed to fishing. Figure 5(c) shows the residual effects plots once all current closures due to marine parks or fishing zones are taken into account – as the effects of current zoning on the cumulative footprint is quite small there is little difference to Figure 5(b), this is because multiple fisheries with different gears operate across Australian waters and closures are typically gear specific so absolute exclusion of all effort is rare spatially. We plotted the area of potential but not realised effects as it may not be useful for retrospective or snapshot status assessments of cumulative effects, but it can be useful for forward looking planning. For example, when considering future areas of potential effect should effort patterns shift or species shift with climate change – this is more for southerly waters, as species will largely range extend poleward.

(a) (b)



(c)

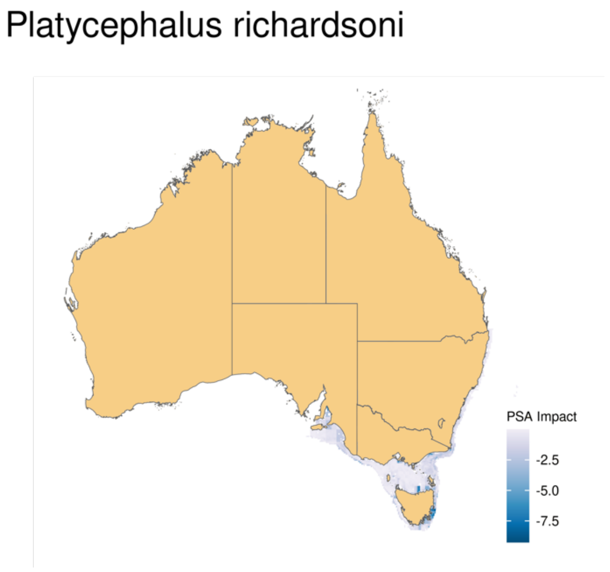


Figure 5: Examples of a species-specific Stage I cumulative (PSA based) score. Darker colours represent larger cumulative scores. This example for Platycephalus richardsoni shows a very wide pale-yellow area (in panel (a)) that marks where fisheries could potentially impact the species if they were active there, this is the area of potential but not realised effect (shown for precautionary planning purposes). The actual impacts (in panel (b)) only occur from south east Queensland through Bass Strait, around Tasmania, to South Australia – where the darker shades show where catches actually occur. Panel (c) shows the residual effects once marine parks and fisheries zoning has been included – the peak score contracts by 0.1.

The distribution of effect sizes are quite skewed in all 3 plots. These kinds of distribution were quite typical – with the majority of the area having only low effects, but with hotspot areas (often quite small in extent) where effects sizes could be many times larger. This is clear from the distribution of scores with the vast majority of species having very skewed score distributions, like those shown in Figure 6. A minority of species had a more constrained (lower maximum score) but more evenly distributed set of scores – as shown in Figure 7 – due to being affected over a smaller geographic area but with a more even fisheries footprint (e.g. see Figure 8). The two species with the strongest mean scores are the Long Snouted Lancetfish (*Alepisaurus ferox)* (-0.584) and the Mandarin Dogfish *Cirrhigaleus barbifer* (-0.466), which had “peak” scores of -3.57 and -3.52 respectively.

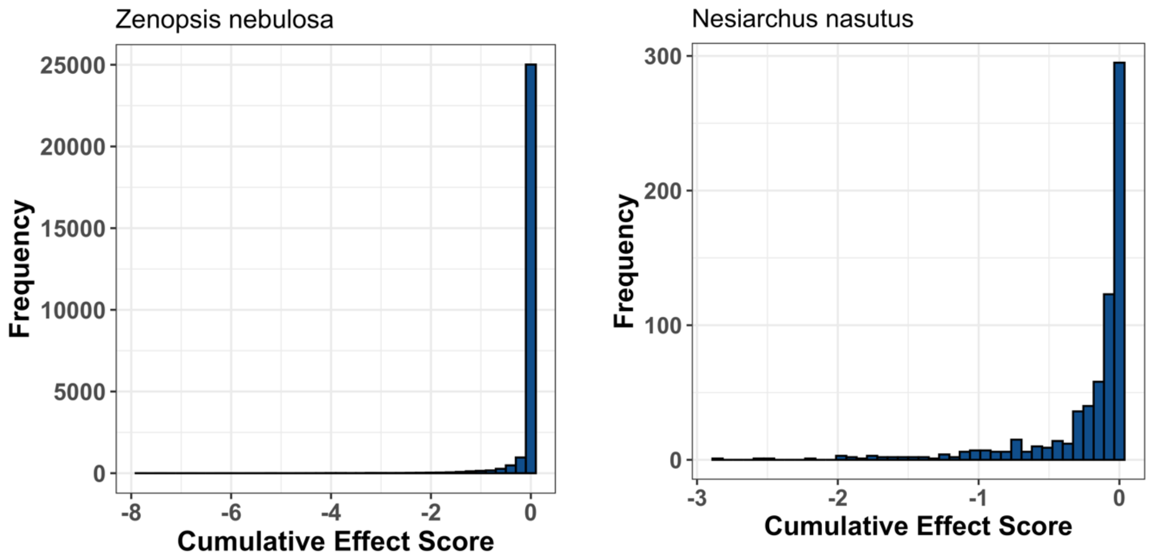


Figure 6: Examples of the cumulative score distributions that are typical of the large majority of species.

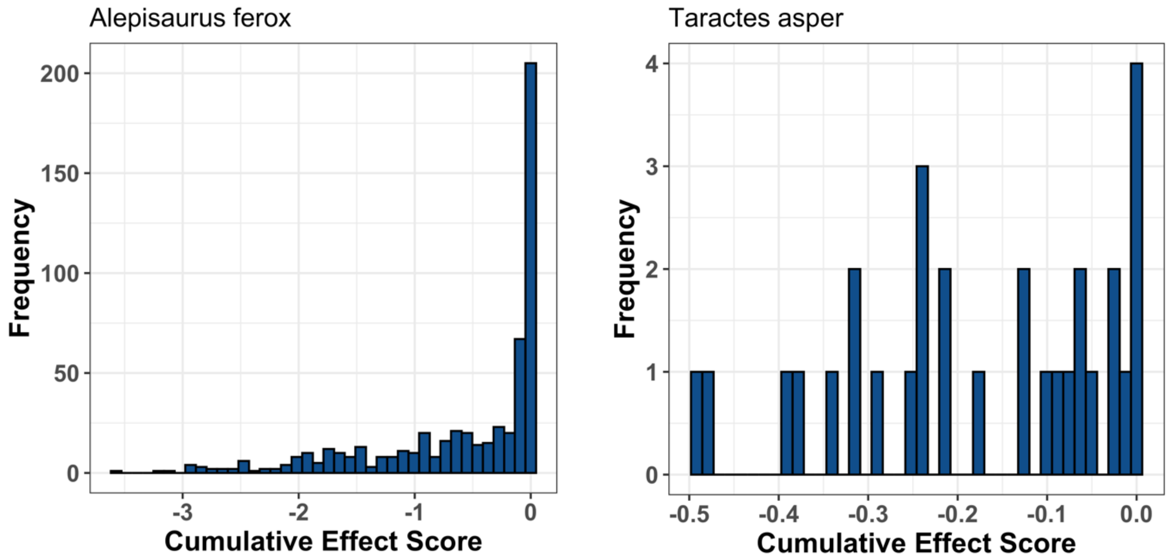


Figure 7: Examples of more even distributions. While Alepisaurus ferox is still skewed, it has a tail that is much fatter (more homogeneous in frequency) than the examples provided in Figure 6.

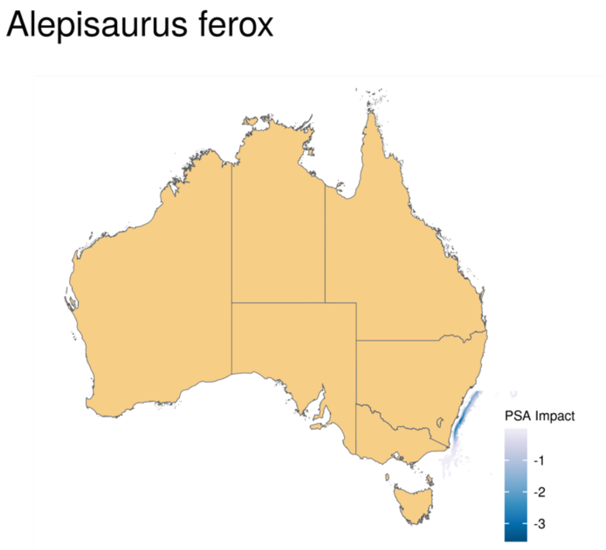


Figure 8: A map of the scores for Alepisaurus ferox showing the restricted geographic extent of the scores for this species, which has the highest mean score of -0.58, but a peak score of -3.57. The more intense colours reflect greater cumulative effect.

Across the entire set of species assessed there was a wide range of maximum scores. If only considering AFMA managed fisheries the range is 0 – -8.4 (Figure 9a) and if State fisheries are also included then the range expands to 0 – -9.72 (Figure 9b). When considering only the AFMA managed fisheries, 14 species had a zero score and 4 species had a peak score off -8 or stronger (full list given in the Data Appendix 5, Table S1). There were two clear crests in these scores, the first was at moderate scores of -0.4 – -1.1 and another at stronger scores (-3.1 – -3.7). Fifty-nine species (15% of assessed species) had scores of -5 or stronger and are listed in the upper part of Table 2 as they may require more in-depth management consideration.

When considering both AFMA and State managed fisheries, only 5 species still had a zero score and 33 species had a peak score off -8 or stronger (full list given in Data Appendix 5, Table S1). While there were still crests in these scores, around -1 and another at stronger scores (-3.3 – -3.7) these peaks were not as high as there was a higher frequency of stronger scores. With the State fisheries included, 107 species (26% of assessed species) had scores of -5 or stronger (the additional species are listed in the lower section of Table 2); the majority of these species have high PSA scores as they are vulnerable pipefish, seadragons or sharks.

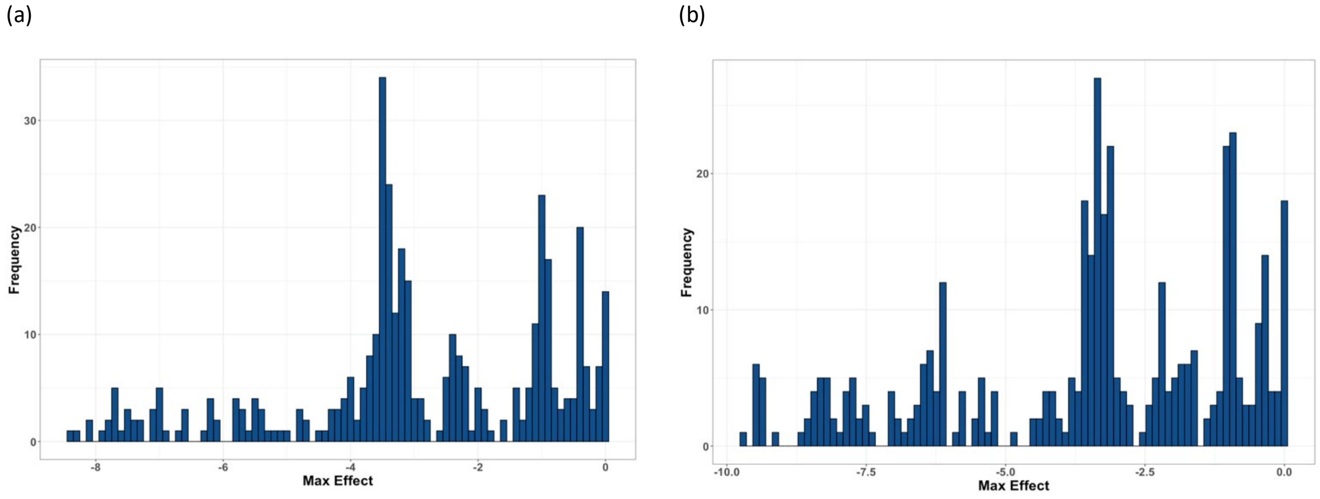


Figure 9: Histogram of maximum species cumulative scores (a) for Commonwealth fisheries only, (b) including State fisheries

Table 2: List of species (in alphabetical order by Latin name) with Stage I cumulative scores of magnitude -5 or larger (i.e. ≤ -5).

Highest priority species – greatest cumulative score	
Latin species name	Common name
When Considering AFMA managed fisheries alone	
Alopias vulpinus	Thresher Shark
Beryx decadactylus	Imperador
Beryx splendens	Alfonsino
Brama brama	Ray's Bream
Callorhinchus milii	Elephantfish
Carcharodon carcharias	White Shark
Centroberyx gerrardi	Bight Redfish
Centrolophus niger	Rudderfish
Cephaloscyllium albipinnum	Whitefin Swellshark
Chelidonichthys kumu	Red Gurnard
Chrysophrys auratus	(Pink) Snapper
Coelorinchus australis	Southern Whiptail
Dalatias licha	Black Shark
Dannevigia tusca	Tusk
Deania calceus	Brier Shark
Deania quadrispinosa	Longsnout Dogfish
Dentiraja cerva	Whitespotted Skate
Dipturus canutus	Grey Skate
Dipturus gudgeri	Bright Skate
Etmopterus lucifer	Blackbelly Lanternshark
Figaro boardmani	Sawtail Catshark
Galeorhinus galeus	School Shark
Genypterus blacodes	Pink Ling
Helicolenus barathri	Bigeye Ocean Perch
Helicolenus percoides	Reef Ocean Perch
Hyperoglyphe antarctica	Blue-eye Trevalla
Irolita waitii	Southern Round Skate
Isurus oxyrinchus	Shortfin Mako
Lamna nasus	Porbeagle Shark
Latris lineata	Striped Trumpeter
Lepidopus caudatus	Frostfish
Lepidorhynchus denticulatus	Toothed Whiptail
Macruronus novaezelandiae	Blue Grenadier
Mora moro	Ribaldo
Mustelus antarcticus	Gummy Shark
Nemadactylus macropterus	Jackass Morwong
Nemadactylus valenciennesi	Blue Morwong
Neocyttus rhomboidalis	Spikey Oreodory
Notorynchus cepedianus	Broadnose Shark
Oplegnathus woodwardi	Knifejaw
Phycodurus eques	Leafy Seadragon
Platycephalus richardsoni	Tiger Flathead
Polyprion oxygeneios	Hapuku
Prinoace glauca	Blue Shark
Pristiophorus cirratus	Common Sawshark
Pristiophorus nudipinnis	Southern Sawshark

Highest priority species – greatest cumulative score

Latin species name	Common name
Pterygotrigla polyommata	Latchet
Rexea solandri	Gemfish
Ruvettus pretiosus	Oilfish
Seriolella brama	Blue Warehou
Seriolella caerulea	White Warehou
Seriolella punctata	Silver Warehou
Solegnathus spinosissimus	Spiny Pipehorse
Spiniraja whitleyi	Melbourne Skate
Squalus megalops	Spikey Dogfish
Thunnus alalunga	Albacore Tuna
Trachurus declivis	Jack Mackerel
Xiphias gladius	Swordfish
Zenopsis nebulosa	Mirror Dory
Additional species with strong cumulative scores once State fisheries are also considered	
Achoerodus viridis	Eastern Blue Groper
Campichthys galei	Gale's Pipefish
Carcharias taurus	Sand Tiger Shark (Gray Nurse Shark)
Centroberyx affinis	Redfish
Cephaloscyllium laticeps	Australian Swellshark
Chimaera ogilbyi	Ogilby's Ghostshark
Conger verreauxi	Southern Conger
Dentiraja confusus	Australian Longnose Skate
Filicampus tigris	Tiger Pipefish
Heraldia nocturna	Upside-down Pipefish
Heraldia sp. 1 [in Kuiter, 2000]	Pipefish
Heteroclinus perspicillatus	Common Weedfish
Hippocampus bleekeri	Potbelly Seahorse
Hippocampus breviceps	Knobby Seahorse
Histiogamphelus briggsii	Brigg's Pipefish
Histiogamphelus cristatus	Macleay's Crested Pipefish (Rhino Pipefish)
Hypogaleus hyugaensis	Blacktip Tope
Hypselognathus rostratus	Knife-snouted Pipefish
Idiotropiscis australe	Southern Pygmy Pipehorse
Kathetostoma canaster	Stargazer
Kaupus costatus	Deepbody Pipefish
Kimblaeus bassensis	Trawl Pipefish
Latridopsis forsteri	Bastard Trumpeter
Leptoichthys fistularius	Brush-tailed Pipefish
Lissocampus runa	Javelin Pipefish
Maroubra perserrata	Sawtooth Pipefish
Mitotichthys mollisoni	Mollison's Pipefish
Mitotichthys semistriatus	Halfbanded Pipefish
Mitotichthys tuckeri	Tucker's Pipefish
Notiocampus ruber	Red Pipefish
Phyllopteryx taeniolatus	Common Seadragon
Platycephalus laevigatus	Rock Flathead
Pugnaso curtirostris	Pug-nosed Pipefish

Highest priority species – greatest cumulative score	
Latin species name	Common name
Rhincodon typus	Whale Shark
Scorpaena papillosa	Red Rock Cod
Seriola lalandi	Yellowtail Amberjack
Solegnathus robustus	Robust Pipehorse
Squalus acanthias	Spiny Dogfish
Stigmatopora argus	Spotted Pipefish
Stigmatopora nigra	Wide-bodied Pipefish
Stipecampus cristatus	Ring-backed Pipefish
Thyrsites atun	Barracouta
Urocampus carinirostris	Hairy Pipefish
Vanacampus margaritifer	Mother-of-Pearl Pipefish
Vanacampus phillipi	Port Phillip Pipefish
Vanacampus poecilolaemus	Australian Long-nosed Pipefish
Vanacampus vercoi	Verco's Pipefish

For the case where only AFMA managed fisheries are considered it was possible to compare the list of species with the outcome of eSAFE assessments (and especially their sum across AFMA fisheries[1], which is possible following the method of Zhou et al (2019)). This analysis indicates that a cumulative cut-off point of -5 does flag species under excessive fishing pressure as 35% of the species with peak cumulative scores of -5 or stronger were rated as at Medium-Extreme risk (most Extreme) using cumulative eSAFE, versus 6% of those with peak cumulative scores weaker than -5 (Figure 10).

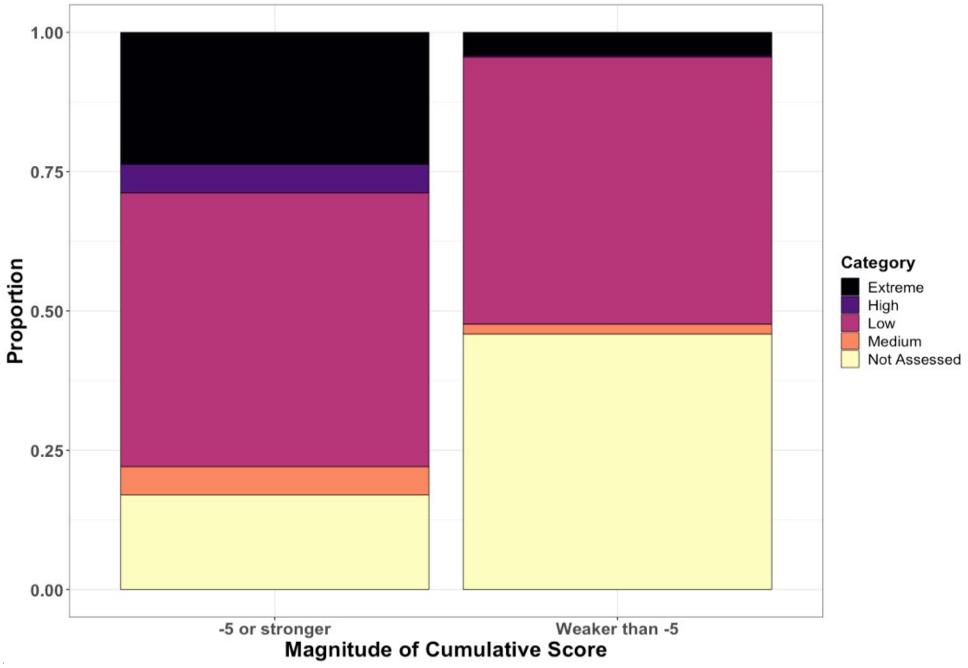


Figure 10: Comparison of eSAFE risk ratings for species with peak cumulative scores -5 and stronger, or weaker than -5.

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[1] This involved all tallying up across all publicly available eSAFE output, the majority of which is available in south east Australia – such as South East Trawl and Danish Seine fisheries – but also including other eastern fisheries, such as the Eastern Tropical and Billfish Fishery. Where these eSAFE already included state-based fishery influences than those were inherently considered in the comparison from the eSAFE perspective. However, no additional eSAFE estimates were made for State fisheries as part of this analysis.

A system level view can also be generated via a cumulative sum over all species, as seen in Figure 11 (which includes all fisheries but also the effects of marine parks and fisheries zoning). This highlights the generally low pressure applied around Australia, but also the existence of a few hotspots across the Great Australian Bight, and in parts of the shelf and upper slope of the south east – in Victoria, Tasmania and New South Wales.

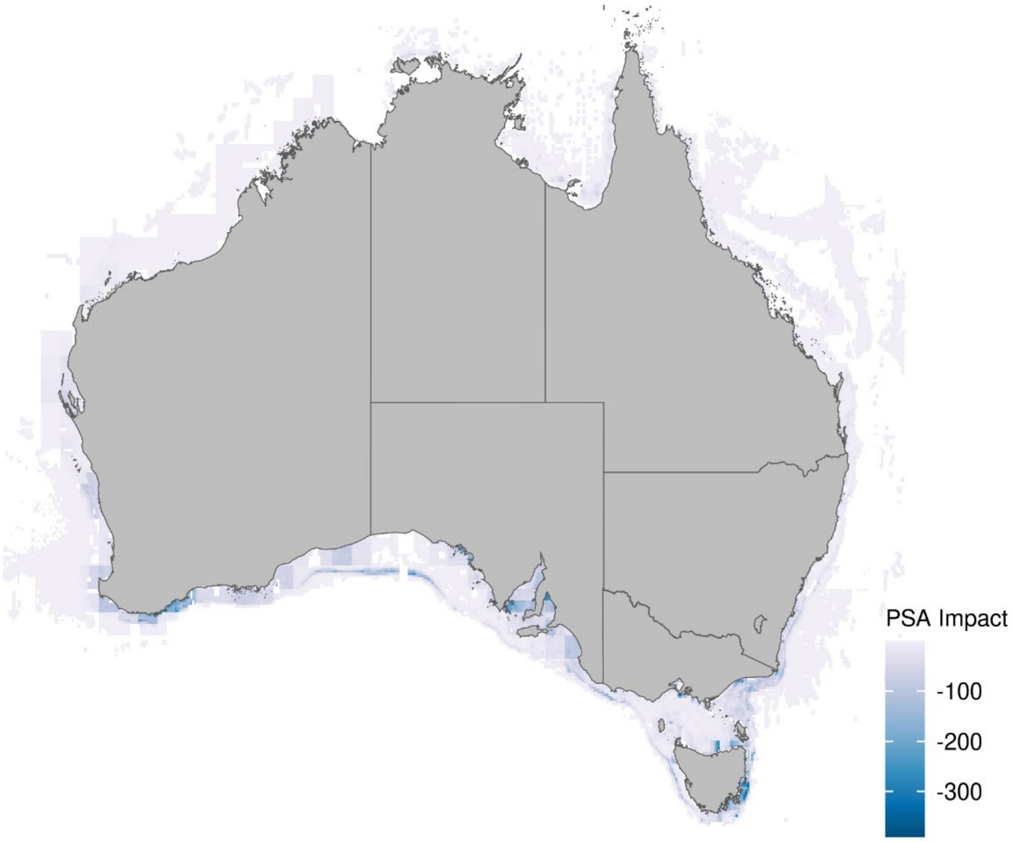


Figure 11: Total Stage I Cumulative Effect Score. Note that the key in the plot is reversed (showing negative not positive scores) so that the more intense colours reflect greater cumulative effect.

Uncertainty

These Stage I scores are associated with a few sources of uncertainty. There were the assumptions of how state fisheries map to Commonwealth equivalents in terms of the gears used and operating practices – this was needed when inferring which species could be exposed to what pressure, as catch composition lists are sparse or difficult to come by especially for state fisheries. This touches on one of the most telling source of uncertainty, which is the state fisheries data used. This information can be exceptionally hard to access across jurisdictions for recent years and in fine resolution so older or coarser data has had to be used for this analysis – this can be seen in the blocky patterns seen in inshore waters in plots such as Figure 11 and the species level equivalents in the appendices. If more recent and more resolved information can be obtained the analysis should be updated to reduce this uncertainty.

Another source of uncertainty is the PSA score, which is by its nature only semi-quantitative. The lack of ability to standardise across fisheries creates uncertainty if only going to this step – drawing equivalency between a line and trawl fisheries is quite difficult. Previous absolute risk estimates have typically been across sectors (e.g. national fleets within an RFMO). Nevertheless, given the level of available information and the diversity of methods used in Australia the approach used here and the summation of eSAFE values are the best available estimates.

Finally, there is uncertainty around interpretation. We have intentionally chosen not to standardise scores across species. This was done for two reasons. First, there is no *a priori* score that signifies "acceptable" from "unacceptable" pressure levels. The comparison with eSAFE was undertaken to provide some insight, but given the "first of its kind" nature of the entire exercise we preferred not to pre-judge on little available information. Second, there may not be a single threshold "unacceptable" score that holds for all species, given the differential susceptibility of species to disturbance. Consequently, species scores were left in their "raw" form. It is however safe to say the stronger (more negative) a score, whether per species or in aggregate, the stronger the pressure being felt at that location.

Stage II

Appendix 6 provides the plots – mean and confidence bands – for the nonlinear cumulative effects scores calculated using the impact-response functions derived from Ecopath with Ecosim (with the response functions given in Appendix 7). The strong non-linearity of the responses can be seen from the plots in Appendix 7 and in the impact-response function for overall biodiversity (Kempton's Q) in Figure 12. With fewer fisheries operating only some gear combinations lead to a decline in biodiversity, but once more than a few gears are in use there is a strong and consistent drop in biodiversity as fishing pressure increases. Results for individual taxa also show a range of outcomes across different levels of fishing pressure and numbers of gears in use. Many show split distributions with clearly distinguishable arms – some flat with an arm increasing, others with a decreasing arm – for others it is more a continuous smear from one bound to the other. Most show monotonic responses (not necessarily linear but consistently trending in the same direction across the increasing levels of pressure), but for some invertebrates and their predators humped or U-shaped responses are seen for some gear combinations.

The final cumulative effects score using this method highlights how release from predation pressure can benefit lower to mid trophic level groups, with Cardinal fish, euphausiids, Jack Mackerel, slope invertebrate feeders, Cucumberfish and Redbait all appearing to benefit from the non-linear responses. In all these instances, the outcome of the cumulative effects in most spatial cells are positive; indeed often all cells in the maps, show a positive effect. Many of the higher trophic level species – such as a number of the shark species, tunas, billfish, Pink Ling, Blue Grenadier, Redfish, and Flathead – show negative outcomes, but had lower peak scores than for Stage I (i.e. once the non-linear impact-response function was applied).

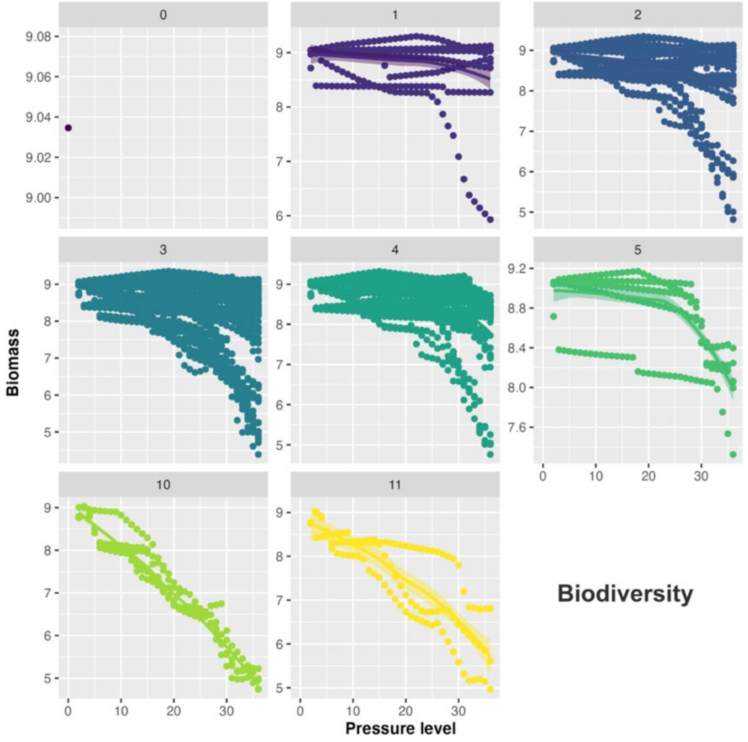


Figure 12: Impact-Response function for Biodiversity (represented by the Kempton's Q index) in the southeast Australia EwE model. The frame labels 0-11 refer to the number of active fleets in the simulations.

The shape of the impact-response functions means there is wide uncertainty in the individual scores with an order of magnitude or more typical between maximum, mean and minimum values. For example, see the example plots for Jack Mackerel in Figure 13, where the Upper CI values are 5x or more of those in the Lower CI. Moreover, the positive Stage II scores indicate that Jack Mackerel benefit from fishing at the system scale, in contrast to the default negative scoring assumptions of Stage I. If the spatial pattern of the two analysis are considered irrespective of the sign of the individual scores, the more restricted spatial extent of the Stage II analysis means that the area of high impact in the Great Australian Bight for the Stage I score is not reflected in the Stage II geographic extent. Although, the area of higher impact off eastern Victoria and up the New South Wales shelf is seen in both the Stage I and Stage II maps.

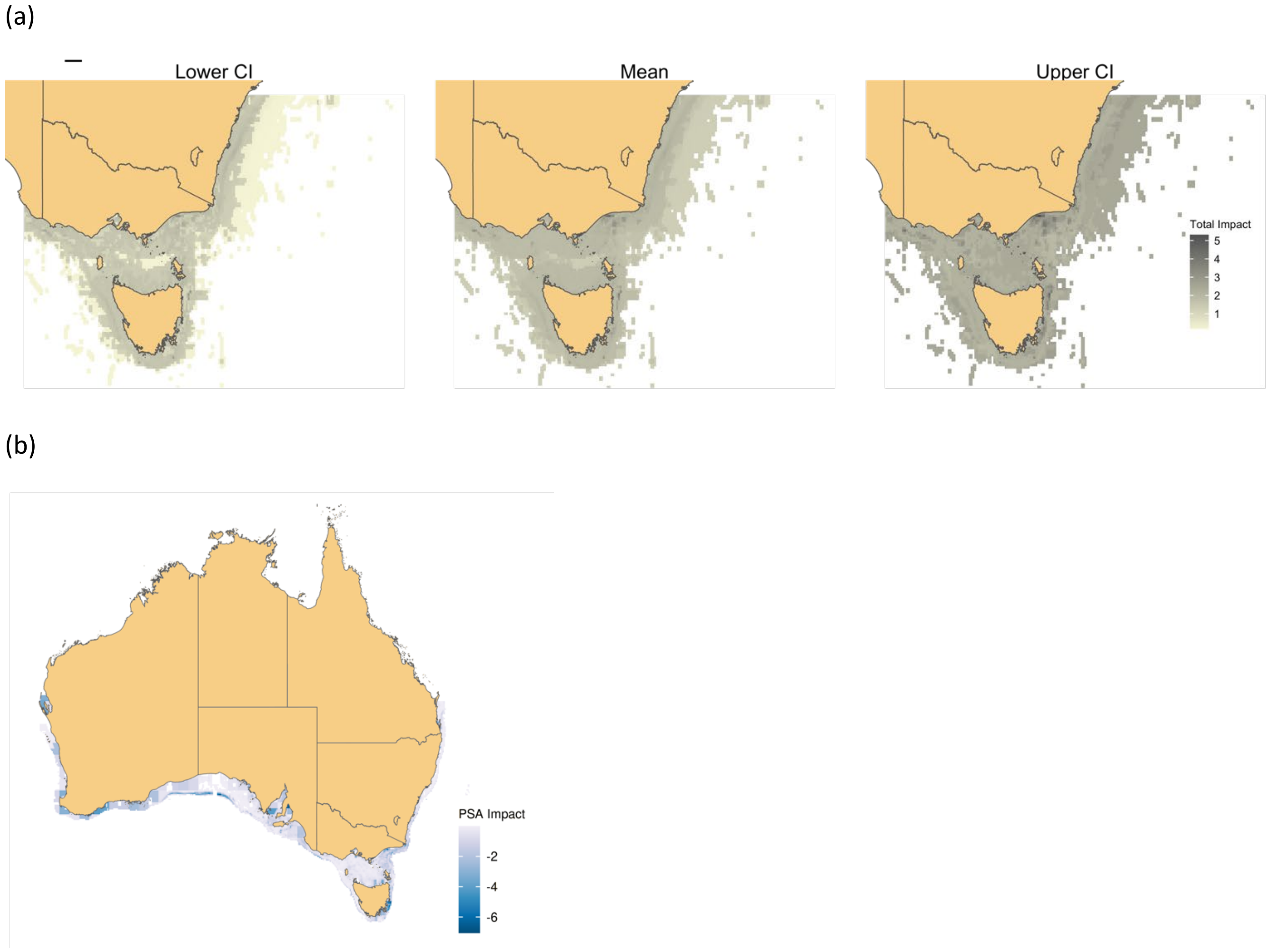


Figure 13: Example cumulative effects scores (a) Stage II non-linear effects scores in comparison to (b) the Stage I PSA-based scores for the same species - Jack Mackerel. Note that the colouring in the plots has been made consistent so that the more intense colours reflect greater cumulative effect.

The fact that final scores span zero for some species suggest that it is possible for some species to benefit from the ecosystem mediated effects of fishing, even when also directly affected. The wide shape of impact response functions within and across species, with groups benefiting in some instances and being strongly negatively affected in others, is why the bounds on the overall system-level score are so broad (Figure 14). While validation would be required to constrain the breadth of the results and get a clearer indication of whether there is a net benefit or loss as the cumulative effect at a system-level (or even for individual species), these maps already highlight the strong spatial variability in scores, as well as the presence of hotspot locations in some species shelf areas and in deeper offshore waters, especially off New South Wales, where more extreme values (positive or negative) occur as a consequence of the mix of fisheries active in those locations.

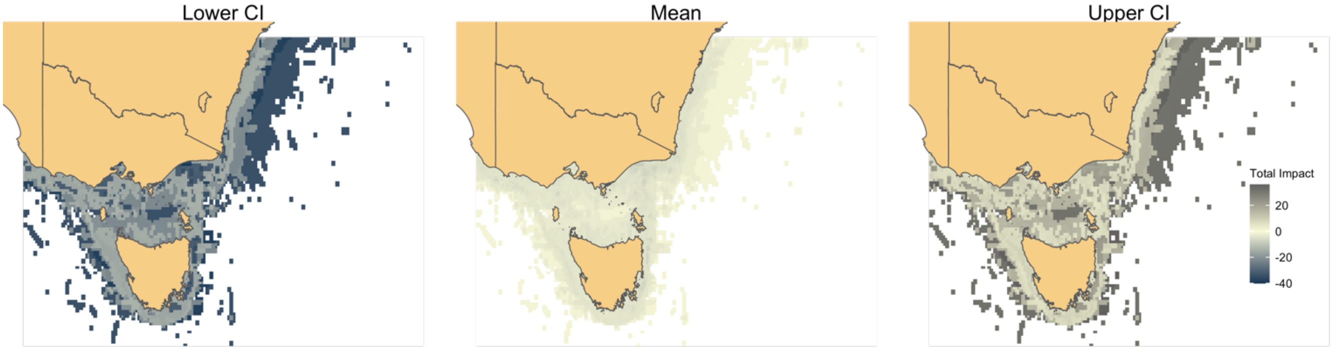


Figure 14: Overall cumulative non-linear effects score (summing across species). Note that the colouring in the plots mean that the more intense colours reflect greater cumulative effect.

Discussion

The work present in this report delivers on each of the objectives defined above for the project.

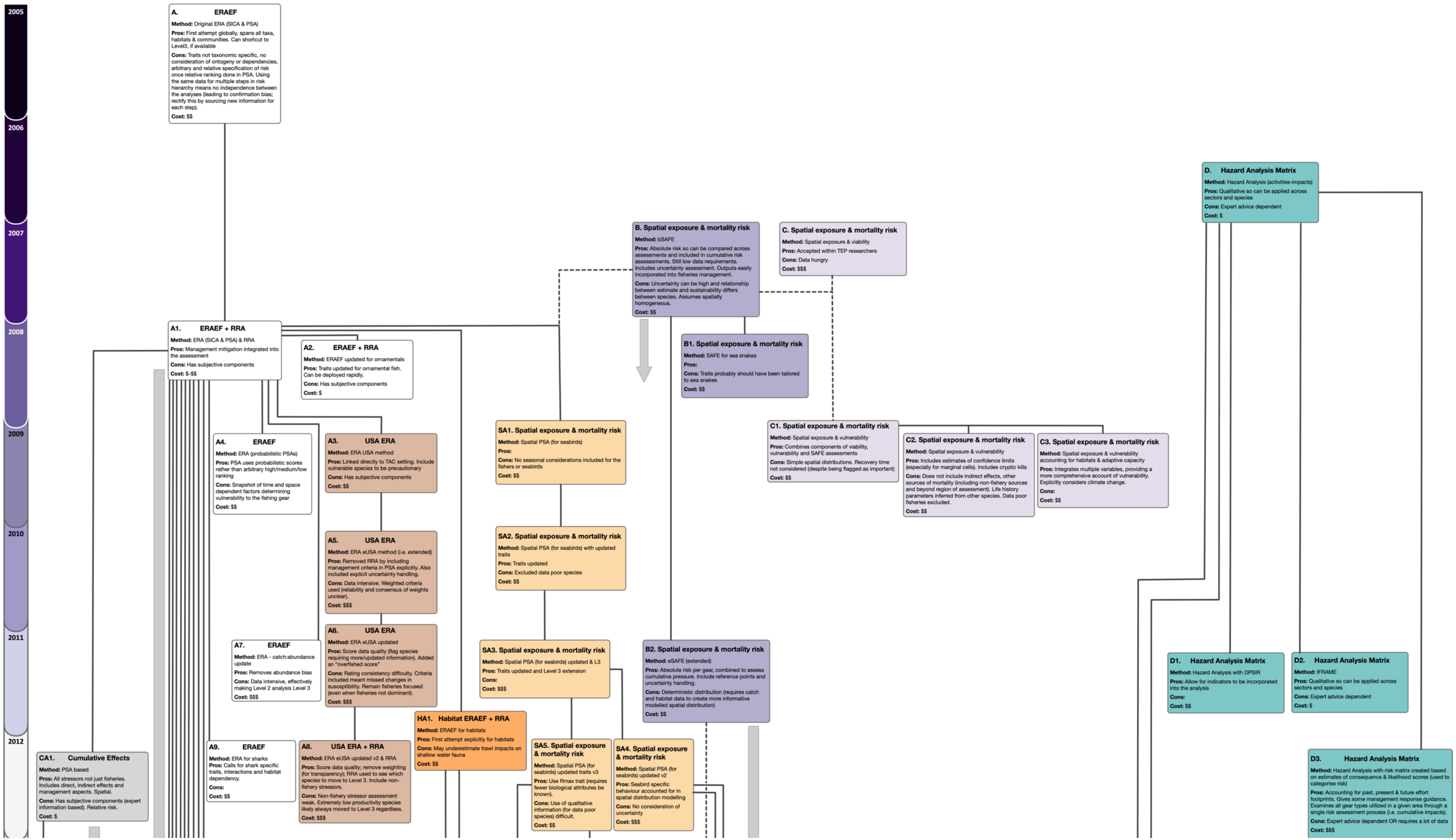
Reviews – Objective 1

ERA Review

The review of ERAs implemented around the globe over the decade since the method was developed uncovered 221 relevant documents (papers or reports); by including grey literature reports this review avoided the published literature bias that many reviews suffer from. This comprehensive review (Fulton et al (2019); Appendix 3) showed that the original method of Hobday et al. (2007) has been repeatedly expanded and adapted as it has been applied in new jurisdictions. These modifications (and their timeline of development) were summarised in a document for AFMA's Ecological Risk Management Working Group using Figure 15, Figure 16 and Table 3. General benefits and issues associated with each method, and the relative cost of each method, are also shown on Figure 15. Figure 16 maps spatial use of these modified ERA in fisheries and conservation bodies globally.

The various ERA methods can be grouped into 8 general classes, which are briefly outlined in Table 3 as a quick reference chart to highlight the key features of the different methods as options for future ERAEF in Australia. Australia's ERAEF remains relatively competitive internationally, but there is potential for refinement – as noted in Table 3 and detailed further in the review of Fulton et al (2019). In brief, it is recommended that extensions to the methods used in Australian fisheries should prioritise re-consideration of biological traits for Level 2 (PSA and SAFE) analyses, to capture more taxon-specific traits and vulnerabilities that influence risks in ways not captured by the more generalised set of attributes used in the original method (as shown in Figure 4). As discussed in the results section above, additional factors for consideration would include:

- exposure or sensitivity of individual life history stages (when strong ontogenetic changes exist)
- cryptic mortalities (e.g. for seabirds)
- habitat and trophic dependencies
- climate and how that adds stress or modifies the attribute values of each species, or how it changes spatial distributions and thereby exposure to fishing, or even which species should be included in the assessment
- "predictability" of stocks (i.e. the influence of environmental variability).



A. ERAEF
Method: Original ERA (SICA & PSA)
Pros: First attempt globally, spans all taxa, habitats & communities. Can shortcut to Level3, if available
Cons: Traits not taxonomic specific, no consideration of ontogeny or dependencies, arbitrary and relative specification of risk once relative ranking done in PSA. Using the same data for multiple steps in risk hierarchy means no independence between the analyses (leading to confirmation bias; rectify this by sourcing new information for each step).
Cost: $$

A1. ERAEF + RRA
Method: ERA (SICA & PSA) & RRA
Pros: Management mitigation integrated into the assessment
Cons: Has subjective components
Cost: $-$$

A2. ERAEF + RRA
Method: ERAEF updated for ornamentals
Pros: Traits updated for ornamental fish. Can be deployed rapidly.
Cons: Has subjective components
Cost: $

A4. ERAEF
Method: ERA (probabilistic PSAs)
Pros: PSA uses probabilistic scores rather than arbitrary high/medium/low ranking
Cons: Snapshot of time and space dependent factors determining vulnerability to the fishing gear
Cost: $$

A3. USA ERA
Method: ERA USA method
Pros: Linked directly to TAC setting. Include vulnerable species to be precautionary
Cons: Has subjective components
Cost: $$

A5. USA ERA
Method: ERA eUSA method (i.e. extended)
Pros: Removed RRA by including management criteria in PSA explicitly. Also included explicit uncertainty handling.
Cons: Data intensive. Weighted criteria used (reliability and consensus of weights unclear).
Cost: $$$

A6. USA ERA
Method: ERA eUSA updated
Pros: Score data quality (flag species requiring more/updated information). Added an "overfished score"
Cons: Rating consistency difficulty. Criteria included meant missed changes in susceptibility. Remain fisheries focused (even when fisheries not dominant).
Cost: $$$

A7. ERAEF
Method: ERA - catch:abundance update
Pros: Removes abundance bias
Cons: Data intensive, effectively making Level 2 analysis Level 3
Cost: $$$

CA1. Cumulative Effects
Method: PSA based
Pros: All stressors not just fisheries. Includes direct, indirect effects and management aspects. Spatial.
Cons: Has subjective components (expert information based). Relative risk.
Cost: $

A9. ERAEF
Method: ERA for sharks
Pros: Calls for shark specific traits, interactions and habitat dependency.
Cons:
Cost: $$

A8. USA ERA + RRA
Method: ERA eUSA updated v2 & RRA
Pros: Score data quality; remove weighting (for transparency); RRA used to see which species to move to Level 3. Include non-fishery stressors.
Cons: Non-fishery stressor assessment weak. Extremely low productivity species likely always moved to Level 3 regardless.
Cost: $$$

HA1. Habitat ERAEF + RRA
Method: ERAEF for habitats
Pros: First attempt explicitly for habitats
Cons: May underestimate trawl impacts on shallow water fauna
Cost: $$

SA1. Spatial exposure & mortality risk
Method: Spatial PSA (for seabirds)
Pros:
Cons: No seasonal considerations included for the fishers or seabirds
Cost: $$

SA2. Spatial exposure & mortality risk
Method: Spatial PSA (for seabirds) with updated traits
Pros: Traits updated
Cons: Excluded data poor species
Cost: $$

SA3. Spatial exposure & mortality risk
Method: Spatial PSA (for seabirds) updated & L3
Pros: Traits updated and Level 3 extension
Cons:
Cost: $$$

SA5. Spatial exposure & mortality risk
Method: Spatial PSA (for seabirds) updated traits v3
Pros: Use Rmax trait (requires fewer biological attributes be known).
Cons: Use of qualitative information (for data poor species) difficult.
Cost: $$

SA4. Spatial exposure & mortality risk
Method: Spatial PSA (for seabirds) updated v2
Pros: Seabird specific behaviour accounted for in spatial distribution modelling
Cons: No consideration of uncertainty
Cost: $$$

B. Spatial exposure & mortality risk
Method: bSAFE
Pros: Absolute risk so can be compared across assessments and included in cumulative risk assesssments. Still low data requirements. Includes uncertainty assessment. Outputs easily incorporated into fisheries management.
Cons: Uncertainty can be high and relationship between estimate and sustainability differs between species. Assumes spatially homogeneous.
Cost: $$

B1. Spatial exposure & mortality risk
Method: SAFE for sea snakes
Pros:
Cons: Traits probably should have been tailored to sea snakes
Cost: $$

B2. Spatial exposure & mortality risk
Method: eSAFE (extended)
Pros: Absolute risk per gear, combined to assess cumulative pressure. Include reference points and uncertainty handling.
Cons: Deterministic distribution (requires catch and habitat data to create more informative modelled spatial distribution)
Cost: $$

C. Spatial exposure & mortality risk
Method: Spatial exposure & viability
Pros: Accepted within TEP researchers
Cons: Data hungry
Cost: $$$

C1. Spatial exposure & mortality risk
Method: Spatial exposure & vulnerability
Pros: Combines components of viability, vulnerability and SAFE assessments
Cons: Simple spatial distributions. Recovery time not considered (despite being flagged as important)
Cost: $$

C2. Spatial exposure & mortality risk
Method: Spatial exposure & vulnerability
Pros: Includes estimates of confidence limits (especially for marginal cells). Includes cryptic kills
Cons: Does not include indirect effects, other sources of mortality (including non-fishery sources and beyond region of assessment). Life history parameters inferred from other species. Data poor fisheries excluded.
Cost: $$

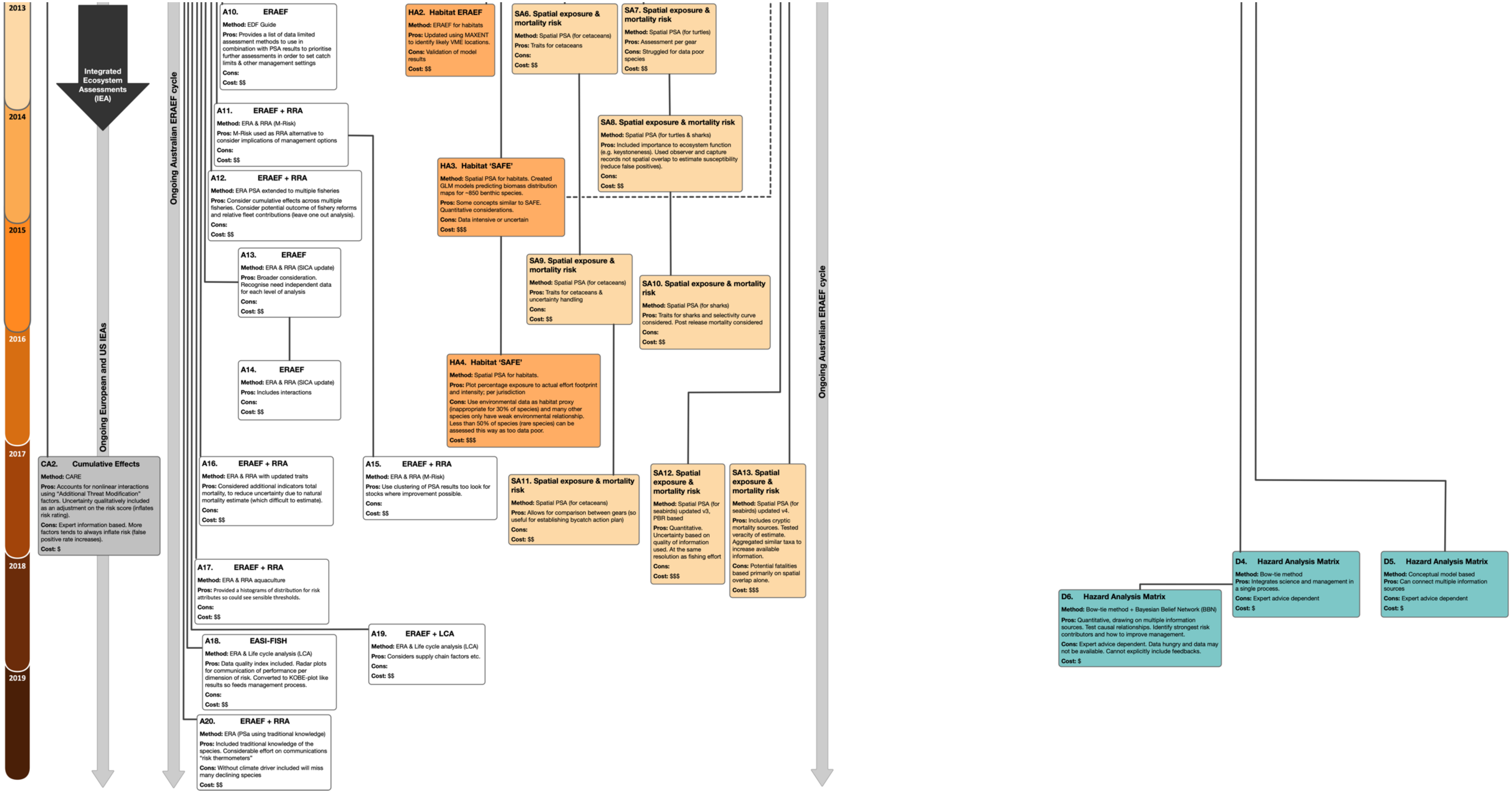
C3. Spatial exposure & mortality risk
Method: Spatial exposure & vulnerability accounting for habitats & adaptive capacity
Pros: Integrates multiple variables, providing a more comprehensive account of vulnerability. Explicitly considers climate change.
Cons:
Cost: $$

D. Hazard Analysis Matrix
Method: Hazard Analysis (activities-impacts)
Pros: Qualitative so can be applied across sectors and species
Cons: Expert advice dependent
Cost: $

D1. Hazard Analysis Matrix
Method: Hazard Analysis with DPSIR
Pros: Allow for indicators to be incorporated into the analysis
Cons:
Cost: $$

D2. Hazard Analysis Matrix
Method: IFRAME
Pros: Qualitative so can be applied across sectors and species
Cons: Expert advice dependent
Cost: $

D3. Hazard Analysis Matrix
Method: Hazard Analysis with risk matrix created based on estimates of consequence & likelihood scores (used to categorise risk)
Pros: Accounting for past, present & future effort footprints. Gives some management response guidance. Examines all gear types utilized in a given area through a single risk assessment process (i.e. cumulative impacts).
Cons: Expert advice dependent OR requires a lot of data
Cost: $$$



A10. ERAEF
Method: EDF Guide
Pros: Provides a list of data limited assessment methods to use in combination with PSA results to prioritise further assessments in order to set catch limits & other management settings
Cons:
Cost: $$

A11. ERAEF + RRA
Method: ERA & RRA (M-Risk)
Pros: M-Risk used as RRA alternative to consider implications of management options
Cons:
Cost: $$

A12. ERAEF + RRA
Method: ERA PSA extended to multiple fisheries
Pros: Consider cumulative effects across multiple fisheries. Consider potential outcome of fishery reforms and relative fleet contributions (leave one out analysis).
Cons:
Cost: $$

A13. ERAEF
Method: ERA & RRA (SICA update)
Pros: Broader consideration. Recognise need independent data for each level of analysis
Cons:
Cost: $$

A14. ERAEF
Method: ERA & RRA (SICA update)
Pros: Includes interactions
Cons:
Cost: $$

HA2. Habitat ERAEF
Method: ERAEF for habitats
Pros: Updated using MAXENT to identify likely VME locations.
Cons: Validation of model results
Cost: $$

SA6. Spatial exposure & mortality risk
Method: Spatial PSA (for cetaceans)
Pros: Traits for cetaceans
Cons:
Cost: $$

SA7. Spatial exposure & mortality risk
Method: Spatial PSA (for turtles)
Pros: Assessment per gear
Cons: Struggled for data poor species
Cost: $$

SA8. Spatial exposure & mortality risk
Method: Spatial PSA (for turtles & sharks)
Pros: Included importance to ecosystem function (e.g. keystoneness). Used observer and capture records not spatial overlap to estimate susceptibility (reduce false positives).
Cons:
Cost: $$

HA3. Habitat 'SAFE'
Method: Spatial PSA for habitats. Created GLM models predicting biomass distribution maps for ~850 benthic species.
Pros: Some concepts similar to SAFE. Quantitative considerations.
Cons: Data intensive or uncertain
Cost: $$$

SA9. Spatial exposure & mortality risk
Method: Spatial PSA (for cetaceans)
Pros: Traits for cetaceans & uncertainty handling
Cons:
Cost: $$

SA10. Spatial exposure & mortality risk
Method: Spatial PSA (for sharks)
Pros: Traits for sharks and selectivity curve considered. Post release mortality considered
Cons:
Cost: $$

HA4. Habitat 'SAFE'
Method: Spatial PSA for habitats.
Pros: Plot percentage exposure to actual effort footprint and intensity; per jurisdiction
Cons: Use environmental data as habitat proxy (inappropriate for 30% of species) and many other species only have weak environmental relationship. Less than 50% of species (rare species) can be assessed this way as too data poor.
Cost: $$$

CA2. Cumulative Effects
Method: CARE
Pros: Accounts for nonlinear interactions using "Additional Threat Modification" factors. Uncertainty qualitatively included as an adjustment on the risk score (inflates risk rating).
Cons: Expert information based. More factors tends to always inflate risk (false positive rate increases).
Cost: $

A16. ERAEF + RRA
Method: ERA & RRA with updated traits
Pros: Considered additional indicators total mortality, to reduce uncertainty due to natural mortality estimate (which difficult to estimate).
Cons:
Cost: $$

A15. ERAEF + RRA
Method: ERA & RRA (M-Risk)
Pros: Use clustering of PSA results too look for stocks where improvement possible.
Cons:
Cost: $$

SA11. Spatial exposure & mortality risk
Method: Spatial PSA (for cetaceans)
Pros: Allows for comparison between gears (so useful for establishing bycatch action plan)
Cons:
Cost: $$

SA12. Spatial exposure & mortality risk
Method: Spatial PSA (for seabirds) updated v3, PBR based
Pros: Quantitative. Uncertainty based on quality of information used. At the same resolution as fishing effort
Cons:
Cost: $$$

SA13. Spatial exposure & mortality risk
Method: Spatial PSA (for seabirds) updated v4.
Pros: Includes cryptic mortality sources. Tested veracity of estimate. Aggregated similar taxa to increase available information.
Cons: Potential fatalities based primarily on spatial overlap alone.
Cost: $$$

A17. ERAEF + RRA
Method: ERA & RRA aquaculture
Pros: Provided a histograms of distribution for risk attributes so could see sensible thresholds.
Cons:
Cost: $$

A18. EASI-FISH
Method: ERA & Life cycle analysis (LCA)
Pros: Data quality index included. Radar plots for communication of performance per dimension of risk. Converted to KOBE-plot like results so feeds management process.
Cons:
Cost: $$

A19. ERAEF + LCA
Method: ERA & Life cycle analysis (LCA)
Pros: Considers supply chain factors etc.
Cons:
Cost: $$

A20. ERAEF + RRA
Method: ERA (PSa using traditional knowledge)
Pros: Included traditional knowledge of the species. Considerable effort on communications "risk thermometers"
Cons: Without climate driver included will miss many declining species
Cost: $$

D4. Hazard Analysis Matrix
Method: Bow-tie method
Pros: Integrates science and management in a single process.
Cons: Expert advice dependent
Cost: $

D5. Hazard Analysis Matrix
Method: Conceptual model based
Pros: Can connect multiple information sources
Cons: Expert advice dependent
Cost: $

D6. Hazard Analysis Matrix
Method: Bow-tie method + Bayesian Belief Network (BBN)
Pros: Quantitative, drawing on multiple information sources. Test causal relationships. Identify strongest risk contributors and how to improve management.
Cons: Expert advice dependent. Data hungry and data may not be available. Cannot explicitly include feedbacks.
Cost: $

Figure 15: Timeline of ERA development over the past 15 years. Boxes coloured in the same way are related methods. The large grey arrows indicate where the one method has been used through time (primarily in Australia where repeated assessments have been undertaken for multiple fisheries).

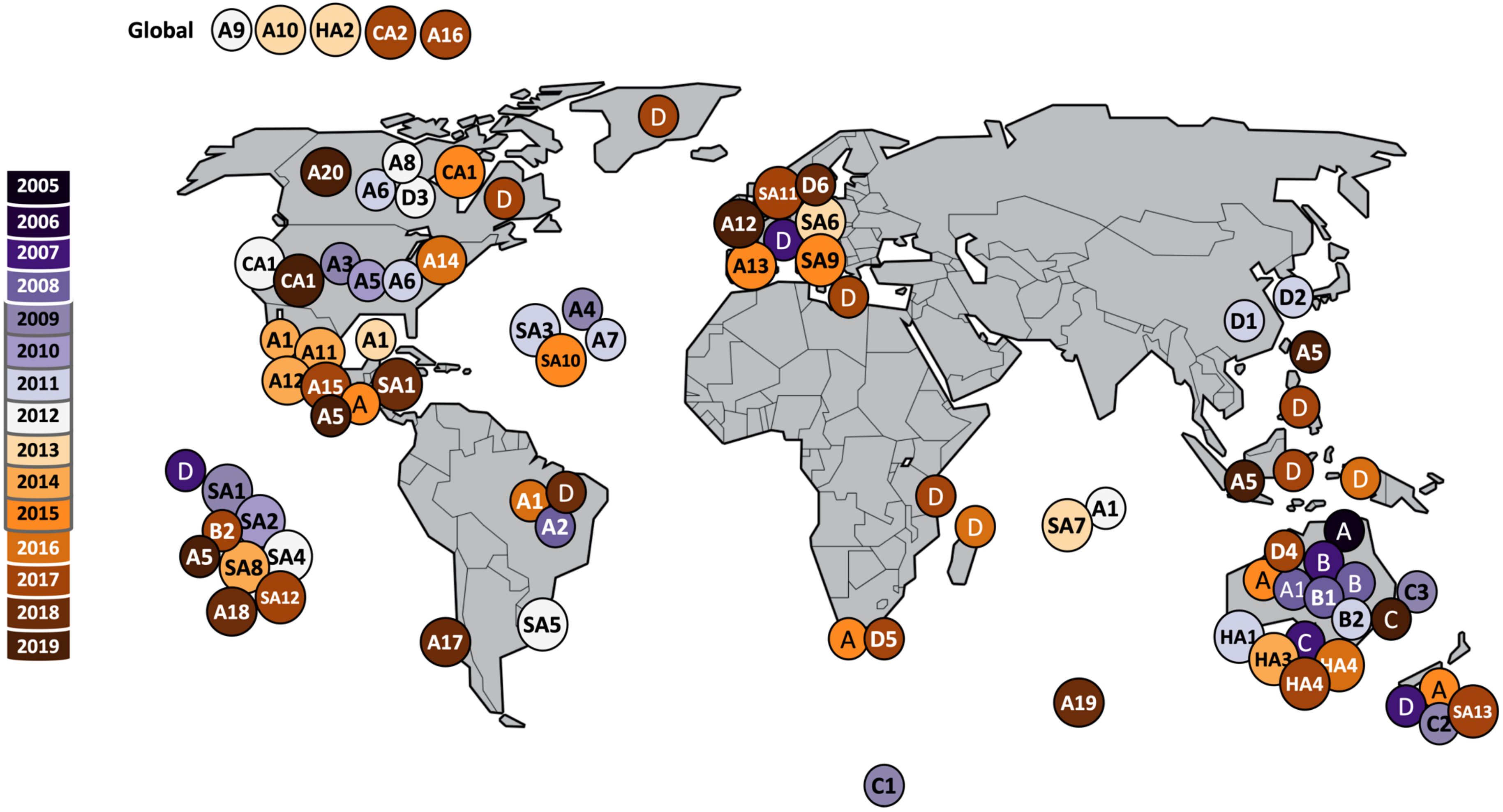


Figure 16: Map of ERA method use globally over the past 15 years (note the codes match the ones used in Figure 1 per ERA variant). The geographic bias no doubt reflects language bias (only English language publications were reviewed), but in some cases (e.g. for Africa, India etc) does reflect that no relevant studies have yet been undertaken there.

Table 3: Outline of major classes of methods (with example references). Note SICA = Scale Intensity Consequence Analysis; PSA = Productivity-Susceptibility Analysis; RRA = Residual Risk Analysis.

Method Type	Method summary	Pro	Con	Resources required	Upgrade note
ERAEF – Standard (Hobday et al. 2007; Hobday et al. 2011; AFMA 2017)	SICA & PSA & RRA as used in Australia (or minor variants including life cycle analysis, handling of uncertainty or defining meaningful thresholds to risk levels)	Deliverable given available information across large number of species. Management mitigation incorporated.	Base case does not have taxonomic specific attributes and includes subjective components.	Moderate (light per species, but typically used for 100s of species per assessment)	Can be expanded to consider interactions, climate and converted to absolute risk to allow for fleet comparisons.
USA ERA (Patrick et al. 2010)	Updated attributes to include management state, uncertainty and data quality. Removed RRA step. Use weighted attribute calculations.	Explicitly linked to management steps and uncertainty handling clear	Data hungry. Weighting can strongly influence assessment outcomes. Most low productivity species promoted to Level 3 assessments.	High	Becoming widely used, but also the focus of scrutiny and negative critique.
Spatial PSA (Filippi et al. 2010)	PSA-like calculations of productivity and susceptibility per species (or functional group) then mapped spatially vs exposure to fishing pressure (e.g. seasonal effort)	Taxonomic specific attributes used, often extended to consider seasonal and ontogenetic shifts in exposure. Includes cryptic mortality.	Struggle with handling of uncertainty or data poor species	Moderate-High	Taxonomic attributes from here could be folded into other methods (like SAFE or standard ERA)
Habitat ERA (Penney and Guinotte 2013; Pitcher et al. 2016)	PSA inspired calculations for habitat forming species mapped spatially vs fishing pressure used to produce spatial risk maps	Tailored specifically to habitat forming species	Struggle with handling of uncertainty. Habitat distribution calculations rarely validated.	High	Australia already leads the way for the methods, so extension would focus on validation.
SAFE (Zhou et al. 2011)	Estimate of risk (F proxy) based on availability, encounterability, selectivity and post capture mortality.	Can be automated for many 100s of species. Absolute risk so comparable across fleets.	Deterministic distributions not updated for habitat/climate influences	Moderate	Use some of the attributes or spatial modelling modifications used for spatial PSA to tailor the method taxonomically
Spatial vulnerability (Waugh et al. 2009)	Vulnerability assessed looking at overlap of species and fleet effort	Well accepted approach in conservation, where it has been linked to cost-benefit and other analyses. Includes cryptic mortality.	Simple distributions used. Does not consider interactions. Life history parameters inferred for many species	Moderate-High	Borrow understanding of cryptic mortality from this method to fold into SAFE.
Hazard analysis (DFO 2012)	Experts rate ways in which activities pose threats to species/habitats etc	Rapid. Can combine multiple information sources. Can be extended to be forward looking (using conceptual models)	Subjective (so hard to repeat and come to the same conclusion)	Low	Borrow the concept of being forward looking as well as backward looking and bring to other methods
Cumulative effects PSA (Samhouri and Levin 2012)	PSA method extended beyond fisheries	Same as for ERAEF – Standard. Can include interactions. Rapid.	Subjective (to date).	Low	Provides perspective on possible future extension as marine areas are used more intensively.

For communities, a review and update of the indicators used would be advisable as there has been a number of studies looking into this topic in recent years (even post Fulton et al (2019)), such as those developed by the Lenfest working group on “Indicators and guidelines for practical Ecosystem Based Fishery Management (EBFM)”.

The recommended modifications to the ERAEF method are straightforwardly implemented via taxon-specific filtering of the traits used in an online assessment tool now used for ERAEF assessments for AFMA.

CEA Review

The review by Fulton et al (2021) covered the development of CEA methods since their first use in the 1990’s and their expansion in the marine space during the 2000s, including 65 relevant documents in total. Consideration of the application of CEAs in an Australian context made clear that while the EPBC Act allows for broad-scale strategic assessments to set the context for developments in Australia, it does not indicate what these assessments should include (Dales, 2011; Dunstan et al., 2020). Consequently, CEAs undertaken by proponents (as part of project-related environmental impact assessments), or by government agencies (federal and state) as part of strategic or regional assessments have been of mixed content and quality. The highest quality applications include those completed under the NSW Marine Estate Management Strategy (MEMA, 2018), Victoria’s Marine and Coastal Policy (DELWP, 2020); Parks Australia’s Monitoring Evaluation Reporting and Improvement (MERI) framework (Hayes et al., 2021); the Spencer Gulf (Gillanders et al., 2016), Gladstone Harbour (Eco Logical Australia, 2019) and the Great Barrier Reef (Dunstan et al, 2020) regional assessments. These assessments took an additive approach, producing cumulative pressures maps. The guidelines for the CEA process for the GBR (Dunstan et al 2020), which is intended to be periodically repeated as part of an adaptive management approach, contained key steps used to inspire the method applied in this report, specifically: understanding pressures, understanding values, understanding ecosystem connections, identifying zones of influence, and the final determination of risk and uncertainty.

Globally, CEAs have grown from the simple use of risk assessment tables (which list stressor specific exposure factors and associated qualitative risk ratings based on severity and likelihood) through the 1970s and early 1980s (Cox, 2008) into tiered hazard assessments that progress from broad qualitative assessment of exposure pathways for ecological components of interest to more quantitative assessments (Bascietto et al., 1990; Hope, 2006). At each level precautionary and conservative assumptions are applied to screen for high risks, with no data equating to high risk by default. Any ecological components found to be at high risk are recommended as candidates for more quantitative tiers, so that the true extent of risk can be more clearly quantified (ASTM, 2003). This hierarchical approach to considering risk remains best practice today – informing both “broad but shallow” (strategic) assessments (e.g. Fletcher, 2005; Breen et al., 2012) and quantitative tactical decision-making (Samhouri and Levin, 2012, Knights et al, 2015) as it is an effective way of dealing with issues of scope and available information, and is at the heart of the framework put forward here. The need for repeatability and transparency has also driven research and regulatory groups to advance clearer use of any qualitative data or modelling and to prioritise quantitative methods (Stelzenmüller et al, 2018).

Maps convey large volumes of information quickly and have become a widespread tool for regulatory and research groups to convey information (Arthurs et al., 2021). The need to balance complexity, data gaps, interpretability and accuracy has also been a motivating force in the widespread uptake of additive GIS-based methods (e.g. Halpern et al 2008; O’Hara et al 2021). Concern over the prevalence of non-linear interactions, non-additive and indirect effects (MacDonald, 2000; Hodgson and Halpern, 2018; Hodgson et al 2019), which make up a sizeable portion of all marine effects (Crain et al., 2008; Brown et al., 2013; but see Stockbridge et al. 2020), have also driven a desire for the development of new approaches that can encapsulate such effects. Australia is a world leader in dynamic system models and these are a logical means of generating response functions that could be used to extend GIS-based approaches. This was the approach demonstrated here. While the proof-of-concept was not taken further here for the reasons described in the Results section, the application was successful and straightforward and shows much promise.

Issues complicating CEAs – Objective 2

Fulton et al (2021) characterise a number of issues that make CEA challenging. In particular: the resources and data needed; the use of expert-based approaches and associated problems with transparency and repeatability; validation of findings; and evaluation of risk mitigation (management) options.

Fulton et al (2021) summarise the main classes of methods used in CEAs, highlighting known strengths and weaknesses associated with each method. The scope and complexity of CEAs mean that they can require extensive data sets and significant resources to collate and analyse the materials. This is a particular challenge in Australia where monitoring data is patchy for even the better-known species and where up-to-date data on activities (e.g. state fisheries) can be exceptionally difficult to access. Even where data is more readily available, such as North America and northern Europe, fully comprehensive assessments resolved to fine scales but encompassing the full scope of marine socioecological systems is a very large undertaking, beyond the resources of the majority of regulatory and research groups globally. All CEAs represent some form of simplification to allow for the assessment to be tractable. In this report the simplification is to consider fisheries alone, in other jurisdictions more industries have been included in the assessment, but the assessment was non-spatial or relied on qualitative, expert-based information alone (Stelzenmüller et al, 2018).

Expert-based information is subjective, dependent on expertise called upon, typically lacking transparency and reproducibility (Stelzenmüller et al, 2018). A lot has been learnt in recent decades about best use of expert information in the context of risk assessment and how to ensure it as reliable as possible (Turschwell et al 2022) and so this approach should not be ruled out of tiered CEA frameworks, especially for scoping, rapid qualitative assessment steps, or environments that are data limited.

At the other extreme, dynamic system models – of the kind used for Gladstone Harbour (Fulton et al 2017) and for the Gascoyne (Fulton et al., 2015) and Kimberley (Boschetti et al., 2020) regions of Western Australia – include multiple human activities, representations of the full food web and habitats and allow for dynamic interactions that vary through space and time. Moreover, they can be used to explicitly consider alternative risk mitigation (management) options. However, such models remain a rarity, require extensive datasets or data collection exercises and specialist users. Nevertheless, those models that do exist can inform statistical models that can be more readily applied given existing data and resources, this is the approach taken here.

One of the strongest challenges to CEA is validation, with the few cases where that has been possible suggesting that the most commonly used CEA approaches do not necessarily reflect realised risk for some ecosystem values, such as seagrass habitat (Stockbridge et al 2021). Having sufficient data and resources to undertake validation will be a significant challenge for the rigorous use of CEAs in Australia, as it was here, due to the large geographic extent and high species and habitat diversity to be characterised. This means that Australian CEAs will need to be considered indicative and uncertain until more widespread data collection and cost-effective validation is possible.

Cumulative Effects Assessment framework – Objective 3

Whether intended to advise management or planning processes (e.g. Halpern et al, 2008; Kappel et al, 2012; Jones et al, 2018; ICES, 2019; United Nations, 2021) all effective CEAs contain five general elements:

- definition of the spatial and temporal extent of assessment
- information on the extent of ecosystem values of interest
- information on the extent (and potentially intensity) of activities or other stressors;
- information (where available) on potential responses by ecosystem components (e.g. an index or response function that characterises the resistance and recovery potential of the ecosystem values); and
- information on mitigation or management measures that might be implemented to reduce the realised extent or magnitude of the stressors.

As mentioned in previous sections of this report, drawing on these components and experience from previous CEA application in Australia, Fulton et al (2021) recommended an approach with the following steps:

1. Define the scope
2. Map the extent of the stressors.
3. Map the extent of the ecosystem values of interest.
4. Use overlays (or sensitivity weighting) to combine pressures and values and generate maps of areas of highest overlap, which can become a priority for management attention
5. Consider nonlinear CEA via conceptual models of system structure, zones of Influence, or ecosystem models
6. Assess risk and associated uncertainty
7. Validation of maps and risk ratings
8. Evaluation of management options/performance.

Marrying these steps with maximum compatibility with the extant or recommended ERAEF analyses lead to the method outlined in the flow diagram in Figure 2. Such compatibility, and the automation of all steps means that the analytical steps of the method should represent little additional overhead on the existing ERAEF process. In addition, to maximise consistency with methods applied in an analysis for Parks Australia looking at multi-sector cumulative pressures (Hayes et al 2021, Dunstan et al 2023) and to avoid the issues encountered by Zhou et al (et al. 2016) regarding species distribution maps for less well-known species, for the Stage I analyses presented here the species distributions were based on presence-absence maps used in ERAs (as noted previously alternative distributions could be substituted at this step if available). While this application of the analysis focused on target, bycatch and protected species, the same approach could be straightforwardly used for habitat forming species – either by using their distributions directly or by using the assemblage maps generated by application of the Pitcher et al. (2016) gradient forest approach, or other statistical methods (e.g. Hill et al 2020). If taking an ecological community perspective, the combined distribution of the consistent species could be used or the distribution of the finer scale, community level, IMCRA bioregions (DEH 2006) could be used instead.

While validation of the final scores via monitoring and the risk management steps were not undertaken in this report, there are conceptually to achieve if resources are available. Validation is undertaken by sampling along pressure gradients and observing whether abundance and disturbance patterns are consistent with the cumulative effects map – much in the way of Stockbridge et al (2021), but on larger taxonomic and geographic scales. Parks Australia are implementing a management effectiveness framework that will priorities monitoring of natural values to test whether AMP zoning is achieving management objectives and there is an opportunity to build on this ecosystem level monitoring to further validation and risk management through time. Evaluation of management options is much simpler, re-estimating and remapping cumulative scores based on modified maps of fishing pressure, which reflect how management actions would modify fishing pressure. The heavy demands COVID put on operators and management agencies through the past few years made such an exercise infeasible at this time, but it could be built into future applications of the method (as, say, part of an extended ERAEF assessment process).

The more resource demanding, and more uncertain step, of the Stage II analyses represents a successful world first estimate of non-linear cumulative effects undertaken in a generalisable and repeatable manner. It is contingent on the existence of ecosystem models as instruments of quantitative coherent ecological synthesis, but there is currently no feasible alternative within the cost recovery monitoring arrangements (which makes direct empirical observation unlikely given Australian fisheries monitoring and manipulative experiments of the scale and complexity required). However, a whole-of-government perspective opens new options. For example, targeted ecosystem monitoring can address key management question. Parks Australia's Management Effectiveness Framework aims to test zoning arrangements at a national scale and coordination between these efforts and fisheries would be of great benefit to understanding non-linear cumulative outcomes and the effectiveness of management interventions. Regardless of whether a model-based approach is the only way forward or a smaller part of larger efforts, this proof-of-concept application would benefit from follow-up as described further below.

Australia wide fisheries focused CEA

An Australia-wide cumulative impacts assessment was undertaken for 409 species influence by state and commonwealth commercial fisheries and overlapping recreational sectors. While the original objective was to also include customary fisheries and present results attributing relative contribution to cumulative scores this was not possible for separate reasons.

In terms of the customary fisheries, information was not available on these fisheries (either in terms of take or spatial extent) and there was no capacity to engage these fisheries during the lifetime of the project due to the constraints presented by the COVID pandemic. If information becomes available on these fisheries they could be added as an additional layer (or layers) in the same way as for other fisheries.

Fishery specific attribution is possible by breaking down the cumulative score in terms of the relative contribution per fleet – both for Stage I and Stage II analyses. The additive nature of Stage I analyses makes such attribution simpler, but it is possible for Stage II especially if the follow-up work described below occurs. Such disaggregation was not done here because of the mixed nature of the available data across the different fisheries. The state fisheries were only available up to 2015, whereas the Commonwealth fisheries data was much more recent. Mixing such disparate data is not ideal but was necessary here to show that the approach was feasible in concept. Consequently, while we felt comfortable to demonstrate the approach using the data mix, we did not feel it was a fair expression of the true current proportional contribution to cumulative effects to perform a fisheries specific attribution of relative contributions.

Similarly, the Stage II analyses were only completed for the southeast corner of Australia rather than Australia wide to demonstrate the approach is feasible, but as outlined in previous sections we have not extended it Australia wide in this project because:

- The taxonomic detail required in ecosystem models used for this part of the analysis is reasonably high and models of that kind are not currently available Australia wide (a large gap exists in southwest Australia)
- Where models do exist, it would be good to verify their individual veracity against more recent data (given large scale changes in environmental conditions, degrading habitat state and the fact that fisheries data used to fit the many of the models is now getting old) – essentially the need to update the models needs to be checked or accounted for in the assessment, somewhat like adding discount factors for aging stock assessment in tactical decision-making processes
- The wide confidence bands generated by the southeast example highlight the need for exploration of additional steps to make sure that the inclusion on nonlinear effects remains precautionary (as outlined in the section on follow-up below).
- Finally, as outlined in Figure 2, the additive assessment may be sufficient for some parts of the Australia EEZ where there is less activity. Full stage II analysis will be costly and time consuming.

All in all, while the application of the method has highlighted some challenges to ensuring it can be smoothly applied on top of existing ERAEF processes without generating significant additional (or unwarranted) overhead, the analyses presented here do illustrate that the method developed does summarise cumulative stress on species interacting with fisheries and does so in a way consistent with existing ERAEF processes, methods used in other parts of the Australian government (e.g. Parks Australia) and is also compatible with the ecological vulnerability analysis steps of the *Adaptation of fisheries management to climate change Handbook* (Fulton et al 2020).

A similar process of cumulative impact assessment has been completed for Parks Australia (PA) to prioritise their Management Effectiveness framework (Hayes et al 2021, Dunstan et al 2023). The assessment covered all activities that occur within Australian Marine Parks (AMP) - effectively all activities that occur within the Australian EEZ. The values within the AMPs were described using a Natural Values Common Language and the pressures against a Pressures Common Language (to be published by PA at Research Vocabularies Australia), which allows ecosystems and human use to be described and mapped in a nationally consistent way. The PA process implemented the assessment to the sum of pressures step, which was used to prioritise the locations for monitoring to determine the management effectiveness of AMP management plans. The implementation of Level 2.5 or Fully Dynamic Quantitative Methods was not completed but noted as a priority moving forward to support approvals.

Comparing the results of the eSAFE assessments and Stage I cumulative scores (from the “Sum of Pressures Analysis”) shows that despite being based on PSA scores the cumulative score is reflective of the degree of unsustainable pressure being applied to a species, with **a peak cumulative score of -5 or stronger in any part of the map indicating a species that may be under excessive pressure**. While in reality only a semi-quantitative rather than a fully quantitative index, this response is reassuring as it indicates that it can be applied with some veracity to species where the more quantitative eSAFE approach is not possible – and it is much more conservative than simple PSA.

As inferred above, the core of this new cumulative effects assessment should be straightforward to apply operationally, as it builds off the existing ERA process and its recommended modifications. However, experience gained during the project has seen an additional operational modification and that is the inclusion of cumulative eSAFE as one of the options to consider as the hierarchy of assessments is traversed. Such analyses are equivalent to the absolute risk ERA/CEA methods used in many jurisdictions already for marine mammals, seabirds and other megafauna (as discussed in Fulton et al (2019)). The final suggested flow diagram of operational CEA methods is show in Figure 17, with the grey boxes represent existing ERA steps of modifications there-of (e.g. updated Level 2 traits for PSA and the use of cumulative eSAFE). The automation of the ERA steps and the Stage I “Sum of Pressures Analysis” makes the workflow to that point relatively easy to execute. From there the resources required step up significantly as the Level “2.5” (or Stage II analysis as it was referred to here) and Fully Dynamic Quantitative Methods rely on systems models that can be quite resource intensive to create and maintain. Stepping all the way to those final steps might only be done in exceptional circumstances or as part of larger strategic assessments or planning processes.

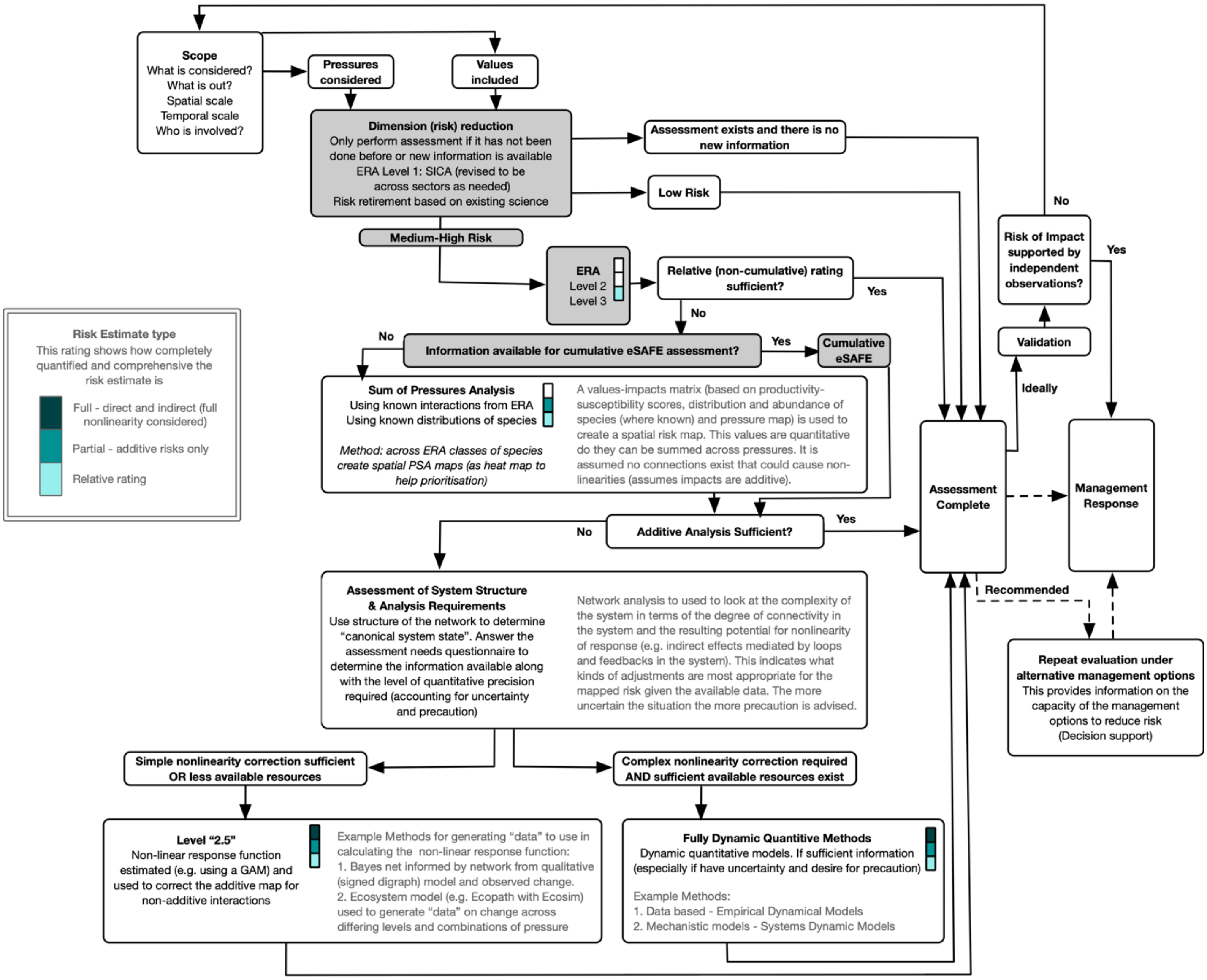


Figure 17: A flow diagram of the final recommended cumulative effects method hierarchy. The boxes in grey represent existing ERA steps of modifications there-of (e.g. cumulative eSAFE, where the eSAFE susceptibility scores per fishery are summed before comparing to F reference points when judging the degree of risk to the species).

Conclusion

Cumulative effects result from interacting activities, whether they overlap in space or through time. These effects may be additive (as seen in physical systems; MacDonald 2000), or nonlinear (Crain et al., 2008). The more complex nonlinear effects are more common in ecological systems and are poorly covered by many of the CEA methods developed to date.

As more fisheries – and more human activities in general – occur in Australia's waters, those interested in the state and management of marine resources require Information on the cumulative effects of all this activity on marine species, habitats and ecosystems. This mirrors a policy and a societal push for such information nationally and internationally, which has engendered increasing attention on the development of CEAs that can be used for regional planning purposes and for assessing the pressure being applied to vulnerable species and regional ecosystems (Halpern et al. 2008; Korpinen and Andersen, 2016; Stelzenmüller et al, 2018).

The focus of this project was the development of methods to estimate the cumulative effects of multiple fisheries and sectors (commercial and recreational) on individual species, habitats and communities. The assessment framework developed is scalable both in terms of spatial extent, taxonomic complexity and the industries included in the assessment. In the applications outlined in this report we show how it can be applied at species level and how it can be extended through to community or even system levels, though the later requires more substantial resources. We also focus on fisheries applications here, but as it is consistent with methods used by Parks Australia and applied to the Great Barrier Reef it could be used to consider the combined pressure of fishing and non-fishing activities in future as required.

The reviews of extant ERA (Fulton et al 2019) and CEA (Fulton et al 2021) approaches from around the globe laid the ground work for making sure Australia's application of these methods remain at the forefront of pragmatic best practice. Constraints on available information mean some options are not possible and that operationalisation must make use of the hierarchical structure of the recommended frameworks, settling for semi-quantitative analyses for data poor species. Nevertheless, by incorporating taxon-specific traits, consideration of differential ontogenetic susceptibility (where appropriate), cryptic mortality, habitat and trophic dependencies, the influence of environmental variability and how climate influences (as summarised in Figure 4) the susceptibility or exposure of the species ERA can remain a reliable means of assessing the sustainability of the exploitation and interaction of Australian fisheries with the nation's marine flora and fauna. Moreover, by using ERA as its foundation the CEA framework presented here (Figure 17) can transparently and repeatedly provide insight into the cumulative effects on Australian marine species. The recommended modifications have already begun to be accounted for in the automated system used to undertake ERA assessments for AFMA. This automation of the CEA process also means that the new workflow does not add onerous resource demands on any assessors, unless they choose to go to the most quantitative models, which is likely only necessary in specific strategic assessment contexts.

This project addressed one of the most scientifically challenging topics currently facing marine resource use and conservation. While it made significant advances and has resulted in a workable and effective CEA framework it would benefit from follow-up to see application of the non-linear assessment to more regions, but also to co-design the inclusion of customary fisheries and co-produce assessments that look at how such fisheries sit within the broader context of other uses of the system. While the project was originally developed in consultation with a number of agencies (state and federal) and was intended to be undertaken in close consultation with customary fishers, that level of collaboration was not possible given the constraints and disruption introduced by the COVID-19 pandemic. It is hoped that follow-up of some kind is possible to see out these additional features and make the most of the proposed framework.

Implications

Through its history the ERAEF process has proven to be an effective means of demonstrating that AFMA (and other fisheries nationally and internationally) are meeting their EPBC (or equivalent) sustainability requirements, and has been adopted as part of the Marine Stewardship Council guidelines (Marine Stewardship Council 2013). The potential for CEAs is just as large. While this project deals with method development, preliminary assessments and proof-of-concept applications, the potential implications for industry and management could be more significant. Based on the trajectory of expectations in Europe and North America around the use of CEA to inform regional planning and assessments of pressures on vulnerable species and regional ecosystems (ICES, 2019), as well as the EPBC Act (1999) requirement to address cumulative effects – and renewed interest in that as part of the review of Australia's Harvest and Bycatch Policies – CEAs are likely to become a standard requirement of industry or regulatory body processes in coming years. This will no doubt come with some additional costs – in terms of data collection or (at the very least) incremental costs of analyses (though hopefully these can be moderated or offset by increased automation) – but by making these assessments proactive not simply retrospective there will also be benefits in the form of faster warning over unsustainable practices and avoidance of costly and wasteful degradation. In addition, it will help with attribution, so that the effects of individual fisheries can be assessed, allowing for prioritisation if pressure reduction is required, or demonstrating which sectors have low impact. The role of climate change is also made clearer when trying to decipher any observed ecosystem or species shifts. For these benefits to be maximally realised, however, Australia would benefit from the capacity to more rapidly and transparently share up-to-date fisheries information for all jurisdictions. That will necessarily need to come with inclusive discussion pertaining to fair use (given the potential confidentiality of data under current legislation and policy), but given the rapid pace of environmental and marine industry change occurring around Australia right now, falling behind international standards around FAIR data use and societal expectations of transparency does not help any part of fisheries systems – producers, managers or researchers aiming to help support thriving but sustainable industries.

Recommendations

The methodological and procedural recommendations regarding how ERA and CEA are undertaken in Australia are documented in the previous sections of the report and in the associated reviews by Fulton et al (2019) and Fulton et al (2021). In terms of uptake, our recommendations would be:

I. Adopt the modification of the ERAEF method used by AFMA (and other Australian regulatory agencies) following the recommendations detailed in Fulton et al (2019)
II. Full automation of all steps of the ERAEF and CEA methods to allow for a reduction in “handle turning” costs so that (a) updates can be made more regularly (potentially even annually as part of standard RAG update processes) and (b) investment in the analyses can focus on the interpretation and response advice end of the assessments (where intellectual input can be of most benefit) rather than in simply working up the analyses. Much of this automation has already been undertaken by the CSIRO teams working on the *Adaptation of fisheries management to climate change handbook*, but it is worth reflecting on the need for automation here (there are online apps for ERA, and the handbook and the CEA steps are currently available as R-scripts available at https://github.com/eafulton/RmapCEA.git, but could be incorporated into the online apps in future allowing for individuals to upload their own pressure fields). ERA and CEA involve assessing hundreds of species, often with little data. While significant effort (e.g. via automation) has been put into making these methods as consistent and cost effective to deploy as possible these are challenging tasks that do need oversight and interpretation
III. As noted elsewhere (and detailed further below) it would be wise to follow up on (a) customary fisheries and (b) the proof-of-concept nonlinear analysis presented here to maximise the potential of the CEA framework presented. Moreover, of the framework is judged to meet needs more generally it could be joined with the existing online ERA app to ease use
IV. Additional extension activities would be useful for sharing the CEA concepts and framework more broadly.

Further development

Due to the challenging nature of the topic being tackled and the constraints imposed by the COVID-19 pandemic, this project did not completely achieve the objectives originally set out. A number of follow-up steps would usefully extend the research, expanding the reach of the approach to the originally envisaged scope or to verify the veracity of the method or refine it so that its results are less uncertain.

Within the research realm, the specific follow-up developments that would be recommended are:

I. Working with First Nations fishers to appropriately include customary fisheries in the CEA framework
II. Refinement of the proof-of-concept “Level 2.5” analysis so that it did not use a bulk GAM applied across all combinations of simulated fisheries, but used a tailored set that matched specific combinations of fisheries found in the individual spatial cells making up the map of fisheries interactions per region (or more broadly around Australia). This should better resolve the predicted risks and reduce associated model-based uncertainties
III. Extension of the proof-of-concept “Level 2.5” analysis around Australia. This would require: accessing more up-to-date state fisheries data; updating existing ecosystem models for current conditions (or verifying that historical conditions can be suitably reproduced if only undertaking retrospective analyses); filling any outstanding gaps in model coverage around Australia (e.g. along the temperate-subtropical coast of Western Australia); batch generating the impact-response functions; applying the “Level 2.5” method using these updated information
IV. Implementation of the CEA framework as either a standalone online app rather than as a set of R-scripts, or more logically as an extension of the existing ERAEF online tool.

In addition, within the management realm there needs to be further discussion (and perhaps trial runs) of how the CEA methods could be most seamlessly fitted into current management processes, how that could realistically occur and what resources would actually be required to achieve that. Such a discussion is partially underway, in terms of refining the ERAEF process on the back of the review by Fulton et al (2021) and broader AFMA considerations, but would need extending to CEA. Such discussions would need to extend conversations/briefings initiated as part of the current project's extension activities.

Extension and Adoption

COVID-19 strongly curtailed the capacity to undertake extension activities. This meant extension was constrained to:

- Sharing the ERA review and progress on the CEA work with the AFMA led ERA/ERM working group, where the ERA recommendations are being considered and acted on as part of their ongoing ERM review and updating
- Dialogues with a project steering group made up of ABRES, AFMA, Parks Australia and other state and federal fisheries management representatives and other consultants.

The CEA review and logic underlying the framework has also informed an International Energy Agency's Ocean Energy Systems Environmental white paper on cumulative effects assessments and ecosystem based management approaches (Fulton et al 2022).

Factsheets and academic papers are also under development to communicate the approach more broadly.

Project materials developed

The project generated two technical reports – one for each of the reviews undertaken – which are attached to this report appendices. Parts of these reports will be used as contextual information for a paper (under development) on the development and application of the CEA method described in this report. In addition, a number of r-scripts were used to automate the steps and these are available from the githib repository at https://github.com/eafulton/RmapCEA.git (note that species names and distributions are provided with the R scripts but not the fishing data, as that is subject to jurisdiction imposed restrictions on sharing, and the final effects maps are too large to store on that site, please contact the authors if that data is required)..

Appendix 1: Researchers and Project Staff

List of researchers

Core research staff:

Beth Fulton, Piers Dunstan, Rowan Treblico

Additional method development project members:

Gabriela Scheufele, Karen Evans, Skipton Woolley and Bronwyn Gillanders

Other advisory researchers:

Jason Hartog, Miriana Sporcic, Cathy Bulman, Mike Fuller, Roland Pitcher and Jackson Stockbridge

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Appendix 3: Review of ERA

The attached technical report that provides the review of ecological risk assessment methods is a reprint of Fulton EA, Bulman C, Thomas L, Sporcic M, Hartog J (2019) Ecological Risk Assessment Global Review. CSIRO, Australia.

Appendix 4: Review of Cumulative Effects Assessments

The attached technical report that provides the review of cumulative effects assessment methods is a reprint of Fulton EA, Dunstan P, Gillanders B, Evans K, Treblico R, Scheufele G (2021) Review of Cumulative Effects Assessments (CEAs): Background to a New CEA process. CSIRO, Australia.

Appendix 5: Maps of Stage 1 Results – Maximum Potential Effect (No Zoning)

Maps of the Stage I “Sum of Pressures Analysis” CEA maps for the 405 species for “Commonwealth Fisheries Only” and “All Fisheries”. Available from *the Cumulative impacts across fisheries in Australia's marine environment – Data Appendices* sister document.

This appendix includes Table S1.

Appendix 6: Maps of Stage 1 Results – Residual Cumulative Effects (with Zoning)

Maps of the Stage I “Sum of Pressures Analysis” CEA maps for the 405 species all fisheries with zoning effects included. Available from *the Cumulative impacts across fisheries in Australia's marine environment – Data Appendices* sister document.

Appendix 7: Maps of Stage II Results

Maps of the Stage II CEA maps for the species and functional groups included in the south-eastern Australian Ecopath with Ecosim model. Available from *the Cumulative impacts across fisheries in Australia's marine environment – Data Appendices* sister document.

Appendix 8: Impact Response Functions Derived from EwE

The plots of the impact-responses of each taxa to increasing pressure from an increasing number of fleets. Available from *the Cumulative impacts across fisheries in Australia's marine environment – Data Appendices* sister document.