Fisheries New Zealand

Tini a Tangaroa

Towards ecosystem-based fisheries management in New Zealand: an ecosystem approach to fisheries management case study in FMA 7

New Zealand Aquatic Environment and Biodiversity Report No. 360.

A. Grüss, S. Datta, V. McGregor-Tiatia, S.J. Holmes, J.P. Davis, E.A. Fulton, K. Sainsbury, É.E. Plagányi, P.J. Dolder, M. Parsa, J.M. Dambacher, S.K. Gaichas, H. Townsend, S. Pascoe, J.L. Blanchard, D. Parsons

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Requests for further copies should be directed to:

Fisheries Science Editor
Fisheries New Zealand
Ministry for Primary Industries
PO Box 2526
Wellington 6140
NEW ZEALAND

Email: Fisheries-Science.Editor@mpi.govt.nz
Telephone: 0800 00 83 33

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PLAIN LANGUAGE SUMMARY

Aotearoa New Zealand has committed to progress integration of broader ecosystem and environmental considerations in fisheries management. These efforts can start with an ecosystem approach to fisheries management, where these broader considerations are explicitly considered in analysis focused on management settings for individual fish stocks.

The research reported here identified and reviewed tools that could support greater analysis of ecosystem and environmental considerations in New Zealand's current fisheries management framework.

The Fisheries Management Area 7 (west coast South Island) inshore mixed bottom trawl fishery was used as a case study for this research. Meetings with managers and key fishery stakeholders were held to establish key management questions around ecosystem and environmental considerations. This included understanding the effects of single species catch limits on other species in a mixed fishery, the ecosystem effects of environmental stressors such as sedimentation, and key predator-prey interdependencies. An international expert workshop was then held to identify tools which have been applied overseas to inform management advice on ecosystem and environmental considerations for fisheries.

There exists a diverse range of ecosystem simulation models, with different configurations, levels of complexity, information requirements, and management applications. Qualitative ecosystem models and ecosystem models of intermediate complexity are the most suitable ecosystem simulation models to assist the ecosystem approach to fisheries management in New Zealand, primarily because of their more limited data requirements and their ability to strongly engage resource managers and other stakeholders. Beyond ecosystem simulation models, tools called "métier analysis", "principal component analysis" ("PCA") and "heatmaps" provide additional technical options for supporting the ecosystem approach to fisheries management in New Zealand.

Our report also includes recommendations to facilitate the inclusion of ecosystem and environmental considerations in resource management, which were provided at the international expert workshop, and directions for future research.

EXECUTIVE SUMMARY

Grüss, A.; Datta, S.; McGregor-Tiatia, V.; Holmes, S.J.; Davis, J.P.; Fulton, E.A.; Sainsbury, K.; Plagányi, É.E; Dolder, P.J.; Parsa, M.; Dambacher, J.M.; Gaichas, S.K.; Townsend H.; Pascoe, S.; Blanchard, J.L.; Parsons, D. (2025). Towards ecosystem-based fisheries management in New Zealand: an ecosystem approach to fisheries management case study in FMA 7.

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Commitments have been made to progress ecosystem-based fisheries management (EBFM) in Aotearoa New Zealand. While working towards achieving EBFM, New Zealand is currently developing its ecosystem approach to fisheries management (EAFM) which constitutes a sensible first step to incorporating ecosystem and environmental considerations into fisheries assessments and management. The research reported here primarily aimed to identify and review tools to progress EAFM in New Zealand, particularly to allow for a better understanding of how total allowable commercial catch (TACC) adjustments for one stock may affect other stocks in a mixed fishery (i.e., technical interactions). The research reported here also aimed to identify and review other EBFM tools that can provide insights not necessarily on the impacts of technical interactions, but also potentially the impacts of biological (a.k.a. trophic), environmental, and cumulative stressor interactions, and that can be operationalised under New Zealand's existing management framework.

In this project, we conducted a literature review on EAFM/EBFM/ecosystem-based management (EBM) and tools to progress these management approaches. We also identified the Fisheries Management Area 7 (FMA 7) inshore mixed bottom trawl fishery as a good EAFM case study and discussed this case study at meetings with resource managers and stakeholders. We organised a workshop with international experts to discuss the applicability of the EAFM tools that we identified for New Zealand, flag any valuable tools that we missed, and learn from experiences with EAFM/EBFM/EBM overseas. After the workshop with international experts, we ranked EAFM tools based on the questions they can answer/their outputs, their requirements, their advantages and limitations, and the resources available in New Zealand to apply them (funding and expertise). Finally, we carried out some EAFM analyses for the FMA 7 case study.

There exists a diverse range of ecosystem models, which can be categorised based on their structure and which have different degrees of complexity and purposes/objectives. Conceptual, qualitative and dynamic structural equation models and dynamic multispecies models are suitable ecosystem models to assist EAFM in New Zealand, primarily because of their more limited data requirements and because these models are simple and conducive to collaborative research with resource managers and other stakeholders. By contrast, more complex ecosystem models, including aggregated (or whole ecosystem) models (e.g., Ecopath with Ecosim models), biogeochemical-based end-to-end models (e.g., Atlantis models) and coupled and hybrid model platforms (e.g., multispecies size-spectrum models) are more suited to guide EBFM or EBM, which consider multiple issues beyond simply those pertaining to particular fisheries. Among dynamic multispecies models, Models of Intermediate Complexity for Ecosystem assessments (MICE models) are particularly useful models for EAFM. MICE models integrate the best characteristics of single-species models and can employ standard statistical methods for estimating model parameters, while also considering broader ecosystem considerations that depend on management objectives.

Beyond ecosystem models, several other tools are valuable to progress EAFM in New Zealand. In particular, métier analysis was given a very high rank, primarily because of its focus on technical interactions. Métier analysis quantitatively categorises individual fishing events (e.g., trawl tows) or fishing trips to a métier (fishing activity or strategy that is defined by area and gear, and is, therefore,

associated with a particular catch composition as a result). Métier analysis is an important building-block required to obtain uniform catchabilities across all the stocks considered with other EAFM tools. However, métier analysis can be useful in itself, for example to characterise a fishery or an ecosystem. In addition to qualitative models (loop analysis), DSEMs, MICE models, ISIS-FISH ecosystem models (which are dynamic multispecies models) and métier analysis, the toolbox that we identified to progress EAFM in New Zealand includes a few other tools: mixed fisheries forecasts using the MixME (Mixed-fishery Multi-stock Evaluation) method; indicators of ecosystem overfishing; cumulative biomass versus trophic level; principal component analysis (PCA) on timeseries data and heatmaps; and risk tables. PCA and heatmaps were given a very high rank, primarily because they provide similar insights as métier analysis but take much less time to develop. Indicators of ecosystem overfishing, cumulative biomass versus trophic level and risk tables were also assigned a high rank, mainly for their simplicity and low data requirements.

We identified the FMA 7 inshore mixed bottom trawl fishery as a good EAFM case study primarily focused on the issue of technical interactions, mostly because the FMA 7 inshore mixed bottom trawl fishery has been relatively well studied compared to other mixed fisheries. We identified 17 stocks for this EAFM case study. We conferred with stakeholders about the FMA 7 case study, which mainly allowed us to draw important considerations for métier analysis for FMA 7 (a tool with a very high rank for EAFM). However, we opted to conduct some first analyses for the FMA 7 case study with PCA and heatmaps instead (another tool with a very high rank for EAFM). The preliminary PCA and heatmaps reported here were an opportunity to showcase this promising EAFM tool.

Recommendations on EAFM/EBFM/EBM and associated tools made by experts present at the workshop included:

- Employing multiple tools together or in sequence.
- Using available complex ecosystem models for scoping in an EAFM project.
- Considering using ecosystem models that require diet data in limited diet data situations.
- Leveraging existing platforms and code bases whenever possible/relevant.
- Fitting tools within assessment/management timelines and cycles.
- Having a more collaborative approach, with more regular meetings between resource managers and stakeholders and scientists.
- Building buy-in from resource managers and other stakeholders with management strategy evaluation (MSE).

Finally, the present report also provides potential avenues for the future. They include: continuing analyses for the FMA 7 case study with the tools that were assigned a very high or a high rank; carrying out EAFM analyses for FMA 7 with other tools; addressing other New Zealand EAFM case studies; more formally integrating EAFM into New Zealand research and management; and continuing the move towards EBM in New Zealand.

1. INTRODUCTION

Commitments have been made to progress ecosystem-based fisheries management (EBFM) in Aotearoa New Zealand. Under the Fisheries Act 1996, the Minister for Oceans and Fisheries is required to consider or take into account a number of ecosystem and environmental considerations when setting total allowable catches (TACs) and sustainability measures for individual fish stocks. The National Inshore Finfish Fisheries Plan approved by the Minister for Oceans and Fisheries under section 11 of the Fisheries Act also includes objectives around progressing integrated management of multi-species fisheries (fish stock complexes) and applying an ecosystem-based approach to management (EAFM) (Fisheries New Zealand 2022). Relevant domestic and international agreements also include the New Zealand Biodiversity Strategy – Te Mana o te Taiao (Department of Conservation 2020), the Food and Agriculture Organisation Code of Conduct for Responsible Fisheries, the United Nations (UN) Convention on the Law of the Sea, and the UN Convention on Biological Diversity.

While analysis of ecosystem and environmental considerations is currently provided to the Minister for Oceans and Fisheries under an output-based single-species management approach (the quota management system (QMS)), the quality of this advice can be limited by available research and tools. Although EBFM is not as advanced in New Zealand as it is in some other countries (e.g., the USA, Australia), stakeholders and fisheries managers often need answers to EBFM questions. Key management questions include the impacts of an increase/decrease in the total allowable commercial catch (TACC) of a given stock on the catches for other stocks (technical interactions), the relationship between increased/decreased fishing pressure for a given species and the function/role of that species in the ecosystem (including as predator or prey), and effects of environmental variables and stressors on individual species and wider ecosystem function. A current example of trophic EBFM considerations being taken into account in fisheries management decisions is the issue of kina (*Evechinus chloroticus*) barrens, which are extensive in northeastern New Zealand and linked to fishing of predators such as rock lobster (*Jasus edwardsii*) and snapper (*Chrysophrys auratus*) (Doheny et al. 2023).

In this context, Fisheries New Zealand aims to identify tools to operationalise ecosystem and environmental considerations in fisheries management decisions. To strengthen our approach to EBFM, the simpler EAFM constitutes a sensible first step to incorporating ecosystem and environmental considerations into fisheries assessments and management. EAFM is currently underway in New Zealand. To move towards EBFM, Fisheries New Zealand commissioned the project “INV2023-10 Ecosystem Based Management: A case study on multi-species inshore fisheries.”

The INV2023-10 project aimed to identify methodologies to incorporate wider ecosystem effects into management advice, with a focus on inshore mixed trawl fisheries, with three objectives (Figure 1). Objective 1 consisted of a review of ecosystem modelling approaches, the selection of an inshore fishery case study for the project, and the identification of candidate ecosystem models and other tools for the inshore fishery case study. Once Objective 1 was completed, it was decided to select the Fisheries Management Area 7 (FMA 7) mixed bottom trawl fishery as the inshore fishery case study. Objective 2 was to choose the most appropriate model or model toolbox and outline steps to operationalise this model with input from fisheries managers and stakeholders. This included a meeting with resource managers and stakeholders in June 2024, to discuss the selected EAFM case study and the candidate ecosystem models and other tools for that case study. Objective 3 consisted of having a workshop with international experts to discuss ecosystem models and other tools (Part 1) and then applying or preparing the chosen model(s) or model toolbox for the FMA 7 case study at the scoping level (Part 2). For Objective 3 Part 2, principal component analysis (PCA) and heatmaps were used.

The INV2023-10 project represents a baseline project providing the first step towards modelling that could become part of the sustainability round process. Discussions with fisheries managers during the project highlighted the following priorities:

(i) To identify tools allowing for a better understanding of how TACC adjustments for one stock will affect other stocks in a mixed fishery (i.e., technical interactions).

(ii) To identify modelling approaches that could provide insights not only on the impacts of technical interactions, but also on the impacts of biological (a.k.a. trophic), environmental, and cumulative stressor interactions, and that can be operationalised under New Zealand's current management framework.

In this report we summarise results across Objectives 1, 2 and 3 of the INV2023-10 project. In the following, we first describe methods (Section 2). Then, we provide a brief overview of commercial fisheries and fisheries management and assessments in New Zealand, with a particular focus on ecosystem and environmental considerations for fisheries management and stock complexes (Section 3.1). Next, we clarify the concepts of EAFM, EBFM and ecosystem-based management (EBM) (Section 3.2). Then, we present tools for EBFM (Section 3.3) and tools for EAFM in New Zealand (Section 3.4). Next, we describe the FMA 7 case study (Section 3.5) and report the first application for that case study (Section 3.6). Finally, we conclude the present report with a discussion of our research (Section 4), suggestions for future research (Section 5) and the detail of the broader outcomes that were fulfilled through the INV2023-10 project (Section 6).

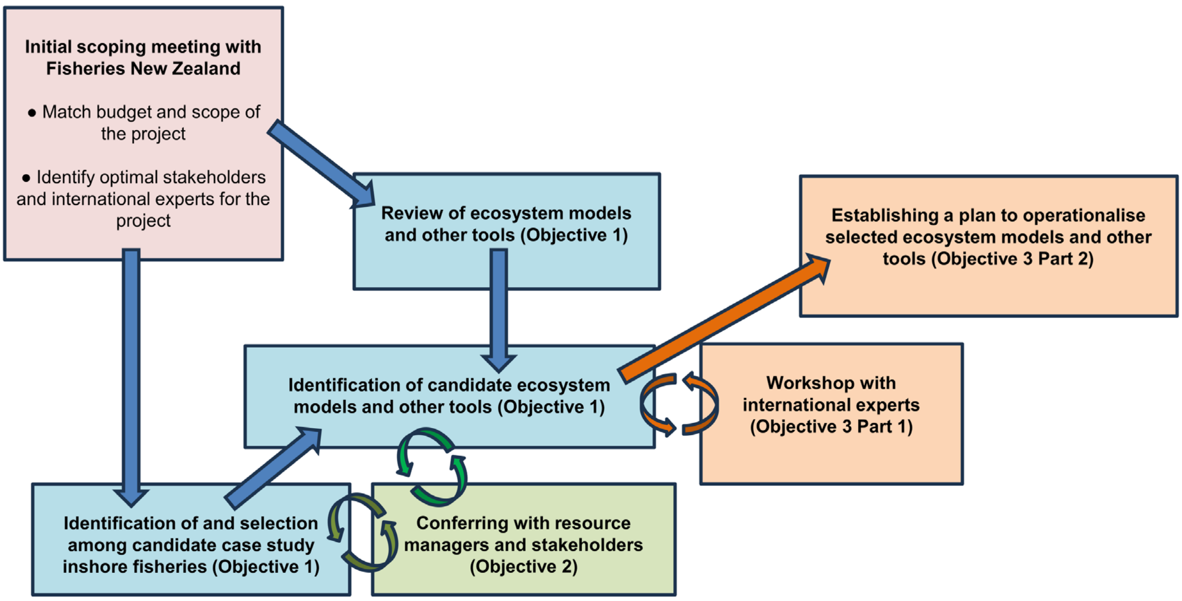

Figure 1: Overview of the INV2023-10 project.

2. METHODS

2.1 Literature review (Objective 1)

An important fraction of the present report consists of a literature review on EAFM/EBFM/EBM and tools to progress these management approaches. The search engines used to carry out this literature review included ISI Web of Science™, Google Scholar and Google. In addition to publications in peer-reviewed journals, fisheries assessment reports (FARs) and aquatic environment and biodiversity reports (AEBRs) were considered as they represent the major source of fisheries research published in New Zealand. Our searches were supplemented through discussions with fisheries scientists and managers from Fisheries New Zealand and overseas collaborators. These discussions allowed us to access additional reports, notably consultation documents and technical documents from overseas.

2.2 Inshore fishery case study (Objective 2)

To select an inshore fishery case study for the project, we first had meetings with Fisheries New Zealand scientists at the start of the project and read the consultation documents that Fisheries New Zealand scientists provided to us, as well as the National Inshore Finfish Fisheries Plan (Fisheries New Zealand 2022). This led us to identify two potential case studies:

- The FMA 7 mixed bottom trawl fishery.
- The FMA 3 (east coast South Island) mixed bottom trawl fishery.

We presented the two potential case studies to the Biodiversity Research Advisory Group (BRAG) on 2nd May 2024. Based on feedback from the BRAG and subsequent discussions with Fisheries New Zealand scientists, we selected the FMA 7 mixed bottom trawl fishery as the case study for the INV2023-10 project. We opted for the FMA 7 inshore mixed bottom trawl fishery primarily because it has been relatively well studied compared to other New Zealand mixed fisheries (e.g., a research trawl survey has been conducted within the inshore domain of FMA 7 for more than 30 years).

We identified: (i) stocks for the FMA 7 case study, based on consultation documents and the National Inshore Finfish Fisheries Plan; and (ii) EAFM tools for the case study, based on the literature review (Section 2.1). We presented our selections of stocks and EAFM tools for the FMA 7 case study to resource managers and the stakeholders at a meeting on 27th June 2024, which helped us improve our selections. Moreover, we had at that time identified métier analysis as a very important EAFM tool for New Zealand (see Section 3.4.1), and the June 2024 meeting with resource managers and stakeholders was also useful to draw considerations for future métier analysis for FMA 7. In particular, we sought advice on the fisher decision variables that should be considered in métier analysis for FMA 7 (start longitude and latitude of tows, fishing time, month, others).

2.3 Workshop with international experts (Objective 3 Part 1)

We had a workshop with international experts (henceforth "the international workshop") on 4th October 2024. The purpose of the international workshop was to discuss the applicability of the EAFM tools that we selected for the FMA 7 case study based on the literature review (Section 2.1) and the June 2024 meeting with resource managers and stakeholders (Section 2.2) and as a transferable methodology for other New Zealand regions. With the international workshop, we also wished to learn from the experience of international experts with the tools and better understand their applicability for supporting progress towards EBFM in New Zealand.

The international workshop included live and recorded presentations from American, Australian and English experts, and discussions focussed on questions circulated beforehand (Appendix 1). Due to time constraints, many European experts were consulted separately via a presentation by Vidette McGregor-Tiatia at the Working Group on Multispecies Assessment Methods (WGSAM) organised by the International Council for the Exploration of the Sea (ICES) in October 2024.

The scope of the international workshop was specifically to refine the EAFM toolbox for the FMA 7 case study. In addition to feedback on the utilisation of the proposed tools, Fisheries New Zealand was interested in better understanding the advantages and disadvantages of more complex ecosystem models, and the steps required to operationalise them in New Zealand's fisheries management framework.

Key questions circulated that were discussed at the workshop included:

- Considering the specific aims of our case study, which of the listed tools would you particularly recommend and why?
- Are there any tools missing for our specific case study and why? What are the main pros and cons of those additional tools?
- Among the tools we listed and potential additional tools, how long does it take to implement them and analyse their results (including or excluding potential training)?
- In your experience, among the different tools, which ones have been successfully used to inform fisheries management/decision-making?
- Would New Zealand's current fisheries management framework, data and/or funding hinder the operationalisation of these tools in New Zealand?

2.4 Ranking of tools and selection of a tool for Objective 3 Part 2

We considered the outcomes from the literature review (Section 2.1), the June 2024 meeting with resource managers and stakeholders (Section 2.2) and the international workshop (Section 2.3) to rank the EAFM tools identified through the literature review supplemented by additional EAFM tools suggested by international experts. The ranking of the EAFM tools was based on the questions they can answer/their outputs, their requirements, their advantages and limitations, and the resources available in New Zealand to apply them (funding and expertise). Each EAFM tool was assigned a low, medium, high, or very high rank.

2.5 First application for the case study (Objective 3 Part 2)

Among the tools to support EAFM in New Zealand, métier analysis was assigned a very high rank because it would support modelling fishery and fleet dynamics under different management scenarios (see Section 3.4.8) and was discussed with resource managers and other stakeholders at the June 2024 meeting (see Section 3.5.3). However, to carry out some first analyses to assist EAFM in FMA 7, we opted for PCA and heatmaps, which were also assigned a very high rank and deliver relatively similar insights to those of métier analysis (see Section 3.4.8). Primary reasons for the choice of PCA and heatmaps rather than métier analysis included the substantial time commitment for development and data limitations (lack of full stock assessments) which meant that métier analysis would not be able to be used to support the fleet forecasting approach required by Fisheries New Zealand managers.

We conducted PCA and generated heatmaps using two alternative sources of data: (i) landings data, as PCA and heatmaps are originally meant to investigate changes in fisheries catch composition over time; and then (ii) research biomass survey data, to explore changes within FMA 7 from an ecosystem perspective. Research biomass survey data are useful from an ecosystem perspective because they are not fraught with the confounding factors associated with fishing such as changes in gear and catch regulations and reporting that may impact species catch mixes over time.

Calendar years rather than fishing years (which start on 1st October of the preceding calendar year) were considered here, but future research could consider fishing years instead. The PCA and generated heatmaps reported in the present report are preliminary and meant to provide an illustration of these EAFM tools.

2.5.1 Data

For the first type of PCA and heatmaps, we requested Fisheries New Zealand to query all the commercial fishing trips landing FMA 7 quota (across all fishing gears) between 1st January 1990 and 31st December 2024 within the Enterprise Data Warehouse (EDW) landings data table. We summed landings by species and year and kept only the species for the FMA 7 case study retained after the June 2024 meeting with resource managers and stakeholders (see Section 2.5.1). In the case of flatfish, landing values were summed over the eight species that comprise the FLA 7 stock. Thus, we had a total of 35 years of data and 17 species for the first type of PCA and heatmaps.

For the second type of PCA and heatmaps, we relied on west coast South Island Tasman Bay/Golden Bay (WCSI TBGB) trawl survey biomasses, which were computed using *SurvCalc* software (Francis 2009). Because the footprint of WCSI surveys has changed over time, we employed the *SurvCalc* biomass estimates for the core areas of the surveys. These *SurvCalc* biomasses were retrieved from MacGibbon et al. (2024). WCSI surveys are not conducted every year, and we had *SurvCalc* biomasses for 16 years of the period 1992–2023. *SurvCalc* biomasses were available for all the species retained after the June 2024 meeting with resource managers and stakeholders except for one of the eight flatfish species, namely black flounder (*Rhombosolea retiaria*). Therefore, flatfish comprises the remaining seven species. In addition, as there could not be more species than years of data in the analysis, we removed the least abundant species, trevally (*Pseudocaranx georgianus*), with a mean abundance of around 0.05% of the total biomass, to leave 16 species.

2.5.2 Methods

PCA methods are described in detail Fulton et al. (under review - b) and involve:

(i) Conducting a spectral decomposition of annual catch, using common species groupings (Pauly et al. 2020). Here, the trajectory in PCA space is traced employing a biplot of the first two principal components (PCs). Clustering is done using R package *FactoMineR*. Species group number has to be less than the number of years. Scree plots are employed to evaluate the variance explained by each PC to understand whether two-dimensional plots are a sufficiently good representation of the data. This evaluation is supplemented by checking for natural clusters of years in catch composition using singular value decomposition, another form of PCA which is not limited by having fewer or equal numbers of species as the number of years of data. If consecutive years are naturally grouped together, then clear regimes in the catch/survey data existed.

(ii) Teasing apart what factors separate the clusters in the PCA by employing dendrograms and factor maps. Mapping species groups to the individual PCs (using PC loadings along with biplots) is also a way of understanding what factors contribute to variance patterns seen in the composition data.

Heatmap plots were created by ranking the catches per individual species group through time, repeated separately for each species group. The matrix was plotted as a heatmap, grouping species with similar patterns through time together. The analysis employed absolute contribution per species through time, not the proportion in any one year (as that can easily be overwhelmed by top economic catch species). By aligning timing of clusters in the PCA with years in the heatmap, it was clear which species helped differentiate which “regime” in the PCA – via when species contributed most to the catch (or survey) or fell away. In principle, if we considered the research trawl surveys to be representative of population sizes through time, and the landings data to show species responses to fisheries’ targeting of different species through time, then between the two heatmaps it should be possible to study the knock-on effects to species of changing fishing effort over time, and also overall ecosystem response to shifting pressures (e.g., fishing effort, climate change, sedimentation).

3. RESULTS

3.1 Fisheries management in New Zealand and progress towards EBFM

3.1.1 New Zealand's fisheries management system

Commercial fisheries represent significant social, economic and cultural assets for New Zealand (Gerrard 2021), with a total output value of $5.2 billion and the employment of 16 522 Full Time-Equivalents (Dixon & McIndoe 2022). New Zealand's commercial fisheries are dominated by trawling. For inshore fisheries, snapper is one of the most important finfish species, both economically (Francis & McKenzie 2015) and as a choke species due to catch restrictions on snapper limiting access to other components of mixed inshore trawl fisheries (Fisheries New Zealand 2019).

As many inshore commercial fisheries were declining in the early 1980s, the New Zealand Fisheries Act 1983 was introduced. This Act resulted in the QMS being established in 1986, which forms the basis for fisheries management in New Zealand today. TACs are decided for individual stocks, which include TACCs, allowances for customary and recreational and customary fisheries, and other mortality associated with fishing (Cryer et al. 2016). Individual transferable quotas (ITQs) are also decided, which provide commercial quota holders transferable rights to a given fraction of TACCs (Lock & Leslie 2007). Currently, there are 98 species/species groupings in the QMS, which are divided into over 642 separate stocks for management purposes (https://www.mpi.govt.nz/legal/legislation-standards-and-reviews/fisheries-legislation/quota-management-system/).

Fisheries New Zealand within the Ministry for Primary Industries (MPI) is the government department responsible for fisheries management in New Zealand (as well as managing the impacts of fishing on the aquatic environment) and providing advice to the Minister for Oceans and Fisheries. Fisheries New Zealand predominantly operates under the Fisheries Act 1996. The purpose of the Fisheries Act 1996 is to provide for the utilisation of fisheries while ensuring the sustainability of fish populations and supporting the aquatic environment.

Decisions under the Fisheries Act 1996 must be based on best available information, often utilising stock assessments to inform TAC adjustments for individual fish stocks. These scientific analyses are presented and discussed at Fisheries New Zealand-chaired working group meetings (e.g., the Inshore Fisheries Working Group in the case of inshore stocks), which include fisheries managers, scientists, fishing industry representatives, and other stakeholders. The MPI Harvest Strategy Standard (HSS; Ministry for Primary Industries 2008) specifies individual fish stock limit and target reference points, to enable stocks to be maintained at or above the biomass corresponding to the maximum sustainable yield (MSY) over the long term (Mace 2001). When setting TACs, the Fisheries Act 1996 requires the Minister for Oceans and Fisheries to have regard to factors including: (i) the biological characteristics of the stock and any environmental conditions affecting the stock (section 13 of the Fisheries Act 1996); (ii) associated or dependent species (section 9a of the Act); (iii) the diversity of the aquatic environment (section 9b of the Act); and (iv) habitats of particular significance for fisheries management (section 9c of the Act).

3.1.2 Ecosystem and environmental considerations for fisheries management in New Zealand

The management of New Zealand fisheries has historically relied on single-species assessments, TACs and ITQs (Fisheries New Zealand 2024), although this has generally been the case worldwide as well (Skern-Mauritzen et al. 2016). However, New Zealand's current management framework does incorporate ecosystem considerations into fisheries management advice by presenting published information alongside stock assessment results (Cryer et al. 2016). The purpose of the Fisheries Act

1996 to provide for the utilisation of fisheries while ensuring sustainability involves: (i) maintaining the potential of fisheries resources to meet foreseeable needs of future generations; and (ii) avoiding, remedying or mitigating any adverse effects of fishing on aquatic environment.

Ecosystem and environmental considerations for fisheries management are specified in sections 9 (Environmental principles), 10 (Information principles), 11 (Sustainability measures) and 13 (Total allowable catch) of the Fisheries Act 1996. Ecosystem and environmental considerations include:

- Technical interactions, which result from multiple fleets fishing multiple species with various gears, as either target or non-target catch (bycatch), i.e., interactions within a fisheries complex. Those are immediate impacts of fishing on other species and the ecosystem.
- Biological interactions, i.e., trophic interactions, which cover predator-prey interactions and competition for the same prey.
- Environmental effects on fishes and fisheries, which cover the effects of environmental and climate variability and climate change.
- Cumulative impacts of fishing together with other impacts (e.g., land-based effects).

Information on ecosystem and environmental considerations for fisheries management are reported in: (i) the ecosystem and environment (E & E) sections of the chapters of the New Zealand Fisheries Assessment Plenary ("Plenary" for short); and (ii) the Aquatic Environment and Biodiversity Annual Review (AEBAR), which provides a summary of information on the impacts of fishing and environmental effects on fisheries on an issue-by-issue basis. The E & E sections of the Plenary chapters can support the incorporation of ecosystem considerations into fisheries advice. E & E sections provide a summary of information on impacts of fishing and environmental considerations, specific to each QMS species. At present, E & E sections only exist for selected species where it has been prioritised (22 of 83 species chapters as of April 2024).

Fisheries New Zealand consultation documents and decision advice for sustainability rounds and other regulatory changes incorporate information from the AEBAR and E & E sections and any other relevant information to support decision-making. For the stock reviewed, there is often analysis under relevant provisions of the Fisheries Act 1996 (sections 9, 10, 11, 13 of the Act) on the impacts of fishing on other species and the broader ecosystem. There have also been efforts in New Zealand to develop more collaborative processes towards weighing up environmental and stakeholder values (e.g., The Sea Change Plan for the Hauraki Gulf), improve environmental performance through the identification of habitats of significance (Fisheries New Zealand 2025), develop threat management plans and risk assessment frameworks, and encourage innovations to avoid, remedy, or mitigate the environmental impacts of fishing (e.g., impacts to the benthos, protected species bycatch or other finfish bycatch) (for example approaches described in AEBAR Chapters 4, 6 and 8).

3.1.3 Considerations for a multi-species approach to fisheries management

To address the issue of technical interactions, considerations for a multi-species approach to fisheries management are being made in the National Inshore Finfish Fisheries Plan (Fisheries New Zealand 2022) and Fisheries New Zealand consultation documents (e.g., Fisheries New Zealand 2019, 2020). Stock complexes are defined toward that aim. The National Inshore Finfish Fisheries Plan defines a stock complex as an ensemble of stocks caught in combination which are grouped to be managed in a coordinated and integrated manner (Fisheries New Zealand 2022). Stock complexes are identified considering the biological range of the species, the fishing methods employed, and the catch mixes involved (in terms of volume and proportion) (Fisheries New Zealand 2022). Stock complexes have been defined across New Zealand for trawl, longline and set net mixed fisheries, with the goal to progress the integrated management of mixed fisheries considering linkages between species, bycatch, and technical interactions.

There have been attempts to adopt a multi-species approach in some New Zealand regions, through concurrent reviews of catch settings for linked species (e.g., snapper, red gurnard (*Chelidonichthys kumu*) and flatfishes (Pleuronectidae sp.) in the top of the South Island within FMA 7; Fisheries New Zealand 2019). This approach has allowed fisheries managers to qualitatively estimate key catch dependencies, whether catch settings for different stocks align well with one another, better understand technical interactions, and identify potential choke species. With this type of work, it is relatively easy to highlight scenarios through discussions with stakeholders and identify trends in abundance for particular species. There is currently no formal method of estimating/illustrating these key catch dependencies, and the methods identified through the INV2023-10 project are meant to fill this gap.

3.2 Clarifications on the concepts of EAFM, EBFM and EBM

Before presenting any tools, it is useful to clarify what is meant by the terms “EAFM,” “EBFM” and “EBM.” “EBFM” is the term used by Fisheries New Zealand (Fisheries New Zealand 2022). However, many other resource managers and stakeholders employ the term “EBM,” as was the case within the Sustainable Seas National Science Challenge (Ellis et al. 2025). COMPASS (2005) describes EBM as “an integrated approach to management that considers the entire ecosystem, including humans. The goal of EBM is to maintain an ecosystem in a healthy, productive and resilient condition.” EBM has been increasingly considered and progressed in recent years for resource management worldwide (Bornman et al. 2025; NOAA 2018; Ramirez-Monsalve et al. 2021). Although formal implementation of EBM has been discussed since the 1970s, concepts behind EBM have existed within Indigenous cultures for centuries (Link & Marshak 2021). EBM embraces the Māori worldview (Te Ao Māori). “Ecosystem thinking,” the extensive knowledge of the whole system and the complex interrelationships between its components, has synergies with Māori knowledge (mātauranga Māori); the fishing industry economy depends upon nature, with which we are connected via our cultures and the places in which we spend time, and nature is an important part of our identity (Department of Conservation 2020).

EBM incorporates all living ecosystem components, including humans, and all marine uses. Unsurprisingly, an overview of EBM programmes revealed that progress is slow in operationalising EBM (Cormier et al. 2017; Levin et al. 2014). Reaching EBM requires strong yet simple foundations. Resource managers and stakeholders need to start from single-species fisheries management (SSFM) to move towards EAFM, before moving towards EBFM, to ultimately reach EBM (NOAA 2018).

SSFM focuses on a single stock and omits explicit consideration of ecosystem factors (the implicit assumption being that these factors are constant through time, although variable). With SSFM, management thinking is centred around harvest reference points and MSY principles. Consequently, with SSFM, the assessment models employed to inform management are largely predictive (tactical). SSFM has a narrow stakeholder base, essentially limited to fisheries stakeholders (NOAA 2018).

EAFM, which is the focus of the present project, consists of incrementally adding pertinent ecosystem factors into assessments for a better understanding of fishery dynamics. EAFM can address the issue of shifting environmental baselines in stock assessments, which requires the development of non-equilibrium single-species tactical modelling approaches, and it can help with rethinking how harvest strategies, targets and limits are defined and utilised. EAFM can provide strategic management advice with the use of management strategy evaluation (MSE; see Section 3.3.4) (NOAA 2018).

EBFM focuses on a system of multiple fisheries as a whole rather than separate stocks, recognising the biological, physical, economic and social complexities of managing the ecosystem. It considers competing interests to optimise fisheries yields while maintaining ecosystem integrity. EBFM represents a more holistic approach compared to EAFM and moves beyond yield-based management goals to include wider societal goals, yet it is still focused on fisheries resources. Thus, the stakeholder base is still relatively narrow with EBFM (NOAA 2018).

EBM is a multi-sectorial approach to management, which accounts for all ecosystem services and considers the management of the ocean as a whole, thereby allowing resource managers and stakeholders to address numerous trade-offs. Under EBM, fisheries management goals are evaluated against other competing environmental management goals. MSE and stakeholder engagement are central to EBM. Because EBM needs to balance a wide and diverse range of societal values (e.g., economic, environmental, cultural), the management decision making processes involved are complex, often requiring the use of complicated discussion support tools and approaches (e.g., multi-criteria analysis) (NOAA 2018).

3.2.1 Integrated ecosystem assessments (IEAs)

Often attached to the EAFM, EBFM and EBM paradigms is the integrated ecosystem assessment (IEA) approach. IEAs provide a framework to help operationalise EBM, by integrating all ecosystem components (including humans) into the resource management processes such that decision-makers can address trade-offs and decide how to most likely reach their goals (Levin et al. 2009). The IEA approach was initially developed in the USA and implemented in NOAA's jurisdictional areas (e.g., the Gulf of Mexico IEA through NOAA's Southeast Fisheries Science Center) (Harvey et al. 2021). IEAs are now also being employed outside of the USA, e.g., in the International Council for the Exploration of the Sea (ICES) (Clay et al. 2023) and in South Africa (Bornman et al. 2025). In New Zealand, NIWA recently initiated an IEA programme in the Whangārei region (Darren Parsons, NIWA, pers. comm.).

IEAs typically involve the following steps (Levin et al. 2009): (i) setting up EBM goals and targets; (ii) developing indicators; (iii) assessing the ecosystems of interest; (iv) analysing uncertainty and risk; and (v) evaluating strategies (a step where MSE usually plays an important role). Key to the success of IEAs is viewing the aforementioned steps as a cycle and repeating that cycle in an adaptive manner (Clay et al. 2023).

3.2.2 Considering EAFM rather than EBM

Internationally, taking an EBM approach to manage fisheries has historically been a largely unsuccessful endeavour due to the layers of complexity involved (Cormier et al. 2017). There is a depth and breadth of knowledge required to develop an EBM approach to a fishery, due to the extensive consultation process with resource managers and stakeholders needed to fully take into account the economic and social impacts that a particular fishery has. To allow for an EBM approach to a fishery in New Zealand, there is a need for co-designing and co-producing research with full support and aligned resources of managers, stakeholders and Iwi and to start such efforts at the scoping stage. Such important efforts could benefit from the implementation of a national or regional IEA programme(s) in New Zealand, resources permitting (see Section 5.5).

In the New Zealand fisheries research and management context, we are currently best positioned to focus on EAFM. To advance EAFM in New Zealand, a prudent and appropriate first step is to incorporate ecosystem impacts directly into New Zealand stock assessments and/or explore modelling approaches to illustrate key ecosystem and stock interactions. This approach broadens the scope of information that can be used in fisheries management decisions to include ecosystem considerations (e.g., technical interactions) in a tactical way.

3.3 Tools for EBFM

In this section, we describe tools for EBFM, including métier analysis and mixed fisheries forecasts, ecosystem models, MSE and dynamic reference points, as well as other, simple EBFM tools presented by Elizabeth Fulton (CSIRO, Australia) at the international workshop. These tools are described and some are discussed in more detail in Section 3.4, if they were tools identified for EAFM in New Zealand.

3.3.1 Métier analysis

In mixed fisheries, multiple fleets fish multiple species with various gears, as either target or bycatch. Métier analysis is a useful approach to characterise such fisheries. Métiers are fishing activities or strategies that are defined by area and gear, and are, therefore, associated with a particular catch composition as a result (Pascoe et al. 2015).

Métier analysis quantitatively categorises individual fishing events (e.g., trawl tows) or fishing trips to a métier. Strictly speaking, métiers are important building-blocks rather than tools; they are required to obtain uniform catchabilities across all the stocks considered with: (i) mixed fisheries forecasts; and (ii) ecosystem models such as ISIS-Fish models (see the description of these other tools in Sections 3.3.2 and 3.3.3.3).

We provide an extensive description and discussion of métier analysis in Section 3.4.1, as métier analysis is one of the primary tools of the toolbox identified for EAFM in New Zealand.

3.3.2 Mixed fisheries forecasts

Mixed fisheries forecasts are very near-term projections to explore the consequences of management scenarios (e.g., changes in the TACC of a given stock) on several stocks within a mixed fishery. The Fcube (Fleet and Fisheries Forecast) method is the most common method for mixed fisheries forecasts (Ulrich et al. 2011). The Fcube method employs catch and effort information to estimate catch potentials for various stocks caught in a mixed fishery using chosen métiers, and then quantifies risks of over- and under-quota utilisation for the stocks (Ulrich et al. 2011). Other methods for mixed fisheries forecasts include MixME (Mixed-fishery Multi-stock Evaluation) (Pace et al. 2025) and FLBEIA (Bio-Economic Impact Assessment using FLR; Garcia et al. 2017).

As for métier analysis, we provide an extensive description and discussion of mixed fisheries forecasts in Section 3.4.2, as mixed fisheries forecasts belong to the toolbox identified for EAFM in New Zealand.

3.3.3 Ecosystem models

Ecosystem models are central tools for EBFM. They can be categorised based on their structure as (O'Farrell et al. 2017):

- Conceptual, qualitative and dynamic structural equation models;
- Extensions of single-species models;
- Dynamic multispecies models;
- Aggregated (or whole ecosystem) models;
- Biogeochemical-based end-to-end models;
- Coupled and hybrid model platforms.

Ecosystem models have different characteristics given their differing degree of complexity and their different purposes/objectives. Ecosystem models can:

- Be conceptual, strategic or tactical;
- Be dynamic or steady-state models;
- Be spatial or non-spatial models;

- Be trophodynamic, age-/size-/stage-structured or individual-based;
- Have different time steps (e.g., year, month, day, 12-hour period);
- Consider different ecosystem components and represent these ecosystem components in a different manner (explicitly or implicitly);
- Represent different processes for the species and/or functional groups considered (growth, survival, reproduction, movement, other processes);
- Handle calibration in different ways (e.g., none, calibration to biomass time series);
- Address different stressors;
- Target different resource management efforts.

3.3.3.1 Conceptual, qualitative and dynamic structural equation models

The simplest forms of ecosystem models are conceptual, qualitative and dynamic structural equation models. Usually, these models represent good starting points before more complex EBFM research is conducted. For example, conceptual and qualitative models represent some ideal preliminary work in preparation for quantitative ecosystem modelling with platforms such as Atlantis.

3.3.3.1.1 Conceptual models

Conceptual models represent the ecosystem qualitatively using simple depictions, including nodes for ecosystem components and arrows for connections (Kelble et al. 2013). They integrate knowledge of ecosystem components (biological and human) while focusing management attention upon the most important aspects of the ecosystem of interest. They are easily communicated, and their presentation is familiar to many model users, resource managers, and other stakeholders.

In New Zealand, a Hapū centric conceptual model is being developed within the IEA initiated for the Whangārei region (Darren Parsons, NIWA, pers. comm.; Table 1).

3.3.3.1.2 Qualitative models (loop analysis)

Qualitative models (loop analysis) offer a qualitative or semi-quantitative representation of the ecosystem of interest to understand dynamics within that ecosystem (Dambacher 2001; Dambacher et al. 2003). They depict the ecosystem using a signed directed graph (also called a “signed digraph”) where ecosystem components are represented by nodes, with positive effects (arrows), negative effects (lines with a filled circle) or self-effects (lines originating and terminating at the same node) also represented. Qualitative models (loop analysis) are steady-state, strategic models.

In New Zealand, a qualitative model is being developed within the IEA initiated for the Whangārei region (Vidette McGregor-Tiatia, NIWA, pers. comm.; Table 1).

In Section 3.4.3, we provide an extensive description and discussion of qualitative models (loop analysis), as these models belong to the toolbox identified for EAFM in New Zealand.

3.3.3.1.3 Bayesian networks

Bayesian networks (also sometimes called “Bayes nets”) offer a graphical representation of a network of variables in a directed acyclical graph, with arrows showing relationships (links) between variables (nodes) and nodes displaying the probability of discrete states (Stelzenmüller et al. 2010). Bayesian networks serve as bridge between science and management implementation and consider trade-offs between different decision options and environmental states. Bayesian networks are steady-state, strategic models.

In New Zealand, a Bayesian network was developed for the Hauraki Gulf (Parsons et al. 2021; Table 1). This Bayesian network focused on key snapper life stages and the consequences of stressors, including fishing and other stressors, on these life stages. Parameters of the Bayesian network were populated through a range of information types, from empirical and model analysis to literature review and expert opinion (Parsons et al. 2021). Other Bayesian networks were developed for: (i) the Tasman Bay/Golden Bay scallop (*Pecten novaezelandiae*) fishery, within the Sustainable Seas National Science Challenge (Jeremy McKenzie, NIWA, pers. comm); and (ii) part of east Northland (Ngunguru) to illustrate factors affecting kina barrens, also within the Sustainable Seas National Science Challenge (Georgina Flowers, Revive Our Gulf, pers. comm.) (Table 1).

3.3.3.1.4 Dynamic structural equation models

Dynamic structural equation models (DSEMs) are a very recent development which evaluate conceptual models with time series data (Thorson et al. 2024). They have not been utilised in New Zealand yet. They are strategic, dynamic models.

As we included DSEMs in the toolbox identified for EAFM in New Zealand, these models are described and discussed in Section 3.4.4.

3.3.3.2 Extensions of single-species models

Extensions of single-species models simply add a few additional features such as the influence of the abiotic environment to existing models. Extensions of single-species models remain single-species analyses with the effect of the environment or other factors incorporated as an effect on the biology or ecology of the focal species.

Extensions of single-species models include:

- Extensions of single-species assessment models;
- Extensions of single-species individual-based models.

3.3.3.2.1 Extensions of single-species assessment models

Extensions of single-species assessment models (ESAMs) are single-species assessment models which are fitted to additional data, e.g., “predation-per-unit-predator-effort” data or “catch-per-unit-stressor-effort” data (e.g., Sagarese et al. 2021). Their goal is to improve the accuracy of stock assessment models to better guide single-species fisheries management. They can improve the fits of a stock assessment model to time series data, deliver more accurate estimates of stock status relative to reference points, and provide more realistic projections of stock dynamics under proposed management tactics. Ecosystem components in ESAM include: (i) one focal species; and (ii) one or several predator species treated as “fisheries” (each having a “fishing effort”, a catchability, and a selectivity-at-age function); or (iii) one or several environmental stressors (e.g., harmful algal blooms) treated as “fisheries” (each having a “fishing effort”, a catchability, and a selectivity-at-age function). ESAMs are tactical, non-spatial dynamic models.

Being tactical models, ESAMs represent a very good EAFM tool. However, because the primary focus of the INV2023-10 project is on technical interactions, we did not include ESAMs in the toolbox identified for EAFM in New Zealand presented in Section 3.4.

3.3.3.2.2 Extensions of single-species individual-based models

Extensions of single-species individual-based models (ESIBMs) have the ability to integrate data across hierarchical scales of organisation and can yield ecological insights useful to single-species stock assessments. They have also potential to generate insights useful to EAFM. In New Zealand, an

ESIBM called the “C++ Agent Based Model” or “CABM” was developed and utilised for hoki (*Macruronus novaezelandiae*) on the Chatham Rise (Marsh 2022; Table 1). The CABM builds upon McKenzie et al. (2018)’s agent-based model and the Spatial Population Model (SPM), a spatially explicit population modelling software package (Dunn et al. 2021).

ESIBMs can relate the biology or ecology of the species of interest (e.g., movement, growth, survival, reproduction) to other ecosystem components or environmental variables. For example, preference functions in the CABM relates movement to prey fields or environmental variables (Marsh 2022). Ecosystem components in ESIBMs include: (i) one focal species (explicitly considered); and (ii) one or several prey species (implicitly considered; fields of biomass for these species are used to force the model). ESIBMs are strategic, spatial dynamic models.

As is the case for ESAMs, we did not include ESAMs in the toolbox identified for EAFM in New Zealand presented in Section 3.4, because the primary focus of the INV2023-10 project is on technical interactions.

3.3.3.3 Dynamic multispecies models

Dynamic multispecies models are ecosystem models which represent a limited number of stocks that are most likely to exhibit large interactions with some stocks of focal interest. Their motivations are investigating the impacts of biological interactions (trophic interactions) or technical interactions. Examples of dynamic multispecies models include:

- MSVPA (multispecies virtual population analysis) and MSFOR (multispecies forward simulation) (Livingston & Jurado-Molina 2000; Kinzey & Punt 2009);
- The Gadget (Globally applicable Area Disaggregated General Ecosystem Toolbox) modelling platform (Begley 2012);
- The ISIS-Fish modelling platform (Mahévas & Pelletier 2004; Pelletier et al. 2009);
- Models of Intermediate Complexity for Ecosystem assessments (MICE models) (Plagányi et al. 2014).

In New Zealand, the preliminary multi-species agent-based model for Tasman Bay/Golden Bay from Allison (2022) can be considered a dynamic multispecies model (Table 1). This work was carried out to showcase the value of designing an agent-based model in a fisheries context. This work was exploratory and mainly qualitative but lacked developments that would make it predictive or useful for decision-making. For the multi-species agent-based model to be useful for decision-making, better datasets (primarily commercial fishing data) should be used, fewer (and better articulated) assumptions should be made, and fisher-fish interactions, inter-and-intra-species interactions and fisher behaviour should be more thoroughly represented to more accurately depict the human-environment coupled system (Allison 2022).

Dynamic multispecies models that are interesting for the INV2023-10 project include those implemented with the ISIS-Fish modelling platform. The ISIS-Fish modelling platform was specifically designed to explore the dynamics of mixed fisheries (Mahévas & Pelletier 2004; Pelletier et al. 2009). ISIS-Fish models are strategic, spatial dynamic models.

MICE models are also of particular interest for the INV2023-10 project, primarily for their ability to thoroughly explore specific interactions (technical or biological). MICE models focus on a few species or functional groups that are most likely to have significant interactions with a focal species (Plagányi et al. 2014). MICE models integrate the best characteristics of single-species models of relative simplicity and the ability to use standard statistical methods for estimating model parameters, while also considering broader ecosystem considerations that depend on management objectives (Plagányi et al. 2014). MICE models are strategic dynamic models. They are spatial or non-spatial and trophodynamic, age-/size-/stage-structured or individual-based, depending on the research questions that need to be answered.

A MICE model for hoki and southern hake (*Merluccius australis*) on the Chatham Rise started to be developed with the stock assessment software Casal2 (Doonan et al. 2016) several years ago, but was never completed (Matthew Dunn, NIWA, pers. comm.; Table 1) (see Section 3.4.6 for more details). Moreover, a preliminary MICE model was designed for the Ross Sea region using the SPM in Mormede et al. (2014). Results were reported with this MICE model, but its behaviour was not explored in enough depth due to a lack of funding. Major challenges with MICE models developed with Casal2 or the SPM include (i) appropriately modelling predator-prey relationships and (ii) deriving sensible biomasses and reference points for all the modelled species. Such challenges can only be overcome with funding available over several years, combined with the right expertise (modellers that are familiar with Casal2 or the SPM and diet experts).

Both the ISIS-Fish modelling platform and MICE models were included in the toolbox identified for EAFM in New Zealand and are, therefore, described and discussed in more detail in Section 3.4.5 and 3.4.6, respectively.

3.3.3.4 Aggregated (or whole ecosystem) models

Aggregated (or whole ecosystem) models are ecosystem models that attempt to consider all trophic levels within the ecosystem of interest to explore energy flows among ecosystem components. These models typically represent a large number of species or functional groups.

Examples of aggregated (or whole ecosystem) models include:
- Ecopath models;
- Ecopath with Ecosim models;
- Ecopath with Ecosim with Ecospace models;
- The energy flow models of Pinkerton et al. (2008, 2015) and Pinkerton (2011).

Aggregated (or whole ecosystem) models are too complex for an EAFM. They are data-hungry and their focus is on biological interactions rather than on technical interactions. Therefore, they are not included in the toolbox identified for EAFM in New Zealand that is presented in Section 3.4.

3.3.3.4.1 Ecopath

Ecopath (Christensen & Walters 2004) is a mass-balance modelling platform implemented with the Ecopath with Ecosim (EwE) software package (Christensen et al. 2008; Heymans et al. 2016). The EwE software comes with comprehensive tutorials and a dynamic community of users and developers, and it can now be run in the R computing environment using the *Rpath* package (Lucey et al. 2020). In New Zealand, an Ecopath model was developed more than 20 years ago for subantarctic waters over the Southern Plateau (Bradford-Grieve et al. 2003; Table 1).

Ecopath models are strategic, non-spatial, steady-state models. They represent a snapshot of the ecosystem of interest at a specified point in time. Ecopath models can be either: (i) trophodynamic; or (ii) trophodynamic and stage-structured, when some species/functional groups are modelled using multistanza life-history models. Their time step is one year and trophic interactions are determined by means of a fixed diet matrix. Ecopath models are balanced by assuming that the energy removed from each functional group, e.g., through fishing or predation, must be balanced with the energy consumed by that functional group. Growth and survival are modelled in Ecopath for stanzas when multistanza life-history models are employed.

3.3.3.4.2 *Ecopath with Ecosim*

Ecosim builds upon Ecopath to offer a dynamic representation of the ecosystem of interest (Christensen & Walters 2004). The model resulting from the combination of Ecopath and Ecosim is called an “EwE model.” Ecosim simulates ecosystem dynamics over monthly time steps by changing fishing mortality, fishing effort, and environmental forcing functions. Trophic interactions in Ecosim are modelled based on “foraging arena theory”: prey populations are partitioned into vulnerable and invulnerable components, such that predation mortality rates are dependent on (and limited by) rates of exchange between these prey components. Trophic interactions in Ecosim depend not only on the Ecopath diet matrix, but also on effective search rate and handling time for the predators, and the risk-sensitive behavior of prey. In New Zealand, an EwE model was developed for the Wellington south coast (including the Taputeranga marine reserve; Eddy et al. 2015) and another EwE model was developed for the Tasman Bay/Golden Bay (McGregor et al. 2021) (Table 1). These EwE models were designed for academic purposes and would need to be substantially tailored to be useful for fisheries management. Importantly, to be useful for fisheries management, these models would need to better represent individual fisheries and their associated fishing pressure and rely on standardised indices of relative abundance derived from research surveys or catch and effort data.

EwE models are non-spatial, dynamic models. The prey vulnerabilities that these models estimate express the maximum increase in predation mortality under conditions of high predator/prey abundance. Growth and survival are modelled for stanzas in EwE models when multistanza life-history models are used.

3.3.3.4.3 *Ecopath with Ecosim with Ecospace*

Non-spatial EwE models can be extended into spatial Ecospace models with a monthly time step (Walters et al. 2010). Ecospace replicates the biomass dynamics of Ecosim over a two-dimensional spatial grid and represents mixing (dispersal, migration, ontogenetic habitat shifts, advection) of biomasses among spatial cells, while also including trophic interactions processes and spatial fishing effort dynamics (Walters et al. 2010). The spatial allocation of functional group biomasses in Ecospace at the beginning of each month is based on habitat capacity (which depends on environmental preference values), as well as on movement patterns and other factors (relative vulnerabilities to predation and feeding rates in non-preferred habitat) (Grüss et al. 2016a).

It is worth noting the development of a “spatio-temporal data framework” for Ecospace (Steenbeek et al. 2013). The spatio-temporal data framework, in combination with habitat capacity model, enables environmental layers in Ecospace to be dynamic and to affect movement according to defined response shapes. The spatio-temporal data framework also allows Ecospace to incorporate remote-sensing derived spatio-temporal time series of chlorophyll-*a* to drive primary producers’ productivity (production over biomass or P/B) (Steenbeek et al. 2013).

Ecospace has not been employed yet in New Zealand. However, Ecospace will undoubtedly be a valuable modelling platform for future EBFM/EBM studies in New Zealand, particularly investigations of climate change impacts on marine resources leveraging the spatio-temporal data framework.

3.3.3.4.4 *Energy flow models*

The energy flow models of Pinkerton et al. (2008, 2015) and Pinkerton (2011) were all produced for New Zealand regions (Table 1). Pinkerton et al. (2008)’s model is for the Te Tapuwae o Rongokako marine reserve (located off Whangara in the Gisborne region), Pinkerton et al. (2015) models the Hauraki Gulf, and Pinkerton (2011) models the Chatham Rise. All these models are EwE models with some modifications:

(i) Consumption (Q) is parameterised based on production (P) and Q/B rather than being based on biomass (B) and Q/B;
(ii) Transfer to detritus is used instead of ecotrophic efficiency;
(iii) Two non-trophic transfer parameters are included, growth transfer (e.g., small fish becoming medium-sized fish) and seasonal transfer (e.g., settling of water column detritus to form benthic detritus).

These energy flow models have been referenced in recent court cases and fisheries management decisions to support our understanding of ecosystem shifts (e.g., changes in the role of rock lobster as a predator) in response to fishing. In other words, these models are already being used to indirectly influence fisheries management decisions in New Zealand (Jean Davis, Fisheries New Zealand, pers. comm.).

3.3.3.5 Biogeochemical-based end-to-end models

Biogeochemical-based end-to-end models consider both bottom-up and top-down interactions via the representation of a very large number of nutrient components, planktonic organisms, fishes, and other top predators.

As is the case for aggregated (or whole ecosystem) models, biogeochemical-based end-to-end models are too complex for EAFM and are not included in the toolbox identified for EAFM in New Zealand that is presented in Section 3.4.

The most popular biogeochemical-based end-to-end modelling platform is the Atlantis modelling platform (Fulton et al. 2011). In New Zealand, Atlantis models have been developed for the Chatham Rise (McGregor et al. 2019a, 2019b, 2020) and Tasman Bay/Golden Bay (McGregor et al. 2021) (Table 1).

3.3.3.5.1 Atlantis

Atlantis models are three-dimensional, dynamic models comprising numerous sub-models which simulate features and processes crucial to a functioning marine ecosystem, including biochemical processes (e.g., nutrient cycling), food-web interactions, fisheries, dependence of functional groups on biogenic and physical habitat, and physical and biophysical features (e.g., light penetration) (Fulton et al. 2011). Atlantis bridges low and high trophic level drivers and processes. This versatility allows the simulation of important physical processes and their impacts on fishes and fisheries in a way inaccessible to simpler ecosystem modelling frameworks.

Trophic interactions in Atlantis models are conditioned by: (i) a diet matrix, which determines the availability of prey to predators; (ii) gape limitation, which directs predation mortality to functional groups; (iii) “clearance” parameters, which dictate predation efficiency when prey items are scarce; and (iv) distribution maps, vertical distribution profiles, and migration rates.

Atlantis models are strategic, spatial dynamic models with a short time step, e.g., a 12-hour time step was employed in McGregor et al. (2021). Atlantis models represent the nitrogen and silicon pools of living, dead, nutrient, physical components and gaseous components of the ecosystem of interest. They represent nearly all the living components of the ecosystem of interest: humans; marine mammals; seabirds; sea turtles; fishes; invertebrates, primary producers (phytoplankton groups, marine plants); detritus; bacteria; and sediment bacteria. A multitude of ecosystem processes other than growth, survival, reproduction and movement can be represented in an Atlantis model. These other processes include, *inter alia*, light limitation, oxygen limitation, temperature dependency, and hydrodynamic flows. Many scenarios can be explored with Atlantis to inform fisheries management and other resource management efforts. For example, the Atlantis model for Tasman Bay/Golden Bay is currently being expanded to include the simulation of land-based effects, to test habitat rehabilitation and protection scenarios (Vidette McGregor-Tiatia, NIWA, pers. comm.)

As is the case with Ecospace, Atlantis will undoubtedly be a valuable modelling platform for future EBFM/EBM studies in New Zealand, particularly investigations of climate change impacts on marine resources.

3.3.3.6 Coupled and hybrid model platforms

The final type of ecosystem models gathers all coupled and hybrid model platforms. Coupled and hybrid model platforms consider both bottom-up and top-down interactions through the coupling or combination of different types of model platforms. Examples include:

- Multispecies size-spectrum models (Scott et al. 2014);
- OSMOSE (Object-oriented Simulator of Marine ecOSystems Exploitation) models (Shin & Cury 2001, 2004);
- InVitro models (McDonald et al. 2006), perhaps the most complex ecosystem models ever developed.

As is the case for aggregated (or whole ecosystem) and biogeochemical-based end-to-end models, coupled and hybrid model platforms are too complex for EAFM and are not included in the toolbox identified for EAFM in New Zealand that is presented in Section 3.4.

In New Zealand, multispecies size spectrum models were developed for Tasman Bay and Golden Bay (McGregor et al. 2021; Datta et al. 2024), the Chatham Rise (Datta et al. 2024), and the Poor Knights ecosystem (Beran 2024) (Table 1). These models were designed for academic purposes and would need to be substantially tailored to be useful for fisheries management. Importantly, to be useful for fisheries management, these models would need to better represent individual fisheries and their associated fishing pressure and rely on standardised indices of relative abundance derived from research surveys or catch and effort data.

3.3.3.6.1 Multispecies size spectrum models

Multispecies size-spectrum models (MSSMs) are often implemented using *mizer*, a freely available R package (Scott et al. 2014). In essence, MSSMs involve setting up growth and feeding parameters for the species of interest and an interaction matrix between all study species. Typically, the interaction matrix between all study species is developed using species overlap information or stomach contents data. Next, simulations can be conducted with the models to reach a steady state and other simulations after that can be carried out to investigate fishing and conservation scenarios (Blanchard et al. 2014). MSSMs are non-spatial, dynamic size-structured models. Traditionally, the components represented in MSSMs include: (i) several fish species and species groups; and (ii) an unstructured resource spectrum, which represents plankton and simply serves as food for the smallest individuals of the community explicitly considered in the model.

Recent extensions of the *mizer* R package include *therMizer* (incorporating temperature effects on life processes) (Woodworth-Jefcoats 2023) and mizerMR (allowing for multiple background resource spectra) (Audzijonyte et al. 2022).

Table 1: Ecosystem models developed for New Zealand regions.

Ecosystem model type	Ecosystem model name	Modelled region	Reference(s)
Conceptual, qualitative and dynamic structural equation models	Conceptual model	Whangārei region	Darren Parsons, NIWA, pers. comm.
Conceptual, qualitative and dynamic structural equation models	Qualitative model (loop analysis)	Whangārei region	Vidette McGregor-Tiatia, NIWA, pers. comm.
Conceptual, qualitative and dynamic structural equation models	Bayesian network	Hauraki Gulf	Parsons et al. (2021)
Conceptual, qualitative and dynamic structural equation models	Bayesian network	Tasman Bay/Golden Bay	Jeremy McKenzie, NIWA, pers. comm.
Conceptual, qualitative and dynamic structural equation models	Bayesian network	Part of east Northland (Ngunguru)	Georgina Flowers, Revive Our Gulf, pers. comm.
Extensions of single-species models	C++ Agent Based Model (CABM)	Chatham Rise	Marsh (2022)
Dynamic multispecies models	Multi-species agent-based model	Tasman Bay/Golden Bay	Allison (2022)
Dynamic multispecies models	Model of Intermediate Complexity for Ecosystem assessments (MICE model)	Chatham Rise	Matthew Dunn, NIWA, pers. comm.
Aggregated (or whole ecosystem) models	Ecopath model	Subantarctic waters over the Southern Plateau	Bradford-Grieve et al. (2003)
Aggregated (or whole ecosystem) models	Ecopath with Ecosim (EwE) model	Wellington south coast	Cornwall & Eddy (2015); Eddy et al. (2015)
Aggregated (or whole ecosystem) models	Ecopath with Ecosim (EwE) model	Tasman Bay/Golden Bay	McGregor et al. (2021)
Aggregated (or whole ecosystem) models	Energy flow (mass balance) model	Te Tapuwae o Rongokako marine reserve	Pinkerton et al. (2008)
Aggregated (or whole ecosystem) models	Energy flow (mass balance) model	Chatham Rise	Pinkerton (2011)
Aggregated (or whole ecosystem) models	Energy flow (mass balance) model	Hauraki Gulf	Pinkerton et al. (2015)
Biogeochemical-based end-to-end models	Atlantis model	Chatham Rise	McGregor et al. (2019a, 2019b, 2020)
Biogeochemical-based end-to-end models	Atlantis model	Tasman Bay/Golden Bay	McGregor et al. (2021)
Coupled and hybrid model platform	Multispecies size spectrum model	Tasman Bay/Golden Bay	McGregor et al. (2021); Datta et al. (2024)
Coupled and hybrid model platform	Multispecies size spectrum model	Chatham Rise	Datta et al. (2024)
Coupled and hybrid model platform	Multispecies size spectrum model	Poor Knights	Beran (2024)

3.3.4 Management strategy evaluation (MSE)

MSE has been a key tool in numerous EAFM/EBFM/EBM projects worldwide. We do not include MSE in the toolbox identified for EAFM in New Zealand presented in Section 3.4, because EAFM is still at an early stage in New Zealand and many other EAFM tools (particularly MICE models) need to be developed before MSE is considered in support of EAFM. However, MSE will without doubt be an instrumental tool in future EAFM research in New Zealand (see Section 4.6).

MSE is a framework using simulations to evaluate trade-offs in performance among candidate management strategies (Punt et al. 2016a). An MSE includes some or all of the following components (within a feedback loop) (Grüss et al. 2016b; Perryman et al. 2021):

- An operating model (OM) which simulates fish and fisheries dynamics;

- A monitoring model (not an essential component);
- An assessment model (not an essential component and not employed in many MSE applications);
- A decision rule (e.g., the broken-stick harvest control rule (HCR));
- An implementation routine, to implement the determined level of management into the OM simulations.

In New Zealand, MSE has been performed for several species and stocks, including, among others, scampi (*Metanephrops challengeri*), southern blue whiting (*Micromesistius australis*), hoki, the LIN 7 ling stock, and the HAK 7 southern hake stock. The OMs used for MSE in New Zealand have always been single-species models so far. Multispecies OMs are not necessarily required for MSE in support of EAFM/EBFM/EBM. For example, an ESAM including predators or environmental stressors as "fisheries" can be useful as an OM within an MSE framework to test the alternative HCRs in the face of changes in predation pressure or environmental stress.

The monitoring model is a subroutine collecting data from the OM that represents information ascertained from monitoring efforts (i.e., fisheries-independent and/or fisheries-dependent data). Implementation error can also be considered in the MSE framework to specify an effective fishing mortality rate or an effective quota from the fishing mortality rate or quota determined by the decision rule.

3.3.5 Dynamic reference points

Dynamic reference points (as opposed to stationary reference points) are not included in the toolbox identified for EAFM in New Zealand that is presented in Section 3.4, although we recognise that this tool is important for EAFM/EBFM/EBM efforts in New Zealand, particularly in the face of climate change. Dynamic B_0 (dynamic biomass in the absence of fishing) is the most frequently investigated dynamic reference point. Typically, assessments use the estimate of B_0 from the first year of the assessment and take this to be the "unfished" level, whereas dynamic B_0 incorporates variation through time due to factors other than fishing. Dynamic B_0 calculates a theoretical biomass trajectory that represents the population size that would have resulted had the stock never been fished, assuming all other parameters (including recruitment deviations) remain as estimated in the assessment (Bessell-Browne et al. 2024).

Several New Zealand projects have explored dynamic reference points, including for the SNA 7 and SNA 8 snapper stocks and the GUR 7 red gurnard stock. For example, Marsh et al. (2024) evaluated the impacts of mean recruitment regime shift on a stock with productivity dynamics based on SNA 8 using simulation modelling. We also note that, with ongoing investigations on milky white-fleshed snapper (snapper in poor condition), temporal changes in natural mortality (due to change in fish condition) are being estimated for the SNA 1 stock, which could serve to estimate a dynamic B_0 for SNA 1. Dynamic reference points have not been utilised to inform fisheries management in New Zealand, because research in Australia and elsewhere has shown that the dynamic B_0 approach may be a risky strategy particularly as stocks decline and it is difficult to attribute the decline to fishing or climate change. New Zealand has decided not to use dynamic B_0 for declining stocks, but it could potentially be useful for increasing stocks (Philipp Neubauer, Dragonfly, pers. comm.).

3.3.6 Other simple EBFM tools

In addition to the tools described above, we identified a suite of simple tools and indicators which could be used to progress EBFM in jurisdictions with varying levels of fisheries data and political willingness and showed promise for application in New Zealand. These tools were presented at the international workshop by Elizabeth Fulton (CSIRO) and include:

(i) Indicators of ecosystem overfishing;
(ii) Cumulative biomass versus trophic level;
(iii) PCA on timeseries data and heatmaps;
(iv) Risk tables;
(v) Size spectra;
(vi) Hub species;
(vii) The green band approach;
(viii) The ecosystem traits index.
(ix) The indicator species-based approach.

Tools (i) to (iv) were included in the toolbox identified for EAFM in New Zealand (for reasons outlined in Section 3.4). In the following, we present tools (v) to (ix).

3.3.6.1 Size spectra

Size spectra are obtained by estimating a linear relationship between log-body mass and log-biomass, using data for multiple species and functional groups of the ecosystem of interest (Gislason & Rice 1998; Shin et al. 2005). Size spectra allow for the quantification of the relative biomasses of small and large fish in the ecosystem of interest and the overall productivity of that ecosystem (Shin et al. 2005). It is expected that, as fishing pressure increases in the ecosystem of interest, the slope of the relationship between log-body mass and log-biomass gets steeper. Harvest strategies or HCRs can be set up based on the slope of the relationship.

The body mass and biomass data for multiple species and functional groups needed for size spectra are usually attainable through size-based ecosystem models (e.g., employing a multispecies size spectrum model or the OSMOSE ecosystem modelling platform). It takes expertise and time to develop and validate this type of ecosystem model. Currently, three models of this type are available, including one for Tasman Bay and Golden Bay (McGregor et al. 2021; Datta et al. 2024), one for the Chatham Rise (Datta et al. 2024), and one for the Poor Knights ecosystem (Beran 2024) (Table 1). These models were designed for academic purposes and would need to be substantially tailored to be useful for fisheries management (see Section 3.3.3.6).

3.3.6.2 Hub species

EBFM can benefit from the identification of "hub species" from the use of network theory and criticality analysis. With network theory, every ecosystem component is represented as a node and all dependencies (trophic and non-trophic) are represented by links. Criticality analysis can then be employed to find which nodes are so critical that, if they are removed, everything falls apart. This analysis enables the identification of "hub species" (Fulton & Sainsbury 2024). Hub species are species that are critical to connect the ecosystem of interest, either through bottom-up (prey) or top-down (predator) connections. There is a combination of metrics that can be established (degree, degree out, and page rank), which can be based on presence/absence or the volume/flow of a link, and that can allow for the identification of species with more conservation needs or in need for higher ecological reference points (ERPs) (Fulton & Sainsbury, under review). The identified species are sometimes keystone species, but they are not always species that would have been identified by other, similar methods. This type of work can help resource managers include ecosystem considerations in single-species ERPs or conservation thinking. This type of work can be MSE-tested through an evaluation of the impacts of the removal of certain species, to confirm whether hub species have a much greater effect on ecosystem restructuring and on the system in general. Hub species have been identified for marine regions where diet data have been collected over the long term, such as the North Atlantic and the North Pacific.

If dynamic flow data/volume data are not available but presence/absence data can be used, other developments in network theory can be used to explore ecosystem robustness. The system can be divided into several regions: resilience, partial resilience, and collapse. A stock is considered to be resilient above the collapse horizon and to collapse or be partially resilient otherwise (Fulton & Sainsbury, under review; Gao et al. 2016).

Ecosystem models such as EwE models are needed to get the dynamic flow data for the identification of hub species, and significant expertise and time are needed to develop and validate this type of ecosystem model. In New Zealand, an EwE model was developed for the Wellington south coast (Eddy et al. 2015) and another EwE model was developed for the Tasman Bay/Golden Bay (McGregor et al. 2021) (Table 1). These EwE models were designed for academic purposes and would need to be substantially tailored to be useful for fisheries management (see Section 3.3.3.4.2). Even if volume or presence/absence data are employed to identify hub species, the outcomes of analyses relying on hub species support strategic EBFM/EBM rather than tactical EAFM.

3.3.6.3 The green band approach

The green band approach consists of checking for distortive pressure in the ecosystem of interest (Fulton et al., under review - a). To accomplish this, a plot needs to be produced that shows a linear relationship between production and biomass for the unfished system, which is the profile of pressure that the ecosystem can take (called a “predation profile”). The slope of the linear relationship can then be taken to create a green band on the plot, where the width of the predation profile dictates the width of the green band, and then it is possible to plot where catch versus production sits relative to the green band. If catch sits inside the green band, there is fishing in the ecosystem of interest in line with the patterns of pressure that are expected by the ecosystem. Being above the green band indicates that too much pressure is being put on the ecosystem. Being below the green band indicates that there is potential to increase fishing pressure in the ecosystem. It is possible to overlay lines for particular species on the green band, which correspond to reference values for that species and can help constrain the green band (Fulton et al., under review - a). With the green band approach, fisheries managers can track distortive pressure through time and examine the effects of management measures on individual species, to ascertain whether some management measures realign fishing with an ecosystem perspective or not.

Ecosystem models such as EwE models are needed to get the biomass and production data for the green band approach, and significant expertise and time are needed to develop and validate this type of ecosystem model. In New Zealand, an EwE model was developed for the Wellington south coast (Eddy et al. 2015) and another EwE model was developed for the Tasman Bay/Golden Bay (McGregor et al. 2021) (Table 1). These EwE models were designed for academic purposes and would need to be substantially tailored to be useful for fisheries management (see Section 3.3.3.4.2). Even if volume or presence/absence data are employed to support the green band approach, the outcomes of analyses relying on the green band approach support strategic EBFM/EBM rather than tactical EAFM.

3.3.6.4 Ecosystem traits index

The ecosystem traits index (ETI) brings together the concepts from topology, resiliency and distortive pressure (Fulton & Sainsbury, under review). More specifically, the ETI is a composite of the hub index (which identifies species critical to ecosystem function), Gao's resilience index (which captures ecosystem resilience) and the green band index (which measures distortive pressure on ecosystem structure). The basic idea behind the ETI is to evaluate the status of different classes of species in the ecosystem of interest both in terms of relative biomass and green band. The ETI can be a dynamic indicator. ETI results can be communicated using a colour-coded system, where green means that the ecosystem is stable (not at risk), yellow means that the ecosystem is still stable and needs monitoring, orange means that the ecosystem is at risk and action is needed, and red means that the structure and function of the ecosystem are degraded and urgent intervention is required.

The ETI builds upon hub species and the green band approach and, therefore, requires inputs from ecosystem models such as EwE models which take expertise and time to develop and validate.

3.3.6.5 Indicator species-based approach

An indicator species-based approach can also be employed in support of EBFM. The basic idea behind the indicator species-based approach is to identify a relatively small number of key species within the ecosystem of interest that are representative of ecosystem health as a whole (Newman et al. 2018).

To implement an indicator species-based approach, all the species within the fishery of interest, including bycatch species, are categorised into bins based on their life history. Usually this results in a bin for the least resilient/most vulnerable species which are likely to be overfished, a bin for the target species in the catch for which fishery yield is optimised, and a bin for the most resilient/least vulnerable species which are likely to be underfished. In addition, a bin can also be created for hub species (i.e., species that are ecologically significant) (Keith Sainsbury, Centre for Marine Socioecology, University of Tasmania, Australia, pers. comm.). Typically, three-four species are found per bin. The stock complex can be managed more efficiently if the most vulnerable species have been identified, because if management of those species is appropriately scaled, management for the whole fishery is more likely to be robust. To identify these indicator species, ecological vulnerability is considered, as well as life history, level of depletion, and management and cultural importance. Western Australia has managed fisheries using these bins (Newman et al. 2018).

There is a repeatable, rigorous way to do this classification. The steps of the indicator species-based approach include:

- Categorising species;
- Identifying indicator species per ecoregion;
- Pairing indicator and non-indicator species;
- Assessing indicator species;
- Applying proportional change in the TACC of indicator species to the TACCs of non-indicator species;
- Periodically reviewing indicator species (so that they remain representative).

The indicator species-based approach now builds upon hub species and, therefore, requires inputs from ecosystem models such as EwE models which require expertise and time to develop and validate. In addition, and more importantly, the indicator species-based approach may be difficult to implement for New Zealand Fishery Management Areas, as the information needed for implementation are likely only to be available for those species that have a stock assessment.

3.4 Tools to advance EAFM in New Zealand

In this section, we describe and discuss in more detail the EBFM tools identified for the toolbox for EAFM in New Zealand. These tools include: métier analysis; mixed fisheries forecasts; qualitative models (loop analysis); DSEMs; ISIS-Fish models; MICE models; indicators of ecosystem overfishing; cumulative biomass versus trophic level; PCA on timeseries data and heatmaps; and risk tables. We also provide a summary table of these tools (Table 2), highlighting their outputs/questions answered, requirements, use (or absence of use) in New Zealand, and limitations to operationalisation in fisheries management.

3.4.1 Métier analysis

A fishery does not consist of a homogeneous group of vessels. Differences between vessels arise from the structural composition of the fleets and differences in geographic mobility, access to quotas, targeting practices, and gear configurations. Therefore, there is a diversity of fishing practices, even within a single fleet targeting multiple stocks. In this context, developing a typology of individual fishing practices allows for a large amount of data to be collapsed into a limited number of components for further analysis. These components are termed "métiers" or sometimes "fishing styles," "fishing tactics," "fishing strategies," or "fishing modes" in the literature.

Métier analysis is commonly used for mixed fisheries with multiple gear types. However, métier analysis is equally useful for single-gear type fisheries, as spatial heterogeneity and temporal variability in the marine environment lead to the diversification of fishing practices in response to changes in the availability and abundance of species over space and time. Some studies use catch composition data to carry out métier analysis, while other studies employ a combination of catch and effort data. Some studies also use qualitative data obtained from fishers for validation.

Métier analysis has several advantages. First, it can identify the "effective effort" directed at a targeted species, which can lead to improved catch-per-unit-effort (CPUE) standardisation. Second, it can provide a baseline to monitor and assess how métiers may respond to future changes in regulations and policies or other changes. Furthermore, it provides a framework for further analyses of impacts on non-target species and other ecosystem components. Every métier analysis includes several steps:

1. Data collection;
2. Data encoding;
3. The selection of (dis)similarity measures;
4. The selection of the number of métiers;
5. The selection of algorithms;
6. The selection of features/variables;
7. The validation of clusters.

3.4.1.1 Data collection

The nature of the fishery dictates the data that are required for the métier analysis. Experts (e.g., fisheries managers, fishers) are important to identify factors that potentially define clusters, as well as to define the study period and study domain. Typically, for métier analysis, data from commercial fishing logbooks are employed. However, if observer coverage is good for the fishery of interest, observer data can be used for the analysis.

3.4.1.2 Data encoding

The data encoding step consists of encoding the data to be able to better reflect on the similarities between records. Moreover, for métier analysis, it is common to use transformation or to convert the catch composition into proportions (relative information). It is common to use the logarithm transformation to normalise the data. Finally, the catch composition data include many zeros. There are several methods in the literature to handle situations with many zeros.

3.4.1.3 Selection of (dis)similarity measures

Several metrics are commonly used, including: (i) Euclidian distance, for continuous data; (ii) Manhattan distance, for continuous data; (iii) Hamming distance, for presence/absence data; and (iv) Gower distance, for mixed data. The Gower distance, can have a different measure for each component of the data.

3.4.1.4 Selection of the number of métiers (“k parameters”)

This step is important because some algorithms require the k parameter as an input. Experts can define a range of values for the k parameter. Otherwise, some quantitative methods are available to estimate a value for the k parameter. One of these methods is silhouette width. Silhouette width considers the density of records within clusters and how sparse records from a cluster are compared to other clusters. Silhouette width values range between -1 and 1 and the higher the value the better. Analysts conducting métier analysis often try to find the number of métiers that maximises the silhouette width.

3.4.1.5 Selection of algorithms

There are two common classes of algorithms: (i) hierarchical clustering; and (ii) non-hierarchical clustering (*k*-means, partition around medoids (PAM)). Hierarchical clustering algorithms do not need the k parameter as input. However, these algorithms are computationally intensive and are sensitive to outliers. On the other hand, non-hierarchical clustering algorithms are more computationally efficient, especially the *k*-means algorithm. However, the *k*-means algorithm is sensitive to outliers. The PAM algorithm is more robust to outliers, yet more computationally intensive than the *k*-means algorithm. Still, the *k*-means algorithm is not considered to be as problematic as hierarchical clustering algorithms.

3.4.1.6 Feature (variable) selection

Not all variables are informative and the fewer variables there are, the easier it may be to determine cluster boundaries. Commonly, PCA is used for dimension reduction. However, dimension reduction can result in a loss of information. There are other methods available for feature selection, which rely on machine learning. These other feature selection methods are useful to select important variables to keep and include correlation-based, information gain-based and learner-based methods. Each of these methods has its own properties. A good practice consists of using the three methods and identifying important variables across the three methods.

3.4.1.7 Validation of clusters

Analysts should seek to determine whether the identified clusters/métiers are the output of a real structure or an artifact of an algorithm. External or internal validation can be used for validation. External validation relies on experts or secondary data. The problem here is that sometimes experts can have biased opinions. Internal validation can make use of bootstrapping; if the structure of the clusters is consistent across the bootstraps, then the identified clusters are stable and reliable. Internal and external validation can be combined to validate clusters.

3.4.1.8 Applications and software

For marine regions where fleets are dynamic or there are changes in the fisheries catch mix over time, the métier analysis should be restricted to a specific period of time where changes were not substantial. For example, the métier analysis for Australia's Eastern Tuna and Billfish Fishery (ETBF) was restricted to the period 2010–2017 (Parsa et al. 2020a). Over that period, there were no real changes in regulations or the climate. When analysts seek to understand fishing strategies over a long period of time, it is good practice to conduct métier analysis for specific blocks of time, which often results in some métiers disappearing from one block of time to the next while other métiers get bigger or smaller. This is a key caveat for using métiers to predict future fishing patterns, as fisher behaviour can change substantially over time.

The methods described above were applied to the Australian tuna and billfish fisheries, as reported in Parsa et al. (2020a, 2020b). Métier analysis has also been employed for many other fisheries, including the Australian Southern and Eastern Scalefish and Shark Fishery (SESSF) to inform the bycatch TACs of rebuilding species (Burch et al. 2021). In New Zealand, métier analysis of fisheries has been recommended to improve the reporting of environmental and ecosystem information for Fisheries New Zealand and preliminary work on this approach was done in Middleton et al. (2024). The final approach for classification in New Zealand is still under consideration (Jean Davis, Fisheries New Zealand, pers. comm.).

Either generic computing environments such as R or specific software packages such as WEKA (https://ml.cms.waikato.ac.nz/weka) can be used for métier analysis. The R package, *RWeka*, makes the connection between R and WEKA. It is also possible to perform métier analysis with the vector autoregressive spatio-temporal (VAST) modelling platform (Thorson 2019), which is widely utilised worldwide, including in New Zealand (e.g., Grüss et al. 2023a, 2023b, 2025; Mormede 2023). The VAST modelling platform is implemented in the R computing environment and relies on the Template Model Builder (TMB; Kristensen et al. 2016) for model estimation. A *VAST* R package is available on GitHub (https://github.com/James-Thorson-NOAA/VAST). VAST models are typically developed for CPUE standardisation and include temporal, spatial and spatio-temporal variation effects, as well as very often catchability and environmental covariates. For métier analysis, VAST models also need to include a random vessel effect, which accounts for miscellaneous catchability variables that are not considered in the models (Grüss et al. 2023a, 2023b, 2025). With a random vessel effect in place the model can be fitted to commercial CPUE data, and ordination can then be carried out on vessels (internally to VAST) to identify vessels that are similar and can be assumed to belong to the same métier (Thorson et al. 2016).

3.4.2 Mixed fisheries forecasts

Mixed fisheries forecasts, which very often require métier analysis (Section 3.4.1) as a preliminary step, have been produced for European fisheries for more than 15 years, initially being conducted in the North Sea in 2009, and then in the Celtic Sea and Iberian Waters in 2015, the Bay of Biscay in 2021, and the Irish Sea in 2022. Therefore, there are now five regions within ICES where mixed fisheries recommendations are produced.

The Fcube method is the first method to have been developed for mixed fisheries forecasts. The Fcube method is structured around the concepts of fleets and métiers, where fleets are groups of similar vessels (e.g., having the same length and the same predominant gear type) and métiers are, as we saw earlier, vessels with similar activities that have a similar catch composition and fish at the same places at the same time (Ulrich et al. 2011). The Fcube method was chosen because it could: (i) employ existing data that were used for ICES stock assessments, yet disaggregated at the levels of fleets and métiers; and (ii) be used to look at the impacts of changes in catch and effort for métiers while providing a clear relationship between fishing effort and fishing mortality for the different stocks.

The Fcube method starts with stock assessment outputs. Fishing mortality estimates for the different stocks are divided among different fleets and métiers. Analysts then have partial fishing mortalities for the métiers. Next, analysts condition the catchability for the métiers and the stocks by dividing partial fishing mortalities by the total fishing mortality by métier. Then, based on management advice for the following year, analysts calculate the new fishing effort that is required to generate catches corresponding to partial fishing mortalities for the fleets. Therefore, making assumptions on the share of the fishing effort among the métiers and the catchability in the following year, it is possible to determine a multiplier of fishing mortality that is required for the individual stocks. These efforts require assumptions about ITQs for the fleets, which translate into partial fishing mortality share. The implementation of the Fcube method results in a range of fishing efforts for the different stocks, which are incompatible because of the technical interactions; therefore, by making some assumptions about what is driving the overall fishing effort, analysts can back-calculate a fishing mortality or a partial fishing mortality for all of the stocks. Ultimately, analysts can put the output of the Fcube method back into a single-species stock forecast, identify what the predicted catch for all the fleets would be for the stocks of interest, and compare the results to the single-species stock assessment advice.

The Fcube method has been used to provide management advice for a number of European regions. For each stock to be included, it requires an age-structured assessment model output, to be able to project the stocks forward. It can be coded/implemented in many ways (first in Excel). A disadvantage with the Fcube method is that there is no package or documentation for it. Analysts implement the Fcube method for their needs using individually developed R scripts. There have been some divergences among case studies, so there can be a lack of consistency among R scripts.

Alternatives to the Fcube method include FLBEIA, a package developed by AZTI (Spain) (Garcia et al. 2017), which implements some of the same approaches as the Fcube method but in an MSE framework structure. There is a lot of documentation and a lot of tutorials for FLBEIA (e.g., https://flbeia.azti.es/; https://github.com/flr/FLBEIA; https://flr-project.org/FLBEIA/). With FLBEIA, it is possible to incorporate covariates and make different mechanistic assumptions (e.g., environmental influences on recruitment). FLBEIA has a more economic focus than the Fcube method.

FLBEIA also divides fleet activities into métiers. Four processes are modelled in FLBEIA:

- Short-term dynamics (tactical): total effort and its distribution among métiers;
- Catch production: the relationship between the effort and the catch, using a Cobb-Douglas catch production function;
- Prices: predetermined or dependent on the level of landings;
- Long-term dynamics (strategic): entry-exit of vessels into the fishery.

Short-term dynamics in FLBEIA are similar to those implemented with the Fcube method, to determine levels of fishing effort required and how fishing effort needs to be distributed mong métiers. However, some FLBEIA applications are interested in profit maximisation and try to find the optimal effort share among the different métiers to maximise profit. FLBEIA can also include seasonal considerations and deal with sequential fisheries.

Unlike the FCube method and other approaches, FLBEIA employs the Cobb-Douglas catch production function, also referred to as "Pope's approximation." The assumption being made here is that all catch is taken halfway through the season, i.e., natural mortality is applied to the fish population for half of the year, then catch occurs, and then the rest of the natural mortality is applied to the fish population. Therefore, the Cobb-Douglas catch production function represents a simplification of the fisheries catch process compared to what is generally used in fisheries science under the Baranov approach. One of the consequences of the use of the Cobb-Douglas catch production function is that there is no linear relationship between fishing mortality and fishing effort as with the Fcube method for example, but rather a linear relationship between catch and fishing effort. This characteristic of FLBEIA leads to divergence of results that FLBEIA and the Fcube methods provide and, for this reason, some analysts have decided to keep employing the Fcube method for their mixed fisheries forecasts.

In terms of stock dynamics, the Fcube method tends to be based around age-structured models, whereas, with FLBEIA, analysts can for instance introduce a biomass dynamic model. The Fcube method tends to assume a stock selectivity pattern that applies to all fleets, while, with FLBEIA, analysts can use different selectivity patterns by fleet or métier.

Another method for mixed fisheries forecasts is MixME (Pace et al. 2025), where the intention is to use multi-fleet Baranov catch equations. The MixME method provides an MSE framework structure and implements multi-fleet Baranov catch equations through numerical optimisation. It can easily incorporate uncertainties and is more robust than most single stock methodologies. There is no fleet or métier structure in MixME, but hybrid fishing units are considered.

MixME was developed to more accurately capture the joint harvesting process. MixME can account for the fact that, the more fleets we have, the more important it is to take into account the catches of the other fleets to estimate the level of fishing effort to catch a target quota. When a fishery includes several fleets, these fleets are competing and have different catchabilities for different stocks. Analysts may fail to correctly identify the choke stock(s) if they fail to take into account the effect of the other fleets on the catches of a given fleet.

The MixME framework was used to carry out longer-term evaluations, as well as to consider uncertainty in the process. Choke species and risks of underutilisation of the quotas are better identified by MixME compared to single-stock approaches. With MixME, analysts can explore different management rules that better account for technical interactions and identify spaces within trade-offs that meet objectives. MixMe is distributed in the form of an R package and its code can also be found in a dedicated GitHub repository: https://github.com/CefasRepRes/MixME/wiki.

Approaches to run mixed fisheries forecasts are useful to identify trade-offs, discuss different options, simulate and discuss different approaches, and allow for an iterative approach to produce management advice for mixed fisheries. In terms of model validation, some work has been done on uncertainty and sensitivity analysis, primarily related to the key assumptions of the models used to run mixed fisheries forecasts, including effort share, ITQs, métiers and stock catchability. Methods have been developed for forecast uncertainty, which are timeseries methods that account for correlation among the catchability for different stocks and capture the effort share dynamics that have occurred over the recent historical period. Moreover, methods have been developed to evaluate the sensitivity of the models used to run mixed fisheries to different inputs and parameters. Finally, methods have been developed for retrospective analysis, looking at prediction skill in relation to the assumptions that are used in the models.

The main result of the forecast uncertainty analyses is that the models used to run mixed fisheries forecasts are sensitive to ITQs because of the relationship between the ITQ and the level of fishing effort that can be exerted to catch given quotas. Regarding sensitivity analyses, the largest uncertainty that was found was around catchability, possibly due to the influence of environmental variability on catchability. Regarding retrospective analyses, they indicated that the assumption that catchability and ITQs are the same as in the last year led to good predictions in the short term.

It was found that uncertainty in mixed fisheries forecasts is generally driven by the catchability assumption and, as a result, has a reasonably high level of uncertainty. However, it was found that the general conclusions around consistencies in quotas against the single-species stock assessment advice were robust to the uncertainty about catchability.

Predictive skill was evaluated for the Irish Sea, to determine whether a mixed fisheries model can do a better job at predicting catches than a naïve model assuming that catches were the same as in the previous year. A key result was that predictions were generally better when considering the main target stocks being the drivers of fishing effort among the interacting stocks (Paul Dolder, Cefas, UK, pers. comm.).

Mixed fisheries forecasts require multiple data sources. These include stock assessment outputs from single-species stock assessment models, as well as a lot of supplementary data from the data that feed into the single-species stock assessments, e.g., discards at the level of métiers and effort and landing values for each of the disaggregated fleets and métiers. All the data that are gathered are converted into a common structure in order to be able to produce the forecasts.

A lot of work has been carried out to make sure that anything that we see from the mixed fisheries model is a result of the technical interactions rather than differences in conditioning from the biological models. This is to ensure that when there are differences, they arise from the mixed fisheries dynamics. Length structure models are more difficult to work with for mixed fisheries forecasts, as well as state-space models and statistical catch-at-age models.

There has been a series of workshops with managers and stakeholders within ICES, to discuss what kind of information would be useful in order to manage mixed fisheries. A key concern expressed is that the advice is not "mixed fisheries advice;" rather "considerations" are being provided to supplement the single-species stock assessments. Stakeholders pointed to a lack of flexibility in the mixed fisheries models to account for changes in behaviour and adaptation to quotas. This situation has led to some resistance to setting catches on a multispecies fisheries basis. Moreover, there have been concerns about "weak" or "false" interactions leading to severe choking of target stocks (Paul Dolder, Cefas, pers. comm.). These outcomes within ICES suggest that mixed fisheries forecasts may be a challenging tool for assisting EAFM in New Zealand. Importantly, the limited number of fully quantitative stock assessment models for New Zealand regions (e.g., individual FMAs) is a major limitation to the use of mixed fisheries forecasts in support of EAFM in New Zealand.

3.4.3 Qualitative models (loop analysis)

Qualitative modelling (loop analysis) can be performed using signed digraphs, which are constructed from nodes and links (Dambacher 2001; Dambacher et al. 2003). With loop analysis, only positive and negative impacts are considered and there is no quantification of strength. Arrows are used for positive effects and filled circles are used for negative effects. Self-effects can also be represented. All of these links correspond to the interaction coefficients in a set of differential equations. It is also possible to represent modified interactions with a dashed line where another variable impacts the strength by which two variables interact (e.g., a mediating effect). When analysts do this, they multiply out the dashed line with the direction of the arrow sign.

An example of qualitative modelling is modelling of an exploited ecosystem where analysts can look at different formulations of how we think the system might work. To that end, if analysts have inputs to some of the variables (e.g., increase in bottom productivity, increase in fishing effort), the different alternative models give different predictions of sign response to the inputs. In qualitative modelling, it is general practice not to work with one model but rather with an array of models that we confront with observations or hypotheses to see which models are more consistent with the way one thinks the world works. Ambiguous predictions are resolved through simple inequalities and prediction weights. Analysts can diagnose the likely source of input. The different models have different sources of input to the system, and analysts can see that if we have some data we can quickly diagnose if the cause of the input is coming through one of the different variables by the pattern of responses of the model predictions.

Qualitative models for an exploited ecosystem were developed for instance for the Bay of Biscay (Dambacher et al. 2009). These models demonstrated correlations in the abundances of anglerfish (*Lophius piscatorius*) and horse mackerel (*Trachurus trachurus*) and negative correlations between the mean sizes of the two species. The qualitative models helped understand that the two species are trophically connected. This understanding was consistent with particular sources of input to the qualitative modelling system. As a result, among the alternative models, the particular models that fit well to data and understanding of the real system can be ultimately retained.

The harvest variable can be viewed as a predator-prey type configuration. This idea has been criticised in the past as harvest does not behave like a predator. Analysts can split harvest apart and offer a mechanistic description of the details with effort, catch and market price interacting with the stock of interest. Analysts can look at feedback and consider capitalisation between effort and catch, market regulation, stock regulation, and scarcity-driven effort. These feedback cycles form the overall dynamics of the equilibrium and system behaviour.

Next, analysts can consider a multispecies harvest model, where harvest can again be broken down into effort, catch and market price. Then, analysts can look at similar types of feedbacks: capacity-driven serial depletion; availability-driven serial depletion; price-drive serial depletion; and a general model of serial depletion. Analysts can then play with scenarios and assume for example a shift of consumer preference towards a particular stock. This creates negative stabilising feedback.

An interesting illustration of qualitative modelling is that of the Benguela ecosystem conducted by Punt (1997). In another study, Yodzis (1998) developed a more complex simulation model for the Benguela ecosystem. Yodzis (1998) explored the feasibility of culling seals and how that might impact South African hake (*Merluccius capensis* and *M. paradoxus*) fisheries. Yodzis (1998) found that, on average, culling seals may result in an increase in hake fisheries yield. Punt (1997) performed a similar analysis but with qualitative models with only a limited number of variables. The simple qualitative model of Punt (1997) with only three variables (seals, hake and fish) was consistent with the more complex model from Yodzis (1998). Punt (1997) also developed a qualitative model with more variables, which predicted that a negative effect on seals had a positive effect on the inshore hake fishery but a negative effect on the offshore hake fishery. This is a typical situation of model uncertainty, which qualitative modelling can explore relatively quickly without the need for substantial parameterisation. Qualitative models are quite quick to draw and analyse.

Regarding solving ambiguity through symbolic inequality, analysts can look at it through a numerical simulation approach. Analysts can break down the feedback properties of the system. If analysts consider two nodes having links with each other within a much larger complex system, the impact of the first node on the second node has numerous total effects, which are negative, positive or net negative. To know how likely a negative response (positive response) in the second node is, the number of net negative effects (number of positive effects) is divided by the number of total effects. This result can then be backed up with numerical simulation, to confirm that there is a decrease (an increase) in the second node a very large fraction of the time, regardless of the parameter distribution thrown into the interaction. Analysts can use this approach of taking the prediction weights of the model based on the signed structure of all the feedbacks and use these probabilities of signed determinacy in response.

An additional advancement that can be conducted utilises the aforementioned probabilities within a Bayesian network with: a "model structure" parent node; a "model input" parent node; and "model variable" child nodes. With this setting, it is then possible to:

- Predict the responses to input;
- Diagnose the likely source of input (given the model and the observations, what is the most likely source of input?);

- Test model structure (given input and observations, what model is most consistent with the observations?);
- Identify informative indicators (given a model, what are the best variables to monitor to get lots of information?).

Another interesting illustration of qualitative modelling is Coll et al. (2019)'s modelling for pelagic fisheries of the western Mediterranean Sea. This qualitative modelling was performed to identify the likely source of input to the timeseries analysis of sardine (*Sardina pilchardus*), anchovy (*Engraulis encrasicolus*) and round sardinella (*Sardinella aurita*). A core signed diagraph model including fish species and the fishery was investigated. Four alternative models were developed, which considered whether there was some interspecific competition for the same food sources. The most consistent model was found to be the model that was forced through temperature. The qualitative models were shown to resource managers and stock assessment scientists, to identify good socio-economic and management variables for the system. The variables considered were, among others, the price per kg, the perception of abundance and quality of the catch, and the fear of stock collapse. Next, a number of options were considered in an MSE to determine what may happen under different scenarios. It was then possible to develop a reduced model encompassing the market, ecological and management influences but in a compact form. This reduced model is the model reported in Coll et al. (2019). Then, different model structures were considered depending on how the market would be managed and how fear of the future may express itself. A number of different models had potential for stability and were viable alternatives. This allowed for equilibrium analyses in response to perturbations. Different management options were tested to identify management options robust to environmental change. Analyses were performed using Bayesian networks and included looking at the impacts of: increases in temperature; a decrease in food quality for anchovy and sardine; a decrease in sustainability management and climate change; an increase in sustainability management; an increase in market price; and an increase in sustainable management and market price. Next, Coll et al. (2019) investigated system adaptations in the future, including ecological adaptation with jellyfish becoming a food source and diversification in the fisheries.

There is now a free app available for qualitative modelling called "Digraph Builder." The code underlying the app is in Python but Australian scientists are also developing R code (Jeffrey Dambacher, CSIRO, Australia, pers. comm.).

3.4.4 Dynamic structural equation models (DSEMs)

DSEMs are very recent developments (Thorson et al. 2024) that test conceptual models (different views of the world from scientists, resource managers and/or other stakeholders) against time series data. They constitute useful tools for EAFM projects, notably at the scoping stage.

DSEMs extend qualitative conceptual models as time series models including ecosystem components/indicators (boxes) and hypothesised linkages (arrows), where the strength of linkage can either be specified *a priori* or estimated from available time series data (Thorson et al. 2024). DSEMs can accommodate a combination of lagged and simultaneous impacts of any variable on any other variable and jointly estimates the strength of impacts ("path coefficients"), can estimate missing values within ecosystem component time series, and can also address potential correlations and complementarity (i.e., trade-offs) among ecosystem components

DSEMs can help resource managers and stakeholders much better understand how ecosystem components impact one another. Such work with simple models is valuable before moving to research investigations with more sophisticated models, because it allows resource managers and stakeholders to identify which ecosystem components have a significant effect on others, evaluate the relative importance of ecosystem drivers, and determine whether and how much impacts from ecosystem drivers and components can be lagged.

An example of use of DSEMs in support of EAFM is an ongoing DSEM application in Aransas Bay and Galveston Bay (Texas) (Raymond Czaja Jr., National Center for Ecological Analysis and Synthesis, USA, pers. comm.). Resource managers are interested in understanding how drought in Texas inshore waters interplays with biotics relationships, including predator-prey relationships and density dependence, to be able to predict the spatio-temporal trends of fishery species, particularly in subtropical estuaries that are prone to severe weather. In the Texas Bays DSEM application, DSEMs were leveraged to assess the ability of drought, salinity, and biotic relationships to predict abundances of key predator and prey species in Aransas Bay and Galveston Bay. The DSEMs were designed and refined through regular meetings with fisheries scientists, resource managers and other stakeholders. The models included lagged and non-lagged effects, as well as direct and indirect effects for predators and prey. The most parsimonious models generally retained density-dependent and trophic relationships, with the former producing the strongest effects and the latter being manifested through bottom-up effects. A key strength of the DSEM approach for Texas Bays is its ability to show that drought can have lagged and indirect effects on predators through bottom-up and density-dependent effects. More specifically, DSEMs suggested that lagged and indirect effects can offset immediate, direct impacts of drought. The results of the Texas Bays DSEM application highlights that trophodynamics, density dependence and the Palmer Drought Severity Index (PDSI) can lead to robust predictions of estuarine predators via DSEM, leading to enhanced strategic fisheries management. Through this DSEM application, resource managers understood that their management actions in response to severe weather should be locale-specific, as baseline conditions affect how different estuaries respond to severe weather.

DSEMs are implemented in the R computing environment and leverage TMB functionalities. A *dsem* R package is available on the Comprehensive R Archive Network (CRAN).

3.4.5 ISIS-Fish models

ISIS-Fish is a seasonal, spatially explicit dynamic multispecies modelling platform, which was developed to explore the dynamics of mixed fisheries but can also be employed for single-species modelling investigations (Mahévas & Pelletier 2004; Pelletier et al. 2009). ISIS-Fish models simulate the dynamics of fisheries resources, exploitation and management in the region of interest. ISIS-Fish was primarily designed to evaluate the impacts of different combinations of fisheries management measures on the fisheries resources of interest, including TACs, fishing effort management measures, restrictions on fishing gears, and marine protected areas and other spatial management measures.

The ISIS-Fish modelling platform is entirely coded in Java and was conceived to be as generic as possible, so that it can be applied to different case studies. The ISIS-Fish modelling platform was also made flexible to enable multiple hypotheses to be investigated, particularly relationships between reproductive capacity and recruitment and selectivity functions for different fishing gears. ISIS-Fish also allows functions describing management measures and fishers’ responses to these management measures and economic and environmental conditions to be coded, via an interactive script editor. So far, ISIS-Fish has been used only in Europe, primarily for French fisheries case studies.

An interesting ISIS-Fish application is the eastern English Channel application reported in Lehuta & Vermard (2023). This ISIS-Fish application is a spatially explicit model with a monthly time step, where fishing mortality results from the interaction between the spatial distribution of fish abundance and the spatial distribution of fishing effort by fleet and métier. In this application, fishing effort is standardised by gear, métier and fleet to account for selectivity, targeting and fishing power. Lehuta & Vermard (2023) explored different management measures, including the landing obligation (a ban on discarding unwanted catches at sea that was first implemented in 2013 and is now fully in force across the European Union) and seasonal closures to avoid catching some species. Landings in the model were counted against total allowable commercial catches at each time step, and fishing activity was stopped or adapted at that stage.

3.4.6 Models of Intermediate Complexity for Ecosystem assessments (MICE models)

MICE models are dynamic multispecies models that focus on a few stocks or functional groups that are most likely to have significant interactions with focal stocks (Plagányi et al. 2014). Plagányi et al. (2014) define MICE models as “intermediate in complexity between traditional single-species stock assessments and whole-of-ecosystem models. MICE attempt to explain the underlying ecological processes for a limited group of populations (typically <10) subject to fishing and anthropogenic interactions, and include at least one explicit representation of an ecological process (e.g., inter-specific interaction or spatial habitat use).” However, discussions at the international workshop highlighted that, nowadays, MICE modelling can be seen as a broader concept, as illustrated by the case studies presented below. A broader and more contemporary definition of MICE models is that MICE models can take different forms and aim to take a focused approach on specific ecosystem issues to conduct detailed and rigorous analyses on these issues. The philosophy of MICE models is to consider the key questions that resource managers and other stakeholders have and capture these key questions in the modelling through appropriate formulations, estimate key parameters, and consider important sources of uncertainty (which is something that is simply impossible to do with a large number of more complex ecosystem models such as EwE or Atlantis models).

As mentioned in Section 3.3.3.3, the only MICE modelling efforts in New Zealand have been for hoki and southern hake on the Chatham Rise and have not been completed (Matthew Dunn, NIWA, pers. comm.). The MICE model for hoki and southern hake on the Chatham Rise was developed with Casal2 with internal NIWA funding, to offer a stock assessment platform allowing the joint assessment of hoki and southern hake rather than the assessment of the biomass of hake and hoki separately. To provide inputs to the MICE model, the amount of hoki consumed by its predators was estimated using information collected from a long-term dietary study of hoki and hake on the Chatham Rise. Preliminary results suggested that predation by hake is likely to comprise an effective component of hoki natural mortality, and the parameter estimation from the MICE model is comparable to, but might be more biologically realistic, compared to the single species stock assessment. There was no funding available to continue these MICE modelling efforts beyond preliminary results. This only experience with MICE modelling in New Zealand primarily highlights that successful MICE modelling in New Zealand would require a strategic view, with funding available over several years and solid plans for improvements and further developments.

In the following, we illustrate MICE modelling with case studies from the USA and Australia that were presented at the international workshop. Then, we report additional considerations about MICE models that were discussed at the international workshop.

3.4.6.1 United States west coast Pacific sardine case study

The first MICE modelling case study from the USA that was presented at the international workshop was about Pacific sardine (*Sardinops sagax caerulea*) from the US west coast (Punt et al. 2016b). There was a steep decline in Pacific sardine abundance on the US west coast at the same time as a major decrease in anchovy abundance (*Engraulis mordax*). While Pacific sardine and northern anchovy are the two major forage stocks in the region, it was expected that Pacific sardine depletion would have impacts on their predators, including brown pelican (*Pelecanus occidentalis*) and California sea lion (*Zalophus californianus*). Therefore, a MICE model focusing on a few species from the northeastern Pacific coast was developed, which aimed to assess the ecosystem and fishery consequences of the current sardine management systems (current HCR management) for the USA, Mexico and Canada. Another goal of this work was to identify the sources of uncertainty in the system that are most consequential for predictions of fishery impacts for predators.

The Pacific sardine MICE model is quite simple. It simulates the population dynamics of Pacific sardine, northern anchovy, brown pelican, and California sea lion, as well as the population dynamics of two other forage groups, squid (Loliginidae sp.) and a generic forage group that includes species like Pacific herring (*Clupea pallasii*). This MICE model is a simple operating model that projects species dynamics, implements the current HCRs that are used on the US west coast, and estimates impacts on predators given assumptions regarding dependencies between Pacific sardine and northern anchovy and their predators. Various performance metrics are computed, including predator abundance, predator reproduction, and Pacific sardine and northern anchovy abundance and catches. The MICE model here is a relatively simple multispecies model capturing key ecological interactions and outputting both single species and ecosystem performance metrics.

The Pacific sardine MICE model has coarse spatial resolution with 13 zones. It captures important aspects of the recruitment process, as recruitment is an important driver for the Pacific sardine and northern anchovy populations. Catches are also outputted by the model, for the U.S., Mexico and Canada.

The MICE model provided insights into impacts on predators. The MICE model predicted that declines in Pacific sardine through time had led to decreases in the brown pelican population but had had less effects on California sea lion. Even with lots of food available, the predator populations were predicted to show some variation. There was less than a 1% predicted decline in California sea lion in years where Pacific sardine abundance was very low versus a 29% predicted decline in brown pelican.

The MICE model predicted strong variations in the Pacific sardine and northern anchovy populations even in the absence of harvest. Declines to 10% unfished levels were common in the predictions. Under a base HCR, 34% of the years were predicted to have minimal sardine harvest. The MICE model identified that brown pelican was more sensitive than sea lion to very low sardine abundance. Major sources of uncertainty were found to be: (i) the extent of environmental effects on prey; and (ii) how prey abundance and availability impact predator reproduction.

The Pacific sardine MICE model was developed as part of a broader framework (a multi-model ensemble) that includes Atlantis and Ecopath models, to support EBM in the study region (Kaplan et al. 2019). The MICE model was presented to the Coastal Pelagic Species Management Team in 2017. It has now been revised and presented to stakeholders and the Coastal Pelagic Species Management Team as part of the Future Seas Climate change project (in 2023). Regarding the code base for this work, it was a one-off experiment led by André Punt (School of Aquatic and Fishery Sciences, University of Washington, USA); the code could be adapted and used, but noone is specifically working on the code base at this time. Some participants of the international workshop pointed out that, rather than trying to adapt this code to New Zealand applications, New Zealand modellers should seek to develop their MICE models using software packages that are commonly employed and understood in New Zealand, such as Casal2 or the SPM.

3.4.6.2 U.S. west coast hake case study

The second MICE modelling case study from the USA that was presented at the international workshop focuses on hake (*Merluccius productus*) from the US west coast (Wassermann et al. 2024). The goal of the US west coast hake case study was to employ the available diet data to quantify cannibalism in hake. The intention was to take a small step in multispecies modelling by including cannibalistic effects in stock assessment considerations and understanding the impacts of considering cannibalism in the stock assessment context on estimates of recruitment and biomass. Old hake tend to eat 0–2-year old hake and there have been periods with low and high cannibalism on the US west coast, including up to 60–80% cannibalism in hake diet in the 1980s and very low cannibalism in the hake diet in recent decades. Cannibalism in the hake diet has also varied spatially over the past five decades.

The modelling platform used for the US west coast is the CEATTLE model (climate-enhanced age-based model with temperature-specific trophic linkages and energetics) (Holsman et al. 2016). CEATTLE is implemented in the R computing environment and leverages TMB functionalities. The code base of the CEATTLE model is being maintained and is available through GitHub (https://github.com/grantdadams/Rceattle). CEATTLE is a stock assessment model with some ecosystem components, including a predation sub-model and temperature effects on growth. The CEATTLE model is not explicitly spatial. Its spatial domain is the US west coast and covers most of the range of the hake stock.

Cannibalism (particularly on age-1 hake) led the CEATTLE model to estimate, retrospectively, higher recruitment, higher biomass and higher spawning biomass. Regarding predicted reference points, with cannibalism, all reference points (unfished total biomass, unfished spawning biomass, unfished recruitment, and target fishing mortality rate) increased. This is because the model needed to deal with the extra mortality from the cannibalism. Something to notice is that, because unfished spawning biomass was higher, estimates of relative spawning biomass were lower in the CEATTLE model when cannibalism was considered.

When hindcasts were made with the model, cannibalism led to higher estimates of recruitment and spawning biomass. However, when projections were made under assumptions of, e.g., increased overlap between old and young hakes leading to increased cannibalism, lower values of biomass were obtained. Therefore, it is important to distinguish between hindcasts and forecasts in this case study.

The major advantage of the US west coast hake case study was to be able to quantify the implications of a source of natural mortality, cannibalism. The results of this work were presented to hake fisheries managers. The stock assessment authors are now working to include CEATTLE's age-dependent mortality into sensitivity analysis within the hake assessment. Currently, major predators are being added to the model, including California sea lion and arrowtooth flounder (*Atheresthes stomas*). CEATTLE has been described in stock assessment and management documents, particularly for eastern Bering Sea walleye pollock (*Gadus chalcogrammus*) (Holsman et al. 2019). CEATTLE is being constantly improved and maintained and some participants of the international workshop pointed out that it would be worth considering using this modelling approach for doing some MICE modelling in New Zealand. In particular, CEATTLE relies on TMB, which was developed from the C++ programming language, which a lot of New Zealand modellers are familiar with.

3.4.6.3 Atlantic menhaden case study

The third MICE modelling case study from the USA that was presented at the international workshop pertains to Atlantic menhaden (*Brevoortia tyrannus*) and is about bringing ecosystem information into reference-point setting for tactical single-species management (Chagaris et al. 2020; Howell et al. 2021). The goals of the Atlantic menhaden case study were to: (i) create ERPs and feed these ERPs into management; (ii) identify trade-offs associated with Atlantic menhaden harvest; and (iii) establish management reference points that account for the dietary needs of Atlantic menhaden predators. The modelling work for this case study actually started with an EwE model. The MICE model for the Atlantic menhaden case study corresponds to a simplification of the EwE model. The MICE model represents Atlantic menhaden, a couple of key predators of Atlantic menhaden, and some prey groups. This is a model for the US east coast.

The MICE model for the Atlantic menhaden case study was primarily developed to illustrate trade-offs between fishing on Atlantic menhaden and predators, particularly Atlantic striped bass (*Morone* *saxatilis*). The biomass of the different modelled species was examined under different scenarios where the fishing mortality rate of Atlantic menhaden and the fishing mortality rate of Atlantic striped bass were altered. There was a strong trade-off between the forage species (Atlantic menhaden) and the predators.

ERPs for Atlantic menhaden that also account for the forage needs of striped bass were examined. A target fishing mortality rate (ERP Ftarget) was determined for Atlantic menhaden that maintained Atlantic striped bass at their target biomass when Atlantic striped bass was fished at its target fishing mortality rate. The estimate obtained was slightly higher than the status quo estimate for the fishery at the time and was higher than the single-species Ftarget value. Later, the ERP Ftarget was adopted by fisheries management. The ERPs developed in this case study were adopted by the Atlantic Menhaden Management Board, marking a shift towards EBFM for Atlantic menhaden which is an economically and ecologically important species. There is now a clear link between the MICE model and the single-species assessment model, where a scaling factor is computed by the MICE model and provided to the single-species assessment model to be applied to the single-species target fishing mortality rate.

3.4.6.4 Case studies from Australia

Several case studies from Australia were also presented at the international workshop, which further illustrated that MICE modelling is a broad concept and MICE models can take many different forms.

A first MICE modelling case study from Australia that was presented was some modelling work that was done to inform integrated pest management on the Great Barrier Reef (Rogers et al. 2023). A simple MICE model was developed with crown-of-thorns starfish (*Acanthaster planci*) preying on coral, with the objective of optimising the amount of coral on the Great Barrier Reef by culling starfish. Investigations were conducted to determine the mix of crown-of-thorns starfish catch and percentage coral cover that could achieve the objective of stemming declines in coral. Different rules were tested to inform on-water management. Moreover, ecological thresholds were defined from the MICE modelling, which are now being employed by resource management. In another study, Rogers & Plagányi (2022) investigated climate change impacts on the same ecosystem with Rogers et al. (2023)’s MICE model, to understand how the ecosystem should be managed in the face of marine heatwaves or coral bleaching. The Great Barrier Reef MICE modelling case study is an example of a stepwise approach where some work started with some key questions to inform resource management and identify thresholds and was later made more complex to also consider other issues (climate change) to further improve resource management advice.

A second MICE modelling case study from Australia that was presented at the international workshop was a krill-whale MICE model for the Southern Hemisphere (Tulloch et al. 2018, 2019). The MICE model that was developed for this case study was fitted to limited catch data for several whale species and represented krill biomass and productivity. The krill-whale interactions were projected to determine how they influence the system dynamics and whether they change predictions for whales, including under climate change. This case study did not use a fully spatial approach but followed the MICE philosophy of simplifying the system using mathematical relationships as a proxy for more complex processes.

A third MICE modelling case study from Australia that was presented was for the northern prawn fishery, one of the most important multispecies trawl fisheries in northern Australia (Plagányi et al. 2024), for which a great deal of complicated modelling has been done in the past. The productivity of the northern prawn fishery depends on river flows, which influence many species in the system (e.g., mud crab (*Scylla serrata*), and largetooth sawfish (*Pristis pristis*) which is a threatened species). Therefore, the system is impacted by the multispecies fishery, bycatch interactions, environmental impacts, and anthropogenic impacts due to dams and water extraction. As such, the question is how to manage all of these issues together. This is where a MICE model was helpful to provide rigorous tactical management advice. The MICE model that was developed focused on some key components of the system. Prawn dynamics were modelled from the stock assessment models for prawns, using simple formulations. Then, habitat variables and important drivers were added to the MICE model to get a more holistic representation of the system.

Investigations were conducted with a MICE model for the northern prawn fishery to understand how environmental drivers are affecting tiger prawn (*Penaeus esculentus*). These investigations were carried out by zooming out on some components of the MICE model, namely tiger prawn and its important environmental drivers. The MICE model for the northern prawn was also employed to examine how flow anomalies over time impact habitats such as seagrass and mangroves and then the rest of the ecosystem. The predicted impacts were compared to data and empirical research. Moreover, the MICE model for the northern prawn fishery was also used for investigations for threatened species such as largetooth sawfish for which there are very little data. An ensemble of model formulations was used with different equations, different fitting scenarios, and different ways to account for uncertainty.

In Plagányi et al. (2024), investigations were conducted to determine whether prawn catch can be well estimated with or without accounting for some environmental drivers, e.g., with or without accounting for river flow which impacts prawn recruitment. It was found that including river flow in the MICE model led to statistically better fits to the data. This is an example of how fitting to the data can be explored with the MICE model. More generally, a stepwise approach was adopted (as with the Great Barrier Reef MICE model), where components and linkages were incrementally added to the model to see if they would improve the fitting to the data.

The MICE model for the northern prawn fishery was also employed to explore different water management scenarios and evaluate their impacts on the ecosystem. The MICE model predicted some important declines in prawn and fish species and some catches under some water management scenarios, in contrast to other water management scenarios that were associated with smaller declines. Impacts on habitats were also considered in this work. This work helped to make the trade-offs between different management decisions explicit. Results were presented using a risk framework. Across the different scenarios, risk for the different species was highlighted using colour coding.

Because the MICE model for the northern prawn fishery includes environmental variables, it can easily be used for climate change projections. to inform climate-ready management. The MICE model for the northern prawn fishery accounts for non-linear interactions and physical drivers and can be employed to explore climate change adaptation issues, e.g., to reflect on how to potentially modify stock assessments and HCRs for tiger prawn in the face of climate change.

Of particular interest to resource managers is climate-ready management of the banana prawn (*Penaeus merguiensis*) fishery, which is affected by El Niño. Research highlighted that banana prawn have inshore habitats within mangrove areas and then move offshore to the fishing grounds and, during El Niño years, decreases in sea surface temperatures and rainfall were important to the point that the linkage between inshore and offshore habitats was disrupted. The research started because the industry indicated that they had very small catches and that tides were unusual. Sea surface height anomalies were examined to come up with hypotheses. Alternative models linking El Niño with banana prawn catches were developed. Then, MSE testing was used to determine whether a new HCR could be implemented for the banana prawn fishery that would be more robust to extreme climate change impacts (Blamey et al. 2022).

The final MICE modelling case study from Australia that was presented at the international workshop was the development and use of an empirical harvest control rule (eHCR) for the Torres Strait rock lobster (*Panulirus ornatus*) fishery. Climate change is a big concern in Torres Strait because, if temperature gets too high (and there is less oxygen in the water), rock lobster mortality increases. The MICE model developed for Torres Strait was able to estimate a mortality multiplier as a function of sea surface temperature. This work provided a good basis to understand how climate change may impact rock lobster and the fishery depending on rock lobster. A climate-linked stock assessment was developed and an eHCR is now employed to set rock lobster TACC. The eHCR was developed from MSE work and in consultation with the Torres Strait Islanders. The eHCR relies on survey data and adjustments can be made up or down based on recruitment. The eHCR is currently being revised to be made more climate-ready, as well as more robust to external market shocks.

3.4.6.5 Additional considerations

For many years, multispecies virtual population analysis (MSVPA) was used in Australia, but many questions could not be addressed with that particular modelling approach. MICE models have been much better tools to address pressing questions around technical, biological or environmental interactions in Australia. The overseas experts attending the international workshop stressed that it is important to develop models to support EAFM in New Zealand that can address the questions of interest as directly as possible. The overseas experts also indicated that MICE modelling is harder than EwE modelling (because EwE comes with sophisticated user-friendly modelling interface), but cheaper and less time-consuming than Atlantis modelling. Not all MICE modelling case studies require a lot of data, and some MICE modelling case studies can be quite data limited. For instance, some MICE models focusing on interactions between two species can have limited data requirements if they are non-spatial.

One advantage of MICE models is that they are easy to update through time as they represent only a few species and/or functional groups. As seen earlier with some of the case studies from Australia, MICE models can advantageously be developed in a stepwise manner while leveraging existing stock assessment work, to ultimately provide tactical resource management advice.

MICE models are valuable for computing multispecies reference levels and rigorously quantifying impacts and uncertainties, while focusing on key species. In some contexts, the outputs of MICE models are translated into risk metrics. Joint targets are useful to identify optimal and acceptable approaches in which increasing/decreasing mortality on one species can conserve another.

MICE models are particularly interesting in that they can serve as OMs in MSE frameworks. Using MICE models as OMs in MSE frameworks is often done in Australia to rigorously test management measures and get some confidence in and management uptake of scientific results.

The MICE modelling developments presented by American and Australian experts at the international workshop are unfortunately not available through packages that people could trial. Most of the MICE models from Australia that were presented at the international workshop were done in AD Model Builder (ADMB), because MICE models often build upon existing stock assessment models (to which components are being added) which are typically coded in ADMB in Australia. Yet, recently, there has been a move to TMB for some of the MICE modelling in Australia. MICE models are usually bespoke models and a problem is that it is usually not possible to share a lot of the data that go into these models. A solution for capacity building in New Zealand would be to produce dummy examples for New Zealand modellers so that they can upskill in MICE modelling. Another solution would be for New Zealand modellers to leverage the Fisheries Integrated Modelling System (FIMS) currently under development at NOAA in the USA, as FIMS will incorporate some MICE-type approaches.

3.4.7 Other tools

Other tools that were presented at the international workshop by Elizabeth Fulton (CSIRO, Australia) and were not covered in Section 3.3.6, were:
- Indicators of ecosystem overfishing;

- Cumulative biomass versus trophic level;
- PCA on timeseries data and heatmaps;
- Risk tables.

3.4.7.1 Indicators of ecosystem overfishing

A simple analysis in support of EAFM/EBFM/EBM consists of calculating indicators of overfishing (Link & Watson 2019). These indicators were designed to document or restrain the overexploitation of marine ecosystems. There are three different indicators of overfishing: (i) the Fogarty index; (ii) the Friedland index; and (iii) the Ryther index. These indices are derived from readily available catch and satellite data which link landings from fisheries to primary production, employing common limits of trophic transfer efficiency. These indices are associated with specific thresholds that help determine whether ecosystem overfishing is taking place in the region of interest or not. The Ryther index is the total catch on a unit area basis. The Fogarty index is obtained by dividing catches by primary productivity for the ecosystem of interest. Finally, the Friedland index is obtained by dividing catches by chlorophyll-*a* concentration for the ecosystem of interest (thereby ignoring some sources of primary productivity such as kelps and microphytobenthos).

Indicators of overfishing tell us how effectively ecosystems of interest are being fished. This tool is currently used in support of resource management in the Gulf of Thailand. The Gulf of Thailand is moving to a multi-layered harvest strategy that has rules about total catch that is in line with production and rules about minimum biomass allowed for indicator species (Elizabeth Fulton, CSIRO, Australia, pers. comm.).

3.4.7.2 Cumulative biomass versus trophic level

Another simple analysis in support of EAFM/EBFM/EBM consists of computing cumulative biomass versus trophic level (Libralato et al. 2019). This analysis examines the S-shaped relationship between trophic level and cumulative biomass to determine the state of the ecosystem of interest (degraded, healthy, or recovering). This analysis requires landings data by species and trophic levels by species, which are readily available through FishBase (Froese & Pauly 2025) and SeaLifeBase (Palomares & Pauly 2025).

A lightly fished system will have a strongly S-shaped relationship between cumulative biomass and trophic level. As an ecosystem is being fished, the asymptote of the S-shaped relationship is pushed down, pushing down the point of inflexion of the S-shaped curve towards the origin as a result. This phenomenon has been observed consistently around the world. Australian applications showed flattening and rebound of the S-shaped curve post management intervention (Elizabeth Fulton, CSIRO, Australia, pers. comm.). With climate change, ecosystems do not rebuild with the same species necessarily, but the shape of the S-shaped relationship is very responsive and the point of inflexion of the S-shaped curve is a very sensitive indicator to track ecosystem state.

3.4.7.3 Principal component analysis (PCA) and heatmaps

Another useful approach in support of EAFM/EBFM/EBM is quantifying the value of catch composition using PCA (Fulton et al. under review - b). The goal with this approach is to understand the ecosystem of interest through the composition of the catch, particularly in mixed fisheries. Here, PCA is performed on catch composition, leading to different species groupings through time and the possibility to identify major species shifts in the ecosystem of interest. Then a heatmap can be employed. A heatmap considers the contribution of species to the catch through time, and how this contribution peaks and changes through time. When a heatmap is being developed, resource managers and stakeholders can be consulted to note when there have been major gear shifts, management shifts and/or environmental shifts, in order to facilitate the interpretation of the heatmap. Then, vertical dash lines can be added to the heatmap to separate different regimes for the ecosystem of interest and other vertical lines can be added as well to indicate other changes in the region of interest such as gear shifts. In marine regions where there is not a lot of enforceable management, the more there are changes in catch recordings or catch retention, the more one needs to understand what has been happening through time to interpret the signals.

Understanding the different regimes that have occurred in the region of interest gives some background about the underlying ecosystem but also provides an understanding about peak production potential in the region. All the different regimes have a different set of species with different dominant species, which leads to a different peak production.

PCA and heatmaps both employ the same catch dataset for a large-scale region (e.g., an FMA) and are merely different ways to look at catch composition. The PCA does clustering based on catch composition through time, while the heatmap determines which individual species contribute the most to the catch in the different years of the study period. PCA and heatmaps are quick to produce if catch data by species are available in the right format. The R codes for performing PCA and generating heatmaps are simple and straightforward and can easily be shared (Elizabeth Fulton, CSIRO, Australia, pers. comm.).

3.4.7.4 Risk tables

Risk tables are standardised frameworks used in the USA, which are designed to document any concerns about a stock assessment model, the dynamics of the stock of interest, and ecosystem and environmental considerations that are explicitly considered in the stock assessment model (Dorn & Zador 2020). Risk tables facilitate the integration of additional pieces of information into the stock assessment and fisheries management processes. Risk tables aim to highlight unanticipated ecosystem and environmental effects on marine resources which might necessitate rapid management interventions.

Risk tables use a scoring system to assess how severe concerns are. Based on the assessment of concerns, it can be argued whether the acceptable biological catch of the stock interest should be decreased or not.

Risk tables provide a transparent documentation of concerns to resource managers and other stakeholders. They consider multiple variables at the stock and community levels and the levels of the environment and the ecosystem and provide qualitative rather than quantitative information. Values for the variables considered in risk tables can come from different sources, including stock assessments, ecosystem models, and expert knowledge. Risk tables have proven useful in Alaska (Dorn & Zador 2020), as well as in support to groundfish EAFM on the US west coast (CCIEA Team 2024).

3.4.8 Comparative discussion of tools identified for EAFM in New Zealand

Table 2 summarises the tools identified for EAFM in New Zealand, including their outputs/questions answered, requirements, use (or absence of use) in New Zealand, and limitations to operationalisation in fisheries management. We also assigned a rank to each of the tools (see Section 2.4). PCA and heatmaps and métier analysis were assigned a very high rank. Indicators of ecosystem overfishing, cumulative versus trophic level and risk tables were assigned a high rank. mixed fisheries forecasts with the MixME method, qualitative models (loop analysis), DSEMs and MICE models were assigned a medium rank. Finally, mixed fisheries forecasts with the Fcube method, mixed fisheries forecasts with the FLBEIA method and ISIS-Fish models were assigned a low rank (Table 2).

Table 2: Potential tools for an ecosystem approach to fisheries management (EAFM) in New Zealand and their outputs/questions answered, data/information requirements, use (or absence of use) in New Zealand, and limitations to operationalisation in fisheries management. Tools that were assigned a very high rank are highlighted in orange, tools that were assigned a high rank are highlighted in yellow, tools that are assigned a medium are highlighted in green, and tools that were assigned a low rank are highlighted in blue.

Tool	Outputs/questions answered	Data/information requirements	Has been used in New Zealand?	Limitations to operationalisation in fisheries management
Métier analysis	• Estimate catchability estimates for other EAFM tools, including mixed fisheries forecasts and ecosystem models such as ISIS-Fish models • Can provide a baseline to monitor and assess how métiers may respond to future changes in regulations and policies and other changes • Provides a framework for further analyses of impacts on non-target species and other ecosystem components • Can provide information for research focusing on individual stocks or for conducting fisheries or ecosystem characterisations	• Fisheries catch and effort data (logbook data), catch composition data or observer data, and associated catchability information • Possibly qualitative data obtained from fishers for validation • Expertise with the treatment of large volumes of fisheries catch and effort data, catch composition data or observer data • Expertise with ordination techniques (e.g., principal component analysis (PCA))	Yes, to a very limited extent: some preliminary work was done in Middleton et al. (2024)	• Applications to New Zealand stocks are still to be completed (beyond existing preliminary applications) • Contrary to methods that provide similar insights (PCA on timeseries data and heatmaps), métier analysis needs to cover a limited number of years where changes in the region of interest (e.g., in terms of regulations or climate) were not substantial
Mixed fisheries forecasts using the Fcube (Fleet and Fisheries Forecast) method	• Delivers insights into the impacts of changes in catch and effort for métiers while providing a clear relationship between fishing effort and fishing mortality for different stocks • Calculates fishing mortalities for multiple stocks (based on alternative assumptions about what is driving the overall effort) and then explores scenarios • Can produce results to be compared with those from single-species assessment models, to support fisheries management accounting for technical interactions	• Fully quantitative age-structured single-species stock assessments and the datasets that these stock assessments rely upon • Supplementary data that feed into single-species stock assessments, e.g., discards at the level of métiers and effort and landings values for each of the disaggregated fleets and métiers • Expertise in fisheries forecasts	No	• Fully quantitative age-structured single-species stock assessments are needed for this method, but there are only a few fully quantitative single-species stock assessments in New Zealand • This method requires a lot of data, which are available for some New Zealand regions but involve extensive grooming and processing • The Fcube method assumes a selectivity pattern that applies to all fleets. • A lot of processing is needed prior to the use of the method because the many data that are required need to be converted into a common structure

Tool	Outputs/questions answered	Data/information requirements	Has been used in New Zealand?	Limitations to operationalisation in fisheries management
				• Substantial training of New Zealand fisheries modellers would be needed to apply the method in New Zealand
Mixed fisheries forecasts using the FLBEIA (Bio-Economic Impact Assessment using FLR) method	• Similar outputs as the Fcube method but in a management strategy evaluation (MSE) framework structure • Outputs can have a more economic focus compared to the Fcube method (e.g., indicate how fishery profits may be maximised) • Can produce results to be compared with those from single-species assessment models, to support fisheries management accounting for technical interactions	• Fully quantitative age-structured single-species stock assessments or biomass dynamic models, and the datasets that these stock assessments rely upon • Supplementary data that feed into single-species stock assessments, e.g., discards at the level of métiers and effort and landings values for each of the disaggregated fleets and métiers • Expertise in fisheries forecasts	No	• Fully quantitative single-species stock assessments are needed for this method, but there are only a few fully quantitative single-species stock assessments in New Zealand • This method requires a lot of data, which are available for some New Zealand regions but involve extensive grooming and processing • The FLBEIA method employs the Cobb-Douglas catch production function, which represents a simplification of the fisheries catch process compared to the Baranov approach • A lot of processing is needed prior to the use of the method because the many data that are required need to be converted into a common structure • Substantial training of New Zealand fisheries modellers would be needed to apply the method in New Zealand
Mixed fisheries forecasts using the MixME (Mixed-fishery Multi-stock Evaluation) method	• Similar outputs as the Fcube method but in an MSE framework structure • Provides insights into the performance of different management rules that better account for technical interactions and identify spaces within trade-offs that meet objectives • Identification of choke species and risks of underutilisation of stocks	• Fully quantitative age-structured single-species stock assessments and the datasets that these stock assessments rely upon • Supplementary data that feed into single-species stock assessments, e.g., discards at the level of métiers and effort and landings values for each of the disaggregated fleets and métiers	No	• Fully quantitative single-species stock assessments are needed for this method, but there are only a few fully quantitative single-species stock assessments in New Zealand • This method requires a lot of data, which are available for some New Zealand regions but involve extensive grooming and processing • A lot of processing is needed prior to the use of the method because the

Tool	Outputs/questions answered	Data/information requirements	Has been used in New Zealand?	Limitations to operationalisation in fisheries management
	• Can produce results to be compared with those from single-species assessment models, to support fisheries management accounting for technical interactions	• Expertise in fisheries forecasts		many data that are required need to be converted into a common structure • Substantial training of New Zealand fisheries modellers would be needed to apply the method in New Zealand
Qualitative models (loop analysis)	• Integration of knowledge about the most relevant components of the ecosystem/region of interest • Exploration of multiple scenarios without the need for a lot of parameterisation • Very often a tool for collaborative work that is more conducive to buy-in of the research produced • Can be extended into Bayesian networks	• Their potential is limited to providing qualitative or semi-quantitative insights into the potential impacts of management measures, which are not always sufficient • Expertise to build and analyse signed digraphs is very limited in New Zealand	Yes, to a very limited extent: a qualitative model is being developed for the Whangārei region (Vidette McGregor-Tiatia, NIWA, pers. comm.)	• Their potential is limited to providing qualitative or semi-quantitative insights into the potential impacts of management measures, which are not always sufficient • Expertise to build and analyse signed digraphs is very limited in New Zealand
Dynamic structural equation models (DSEMs)	• Confrontation of conceptual models (different views of the world from scientists, resource managers and/or other stakeholders) with time series data, making them useful for collaborative research and buy-in, particularly at the scoping stage of EAFM projects • Insights into the significance of lagged and simultaneous impacts of any variable on any other variable, and extrapolations of time series • Better understanding of how ecosystem components impact one another, thereby facilitating research investigations with more sophisticated models, including more complex ecosystem models	• Multiple timeseries datasets, such as indices of relative abundances for individual species and/or functional groups, annual environmental indices (e.g., El Niño-Southern Oscillation) and annual fishing mortality rates or fisheries catches for individual species • Some expertise in timeseries analysis in the R computing environment	No	• There is currently limited capacity to develop and run DSEMs in New Zealand
ISIS-Fish models	• Investigations of research questions around technical interactions	• Expertise with multispecies simulation models	No	• There is currently no capacity to develop and

Tool	Outputs/questions answered	Data/information requirements	Has been used in New Zealand?	Limitations to operationalisation in fisheries management
	• Evaluation of different types of management measures, alone or in combination (e.g., total allowable catches, fishing effort management measures, restrictions on fishing gears, spatial management measures) • Investigations of multiple processes (e.g., recruitment in relation to reproductive capacity, selectivities for different fishing gears)	and the Java programming language • A lot of data and information, including data for stock assessments but also a lot of data and information to parameterise processes such as spatial distributions and reproduction		run ISIS-Fish models in New Zealand • ISIS-Fish is coded in the JAVA programming language which is not as commonly used in New Zealand as C++ • ISIS-Fish models and scenarios are data hungry
Models of Intermediate Complexity for Ecosystem assessments (MICE models)	• Outputs similar to those from single-species models of relative simplicity but also considering broader system considerations that depend on the management objectives being addressed • Outputs directly answering the key questions that resource managers and other stakeholders have and capturing these key questions in the modelling through appropriate formulations, estimating key parameters, and considering important sources of uncertainty (which is something that is simply impossible to do with many of the more complex ecosystem models such as EwE or Atlantis) • Are much more likely to produce outputs that will be used in tactical fisheries management compared to more complex ecosystem models, because of their focused and thorough attention to very specific questions • Can be employed in a stepwise approach where they can be quite easily modified to address other	• Solid experience in modelling and capacity to design models to respond to very specific questions • Very often single-species stock assessments, which the MICE model can build upon • Data requirements vary, but MICE models tend not to be data hungry	Yes, to a very limited extent: a MICE model was developed for hoki and southern hake on the Chatham Rise but was never completed (Matthew Dunn, NIWA, pers. comm.)	• MICE models are harder to develop than the models that employ the popular Ecopath with Ecosim (EwE) platform • Usually, MICE models are not available in the form of a package and need to be written specifically • There is currently limited capacity to develop and run MICE models in New Zealand, and significant training would be needed for New Zealand modellers to upskill in MICE modelling

Tool	Outputs/questions answered	Data/information requirements	Has been used in New Zealand?	Limitations to operationalisation in fisheries management
	very specific questions for the region of interest • Can compute multispecies reference levels and the impacts and uncertainties, while focusing on key species • Can produce risk metrics and be used as operating models within an MSE framework			
Indicators of ecosystem overfishing	• Insights into whether ecosystem overfishing is taking in place in the region of interest or not	• Readily available catch and satellite data	No	• Indicators of ecosystem overfishing are more tools for strategic EBFM/EBM than tools for tactical EAFM (yet are useful in the toolbox identified for EAFM in New Zealand)
Cumulative biomass versus trophic level	• Insights into the state of the ecosystem of interest	• Readily available data, including: landings data by species, and trophic levels by species that are easily obtained through FishBase and SeaLifeBase	No	• Cumulative biomass versus trophic level is more of a tool for strategic EBFM/EBM than a tool for tactical EAFM (yet is useful in the toolbox identified for EAFM in New Zealand)
PCA on timeseries data and heatmaps	• Understanding of the ecosystem of interest through the composition of the catch, particularly in mixed fisheries • Tools involving resource managers and/or other stakeholders in identifying major gear shifts, management shifts and/or environmental shifts to facilitate the interpretation of the heatmap, thereby encouraging collaborative work and increasing buy-in of the research produced	• Catch per species over time (e.g., annual landings per species) for a large region (e.g., a fisheries management area)	No	
Risk tables	• Transparent documentation of concerns to resource managers and other stakeholders • Integration of additional information into stock assessments and fisheries management processes	• Multiple pieces of information at the stock and community levels and the levels of the environment and the ecosystem, coming from different sources such as stock assessments, ecosystem models, and expert knowledge	No	• Risk tables provide qualitative rather than quantitative information

3.5 Fisheries Management Area 7 (FMA 7) case study

FMA 7 encompasses several distinct ecosystems and fisheries, with different oceanographic characteristics (Figure 2), and it can be broken down into three areas (Alex Kroch, Fisheries New Zealand, pers. comm.):

i. The west coast where fishing takes place between 20 and 200 m for inshore species and where in shallow water flatfishes, elephant fish (*Callorhinchus milii*) and red gurnard are targeted; deeper, and in deeper water target species include tarakihi (*Nemadactylus macropterus*), blue warehou (*Seriolella brama*) and stargazer (*Kathetostoma giganteum*).
ii. The Top of South Island (Tasman Bay and Golden Bay), which is a lower-energy area within bays extending from the coast to 50 m, where key target species include snapper, John Dory (*Zeus faber*), red gurnard and sand flounder (*Rhombosolea plebeian*).
iii. The northeast coast (Cook Strait area), a small area, which is more similar to the rest of the east coast of the South Island in terms of catch mixes and species connectivity and where the main target species are red gurnard, elephantfish, dark ghost shark (*Hydrolagus novaezealandiae*) and sand flounder.

There is strong seasonal variation within FMA 7, with a number of species migrating between Tasman/Golden Bay, the west coast, and various areas/depths. There are numerous and complex technical interactions in the FMA 7 inshore mixed bottom trawl fishery, with various species distributions, fishing fleets, and common catch mixes within the FMA 7 region. Catch mixes in the region are also dynamic.

3.5.1 FMA 7 stock complex

The stock complex that we considered in our case study includes: (i) the 15 stocks listed in the National Inshore Finfish Fisheries Plan for the FMA 7 inshore mixed bottom trawl fishery (Fisheries New Zealand 2022); plus (ii) the BAR 7 barracouta (*Thyrsites atun*) and the RSK 7 rough skate (*Zearaja nasuta*) stocks, which we added at the request of fisheries managers and the stakeholders present at the June 2024 meeting due to important interactions with the other stocks (Figure 2 and Table 3). Only three of these seventeen stocks have a fully quantitative assessment, which is age structured in all three cases: the SNA 7 snapper stock; the GUR 7 red gurnard stock; and the TAR 7 tarakihi stock (Table 3). Nine stocks have a partial quantitative assessment using CPUE or trawl surveys. Five stocks have trawl survey data but no established management targets (Table 3).

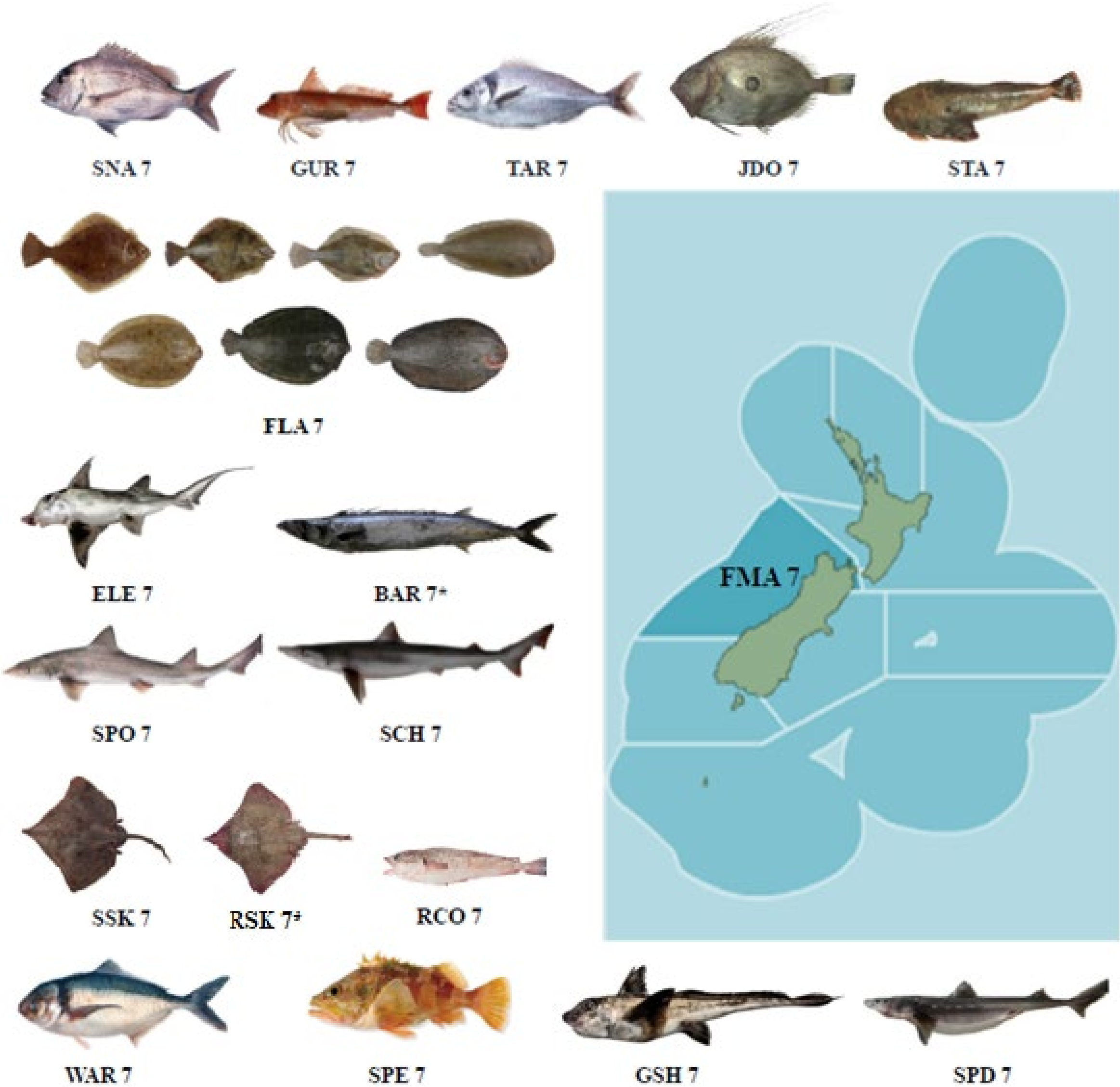

Figure 2: Fisheries Management Area 7 (FMA 7) and stocks in the inshore mixed bottom trawl stock complex. *: BAR 7 and RSK 7 were not identified in the stock complex reported in the National Inshore Finfish Fisheries Plan (Fisheries New Zealand 2022). but were included at the request of fisheries managers and stakeholders due to important interactions with the other stocks.

Table 3: Levels of information for stocks in the FMA 7 inshore mixed bottom trawl stock complex.

Stock	Species	Assessment type
SNA 7	Snapper (*Chrysophrys auratus*)	Fully quantitative - age structured model
GUR 7	Red gurnard (*Chelidonichthys kumu*)	Fully quantitative - age structured model
TAR 7	Tarakihi (*Nemadactylus macropterus*)	Fully quantitative - age structured model
JDO 7	John Dory (*Zeus faber*)	Partial Quantitative – catch per unit effort (CPUE) and trawl surveys
STA 7	Stargazer (*Kathetostoma giganteum*)	Partial Quantitative – Trawl survey biomass estimates
FLA 7	Eight flatfish species: yellow-belly flounder (*Rhombosolea leporine*) (YBF); sand flounder (*Rhombosolea plebeian*) (SFL); black flounder (*Rhombosolea retiarii*) (BFL); greenback flounder (*Rhombosolea tapirine*) (GFL); lemon sole (*Pelotretis flavilatus*) (LSO); New Zealand sole (*Peltorhamphus novaezeelandiae*) (ESO); brill (*Colistium guntheri*) (BRI); and turbot (*Colistium nudipinnis*) (TUR)	Partial Quantitative – CPUE for SFL, ESO, BRI and TUR
ELE 7	Elephant fish (*Callorhinchus milii*)	Partial Quantitative – CPUE
BAR 7 [1]	Barracouta (*Thyrsites atun*)	Partial Quantitative – CPUE
SPO 7	Rig (*Mustelus lenticulatus*)	Partial Quantitative – CPUE and trawl surveys
SCH 7	School shark (*Galeorhinus galeus*)	Partial Quantitative – CPUE and trawl surveys
SSK 7	Smooth skate (*Dipturus innominatus*)	Partial Quantitative – Trawl survey biomass estimates
RSK 7 [1]	Rough skate (*Zearaja nasuta*)	Partial Quantitative – Trawl survey biomass estimates
RCO 7	Red cod (*Pseudophycis bachus*)	No established management targets - Trawl surveys
WAR 7	Blue warehou (*Seriolella brama*)	No established management targets - Trawl surveys
SPE 7	Sea perch (*Helicolenus barathri*)	No established management targets - Trawl surveys
GSH 7	Dark ghost shark (*Hydrolagus novaezealandiae*)	No established management targets - Trawl surveys
SPD 7	Spiny dogfish (*Squalus acanthias*)	No established management targets - Trawl surveys

[1] BAR 7 and RSK 7 were not identified in the stock complex reported in the National Inshore Finfish Fisheries Plan (Fisheries New Zealand 2022). but were included at the request of fisheries managers and stakeholders due to important interactions with the other stocks.

The SNA 7 stock is a key stock within the stock complex, which is particularly economically important (Fisheries New Zealand 2019). The abundance of snapper (SNA 7) has increased rapidly from low levels over the last decade. Snapper is the most abundant fish species within Tasman Bay/Golden Bay. Given constrained snapper catch limits, in an attempt to avoid snapper fishers have modified trawl net headline height, fishing behaviour, and areas fished, resulting in changed catch mixes (Fisheries New Zealand 2019). When snapper is targeted, bycatch includes mainly red gurnard, flatfish, rig, red cod and tarakihi, as well as a small amount of barracouta and blue warehou. Bycatch of SNA 7 mainly takes place in Tasman Bay/Golden Bay. Snapper bycatch within FMA 7 is far more prevalent nowadays than 20 years ago, because fishers have been restricted by the availability of SNA 7 quota.

The FLA 7 flatfish stock is another key stock within the stock complex (Fisheries New Zealand 2019). When flatfishes are targeted, bycatch includes mainly red gurnard, snapper, John Dory, red cod, barracouta, and tarakihi. Flatfish are highly variable species and historically common targets whose abundance and catches have declined substantially in recent years, potentially due to environmental factors.

The TAR 7 tarakihi stock has become a more important stock in recent years (Fisheries New Zealand 2024). Bycatch of tarakihi is more important when barracouta and red cod are targeted.

The GUR 7 red gurnard stock is primarily taken in conjunction with flatfishes, barracouta, stargazer, red cod, and tarakihi (Fisheries New Zealand 2019). In red gurnard target tows, the main bycatch species include snapper, John dory, and rig. GUR 7 abundance has increased markedly in recent years. Recent TACC increases for SNA 7 are now making red gurnard a choke species in FMA 7 (Darren Parsons, NIWA, pers. comm.).

Red cod (RCO 7) is primarily taken in conjunction with stargazer, red gurnard, and tarakihi (Fisheries New Zealand 2024). Red cod target tows are associated with important bycatch of smooth skate (*Dipturus innominatus*). Red cod is a highly variable species and an historically common target whose catches have declined substantially in recent years, potentially due to environmental factors.

Stargazer (STA 7) is caught both as a target and a bycatch species (Fisheries New Zealand 2024). Stargazer is a highly variable species and the stargazer fishery is a recruitment-driven fishery. In recent years there has been a decline in the abundance and catch of STA 7.

Smooth skate (SSK 7) represents an important bycatch species that is widely distributed and hard for trawlers to avoid and is particularly caught as bycatch in tarakihi tows (Fisheries New Zealand 2024). The SSK 7 biomass index has declined substantially since 1997.

Elephant fish (ELE 7) is not a target species but does occur as bycatch, mainly in red gurnard, John dory, flatfish and red cod target trawls (Fisheries New Zealand 2019). ELE 7 abundance has increased in recent years.

Regarding the other stocks that comprise the FMA 7 inshore mixed bottom trawl fishery (Fisheries New Zealand 2019, 2024):

- The JDO 7 John dory stock is primarily caught in conjunction with snapper, flatfish, red gurnard, barracouta, stargazer, red cod, and tarakihi.
- Blue warehou (WAR 7) is mainly taken as bycatch.
- Sea perch (SPE 7) is taken as bycatch and discarded at an important rate.
- The SPO 7 rig stock is caught as bycatch in tows targeting flatfishes, snapper, tarakihi, and red gurnard.
- The SCH 7 school shark stock is mainly caught as bycatch in tows targeting tarakihi, barracouta, red gurnard, and flatfishes.
- The SPD 7 spiny dogfish stock is caught as bycatch in tows targeting flatfishes, snapper, tarakihi, and red gurnard.
- Dark ghost shark (GSH 7) is taken almost exclusively as bycatch.

The different species that comprise the FMA 7 inshore mixed bottom trawl fishery have different levels of productivity (Fisheries New Zealand 2019). For example, snapper is a low productivity species (is long-lived and has low natural mortality) and school shark is a very low productivity species (is a very vulnerable elasmobranch), while red gurnard and John dory have high productivity (are shorter lived and have relatively high natural mortality). These different ranges of productivity will make multispecies assessments and management challenging in FMA 7, because species with different ranges of productivity do not have the same resilience to fishing pressure (e.g., low productivity species take more time to rebuild). For example, management of high productivity stocks such as GUR 7 and JDO 7 needs to be responsive to fluctuations in stock biomass (e.g., increase catches at times of high stock biomass and reduce catches at times of low stock biomass), whereas management for low productivity stocks such as SNA 7 requires longer-term, more stable TACs.

3.5.2 Other considerations for FMA 7

The environmental and ecosystem information for the species comprising the FMA 7 inshore mixed bottom trawl fishery is generally limited, except for snapper (Fisheries New Zealand 2024). In particular, diet information for FMA 7 and our understanding of predator-prey interactions in the region are limited (although we note that they are limited for all New Zealand regions except perhaps the Chatham Rise). Where diet and/or trophic level information is available for species other than snapper, it is often historical and based on small studies from one or two regions, often from outside of FMA 7.

Snapper is a key species in FMA 7, not only for its socio-economic importance, but also for its role in FMA 7 ecosystems (Fisheries New Zealand 2024). Snapper are the most abundant demersal generalist predators in FMA 7 inshore ecosystems and are, therefore, involved in various trophic interactions, hence any substantial changes in local snapper abundance can have important consequences for local ecosystem functioning. Large snapper are important predators of kina and may play a major role in the recovery of kelp to inshore reefs in the region impacted by kina barrens (Doheny et al. 2023).

Environmental and climate change within FMA 7 may particularly impact snapper. Warming may have both positive (may enhance recruitment; Francis 1993) and negative effects (may alter juvenile habitat; Parsons et al. 2014) on snapper. There have been regular marine heatwaves in the FMA 7 region since 2017/2018, with positive effects for some species such as snapper (higher recruitment) but potentially negative effects for other species such as red cod.

Environmental interactions in FMA 7 include interactions with Hector's dolphin (*Cephalorhynchus hectori*) and seabirds, benthic impacts of trawling, and sediment impacts (e.g., sediment deposits in the bays due to cyclones exacerbating land-based effects).

Finally, we note that set net closures were established in FMA 7 in 2020, which have led to increased trawl targeting of some species such as rig.

3.5.3 Information for métier analysis for FMA 7

The meeting with resource managers and stakeholders in June 2024 (Section 2.2) was particularly useful to draw the following considerations for future métier analysis for FMA 7:

(i) To account for the large changes in dynamics and catch composition within FMA 7 over time, separate métier analyses should be conducted for different periods of time, or a single métier analysis could be conducted only for the most recent years where we can assume that the dynamics have not changed dramatically within FMA 7. This is important if mixed fisheries forecasts are produced for FMA 7 in the future, as mixed fisheries forecasts assume that catchabilities within métiers will remain the same over the forecasting period. If a single métier analysis is conducted, only the last five-seven years should be considered (five years corresponds to one snapper stock assessment cycle).

(ii) For métier analysis, analysts could start with all bottom trawl tow data, retain species which represent at least 1% of the total catch, and conduct the métier analysis then. Keeping only species which represent at least 1% of the total catch for métier analysis reduces the number of species (over 100 in FMA 7) to a manageable number. Considering too many species in métier analysis will not result in useful outcomes.

(iii) Two types of métier analysis could be carried out for FMA 7 (and for any FMA in general): a métier analysis for the characterisation of the system (FMA 7 bottom trawl fishery); and another métier analysis considering only a few species to define métiers for subsequent analyses (ecosystem modelling, mixed fisheries forecasts).

(iv) Fisher decision variables to consider for métier analysis for FMA 7 include longitude and latitude, month, target species (which are generally genuinely reported by fishers), vessel speed (which gives a good indication of the behaviours of fishers, e.g., the avoidance of some species), headline height, and fishing duration. Vessel characteristics such as vessel length, age and power could be considered as well. Interview with skippers could be conducted to identify other relevant/useful variables.

(v) If the longitude and latitude are considered for métier analysis, the analysis should start after 2007–08, to employ only data reported in the Electronic Reporting System (ERS)-Trawl, Trawl Catch Effort Return (TCER) and Trawl Catch Effort Processing Return (TCEPR) forms that are associated with good positional information.

3.6 First application of tools to assist EAFM in FMA 7

3.6.1 Principal component analysis (PCA) and heatmap using landings data

The proportion of catch attributed to each species over 1990–2024 is shown in Figure 3. Barracouta (BAR) made up the highest proportion of the catch (44.6%), with red cod (RCO) having the next largest catch (10%). The remaining species all had progressively lower contributions to the overall catch.

The Scree plot in Figure 4 shows the variation explained by first ten PCs. The percentage variance explained was: PC1 (35.9%), PC2 (16.7%) and PC3 (13.5%), with the remaining PCs explaining progressively less variation. Thus, including the first two PCs covered around 53% of the observed patterns in the data and was chosen for the remainder of the analyses.

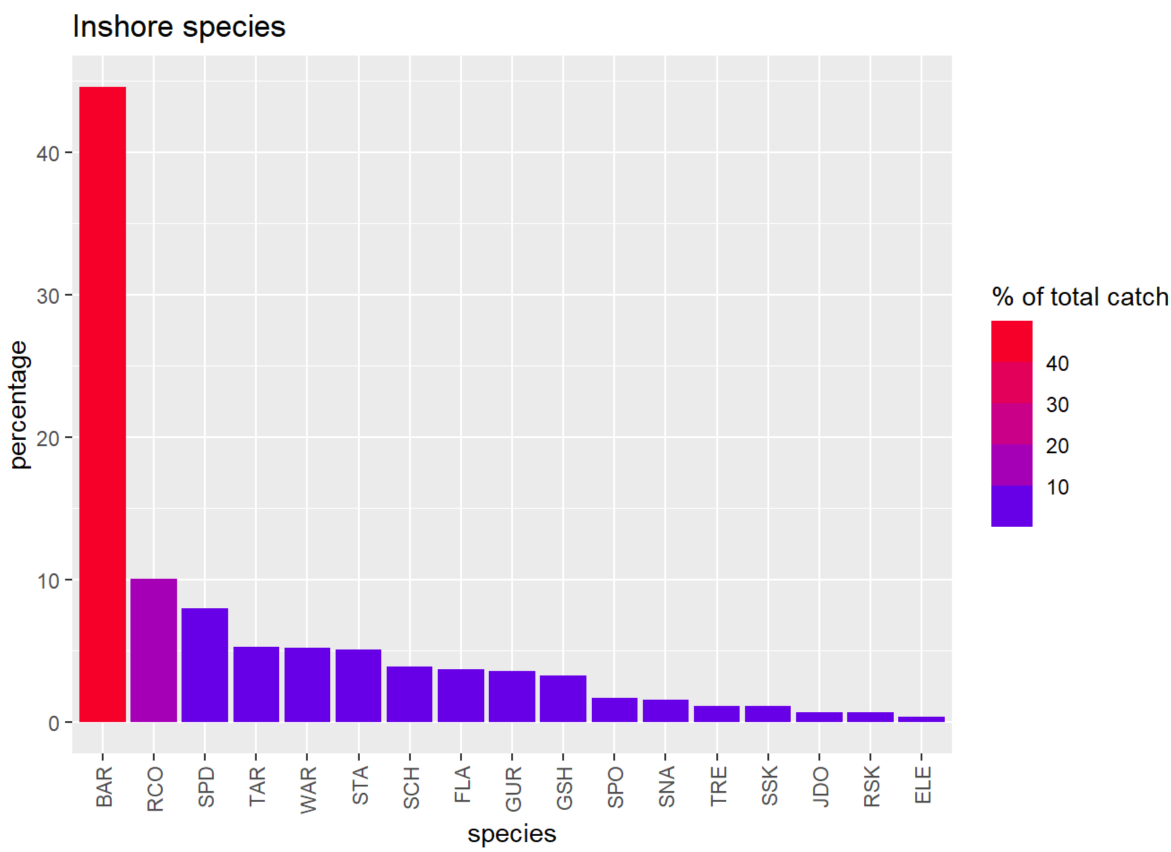

Figure 3: The proportion of catch attributed to each of the 17 inshore species selected in FMA 7 over 1990–2024, sorted by largest catch.

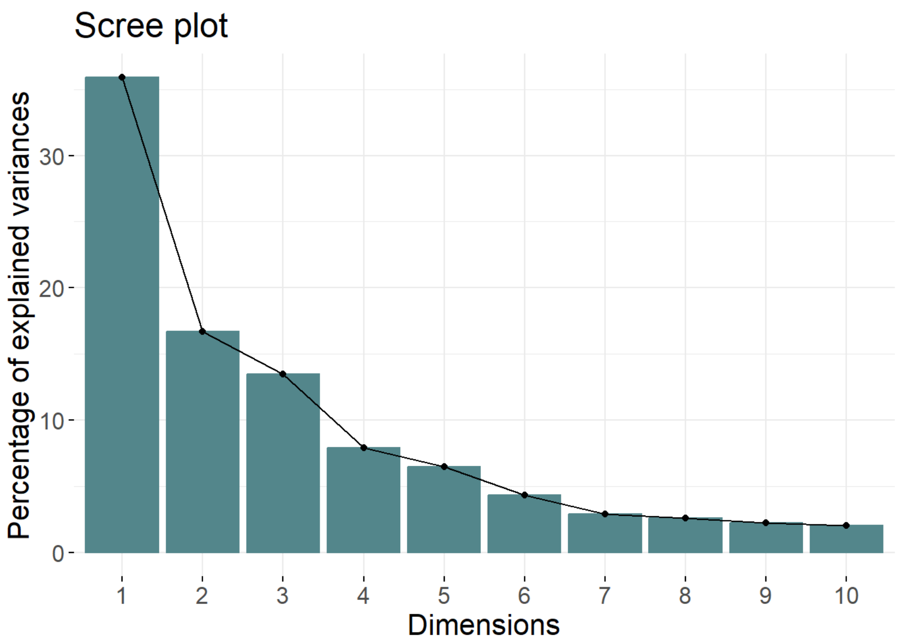

Figure 4: Scree plot showing the percentage of variance explained by each principal component in the PCA.

To study the impacts of each variable (year and species) on the first two PCs, we plotted a graph of variables (Figure 5). Here, each arrow represents a species or the year as a variable, with the direction of the arrow indicating the direction in which the variable increases across the first two PCs. Longer arrows indicate stronger contributions of the variable to the PCs. Arrows that point in the same direction are positively correlated, while arrows that point in opposite directions are negatively correlated. The angle between arrows indicates the correlation between variables. Examples of positive correlations included the correlations between: (i) John dory (JDO) and red gurnard (GUR); and (ii) dark ghost shark (GSH), flatfish (FLA) and smooth skate (SSK). An example of negative correlation was the correlation between red cod (RCO) and rig (SPO).

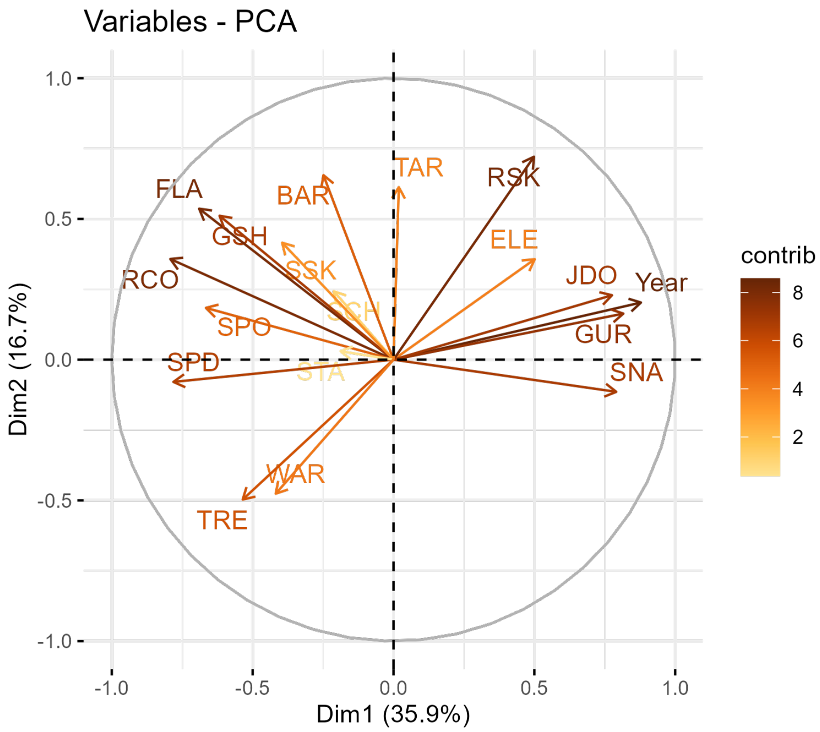

Figure 5: Graph of variables, showing the contribution of each variable (year and species) to the first two PCs in the PCA.

Next, we checked for natural clusters of years in catch composition, using singular value decomposition, which can handle situations where there are more variables than observations (although this was not the case in this analysis). Figure 6 shows a graph of the variables from the PCA output, to understand the distribution and grouping of observations in the PC space. Each point is a year of catch, across all species. The position of each point is determined by the first two PCs, which are linear combinations of catch by species each year. Points that are close to each other in the plot have similar values for the original variables (catch by species), while points that are far apart have different values.

There appeared to be natural clusters at the beginning years (1992–2000, left side of plot) and final years (2018–2024, right side of plot) of the time series. The intervening years seemed more well-mixed, with a gradual trend of negative to positive along the PC2 axis.

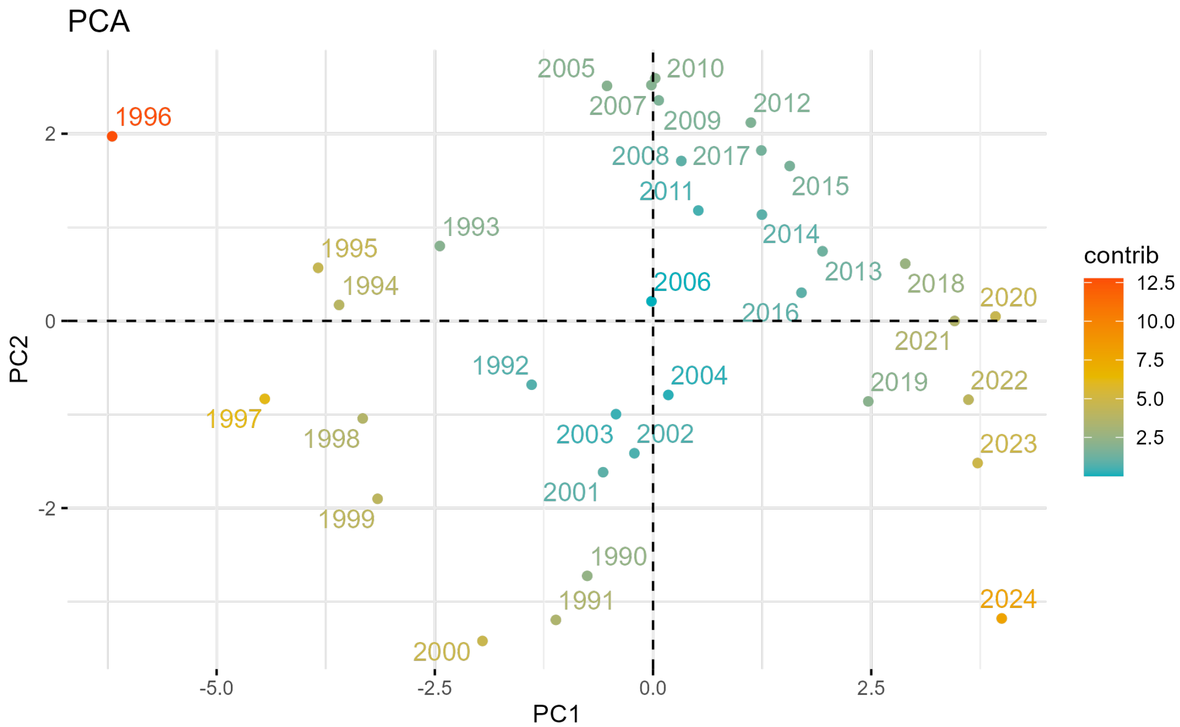

Figure 6: **Plot showing clustering of years by catch composition.**

Next, we performed a hierarchical cluster analysis of the years of data and displayed results in two different ways. First, we looked at a dendrogram (Figure 7), where each branch represents a cluster of observations. The length of the branches indicates the dissimilarity between clusters. The branches at the very bottom of the dendrogram represent catch in a particular year. The height at which two branches merge represents the dissimilarity between the clusters being merged, with higher merges indicating greater dissimilarity.

To further aid visualisation of the clusters, we then plotted the catch composition by year in PCA space (Figure 8). Note that the clustering is not identical in the two plots, but very similar. The hierarchical clustering naturally grouped the years into the following four periods: two largely overlapping clusters representing approximately 1990–2003, a cluster for 2004–2017, and a final cluster for 2018–2024 (Figure 8). This gave us a better idea of how the clusters of years compared with each other compared with Figure 7.

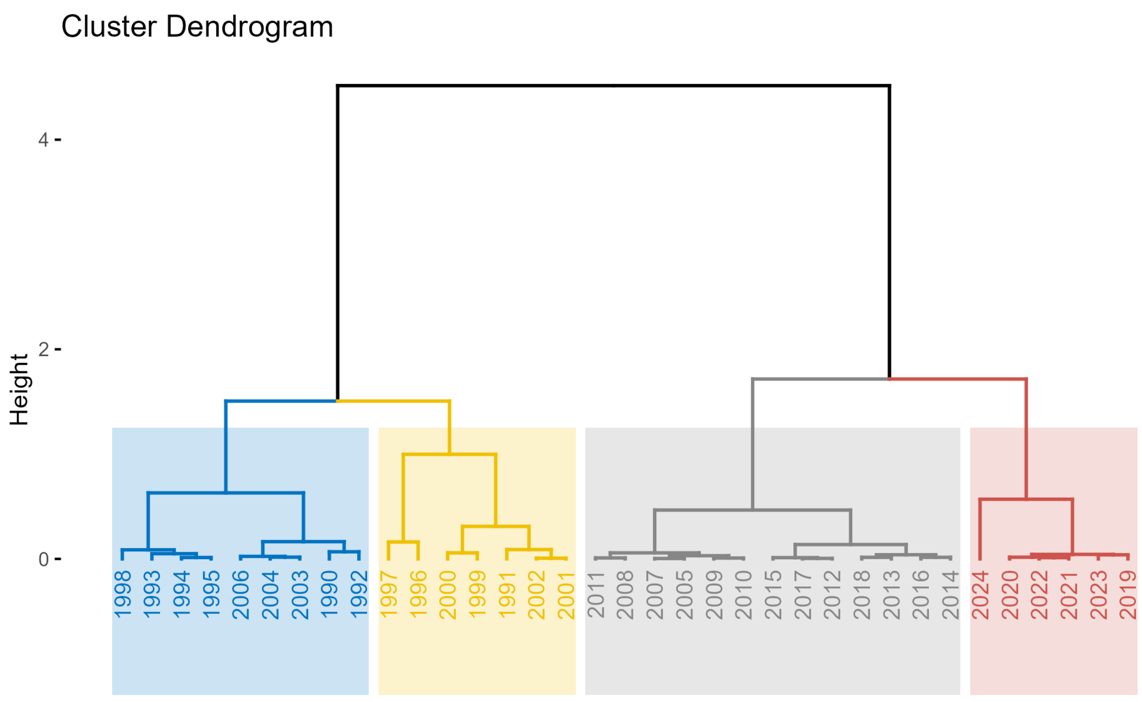

Figure 7: Dendrogram of hierarchical clustering of catch composition by year on principal components.

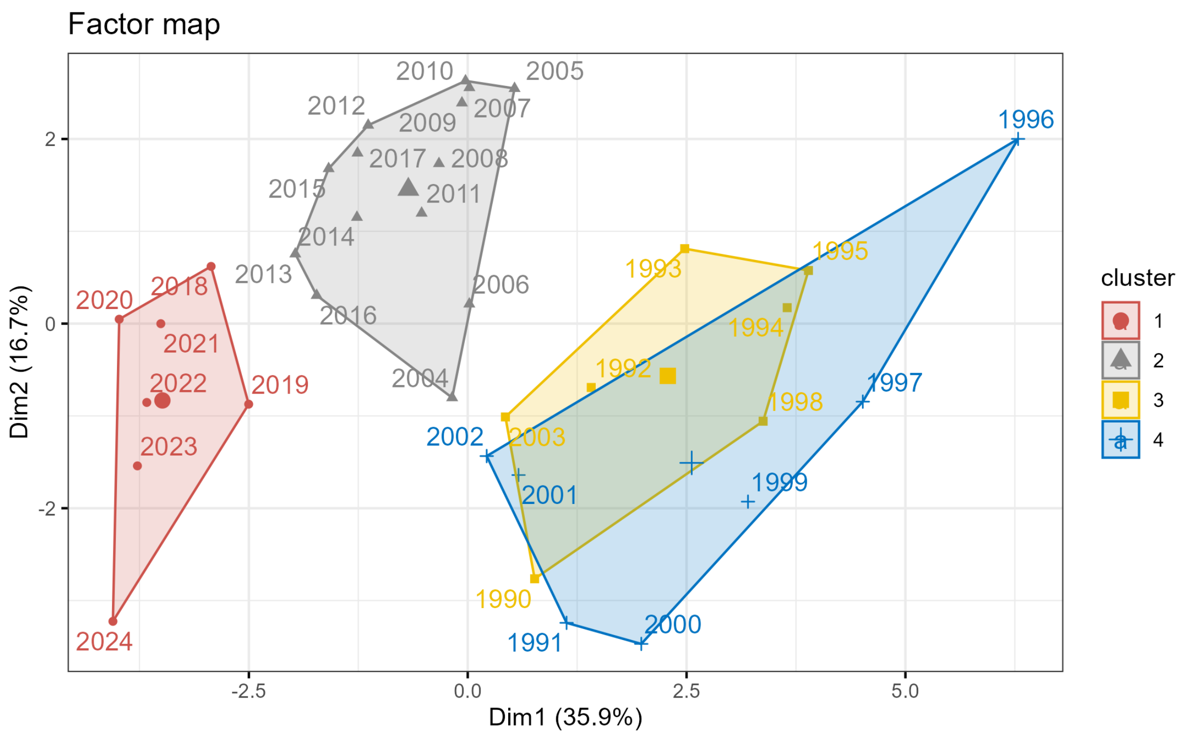

Figure 8: Visualising clusters of catch composition by year in principal component analysis space.

Finally, we produced a heatmap summarising catch composition through time (Figure 9). We ranked species by catch each year. We did not employ proportion of each species each year, as this would have been dwarfed by barracouta in most years. We then visually looked for patterns of similarly shaded cells in certain periods. Dendrograms on the left also show species with similar temporal patterns.

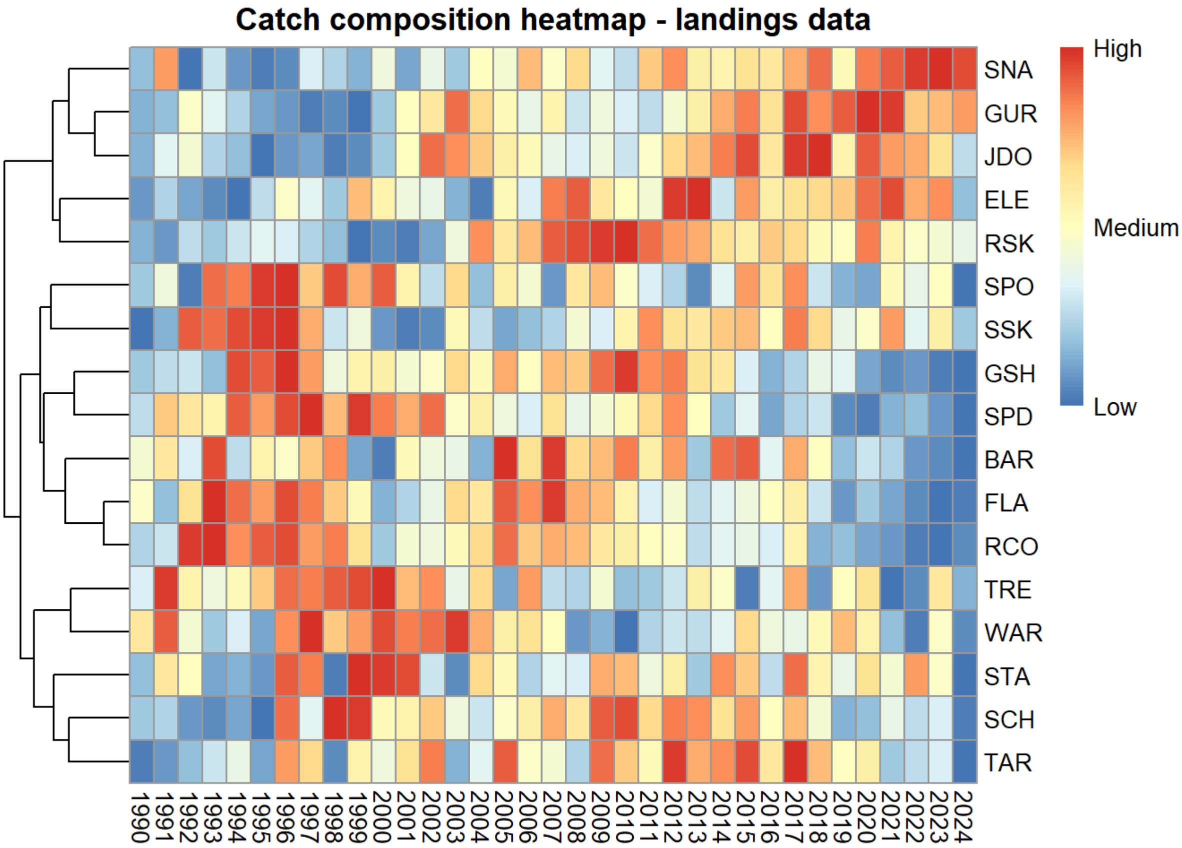

Figure 9: Heatmap plot created by ranking the catches per individual species through time. Species with similar patterns through time are grouped together.

We identified a patch of species in the early years (second quarter from top), 1994–2000 where rig (SPO), smooth skate (SSK), dark ghost shark (GSH) and spiny dogfish (SPD) were all highly ranked. Following this, clusters were less clear, with similarities in 1996–2001 between trevally (TRE), blue warehou (WAR) and giant stargazer (STA) and in 2009–2017 between giant stargazer (STA), school shark (SCH) and tarakihi (TAR). Since approximately 2017 there has been a clear grouping in the top-right corner, including snapper (SNA), red gurnard (GUR) and John dory (JDO). This particular grouping is also spatially separated from the rest of FMA 7 as it corresponds roughly to the Tasman Bay/Golden Bay area. However flatfish which are found mostly in the Tasman Bay/Golden Bay area have a decreasing (as opposed to an increasing) abundance trend.

3.6.2 Principal component analysis (PCA) and heatmap using survey data

Carrying out the analysis on trawl survey data resulted in the cluster visualisation shown in Figure 10 and the heatmap plot shown in Figure 11. The trawl survey years showed temporal trends with four non-overlapping clusters: 1992–97, 2000–05, 2007–19 and 2021–23. This showed a consistent trend in shifting relative biomass composition.

Visually examination of the heatmap (Figure 11) showed three main clusters of species: smooth skate (SSK), tarakihi (TAR), flatfish (FLA), red cod (RCO) and school shark (SCH) (1992–1997), barracouta (BAR), elephantfish (ELE), ghost shark (GSH), spiny dogfish (SPD) and giant stargazer

(STA) (2009–2013), and John dory, red gurnard and snapper (2015–2023). The period 1997–2009 did not show an obvious strong species grouping.

Comparing these clusters with those produced from the landings data (Figure 9), the main similarity appeared to be the recent contribution of snapper, red gurnard and John dory to the composition of the ecosystem.

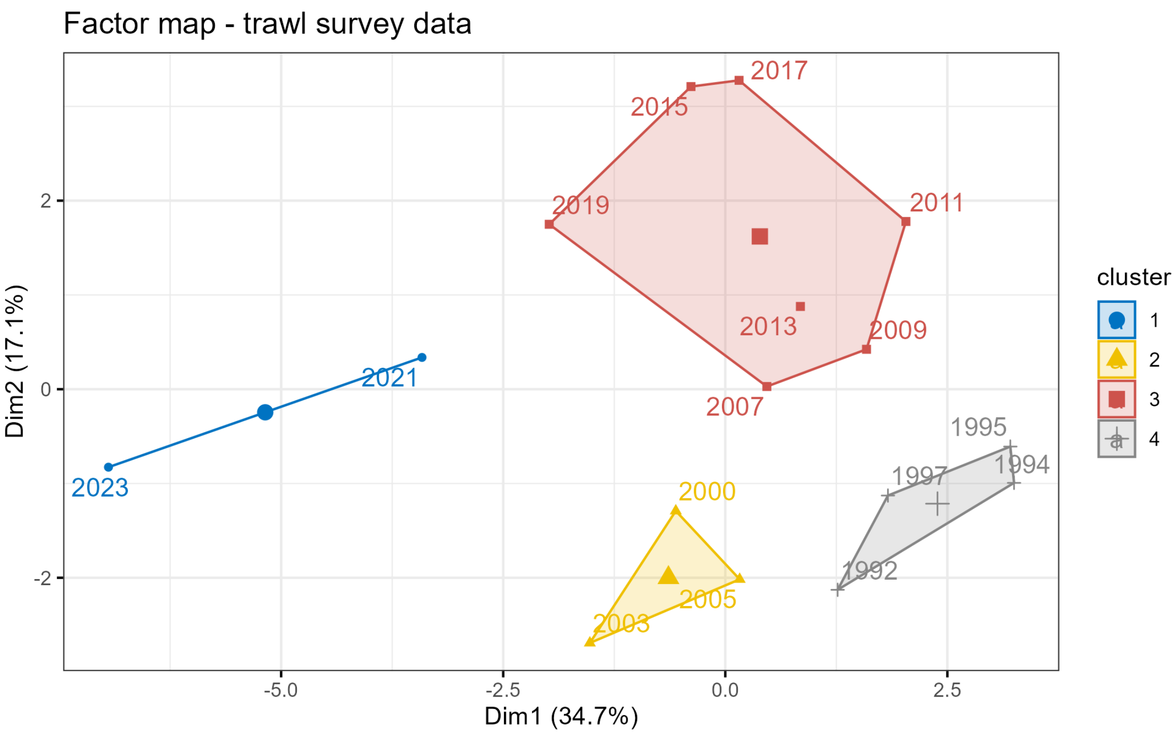

Figure 10: Visualising clusters of relative survey biomass by year in the principal component analysis space.

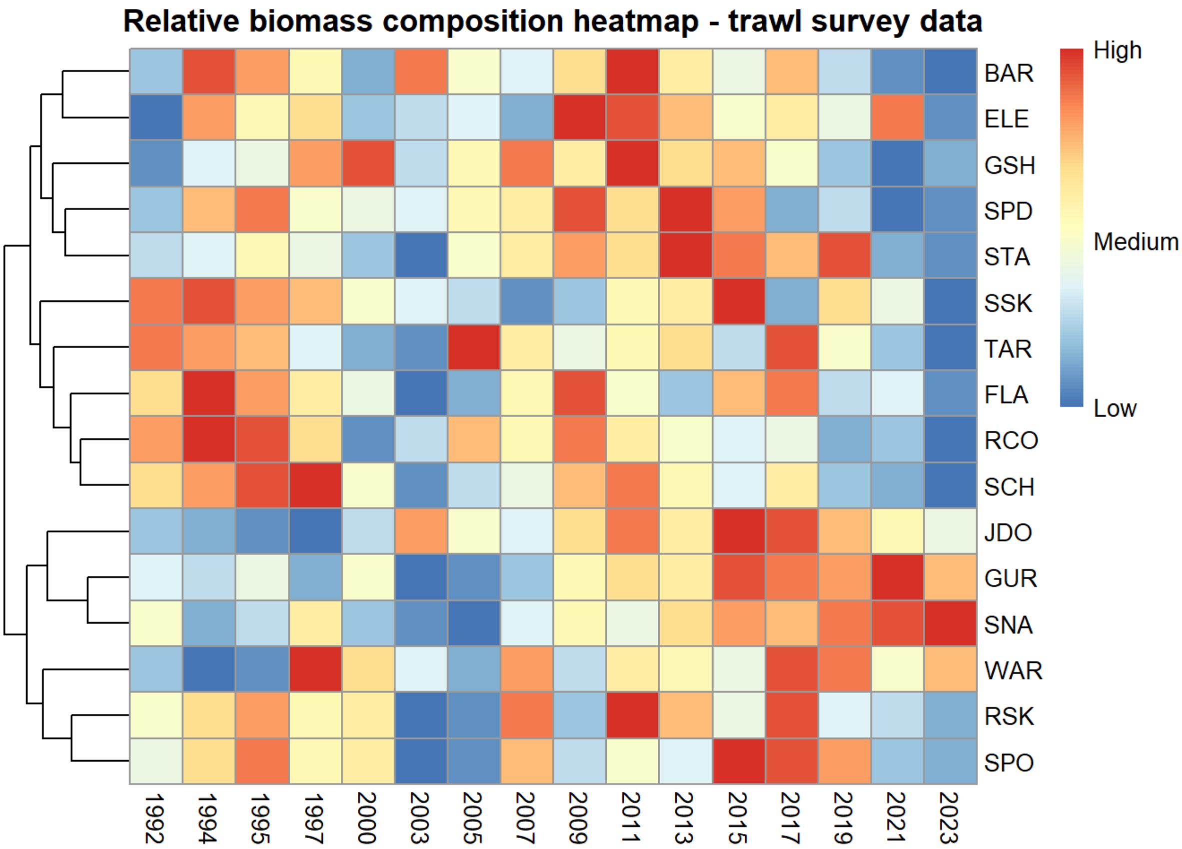

Figure 11: Heatmap plot created by using the trawl survey data, ranking the relative biomass by individual species through time. Species with similar patterns through time are grouped together.

3.6.3 Concluding remarks

PCA and heatmaps are simple tools, requiring relatively limited and readily available data. Employing PCA to analyse landings and survey data, we were able to statistically separate 1990–2024 into three or four distinct periods with distinctive species compositions. We also found species whose temporal catch patterns were similar (and dissimilar) to others. The non-negligible differences in results between the two types of PCA and heatmaps (using landings data and using survey data) suggest that predicted patterns with the first type of PCA and heatmap (using landings data) are more driven by fishing regulations and fisher behaviour than by changes in the ecosystem. The heatmaps pulled together the time and species aspects of the analysis into a single visually interpretable metric.

The two types of PCA and heatmaps reported here are only preliminary and are merely meant to provide an illustration of PCA and heatmaps as part of the toolbox identified for EAFM in New Zealand. Efforts need to continue in the future to improve PCA and heatmaps for the FMA 7 case study, to deliver results to fisheries management. Importantly, the future PCA and heatmaps for the FMA 7 case study should be: (i) produced from bottom trawl commercial catch data, which are better than landings data because they include discards, as well as from research survey data; and (ii) annotated with resource managers and stakeholders to indicate management shifts, environmental shifts and changes in fishing methods and gears within FMA 7 to better distinguish, interpret and discuss clusters (see Section 5.1).

4. DISCUSSION

The present report highlighted that there is a range of ecosystem models available, which can be categorised based on their structure and which have different levels of complexity and different purposes/objectives. Qualitative models (loop analysis) and DSEMs and dynamic multispecies models are suitable ecosystem models to assist EAFM in New Zealand, primarily because of their more limited data requirements and because these models are simple and conducive to collaborative research with resource managers and stakeholders. By contrast, more complex ecosystem models, including aggregated (or whole ecosystem) models (e.g., Ecopath with Ecosim models), biogeochemical-based end-to-end models (e.g., Atlantis models) and coupled and hybrid model platforms (e.g., multispecies size-spectrum models) are more suited to guide EBFM or EBM, which consider multiple issues beyond interactions for specific fisheries. Among dynamic multispecies models, MICE models are particularly useful models for EAFM, as they integrate the best characteristics of single-species models and can employ standard statistical methods for estimating model parameters, while also considering broader ecosystem considerations that depend on management objectives.

Ecosystem modelling most appropriate to EAFM (qualitative models (loop analysis), DSEMs, and MICE models) is still at its very infancy in New Zealand. Specifically, a qualitative model is being developed for the Whangārei region (Vidette McGregor-Tiatia, NIWA, pers. comm.), while MICE modelling efforts for hoki and southern hake on the Chatham Rise have never been completed (Matthew Dunn, NIWA, pers. comm.). Both efforts were supported by internal NIWA funding. Successful ecosystem modelling appropriate to EAFM will require strategic funding over several years and solid planning for engagement with resource managers and stakeholders, improvements, and further developments. This is particularly true for MICE models. There is also very limited expertise with qualitative models (loop analysis), DSEMs and MICE models in New Zealand, which highlights the need to invest in training modellers in the use of these tools, e.g., through training workshops supervised by overseas experts or scholarships in quantitative modelling for postgraduate students.

Beyond ecosystem models, we found in this study that several other tools would be are valuable to progress EAFM in New Zealand. In particular, métier analysis was given a very high rank, primarily because of its focus on technical interactions. Métier analysis is an important building-block required to obtain catchabilities required by other EAFM tools. However, métier analysis can be useful in itself, for example to characterise a fishery or an ecosystem. In New Zealand, métier analysis of fisheries has recently been recommended to improve the reporting of environmental and ecosystem information for Fisheries New Zealand, with preliminary work done in Middleton et al. (2024). Métier analysis is a long process involving numerous steps (see Section 3.4.1). Therefore, as is the case for ecosystem modelling in support of EAFM, successful métier analysis will require strategic funding over several years and solid planning for engagement with resource managers and stakeholders, improvements, and further developments.

In addition to qualitative models (loop analysis), DSEMs, MICE models, ISIS-FISH ecosystem models (which are dynamic multispecies models) and métier analysis, the toolbox that we identified to progress EAFM in New Zealand includes the following other tools: mixed fisheries forecasts using the MixME (Mixed-fishery Multi-stock Evaluation) method; indicators of ecosystem overfishing; cumulative biomass versus trophic level; principal component analysis (PCA) on timeseries data and heatmaps; and risk tables. None of these tools have been used in New Zealand yet. We gave PCA and heatmaps a very high rank, primarily because they provide similar insights as métier analysis but take much less time to develop. We also assigned a high rank to indicators of ecosystem overfishing, cumulative biomass versus trophic level and risk tables, mainly for their simplicity and low data requirements. The MixME (Mixed-fishery Multi-stock Evaluation) method is more complex and has larger data requirements and would involve more substantial funding and training to be employed in New Zealand.

We identified the FMA 7 inshore mixed bottom trawl fishery as a good EAFM case study primarily focused on the issue of technical interactions, mostly because the FMA 7 inshore mixed bottom trawl fishery has been relatively well studied compared to other mixed fisheries. We identified 17 stocks for this EAFM case study. We conferred with stakeholders about the FMA 7 case study, which mainly allowed us to draw important considerations for métier analysis for FMA 7. However, we opted to conduct some first analyses for the FMA 7 case study with PCA and heatmaps instead (another tool with a very high rank for EAFM). The preliminary PCA and heatmaps reported here were merely an opportunity to showcase this promising EAFM tool, and future work will be needed to improve PCA and heatmaps for the FMA 7 case study to deliver results to assist fisheries management (see Section 5.1).

New Zealand's current management framework already incorporates ecosystem considerations into fisheries management advice in a qualitative way by presenting published information alongside stock assessment results, with references incorporated into sustainability round papers and the ecosystem and environment (E & E) sections of the Plenary report. In other words, EAFM is already underway in New Zealand. The toolbox for EAFM identified in the present report will help advance EAFM in New Zealand and the applications of this toolbox can support current Fisheries New Zealand activities in several ways, such as:

- (i) The applications of the toolbox can provide information for the E & E sections of the Plenary report. Importantly, sections on the "role in the ecosystem" and "trophic interactions" are a gap for most species and the applications of the tools that we presented in this report can allow Fisheries New Zealand to have a better grasp on these sections and incorporate these ecosystem considerations into decision-making in a more concrete way.
- (ii) The application of the tools that we presented in this report can contribute to the upcoming "fisheries impacts report" produced by Fisheries New Zealand, which will publish annually a fishery-by-fishery summary of the environmental impacts of fishing.
- (iii) These applications can feed into the development of stock-by-stock tables listing the fisheries that catch a stock, which will serve as pointers to relevant fisheries summaries in the fisheries impacts report, ensuring that this information can still be accessed at a stock level.
- (iv) These applications can provide information for Fisheries New Zealand consultation documents related to sustainability rounds and other regulatory changes and provide a more formal way of synthesising available information for consideration by stakeholders and MPI/the Minister for Oceans and Fisheries.
- (v) PCA, heatmaps, and métier analysis can contribute to a better framework for defining fisheries, by delivering an understanding of catch composition as an emergent property of fisheries.

The international workshop was instrumental to the work reported in the present report. At the international workshop, experts also delivered recommendations on EAFM/EBFM/EBM and associated tools. There recommendations are detailed in the following and include:

- (i) Employing multiple tools together or in sequence.
- (ii) Using available complex ecosystem models for scoping in an EAFM project.
- (iii) Considering using ecosystem models that require diet data in limited diet data situations.
- (iv) Leveraging existing platforms and code bases whenever possible/relevant.
- (v) Fitting tools within assessment/management timelines and cycles.
- (vi) Having a more collaborative approach, with more regular meetings between resource managers and stakeholders and scientists.
- (vii) Building buy-in from resource managers and other stakeholders with MSE.

4.1 Employing multiple tools together or in sequence

One of the main recommendations of the international workshop was to employ multiple tools together or in sequence to support EAFM/EBFM/EBM. In particular, attendees of the international workshop recommended that developing an ensemble ecosystem modelling approach or coupling a number of models to address an EAFM/EBFM/EBM issue would be advantageous. A lot of structural uncertainty can be addressed by using an ensemble of approaches to test management procedures. Overseas experts stressed that the success of many EAFM/EBFM/EBM projects in the USA and Australia was in large part due to the use of multiple models/tools in the management process because this:

(i) Gave higher confidence to resource managers to employ the results provided by models/tools when different models/tools provided a similar outcome.
(ii) Allowed numerous questions to be addressed as they arose through time, to best answer stakeholder needs through time.

Australian experts at the workshop argued that approaches that can be applied more generically, easily, cheaply and rapidly across a number of examples as possible are ideal. However, research investigators need to consider how widely these sorts of approaches should be applied, versus addressing only the high priority questions from resource managers and other stakeholders. This trade-off needs to be addressed in order to select a set of tools for the case study of interest. In most case studies, indicators and qualitative models (loop analysis) are good approaches to use which are cost-effective and quick, at least at the start of the project of interest. Many Australian projects now benefit from a toolbox of approaches, including qualitative models, MICE and Atlantis models and other models, which allows scientists to work with more cost-effective approaches in all situations and more expensive approaches as well where this is desirable.

In addition to having multiple tools/models available for a case study, it is also good practice to explore multiple versions of the same tool/model. In situations of information gaps or uncertainties, it is advantageous to consider alternative structures for the same model (e.g., alternative versions of the same qualitative model with some links present or absent) and find the model structure that is most consistent with the available observations. In the case of ecosystem models, working with an array of alternative models allows scientists to interrogate uncertainty formally.

4.2 Using available complex ecosystem models for scoping in an EAFM project

Some overseas experts at the international workshop noted that a lot of work has already been done with Atlantis, EwE and multispecies size spectrum models for Tasman Bay/Golden/Bay, so that it was surprising to see that there was no plan to employ these more complex ecosystem models for the FMA 7 case study. New Zealand modellers answered that these Atlantis, EwE and multispecies size spectrum models were designed for academic purposes and would need to be substantially tailored to be useful for fisheries management. Importantly, to be useful for fisheries management, these models would need to better represent individual fisheries and their associated fishing pressure and rely on standardised indices of relative abundance derived from research surveys or catch and effort data. The overseas experts thought that, regardless, the more complex ecosystem models for Tasman Bay/Golden/Bay can provide some valuable insights into the state of ecosystems to the FMA 7 project. In the future, the more complex ecosystem models for Tasman Bay/Golden/Bay could be used alongside simpler tools and MSE testing. For now, these more complex ecosystem models can be useful for scoping the FMA 7 case study.

In particular, it would be interesting to leverage the existing EwE model for Tasman Bay/Golden/Bay to scope the métier analysis for FMA 7 because we consider that it would be too complicated to incorporate the 100+ fish and invertebrate species that inhabit the FMA 7 ecosystem into a métier analysis (see Section 2.5.3).

4.3 Considering employing ecosystem models that require diet data in limited data situations

New Zealand ecosystem modellers raised the issue that diet data are one of the greatest barriers for ecosystem modelling in New Zealand. In New Zealand, we have existing diet studies (e.g., from Peter Horn, a retired NIWA scientist; Horn & Dunn 2010) that can help us understand what different species may eat, but these diet studies are mainly for the Chatham Rise.

However, several overseas experts at the international workshop stressed that we should not wait for new diet data to continue to develop and use ecosystem models that require diet data, to support EAFM/EBFM/EBM. For example, investigators of the US west coast hake MICE modelling project had diet data for some decades and a twenty-year gap in between, but they were still able to derive a lot of information from the limited amount of diet data available. Moreover, investigators of the Atlantic menhaden project pointed out that complex ecosystem models such as EwE models are not that sensitive to the exact diet proportions that are fed into the models. Furthermore, diet proportions tend to be adjusted during model tuning. Ultimately, it is more important for ecosystem modellers to have a good overall understanding of what the different predators eat than exact diet proportions.

4.4 Fitting tools within assessment/management timelines and cycles

Some overseas experts at the international workshop emphasised that it is important to be realistic when developing EAFM/EBFM/EBM tools to be able to fit them within assessment/management timelines and management cycles. For example, EAFM tools benefit from the organisation of meetings/workshops with stakeholders to guide model development and narrow down research questions that are aligned with relevant stock assessment cycles. On the US west coast, the annual timing of EBFM science advice match the calendar of management and fisheries (e.g., Ecosystem Workgroup 2024). Fisheries New Zealand scientists present at the workshop noted that the alignment of science and management processes has long been discussed within Fisheries New Zealand. As such, to further advance EAFM in New Zealand it will be important to make sure that the required information is put in front of the decision-makers at the right time and commissioning of research projects is done at the right time. It is essential to align science discussions with fisheries management prior to the development of management options and the right timing is necessary to ensure that ecosystem information can be incorporated into potential management actions.

An Australian expert at the international workshop argued that nothing happens when large-scale legislative changes are asked for and that it is better for EAFM/EBFM/EBM scientists to work within the system that they have got. This expert also noted that the legislation which countries like Australia or New Zealand use to manage their fisheries cannot be biologically achieved if MSY is interpreted in its purest sense (i.e., it is not biologically possible for all stocks to be managed at MSY simultaneously). As such, developing countries can more easily reach EAFM/EBFM/EBM because they are not constrained by this type of legislation.

4.5 Leveraging existing platforms and code bases whenever possible/relevant

When developing new ecosystem models, it can be advantageous to build them upon existing stock assessment models or at least use the same programming language as that employed in existing stock assessment models. This idea is particularly relevant for MICE models. For example, the CEATTLE modelling platform described in Section 3.4.6.2 is derived from stock assessment models for the northeastern Pacific coast, so the results of this modelling platform are very easy to communicate to fisheries managers and stakeholders from the region.

American experts present at the international workshop emphasised that there are lots of code bases available and that, in limited-funding environments, ecosystem modellers should not try to develop new modelling platforms/code bases from scratch but should rather use existing modelling platforms/code bases. For instance, ecosystem modellers interested in EwE modelling should try to employ the *RPath* package (Lucey et al. 2020) and those interested in a state-space version of EwE should employ the new EcoState modelling platform (Thorson et al. 2025), which is implemented with R-package *ecostate* that relies on RTMB (Kristensen 2024) and is available on the CRAN. Existing modelling platforms/code bases often come with helpful training materials and user communities.

4.6 Building buy-in from resource managers and other stakeholders with MSE

The overseas experts present at the international workshop stressed that it is important to build trust with resource managers and other stakeholders through frequent interaction where it can be demonstrated that the research being performed aims to identify trade-offs. A good way to identify these tradeoffs with resource managers and other stakeholders and get buy-in from them is through MSE and scenarios, making sure that everybody's concerns are included in the OMs. In these efforts, the nature of the modelling platform used for the OM is almost secondary compared to covering everyone's concerns.

5. POTENTIAL RESEARCH

Potential research includes:

- Continuing EAFM analyses for FMA 7 with tools that were assigned a very high or a high rank;
- Carrying out EAFM analyses for FMA 7 with other tools;
- Addressing other New Zealand EAFM case studies.

Additional avenues for the future, which also pertain to resource management include:

- More formally integrating EAFM into New Zealand research and management;
- Continuing the move towards EBM in New Zealand.

5.1 Continuing EAFM analyses for FMA 7 with tools that were assigned a very high or a high rank

In this report, we conducted some first EAFM analyses for FMA 7, with PCA and heatmaps (Section 3.6). PCA and heatmaps would need to be continued and improved to further understand changes in catch composition for the FMA 7 inshore mixed bottom trawl fishery in relation to various other changes, including management shifts, environmental shifts and changes in fishing methods and gears. The annotation of heatmaps by resource managers and other stakeholders will be important to reach this goal. Importantly, bottom trawl catch data rather than landings data should be used for future PCA and heatmaps for the FMA 7 case study (in addition to research survey data). This is especially relevant as many of the FMA 7 case study species are Schedule 6/72A species that are caught and discarded and do not show up in the landings data.

Métier analysis is a tool with a very high rank for the FMA 7 case study that could be undertaken in the near future, building upon the considerations raised at the June 2024 meeting with resource managers and stakeholders, which are reported in Section 3.5.3. In particular, two types of métier analysis would ideally be carried out for the FMA 7 case study: a métier analysis for the characterisation of the system (FMA 7 bottom trawl fishery); and another métier analysis considering only a few species to define métiers for subsequent analyses (ecosystem modelling, mixed fisheries forecasts). Because it is good practice to leverage existing platforms and code bases whenever possible/relevant (Section 4.5), any future métier analysis for FMA 7 should incorporate learnings from previous applications, particularly efforts for the Australian tuna and billfish fisheries reported in Parsa et al. (2020a, 2020b). Conducting métier analysis with the VAST modelling platform (as described in Section 3.4.1.8) could also be considered. If this research idea was pursued, it would be interesting to develop a joint species distribution model with the VAST modelling platform that would consider multiple species at the same time and the effects of environmental variables and a vessel effect (where, as mentioned in Section 3.4.1.8, the vessel effect would help group vessels into métiers using an ordination procedure). Such a modelling approach would allow for several pressing topics for the FMA 7 region (technical interactions, métiers, distribution shifts in response to temperature) to be addressed with one single model.

Tools with a high rank for the FMA 7 case study include indicators of ecosystem overfishing, cumulative biomass versus trophic level, and risk tables. All these analyses are relatively quick to implement (compared to the other tools described in Sections 3.3 and 3.4) and are attractive compared to other tools because they are not dependent upon any quantities predicted by ecosystem models. However all of the analyses for FMA 7 with tools that have a very high or a high rank would involve a lot of interactions with resource managers and stakeholders for the development of the analyses and the interpretation and discussion of results, enabling real collaborative research that is more conducive to robust outcomes and buy-in.

Finally, we reiterate that the ecosystem models for Tasman Bay/Golden Bay (Table 1) may be useful for scoping for the FMA 7 case study (see Section 4.2). In addition, the results of the existing ecosystem models for Tasman Bay/Golden Bay can help interpret or discuss the outputs of PCA, heatmaps, métier analysis and the tools with a high rank (indicators of ecosystem overfishing, cumulative biomass versus trophic level, and risk tables).

5.2 Carrying out EAFM analyses for FMA 7 with other tools

Once EAFM analyses have been conducted for the FMA 7 case study with the tools with a very high or a high rank, tools with a medium rank (Table 2) could be considered. As highlighted in Section 4.1, EAFM in FMA 7 will have more chances to succeed with the use of multiple tools together or in sequence. Tools that have a medium rank include:

- Mixed fisheries forecasts with the MixME method;
- Qualitative models (loop analysis);
- DSEMs;
- MICE models.

5.2.1 Mixed fisheries forecasts with the MixME method

Among the tools with a medium rank, mixed fisheries forecasts with the MixME method will be the most challenging to implement because of the limited number of fully quantitative single-species stock assessments available. Other challenges to address to allow for the use of the MixME method for FMA 7 (and other FMAs) include (Table 2):

- This method requires a lot of data, which are available for some New Zealand regions but involve extensive grooming and processing.
- A lot of processing is needed prior to employing the method because the many data that are required need to be converted into a common structure;
- Substantial training of New Zealand fisheries modellers is needed.

5.2.2 Qualitative models (loop analysis)

Qualitative models have proven utility overseas, where they have been valuable for collaborative research with resource managers and other stakeholders and designing more complex ecosystem models. Their major challenge is that takes some expertise to build and analyse signed digraphs, and this expertise is very limited in New Zealand and needs to be developed.

5.2.3 Dynamic structural equation models (DSEMs)

DSEMs represent very recent and promising developments, which will be advantageous for EAFM research and other efforts in New Zealand. However, there is currently reduced capacity to develop and run DSEMs in New Zealand.

5.2.4 Models of Intermediate Complexity for Ecosystem assessments (MICE models)

MICE modelling was highly recommended during the international workshop, primarily for its ability to thoroughly answer specific questions and generate buy-in. A clear recommendation from the international workshop was to build upon existing stock assessment modelling platforms to design MICE models. We foresee that efficient MICE modelling efforts in support of EAFM in FMA 7 (and other FMAs) would rely on MICE models developed from existing Casal2 or SPM codes. However, there is currently limited capacity to develop and run MICE models in New Zealand and significant training will be needed for New Zealand modellers to upskill in MICE modelling.

5.3 Addressing other New Zealand EAFM case studies

The frameworks and methods developed for FMA 7, starting with the present report, will be easily adaptable to other EAFM case studies in New Zealand, for example the fishery complexes reported in table 3 of the National Inshore Finfish Fisheries Plan (Fisheries New Zealand 2022), to allow for a better understanding of how TACC adjustments for one stock will affect other stocks in these fishery complexes. The application of the frameworks and methods would be suitable for the following fishery complexes:

(i) The FMA 2 (Central East) mixed trawl fishery;
(ii) The FMA 3 (South Island East Coast) mixed trawl fishery;
(iii) The FMA 5 (Southland) mixed trawl fishery;
(iv) The FMA 8 (Central West) mixed trawl fishery;
(v) The FMA 9 (Auckland West) mixed trawl fishery.

Besides the fishery complexes outlined in the National Inshore Finfish Fisheries Plan, other relevant EAFM case studies to consider in future projects are Tasman Bay/Golden Bay, the Chatham Rise and the Hauraki Gulf, primarily because several tools have already been developed for these regions (Table 1). The Hauraki Gulf is also the main region where Fisheries New Zealand and other government departments (mostly the Department of Conservation) are currently trialling EAFM/EBFM/EBM, through the "Revitalising the Gulf" marine work programme. The ecosystem models available for Tasman Bay/Golden Bay, the Chatham Rise and the Chatham Rise may be particularly useful for scoping and provide inputs to other tools.

The Tasman Bay/Golden Bay mixed trawl fishery, which is a fishery operating in only a fraction of FMA 7, was considered in an Fisheries New Zealand consultation document (Fisheries New Zealand 2019). The key stocks of the Tasman Bay/Golden Bay mixed trawl fishery are SNA 7, FLA 7, GUR 7, SPO 7, JDO 7 and ELE 7, with SNA 7 and FLA 7 being the most important ones. Three tiers of interdependency were identified within the fishery when considering the key stocks. As is the case with the FMA 7 case study (Section 3.5.1), the different ranges of productivity of the key stocks would make multispecies assessments and management challenging for the Tasman Bay/Golden Bay mixed trawl fishery. One of the primary issues with the Tasman Bay/Golden Bay mixed trawl fishery is that fishers have modified headlines and changed target species to avoid over-catching snapper, which has led to fishing effort shifting to other fish stocks and potentially constraining the catch of flatfish (under caught) (Fisheries New Zealand 2019).

5.4 More formally integrating EAFM into New Zealand research and management

In order to advance EAFM in New Zealand it must be more formally integrated into New Zealand's research and management processes. To reach this goal, two recommendations from the international workshop are particularly relevant:

(i) Fitting EAFM tools within assessment/management timelines and cycles (Section 4.4);
(ii) Making more use of MSE, to evaluate how well fisheries management perform under uncertainty and generate more buy-in from resource managers and other stakeholders (Section 4.6).

The system for peer review that Fisheries New Zealand implements with science working group (WG) meetings will be helpful to address these two recommendations. For example, project leads for future ecosystem modelling projects can take advantage of WG meetings early on in the project to develop and explore conceptual models, qualitative models and/or DSEMs with the WG community before moving to more complex quantitative ecosystem models. This system will also be advantageous for MSE, with (i) the development of scenarios and performance metrics with the WG community at early WG meetings and (ii) the analysis, interpretation and discussion of MSE outcomes with the WG community at later meetings.

In addition to leveraging the system that we have in place in New Zealand, fisheries managers could envision here (an) IEA programme(s), i.e., programme(s) that integrate all ecosystem components, including humans, into the resource management processes such that decision-makers can address trade-offs and decide how to most likely reach their goals (acknowledging this approach was recently initiated by NIWA in the Whangārei region). The IEA approach (described in Section 3.2.1) has proven useful to operationalise EAFM/EBFM/EBM in the USA (Harvey et al. 2021) and elsewhere (e.g., Bornman et al. 2025; Clay et al. 2023). However this approach would require substantial resourcing, which may limit implementation in the near term.

5.5 Continuing the move towards EBM in New Zealand

After EAFM has been further advanced in New Zealand, efforts will continue to further advance EBFM and then EBM. Some EBFM/EBM issues are already being addressed in New Zealand, e.g., water quality and land-based sedimentation in FMA 7, including with some Atlantis modelling (Vidette McGregor-Tiatia, NIWA, pers. comm.). However, some work will be needed to make EBFM/EBM a stronger and more formal part of fisheries research in New Zealand.

At the international workshop, an Australian expert argued that, while it is a good idea to focus on tools for EAFM, it would also be beneficial to start developing more complex EBFM/EBM tools now. This is important because non-fisheries issues such as dams have the potential to have much larger impacts than fisheries (Eva Plagányi, CSIRO, Australia, pers. comm.). Second, even if outputs from more complex tools have a high level of uncertainty, there is value in having them ready for future challenges. In the EBFM and EBM spaces, with so many stakeholders and different industries involved, there is a need to find a middle ground and this is where more complex ecosystem models can help bring everything together; having these more complex ecosystem models available in some form when needed to address New Zealand's EBFM and EBM issues (including current ones such as the cumulative impacts of fishing, aquaculture, land-use and climate change) will be advantageous to further advance EBFM and EBM in New Zealand.

On a final note, the present report focuses on commercial fisheries, while customary and recreational fisheries are also important in New Zealand, particularly in the EBM space. Customary and recreational fisheries do not necessarily see changes in biomasses and yields the same ways as commercial fishers. Their concerns and values may be different, e.g., self-determination in the case of iwi. It will be paramount to carefully consider these concerns and values when developing models and scenarios to support EBM in New Zealand.

6. FULFILMENT OF BROADER OUTCOMES

New Zealand has only a small research capacity for modelling in support to EBM. The present project contributed towards capacity building, by gathering: (i) Vidette McGregor-Tiatia, Matt Pinkerton and Samik Datta, who are actively developing ecosystem modelling approaches in New Zealand; (ii) Darren Parsons and Mark Morrison, who are actively engaging with EBM in Whangarei Harbour and the Hauraki Gulf; (iii) Arnaud Grüss, who drew upon his five-year experience of the IEA process and achievements in the EBM space in the USA; and (iv) Steven Holmes, who drew upon his many years of experience with métier analysis and mixed fisheries forecasts in Europe. The present project also ensured New Zealand researchers maintain very strong links with experts in EBM overseas, including: (i) in Australia with, among others, Beth Fulton, Eva Plagányi, Julia Blanchard, Jeffrey Dambacher, Mahdi Parsa, Paul Burch, Sean Pascoe, and Keith Sainsbury; (ii) in the USA with, among others, Isaac Kaplan, Sarah Gaichas, and Howard Townsend; and (iii) in the UK with, among others, Paul Dolder. By using a team approach, we: (i) promoted a more diverse use of staff; and importantly; (ii) shared expertise and grew institutional knowledge of New Zealand fisheries, ecosystem modelling approaches and EBM amongst these staff. This strategy reduced the risk of such knowledge being lost in the future and will potentially benefit a wide range of future fisheries research projects. The present project also brought together understanding of many different tools for an EAFM, including primarily métier analysis, mixed fisheries forecasts, qualitative modelling (loop analysis), MICE models, and miscellaneous other tools such as PCA and indicators of ecosystem overfishing.

This present project also contributes to starting transformational research in the EBM space for New Zealand, as the tools for EAFM reviewed for the present project constitute a key component of the wider EBM approach. EBM research has for many years been encouraged in New Zealand to protect biodiversity and taonga (treasures), but efforts in the EBM space have been hindered by a lack of resources and capability. The Sustainable Seas National Science Challenge has enabled progress in EBM research, with input from Māori and stakeholders, but came to an end in June 2024. Therefore, we see the present project as contributing to build a legacy for the Sustainable Seas National Science Challenge, with the review and development of relevant ecosystem models for inshore trawl fisheries. We mobilised an experienced and multidisciplinary workforce capable of building transformational EBM research for Aotearoa New Zealand, starting with the present project, to contribute to enhance New Zealand's marine economy into a blue economy (Gerrard 2021). Solid EBM and IEA will require long-term efforts, beginning with the present and follow-up projects, to help improve the use of EAFM within New Zealand's current legal frameworks, particularly The Fisheries Act 1996.

Importantly, we see our efforts to build transformational EBM research in Aotearoa New Zealand, starting with EAFM with the present and follow-up projects, as an opportunity to embrace the Māori worldview (Te Ao Māori), recognising that a key aspect of Te Mana o te Taiao is upholding the principles of the Treaty of Waitangi (Department of Conservation 2020). "Ecosystem thinking," the extensive knowledge of the whole system and the complex interrelationships between its components, has synergies with Māori knowledge (mātauranga Māori). The Māori worldview is that fishing industry economy depends upon nature, with which we are connected via our cultures and the places in which we spend time, and that nature is an important part of our identity (Department of Conservation 2020). Holistic EBM research based on a shared vision of the world combining western science and mātauranga Māori (thereby recognising the social, economic, cultural and spiritual dimensions of EBM) will strengthen fisheries management and, more broadly, resource management in New Zealand (Gerrard 2021). We engaged with stakeholders in Objective 2 of the present project and foresee more engagement with more stakeholders and Māori partners in follow-up projects, building upon our prior experience with EBM in Whangarei Harbour and the Hauraki Gulf and ongoing collaborations with Te Ohu Kaimoana and Moana New Zealand.

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APPENDIX 1: AGENDA OF EAFM CASE STUDY WORKSHOP

New Zealand EAFM case study workshop
Friday 4th October 2024 7:30 am – 4 pm

Attendees: Jean Davis, Alex Kroch, Ian Tuck, Pamela Mace, Hannah Mello, Anthony Brett, Karen Tunley, Bruce Hartill, William Gibson, Vikki Ambrose, Philip Heath, Marine Pomarede, Milan Cunliffe-Post, Gretchen Skea, Rich Ford (Fisheries New Zealand (FNZ)); Arnaud Grüss, Samik Datta, Vidette McGregor, Darren Parsons, Steven Holmes, Jeremy McKenzie, Mark Morrison, Matthew Dunn (NIWA); Isaac Kaplan, Sarah Gaichas, Howard Townsend (NOAA Fisheries); Beth Fulton, Eva Plagányi, Jeffrey Dambacher, Paul Burch, Sean Pascoe (CSIRO); Mahdi Parsa (Australian Bureau of Agricultural and Resource Economics and Sciences; Julia Blanchard (University of Tasmania), Paul Dolder (Cefas – recorded talk)

Agenda

7:30 am – 8:30 am Chair: Darren Parsons (NIWA)
7:30 am. FNZ presentation of the project (Jean Davis and Alex Kroch; FNZ)

7:45 am. NIWA presentation of the project (Arnaud Grüss; NIWA)

8:00 am. Introductions

8:30 am – 9:40 am Chair: Arnaud Grüss (NIWA)
8:30 am. MICE modelling in the U.S. (Isaac Kaplan; NOAA Fisheries)
20 minutes talk + 20 minutes Q/A and discussion

9:10 am. Feedback on the questions circulated ahead of the workshop from American collaborators and discussion
The questions are listed below.

9:40 am. Break

9:55 am – 11:20 am Chair: Jean Davis (FNZ)
9:55 am. Workshop resumes, Australian collaborators join the workshop, and recap of the first hours of the workshop

10:10 am. Introductions

10:40 am. EAFM for data-poor systems (Beth Fulton; CSIRO)
20 minutes talk + 20 minutes Q/A and discussion

11:20 am – 12:40 pm Chair: Vidette McGregor (NIWA)
11:20 am. Dynamic multispecies modelling in Australia (Eva Plagányi; CSIRO)
20 minutes talk + 20 minutes Q/A and discussion

12:00 pm. Qualitative models/loop analysis (Jeffrey Dambacher; CSIRO)
20 minutes talk + 20 minutes Q/A and discussion

12:40 pm. Break

1:25 pm – 2:50 pm Chair: Alex Kroch (FNZ)
1:25 pm. Workshop resumes

1:30 pm. Métier analysis in Australia (Mahdi Parsa; Australian Bureau of Agricultural and Resource Economics and Sciences)
20 minutes talk + 20 minutes Q/A and discussion

2:10 pm. Mixed fisheries forecasts – recorded talk (Paul Dolder; CEFAS)
20 minutes talk + 20 minutes discussion

2:50 pm. Break

3:00 pm – 4:00 pm Chair: Samik Datta (NIWA)
3:00 pm. Feedback on the questions circulated ahead of the workshop from Australian collaborators and discussion.
The questions are listed below.

3:30 pm. Further discussions and workshop wrap-up

4:00 pm. Workshop ends

Questions discussed at the workshop

1. Considering the specific aims of our case study, which of the listed tools would you particularly recommend and why?
2. Are there any tools missing for our specific case study and why? What are the main pros and cons of those additional tools?
3. Among the tools we listed and potential additional tools, how long does it take to implement them and analyse their results (including or excluding potential training)?
4. In your experience, among the different tools, which ones have been successfully used to inform fisheries management/decision-making?
5. Would New Zealand's current fisheries management framework, data and/or funding hinder the operationalisation of these tools in New Zealand?