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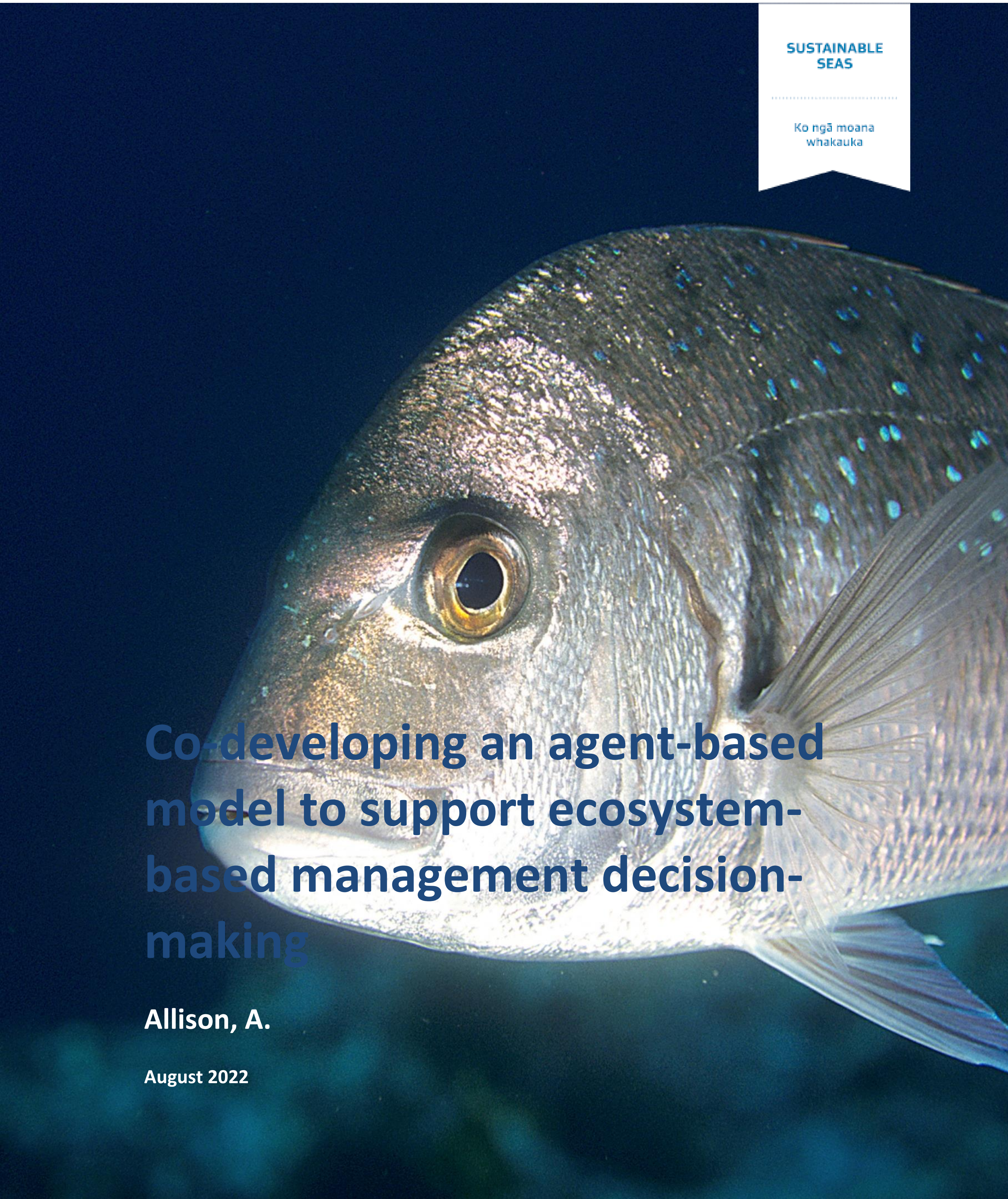

Co-developing an agent-based model to support ecosystem-based management decision-making

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Report for Sustainable Seas National Science Challenge project *Options for policy and legislative change to enable EBM across scales (Project code 4.2)*

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For more information on this project, visit: https://www.sustainableseaschallenge.co.nz/our-research/policy-and-legislation-for-ebm/

About the Sustainable Seas National Science Challenge

Our vision is for Aotearoa New Zealand to have healthy marine ecosystems that provide value for all New Zealanders. We have 60+ research projects that bring together around 250 scientists, social scientists, economists, and experts in mātauranga Māori and policy from across Aotearoa New Zealand. We are one of 11 National Science Challenges, funded by the Ministry of Business, Innovation & Employment.

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Background

The Sustainable Seas National Science Challenge (hereafter: Sustainable Seas) aims to improve the health of our seas and facilitate better decision-making through ecosystem-based management (EBM). This project is undertaken as part of the Sustainable Seas Program 4.2: Options for policy and legislative change to enable EBM across scales. The first case study of this project seeks to explore the use of a system diagram, multi-variate analysis and agent-based modelling (ABM) to understand multi-species complexes in fisheries, with a focus on Fisheries Management Area 7. This report focuses on the ABM component of the research, where a simple ABM was developed, seeking to achieve two objectives: 1) to explore the process of scoping and developing an ABM in/for a fisheries context, and 2) to demonstrate the potential utility of ABM to help inform EBM in fisheries.

The introduction provides an overview of ABM and a comparison of exploratory and predictive modelling. The methods section considers the process undertaken to develop the research question and the data sets used to populate the model. The model development and testing process is outlined, results are presented, followed by consideration of how the model – and modelling process – achieved the two objectives. Finally, conclusions and suggestions for future work are presented.

Introduction

ABM is a computational modelling approach for simulating the interactions between autonomous individuals and their impacts on the system. An agent is any autonomous entity that makes decisions (or appears to make decisions) for itself, such as people, fish, and management agencies. ABM is spatially explicit and temporally dynamic, meaning that agent actions can be analysed across space and over time. ABM is an appropriate modelling approach when seeking to understand individual-level interactions rather than aggregated ones, is well-established to help improve system understanding, and is often used in conjunction with participatory processes (in this case study a system diagram).

Models can be developed for many purposes. One categorisation of models divides them into exploratory and predictive models. Exploratory models are suitable to investigate interactions across subsystems (e.g., ecological, physical, social, economic, etc) and for developing system understanding and how it may respond to internal and external drivers (Kelly et al., 2013). Predictive models are useful for estimating the value of a specific variable at a certain time when other relevant variables are well-understood. Predictive models can be simple but need to be data-driven; if insufficient data is available, claims of prediction cannot be established. It is imperative that a model developer clearly states the reason for the modelling: whether the model is designed to be exploratory or predictive. Using models for purposes that they were not developed for – specifically using an exploratory model as a decision-making tool – can lead to poor decision-making based on inappropriate input data (Allison et al., 2018). Exploratory models can be used to guide decision-making, but not to make management decisions. Models can be used to explore the dynamics of marine ecosystems under different potential future scenarios when it is not possible to empirically test these scenarios at an appropriate spatial or temporal scale needed to inform science and management (Lundquist et al., 2022).

Much science revolves around understanding the patterns of a single variable (for example single stock assessment, species distribution modelling, biodiversity indices). Multi-variate analysis (MVA) is simply a set of methods used to understand the patterns displayed by many variables at once (e.g., species assemblages), measured in multiple samples. Data for each variable/sample is collated in tabular form (a matrix) with variables generally being rows and samples being columns. For example, a number of cities with their latitude and longitude. Each method is underpinned by a 'distance' measure that calculates how similar the samples are based on the variable entries. In the case of the cities, it is simply how far apart they are. Here we use data that was collected for an MVA to provide underlying information and assumptions for the ABM.

Focus question development

This section is comprised of section 11 of a recent Sustainable Seas publication on systems diagramming (Connolly, 2022), with minor alterations.

A series of four workshops was held in Nelson to develop explore the use of a system diagram, multi-variate analysis and ABM to understand multi-species complexes in fisheries, with a focus on FMA 7. During the first three workshops, the research team considered the discussions between the group and the interests of the group members, Fisheries New Zealand (FNZ) and Sustainable Seas. The research team teased out areas of focus and interest for all/most parties and generated questions that could be investigated using ABM and had the potential to inform or advance multi-species management. As ABM is spatially explicit and temporally dynamic (operates over a pre-defined spatial area and runs scenarios within that area over time), the focus question for the ABM needed to have spatial and temporal components. An iterative process was followed where the research team formulated, discussed and refined questions that could be tested using ABM.

In iteration one, four preliminary scenario questions were drafted after workshop 2, informed by the workshop discussions and systems mapping. These focussed on a) stock abundance variability, b) management options, c) managing stocks to a higher abundance, and d) market feedbacks to fisher behaviour. The project team discussed these and ruled out option d based on the absence of a spatial component.

In iteration two, four questions were drafted. Three focused on integrating stock assessment, inter-species interactions and TAC and investigating their impacts on the multi-species complex, a) considered volumetric changes, b) considered spatial changes and c) considered temporal changes. A fourth option, d), was based around market pressures and governance/regulatory influences on fisher behaviour, with flow on effects on fish stocks.

In iteration three, two questions were drafted. These two questions were presented to the group in workshop 4.

A. *How might a change in management arrangements (TAC / legal sizes / fishing seasons / area managed / deemed values) impact on the multi-species complex, fisher behaviour and/or commercial viability? And what if the change happens at different times within the abundance cycles of different species?*
B. *How might a spatial change in management arrangements (e.g. trawl corridor) impact on the multi-species complex?*

Question A focused on the immediate interests of FNZ, while B was of greater interest to the wider Sustainable Seas challenge. As this project aimed to assist FNZ in advancing multi-species management, the preferred option of the research team was A, with scope for feedback from the group on what changes in management arrangements they would like to consider, and whether they would like to investigate the impacts on the multi-species complex, fisher behaviour, or commercial viability. This was made clear to the group in workshop 4.

After further discussion in workshop 4, the group decided to focus on option A, with some refinements. There were several reasons for this:

- Option A was the more dynamic question; it is more likely to reveal unknown aspects of the system and uncover relationships within the multi-species complex.
- Option A was more flexible; workshop participants could choose one (or more) of the hypothetical management arrangements to test *as well as* the impacts on the multi-species complex and commercial viability (workshop discussion yesterday ruled out exploring fisher behaviour, as this would require gathering further information that has not been generated during the workshop series). Option B only gave the participants the choice of a single change in spatial management arrangements.
- Option A was more likely to demonstrate the strengths of ABM (improving system understanding, revealing emergent behaviour, exploring directions of system change, etc.) to FNZ than option B.

There remained the need to determine what hypothetical change in management arrangements the group wanted the model to focus on: TAC, TACC, legal sizes, area managed or deemed values. Fishing seasons was ruled out as this is not a management intervention; rather it is something that may occur because of a management intervention. While investigation of area managed or deemed values would have to occur in isolation, it would be possible to model changes in both TACC and legal sizes in one model.

As a result of the discussion during workshop four and in an email thread including the research team and all workshop invitees, the final question was determined over the following week:

"How might a change in TACC of one or two primary/dominant stock(s) impact on the multi-species complex and commercial viability?
And what if the change happens at different times within the abundance cycles of different species?"

The single primary/dominant stock chosen was snapper.

Model development and testing

The systems map was used to inform the structure of relationships between fish and habitat and between fishers and fish. Data collected for the multi-variate analysis was used to populate these relationships with quantitative data.

The model was developed using NetLogo 6.2.0, an open-source software freely available online and widely used to develop simple ABMs. A 'rule-based' code structure was used, with annotations added to provide a description to commands and procedures.

A prototype model was developed to encode the relationships:

- between different species
- between species and fishers
- between species and the environment, and
- between fishers and the environment

The final model (hereafter: FMA7 ABM) used the multi-variate data, an existing habitat map (Sustainable Seas, 2020), and other information provided by FNZ to populate these relationships. FMA7 ABM simulates Tasman and Golden Bays, which are part of FMA7 and the area of focus during the workshop series. It simulates an 80-year period, beginning January 2022, with a monthly timestep.

FMA7 ABM contains three submodels: biophysical, socio-economic, and closing boundaries. The biophysical submodel controls the month and year, and allows fish to move, feed, breed, interact and die. The socio-economic submodel controls the change in TACC that FMA7 ABM was developed to test, contains an economic return measure for fishers, changes species preference for fishers, measures seasonal catch for fishers, updates port price and ACE price, allows fishers to move and catch fish, and sets levels of non-commercial catch (customary, recreational, and other sources of fishing related mortality (OSFRM)). The closing boundaries submodel updates the visual interface of the model and moves the timestep by one month per tick (timestep).

A mixed-methods (quantitative and qualitative) testing regime was implemented for FMA7 ABM. Structured walkthroughs are a form of face validity, where models are evaluated based on their ability to simulate a system as stakeholders and users understand it. A successful structured walkthrough (Sargent, 2013) was undertaken by the developer to describe the function of each command and procedure in the model to an independent researcher.

A Monte Carlo approach was used, with 1000 iterations runs for each predictor variable setting. We qualitatively analysed whether a change in the predictor variable (change in TACC) generated a difference in the response variables (stock abundance and economic return of fishers) between the different scenarios. A predictor variable is something that a model user changes, to explore its impact on the system, while a response variable is something that changes during a model run, partly in response to a change in one or more predictor variables. The four changes in TACC tested were (Figure 1): one-off decrease of 25% in 2030, one-off increase of 25% in 2030, incremental decrease totalling 25% in 2045, with incremental decreases occurring in 2030, 2035, 2040 and 2045, and incremental increase totalling 25% in 2045, with incremental decreases occurring in 2030, 2035, 2040 and 2045. The null hypothesis (no change TACC) was also tested. These five scenarios are hereafter referred to as ‘one-off decrease’, ‘one-off increase’, ‘incremental decrease’, ‘incremental increase’, and ‘stable’. The timing of each of these changes at different times in the abundance cycle of the six species is covered in the Monte Carlo analysis. Within the 1000 iterations per predictor variable setting, a similar number of TACC changes occur at high, moderate and low abundance for each species.

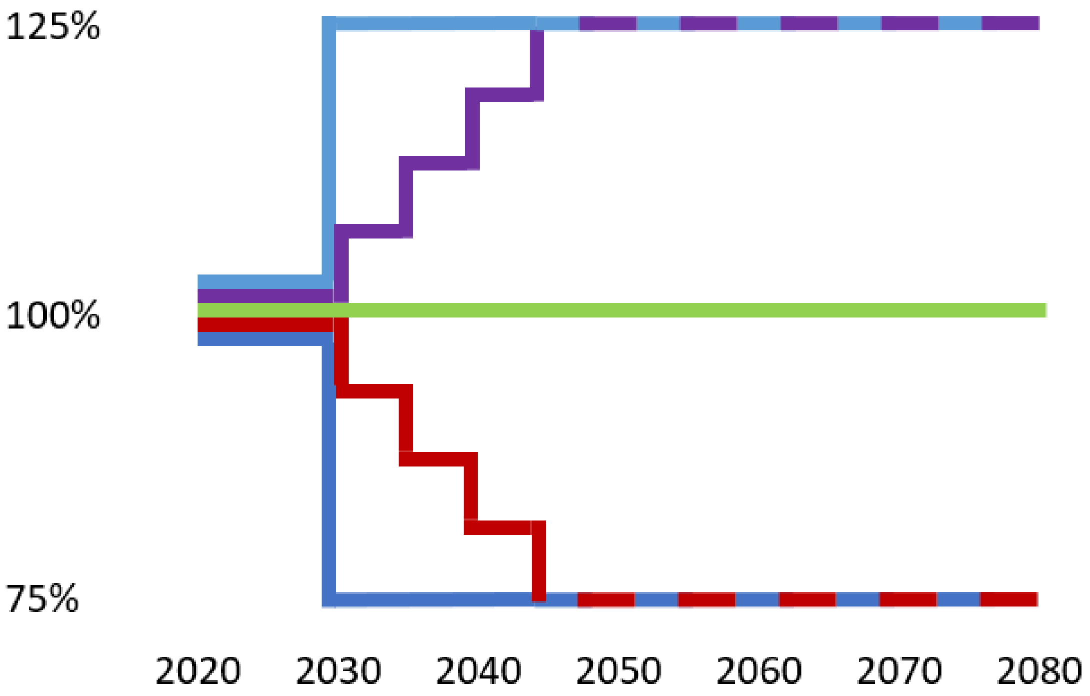

Figure 1. Visualisation of changes in TACC over time. Y axis shows change in TACC, X axis shows years that changes occur. Light blue (top) = one-off increase. Purple = incremental increase. Green = stable. Middle blue = one-off decrease. Red = incremental decrease.

Model assumptions

FMA7 ABM operates under the assumption that catch per unit effort (CPUE) is stable across the five scenarios. This is because current practice does not see reductions in TACC/ACE in times of higher abundance, and conversely, current practice does not see increases in TACC/ACE at times of lower abundance.

In the case of increased TACC for snapper, while fishers intend to catch their full increased quota of snapper, they do not intend to catch more of the five other species. If an increase in TACC for snapper meant that fishers cannot avoid catching the same relative amount of the other five species when fishing for snapper, then decisions as to whether TACC for snapper is increased would need to be made relative to the amount of quota each fisher has for the other species in the multi-species complex. This could be done in an ABM, but would involve understanding the distribution of fishers' quota arrangements within the area.

The variation in stock abundance between runs within the same scenario is driven by fish movement. There are rules that govern fish movement for each species at each stage of the lifecycle, but each fish chooses to move anywhere that accords to those rules. Thus, there is a constantly changing dynamic between fish and fishers that results in changes to fish stocks and fisher economic return in each model run. In some iterations, fishers are highly successful at catching fish and stocks are accordingly lower, while in other iterations fishers are less successful at catching fish and stocks are accordingly higher.

A procedure had to be included to allow fish of the six species to move into the Tasman/Golden Bays area, from other parts of FMA 7 and beyond, to prevent their species from being fished out during some simulations; this is a proxy for fish migration in and out of the real-world area simulated and may not actually occur (either at the level required or even at all) for some species. Because of this, it is important not to view the results as an indicator of the sustainability or otherwise of different TACC scenarios in Tasman and Golden Bays. Models cannot accurately predict the real spatial distribution of species in any scenario, but they can be used to improve understanding of social-ecological systems in the various scenarios (Lundquist et al., 2022).

FMA7 ABM is populated with current data on stock assessments, fisher behaviour and fish behaviour. The FMA7 fishery is very different to what it was 10-15 years ago, when flatfish were the main target species and others were largely viewed as bycatch. Subsequent environmental changes led to a large increase in snapper populations within the study area, showing that the fishery changes due to both internal interactions and externalities.

The number of fish in any scenario is unimportant as it is a proxy – the model does not simulate every fish in Tasman and Golden Bays; the relative number of fish in different scenarios is the important consideration.

Results

- Increases in TACC resulted in lower stock abundance across the multi-species complex
- Increases in TACC resulted in lower economic return for fishers
- Decreases in TACC resulted in higher stock abundance across the multi-species complex
- Decreases in TACC resulted in higher economic return for fishers
- In all scenarios mean stock abundance was higher in 2080 than in 2050

The Monte Carlo analysis suggested differences in stock abundance and economic return of fishers between the five scenarios tested, both in 2050 and 2080. By 2050, incremental and one-off decreases in TACC both led to marginally higher stock abundance across the multi-species complex (Figure 2A) and a greater percentage of fishers making profit (Figure 2B) when compared to a stable TACC[1]. Incremental and one-off increases in TACC both led to lower stock abundance in the multi-species complex (Figure 2A) and a smaller percentage of fishers making profit (Figure 2B) when compared to a stable TACC. While the differences were numerically small, they were statistically significant ($p < 0.05$). So, the model is suggesting a clear direction of change in both response variables caused by a change in TACC.

By 2080, Incremental and one-off decreases in TACC both led to marginally higher stock abundance in the multi-species complex (Figure 3A) and a greater percentage of fishers making profit (Figure 3B) when compared to a stable TACC. Incremental and one-off increases in TACC

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[1] Units have intentionally been excluded from all figures, to stress the exploratory nature of the model, and the importance of comparing figures between scenarios rather than considering numbers themselves.

both led to lower stock abundance in the multi-species complex (Figure 3A) and a smaller percentage of fishers making profit (Figure 3B) when compared to a stable TACC.

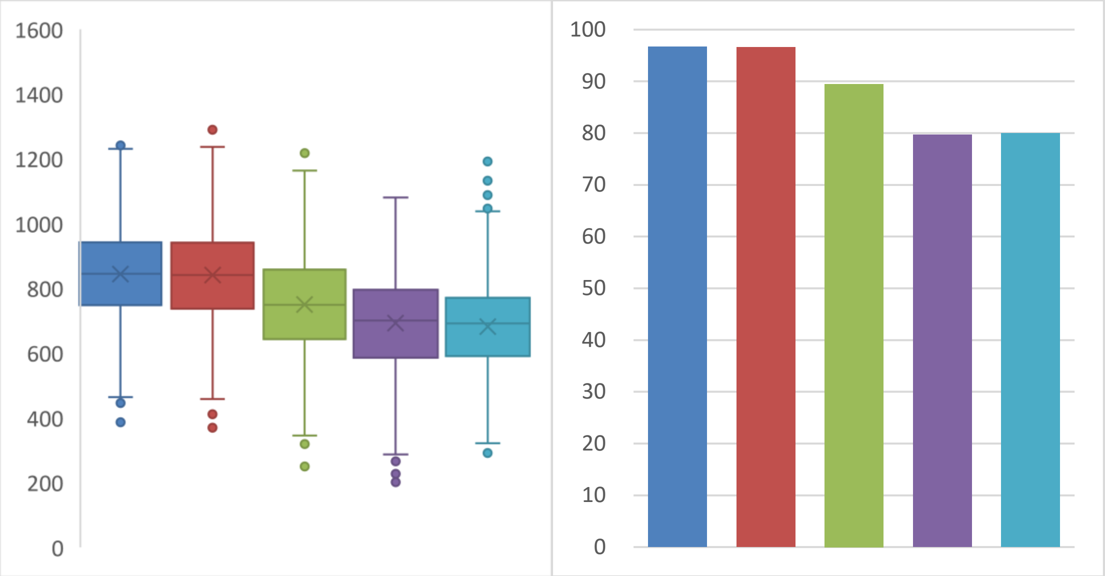

Figure 2. A. Aggregated stock abundance in multi-species complex in 2050, measured in number of fish. B. Percentage of fishers profitable in 2050. In this and figure 3, from left: One-off decrease, incremental decrease, stable, incremental increase, one-off increase. The values themselves are unimportant, as FMA7 ABM is an exploratory model: the important consideration is the relative values for the different scenarios.

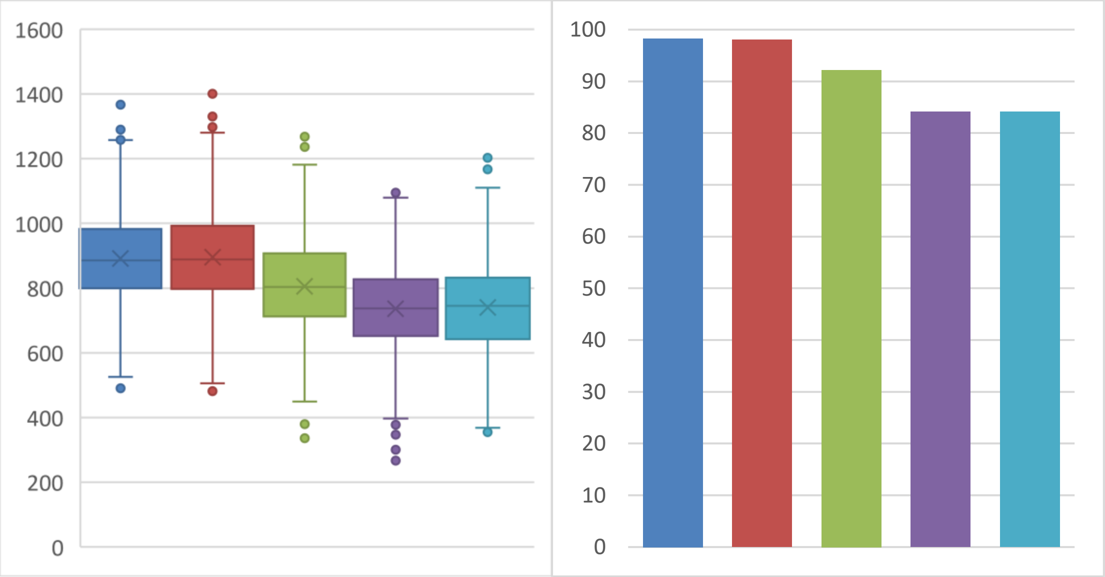

Figure 3. A. Aggregated stock abundance in multi-species complex in 2080, measured in number of fish. B. Percentage of fishers profitable in 2080.

In both 2050 and 2080, the boxplots highlight the high variation in stock abundance across all scenarios. This results from variation across model iterations in fish movement.

However, there is consistency in that the 50% of samples closest to the mean cluster together, while the outer quartiles are more widely distributed. This pattern holds across all TACC scenarios, including stable TACC, and demonstrates why a Monte Carlo approach is required; using a smaller sample could skew results in either direction, and so may fail to account for the potential outcomes within the simulated system.

Comparing the outputs for 2050 and 2080, there is a small increase in both stock abundance and economic return of fishers by 2080 in all scenarios. This is because the change in TACC is more temporally distant. Under decreases in TACC the stocks are more abundant in 2080 compared to 2050 as they have had longer to reach that stable high level. This allows economic return of fishers to be higher, as they are more likely to meet the performance metric when stocks are high. Under increases in TACC, the stocks are still more abundant in 2080 compared to 2050 as they have had longer to adjust to the higher level of catch. Accordingly, economic return of fishers is higher as it is driven by stock abundance.

The wide distributions of stock abundance in all scenarios, including stable TACC, suggest that this model is unable to discern the influence of changes in TACC happening at different times in the abundance cycle of the multi-species complex. The impacts of this change are hidden by the natural variability in stock abundance in the model, demonstrated by stable TACC having similar distributions to the other scenarios. This is not to suggest that the timing of a change in TACC in relation to stock abundance is unimportant; rather that this model, developed to be simple and proof-of-concept, is unable to discern the importance of timing of the change in TACC.

Model limitations

A fishery is a highly complex system, comprised of ecological, physical, social, cultural and economic components and their interactions. The model developed in this work is a simplistic interpretation of the fishery, reduced to a few components of interest to the workshop group and research team. While inclusion of more variables and more components *may* lead to more quantitatively sound outputs and interpretations, it may alternatively lead to an unwieldy model that is unable to explore dynamics within the system and only does what the code directs it to (Sun et al., 2016). Limited data lends itself to a limited model. To emphasise – FMA7 ABM is strictly exploratory and not able to be used as a decision-making tool; it can however, be used to inform decision-makers on knowledge gaps and interactions between social, economic and ecological components of what is a highly complex system.

As FMA7 ABM is exploratory, a more qualitative testing process was undertaken than if the model were for predictive or decision-making purposes – that would require additional quantitative approaches and more detailed data sets to ensure model results were appropriate to use in decision-making. More specifically, a statistical test would need to be undertaken using generalised linear models to determine whether a change in the predictor variable generated a statistically significant difference in the response variables between the different scenarios. However, that approach is inappropriate for an exploratory model, and would give undue confidence in the results that an exploratory model cannot provide. FMA7 ABM was not developed for predictive or forecasting uses, and model outputs are not suitable for use in decision-making other than to suggest further avenues of research.

While FMA7 ABM includes benthic characteristics, the information provided was that they are fairly uniform across the study area and thus have limited impact on system form and function. As fish behaviour at different stages in their lifecycle is influenced by their environment, including more detailed site-specific information, such as the location of spawning and aggregation areas may well influence model behaviour and outputs. This example highlights the influence of resolution in modelling. A finer spatial simulation or management scale would likely change fish distributions, with flow-on effects on fisher behaviours.

Discussion

The purpose of this ABM endeavour was two-fold: 1) to explore the process of scoping and developing an ABM in/for a fisheries context, and 2) to demonstrate the potential utility of ABM to help inform EBM in fisheries. The research question developed to achieve this contained elements of both EBM, and commercial realities.

Analysis of the process of scoping and developing an ABM in a fisheries complex is a subjective exercise. Feedback and questions asked in the workshop about the form and function of the model suggested an appreciation of the potential of ABM and a desire to use the method and model further. All participants highlighted that the model scoping and development process was enlightening and non-confrontational. Contributing to model focus, seeing the model in prototype form, providing feedback, and seeing the model in final form was very valuable and facilitated a greater understanding of the model than simply being presented with a final version. Observing the model running and having the ability to ask questions and provide feedback shows how an ABM can be used to improve stakeholder engagement in a fisheries context, and thus achieves objective 1.

Many examples of the potential utility of ABM to help inform EBM in fisheries, and answer objective 2, were uncovered during this research. For the sake of brevity, we present one example here.

The economic return measure we developed for fishers is: seasonal catch value minus the cost of ACE. This measure provides a simple metric for whether a fisher’s return is economically viable, as per the research question. However, the performance measure does not account for other costs fishers bear – fuel, maintenance, labour, etc. But those additional costs are not static. Expenditure on fuel and bait, for instance, varies not only according to fishing effort but can also be driven by external drivers. So, the current performance measure is sufficient for exploratory purposes, and not misleading. It simply assumes that all costs fluctuate based on fishing effort, which is broadly true: if TACC was changed in a relatively timely manner the operational costs per unit of catch should be relatively stable as they are largely driven by effort: more effort equals more cost. This is an example of the value of using simple metrics, or proxies, to analyse complex systems: not all elements of system form and function – in this case costs – must be simulated to explore the influence of a relative change in economic return on fisher commercial viability and on the multi-species complex. One caveat is that this metric does not account for rapid and significant changes to operational costs, such as a large jump in fuel prices that has occurred in the 2021-2022 financial year and has resulted in some fishers in the study area currently not going to sea due to economic factors.

The simple cost metric used (return: incomings minus outgoings) highlights the fisher-centric nature of the performance metric. It is an individual metric calculated for each fisher. Thus, it also raises a question: what influence would including the different ‘types’ of fishers (ACE fisher, owner operator, etc.) have on this metric? As different types of fishers have different types of costs, and generate income from different sources, how would including different types of fishers in the model highlight the impact of a change in TACC on commercial viability for each type of fisher, along with the multi-species complex? Whether each individual fisher remained commercially viable would be dependent on the types and levels of costs each fisher has, and the types and levels of income they derive from fishing.

These deliberations on the nature and impacts of the performance metric demonstrate the utility of exploratory agent-based modelling to raise questions about human-environment systems. These questions can be tested using a more complicated version of the same model, or other analytical methods and more extensive data sets. A small change to the rules governing agent attributes could lead to significantly greater insight into the impacts of a change in TACC on fisher behaviour, commercial viability, and the multi-species stock. Raising questions about the system and providing ways of answering these, through either ABM or other analytical or modelling approaches, achieves objective 2.

The spatial scale used in FMA7 ABM was found to reveal interesting dynamics within FMA 7. Tasman and Golden Bays are within FMA 7 but do not comprise the entirety of FMA 7 and some species and some fishers move in and out of the area simulated. As such, it was possible for a species in the model to be fished to 'extinction' in the model and a procedure was included to 'reseed' a species if its numbers got too low, a proxy for movement of species into the simulated area. In real terms, the size of FMA 7 benefits fishers that are not restricted in their ability to travel further distances, and the size of FMA 7 is only appropriate for species that are highly mobile. This example highlights the importance of scale in simulation, with implications for management. If fisheries management was to be based on data, estimates, or simulation of an inappropriate area, then suboptimal management would be the likely outcome.

Conclusions

Our research has demonstrated the value of scoping and developing an ABM in a fisheries context and has demonstrated the potential utility of ABM to help inform EBM in fisheries. In the process, we have identified several future areas for potential research.

First and foremost is data availability. While all science is based on the most relevant information, marine data is known to be difficult and expensive to obtain. While decisions must be made based on the information we have available now, we emphasise the importance of improving data collection, analysis and availability in the fisheries space. As the multi-variate data collection highlighted (Connolly, 2022), there was minimal information on location and timing of spawning aggregations, larval and juvenile durations, growth rates and habitat requirements, as well as predator-prey relationships and competition between species caught by fishers using the same gear type at the same time. All this missing data blunted the ability of the ABM to explore realistic changes in abundance and CPUE over time. This data can come through science agencies, management agencies and fishers and fisheries agencies/companies themselves.

Details around fisher behaviour and the performance metric could be further investigated, as covered in the discussion. How might including the different 'types' of fishers (ACE fisher, owner operator, etc.) in the model influence fisher performance?

FMA7 ABM is a simple model based on simple data sets and many assumptions about system form and function. Developing a model simulating human-environment interactions that could be used in decision-making would require use of better datasets, fewer (and more thoroughly articulated) assumptions, and a more comprehensive and nuanced depiction of fisher behaviour, fisher-fish interactions and intra-and-inter-species interactions to ensure that the system broadly represents stakeholder understanding of the system and how it operates.

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