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Food for Thought

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Increasing the uptake of multispecies models in fisheries management

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Multispecies models have existed in a fisheries context since at least the 1970s, but despite much exploration, advancement, and consideration of multispecies models, there remain limited examples of their operational use in fishery management. Given that species and fleet interactions

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are inherently multispecies problems and the push towards ecosystem-based fisheries management, the lack of more regular operational use is both surprising and compelling. We identify impediments hampering the regular operational use of multispecies models and provide recommendations to address those impediments. These recommendations are: (1) engage stakeholders and managers early and often; (2) improve messaging and communication about the various uses of multispecies models; (3) move forward with multispecies management under current authorities while exploring more inclusive governance structures and flexible decision-making frameworks for handling tradeoffs; (4) evaluate when a multispecies modelling approach may be more appropriate; (5) tailor the multispecies model to a clearly defined purpose; (6) develop interdisciplinary solutions to promoting multispecies model applications; (7) make guidelines available for multispecies model review and application; and (8) ensure code and models are well documented and reproducible. These recommendations draw from a global assemblage of subject matter experts who participated in a workshop entitled "Multispecies Modeling Applications in Fisheries Management".

Keywords: multispecies models, fisheries management, ecosystem-based fisheries management, stock assessment, trophic interactions.

Introduction

Traditional approaches to fisheries management primarily operate from a single-species perspective. However, species are part of the larger ecosystem such that changes in biomass across species—caused by biotic, abiotic, or management actions—could affect species interactions (Hunsicker *et al.*, 2011), fisher behaviour, fishing effort (Fulton *et al.*, 2011), and subsequently, sustainable harvest levels (Ulrich *et al.*, 2002, 2011; Thorpe *et al.*, 2017; Thorpe, 2019). It is becoming increasingly clear that single species approaches carried out without consideration of these fishery technical (e.g. more than one species being caught by a fishery, or different fleets catching differing proportions of various species) and biological interactions (e.g. competition, predator–prey interactions) are potentially problematic (Ulrich *et al.*, 2002; Vinther *et al.*, 2004). For example, ignoring predation in stock assessments has been shown to produce biased estimates of population parameters and lower predictive skill (Trijoulet *et al.*, 2020). This has led to a global push to move towards a broader, ecosystem-level approach that takes into account the biotic, abiotic, and management interactions among species and fisheries and the tradeoffs they may present (UNFAO, 2008; Lynch *et al.*, 2018; Townsend *et al.*, 2019). This ecosystem-level approach within a fisheries context has been termed ecosystem-based fisheries management (EBFM). EBFM is expected to lead to more holistic management by taking a systems-level approach (Ostrom, 2009) to focus on multiple fisheries and species within an ecosystem and enable analysis and consideration of tradeoffs among fisheries and/or species. Some form of EBFM is now an acknowledged goal within both international policy (UNFAO, 2003, 2008) and the policy or strategy of multiple countries/regions (e.g. United States, NOAA, 2016; Europe, EU, 2008, 2013; Australia, DAWR, 2018).

A variety of ecosystem models are available to support advice to meet the goals of EBFM, ranging from simple extensions of single species models that include some primary biological, environmental, or technical interactions (e.g. Hollowed *et al.*, 2000) to "end-to-end" models that encompass a full suite of complex biotic and abiotic interactions within an ecosystem (Butterworth and Plaganyi, 2004; Plaganyi, 2007; Fulton, 2010). Multispecies models fall within this range of ecosystem models (Figure 1) and aim to assess multiple stocks simultaneously, with some form of interaction between them, including both technical (e.g. mixed fleet/fisheries) and/or biological (e.g. trophic predator–prey and competition) considerations. Ideally, the interactions included in multispecies models should capture the major dynamics of the modelled stocks and be relevant to management decisions. For the purposes of this paper, we consider multispecies models ranging from extended single-species assessment models (ESAMs) on the simpler end to MICE, or "Models of Intermediate Complexity" (Plaganyi *et al.*, 2014), versions of more complex models [e.g. simplified versions of Ecopath with Ecosim (EwE); Christensen and Walters, 2004; Plaganyi, 2007; Townsend *et al.*, 2008; Chagaris *et al.*, 2020], but not the more complex whole-of-ecosystem models.

Multispecies models have several advantages over single species models for addressing multispecies problems, including potential improvements in estimation of natural mortality (e.g. Adams *et al.*, 2022), more accurate estimates of biological reference points and stock status determinations (Tyrrell *et al.*, 2011), the ability to address prey limitations on predator growth and fecundity (Tulloch *et al.*, 2019; Fitzpatrick *et al.*, 2022), the ability to address different gear effects and technical interactions (Garcia *et al.*, 2017), and the potential to explore tradeoffs across taxa and management scenarios (Gislason, 1999; Fulton *et al.*, 2019; Fitzpatrick *et al.*, 2022; Pérez-Rodríguez *et al.*, 2022). In fact, in some instances multispecies models can outperform single-species models, exhibiting greater predictive ability and less bias (Trijoulet *et al.*, 2019; Trijoulet *et al.*, 2020), and even when single-species models fit the data well, oftentimes their predictive performance is less than the multispecies approach (Trijoulet *et al.*, 2020).

Multispecies modelling has been used for fisheries management with some modicum of success; however, its use is often through informing or adjusting single-species stock assessments and not as a stand-alone assessment model that serves as the basis for management advice. For example, multispecies models are currently used operationally to provide improved estimates of natural mortality (*M*) that take into account changes in predation over time for single species stock assessments in multiple regions, including the Gulf of Alaska, Baltic Sea, North Sea, Barents Sea, and Iceland (Danielsson *et al.*, 1997; Dorn *et al.*, 2014; ICES, 2011, 2020a, b, 2021b; Pope *et al.*, 2021). They have also been used to adjust single-species management reference points to account for multispecies interactions and ecosystem understanding in the US Atlantic [focused on menhaden (*Brevoortia tyrannus*), SEDAR, 2020; Chagaris *et al.*, 2020; Anstead *et al.*, 2021; and Irish Sea, Bentley *et al.*, 2021; Howell *et al.*, 2021]. Multispecies models have been used to provide context and ecosystem indicators to inform single species advice in the Eastern Bering Sea [focused on walleye pollock (*Gadus chalcogrammus*), pacific cod (*Gadus microcephalus*), and arrowtooth flounder (*Atheresthes stomias*); Holsman *et al.*, 2020; Adams *et al.*, 2022]. These works suggest not only that multispecies modelling and management are feasible, but that they can provide improved advice and contribute towards the move to EBFM.

Despite this progress and the growing recognition by regional fisheries management organizations, the scientific community, and fisheries stakeholders that EBFM can lead to more effective fishery management

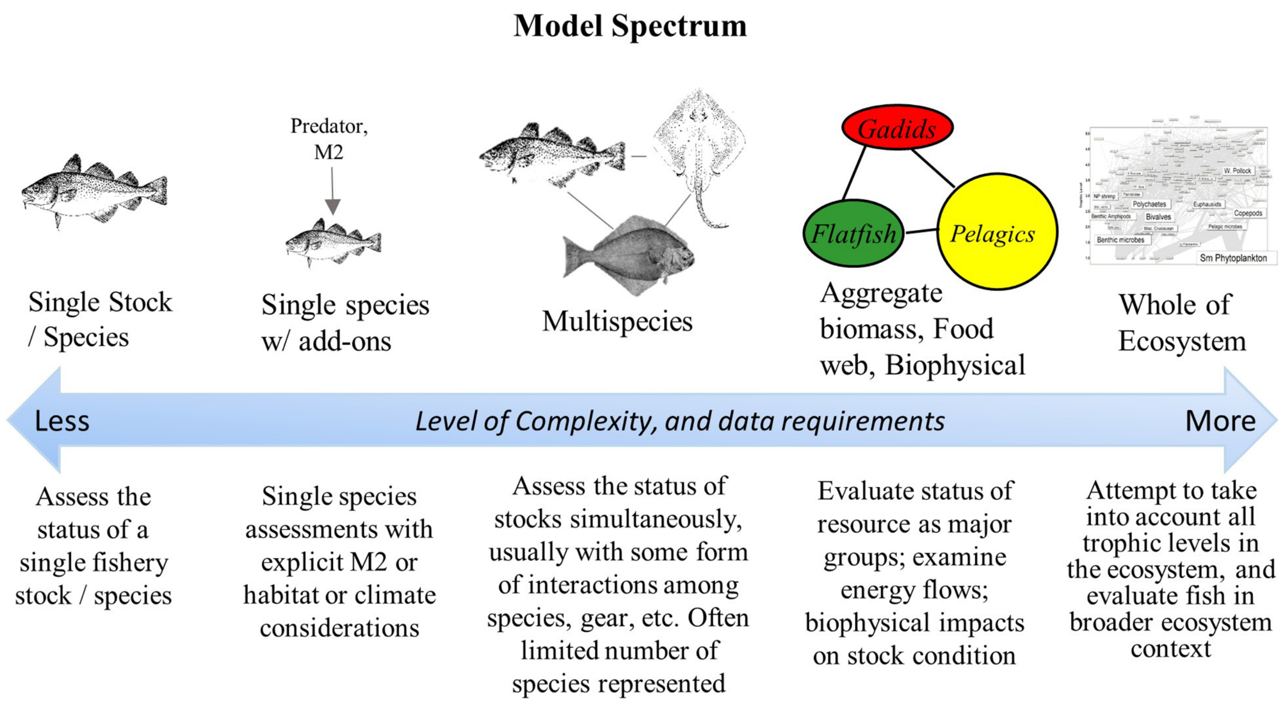

Figure 1. Continuum of models based on level of complexity and ecosystem information incorporated. Multispecies models fall in the middle between single-species and full end-to-end ecosystem models (modified from: Link, 2002, Figure 1).

by directly addressing interactions (e.g. Fulton *et al.*, 2019; Holsman *et al.*, 2020), single species assessments and management remain the norm, with rather limited use of multispecies models to inform management decisions. Issues that inhibit the uptake of multispecies models in routine and operational use in fisheries management include a lack of stakeholder engagement, unclear management objectives, data gaps and resource limitations, modelling issues (complexity, parameterization, validation, technical review), and social/institutional/governance constraints (e.g. lack of familiarity, discomfort with tradeoffs, value metrics for biological reference points and harvest control rules, management inertia).

Here, we provide recommendations to help address some common challenges with operationalizing multispecies models, with the aim of improving the uptake and effective operational use of multispecies models in fisheries management applications. By operational we mean routine and regularly accepted use in a fisheries management context, whether for short-term decisional advice (i.e. tactical; e.g. quota setting) or long-term, directional advice (i.e. strategic; e.g. bracketing a range of viable options), though in practice the discipline has tended to use operational synonymously with tactical. Our recommendations resulted from both presentations and conversations during breakout group discussions at a workshop convened in June 2021 by the NOAA National Marine Fisheries Service and the University of Massachusetts Dartmouth's School for Marine Science and Technology, entitled "*Multispecies Modeling Applications in Fisheries Management*". The workshop, held remotely due to COVID-19 considerations, brought together over 60 subject matter experts representing academic and government scientists and resource management staff from eight different countries around the world.

Factors hampering the move towards increasing operational multispecies model applications

We categorized the factors hampering the more operational use of multispecies models in management into two main categories: institutional and societal constraints and perceptions, and technical challenges.

The first category of impediments involves institutional and societal constraints that have limited the operational application of multispecies models (Murawski, 1991; Link, 2010; Fulton, 2021). Most fishery management systems co-evolved with single species assessment methods (Howell *et al.*, 2021), and as such, fishery managers have been conditioned to and are familiar with single species models and advice (Miller, 2010; Fulton, 2021), including their use for calculating reference points, determining stock status, and supporting definitions of optimum yield. Multispecies modelling products have not had as extensive a history of operational management use, leading to a lack of familiarity (even though many of their outputs are the same, albeit calculated differently), interest in, and understanding of multispecies models by managers and scientists. This lack of familiarity makes it difficult to incorporate multispecies models into the fishery management process. It can be challenging to engage with stakeholders and managers early in the operational modelling process if they are still primarily using a single species frame of reference and are not sure how multispecies models can be applied. Additionally, it is difficult to communicate the various capabilities, limitations, and uncertainties associated with multispecies models to stakeholders and managers.

Multispecies models naturally lead to consideration of tradeoffs between harvested species and protected predators such as marine mammals and seabirds. Thus, multispecies models offer the potential to serve as a bridge between management decisions related to fishing and bycatch, species recovery plans, protected species conservation, spatial management, and multi-sector ocean use decision-making (e.g. Robinson *et al.*, 2015; Garcia *et al.*, 2017; Tulloch *et al.*, 2019). However, fisheries management in most jurisdictions is not well suited to evaluate and make the inevitable trade-off decisions across species and fisheries sectors, which can pose a significant hurdle when the component species in a multispecies model are managed under different management plans or even different institutions. Additional challenges around making tradeoff decisions include the contentious nature of accounting for protected or non-targeted species interactions, the need to make explicit choices about the relative value of different ecosystem states, and the legal aspects of multispecies and multisector decision-making. Additionally, fisheries management in most jurisdictions is dominated by stock-by-stock, single-species perspectives, and a lack of explicit multispecies management objectives has been an impediment to multispecies thinking (e.g. Koehn *et al.*, 2017). While current management frameworks generally rely on clearly defined quantities for single species management [e.g. single stock total allowable catch (TAC), annual catch limits (ACL), maximum sustainable yield (MSY) in the USA, or maximum economic yield (MEY) in Australia], there is no single, commonly accepted approach for multispecies management quantities, though there have been demonstrations of how multispecies optimum yield can be defined (Moffitt *et al.*, 2016). The lack of accepted definitions for multispecies reference points poses a challenge for understanding and communicating the benefits and implications of using a model with biological or technical interactions. Management systems focused on individual species objectives can be more prone to viewing issues as problems to solve on a stock-by-stock basis rather than as issues that may be linked across stocks. These issues contribute to institutional and societal inertia and reluctance to consider multispecies approaches (Skern-Mauritzen *et al.*, 2016), which sets a high bar for change.

The second category of impediments is related to the technical challenges associated with multispecies models. The first technical impediment relates to the perceived complexity and lack of transparency with regard to uncertainty in multispecies models. Multispecies models are thought to be mathematically more complex, requiring more time for model development and parameter estimation than single species models (Spence *et al.*, 2021). With two or more species being represented, multispecies models generally have more state variables and parameters to estimate than the comparable single species model (Collie *et al.*, 2016). However, whether this remains true is unclear if one adds up multiple single species models, but the interaction terms are extra. With an increasing number of parameters comes a tradeoff between reducing model bias and increasing parameter uncertainty (Collie *et al.*, 2016; Marquez *et al.*, 2022, preprint: not peer reviewed), which can be complicated to communicate to stakeholders. This is especially true if the multispecies models do not address clearly defined management questions and goals. Additionally, while multispecies models generally outperform single species models when strong multispecies interactions are present (Trijoulet *et al.*, 2019, 2020), determining and demonstrating this improvement over the single species model, and thereby supporting the increased complexity, can be a challenging and time-consuming process; one that may not always be feasible given resource limitations (as described below). This is further exacerbated by the need for a special technical review process when the multispecies model covers species from multiple management jurisdictions and requires reviewers knowledgeable of multispecies models.

Building new multispecies models is also often constrained by limited resources, including data and technical expertise (both in terms of modelling capability and subject matter expertise). Multispecies modelling often requires data to inform understanding of processes governing species interactions (for multispecies models with biological interactions) or information to understand fleet activity and breakdown of catches by species for those fleets (for multispecies models with technical interactions). However, many ecosystems have substantial data gaps that affect the parameterization of multispecies models, particularly multispecies models with trophic interactions. Often, the diet data needed to fit multispecies models and understand the functional relationships between species are sparse or noisy, resulting in biased parameter estimation (Kinzey and Punt, 2009; Trijoulet *et al.*, 2019). When making operational decisions, sometimes the limited amount of trophic data has led to increased uncertainty. However, we note that there exist data-limited methods to robustly and accurately estimate diet and functional responses (Link, 2004; Moustahfid *et al.*, 2010; Hunsicker *et al.*, 2011; c.f. the NOAA national integrated toolbox, the Donut tool).

As with single species modelling, multispecies modelling efforts focus primarily on biological interactions, with relatively limited attention given to the human dimensions of social-ecological systems (Fulton *et al.*, 2011; Stephenson *et al.*, 2017). This is further evidenced by the limited social and economic expertise on both assessment and peer-review panels, which often means that the socio-economic consequences of trade-off and management decisions are not fully evaluated. The bias towards biological and ecological objectives and considerations in fisheries management can lead to dissatisfaction with and mistrust of management by stakeholders (Stephenson *et al.*, 2017). To more fully evaluate the impacts of a management decision and tradeoffs, managers need to consider the direct or indirect socioeconomic impacts of a range of alternative management decisions (Fulton *et al.*, 2011).

Key lessons and recommendations

Here, we discuss eight key recommendations for moving towards increasing the operational use of multispecies models in fisheries management (Table 1). Three recommendations are geared towards addressing institutional or societal constraints: (1) engage stakeholders and managers early and often; (2) improve messaging and communication about the various uses of multispecies models; and (3) move forward with multispecies management under current frameworks while exploring more flexible assessment and decision-making frameworks, especially for handling tradeoffs. We identified five recommendations to address the technical challenges: (4) evaluate when a multispecies modelling approach may be more appropriate; (5) tailor the multispecies model to a clearly defined purpose; (6) develop interdisciplinary solutions to promoting multispecies model applications; (7) make guidelines available for multispecies model review and application; and (8) ensure code and models are well documented and reproducible. While, as mentioned previously, multispecies models can incorporate technical interactions, biological interactions, or both, each with

Table 1. Recommendations, specific actions, and impediments addressed.

Recommendations	Specific details	Impediments addressed
Recommendations to address institutional and societal constraints		
(1) Engage stakeholders and managers early and often.	• Iterative scoping process with stakeholders. • Use of tools such as conceptual models and interactive web applications to increase collective understanding of the important interactions in the system.	• Lack of interest from managers and stakeholders. • Lack of familiarity and understanding by stakeholders. • Lack of clear management goals.
(2) Improve messaging and communication about the various uses of multispecies models.	• Evaluating tradeoffs. • Improve estimates of key parameters in single species assessments (e.g. natural mortality). • As operating model of a MSE. • Survey design/planning, mitigate bycatch, joint species distribution modelling.	• Lack of familiarity and understanding by stakeholders. • Lack of clear management goals. • Hard to determine or understand when MSMs are needed.
(3) Move forward with multispecies management under current frameworks, while exploring more flexible assessment and decision-making frameworks, especially for handling tradeoffs.	• Develop inclusive and participatory governance structures with procedural flexibilities and protocols on conducting tradeoff analysis. • Explore integrated, full fishery-system protocols so that tradeoffs are addressed in an equitable and transparent manner. • Expand assessment terms of references (TORs) to include consideration of predator–prey interactions or ecosystem trends.	• Management inertia/high bar for change.
Recommendations to address technical challenges		
(4) Evaluate when a multispecies modelling approach may be more appropriate.	• Strong, well-known trophic interactions (e.g. forage fish). • Clear evidence or understanding of habitat and environmental effects. • Multiple drivers causing a change in the ecosystem and the stocks of interest. • Ecosystems undergoing rapid changes in both predator and prey abundances. • Technical interactions and bycatch issues. • The single-species model does not have good fit to the indices of abundance from the survey. • Strong retrospective pattern indicating shifts in M or productivity.	• Hard to determine or understand when MSMs are needed.
(5) Tailor the multispecies model to a clearly defined purpose.	• Complexity within multispecies models should be tailored to the particular question(s) at hand. • Compare models using multi-model approach.	• Multispecies models can quickly become complex.
(6) Develop interdisciplinary solutions to promoting multispecies model applications.	• Form interdisciplinary teams, composed of members of the various disciplines involved (social, economics, oceanography, ecology, and stock assessment).	• Lack of interface to socioeconomics.

their own data needs, modelling challenges, and objectives, the recommendations provided here are generally applicable across multispecies model types. Additionally, several of these recommendations serve to generally improve model-based advice processes and are not exclusive to multispecies models.

Table 1. Continued

Recommendations	Specific details	Impediments addressed
(7) Develop and make guidelines available for multispecies model review and application.	• Develop a suite of model diagnostics, that includes those from both full ecosystem and single species models, but also those unique to multispecies models. • Conduct periodic informal reviews with stakeholders and peers to help guide model development.	• Lack of formal technical review process/models are hard to review.
(8) Ensure code and models are well documented and reproducible.	• Establish of clear protocols with standardized documentation requirements and formats. • Develop multispecies modelling toolboxes, with modularity to permit customization.	• Lack of formal technical review process/models are hard to review.

Recommendations to address institutional or societal constraints

Engage stakeholder and managers early and often

Increased interactions between stakeholders, scientists, and managers could help increase the development, understanding, familiarity, and uptake of multispecies models (e.g. Link *et al.*, 2010; Francis *et al.*, 2018; Townsend *et al.*, 2019; Bentley *et al.*, 2021). Lack of stakeholder and/or manager engagement can lead to objectives that are not clearly defined or linked to stakeholder needs and interests, which can make the implementation of the multispecies models an uphill battle. In the absence of clear, explicit management objectives, scientists often create substitute or interim objectives or make implicit assumptions without legitimacy.

To increase stakeholder engagement in the process, model development should proceed as part of an iterative manager/stakeholder engagement process. The process should begin with a scoping workshop before any modelling takes place (Townsend *et al.*, 2019; Chagaris *et al.*, 2019). This scoping process should have a focus on the research questions, objectives, or management challenges that the modelling exercise is seeking to address. Engagement should not end with objective setting and scoping but should continue throughout all remaining steps of the process, from model design and development to evaluation and review. Therefore, in addition to the initial scoping workshop, additional workshops could be held to discuss more operative/technical issues related to shaping and discussing the model and to share and discuss results. This iterative process will allow for multiple opportunities for scientists to engage with stakeholders/managers and convey to them the potential benefits and needs of multispecies models (see the next section for recommendations regarding communication of various uses of multispecies modelling). This will set stakeholders/managers up to be better able to provide useful input on objectives and help ensure models are aligned with stakeholder interests and that objectives are clearly defined. For example, the successful development of ecosystem reference points for the Atlantic menhaden to protect their role as prey for striped bass (*Marone saxatilis*) involved conducting an initial workshop with stakeholders and managers to develop concrete objectives (Anstead *et al.*, 2021), followed by regularly interacting with managers as progress was made on the tools that could address those concrete objectives. Through this interaction, managers were able to bring new hypotheses to the table and highlight those of greatest priority, which the modellers may not have recognized beforehand. A similar situation occurred with the development of an EwE model for the Irish Sea, where objectives were identified to address a specific problem by bringing together biologists, industry stakeholders, managers and policy advisors, social scientists, and stock assessment experts (Bentley *et al.*, 2021). The engagement process should seek to address the range of affected management entities and their differing objectives. Ultimately, the stakeholder/manager engagement process may conclude that a multispecies model is not the ideal solution to meet a particular objective; however, this iterative approach is still a useful exercise.

The development of tools that can support managers' and stakeholders' engagement and understanding of multispecies models and that highlight their value is critically important (e.g. Jollif *et al.*, 2009; Link *et al.*, 2010; Collie *et al.*, 2016). There is a wealth of available tools to draw from and use in such participatory, stakeholder-engaged modelling processes (Voinov *et al.*, 2018). The question then becomes how to select the most appropriate tool for the specific modelling activity. Conceptual models are a useful tool to use during the scoping process of multispecies modelling efforts to gather and visualize information from stakeholders on the most important relationships in an ecosystem and perceptions of the key stressors, and refine key management questions and objectives (Harvey *et al.*, 2016; Grüss *et al.*, 2017; Cochrane *et al.*, 2019; De Piper *et al.*, 2021). Grüss *et al.* (2017) elaborate further on how these models can serve as useful ways to capture local ecological knowledge and ensure that the multispecies model will capture the important ecosystem features of interest while encouraging increased stakeholder engagement and buy-in in the process. Additionally, interactive web applications can allow stakeholder/managers to visualize and interact with models, and in so doing increase their understanding and familiarity with their functions, strengths, weaknesses, and utility (Cartwright *et al.*, 2016; Grüss *et al.*, 2017). We recognize that the process outlined here may be resource intensive and may be an add-on to an already strained management system, so it's important to implement a process in accordance with available resources, and an initial investment may allow subsequent efforts within a particular system to be more streamlined.

Improve messaging and communication about the various uses of multispecies models in addition to setting tactical quotas

There is currently more reliance on single species models since these models provide (tactical) advice on a regular basis, and as such, managers have a general familiarity with the data needs, modelling approaches, and products of these efforts. However, fisheries management requires advice beyond solely quota setting, and some problems currently viewed as single-species problems are actually multi-species problems, and therefore multi-species models are better suited to address them. The challenge remains, however, that the fisheries science community has not yet fully conveyed to managers the full suite of roles and uses of multispecies models, despite their development over several decades. Showing how multispecies models can provide comprehensive information and help inform a broad range of management decisions is crucial to increasing the development and consideration of multispecies models by managers. This should be carried out through the early engagement with stakeholders and decision-makers described above. Here, we lay out various uses of multispecies models beyond setting tactical quotas.

It is impossible to fish all species simultaneously at their single species target biological reference points (e.g. MSY, MEY) when there are multispecies interactions, either through technical fishery interactions or biological interactions such as competition or predation (Ulrich *et al*., 2002, 2011; Thorpe *et al*., 2017; Thorpe, 2019). Therefore, multispecies management inherently involves the need to make tradeoffs. These tradeoffs include those between yield and risk or economic value (Pascoe *et al*., 2017), fishing sectors (Voss *et al*., 2014), and/or managed species and protected resources (e.g. Robinson *et al*., 2015; Tulloch *et al*., 2019). Multispecies models provide a means for explicitly evaluating tradeoffs that are not well defined in single species assessments and management. Multispecies models enable an evaluation of the risks (e.g. risk of collapse, biomass <5% unfished biomass) to bycatch species in the ecosystem under different combinations of fishing rates on target species (Thorpe *et al*., 2017; Thorpe, 2019). One way this can be done is through management strategy evaluations (MSE), where multispecies models can be used as the operating model (e.g. Grüss *et al*., 2016; Mackinson *et al*., 2018; Kaplan *et al*., 2021; Pérez-Rodríguez *et al*., 2022) and can provide a strategic evaluation of the long-term consequences of alternative management actions across a suite of species. However, we note that projections of multispecies models can be useful in revealing tradeoffs associated with particular policy choices or sets of expectations about reference points (e.g. stock size or goals for other species) on their own, without having to be connected to a feedback management control mechanism as done within an MSE. Additionally, some multispecies models can provide information that would result in more informed and realistic recovery efforts compared to single species models as they have a more realistic view of system constraints due to food limitations and other tradeoffs (e.g. Tulloch *et al*., 2019; Fitzpatrick *et al*., 2022).

Multispecies models can also be used to provide information and improve estimates of key parameters in single-species assessments. For example, some single species models might suffer from invalid assumptions regarding an estimate of a species' natural mortality (M; e.g. 0.2 for all ages and time steps; Pope *et al*., 2021; Plaganyi *et al*., 2022), and misspecification of natural mortality in stock assessment can impact model performance and fisheries management (Deroba and Schueller, 2013; Punt *et al*., 2021). Multispecies models can provide an improved estimate of time- and age-varying M that takes into account changes in predation over time to incorporate into the single species model (e.g. ICES, 2021a). In these cases, having a way to estimate M across multiple species within an ecosystem using a multispecies model, even if the multispecies model is not directly used as the assessment model, improves the assessments used in management in that ecosystem.

Multispecies models can also address a broader suite of fisheries management questions beyond those related to setting catch limits. Spatially explicit multispecies models, or joint species distribution models, (Thorson *et al*., 2016, 2019) can help inform multispecies survey design and planning (Zhang *et al*., 2020; Oyafuso *et al*., 2021), identify spatial mechanisms for why species are caught together ("technical interactions"; Dolder *et al*., 2018), mitigate bycatch (Smith *et al*., 2021), identify habitat utilization, and prioritize protections (Roberts *et al*., 2022), identify potential consumptive or indirect interactions (Thorson *et al*., 2019; Grüss *et al*., 2020), and identify species to aggregate into "species complexes" for management (Omori and Thorson, 2022). Another use of multispecies models is to understand long-term changes due to climate change, at least as a strategic context for management organizations (e.g. Woodworth-Jefcoats *et al*., 2019; Holsman *et al*., 2020; Reum *et al*., 2020). The increased understanding gained from such wide-ranging studies can inform decisions about which processes should be included in the quota-advice assessment models. More so, as EBFM progresses, it is recognized that more than just tactical quota-setting information will be needed.

Move forward with multispecies management under current frameworks, while exploring more flexible assessment and decision-making frameworks, especially for handling tradeoffs

Current fisheries management takes a primarily single species perspective in terms of management objectives, but it has the ability to evolve to consider broader ecological, economic, and social considerations as is necessary for multispecies management. Such an evolution will require governance structures that are inclusive and participatory, with procedural flexibilities and protocols for conducting tradeoff analysis. Governance structures need to: clarify the tradeoff decision-making process (who is involved, how decisions are made); emphasize adaptive, collaborative management; have the ability to integrate across sectors and jurisdictions; and provide opportunities to explore new approaches. Additionally, flexibility to move away from single-stock perspective definitions or thinking around MSY and optimal yield (OY) management objectives to consider broader, system-level objectives would be helpful. Such broader, more flexible definitions have begun to be explored by or have been proposed by several jurisdictions (Rindorf *et al*., 2017a, b; Link, 2018; Fulton *et al*., 2022). However, communities within governance structures may be reluctant to change before they understand and become familiar with the proposed changes (Link, 2018; Fulton, 2021), highlighting the importance of a participatory process with stakeholder engagement (c.f. recommendation 1). Therefore, it is unlikely that such a reshaping of thinking will occur quickly. Realizing this, near-term ways to include multispecies perspectives through current management channels are needed.

Management strategy evaluations provide an opportunity to move towards multispecies management and tradeoff decision making under current authorities and help pave the way for a transition to more operational multispecies management. In fact, it may be easier to adopt multispecies models in the management process where other multispecies or ecosystem models, or multispecies MSEs, already provide strategic advice. This is because multispecies thinking has been socialized with stakeholders, and a dedicated group of stakeholders and managers has already been identified and is familiar with the benefits and uses of multispecies models (e.g. Holsman *et al*., 2016; Adams *et al*., 2022 in the North Pacific). Therefore, the move towards more operational multispecies advice and tradeoff analysis should proceed through a careful, collaborative, and iterative approach, building off past examples where multispecies advice has been applied within the existing frameworks. There are already many examples from which to draw where multispecies information provides contextual or strategic advice to managers (e.g. Risk Tables, Ecosystem Status Reports, hypothesis testing, etc.; e.g. Plaganyi and Butterworth, 2012; Blamey *et al*., 2013; Robinson *et al*., 2015; Angelini *et al*., 2016; Tulloch *et al*., 2019; Dorn and Zador, 2020; Siddon, 2021; Harvey *et al*., 2022; Morrison *et al*., 2022; NEFSC, 2022), or for adjusting existing reference points and generating catch advice from single species models (Chagaris *et al*., 2020; Bentley *et al*., 2021; Howell et al., 2021).

Another recommendation is to ensure that stock assessment TORs include the need to consider predator–prey interactions, ecosystem trends (e.g. system productivity), and evaluate scenarios. Such expanded TORs could encourage the fisheries science and management process to address these broader issues, and can formalize the need for multispecies models and tradeoff analyses. For example, the Northeast Region Coordinating Council (NRCC) in the northeast US now includes as a TOR in all its research track stock assessments the explicit need to consider any relevant ecosystem and climate influences on the stock (https://www.fisheries.noaa.gov/resource/document/research-track-terms-reference). Additionally, some consideration of integrated, full-fishery-system protocols should begin to be explored so that tradeoffs are addressed in an equitable and transparent manner and so that stakeholders and decision-makers can begin to learn about the benefits that using multispecies models under such a full-system protocol/approach can provide.

Recommendations to address technical challenges

Evaluate when a multispecies modelling approach would be more appropriate

All models are simplifications of complex systems, but it is difficult to determine when multispecies or ecosystem models are preferred over single species models to help meet management objectives. Every case will need to be evaluated on its own, with stakeholders involved early in the process during objective setting. To help with this process, we have identified key characteristics of the ecosystem, the fishery being managed, and the current single species model used to provide management advice that point to when a need to consider multispecies or ecosystem models exists.

Characteristics of ecosystems that are *a priori* good candidates for multispecies models are those with strong, well-known trophic interactions (e.g. forage fish) or with clear evidence or understanding of habitat and environmental effects (e.g. productivity regime shifts). Other strong candidates include systems with multiple drivers causing a change in the ecosystem and the stocks of interest, ecosystems undergoing rapid changes in both predator and prey abundances, as well as ecosystems that are undergoing changes to their trophic structure (including as a result of range shifts) and the relationship between stocks. Fisheries with high-volume mixed fisheries (i.e. technical interactions and important bycatch), with clear and obvious overlap with or competition with protected species, or situations where there are bycatch issues, would also warrant consideration in multispecies models.

The output and performance of single species models can also indicate the need to explore multispecies models. For instance, multispecies models could be considered when the single species model is unable to satisfactorily explain data sources and trends; for example, when the model does not have a good fit to the abundance indices from the survey or when there is a strong retrospective pattern. Strong retrospective patterns can occur when processes such as natural mortality, growth, or selectivity vary over time and are misspecified in the model (Hurtado-Ferro *et al*., 2015; Richards and Jacobson, 2016; Szuwalski *et al*., 2018; Szuwalski 2022). The presence of retrospective patterns thus suggests that when stationarity assumptions are made in single species models, they may not be adequate for explaining some aspects of the underlying population dynamics. In this case, multispecies models may be able to disentangle and more correctly attribute the confounding sources of *M* and better capture the dynamics of the system (Blamey *et al*., 2013; Plaganyi *et al*., 2022). Another indication that multispecies models should be considered is when single species models indicate that the estimate of fishing mortality (*F*) is much lower than that of *M*. In this condition, a multispecies model (and environmental effects) may better capture factors that cause changes to the stocks of interest, such as when the age structure has been truncated to the point that it responds more closely to environmental variation (Anderson *et al*., 2008).

Tailor the multispecies model to a deliberate and clearly defined purpose

To ensure multispecies models don't become overly complex and therefore difficult to implement and communicate to stakeholders, they need to be tailored to address defined management goals and objectives, ideally developed through a stakeholder/manager engagement process (c.f. recommendation 1), and provide actionable advice for managers to consider.

While this is important for all modelling activities and has been recommended for broader ecosystem models (Lehuta *et al*., 2016; Grüss *et al*., 2017), we recommend it here as a means to avoid two common multispecies modelling missteps. First, there is a tendency to extend multispecies models beyond their scope, increasing the chance of asking the multispecies model to answer questions it was not designed to address. An example is the distinction between modelling aimed at understanding trophic interactions compared to models addressing sustainable yields in mixed-species fisheries, where the focus and scope of the modelling are likely to be different. We recommend avoiding this trap of unnecessarily increasing model scope and complexity during management applications. Second, some researchers have come across as presenting a multispecies model as a model in search of a purpose, which is not desirable. Applying and presenting models within a management forum that do not have a clearly defined purpose may impede uptake because the benefits of the modelling approach have not been demonstrated. Co-developing models with end users and managers can help ensure appropriate targeting of the relevant question/problem as well as increase acceptance once the model is completed (c.f. recommendation number 1; Meadow *et al.*, 2015). Similarly, collaboration among practitioners should occur when, for example, one analyst is developing a single species model and another a multispecies model. Seeking alignment on purpose and a general understanding of each other's methods and assumptions will reduce confusion in the process and help arrive at advice that best meets objectives.

To aid modellers in tailoring the complexity within multispecies models to the particular question(s) at hand (Plaganyi *et al.*, 2014; Collie *et al.*, 2016), modellers should ask, "What level of complexity is necessary for the (predetermined) task"? Comparing models with different levels of complexity through a multi-model approach (e.g. Collie *et al.*, 2016; Drew *et al.*, 2021) can help to identify a balance between simplicity and complexity and allow modellers to explore the effects of model structure and assumptions on modelled outcomes. Such an approach already occurs within the range of potential complexity to include in single species models, with many species being assessed only through very data-limited simple models. Multi-species models can be viewed as simply an extension of the range of complexity. One method for matching complexity to needs is a rapid prototyping approach (Garrand *et al.*, 2017), whereby models are built iteratively with stakeholders and decision-makers through the full application of example analyses, thus helping judge when enough realism is considered.

Given that, there remains an important caveat to advancing the implementation of multispecies models. Though models need to be *applied* to a particular situation, we also do not want to increase inefficiencies in model *development*. Hence, standard and common model packages are and should be developed and made available to the community modularly, but their specific application to a particular fisheries challenge should be designed and built for that express purpose. Thus, there is a middle ground between developing or substantially altering a model for each particular scenario versus using a model that was designed for another use and applying or adapting it to a different situation (see below for further details on model toolboxes).

Develop interdisciplinary solutions to promote multispecies model applications

There is an increasing recognition that biological and ecological interactions are not the only interactions within marine ecosystems that impact fisheries management. Other dimensions include human dimensions (e.g, socioeconomics, fisher behaviour, fleet dynamics), and oceanography. For instance, fishers may change behaviour (e.g. effort allocation) in response to a policy change in another fishery (e.g. Reimer *et al.*, 2017). However, though this awareness of the need to incorporate these other dimensions into EBFM has been long recognized, the capability to address it via modelling has only recently emerged (Curtin and Prellezo, 2010; van Putten *et al.*, 2018) and is therefore a less developed part of EBFM and multispecies modelling.

As multispecies models often deal with trade-offs explicitly, further connections with human dimension disciplines would be beneficial to evaluating such trade-offs. Additionally, as discussed in recommendation two above, multispecies models can be used to answer broader ecosystem context questions and understand the impacts of changing climate on the ecosystem. Therefore, to more fully address the complex interactions present in socio-ecological systems, interdisciplinary teams, composed of members of the various disciplines involved (social, economics, oceanography, ecology, stock assessment) need to be developed (Higgins and Smith, 2022). This will require increased prioritization to build up staff with social science and climate/oceanographic modelling expertise and the inclusion of these experts on assessment teams and review panels. However, we note that not all multispecies modelling activities will require such broad teams with a full suite of disciplinary expertise. The suite of experts necessary to include on a team will depend on the specific questions or objectives and the modelling approach being used. For example, running an MSVPA may simply require someone with knowledge of diet and assessment data and not socioeconomics.

Having a more integrated approach may result in better success in meeting objectives, fewer unintended consequences, better appreciation and support of management, and increased management credibility (Stephenson *et al.*, 2017). However, it is important to recognize that the creation of teams composed of experts from multiple disciplines (e.g. multidisciplinary), while an excellent first step, does not necessarily lead immediately to interdisciplinarity. Interdisciplinary teams go beyond simply bringing researchers from various disciplines together to draw from and integrate knowledge across these disciplines to work towards a common goal (Starfield and Jarre, 2011). There can be challenges in connecting across disciplines, especially if the relationships are newly developed (Higgins and Smith, 2022). For instance, the types of data, models, and even language used to talk about the issues can differ between disciplines, hindering effective communication and integration. Early communication and collaboration amongst team members can help to build the relationship and mutual understanding of the problem at hand, which can increase the success of the team.

Develop and make guidelines available for multispecies model review and application

Multispecies models differ from single-species models in some key aspects that ultimately necessitate the development of a formal and technical review process tailored to multispecies modelling. By including guidance on appropriate data, model development, documentation, and performance evaluation criteria, the review process will help to build familiarity and establish acceptable use of multispecies models. In many ways, multispecies models are intermediary between single species stock assessments and full ecosystem models, and therefore can pull from some general best practices for reviewing both. These include issues with the data used to support the model (spatiotemporal coverage, sampling intensity, assumptions made when including the data in the model), the ability of the model to provide accurate estimates from data simulated from known parameters, and the ability of the model to correctly predict observations not used in model fitting. The ICES Working Group on Multispecies Assessment

Methods (WGSAM) has developed review criteria for "model key-runs" that can be used as a starting point for the questions that could be asked of a model when it is presented for review and evaluation to help diagnose performance (ICES, 2021b).

Comparisons between single and multispecies models can help elucidate why the advice may be different (Gislason, 1999). These comparisons could be done in simulation experiments rather than as part of the tactical advice process, with results being available to reviewers/stakeholders (e.g. Kaplan and Marshall, 2016). There is also value in simulation testing of multispecies models, particularly to evaluate various metrics of model skill. For example, Trijoulet *et al.* (2020) explored how model skills, such as model estimation and predictive abilities, improved when including predation.

Finally, a suite of model diagnostics that includes those from both full ecosystem and single species models as well as those unique to multispecies models is needed (Steffansson, 2003). There are a wide array of model skill measures that can and should be used to evaluate model performance (e.g. Townsend *et al.*, 2008; Link *et al.*, 2010; Olsen *et al.*, 2016). Many of these are standard statistical evaluations that particularly explore the information content and value-added among multiple parameters, species, and outputs. It is one thing to note changes to *M* or *F* for one taxa, but doing so for multiple taxa invokes the need for a broader evaluation of the full suite of parameters and outputs. Yet because these are still focused on populations, it constrains the need to evaluate a fuller suite of parameters and output sets one would need to examine in an end-to-end model. Additionally, evaluation of forecast skill is particularly germane in this context, and methods exist to ascertain the value-added of multispecies models (and again, demonstrate that multispecies models can improve model skill and performance; e.g. Trijoulet *et al.*, 2020). These diagnostics will also help with model review.

In addition to the formal review process for multispecies models, we also recommend that periodic informal reviews with stakeholders and peers be carried out to help guide model development. These periodic reviews can serve to identify issues early on and decrease the chances of models being rejected during the formal review process at the end (Townsend *et al.*, 2019). This approach proved quite successful in the development of the EwE models for the Irish Sea (Bentley *et al.*, 2021).

Ensure code and model are well documented and reproducible

Considering the complexity and time involved in developing multispecies models, it is crucial to maintain multispecies models and code bases in a manner that makes them both accessible, reproducible, and easily understandable/reviewable by others. This can be accomplished through the establishment of clear protocols with standardized documentation requirements and formats, especially when models are to be used for management advice, a recommendation also emphasized by several other authors (e.g. Townsend *et al.*, 2008; Schmolke *et al.*, 2010; Lehuta *et al.*, 2016; Planque *et al.*, 2020). If every model treats this differently, it is difficult for reviewers and decision-makers to digest. A standardized set of information for reporting will ease uptake into decision making. A standardized workflow will also decrease development time. As part of the reporting, modellers should document why and what was done (and how), as well as provide necessary information to ensure that others can understand the model parameterization (i.e. parameter reporting, derived model quantities, and evaluation of model fit) and use the model to answer appropriate questions. Modellers should also make use of "best practice" guidelines where these exist (e.g. Heymans *et al.*, 2016 for EwE). Documenting decisions for non-technical aspects is as important as the technical details to make sure the model is well constructed and properly used.

The development of multispecies modelling toolboxes is suggested as a means to improve documentation and reproducibility, and hence ease of review. These toolboxes can serve to provide access to model vignettes, diagnostic guidelines, review guidelines, decision trees for model building, application, and selection, and best practices for communicating results. A multispecies modelling toolbox could involve building off of existing code repositories and toolboxes [e.g. ICES Transparent Assessment Framework (TAF), NOAA's Fisheries Integrated Toolbox, Australian Stock Assessment Toolbox] to include diagnostic tools and standardized tools to check performance [e.g. (r4ss) package; Taylor *et al.*, 2021] specific to multispecies modelling applications. Alternatively, a toolbox could take the form of developing a community of practice (and support for interaction thereof) where analysts and managers can reach out and ask questions and share work. Either way, the ultimate goals of any toolbox are to increase efficiency and provide access to updated versions and maintained tools. For example, models in a toolbox could undergo periodic "Methods Reviews", where tools are pre-reviewed and vetted by panels of managers and scientists. This could help ensure that reviews of the operational uses of these models can focus on the specifics of each application and hence occur more efficiently. At the most basic level, a "toolbox" could be a living documentation of current multispecies models (e.g. an updated, living version of Plagányi, 2007). With any toolbox, training people to use the elements of the toolbox and tools therein will be essential.

While centralizing model development is generally supported, we note some potential drawbacks to such an approach. On the one hand, standardized components help reduce the burden of review (of both models and implementations) and help develop a community of practice. However, there is also danger in providing generic/standard tools given the emphasis on these models being built for a purpose or based on data availability (as noted above; e.g. a region without surveys may be more data limited and require different approaches). Therefore, we suggest that a modular suite of tools be developed to be flexible enough to be customized. Doing so would require a more structured, integrative approach than providing links to examples or existing software repositories. An example of such a framework is the FishPath tool (Dowling *et al.*, 2016; Dichmont *et al.*, 2021), where given the specific data, management objectives, and ecological interactions of a system, the tool provides some potentially useful models that may be worth looking at for that specific case, with pros and cons for each approach provided. Another useful approach would be to develop a library of functions that do different things related to multispecies modelling that could enable modellers to pull complex models together without starting from scratch (e.g. plug and play).

Conclusions

Traditional fisheries management approaches are limited in their ability to account for multispecies and ecosystem interactions. As a result, they may not capture changes or uncertainty caused by the broader ecosystem and will face challenges in tackling the complex tradeoffs that occur in fisheries and ecosystems. For example, the single-species catch limits set under traditional fisheries management do not incorporate interspecies interactions and may miss changes to these interactions that occur across time and space. As a result, these catch limits may fail to meet their objectives related to sustainability, optimizing yield, and economic value. Providing advice in systems with strong ecological and/or technical interactions is a multispecies problem; when addressed with multispecies models, more information can be brought to the table. Incorporating multispecies information is especially important when considering forage fish, top predators, and bycatch species. Multispecies models can aid in achieving diverse ecosystem management objectives while better informing the management of individual fisheries.

It is clear that there has been progress on multispecies models and that the lessons learned over the past few decades have advanced their application and uptake.

The eight recommendations presented in this paper (Table 1) represent the collective perspectives of a group of international subject matter experts in ecosystem modelling, stock assessment modelling, and multispecies modelling as a path forward to enhance multispecies modelling applications and uptake in decision making. We recognize that even if all the recommendations presented here are followed, some challenges to EBFM and multispecies modelling may remain, such as data and capacity limitations, and efforts should be made to address those issues. Additionally, in some situations, the cost of executing multispecies approaches may not be worth it, or the overall benefits are limited relative to improvements in model skill and performance. Therefore, as multispecies modelling continues to progress, careful evaluation of costs versus benefits should be undertaken to ensure the approach is appropriately used in situations likely to see its benefits.

There is currently a robust field of research and strong interest among the scientific community in the continued development of multispecies models, and there is a steady and growing suite of multispecies models being used for a range of living marine resource management applications globally (Marquez *et al*., 2022, preprint: not peer reviewed). There is also a growing recognition that multispecies models are uniquely positioned to address management questions that traditional, single-stock-oriented living marine resource approaches cannot, i.e. to address some of the necessary tradeoff issues. The recommendations presented in this paper are intended to provide useful guidance on a path forward to increase the effective application of multispecies modelling in fisheries management.

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The authors have no conflict of interest to declare.

Author contributions statement

MAK, JSL, MG, GF, SC, PL, HT, and RDM designed and facilitated the workshop and conceived of the initial idea for the manuscript. All authors participated in the workshop and in the development and discussion of key arguments presented in the manuscript. MAK led the writing of the manuscript, and all authors contributed to writing and editing the manuscript and approved the final draft.

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