Workshop report: Multispecies Modeling Applications in Fisheries Management

Hosted virtually by NOAA Fisheries and UMASS-SMAST | June 22-24, 2021

Melissa A. Karp, Max Grezlik, Jason Link, Steve Cadrin, Gavin Fay, Patrick Lynch, Howard Townsend, and Rick Methot (editors)

U.S. Department of Commerce
National Oceanic and Atmospheric Administration
National Marine Fisheries Service

NOAA Technical Memorandum NMFS-F/SPO-223
November 2021

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NOAA Technical Memorandum NMFS-F/SPO-223
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U.S. Department of Commerce
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National Oceanic and Atmospheric Administration
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National Marine Fisheries Service
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Recommended citation:

Karp, Melissa A., Max Grezlik, Jason Link, Steve Cadrin, Gavin Fay, Patrick Lynch, Howard Townsend, and Richard Methot (eds.). 2021. Workshop report: Multispecies Modeling Applications in Fisheries Management. NOAA Tech. Memo. NMFS-F/SPO-223, 56 p.

This report is available online at:
http://spo.nmfs.noaa.gov/tech-memos

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EXECUTIVE SUMMARY

It has been recognized for some time now that species interact within the marine environment, both biologically through trophic interactions and competition, and technically through bycatch or mixed fisheries. There has been copious exploration and consideration of multispecies models, which explicitly represent some or all of these interactions, in a fisheries context over the last 40 or more years. However, despite the years of interest in these models and management, and the widely acknowledged need to take into account multispecies interactions, the application for tactical management is quite limited. This led us to ask: why are multispecies models not used more frequently in a tactical fisheries context, and what can we do/should we do to move these models forward? We thus convened a virtual workshop from June 22-24, 2021 as a first step towards addressing that question and identifying tangible steps to move multispecies model use in management forward.

The workshop was organized around six questions: (1) What is the state of the science regarding multispecies models?, (2) What are the factors that impede or present a challenge for and factors that facilitate the uptake of multispecies model for use in operational/tactical management advice?, (3) How can we identify where multispecies advice would be better than single species?, (4) What are "best" practices for multispecies model development, (5) How can a fisheries management system better use results from multispecies models in their decision making?, and (6) Are there any changes needed to the management system for increased multispecies model uptake? Prior to the workshop, participants responded to a pre-workshop survey and viewed six pre-recorded Keynote presentations related to each topic question. During the workshop, participants broke into breakout groups to discuss each topic question. This report provides summaries of these discussions and the major recommendations coming out of those discussions.

There were many recommendations that arose from the discussions. To synthesize these, the major recommendations include:

- Develop guidelines/decision trees to help determine when single species models might not be sufficient and multispecies model would be preferable
- Multispecies models should be applied/tailored/built for purpose
- Include managers and other stakeholders in process from the beginning
- Formalize guidelines for multispecies model review and use
- Multispecies models can be used within existing frameworks, however, a new, more flexible framework may improve use, especially with regard to handling tradeoffs

In conclusion, there were some key points and observations that emerged from the workshop. These include:

- Case studies demonstrate clear benefits to multispecies models
- There are challenges to implementing multispecies models, but they can mostly be overcome
- Reproducibility of model is an important criterion for determining best scientific information available for fishery management, leading to recognition of the value of a Toolbox
- There are many dimensions of socio-ecological complexity, but all of them cannot be represented in operational models, so the most important complexities need to be identified
- Communication with stakeholders and managers is key (initial, regular, frequent, effective)

- There are more uses of multispecies models than just tactical BRPs/quota setting
- Legally there are no issues to doing multispecies models, but governance and authorities to deal with tradeoffs (crossing lines within MSA, ESA, MMPA) remain a coordination challenge

LIST OF ACRONYMS AND TERMS

ACL	Allowable Catch Limits
BRP	Biological Reference Point
EBFM	Ecosystem-based fisheries management
ESA	Endangered Species Act
EwE	Ecopath with ecosim
F	Fishing mortality
HCR	Harvest control rule
ICES	International Council for the Exploration of the Seas
LMR	Living Marine Resources
M	Natural mortality
MICE	Models of intermediate complexity
MMPA	Marine Mammal Protection Act
MSA	Magnuson Stevens Act
MSE	Management strategy evaluation
MSY	Maximum Sustainable Yield
PICES	North Pacific Marine Science Organization
TAC	Total Allowable Catch
TOR	Terms of Reference

I. INTRODUCTION

Multispecies models[1] have been explored in a fisheries context since at least the 1970s. The background of multispecies models in general ecology goes back another 70 years. There have been major points of emphasis of these multispecies models in a fisheries context. Notably the 1981 and 1991 year of the stomach in the North Sea to support these models, a major multispecies model symposium in 1991, periodic reviews seemingly every half-decade or so (Whipple et al., 2000; Hollowed et al., 2001; Plagányi, 2007; Fulton and Link, 2014; FMS, 2021), major working groups (esp. ICES WGSAM[2], WGECO[3]) and applications in the International Council for the Exploration of the Seas (ICES) and North Pacific Marine Science Organization (PICES) context, major computing advances (c.f. Megrey and Moksness, 2009), exploration in a bioeconomic and portfolio context (Edwards et al., 2004; Sanchirico et al., 2006), major model advancements (in terms of modeling, model types, fitting criteria, and model validation; and to be clear, this is not including fuller end-to-end or food web models), major steps in US national considerations of multispecies models (NEMoW 2-5), cross-NOAA explorations (joint OAR-NMFS meeting, Unified Modeling Committee), and so on. In short, there has been copious exploration and consideration of multispecies models in a fisheries context. In principle, there is no credible reason that multispecies models couldn't routinely provide direct fishery management advice.

Yet apart from a few limited instances in the Baltic Sea, North Sea, Barents Sea, Iceland, and Atlantic (U.S.) states (focused on menhaden), multispecies models are not used tactically (e.g., as the lead assessment model used to provide advice for status determinations, establishing control rules, and ultimately catch quota advice; as compared to strategically in a management strategy evaluation context to explore a range of options or as a research simulation tool). Perhaps one could argue that a couple others in the Northeast U.S., Bering Sea, Southeast Australia, Northeast Australia, Antarctica, and South Africa have been used to support management strategy evaluations to inform living marine resource management decisions. And admittedly there has been notable progress made even in the past 1-2 years (FMS, 2021). But again, the actual application is quite limited relative to the number of stocks that are assessed globally. Given the amount of attention on multispecies models, and the widely acknowledged need to take into account multispecies interactions, it is both surprising and compelling that they are not used much more than they are in an operational sense. A clear examination of the rationale why this is, and identifying both impediments to and conditions of success for actually implementing such multispecies models operationally, is warranted.

From first principles, one can come up with a quick list of reasons why multispecies models may be beneficial (e.g., better estimates of natural mortality and thus more accurate estimates of biological reference points, possible efficiencies by modeling multiple taxa simultaneously, the potential to address predator limitation, the ability to address different gear effects and technical interactions, the potential to explore tradeoffs across taxa, more accurate estimates of biological reference point (BRP)s and related

[1] A mathematical model with more than one species (but not fully end-to-end) that captures some (but not necessarily all) of the inter-connectivities across and between taxa that represent major dynamics of the modeled species, and that are constructed to inform assessments of living marine resources. Here we consider both biological (e.g. trophic) and technical (e.g. mixed fisheries, bycatch) interactions.
[2] Working Group on Multispecies Assessment Methods
[3] Working Group on Ecosystem Effects of Fishing Activities

status determinations, etc.). It is also equally as easy to come up with a quick list of reasons why multispecies models are likely not used for tactical management (e.g., real or perceived higher information requirements, data limitations (esp. diet data), complexity in tuning and structuring the models, uncertainty on multiple and potentially confounding model parameters, uncertainty in model fitting protocols, an inappropriate review venue or reviewer expertise of multispecies models, inappropriate or unspecified statistical criteria for model evaluation, exposure of different policy objectives that managers prefer to keep circumspect, inadequate governance structure for addressing potential trade-offs, comfort and familiarity with the status quo, etc.). These lists can inform the situation but do not really address nor suggest solutions to the main question at-hand: *Why are multispecies models not used more frequently in an operational, or tactical, fisheries context?*

We thus convened this workshop as a first step towards addressing that question and identifying tangible steps to move multispecies model use in management forward. The primary goals of the workshop were to:

1. Review/discuss the state of the science and use of multispecies models, identifying conditions (globally) when multispecies models are beneficial to consider. (Benefits, State of the Science)
2. Review and identify factors that impede uptake of multispecies model in management (i.e., key challenges to operationalizing multispecies models), or facilitate the uptake and use of multispecies model output. (Impediments)
3. Discuss situations where science is providing the "wrong" answer by not using a multispecies model and sticking to single species models/management? And how to identify/diagnose such a situation. (Diagnose when)
4. Discuss and provide recommendations for what makes a good multispecies model. (Best practice)
5. Discuss how to increase the uptake of multispecies model results/output/advice into management decision making. And what, if anything, in the fisheries management system might need to change. (Uptake)

The workshop was held virtually, due to COVID-19 precautions and restrictions, over three days, from June 22-24, 2021, for 3 hours each day (see Appendix I for agenda and Appendix II for instructions on participants' roles and responsibilities). Approximately 67 people participated in the workshop, representing all six Fisheries Science Centers in the US, eight different countries, and academia, government scientists, and managers (see Appendix III for list of participants).

The workshop was organized around six topics or questions. To ensure the most efficient use of the meeting time, participants were asked to read a pre-workshop literature review (section II), fill out a pre-workshop survey (results summarized in section III, and full questions and results in Appendix IV) and watch six pre-recorded keynote presentations (one for each of the six topics) prior to the workshop. The workshop itself was primarily discussion based, with the larger group breaking into smaller breakout groups to better facilitate discussion of each topic question. This report provides a summary of both the pre-workshop survey and discussions during the six topic sessions during the workshop.

II. BACKGROUND AND REVIEW

Multispecies models have been developed in many regions (Figure 1) to support management decisions or to evaluate management options through use of management strategy evaluations (MSEs). Examples were expanded during the workshop (c.f., e.g., plenary talks), but this initial mapping provided a rough idea of the scale and scope of multispecies models globally. As previously noted, multispecies models are rarely used for providing advice to support tactical fishery management. Tactical advice is focused on informing short-term management actions, like harvest control rules (Plagányi et al., 2014) and 1-5 year catch forecasts (Townsend et al., 2020). In some cases, single-species and multispecies models produce similar catch advice (Daan, 1987), but catch advice is substantially different between the two approaches for other stocks (Hildén, 1991; Link et al., 2010), and ignoring strong trophic interactions in assessment models can produce biased estimates of population parameters and low predictive power (Trijoulet et al., 2020). Hollowed et al. (2000) reported similar estimates of recruitment from single species and multispecies models but concluded that multispecies models are more appropriate for short-term forecasts of forage fish. Kinzey and Punt (2009) estimated different population trends among three fish species in a multispecies assessment that included predation interactions compared to the trends in single-species assessments, demonstrating that decisions on whether to include multispecies trophic interactions can affect the estimates of population feature of interest.

There are advantages to both multispecies and single species models. Multispecies models can outperform single species methods in a variety of ways. Multispecies models offer potential improvements in estimates of the predation component of natural mortality (M), and recruitment (e.g., Trijoulet et al., 2020). They offer better understanding of changes in growth rates and stock-recruit relationships (Hollowed et al., 2000). They can also be used to generate or inform biological reference points (Hvingel and Kingsley, 2002; IWC, 2008; ICES, 2010, 2012; ASMFC, 2010; Chagaris et al., 2020; SEDAR, 2020). All of these improvements benefit our ability to assess competition, predation (e.g., consumption or predator limitation), and environmental variability. Link (2010) listed the types of stocks that are most suitable for multispecies modeling: forage species, species with strong linkages between lower and upper trophic levels, species with high trophic efficiency, high tropic linkage density, highly variable, highly migratory, wide ranging, locally dominant, competitors of target species, predators of target species larvae, and potential target species.

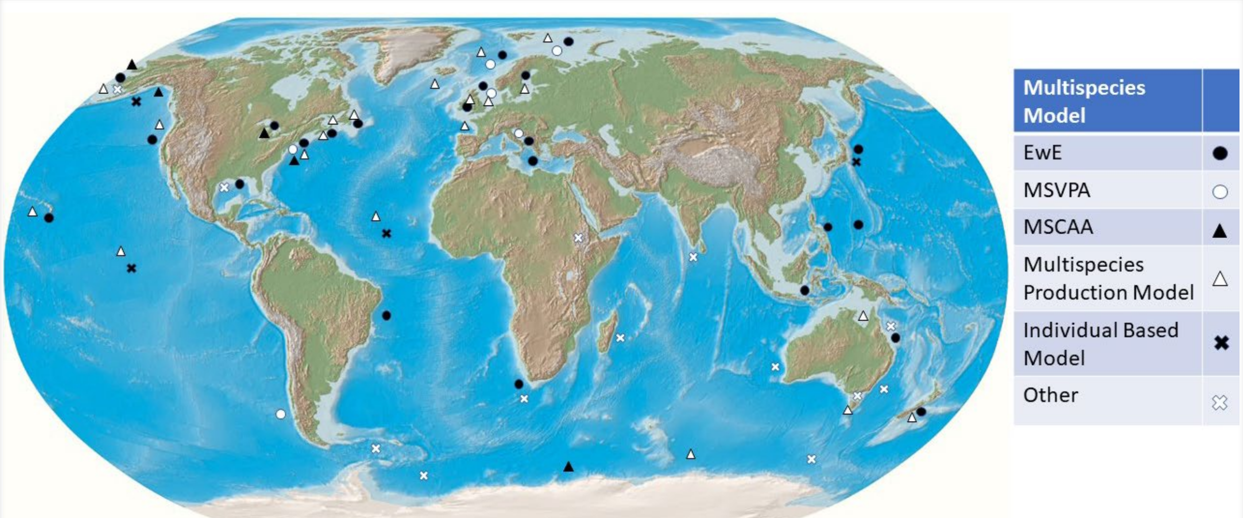

Figure 1: Global distribution of multispecies models identified by participants developed to evaluate or inform fisheries management advice around the world. Points represent a region where at least one model of a given model type exists.

However, not all situations require multispecies assessments, and single species stock assessments may be sufficient in some cases and have some advantages over multispecies models. Single species assessments limit nominal uncertainty by focusing on fewer processes, with more implicit assumptions. Single species assessments have co-evolved with needs of current management systems that limits adoption of multispecies models. Data-collection programs in many cases have been designed to fulfil data requirements of single species assessments in a way that might not be ideal for multispecies models (Hollowed et al. 2000). Single species assessments have also been designed to assess the probability of stock collapse which directly addresses mandates for precautionary fishing (UN FSA, 1995) in a way that most multispecies models cannot.

Due to the unique benefits of multispecies and single species modeling, the two are commonly used in tandem. Single species assessments can be used to provide short-term, tactical management advice, and multispecies models for the same system can provide longer-term, strategic advice. This can be done through management strategy evaluation (Overholtz and Link, 2007; Masi et al., 2018; Deroba et al., 2019) or with direct integration into the stock assessment of a target species (SEDAR, 2020). In doing this, mandates are met without drastic deviation from the status quo, however, the full range of potential benefits of multispecies models are not utilized.

Several case studies demonstrate that multispecies models can also provide tactical advice for fishery management (c.f. plenary talks). The ICES Working Group on Multispecies Assessment Methods regularly develops and applies models for tactical catch advice for several regions (e.g., ICES, 2021). Multispecies models with technical interactions can be used to support catch advice for mixed-stock fisheries (e.g., Ulrich et al., 2002, 2011). Multispecies models can be used to estimate time-varying natural mortality rates that are then used in single species stock assessment (e.g., Sissenwine and Daan, 1991; ASMFC, 2010; ICES, 2004, 2010, 2012, 2020a, 2020b; Howell et al., 2021), ecological reference points for forage species (Danielsson et al., 1997; Hvingel and Kingsley, 2002; Geers et al., 2016; Chagaris et al,. 2020; Howell et al., 2021), or other approaches that pair the relative strengths of single species and multispecies models for a blended approach to tactical advice (e.g., O'Boyle et al., 2012). The Eastern Bering Sea Integrated Ecosystem Assessment program demonstrates how a suite of models, including minimally realistic single-species assessments, climate enhanced multispecies models, and whole ecosystem models can be integrated to support tactical and strategic management advice (Hermann et al., 2016; Ortiz et al., 2016).

Previously noted multispecies modeling research needs and priorities

Several previous reviews concluded that simpler models (e.g., minimum realistic models) are most suitable for providing operational advice for fishery management (Plagányi, 2007; Link et al., 2010; Fulton and Link, 2014). Minimum realistic models are intended to account for the optimal level of complexity for the number of species and aggregation of ecosystem components (Sissenwine and Daan, 1991; Butterworth and Plagányi, 2004; Plagányi, 2007; Plagányi et al., 2014; Collie et al., 2016). For example, Multispecies Virtual Population Analyses have moderate data requirements, moderate realism, and relatively high precision of quantitative advice (Whipple et al., 2000). Plagányi (2007) considered GADGET (Globally applicable Area Disaggregated General Ecosystem Toolbox; Begley, 2014; Begley and Howell, 2004) to have the most potential for supporting tactical advice for systems with relatively few ecosystem components. More complex models like ecopath with ecosim (EwE) (Christensen and

Walters, 2004) and Atlantis (Fulton et al., 2011) are more suitable for representing more complex systems (Plagányi, 2007), but some are not designed for tactical advice (e.g., Atlantis; Fulton et al. 2011). The adoption of ecosystem and multispecies modeling for fisheries management has been described as following a similar path to the Gartner Hype Cycle (Townsend et al., 2020; https://en.wikipedia.org/wiki/Hype_cycle). The Hype cycle is a graphical representation of the maturity, adoption, and social applications of specific technologies and is broken into five phases. Multispecies modeling can be thought of as being in the "Slope of Enlightenment" phase, requiring demonstrations of how the approach can benefit fishery management to be more widely understood and adopted.

Previous recommendations for tactical advice from multispecies models

Several previous reviews developed recommendations that are relevant to applying multispecies models for tactical fishery management advice. Progress toward previous recommendations should be considered for updated guidance and action plans. We provided them to participants (as repeated here) as background and starting points for this workshop.

Sissenwine and Daan (1991): 1) more complex feeding submodels, 2) consider all prey species, 3) consider predation of pre-recruits (e.g., age-0), 4) better estimates of consumption, 5) better understanding of socio-economic factors of technological interactions, and 6) determination of optimal complexity.

Hollowed et al. (2000): 1) multispecies interactions need to be considered in the context of other factors of productivity, 2) models with spatial and ontogenetic structure are more likely to have predictive capacity, 3) alternative models for a system need to be developed within a rigorous and testable modeling framework, and 4) nonequilibrium models are needed for the multispecies interactions that are most important for stock assessment and tactical advice.

Whipple et al. (2000) factors for model selection: 1) spatial and temporal extent and resolution for model selection, 2) conservation of mass or numbers, 3) mathematical representation of predator-prey interactions, and 4) mathematical representation of technical interactions. Evaluate multiple model configurations.

Butterworth and Plagányi (2004): 1) flexibility of prey selection functions, age-structuring or aggregation, spatial resolution and temporal resolution, 2) transparency, 3) include ecological interactions that account for most natural mortality of the species of concern, 4) account for uncertainty in data and model structure.

Plagányi (2007): 1) consider model uncertainty (e.g., sensitivity to model complexity, formulations and assumptions), 2) better evaluation of uncertainty, and 3) represent socio-economic factors and human behavior.

Link et al. (2010): 1) establish distinct model review panels, 2) identify sources of model uncertainty, 3) use commonly accepted ways to address model uncertainty, 4) enhance stakeholder interactions and communication, 5) bolster modeling capacity, and 6) recruitment variability and fleet structure in multispecies models are important for tactical advice.

Plagányi et al. (2014): 1) restrict focus to components needed to address the main effects of tactical management, 2) estimating current stock size and fishing mortality is important for many harvest control rules, 3) stakeholder consultation for model conception, development and implementation.

Voss et al. (2014a,b): Adding equity considerations between different user groups (depending on different, but interacting species) might improve acceptance of management measures.

Link et al. (2015): 1) establish guidelines for uniform application of multi-model inference, 2) document model skill for all ecosystem assessment models, 3) establish guidelines to determine minimal performance standards of skill criteria for the different levels of model application, 4) explore communication training options for the modeling community, 5) establish venues for further interaction among communications and cognitive experts with the modeling community, and 6) codify protocols for effective reporting on various sources of model output and uncertainty.

Townsend et al. (2019): major recommendations from multiple workshops: 1) maintain modeling capacity and infrastructure, 2) iterative communication with managers and stakeholders, 3) periodic review, 4) use multiple models to address uncertainty in model structure, and 5) implement MSE frameworks.

Townsend et al. (2020): 1) develop multiple models, 2) regularly present and discuss ecosystem models at regional management bodies to focus ecosystem objectives, and 3) coupled social-ecological models to increase stakeholder engagement and improve understanding of human behavior.

Howell et al. (2021): combine strategic advice from ecosystem modeling with the tactical advice of single-species assessment models to provide practical ecosystem-based management advice.

Summary

A more detailed version of the above background and review was provided to participants prior to the workshop as a jumping-off point for workshop discussion. The published literature informed and structured our conversations, so we built on previous efforts rather than replicated them. The workshop considered a range of model complexities, with emphasis on models that account for multispecies interactions to provide tactical management advice.

III. PRE-WORKSHOP SURVEY

Prior to the workshop, participants were asked to fill out a survey of primarily open-ended questions aimed at getting people to think about why we need multispecies models, in what situations they might be beneficial to consider over single species models and management, and why we don't see more operational use of them. Thirty-nine people filled out the survey. For each survey question, we conducted a qualitative analysis of responses due to the open-ended nature of the questions, identifying themes and counting the number of responses which fall under each theme. Here we provide a summary of the responses to the survey; for more detailed information on the questions and responses see Appendix IV.

Why do we need multispecies modeling and management?

Two questions in the survey were aimed at getting at the reasons for why we need multispecies models. The first question asked participants to name the top 3 reasons they think we need multispecies models, and the second asked about what improvements are provided by operational multispecies modeling and management. Responses to these two questions brought up very similar themes. Among participants who responded to the survey, the top three themes identified for why they are needed were to 1) account for species interactions (primarily food web/trophic interactions), 2) understand climate or ecosystem drivers of population dynamics, and 3) explore trade-offs. Seven additional themes were also identified for why multispecies models are needed: 1) to provide broader ecosystem understanding/realism, 2) give more realistic advice, 3) move towards ecosystem-based fisheries management (EBFM)/system-level thinking, 4) better manage multispecies fisheries, 5) improve efficiency, 6) mandated by legislation, and 7) as operating models in MSE/scenario planning.

Improvements provided by multispecies models over single species models were very similar to participants' responses for why they are needed. Top improvements related to their ability to explicitly consider tradeoffs between species and stakeholders, provide a better understanding of population dynamics (especially natural mortality, but also growth and reproduction), explicitly account for species interactions, and generally provide better advice.

When, or in what situations, is multispecies modeling appropriate or beneficial to consider?

Three questions related to identifying situations where multispecies models were appropriate. The first asked participants to think about when multispecies models and management are beneficial to consider? The second asked participants to identify the top three situations they think a multispecies model would be appropriate? And Why?—while the third asked them to identify if there are aspects of an ecosystem that point to the need to move towards multispecies models?

The first two questions resulted in very similar themes coming out. Responses to both questions identified situations where there are strong species interactions, a mixed fisheries or technical interactions, M is time-varying or has more influence on population dynamics than F, presence of resource conflicts or tradeoffs, there is sufficient data (especially diet data), or managers are dealing with a forage species, as key situations when a multispecies model is beneficial to consider.

The third question also resulted in similar themes coming out, however, with more of a focus, unsurprisingly on the characteristics of an ecosystem which make it more amenable to or in need of multispecies modeling. Similar to the previous two questions, respondents identified ecosystems with strong species interactions (both biological and technical in nature) and user conflicts between species in the ecosystem as key aspects which point towards the need for multispecies modeling and management. However, several additional themes were noted, such as the presence of rapid environmental change or a regime shift, a simple food web or low-diversity system, presence of invasive species which impact a target species of interest, systems with many species at overfishing level, or food limited systems.

Why aren't multispecies models used more operationally? What are the key challenges and impediments to their use?

The next two questions asked participants to identify the top three reasons for why we don't see more use of multispecies models and the top three limitations for why we haven't seen multispecies models executed in those situations where it would be beneficial. Responses to these two questions were extremely similar and are therefore summarized together.

Participants identified several impediments or challenges to applying multispecies models for operational or tactical fishery management advice. The top five themes coming out of both questions for why we don't see more multispecies models in operational fisheries management were data limitations, management structure of frameworks, capacity limitations (time, staff, money), the complexity and uncertainty surrounding multispecies model results, and scientific or management inertia. Data limitations may be the most tangible barrier to developing multispecies models in many regions (Kerr and Ryder, 1989). Among respondents who suggested data limitations as a key challenge, many indicated specifically a lack of diet data. For those who responded something to do with model complexity or uncertainty, responses largely had to do with the difficulty in communicating and reviewing outputs from multispecies models.

What are the key research needs moving forward?

The last question of the survey asked participants to take a forward looking view, and think about what key research is needed to advance the operational use of multispecies modeling in the future. The identified research needs fell under four overarching themes: data and ecosystem understanding, modeling methods and frameworks, model performance, and management.

Under data and ecosystem understanding, top priority research needs were collecting more diet data (both spatially and temporally) to understand predator-prey relationships and species interactions, and identifying mechanistic linkages between environmental drivers and biological responses (e.g. growth, recruitment, distribution, natural mortality). Under modeling methods and frameworks, top research themes were exploring ways to be able to construct a forecast system that was validated and able to conduct repeated forecasts, explore ways to handle lack of/limited amount of diet data to inform multispecies relationships and to what extent can data gaps be filled in by alternative methods (e.g., local knowledge), improve integration of multispecies models and management with wider ecosystem modeling, and development of modeling frameworks that provide the ability to include spatial interactions. Under model performance, key research priorities were to evaluate in what contexts multispecies models out-perform simpler models and lead to better management outcomes, and evaluate the performance of alternative single species vs. multispecies models, and improve the understanding of model uncertainty (e.g., structural) in multispecies models. Lastly, key priority research questions/areas under the broader management theme were, explore ways to increase the understanding of and acceptance of multispecies models in management, explore how to include trade-offs between species/stakeholders in the advice and management, and develop a better understanding of and guidelines for when and how to do multispecies modeling and management (using "have to do multispecies modeling" situations as examples to draw from).

IV. DISCUSSION SESSIONS

Discussions during the meeting were organized around six overarching topic questions:

1. What is the state of the science regarding multispecies models?

2. What are the factors that impede or present a challenge for and factors that facilitate the uptake of multispecies models for use in operational/tactical management advice?
3. How to diagnose/identify when single species advice might be wrong, and multispecies advice could be preferable?
4. What are "best" practices for multispecies model development?
5. How can a fisheries management system better use results from multispecies models in their decision making?
6. Are there any changes needed to the management system for increased multispecies model uptake?

To help participants prepare for the discussions during the workshop, participants were asked to listen to a pre-recorded presentation related to each of the six topics above. Then, during the workshop participants broke into breakout groups to discuss and respond to trigger questions under each topic area. In the following sections we provide summaries of the keynote presentations and discussions from the breakout sessions related to each topic.

Topic 1: What is the state of the science regarding multispecies models?

The goal of this session was to set the context, noting the state of the science and more so the uptake of multispecies models for management use, and to capture any major lessons learned that could be inferred from examples discussed or presented in subsequent sections.

Keynote Presentation Summary

Title: Multispecies Models: where are we now and where are we headed?
Presenter: Eva Plaganyi, *Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia*
This talk provided a brief overview of multispecies models used for fisheries management with a focus on why these models are needed to complement single-species models. Some of the challenges to greater uptake of multispecies models were explored, including that multispecies models are often lumped in the same 'dubious' bag as models attempting to explicitly incorporate environmental-recruitment relationships, noting that there has been limited success to date but that escalating climate change signals will afford opportunities for greater contrast in data and signals.

The talk focused on providing examples of Models of Intermediate Complexity for Ecosystem assessments (MICE) as tactical ecosystem modeling tools as this approach focuses on specific questions, fits to data and accounts for uncertainties and aims for the "sweet spot" of intermediate complexity. The talk acknowledged that multispecies models that use trophic interactions have seldom been used to actually set total allowable catch (TAC), but stressed that the only measure of success shouldn't be the use for setting catch limits. MICE examples were used to show that multispecies models have much broader applications including to provide rigorous answers to more complex management questions from climate-related, pest management, trade-offs regarding anthropogenic development scenarios, managing recovery of species given complex interactions, bycatch, spatial management, range shifts and ecosystem changes. They are rarely intended to replace single-species models, rather complement, inform and contribute components. Multispecies model variants may be particularly useful as operating models in

Management Strategy Evaluation (MSE) as well as to explore impacts of climate change and inform adaptation planning. New data possibilities (e.g., eDNA) and techniques such as close-kin could also rapidly advance multispecies model capability. The science is increasingly ready for greater uptake of these approaches, but requires resources (especially good stakeholder communication) and appropriate frameworks to feed model results into: this requires scientists, managers and stakeholders to buy-in to new approaches.

Breakout Group Discussion

What are multispecies models?

There was copious discussion on this point, and the distinction between extended (single) stock assessment models through the full gradient to full end-to-end models were noted, with a precise and specific demarcation not always clear (or necessarily helpful). The taxonomic, spatial, and temporal dimensions, degree of complexity and resolution constructed, as well as the range and type of interactions of what constituted a multispecies model were also discussed. Given this range of discussion, and the recognition that there is a continuum of models that could be categorized as multispecies models, the participants largely settled on this definition of an multispecies model as:

> A mathematical model with more than one species (but not fully end-to-end) that captures some (but not necessarily all) of the inter-connectivities across and between taxa, that represent major dynamics of the modeled species, and that are constructed to inform assessments of living marine resources

What are the different kinds of multispecies models (e.g., technical, one-way biological interactions, multiple biological interactions; degree of complexity; inclusion of HD; etc.)?

There are many different kinds. The brief review noted above (Figure 1) and all the plenary presentations but particularly the one by Plaganyi, noted these, but historically the majority of multispecies models have focused on trophic interactions (i.e., predator-prey). It was clearly recognized that there are other interactions where multispecies models can and have been useful, especially regarding technical interactions (e.g., bycatch). The degree of spatial features (e.g., multispecies distribution), the inclusion of human dimensions (e.g., multispecies bioeconomic and portfolio models), and increasing uses for different management options all also highlighted that the range and type of multispecies models is varied and broader than classically considered.

A key point of multispecies models was that there is usually some form of tradeoff being considered in the modeling, regardless of what specific feature or dimension of living marine resource (LMR)s resulting in that tradeoff which is being modeled. The other key point regarding the type of multispecies model is that any selection thereof needs to be “built for purpose” meaning that the use of multispecies models needs to be applied to address a particular question, objective or goal. Eliciting what those goals, objectives or ultimate questions are is often a process unto itself, but was clearly recognized as having been crucial for the development and successful use of multispecies models.

We estimate that there are currently on the order of 50-60 multispecies models used in LMR management contexts around the world. An important, emergent feature from the discussions was that although only about half a dozen or so are used to set or directly inform quotas, or similar operational fisheries management advice, there are additional types of management advice that are needed, particularly a more holistic and strategic approach to development of fishery control rules, that are just as germane to “operational” uses. Further, these have growing demands for such information that can be provided by multispecies models.

Where are there major modeling gaps?

These gaps were centered on geography, taxonomy, disciplinary representation, and degree of model complexity. There were also gaps in multispecies model application regarding use and process.

Geographically speaking, from a global perspective, the southern hemisphere (with the exception of Australia and South Africa) was noted as a limited place where multispecies models are being used, but could have strong utility. In the U.S. perspective, most of the tropical or sub-tropical regions similarly lacked multispecies models.

Posing this question another way, where are there obvious opportunities to get a big win? This led to the taxonomic emphasis that each region should likely have a model that focuses on key species particularly forage fish. The obvious next step in the U.S. context would be to develop or expand multispecies models, in conjunction with appropriate partners, for all regions to deal with impacts of forage fish populations, impacts to commercially targeted predators, and impacts to protected resources. For example, Gulf menhaden could readily benefit from a multispecies model approach as seen in Atlantic menhaden examples. The other obvious taxonomic gap was the use of multispecies models to better explore invertebrate populations.

It was consistently recognized that disciplinary representation needs to be expanded to better include human dimensions in multispecies models. There are many ways that this could be done, and to be fair there was limited social science participation in this workshop (but on the other hand, bridging the stock assessor and ecosystem modeler communities itself is not trivial) so the discussion thereon was relatively limited. That said, the obvious economic applications using a suite of extant portfolio, fleet dynamic, and market dynamic models applied to multispecies situations would be beneficial. As multispecies models often deal with tradeoffs explicitly, further connections with human dimension disciplines would be beneficial to evaluate such tradeoffs. Additionally, the other interdisciplinary consideration was the expansion of environmentally-linked multispecies models. This is especially germane when considering multispecies models as spatially resolved tools to explore LMR distributions.

Summary

To summarize, there remains a robust field of research and strong interest among the scientific community in the continued development of multispecies models. There are a steady and growing suite of multispecies models being used for a range of LMR management applications globally. There is also a growing recognition that multispecies models are uniquely positioned to address management questions that traditional, single-stock oriented LMR approaches cannot; i.e., to address some of the necessary tradeoff issues.

The key recommendations from this discussion topic are:

- The continued development and investment in multispecies models remains warranted.
- Making the case for when multispecies models are necessary remains a need, but is increasingly obvious. For example, rebuilding or failure to rebuild may emphasize the need for multispecies models.
- Recognition that there are many more "operational" uses of models in general and multispecies models in particular beyond setting tactical quotas is more broadly needed.
- The discipline and practice of LMR management must increasingly consider tradeoffs. Though there needs to be specific goals of management to best tailor to a given situation, multispecies models are well suited to address these tradeoffs.
- Developing a portfolio of models is warranted.
- Expansion of multispecies models to be more spatially explicit needs to continue.
- Expansion of multispecies models to be more inclusive of or linked to human dimensions needs to continue.

Topic 2: What are the factors that impede or present a challenge for and factors that facilitate the uptake of multispecies model for use in operational/tactical management advice?

In this session participants focused on the factors that either impede or present challenges for conducting and using multispecies models and advice in management, and what factors help facilitate their use and uptake. To do so, participants watched a pre-recorded keynote presentation and then addressed three primary questions in the breakout sessions during the workshop. Here we summarize the keynote presentation and responses to the breakout trigger questions.

Keynote Presentation Summary

Title: What decides uptake of multispecies models in management advice?
Presenter: Anna Rindorf, *Professor, Technical Institute of Denmark, Denmark*
This talk discussed several factors which affect management uptake of multispecies modeling advice. Before jumping into the factors which impact uptake, the talk first discussed what is meant by "uptake". There are several ways multispecies advice may be brought into, or taken up, by managers. These include providing advice from single species model output using multispecies model input, providing advice directly from multispecies model output, or providing advice from single species model output but consistent with multispecies models. The talk next discussed several factors which will make managers skeptical and slow down management uptake. These include when advice cannot be implemented in the existing management setting, is inconsistent between years, or requires large changes but carries uncertain benefits, when the result does not fit the political agenda, or when scientists or stakeholder disagree greatly. The ability to produce consistent agreed output is a key determination of uptake. Managers are more likely to uptake multispecies model advice when there is good ability to predict ecosystem response to management. This is maximized when changes are well monitored and good data exists, the ecological explanation behind the change is well understood (= model is sound and has predictive power), and the addition of time variation in a parameter is justified statistically and in a management strategy evaluation.

Breakout Discussion Session

What conditions have led to multispecies model adoption? Were there any that seem to be common?

In general, participants highlighted that having interest and buy-in from stakeholders or managers is needed to apply multi-species models for tactical advice. Stakeholder interest and buy-in is often greatest when there are conflicting objectives between stakeholder groups, as this can promote 'political will' for applying multispecies models for tactical advice (e.g., Atlantic menhaden vs. striped bass, sea lions vs. Alaskan salmon, commercial vs. recreational fleets). Additionally, increased communication (e.g., demonstrations of benefits from relatively simple applications; regular interaction of multispecies modelers with advisers, managers; stakeholder engagement; tradeoff storytelling) can help facilitate the transition of multispecies models from research to tactical advice.

Additionally, having well developed procedural mechanisms, such as developed scientific infrastructure (data, methods, processes), peer review system, and flexible fishery management frameworks, can promote the application of multispecies models for tactical advice. For instance, the ICES WGSAM 'key run' review procedure provides a standard framework for model assessment, and an "on-ramp" to ICES applications. The scientific infrastructure (data, methods, process) needs to be developed in advance so that management-driven questions can be answered. Contributing multispecies alternatives to stock assessment processes was also suggested as a means to facilitate uptake into management. Human resources, expertise, and commitments were also highlighted as essential for developing and applying multispecies models.

What are some of the factors that make multispecies models attractive and beneficial to consider?

Discussions during the workshop highlighted that there are many factors that make multispecies models attractive and beneficial to consider. Multispecies models can help explain what factors other than fishing influence stocks and allow for evaluating multispecies tradeoffs. Tradeoff evaluations are attractive, but tradeoff decisions are difficult. So, multispecies models can help to develop tradeoff policies. Multispecies models can also be used for more simple tactical applications to estimate natural mortality rates for single species models.

Even if multispecies models are not used for advice directly, multispecies models can help develop stories and narratives which can be helpful to explore or scope issues, and multispecies models can be used to provide increased understanding of the systems context, which can help improve management. For example, multispecies models can provide a broader perspective to support management procedures (e.g., closed areas). Additionally, although multispecies models are relatively complex, they can support simpler management procedures (e.g., managing multispecies fisheries as functional assemblages).

What are some of the underlying shortcomings and assumptions of available multispecies modeling approaches?

Results of multispecies models are usually sensitive to several major assumptions (e.g., constrained interactions, consumption rates, prey and size preferences, total biomass) and structural uncertainty. Participants identified several of these:

- More interactions and parameters can be difficult to estimate.
- Interactions can vary over time (e.g., spatial overlap of species varies, fisheries target seasonal aggregations).
- Often include assumptions regarding bottom-up impacts (effect of prey abundance on predators), with empirical evidence to parameterize this sometimes weak or borrowed from similar species or nearby regions.
- Data are insufficient in some regions.
- Difficulty in operationalizing multispecies models is demonstrating that they work.
- Age-structure is often considered in multispecies models, even though it may not always be needed.

Several groups also brought up how complex models are not well suited for operational updates or short-term management processes (e.g., annual catch limits), and expertise is lacking in operational processes.

Another potential shortcoming has less to do with the models themselves and more to do with the implications of their results, and how tradeoffs are evaluated. Tradeoff decisions often result in winners (e.g., striped bass fishermen) and losers (e.g., menhaden fishermen) with political implications, but socio-economic consequences of tradeoff decisions are not usually evaluated. Additionally, many highly migratory species and international fishing agreements are not well-suited for multispecies tradeoffs due to these multi-jurisdictional considerations.

What has made multispecies modeling difficult, and prevented its uptake in operational management? What are some of the key challenges? What factors impede the uptake of multispecies model for use in operational/tactical management advice?

Many of the challenges were highlighted through the pre-workshop survey, and therefore participants during the workshop did not spend as much time discussing this question as the others during this session. However, of the groups which did address this question during the discussion the challenges around tradeoff analysis came up most. The lack of explicit management objectives, particularly with respect to transparent multispecies tradeoff policies, has been an impediment to operational applications (e.g., Koehn et al., 2017). In particular, key challenges around tradeoffs that were discussed include the unpopularity of accounting for tradeoffs with protected species, legal implications of tradeoffs, and the difficulties of communicating the limitations and uncertainties of multispecies models to stakeholders and managers.

Another key challenge was how most assessment and management systems are tailored to single-species models (e.g., estimating management reference points like F_{MSY}), without formal linkages among separate assessments. Additionally, it is time-consuming to update multispecies models in an operational process and it demands greater human resource capacity, training, and peer reviewers. This is made even greater a challenge considering that multispecies modeling is not often a funding priority. Lastly, participants acknowledged that changing management processes can be slow.

Given that this topic focused on identifying the conditions that impede or facilitate multispecies model uptake, no specific recommendations were provided beyond the general characterizations thereof.

Topic 3: How to diagnose/identify when single species advice might be wrong, and multispecies advice could be preferable?

This session was focused on identifying situations when a single species model might provide "wrong" advice and a multispecies model could potentially do better, and whether there are diagnostics which can be used to identify these situations.

Keynote Presentation Summary

Title: How to diagnose when multispecies modelling is required in advice
Presenter: Daniel Howell, *Institute of Marine Research, Norway*
This talk highlighted the issues that would need to be considered to decide if and how to incorporate multispecies considerations into advice. The talk presented a number of examples of where multispecies considerations are already incorporated in order to highlight the key factors. Rather than attempt to give generic answers, the talk concluded by highlighting the key questions that need to be asked.

All fish stocks, and hence all stock assessments and advice, are impacted by multispecies considerations. Equally, on the basis that "all models are wrong, but some models are useful", all advice could be improved given unlimited resources. Using multispecies models obviously increases the realism of the assessment and advice, but comes with associated costs in terms of increased data requirements; development time; update assessment workload; and more complex and less transparent models.

Multispecies effects may involve food limitation for predators, induced mortality on prey, or technical interactions (mixed fisheries). It is important to recognize that there are multiple steps in the advice process: hindcast modeling, setting reference points, evaluating harvest control rules (HCRs), short term forecasts, and the overall precautionary framework. Clearly identifying which processes and steps in the advice process require improvement can help to focus the required work. For example, in considering the appropriate fishing level for a forage fish to account for predator needs, it may be necessary to focus on food limitation effects in setting the reference points and HCR but focus on the actual assessment model or technical interactions may not be required.

Stocks which exhibit strong variation in predation mortality, which form key links in a food chain, or are cannibalistic are obvious candidates for the potential inclusion of multispecies effects. Every case will need to be examined on its merits, balancing the likely improvements to be gained against the resource implications. There are a number of key questions which need to be asked in determining if multispecies considerations should be added to advice. First, "is there a deficiency in the model which clearly needs to be rectified?", second "Are multispecies effects at the top of the priority list for improvements that need to be made?", third "Do we have the data to support this modeling", and not least "Is the revised advice likely to be useful and adopted in management?"

Breakout Group Discussion

There were four trigger questions to help facilitate discussion during this session:

1. How can we identify when/where multispecies advice would be better than single species?
2. What are the symptoms (and risks) of single species models providing wrong advice because it lacked species interactions?
3. What are some key diagnostics to identify such a situation?
4. Are there general rules of thumb, guidelines, or similar recommendations about when multispecies model would be a preferred option?

However, the discussions tended to flow between the questions and therefore we provide a summary of the discussion as a whole here, instead of under each specific trigger question.

A key point that was raised during this session was that it may be that single species models will often be wrong, but it is hard to determine when multispecies models will necessarily be better. The reasons were not always specified beyond the usual data limitation concerns and the general challenges of evaluating the veracity of any model. Often these were rooted philosophical differences in approaching complexity of modeling, which multispecies models directly surface.

However, there were general characteristics of the ecosystem and of the single species model which could point to the need to move towards a multispecies model. In terms of characteristics of the ecosystem, there was general agreement that for forage fish or where there are strong species interactions, multispecies models and management will often be preferable and should be considered. Additionally, ecosystems which have experienced a regime shift or rapid environmental change could be good candidates to explore multispecies models, though it was recognized that multispecies models are only one tool in the adaptive management toolbox, and are not the only way to deal with such changes. For example, improved, real-time monitoring of the ecosystem can also help understand and address environmental change in an ecosystem. Also, systems where there are multiple known or unknown drivers causing change in the ecosystem, or there are decreasing or increasing trends in the abundance of key predators on a stock of interest are good candidate systems for multispecies modeling. Conceptual models can help determine and understand species interactions in the ecosystem, and should be done as part of initial exploration of multispecies models. Similarly, broad scale ecosystem models could be constructed to see how closely linked trophic levels are and provide insights into reasons for linkages. Situations where there are obvious bycatch issues would also warrant consideration in multispecies models

Several characteristics of a single species model which, if observed, could indicate a problem and point to need to explore multispecies models, were also suggested. For instance, multispecies models should be considered when one sees stock indicators going one way and single species model predictions going another way. This suggests that the single species model is not able to explain the population dynamics. One would not know that a multispecies model will fix it, but multispecies model should be considered. Another key indication that multispecies models should be considered is if the single species model finds that fishing mortality (F) is much less then M (i.e., $F<<M$), hence multispecies model (and environmental effects) may be better at modeling factors that cause changes to the subject species. It was noted that for

when M is swamping F, this may be able to be handled in single species model, but when there are trends in M, multispecies models may be needed.

Summary

One could almost envision a decision tree (sensu Link et al., 2020) of when multispecies models might be warranted. Not by way of requirements, but guidance for when this might be the most appropriate or preferred option when evaluating a set of LMRs.

The major recommendations from this discussion topic are:

- Examine any situation for obvious conditions of when a multispecies model might be considered in its own right. Specifically--
    - Dominant forage species or forage species at risk
    - Known ecosystem changes impacting predator-prey dynamics
    - Strong species interactions
        - Create a conceptual map of system to identify strongest species interactions
    - Clear technical interactions or obvious bycatch conditions
- Examine any situation for obvious diagnostics of when a single species model might be considered insufficient. Specifically--
    - Single species model finds F<< M, especially with trends in M
    - Single species model predictions and stock indicators don’t match (misfits)

However, a general theme coming from this discussion session was that we are much better at articulating general rules of thumb for when multispecies models should be considered (as described above), but have a more challenging time evaluating the multispecies models. Participants noted that rigorous skill testing of multispecies models is warranted.

Topic 4: What are “best” practices for multispecies model development?

The focus of this session was on the development of the multispecies model itself. After watching the pre-recorded keynote presentation, participants were asked to consider what makes a good model, how to balance model complexity and data requirements, how to encourage more pilot projects, and whether a national toolbox would be beneficial to help increase the development of more models.

Keynote Presentation Summary

Title: What makes a good multispecies model?
Presenter: Sarah Gaichas, *NOAA Fisheries Northeast Fisheries Science Center, United States*
This presentation sought to address this question using standards developed for reviewing models used in environmental and regulatory decision making, which differ from a purely academic model. The general standards are outlined in National Research Council (2007) and applied by ICES WGSAM (2019, 2021), an international multispecies assessment expert group. There are three key attributes of “good” models spanning the range from stock specific through multispecies up to ecosystem models intended for decision making: they are based on generally accepted science and methods, they serve the intended purpose, and they behave similarly to the actual system. Best practices are derived from these three

attributes, and are modified for different phases of the model life cycle, from problem identification to conceptual model and constructed model, through model use. Different phases of the model life cycle align with different evaluation issues. In this keynote we outline six best practices for model use.

The first and most important best practice is problem identification, where we critically evaluate our objectives and why we need a model at all. Once the problem is clear, we then determine whether the model is appropriate for the problem. For multispecies and ecosystem models, it is important to clearly specify the need for models of this level of complexity, and the key output(s) of interest.

The second best practice is to determine whether the scientific basis of the model is sound and appropriate for the problem. This applies to model framework and constructed model phases of the life cycle, but is also important for model use. The presentation provides details based on criteria outlined in Kaplan and Marshall (2016) for general soundness of complex ecosystem models.

The third best practice is to determine whether input data quality and parameterization are adequate for the problem? Further suggested best practices are to provide summary charts of data showing which types are available and used, time series length, gaps, and species comparisons across species. Data pedigree and uncertainty measures should also be provided. Assumptions behind modeled ecological, biological, and other processes must be clearly stated and appropriate, and basic diagnostics of model inputs/outputs evaluated for ecological soundness.

The fourth best practice is where we spend much of our time in evaluating stock assessment models. How does model output compare with observations? Best practices for comparing model output with observations include the usual evaluation done for stock assessment models of fits to surveys, catches, composition data, etc. However, there are other equally important considerations. Clear definition of the hindcast period, key species/groups/indicators, spatial patterns, and outputs of interest that are most critical to addressing the problem ensures that the model is working well enough, but not setting up unrealistic expectations to fit everything. Finally, we note that fitting data well does not imply predictive ability! Fit diagnostics are not the same as skill assessment against a known dataset.

The fifth best practice is to assess model uncertainty and sensitivity. Has uncertainty been estimated in the output(s) of interest for the problem? Has sensitivity to key datasets and parameters been assessed? Model analyses should include retrospective analysis, forecast uncertainty (if forecast necessary for the problem), and it is recommended to retain multiple parameterizations of a model that all meet performance criteria to bracket parameter uncertainty in model applications.

The sixth and final best practice is peer review. Peer review is most effective at each stage of model life cycle. In addition, peer review within a management process in association with a policy problem is a best practice to ensure that the model is most effective and likely to be used. Iterative feedback between modelers, managers, and stakeholders has been shown to be effective in building models useful to management (Townsend et al., 2019; Bentley et al., 2021).

The remainder of the presentation used the New England Fishery Management Council's Atlantic herring Management Strategy Evaluation (Deroba et al., 2019 Feeney et al., 2018) modeling to illustrate the application of each best practice.

Breakout Discussion

What makes a well-constructed (multispecies) model? What should be included in multispecies models? (data and model requirements)

Overall, a good multispecies model was viewed to be something that can gain broad support from technical reviewers, managers, peer reviewers, and stakeholders, and that produces management advice that is actionable and can meet the time steps in which management needs the information. This was an important distinction from the usual technical definitions of what constitutes a good model. Several discussions highlighted different ways this can be accomplished, including the existing challenges to doing so.

There was substantial consensus on the need to be clear about the question being asked before constructing the model to answer the question; a well-constructed multispecies model is one built to a deliberate and clearly defined purpose, or at least using an extant model as particularly adapted to that purpose. The purpose should be very clearly defined from the outset to help scope and guide development. This should include what the model is going to address and what the product will be. However, it was also noted that sometimes a multispecies model can be a model in search of a purpose, which is not desirable. Understanding model purpose is important as different types of multispecies models may be better for particular objectives (e.g. establishing catch limits, finding an appropriate management framework), so understanding model objectives can help ensure that the most appropriate model for the task is developed. Participants expressed concern regarding the tendency sometimes for people to ask to extend existing models, and cautioned to avoid this trap of 'adding on' to existing models as this may increase the chance of asking the multispecies model to do something or answer questions it wasn't designed to. This further emphasized the importance of knowing and defining what question needs answered at the beginning, and there was broad support for early engagement with managers and stakeholders in the model design process. Codeveloping models with advice users was recommended to help ensure targeting of the relevant question/problem.

It was also noted that multispecies modelers can learn from other modeling fields – part of what will make a good multispecies model is the same as what makes a good model in general. This speaks to being able to understand and characterize uncertainty and aspects of these that are most relevant to the research question. A good model would have had a transparent evaluation of assumptions, and sensitivity and performance analysis that demonstrates where models are robust and where they're not. Additionally, the input data and parameterization should be evaluated to ensure it is sufficient for the problem. As noted in the previous section, parameterization between prey abundance and predator numerical response is often a key part of multispecies models, and is difficult to parameterize empirically in some models. Well-constructed models may need to explore this in depth (e.g., Deroba et al., 2019; Punt et al., 2016). Participants noted the need to recognize community bias in determining tolerance for these model properties. Perhaps it is advisable to look for cases where it is possible to show that a multispecies model is the least wrong method; however, participants noted that this might prove more challenging for multispecies model due to the fewer examples of use compared with single species model.

Participants generally agreed that some form of performance criteria is necessary, and should be standardized to enable stakeholders and managers to evaluate model performance. As a starting point this could be related to a simplified dimension (parallel to single species model and demonstrating that abundance trends are driven by catch). Some models can produce advice similar to those available to SSMs, presentation of which may help to bridge gaps, but it's also important to remember that there is a reason for applying a multispecies model so replicating single species model presentation and evaluation of results may not suffice. Comparisons among models can help understand if and why the advice is different (issue is communication rather than model validity). For instance, does F mean the same thing and is it comparable among models? These comparisons could be done in simulation experiments rather than as part of the tactical advice process, with results being available to reviewers/stakeholders, etc. Standard or recommended diagnostics are also needed. The ICES WGSAM key run review section was suggested as a good guide for the questions that could be asked of a model when presented for review and evaluation to help diagnose performance (ICES, 2021). These questions are:

- Is the model appropriate for the problem?
- Is the scientific basis of the model sound?
- Is the input data quality and parameterization sufficient for the problem?
- Does model output compare well with observations?
- (How) Has uncertainty been addressed?

Additional recommended diagnostics approaches or evaluation criteria included:

- Evaluate how variability (spatial, seasonal, etc.) in process and sampling may lead to poor assumptions about representativeness of observations (e.g. spatial changes in prey availability resulting in perceived differences in diets)
- Show model fit on the one hand, and adherence to ecosystem dynamics on the other.
- Conduct sensitivity analysis on diet data to guide in how well the model fits the data, or how sensitive the model is to the data
- Account for uncertainty by removing implausible scenarios. Not fully statistical, e.g. remove results outside of realistic bounds
- If model aspect is known to be sensitive or uncertain then bound the scope of possibility and be transparent about the implications of the uncertainty range

Another aspect that makes a good model that was discussed was its reproducibility. Participants highlighted the importance of demonstrating that results of multispecies model fits and analyses are reproducible. Multispecies model misfit reproducibility exists and has been a particular problem. While it is also an issue with single species assessments, reproducibility has become less of an issue over time for single species as the field has learned what is needed to move toward demonstrating this and its effects on product trust. Modelers should document what was done (and how), but also provide necessary information to ensure that others can find your parameters. Documenting decisions for non-technical aspects are as important as the technical details to make sure the model is well constructed. Defining appropriate workflows around documentation standards may be more important the more complex the model.

It is also important to recognize that time taken between model updates for multispecies models compared to single species models will likely mean that data (processing) and other model choices will change between iterations (true for single species, but multispecies model applications/revisions will have longer development time). Therefore, we need to build in expectations for this process and for review (speaks again to reproducibility and documentation points above).

How would it be best to balance model complexity and data requirements among the dimensions of model construction?

There is a balance in making the model only as complex as it has to be, focusing on data-rich core species and then adding layers as is needed from a management perspective, but not exploring further. Including performance metrics in discussion workshops with stakeholders can be a useful tool to help narrow the scope of a model and help to target the multispecies models around central data-rich species. We have to balance between complexity and simplicity. With no or limited data, even ecologically important species might need to be left out.

Parsimony is important – There has to be a balance between utility and size, and therefore modelers should ask what level of complexity is necessary for the (pre-determined) task? It is also wise to compare among models with different complexities, as multi-model outlook can provide a sweet spot between simplicity and complexity. Conceptual models (e.g. Harvey et al., 2016) were one tool mentioned to help find this sweet spot of model complexity.

What steps can be taken to encourage and facilitate more pilot applications of multispecies model?

For this question there was general thought about whether pilot applications are still needed as a focus, or if the priority just needs to exist for more uptake and how this can be done. Therefore, discussions and recommendations under this question apply to how to improve development and utilization of multispecies models in general and not simply focusing on pilot studies.

A key area which, if improved, participants felt could help increase the development and uptake of multispecies models is increased interactions between managers (and stakeholders) and modelers. There are a lot of these interactions in the single species modeling realm since they provide (tactical) advice on a regular basis, however ecosystem modelers aren't interacting with managers the same way as single species modelers. The limited or lack of these interactions makes it quite hard to get these models into application; scientists have to be embedded within governance structures and communicate with managers (i.e. be at the meeting in the first place, show some examples, and then move slowly towards updating to multispecies model). Participants noted a need for more platforms to engage in these interactions. A key recommendation from this discussion is to remove stovepiping within institutional and organizational structures (in scientific agencies) that prevents those being asked to do tactical modeling from interacting with those working on ecosystem applications (and thus the lens on utility or on-ramps for different approaches is clouded in both cases).

Discussion also centered on the fact that the science community hasn't sold managers yet on why they may want to consider multispecies models or ecosystem models. Doing so is crucial to increasing the development and consideration of multispecies models due to the competing resources for time and attention. A key recommendation coming from this discussion was the need to develop a process for better communication to the full breadth of managers about the benefits of multispecies models, what the potential outcomes could be, and the costs of not using them. Additionally, focusing on not just the ecosystem but the economic benefits and costs which can be potentially better understood through multispecies models may be helpful. For instance, modelers may highlight how managers may be leaving money on the table by missing dynamics leading to under/overfishing if they rely on single species models and management instead of multispecies models. Showing potential net benefit to a fishery or region of using multispecies models would also be helpful. Additionally, multispecies models can help rebuild stocks and ecosystems faster because they better approximate reality and so have a more appropriate view of system constraints due to food web biomass tradeoffs.

As was brought up earlier, including managers in model development as early as possible should help with understanding and uptake. This may necessitate the creation of processes that allow for integration of participants in the model development and construction timeline as being present during model development will help improve stakeholder understanding of the model. One suggested approach is to develop multispecies models from conceptual models designed with stakeholder input, as this would go along with data input and match up with management concerns. Additionally, engaging with stakeholders early in the process may help bring more hypotheses to the table. Lastly, increased engagement with managers, can lead to champions on councils, resource committees, or staff who can help to push these things through the council process.

Developing some standard tools (and making them available) that people could be acclimated to could help improve engagement and communication. Outreach and communication was highlighted as a huge part of things – developing tools that can help managers and stakeholders understand multispecies models and their value is going to be incredibly important. Development of tools that help laypersons understand multispecies model output and skill/utility. The key is to develop tools which are flexible and adaptable to meet regional needs. Additionally, communication with managers about the benefits and risks of not using multispecies models will largely need to draw on good existing examples. A database of previous examples for managers to provide a better understanding of real applications would be useful. As with most things, uptake is encouraged by successes. A decision tree could be helpful that can point to which tools have been successful in various scenarios (help stakeholders and scientists identify when multispecies models might be useful, and potentially which models could be optimal).

In addition to improved communication and engagement developing and documenting model building guidelines could help. This could involve guidance on multispecies model parameterization, focusing on good examples as defaults to use as "guard rails" for when things go out of the realm of normalcy. Additionally, these guidelines could outline basic methods for going from data to model so people aren't doing different things to come up with parameters from data (e.g., diagnostics for food web models – i.e., they should be in this range, if you're out of this range come back). Therefore, a recommendation was to potentially focus on a few classes of models to try to do standardization. Another key aspect of model building is training, in particular training in using models, diagnosing outputs, and communicating results. The more people that can understand (and communicate) what is going into multispecies models, what about applications that make bad vs good models, and make sure the analytical process is sound, the better.

Would a national or international toolbox be beneficial? If so, what would that look like?

There was lots of support for toolboxes or resources for finding example models, diagnostic guidelines, review guidelines, decision trees for model building and application and selection, best practices for communicating results, etc. There was also support for interactive decision support tools that can be put in the hands of managers and stakeholders, including tools aimed at education and improving literacy around utility and types of outputs/questions multispecies models can address.

Participants highlight some examples of current Toolbox frameworks:

- ICES transparent assessment framework (TAF)
  - Addressing repeatable and transparency issues
  - Whole pipeline from data to advice, not just model
- NOAA national integrated toolbox recently established
- Australian stock assessment toolbox
- NMFS Fisheries Integrated Modeling System WG
- Many models have dedicated websites / open code repositories, but links to them are not collected / organized, e.g., EwE, SMS, Gadget, Atlantis, FLR (FLBEIA?), CEATTLE

A multispecies modeling toolbox could involve building off of existing toolbox as listed above to include diagnostics tools and standardized tools to check performance (e.g. {r4ss} package; Taylor et al., 2021) specific to multispecies modeling applications, or it could be more of 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 goal of any toolbox developed is to make things more efficient. For example, the Stock Synthesis Community was mentioned as an example of how beneficial and vital it can be to be able to access people who can help. Either approach to the toolbox could also include collecting vignettes and examples on "how to use" tutorials which can improve use and accessibility (e.g., energy put in by RStudio on education materials for tidyverse has empowered many new data scientists). A minimum "toolbox" could be a living documentation of current multispecies models (e.g., update, living version of Plagányi, 2007). With any toolbox, training people to use the elements of the toolbox should be part of the toolbox.

While centralizing resources was generally supported as a good idea, participants did note some uncertainty surrounding the extent to which that would aid in overall multispecies model development. On the one hand standardized components help reduce burden for review (of both models and implementations) and help develop a community of practice, but there was also some mention of the danger of providing generic / standard tools given the emphasis on these models being built to purpose or different data availability (e.g. a region without surveys may be more data limited and have to use different approaches). Participants posed the questions of whether it is possible to build a suite of tools that are flexible enough (i.e., modular) to be customized and move away from the single-use approaches that we're using now. There was discussion regarding whether components of a toolbox should be modular to allow for customization. Doing so would require a more structured, integrative approach than providing links to examples, existing software repositories, etc. However, developing something like a Library of functions that do different things related to multispecies modeling, can pull it together without starting from scratch (e.g. plug and play). On the other hand, however, some participants felt that standardization of outputs (so results can be used) is more important than the ability to customize/utilize different models.

Another challenge is if a “toolbox” is a portal for software, resources for maintenance are needed, and there may be difficulty getting funding for this. Therefore, national tools might be more realistic; both in terms of portfolio of methods (most likely to match management needs) and long term maintenance, curating the tools.

A key take-away from this discussion was that Toolboxes should be available, but not required because may not be applicable in all cases. Additionally, it is important to understand what is needed before something is acceptable for a generic toolbox – review guidelines and checklists, etc.
Is there a user guide? Is it well tested? Well commented? What are unique checks and passes that multispecies model needs to pass?

Other Considerations

The concerns often espoused over the use and uptake of multispecies models and broader ecosystem models center on data demands. This is particularly true if the multispecies model is used to improve upon estimates of the age-specific natural mortality and recruitment of major species included in the multispecies model (e.g. MSVPA). Copious discussion occurred and it was noted the dimensions that lead to model complexity need to be more thoroughly challenged. To the point that several stock assessors commented that we may not need fully age-structured models and instead should focus on other dimensions impacting LMR populations, such as predation or bycatch or similar threads of information more directly. Also relatively nascent to the field, but with high potential and promise, yet having had limited use by many modelers, are qualitative models. These have particular appeal as simpler, data-free multispecies models that can be used in stakeholder engagement contexts. Participants also highlights the use of qualitative and conceptual models as good starting points for multispecies modeling, particularly in regions with limited data and capacity (e.g., as described in Cochrane et al., 2019 for Madagascar).

The role of model ensembles also warrants mentioning. Beyond one or two single species models, beyond sensitivity analyses, there was a clear recognition that having a few multispecies models to complement SSMs and E2E models is useful. Though the cost of developing a model is high, the insights and ability to compare across models is valuable. Several case studies noted in many of the plenaries that having a few models to compare, contrast and contextualize was beneficial. Development of standard multispecies models, and a veritable “toolbox” of models was recognized as wise.

The other potential use of multispecies models is as operating or assessment models in MSE. This has been somewhat recognized (see Kaplan et al., 2021).

Summary

The major recommendations from this this discussion topic are:

- Clarify the question
- Establish and use clear performance criteria, with clear model diagnostics
- Ensure model reproducibility
- Embrace parsimony

- Increase interactions and communication among modelers and managers (and stakeholders)
- Develop, support and wisely use modeling toolboxes

Topic 5: How can a fisheries management system better use results from multispecies models in their decision making?

In this session, participants discussed the core points of the workshop – how multispecies models can be used for management and how to ensure that multispecies models are useful for management. During the breakout session participants focused on four sets of questions, the responses are summarized below.

Keynote Presentation Summary

Title: Use of multispecies information in ICES advice
Presenter: Mark Dickey-Collas, *ICES, Denmark*
The presentation concentrated on the application of multispecies information into advice. It covered the nature of ICES advice on fishing opportunities, the development over time of the methods and approaches, the distinction between multispecies (ecological and trophic interactions) and mixed fisheries (selectivity, technical and fleet based interactions) and then looked to the future developments coming across the ICES region. The basis of ICES maximum sustainable yield (MSY) approach, with precautionary considerations for data rich and data limited stocks was explained, as ICES has an agreed harvest control rule for data limited stocks. Some ICES areas use pretty good yield as the basis for the advice. The presentation illustrated where ICES currently uses multispecies and mixed fisheries in advice. It also emphasized the importance of quality assurance and peer review of the methods.

In almost all ICES regions, further development is concentrating on combining multispecies/ecosystem dynamics with mixed fisheries information in advice. Examples were given from the Baltic, Irish, North and Barents Seas. All of these examples looked towards providing operational and strategic advice, based on MSE informed decision support with fleet and environmental information. A risk based approach is considered key. Work was also mentioned from the Bay of Biscay and Iberian coast.

Breakout Group Discussion

What management questions can multispecies models help address? What are the benefits over SSMs for these?

Discussion on this topic centered on using broader strategic questions like evaluating tradeoffs (e.g., effects on multiple stocks of allowing fishing vs. allowing rebuilding for a focal stock). Single species models are not designed to address tradeoffs among fisheries stocks or among stocks and protected species populations. Multispecies models are an essential tool for quantifying these tradeoffs. A key way to address tradeoffs is often through MSEs (we discussed MSEs further below). Beyond the necessity, flexibility within multispecies model is attractive for managers. Outputs from multispecies models can offer a range of decision options rather than traditional "pinpoint" or very precise recommendations. When thinking about how the decision-making process works, traditional approaches are limiting. Decision making comes down to setting Allowable Catch Limits (ACL) for a given species, but it is done in a vacuum. With multispecies models more info could be brought to the table especially when considering forage fish and top predators. Participants stated that multispecies models can aid in optimization of fishing in a given region for a range of interacting stocks. Top predators have large impacts on stocks, which are often not considered but may have important consequences for rebuilding stocks. multispecies model applications focused on forage fish, where adequate information on the primary predators exists, would similarly be important for understanding tradeoffs. Similarly, technical interactions and bycatch issues would be key issues for multispecies models to address. With a broader range of management options, a better understanding of stakeholder needs and management objectives arises. However, conflicting interests among stakeholder groups will require a framework for decision-making to help develop objectives.

Participants also raised the important point that fisheries management is more than just setting TAC and ACL for focal stocks. multispecies models can also be used to address other types of fisheries management questions; e.g., essential habitat, fishery closures. Using spatially explicit multispecies models can help with survey planning, technical interactions, bycatch, habitat, protected species issues, and answering life history questions. Multispecies models can also be used to understand long term changes that may be due to climate change, at least as strategic context for the US Fishery Management Councils (e.g., Woodworth-Jefcoats et al., 2019).

How should results from these models be presented to managers – guidance on how to use the results in management decision making (e.g. which visualizations, formatting, engagement process)

Participants noted that fisheries managers are accustomed to single species models and output, so presenting multispecies models in conjunction with, and with similar outputs, as single species models is important. Giving an output that is familiar to managers (in the context of tradeoffs) could be beneficial for forming that link between the complex modeling side and the managers. It was noted that ICES is moving towards this type of joint multispecies model and single species model review framework; however, applying this sort of framework may require some organizational efforts for the US. Also, communication should begin early in the multispecies model application development process. Communicating with managers from the beginning and along the way to provide updates is important ensuring an understanding of model results is necessary. Ultimately using a multispecies model to provide a reference point, such as F_{eco} (Howell et al., 2021), will be most useful.

Beyond these general ideas about communication, participants discussed specific approaches. Multispecies model outputs can be used to show managers new ways of looking at an ecosystem; however, outputs can be complex as a threshold reference point level for one species may vary depending on another. Trying to present complex information in a simple interface is a nontrivial task. Tools that allow managers to interactively explore results (e.g., Rshiny applications) may be useful for some, but they may result in information overload. In addition to interactive apps, simple tools, like risk analysis tables, are likely necessary for presenting results. When tasked with presenting results, a multispecies modeler is well advised to not be infatuated with the model but focus on results and display tradeoffs explicitly. Some modelers have found it helpful to work with communications specialists to develop multispecies model output visualizations.

Would a national or international set of model, model output, and model use review criteria be helpful? If so, what would that look like?

Generally, participants agreed that a set of multispecies model-specific models, outputs, and review criteria would be beneficial. More specifically, standard software for model building and a vetted set of functions that could be used to build a model which would allow for customization to each scenario would help expedite model development. With this approach code would have been tested to save time for modelers and reviewers. Review process would therefore be more focused on how the functions/codes were put together, being that the functions have already been proven acceptable.

From the software set, modelers could build a portfolio of models specific to the needs in their regions. Often, when the need for a multispecies model arises, managers are responding to a crisis. Having a set of tools ready for application can accelerate that development of model-based information to inform the issue rapidly.

Participants noted that model development (for a set of regional models) should proceed with a manager/stakeholder engagement process, so that they understand how the tool is being used. In addition, a standard set of plots and outputs would be necessary to foster familiarity. Similarly, a review process tailored to multispecies models is necessary for building familiarity and establishing acceptable use of multispecies models, and participants again noted here that the ICES WGSAM provides a good starting point for this sort of review process (e.g., https://ices-eg.github.io/wg_WGSAM/ReviewCriteria.html).

What is the role of multispecies models in MSE and related scenario planning?

Employing multispecies models for MSE and scenario planning was considered an important goal. Multispecies models should be used in situations where managers want to consider tradeoffs among potential management actions that would influence multiple stocks (e.g., forage fish). Multispecies models could be used as the operating model and single species models could be used as the assessment model in the MSE loop. Also, multispecies models could be used alongside single species models as assessment models with a more complicated (i.e., holistic ecosystem) model as the operating model. Evaluating outcomes when managing according to multispecies models and single species models, MSE-style simulations is a way to evaluate potential benefits (or costs) of shifting from single species to multispecies models. Participants noted that employing a suite of models for MSE would be a desirable approach as doing so would enable accounting for model structure uncertainty. In addition, a full stakeholder participatory MSE would be highly useful as doing so would also help deal with communication uncertainty when discussing MSE and model outputs.

Some participants noted that employing a full MSE (i.e., with stakeholder participation) with a suite of models would be difficult to accomplish under typical management decision-making timelines with limited staffing available to develop multispecies models. As an interim step, multispecies models could be used for scenario planning or a simpler MSE. Some participants, who were familiar with model development as well as management process, pointed out that developing models take time and resources already, so if taking some of these stakeholder process steps in the beginning (developing objectives, engagement, etc.) helps ensure project is successful and implemented, then the cost of doing so is worth it.

Summary

As we move towards implementing EBFM, using multispecies models and other approaches is essential. Several examples of successful uptake of multispecies models for management have been discussed.

From these examples lessons are being learned on how to increase uptake of multispecies models for management. There are no silver bullets to address how multispecies models can be used for management and how to ensure that multispecies models are useful for management. However, this discussion resulted in some key conclusions and recommendations for moving forward; they are listed below.

- Tradeoffs choices should be decided explicitly by managers rather than implicitly by scientists (who can present the range of choices), and multispecies models are probably *the* best available tool to quantify tradeoffs for informing decision making.
- Conflicting interests among stakeholder groups may require modified or specific frameworks for decision making
- Flexibility provided by multispecies is very beneficial and important for management decision making
- The largest challenge to overcome when presenting multispecies model results is the complexity of these results, though some ways to combat this are:
  - Involve stakeholders from the beginning – Participatory Modeling
  - Interface with Communications Specialists
  - Relate results to single species outcomes to help managers understand
  - Use multispecies models as a new way to look at ecosystem
- Interactive tools for viewing model output along with simpler digested output (for example, in a risk analysis table) should be used for communicating model results.
- A standard set of modeling tools, outputs, and review criteria would expedite the implementation of multispecies models for addressing management questions.
- multispecies models should be used for MSE. Ideally full MSEs (with stakeholder participation) should be pursued. Along the way to full MSE, simplified MSEs and scenario planning should be implemented.
- Though stakeholder engagement is costly in many ways, if it helps to accomplish the ultimate goal of improved decision making and better accounting of tradeoffs, this effort is likely worth it

Topic 6: Are there any changes needed to the management system and need for increased multispecies model uptake?

This session had an explicit management focus to initiate a practical discussion on whether changes in management systems are needed before multispecies models can play a prominent role in the science advisory process.

Keynote Presentation Summary

Title: Challenges and Opportunities for Multispecies Model Uptake in Fisheries Management in the Western Pacific Region
Presenter: Marlowe Sabater, *West Pacific Fisheries Management Council, United States*
Not all Council regions are created equal. The high species and cultural diversity in the Western Pacific region make it prime grounds for multispecies modeling. The Western Pacific Fishery Management Council (WPFMC) transitioned from species-based management to ecosystem-based management in 2009 with the approval of the Fishery Ecosystem Plans. With this plan is the aspiration for multispecies

management, looking at species interactions and trophic level management. However, the ACL requirement in the 2007 Magnuson Stevens Act (MSA) reauthorization delayed progress towards multispecies management. The Council and Science Center spent much of the energy developing single-species or species-complex stock assessments to support ACL management for the domestic fisheries and quota-based management for the international pelagic fisheries. Therefore, multispecies modeling work in the Western Pacific is sparse. Those few scientific endeavors fed directly to tactical management like ACL specification for the main Hawaiian island deep seven bottomfish fisheries and the strategic management on high seas area closures.

Significant challenges are facing the region before operationalizing multispecies modeling. First is the data-limited situation impedes the development of a multispecies model to support fisheries management. It's challenging enough to develop a single species assessment based on reliable fishery-dependent data. Incomplete life history data and lack of diet/physiological studies of management unit species inhibit the development of multispecies models to answer fishery management objectives. Much of the domestic and international fisheries management focuses on tactical approaches, mainly input and output controls. Shifting to strategic approaches would require a stronger push to overcome this management inertia. Lastly, the jurisdictional issue. Much of the multispecies fisheries occur in territorial or state waters without federal oversight. The impact of the domestic pelagic fisheries is negligible compared to the international fleet.

When there are challenges, there are opportunities. A shift in the management paradigm is needed to increase the uptake of multispecies modeling in the Western Pacific region. It is a balancing act of meeting the requirement of tactical management and augmenting it with the development of strategic management supported by multispecies modeling. This would require a change in the science focusing more on collecting biological and environmental information and upgrading the basic fishery-dependent data collection. This also requires better coordination between science providers, territorial, state, and federal fishery management agencies. The balance also includes a third dimension which is the traditional and local ecological knowledge. Uptake of multispecies modeling in fisheries management must also consider its sensitivity to cultural resource users. There are opportunities now to shift the paradigm with the MSA reauthorization, Forage Fish Act, and Ocean Solution Act that could utilize more multispecies modeling work to support the information needs for these legislations.

Breakout Group Discussion

There were three trigger questions designed to facilitate this discussion. Summaries of the discussions around each question are summarized below.

What changes in the current management system may be needed to facilitate/move towards multispecies model-based advice for management?

It was made loud and clear from all groups that scientists and managers need to closely collaborate on articulating objectives and identifying the best approaches for meeting those objectives. If a change from the status quo is warranted, then an iterative approach may prove to be most successful (c.f., Atlantic menhaden). Nevertheless, multispecies models can be, and are being used in existing management frameworks. Generally, it may be easier to adopt multispecies models in the management process when they are used to provide strategic, rather than tactical advice. There are many examples where multispecies models provide contextual/strategic advice to managers (e.g., Ecosystem Status Reports, Ecosystem and Socioeconomic Profiles, etc.). However, there are genuine challenges when considering the use of multispecies models for tactical advice, such as a reliance on single stock TACs/ACLs, MSY driven objectives (MSY for all isn't realistic but is often the goal), stocks moving between or shifting across management jurisdictions, and perhaps the most notable challenge is institutional inertia. Overall, multispecies models can be used within existing frameworks, but a careful, collaborative, and iterative approach is an agreed best practice for facilitating broader use.

How do we conduct trade-off analyses?

Tradeoff analyses are a regular part of the management process, but it is often done implicitly, or at least it is not clearly identified as a tradeoff analysis. In most cases, there is not a formal system in place for conducting tradeoff analysis, and the analyses are difficult to do explicitly, because someone (at least has the perception of) loses. Nevertheless, multispecies models are useful tools that can support tradeoff analyses. However, a recurring theme across most aspects of this workshop is that a collaborative and iterative approach should be used, particularly because there is often a very low bandwidth for evaluating new ideas and adopting new approaches. This is certainly the case for conducting tradeoff analyses within a management setting. In addition to being collaborative and iterative, other good practices are to provide incentives for conducting tradeoff analysis (particularly economic), to ensure a diversity of approaches and participants, to structure all discussions, to focus those discussions because too many decisions can cause confusion, and finally, tradeoff analyses should be done using effective facilitation. Additionally, there was some discussion about potentially conducting tradeoff analysis at the guild rather than the species level. This would provide a more systems functionality perspective and may be better suited for very specious and diverse systems such as tropical systems.

Under what authorities/jurisdictions can multispecies models and tradeoff analyses be done?

Generally, multispecies modeling and tradeoff analyses can be conducted within most authorities and jurisdictions, although there is a perception that they are not within scope. There is more flexibility to do so at the state and provincial level than at the federal level, and changing national regulations is a protracted process. Thus, working within existing management frameworks is a practical approach, and expanding terms of references (TOR) to include statements related to e.g., predator-prey interactions and evaluating scenarios can formalize the need for multispecies models and tradeoff analyses. Within the context of NOAA and US mandates, multispecies models naturally lead to consideration of tradeoffs between harvested species and protected predators such as marine mammals and seabird – thus multispecies models offer the potential as a bridge between fisheries scientists operating under the MSA, and protected resources scientists primarily grappling with the Endangered Species Act (ESA) and Marine Mammal Protection Act (MMPA) (e.g., Robinson et al., 2015; Tulloch et al., 2019).

Overall, there are relatively few scientists that do multispecies modeling and produce outputs that are directly relevant to fishery management, so for this work to be ubiquitous, capacity building is needed.

Further, if the modelers are delivering advice and conducting tradeoff analysis, additional training is needed in communication and conflict resolution.

Summary

The major recommendations from this this discussion topic are:
- Again, increase interactions and communication among modelers and managers (and stakeholders)
- Again, clarify the question (or objectives)
- Develop clearer protocols to evaluate tradeoffs

V. RECOMMENDATIONS AND CONCLUSIONS

Convening a group of 50+ experts from global ecosystem modeling, stock assessment modeling, and multispecies model communities was a productive thing to do, and resulted in well-debated and seriously considered outputs that represent a consensus from a wide range of perspectives, thereby strengthening the outcomes of what was noted. It is clear that there is progress occurring on multispecies models, and that we have learned lessons during the past few decades to advance multispecies model application and uptake. The observations, conclusions, and recommendations are generally consistent with previous workshops and reviews and represent good, solid advice and obvious areas for progress.

There were many recommendations that arose from the discussions. We don't repeat every one of them from each of the main topic areas above, but we do generally reiterate them here.

To synthesize these, the major recommendations include:
- Develop guidelines/decision trees to help determine when single species models might not be sufficient and multispecies model would be preferable
- Multispecies models should be applied/tailored/built for purpose
- Include managers and other stakeholders in process from the beginning
- Formalize guidelines for multispecies model review and use
- Multispecies models can be used within existing frameworks; however, a new, more flexible framework may improve use, especially with respect to handling tradeoffs

To unpack these further:

Develop and utilize guidelines/decision tree to help determine when single species models might not be sufficient and multispecies model would be preferable
- There is clear stakeholder or manager demand or question/problem for which a multispecies models is best suited to address
- Dominant forage fish fishery/forage species in danger – Forage fish, forage fish, forage fish!
- Known ecosystem changes impacting predator-prey dynamics
- Strong species interactions – create a conceptual map of the system to identify strongest species interactions
- Clear technical interactions or obvious bycatch conditions

- Single species model finds F<< M, especially with trends in M
- Single species model predictions and stock indicators don't match (misfits)

Multispecies models should be applied/tailored/built for purpose

- Scientists and managers need to closely collaborate on articulating objectives and identifying the best approaches for meeting those objectives
- Involve stakeholders from the beginning
- Interface with communications specialists
- Modelers should document what was done (and how, and why), but also provide necessary information to ensure that others can find your parameters.
- Develop, support and wisely use modeling toolboxes

Formalize guidelines for multispecies model review and use

- Is the model appropriate for the problem?
- Is the scientific basis of the model sound?
- Is the input data quality and parameterization sufficient for the problem?
- Does model output compare well with observations?
- Develop standardized review criteria
- (How) Has uncertainty been addressed?
- Show model fit on the one hand, and adherence to ecosystem dynamics on the other
- Account for uncertainty by removing implausible scenarios. Not fully statistical, e.g. remove results outside of realistic bounds
- Consider model ensembles
- If model aspect is known to be sensitive or uncertain then bound the scope of possibility and be transparent about the implications of the uncertainty range

Multispecies models can be used within existing frameworks

- Expanding TORs to include statements related to e.g., predator-prey interactions or bycatch
- Increased communication
- Make existing processes more flexible (gain familiarity), tailored to purpose/use of model (esp. with respect to tradeoffs)
- Develop clearer protocols to evaluate tradeoffs – should take a careful, collaborative, and iterative approach to facilitate broader use and/or handling of tradeoffs

In conclusion, there were some key points and observations that emerged from the workshop. These include:

- Case studies demonstrate clear benefits to multispecies models
- There are challenges to implementing multispecies models, but they can mostly be overcome
- Reproducibility of model is an important criterion for determining best scientific information available for fishery management, hence the recognized value of a Toolbox
- There are many dimensions of socio-ecological complexity, but all of them cannot be represented in operational models, so the most important complexities need to be identified
- Communication with stakeholders and managers is Key (initial, regular, frequent, effective)
- There are more uses of multispecies models than just tactical BRPs/quota setting

- There are many opportunities ripe for multispecies model applications (where can we get big/quick wins)
- Legally there are no issues to doing multispecies models, but governance and authorities to deal with tradeoffs (crossing lines within MSA, ESA, MMPA) remain a coordination challenge

It is also important to not miss the intangibles from such a workshop. There were really excellent interdisciplinary and international connections made at this workshop. That the different communities approaching LMR modeling and management had an open forum in which to discuss these issues was important and warrants continuing. Though several social and economic scientists were invited, only a few were able to attend; even those few provided perspectives and insights that natural scientists might miss. Several fisheries managers were invited to the workshop, and that some made it and were able to interact with the multiple modeling communities, and individuals from around the country and world, was also a valuable outcome. Certainly more colleagues that are managers and from other disciplines (i.e., socio-economic colleagues) would improve the discussion, but that we had them at this workshop was a positive step and benefited all involved by hearing these distinct perspectives.

Additionally, that the workshop was postponed due to COVID-19 and ultimately precluded an in-person workshop was a challenge, but ultimately it worked out well. We found that the pre-recorded plenary talks and pre-workshop survey provided a bit of "homework" that encouraged participants to be more prepared than perhaps they would have been under more normal circumstances. Furthermore, the virtual nature forced us to establish smaller break-out groups that were designed to engender interaction and discussion, which occurred not only frequently but with clear purpose, direction and intentionality that resulted in so many clear observations and recommendations.

Finally, we were intentional about having several graduate student and early career staff participate in the workshop as rapporteurs given the larger demand of higher numbers of breakout sessions. They did an excellent job, and more so it exposed nearly 20 such individuals to multispecies models. These individuals are likely the ones who will be conducting and carrying out multispecies models in the future, so that too was an intangible benefit that emerged from the workshop.

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VII. APPENDIX I: WORKSHOP AGENDA

This workshop took place over three days, for about 3 hours each day. The general format was a brief introduction each day, followed by breakout sessions and plenary discussions for two topics. Participants were responsible for watching pre-recorded keynote presentations for each topic (identified on the agenda, total of 6 presentations) and came prepared to discuss the breakout discussion questions (linked to under workshop materials) for each topic.

Day 1 6/22/21 **2:00pm start** (Eastern Daylight Time)- Introduction to multispecies model: benefits, challenges, factors that impede or facilitate their use in management (Goals 1, 2)

Session 1 chair: Jason Link

- **2:00 - 2:15pm** Introduction & Orientation - Jason Link (NOAA, USA)
  - Introductions, review agenda, workshop materials
  - What is meant by multispecies model for purposes of this workshop?
- **2:15 - 3:15pm** Overview of multispecies models and generally the global state of the science on multispecies models
  - Short review of pre-recorded keynote (5 mins)
  - Breakout Discussion Groups (40 mins)
  - Plenary Discussion (15 mins)
- **3:15 - 3:45pm** Review/Discuss results from pre-workshop survey & white paper - Max Grezlik (UMASS, USA)/Melissa Karp (NOAA, USA)
  - Short review/presentation on the key results of pre-workshop survey, and white paper
  - Focus on: What are the benefits of multispecies model, why we need them, and why they are not used more often
- **3:45 - 3:55pm** BREAK

Session 2 chair: Steve Cadrin

- **3:55 - 4:55pm** Factors that impede or present a challenge for and factors that facilitate the uptake of multispecies model for use in operational/tactical management advice
  - Short review of pre-recorded keynote (5 mins)
  - Breakout Discussion Groups (40 mins)
  - Plenary Discussion (15 mins)
- **4:55 - 5:15pm** Wrap-up
  - Summarize key recommendations/conclusions from the days conversations

Day 2 6/23/21 **2:00pm start** (Eastern Daylight Time)- Moving towards operationalizing multispecies model: Science Needs (Goals 3, 4)

Session 1 Chair: Rick Methot

- **2:00 - 2:15pm** Recap of Day 1
- **2:15 - 3:15pm** How to diagnose/Identify when single species advice is wrong, and multispecies advice would be better
  - Short review of pre-recorded keynote (5 mins)
  - Breakout Discussion Groups (40 mins)

    - Plenary Discussion (15 mins)
- **3:15 - 3:30pm** BREAK

Session 2 Chair: Gavin Fay

- **3:30 - 4:30pm** The makings of a good multispecies model (data and modeling requirements)
    - Short review of pre-recorded keynote (5 mins)
    - Breakout Discussion Groups (40 mins)
    - Plenary Discussion (15 mins)
- **4:30 - 5:00pm** Wrap-up
    - Summarize key recommendations/conclusions from the days conversations

Day 3 6/24/21 **2:00pm start** (Eastern Daylight Time)- Moving towards operationalizing multispecies model: Management Needs (Goal 5)

Session 1 chair: Howard Townsend

- **2:00 - 2:15pm** Recap of Day 1 & 2
- **2:15 - 3:15pm** How a fisheries management system can use results from multispecies models in their decision making
    - Short review of pre-recorded keynote (5 mins)
    - Breakout Discussion Groups (40 mins)
    - Plenary Discussion (15 mins)
- **3:15 - 3:30pm** BREAK

Session 2 Chair: Patrick Lynch

- **3:30 - 4:30pm** The management system and need for changes
    - Short review of pre-recorded keynote (5 mins)
    - Breakout Discussion Groups (40 mins)
    - Plenary Discussion (15 mins)
- **4:30 - 5:00pm** Wrap-up
    - Overview of last three days of discussion
    - Summary of key recommendations from each section
    - Discussion of Next steps of writing workshop report/manuscript

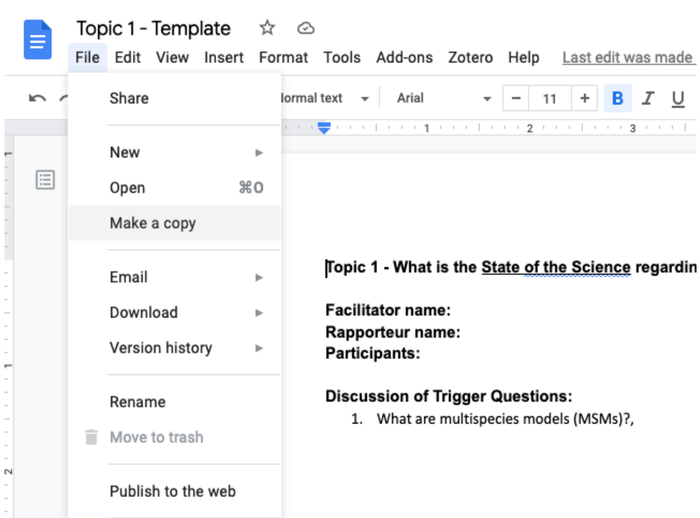
VIII. APPENDIX II: ROLES AND RESPONSIBILITIES

In order to clarify the role of each participant during the breakout and plenary discussions, we provided the below explanations of what was expected from participants:

1. **Facilitator** – The facilitator is asked to direct, guide and facilitate discussion. They should be following and referencing the breakout discussion trigger questions, ensuring that working group session questions are addressed comprehensively and with the aim of securing conclusions; however, a reasonable degree of flexibility should be applied according to the evolution of the discussion and the interests from participants. Try to hold space for all in the group to participate, including encouraging a "Step up, Step back" approach. It is also the responsibility of the facilitator to ensure that there is enough time at the end of the breakout session to summarize the discussion and check-in with the rapporteur to ensure that this summary is captured.

2. **Rapporteurs** – The rapporteurs play an important role in the successful follow up of the working group sessions. Their aim is to ensure that the proceedings and outcomes of the breakout session are clearly recorded so that the discussions can then be of genuine practical value for the meeting outcome. For this meeting we will have 2 rapporteurs for each breakout group, and 2-3 rapporteurs for the Plenary discussions after each breakout session. Each rapporteur will have a specific role/task during the breakouts and Plenary.

   For Breakout sessions:
   Rapporteur #1
   One rapporteur will be responsible for capturing the discussions during the breakout session. To this end they should:
   a. Use the appropriate notes document Template located in each day's folder under the Templates folder linked to (here) to capture the discussion during the session. Please do not write directly in the template, but instead create a copy to use for note taking as there will be more than one breakout group per each topic.



ii. Then, change the files name to be: **Topic # - Breakout group # - your last name**

b. Keep track/take notes from the discussion around each trigger question under that trigger question in the notes document (which you created a copy of in "a" above), and capture any additional discussion which may not fall under a particular trigger question in the "Additional Discussion" section of the template.
c. Work with the group to summarize the main conclusions/recommendations/best practices and note any areas of disagreement or which the group believed warrants further discussion.
d. After the workshop sessions are finished for each day, the rapporteur will be responsible for cleaning up the notes if needed.

Rapporteur #2 (and #3 if applicable)
The second rapporteur will be responsible for monitoring the Zoom chat window, the participants window for raised hands, and pulling out any important discussions and comments, links etc. from the chat window and archiving them at the end of the notes sheet under the section "**Archive Important Information from Zoom Chat Window"**. They will also be responsible for helping the breakout group facilitator manage any questions or points raised in the chat-windows, and highlight any that should be brought up to the group. 2nd rapporteur should keep their "Participants" window open to keep track of raised hands; also need to monitor the chat window, can use private chat to facilitator to alert them to something, or can interject to let facilitators know someone has hand up or has put something in chat window.

The 2nd rapporteur will also be responsible for making sure that if discussion/thoughts are solicited via IdeaBoardz or something similar, that those are saved so they can be referenced in the future. This can be done by clicking on the "Export" button and clicking as either pdf or excel sheet. Additionally, Rap #2 serves as backup to Rap #1 helping to capture notes if the lead misses something or has to step away.

For Plenary:
Each breakout session will end with a 15 minute plenary, whole workshop discussion. Like the breakout discussions, these discussions also need to be captured. Three rapporteurs will be responsible for taking notes and keeping an eye on the Zoom chat windows during the plenary discussions. Notes should be captured here under the appropriate day and topic. One rapporteur will serve as "lead note taker" for that day, and the other two will serve as backups, helping keep track of and archive important conversations and information from the Zoom chat window, and adding notes if the lead misses something or has to step away.

3. **Rest of participants** – The rest of the participants are asked to ensure they have viewed all the pre-recorded presentations, and come prepared to participate actively in the discussion, bringing in examples and experiences they have accumulated. The breakout trigger questions for the discussions will have been sent to all participants beforehand, please read them carefully and prepare for the discussion. Participants are reminded to hold space for all in the group to

participate. We recommend following the ‘one and through’ approach, in that if you have contributed perhaps wait until everyone else has had a chance to contribute before engaging again. If there are *n* people in a discussion, each person should speak for roughly *1/n* of the time. Practice “Step up, Step back”.

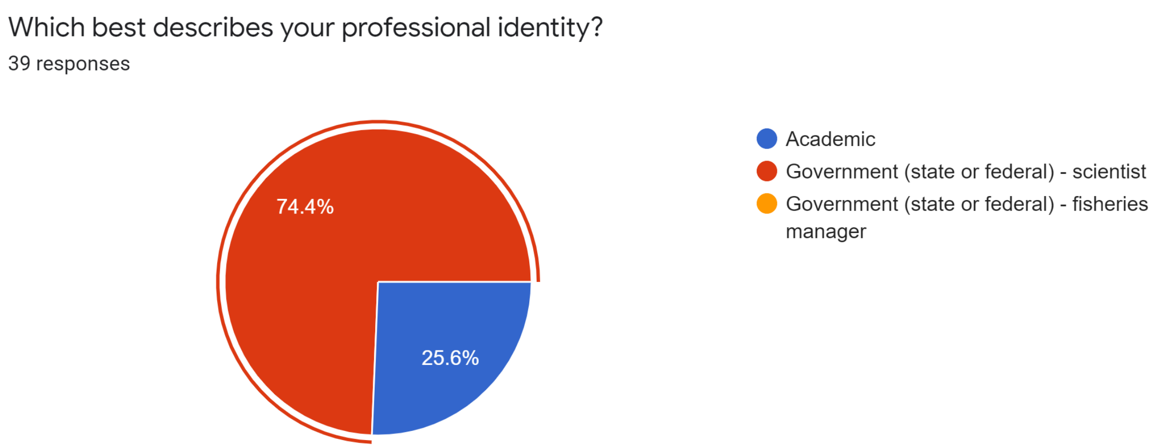
IX. APPENDIX III: PARTICIPANTS LIST

(= Steering Committee)**

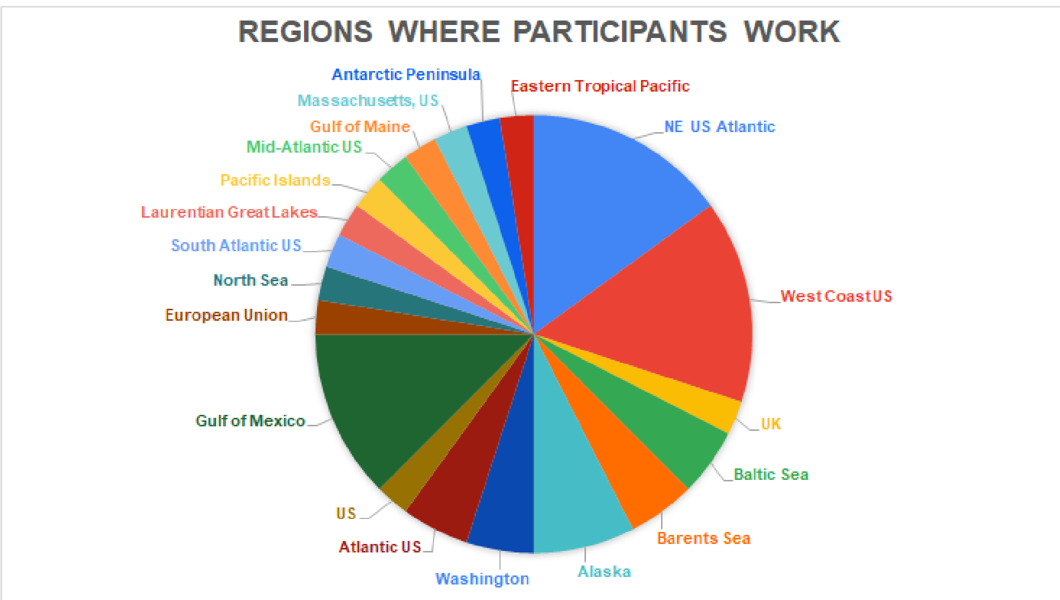
Ali Frey
Amanda Hart
Amy Schueller
Andre Buchheister
Andrea Havron
Andrea Perreault
Angelia Miller
Anna Rindorf
Bai Li
Bjarki Elvarsson
Bjarte Bogstad
Brandon Muffley
Caren Barcelo
Christine Stawitz
Clara Ulrich
Cole Carrano
Daniel Howell
Dave Reid
David Chagaris
Desiree Tommasi
Diana Stram
Doug Kinzey
Eva Plaganyi-Lloyd
Felipe Carvalho
Fiona Edwards
Gavin Fay **
Haley Oleynik
Howard Townsend **
Isaac Kaplan
Janne Haugen
Jason Link **
Jason McNamee
Jeff Vieser
Jim Bence
Jim Ianelli
Jim Thorson
Jonathan Cummings
Kevin Craig
Kiersten Curti
Kristan Blackhart
Lucy McGinnis
Maciej Tomczak
Mackenzie Mazur
Mark Dickey-Collas
Marlowe Sabeter
Matt Cieri
Matt Damiano
Matthew Nuttall
Max Grezlik
Melissa Haltuch
Melissa Karp **
Michelle Masi
Mike Fogarty
Patrick Lynch **
Phoebe Woodworth-Jefcoats
Richard Methot **
Robert Thorpe
Rudi Voss
Sarah Gaichas
Sarah Murray
Scott Large
Skyler Sagarese
Steve Cadrin **
Tim Essington
Vanessa Trijoulet
Villy Christensen
Will Klajbor

X. APPENDIX IV: PRE-WORKSHOP SURVEY QUESTIONS & RESPONSES

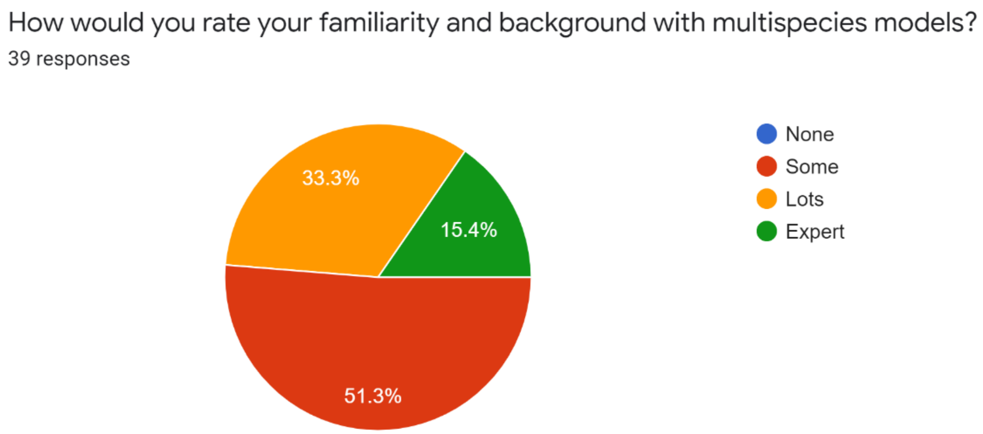
1. What best describes your professional identity?



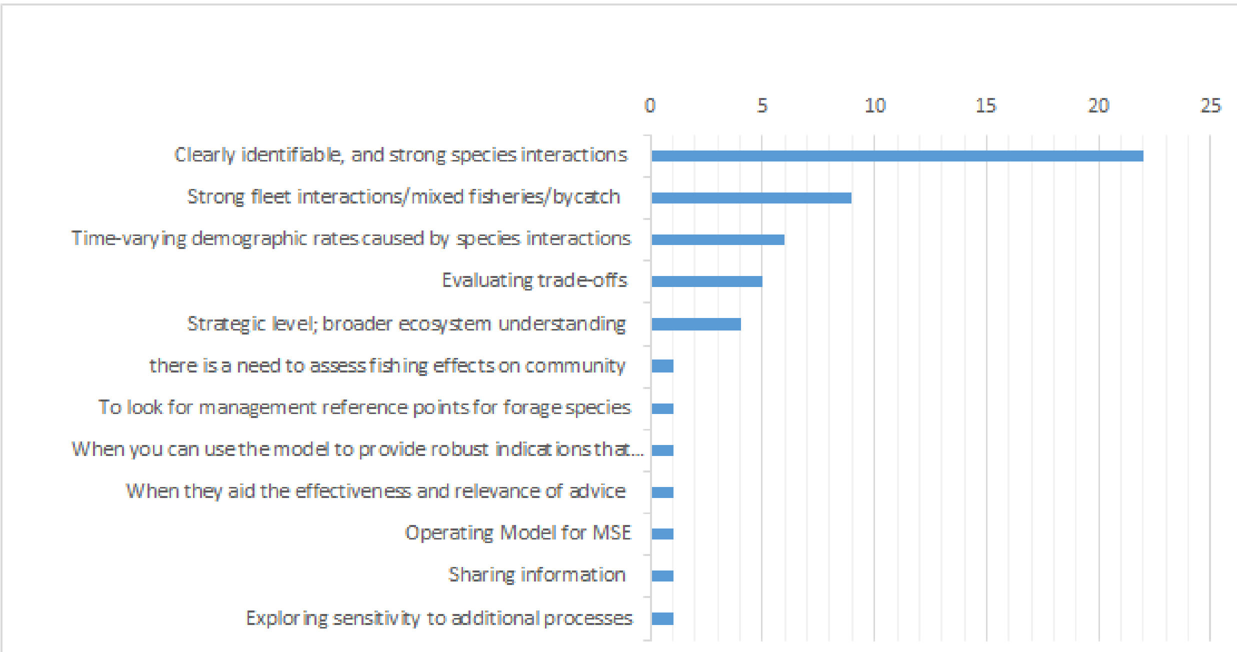
2. What regions have you worked in the most?



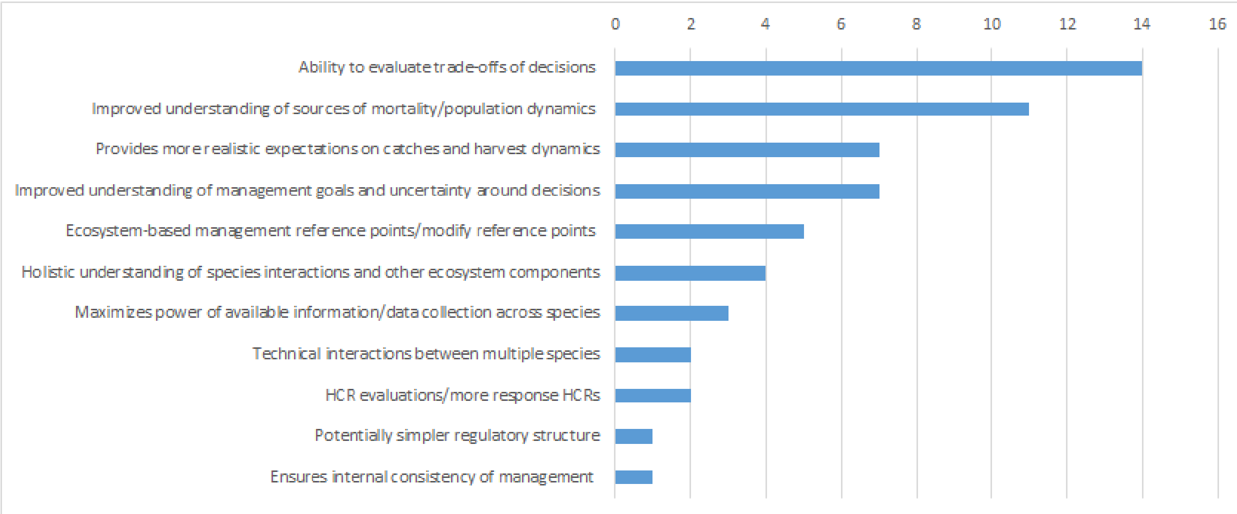
3. How would you rate your familiarity and background with multispecies models?



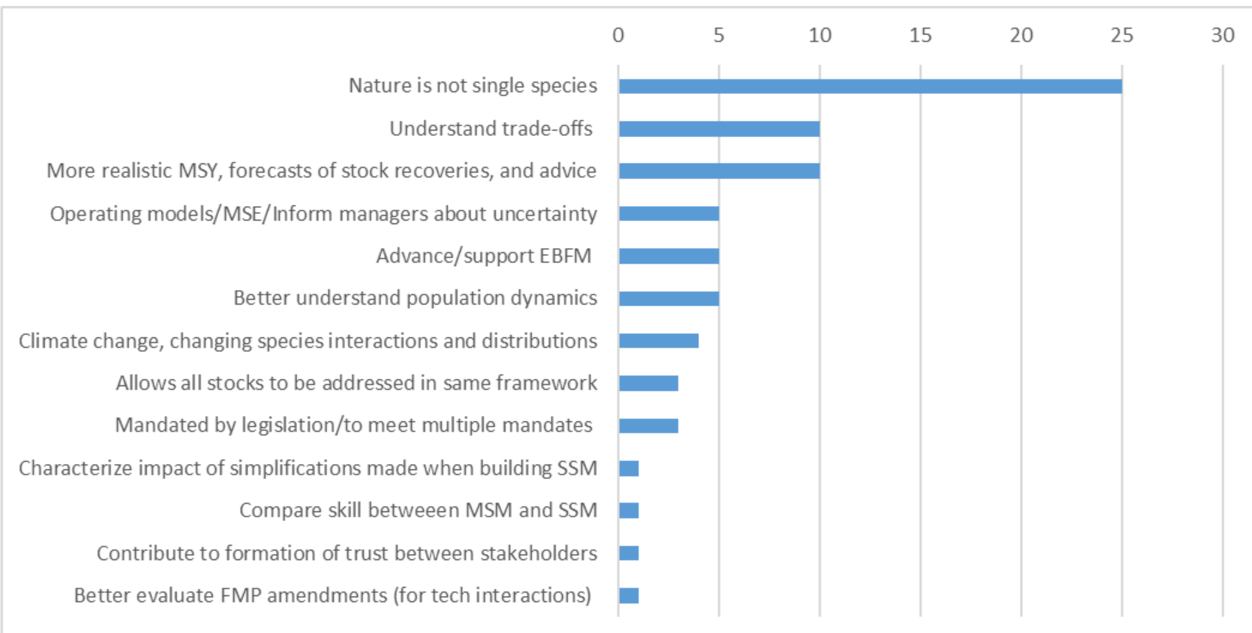
4. When are multispecies models and management beneficial to consider?



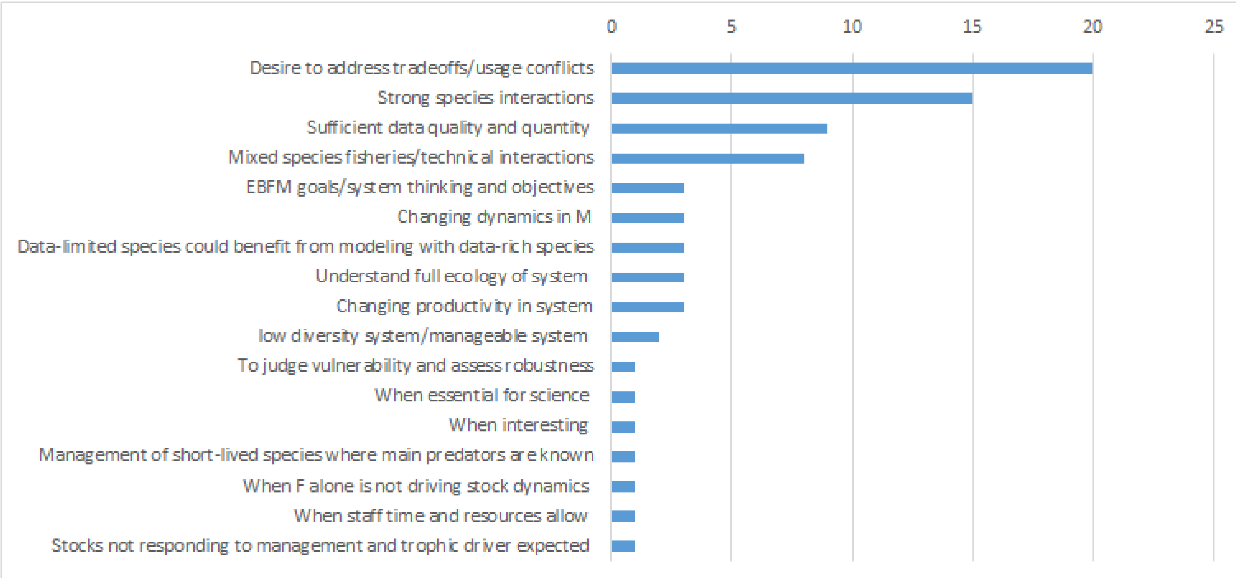
5. What improvements are provided by operational multispecies modeling and management?



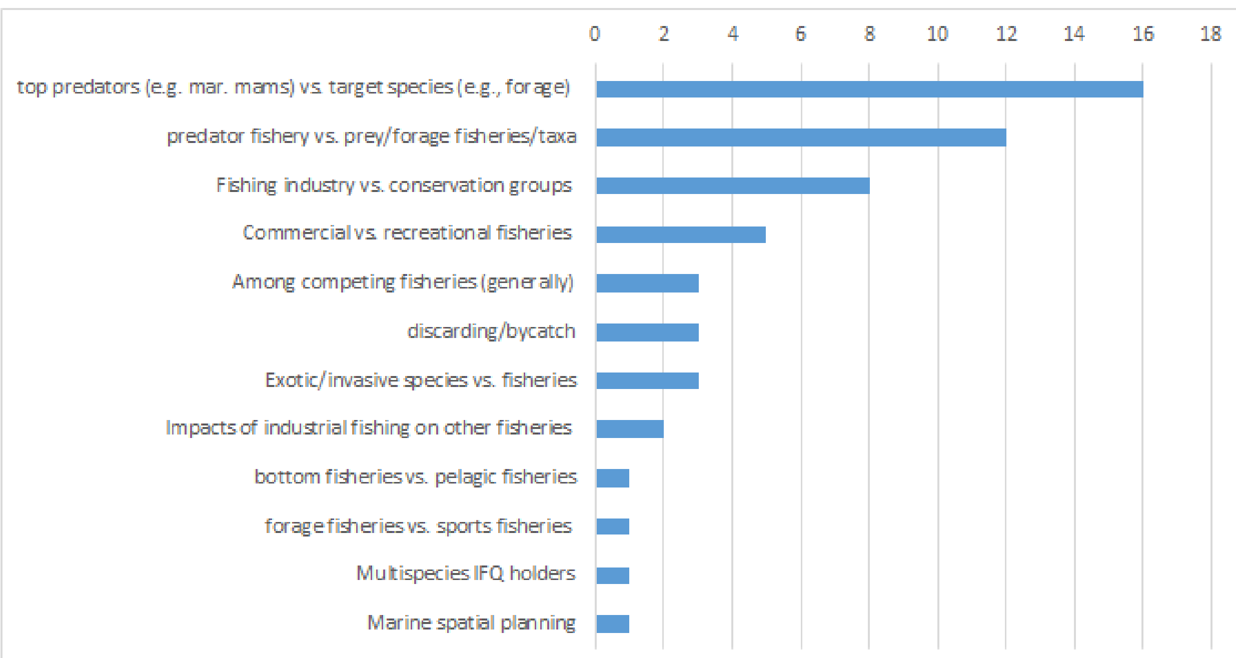
6. What are the top 3 reasons you think we need multispecies models?



7. What are the top 3 situations you think a multispecies model would be appropriate? And Why?



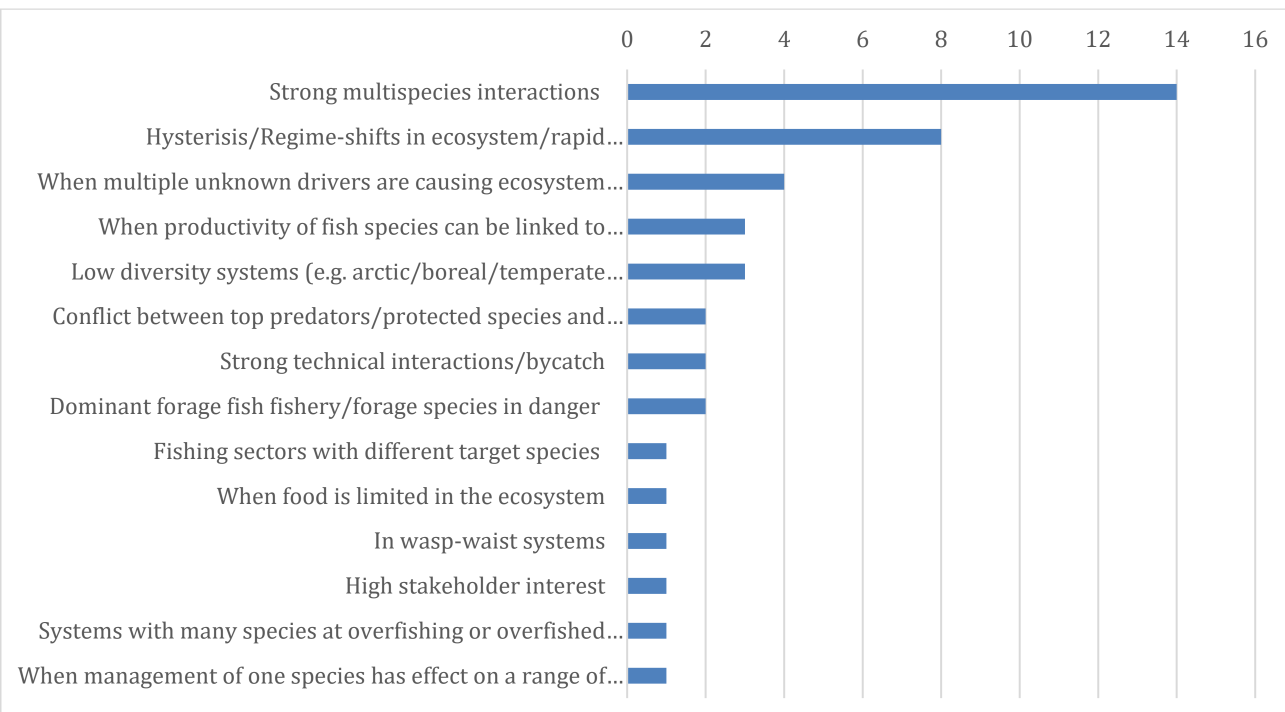
8. What are the top 3 competing interests/stakeholders/taxa groups that you think a multispecies model would help to better address?



9. Can traditional single-species fisheries management continue to meet mandates in the long-term? If not, why? And how and why could multispecies models do better?

Summary of Yes:	**Summary of No:**
Ecosystem does not change/stationary	Ecosystems are not stationary, but are dynamic and nonlinear
When there is is adequate data and assessment frequency (e.g. management objectives and ref points re-assessed regularly to reflect recent past changes)	When relative importance of non-fishing drivers increases (e.g. climate pressures)
In ecosystems or for species with weak species interactions	Systems with strong species interactions/tight linkages
State-space models accounting for multispecies effects through random processes OR models w/ time-varying parameters	SSMs, even when using advanced state-space models, can fail to estimate processes correctly
When M is close to correctly specified or stable	When mandates involve wider aspects of the ecosystem (e.g., EBFM)
To provide tactical catch advice	Long-term planning/longer-term ecosystem objectives (esp when considering impacts of climate change)
Used along with more adaptive HCRs or quota setting that takes into account multispecies interactions	Strategic evaluations/need to evalute management impacts across species or fleets (MSMs improve context, understanding, and tradeoffs evaluations)
	Mixed/multispecies fisheries -- can't meet optimum yield mandate w/o MSM

10. Are there aspects of an ecosystem that point to the need to move towards multispecies models?



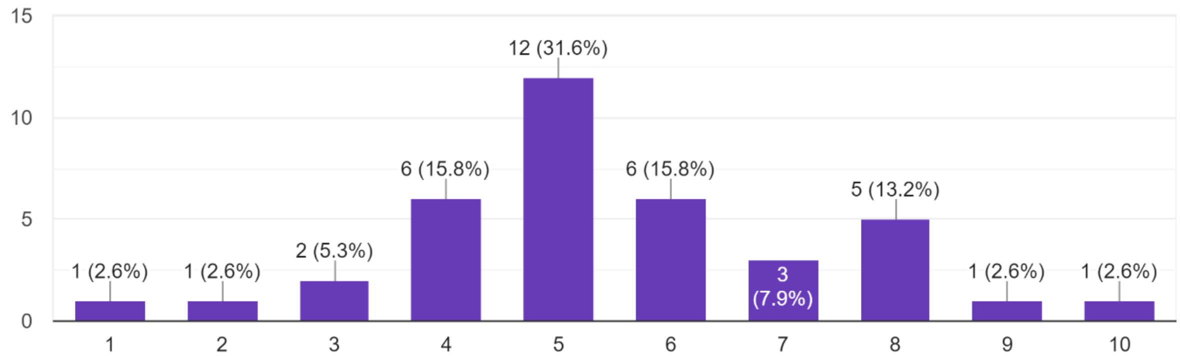
11. What are the top 3 reasons you think we don’t see more use of multispecies models?

THEMES	# RESPONSES
Data limitations (e.g. diet data)	23
Scientific and management convenience/inertia; high bar to implimenting change	11
Model complexity and uncertainy/hard to review/lack formal technical review process	10
Time and money (e.g. staff time, resources, and training)	7
Lack of understanding/opaque hard to explain to non-specialists	7
Management framework not set up for it, MSM development and reference points aren't aligned with management actions, not fully fitted to precise annual fisheries advice	5
Managers are afraid of trade-offs/aren't ready to be faced with prioritizing one group over another	5
Poor predictive behavior/MSMs don't always outperform simpler models	5
Lack of skilled technical experts	4
Lack of availability/applicability of MSMs to learn from	4
Computational demands/Modeling effort and capabilities	4
Lack of interest (from stakeholders and managers)	3
Different management jurisdictions (both nationally and internationally)	2
MSMs are sensitive to assumptions we cannot validate	2
Fear from industry that MSMs will result in reduced quotas	1
Lack management goals	1
Lack of a clear legislative mandate to consider ecosystem dynamics by management	1
Percieved issues of legality in using MSM in management	1
Hard to get complex models to converge	1
Importance of size/age structure within species	1
I've seen increasing use of MSMs, so not sure it's not being "used more"	1

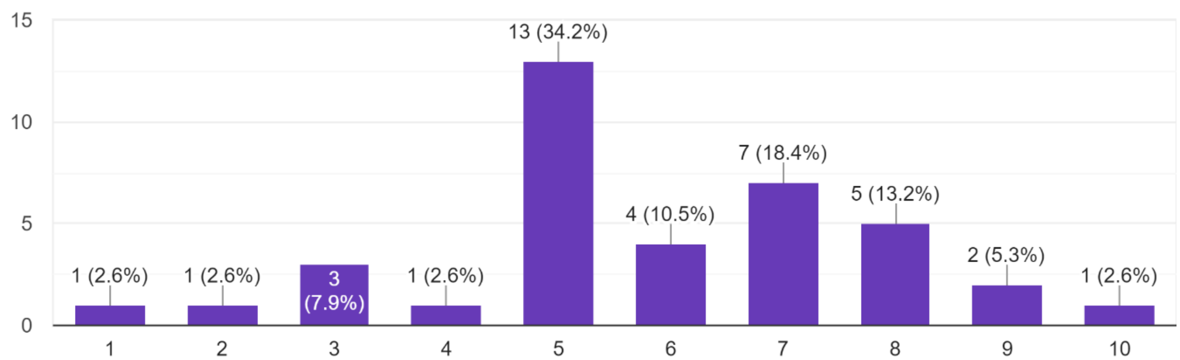
12. What are the top 3 limitations for why we haven't seen multispecies models executed in those situations where it would be beneficial?

THEMES	# RESPONSES
Lack of reliable/robust diet data or understanding of species interactions	8
Management & scientific inertia ("maybe single species models are good enough")/business as usual	7
Expensive/time & money & staff	7
Management favors minimal models (as little extra complexity as needed) & MSMs quickly get complicated	3
Management afraid of trade-offs	3
Lack of clear ability to demonstrate MSMs are "better"/difficult to evaluate & thus sell	2
Lack of trust from stakeholders/transparency in models	2
Timing and output from MSM doesn't align with management needs/timelines	2
No easy definition of what multispecies MSY reference point would be = choices of what to model (which species to include, etc)	2
No trade-offs in legislation	1
Interface to socio-economics not developed	1
Likely hysteresis	1
Poor predictive behavior	1
Fear from interest groups that outcomes would not be in their favor	1
Model uncertainty	1
Lack of operational examples/applications; been mostly academic	1
Lack of interaction between ecosystem modelers, stock assessment scientists, and managers	1
Mismatch between MSM research efforts and the key management questions that could/should be answered with MSMs	1
Lack of knowledge	1
The constraining limitations imposed by interpretation of the NS1 guidelines that perpetuate SS management	1
Emphasis on extended SS models rather then full multispecies models	1
Failure to emphasize the availability of simpler multispecies models that can be more readily implemented and tailored to available data than more complicated MSMs	1
Lack of a clear approach to make incremental steps to transition to multispecies modeling or develop info within SS approach	1
Lack of clear technical review process for these types of models	1
MSMs saddle both fisheries and protected species realms, but modeling for protected and endangered species is usually in completely different frameworks	1

13. How much do you think the limitations to multispecies models are technical (e.g. data, modeling capacity, model development, etc.), with 1 being not at all and 10 being limitations are all technical.



14. How much do you think the limitations to multispecies models are non-technical (e.g. demand by stakeholders, philosophy of science, biological emphasis, management context, etc.)



15. Identify up to 3 priority research questions that if answered would greatly increase the ability to make more effective use of multispecies modeling in operational management.

PRIORITY RESEARCH QUESTION CATEGORY & QUESTIONS	# responses
Data & Ecological Understanding	
Need more extensive diet data (both spatially and temporally) to understand pred-prey relationships & species interactions	9
Identifying mechanistic linkages between environmental drivers and biological responses (e.g. growth, recruitment, distribution, natural mortality)	3
Does food availability have an effect on fisheries productivity?	1
Better information on bottom-up controls	1
How important are multispecies interactions compared with other drivers in the ecosystem?	1
Monitor changes in predation to identify when reference points need to be re-evaluated	1
What is the interaction strength between species caught in multispecies fisheries?	1
Understanding of the role of energetics in ecosystem function	1
Improved understanding of food-web structure	1
Evaluation of competitive species interactions (e.g. red snapper)	1
How to develop data collection/input standards for multispecies models?	1
Model Performance	
In what contexts do multi-species models out-perform simpler models? lead to better management outcomes? Evaluating the performance of alternative single species vs. multispecies models	11
Understanding of model uncertainty (e.g., structural) in multispecies models	3
Rapid diagnosis of poor model output/lack of convergence/estimability	1
How does the uncertainty in the diet matrix impact model performance?	1
How can multispecies models be used for, and improve, species currently in an overfished condition?	1
Modeling Methods & Frameworks	
Being able to construct a forecast system that was validated and able to construct repeated forecasts	4

How to handle lack of/limited amount of diet data to inform multispecies relationships? To what extent can data gaps be filled in by alternative methods (e.g., local knowledge)?	4
Better integration of multispecies models and management with wider ecosystem modeling	2
Better modeling frameworks that provide the ability to include spatial interactions	2
Ways to improve/increase speed by witch multispecies models could be fit to available data	1
What are robust assessment and management models, and accompanying management tools that account for species interactions	1
Can we link single species single species models into a multispecies framework to set multispecies HCRS?	1
Better techniques for integrating different model types within a single multispecies model framework (in other words allowing for a statistical model and biomass dynamic)	1
How can software packages and tools be improved and adapted to facilitate greater use?	1
Management	
How to increase the understanding of and acceptance of models in management	3
How to include trade-offs between species/stakeholders in the advice and management	2
Better understanding and guidelines for how to do multispecies modeling and management (using "have to do multispecies model" situations as examples to draw from). In what situations are multispecies models likely to be the most informative/ most beneficial for the fisheries and ecosystem involved? Some way to triage fisheries into different bins and identifying which ones are actually worth pursuing a multispecies model for.	2
Where in the advice process would multispecies model be most beneficial	1
How often does multispecies model result in increased vs. decreased quotas?	1
How can you flag systems at high risk of management failure from single-species management	1
Socio-economic impacts of multispecies tradeoffs	1
Can multispecies harvest control rules provide benefits stakeholders need?	1
How to involve stakeholders in the transition to multispecies model and increase stakeholder buy-in	1

How can management effectively transition to multispecies model? Are there best practices for first steps, intermediary solutions etc. How can we improve manager buy-in?	1