NOAA Fisheries Strategy for Ecosystem Modeling to Support Operational EBM/EBFM

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U.S. Department of Commerce
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While the listed authors developed this strategy, they did so with input from several working groups and committees in NMFS. The lead developers circulated several outlines and drafts for review, and after each round of development, committee members reviewed and provided comments that were incorporated into this strategy so that it reflects a consensus view of the direction that NMFS should take in developing its ecosystem modeling capacity. The authors would like to thank the following working groups and committees for their input: Ecosystem-based Fisheries Management Working Group, Integrated Ecosystem Assessment Steering Committee, National Ecosystem Modeling Workshop Steering Committee, Management Strategy Evaluation Working Group, Fisheries Integrated Toolbox Technical Team, and the Fisheries Integrated Modeling System Team.

Introduction

Ecosystem models (EMs) are important tools for ecosystem-based management (EBM) and ecosystem-based fishery management (EBFM). Implementing EMs is essential for achieving NOAA Fisheries EBFM and EBM goals. Both EBFM and EBM are needed given the multiple tradeoffs within the fisheries sector (EBFM) and the many tradeoffs across multiple ocean use sectors (EBM) that are ever-increasing. EMs support both EBM and EBFM, though we largely emphasize EBFM here. EMs include a broad suite of modeling approaches, from single-species habitat models to end-to-end EMs that represent an entire ecosystem. There are real benefits and demands for EMs - for example: National Environmental Policy Act analyses for aquaculture, Environmental Impact Statements for offshore wind energy facilities, tradeoffs among commercially or recreationally harvested species, conflicts between goals for protected resources and harvested species management, habitat impacts of human activities, and long-term projections of fish communities' abundance and distribution under climate change all require some level of EMs.

However, uptake and use of EMs are hindered because managers/stakeholders are often unfamiliar with EMs, their benefits, and how they can be used operationally to support ecosystem-based decision-making. Likewise, EM modelers lack guidance on how to tailor outputs to meet a range of specific requirements and conditions for manager and stakeholder decisions. Technical challenges for upgrading research products to operational tools can further hinder uptake and application of EM outputs. Engagement at the policy level, management level, science level, and modeling level is necessary to make full use of EMs and advance EBFM.

To address the needs for and operational use of EMs, NOAA Fisheries provides this EM Strategy to specifically help implement Guiding Principle 4 of the EBFM Roadmap[1], *Explore and Address Tradeoffs within an Ecosystem*. This EM strategy is explicitly intended to ensure that the agency assesses and develops its analytical capacity to evaluate a full range of tradeoffs when making ecosystem-based, living marine resource (LMR) and related decisions.

An EM Strategy will enable a more efficient use of overall agency analytical capacity (e.g., by enabling coordinated management of multiple stocks) and an increased, more strategic use of modeling capacity to serve multiple programmatic needs in different regions. In addition to the EBFM Roadmap, numerous ongoing programs and initiatives require the development and implementation of EMs and model components. EMs can leverage advances in the production of regional climate and ocean information provided through the cross-line office Climate and Fisheries Initiative (CFI)[2], which will span U.S. coasts and timescales from nowcast through long-term climate projections. The Integrated Ecosystem Assessment (IEA) Program[3] uses EMs for stakeholder engagement (e.g., conceptual and semi-quantitative models of regional social-ecological systems) and scenario evaluation of management strategies (e.g., evaluation of forage fish management strategy evaluations (MSEs) for the Pacific Council, MSE development for Atlantic herring in the New England Council, etc.). The Fisheries Integrated Modeling System[4] (FIMS) endeavors to transition from advice that has been mostly focused on population dynamics of single species to advice that is better linked to environmental, ecosystem, and human dimension factors by integrating ecosystem, climate, and oceanographic processes and models into tactical stock

[1] https://www.fisheries.noaa.gov/resource/document/ecosystem-based-fisheries-management-road-map
[2] https://cpo.noaa.gov/Meet-the-Divisions/Climate-and-Societal-Interactions/The-Adaptation-Sciences-Program/Climate-and-Fisheries-Adaptation-CAFA
[3] https://www.integratedecosystemassessment.noaa.gov/
[4] https://www.fisheries.noaa.gov/national/population-assessments/fisheries-integrated-modeling-system

assessments for stock status determination. The Interdisciplinary Forecasting Approach for Ecosystem-Based Fisheries Management Project[5] aims to similarly incorporate ecosystems and other drivers to provide advice on future catch levels developed by applying a management harvest policy to a forecast of stock and fishery dynamics. The Human Integrated Ecosystem Based Fishery Management Research Strategy[6] (HI-EBFM) specifically sets a goal to develop integrated EM approaches that couple humans and the environment. Doing so will create modeling and evaluation frameworks that contribute to IEAs, MSEs, and other frameworks that facilitate an EBM approach. All of these initiatives, efforts, and strategies will rely on and place increasing demands on EMs.

Developing and implementing the strategy, in conjunction with other initiatives and programs, will additionally aid NOAA Fisheries in achieving the goals laid out in other strategic documents (e.g., EBFM Policy[7], NOAA Fisheries Climate Science Strategy[8], Next Generation Stock Assessment Improvement Plan [Lynch et al., 2018], HI-EBFM plan, Habitat Assessment Improvement Plan [NMFS, 2010], etc.). Further development of a modeling capacity that integrates existing modeling and management approaches will create a comprehensive strategy in support of our mandates. A more comprehensive and transparent approach to addressing multiple mandates will result in smarter decision-making and fewer surprises (unintended, unanticipated effects of decisions) for managers. Smarter decisions will result in an improved status of LMRs, which will result in improved stakeholder adaptive capacity. In addition, improvements to EM capacity laid out in the strategy will ultimately save the agency resources by ensuring more optimal use of current and newly developed capacity and by planning for more efficient use of models and staff that support the models.

Goal and Objectives

The goal of this strategy is to accelerate operational delivery of EBM/EBFM advice (i.e., incorporating ecosystem considerations into management advice) provided by EMs.

The objectives to be met to achieve this goal are:

1) Promoting knowledge sharing among ecosystem modelers, protected resources, and fish stock assessors, managers, and stakeholders to improve how EM outputs can better serve decisions,
2) Streamlining model development, operational implementation, and management review by ensuring timely and efficient data streams, using established EM software, and developing new software where current structures do not adequately capture key ecosystem factors, and
3) Ensuring future capacity needs are met by expanding NOAA Fisheries EM capabilities and capacity.

[5] https://bai-li-noaa.github.io/IFA4EBFM/
[6] https://www.fisheries.noaa.gov/human-integrated-ecosystem-based-fishery-management-research-strategy-2021-2025-executive-summary#integrated-ecosystem-research
[7] https://www.fisheries.noaa.gov/resource/document/ecosystem-based-fisheries-management-policy
[8] https://www.fisheries.noaa.gov/national/climate/noaa-fisheries-climate-science-strategy

Background

EM comprises "a wide range of modeling and analysis tools that are used to support the implementation of EBFM. These tools include conceptual models and related analytical approaches ((Harvey et al., 2016) and a variety of expanded assessment, biophysical, multispecies, food-web, and end-to-end EMs (further described in Plagányi, 2007; Townsend et al., 2008). This range covers models and analyses that consider only a few external factors influencing a single fish stock to a more holistic set of factors (e.g., climate, currents, biogeochemistry, trophic interactions, fisheries, human dimensions [Rose et al., 2010; Fulton et al., 2011]) influencing multiple, interacting fish stocks (Townsend et al., 2019). Throughout this document, EMs can be thought of more broadly as analytical tools to support EBM/EBFM that address more holistic questions than can be addressed by the principally single-species population dynamics models and supports interoperability between these two scales of integration.

EMs are needed for integrating across NOAA Fisheries mandates and advancing EBM/EBFM. Incorporating ecosystem considerations into fisheries management is underscored in the Magnuson-Stevens Fishery Conservation and Management Act. Similarly, incorporating ecosystem considerations is important for marine mammal and endangered species population assessment as required in the Marine Mammal Protection Act, the Endangered Species Act, and more broadly for cumulative effects analysis under the National Environmental Policy Act. In addition, ecosystem interactions are core considerations in the habitat conservation carried out by NOAA Fisheries under multiple mandates.

Within NOAA Fisheries, EMs are important for supporting holistic, EBM advice that quantifies cumulative impacts, pressures, and drivers, and to identify non-intuitive outcomes. Initially, EMs were used heuristically to improve understanding of ecosystem function and structure. EMs in conjunction with Ecosystem Status reports are now used operationally in most Fisheries Science Centers (FSCs) to provide heuristic and strategic management advice on an operational basis (e.g., operating models in MSEs). The aim of this operational ecosystem advice is to increase efficiency and synergy across management actions through quantification of direct and indirect interactions and tradeoffs, and to ensure desired management outcomes through accounting for uncertainty in model projections of management performance.

With recent successful application of EMs to fisheries management and other decision-making (examples summarized in Appendix A), EMs are moving into tactical applications and thus the need and demand for models to support EBM/EBFM is increasing. Increasing demand coupled with multiple impacts and pressures requires approaches that account for cascading and interacting effects. Several examples (e.g., Pacific Marine Heat Waves, Gulf of Mexico red tides) show how extreme events and requests from stakeholders create demand for EM and support for EBM/EBFM. In addition, the inability of single-species models to objectively assess trade-offs, where management bodies need to address conflicts within and between fisheries stocks and other LMRs, highlights the increasing demand for EMs. Ecosystems can amplify or attenuate effects of various natural and anthropogenic drivers. EMs can be linked to climate projections to evaluate the implications and trade-offs in a non-stationary system. Accounting for such effects enables management of LMRs to be closer to the efficiency frontier (Sanchirico et al., 2008) and provides tools that are responsive to changes and account for lags in the system to drivers and pressures. Incorporating socioeconomic models and tools with EMs allows testing of ecosystem response to various scenarios for proactive management.

With these successes, along with increased awareness of ongoing tradeoffs and increased awareness of sentinel species warning of ecosystem change, demand for EMs to support EBM/EBFM will increase. NOAA Fisheries' capacity to execute EMs has improved during the past 20 years. Only one FSC had formal EM capacity (i.e., a focused modeling group or team) 20 years ago; now all FSCs have formal EM groups or capacity, yet needs still remain. Plans for how to ensure each FSC has adequate EM capacity and capabilities are outlined below. FSCs may modify aspects of the plan to address key regional issues more specifically.

Strategy to Ensure Regional Modeling Capacity to Support EBM/EBFM

To address major EBM/EBFM issues in their regional ecosystems, FSCs need adequate EM capabilities and capacity. This requires a portfolio of models that are developed, fitted, or tuned to data, updated and applied at regular intervals, and applied for EBM/EBFM-related issues. A model portfolio should include models with a range of structural complexity. A minimal model set in each region would ideally include: one to three simpler models (e.g., extended stock assessment models, multispecies surplus production models), one to three models of intermediate complexity (MICE; beyond MS Production models), and at least one or two more complex models (e.g., end-to-end models, food web models, coupled biophysical models, coupled socioecological models, other network models). Within the model portfolio, a few should be spatial models that can be used for spatial planning, survey optimization, and spatial climate linkages. In addition to the core EMs, a model portfolio should also include visualization tools for stakeholders and managers to explore and better understand ecosystem structure, function, and potential scenarios or responses to management actions. Fortunately, in many regions, parts of this modeling portfolio already exist, but the interfacing and interoperability within and among regions warrants improvement.

Developing a model portfolio requires input from other analysts, communication experts, resource managers, and stakeholders to identify appropriate modeling systems and focal ecosystem issues, which can, in turn, promote knowledge sharing and ensure ecosystem information supports better decisions. Operationalizing a model portfolio requires a streamlined process for standardizing and delivering model inputs, use of established software or software modules, and review of the software and applications for accuracy. Maintaining and expanding a model portfolio is necessary to ensure future EBM/EBFM-related advice and needs are met.

Developing an EM portfolio does not mean that we intend to apply just a few model types to all EBM/EBFM problems confronting LMR managers. On the contrary, we expect that customization and new modeling will often be required to address emerging challenges; however, model building blocks must be available to analysts since management timeframes (often months) are short compared to the years required to develop and vet most EMs. "As fishery managers tackle complex questions involving spatial relationships, species interactions, and climate effects as well as stock assessment performance, having a range of mix-and-match tools available to analysts will answer these questions more effectively and efficiently" (Kaplan et al., 2021).

1) Promoting knowledge sharing among ecosystem modelers, protected resources and fish stock assessors, managers, and stakeholders to improve how ecosystem model outputs can better serve decisions

FSCs should have a stakeholder-oriented process, which must include resource managers, to determine the models (based on objectives and needs) to be included in a model portfolio and to participate in the development process for each model application. Biological and oceanographic scientists can identify biophysical factors that drive and organize system dynamics. Social scientists can identify human activities that influence and are dependent on ecosystems. In developing the model portfolio, modelers should give some attention to spatial and temporal scale – for hindcasts and for forward-looking projections (e.g., nowcasts, seasonal forecasts, decadal projections). A co-development process between modelers, scientists, managers, and stakeholders will improve modelers' and scientists' understanding of management needs as well as managers and stakeholders understanding of ecosystems and EMs. This knowledge-sharing process will help regions identify the levels of information that can be provided by EMs. In early phases, conceptual models (and related tools) will help develop a shared understanding of ecosystem structure and function. These models then can provide a background for more quantitative models that can be used to provide general quantitative ecosystem information relevant to a specific topic, as well as specific ecosystem interactions and functions that may be incorporated to adjust management reference points or for direct ecosystem-level reference points.

Conceptual models are a useful way to incorporate stakeholder input on important ecosystem components and drivers. In addition, they are useful for identifying important ecosystem indicators. Stakeholders can identify ecosystem issues with which they are concerned (e.g., fisheries management options, protected resources take, habitat permitting, etc.). Conceptual models and stakeholders process could arise *de novo* from external partners/research programs, but they will need to involve adding modeling to support existing management and stakeholder processes at the level of regional fishery management councils (FMCs), states, tribes, commissions, and other entities such as National Marine Sanctuaries and regional ocean planning groups.

This type of stakeholder process can promote knowledge sharing and lead to development of on-ramps for including ecosystem information into management advice. Many regional planning bodies have regular meetings where decisions are made and regulations are set, but often meeting agendas are quickly filled with regular business. Opportunities to present new ecosystem information for management (on-ramps) can be hard to find, as many management bodies (e.g., FMCs) have full agendas for regular business and are not often set up to onboard new approaches. When stakeholders work with modelers to establish model portfolios, on-ramps can be identified. Modelers should also identify existing and potential on-ramps for EBM advice such as ecosystem status reports, ecologically enhanced stock or habitat assessments, social-ecological indicators, and MSE evaluations. In addition, within this stakeholder development process, stakeholders can work together to identify specific means to 1) connect ecosystem function to specific management indicators (e.g., reference points for fisheries) and 2) develop management decision tools from EM output (e.g., vulnerability analyses, scenario planning, and risk assessments).

As FSCs develop their model portfolio and model applications, sharing of models nationally across regions will be necessary – both in terms of models themselves but also best practices. A shared modeling tool set and national workshops will facilitate cross-regional sharing. These components of this strategy are discussed below.

2) Streamlining model development, operational implementation, and management review by ensuring timely and efficient data streams, using established ecosystem modeling software, and developing new software where current structures do not adequately capture key ecosystem factors

As model portfolios are established, systems are needed for software and data streams to ensure timely and operational applications of models and provisioning of results to managers and stakeholders. In addition, standardized review processes for software and model applications will further expedite operational model applications.

Software

To facilitate model code sharing, standardization, and review, a model software portal is necessary. Using established software for operational analyses will enable more efficient use of resources when developing model applications for management. The Ecosystem Tools[9] section in the Fisheries Integrated Toolbox[10] (FIT) is the software portal that can meet these needs. FIT has both internally developed software and external software. The FIT will make it easier to share and access a multitude of software tools from a consistent location and interface.

Within the FIT, standards for software testing, vetting, and "badging" are being developed. For each model type, a "documentation template" will be needed. The template must at a minimum include 1) reference documentation for input/output interface (targeting users); 2) model documentation listing all relevant equations, logic, and assumptions embedded within the ecology or population dynamics (targeting reviewers); and 3) software code reference documentation providing descriptions of exported functions and methods, examples, and links between functions/objects (targeting future maintainers). Using nationally consistent and standardized software will help with the management review process, as external reviewers can spend most of their review time focused on reviewing model applications rather than model code.

As need for new modeling software arises, model software developers interacting with the FIT Technical Team can support development. Working through an organized national team, like the FIT Technical Team, can help identify and coordinate needs (minimizing duplication), and provide space for innovation. By connecting with a larger global community through this modeling portal, regional NOAA Fisheries modelers can more readily adapt to externally developed software for regional applications, while ensuring that the software meets established standards. In addition, with the FIT team, model software developers can work together to improve the user experience (e.g., GUIs, visualization).

Data Streams

Beyond standard fisheries survey and catch data, EMs require a range of biological, physical, and socioeconomic data. For these models to be applied on an operational basis, systems for ensuring data availability at appropriate intervals are necessary. This will require regular assessment of data needs and automated processes to prepare data inputs for models. Regular assessment of data needs is necessary because in many cases needs are known but in other cases data may become important later as environments change (e.g., sea ice, loss of habitat, etc.).

To ensure comparability of models in a regional model portfolio, consistent processing, metadata, and data standards should be applied to input data. The input data types for each model in the portfolio may vary depending on the model structure. For typical fisheries data (e.g., catch and surveys) existing approaches for data collation can be standardized. For non-fisheries EM components (e.g., protected resources, non-target species, habitats), additional work is needed to integrate data streams. In addition, for data from other sources (e.g., state agencies) long-term data agreements may be necessary.

Development of operational "end-to-end" data toolchains (all steps from field data to initial processing to model running/updating reproducibility, easy to regularly update, and streamlined) will aid in operationalizing models. Documented automated processes for converting raw data to

[9] https://nmfs-ecosystem-tools.github.io/

[10] https://noaa-fisheries-integrated-toolbox.github.io/

model input are necessary to ensure models are using the same data, which will be important for synthesis of outputs and for management review of model applications. In addition, time saved on data "wrangling" allows more time for portfolio development and output synthesis. Standardization also ensures data are portable between models of different scales (e.g., FIMS) and in different regions

Review Processes for Model Applications and Software

Largely, FSCs have used ad hoc protocols for applying a model to a management issue, i.e., how to conduct model development/refinement; validation/calibration; clear diagnostics; and standards of model use and output reporting (Townsend et al, 2008; Link et al, 2010). To streamline the process, a standard, cross-regional, external review process that ensures model applications are adequate for supporting operational EBM/EBFM decision-making at the strategic and tactical level will need to be implemented. There needs to be capacity for understanding this type of information at the Scientific and Statistical Committee/ Council level to ensure that a model application 1) is providing the best scientific information available and 2) can be reviewed and translated into management (e.g., harvest) guidelines. Apart from model applications the modeling software requires review to ensure that model equations and logic are being produced correctly in the software. The software review process will be facilitated through a software portal – FIT. The portal will facilitate specific code review and code management (versions, repository, archiving) as well as model code templates and styles to ensure consistency and transparency.

3) Ensuring future capacity needs are met by expanding NOAA Fisheries ecosystem modeling capabilities and capacity

Building capabilities and capacities in the FSCs will require collaboration, training, and additional personnel. Often regions have more expertise in a given model type than exists in modeling teams in other regions. Cross-regional collaboration can facilitate developing new capabilities in a region. As new capabilities are built, instituting processes for transitioning research models to operational models will be necessary. Measures for long-term support and maintenance of all models in the portfolio will have to be put in place at FSCs. Shorter-term research can be used to adapt existing models in the portfolio to address novel management issues, to develop and incorporate new models into the portfolio, and to develop approaches for quantitative synthesis of model portfolios to enable multi-model ensembles.

To share ideas and best practices and for operationalizing models and supporting the research-to-operations transition (and support the goals and objectives of this strategy), a national steering committee is necessary. Currently the National Ecosystem Modeling Workshop (NEMoW) Steering Committee convenes every two to three years to plan workshops that focus on best practices and new ideas for developing and implementing EMs for EBM/EBFM. The NEMoW Steering Committee could be adapted into a broader purpose committee that meets more regularly (quarterly) and works on a wider range of issues with respect to operationalizing EM across regions. The committee would need an expanded membership (i.e., include policy experts from the NOAA Fisheries Regional Offices, social scientists, and stock and protected resource assessors) that rotates periodically to promote interdisciplinary collaboration and help ensure that models meet management needs.

This steering committee should identify points-of-contact for each tool in each region, so that users for each model can be associated as a "community of practice" both within and across regions. This will help any given region that lacks a particular capability to develop it. More specifically, the

Steering Committee could work to fulfill more immediate needs (especially for regions with current, limited capacity) by intermittently providing a National Implementation (matrixed) team of modelers, social scientists, and others to develop needed models. The EM coordinator will organize the steering committee. An EM programmer will work with the committee and the FIT Technical Team to bring new models into the FIT and conduct software testing and review.

By developing a national community of practice for EM, NOAA Fisheries would be better able to leverage international partners. These include working groups at PICES and ICES, such as the PICES WG43/ICES Small Pelagic Fish teams, and the ICES Working Group on Multispecies Assessment (WGSAM), among others. Individual staff engaged in these working groups can transmit information learned to other NOAA Fisheries modelers engaged in the community. Establishing international collaborations for modeling will be necessary for transnational EBM/EBFM issues. These connections will also be useful for the rapid uptake and dissemination of EM innovations developed abroad. An added benefit of international collaborations is that these connections can be used to develop a pool of international reviewers who can critique and guide NOAA EM efforts.

Future demands will require expanded EM capacity. This will require training and support for cross regional collaborations and mentoring (both within NOAA and cross-institutional scientists and early career researchers). This training can be accomplished through training sessions at all FMCs and partner organizations and through teaching partnerships with university partners (training workshops for early career researchers). The QUEST Program, Sea Grant, Cooperative Institute partners, etc. can be used to facilitate this education and outreach. Many FSCs leverage short-term cooperative agreements and contracts to develop models, however, to maintain models for operational applications permanent staffing within the FSCs will be necessary.

Outcomes and Requirements

The goal of this strategy is to accelerate operational delivery of EBM/EBFM advice (i.e., incorporating ecosystem considerations into management advice) provided by EMs, which should result in these high-level outcomes:

1) Improved quantification of cumulative impacts, pressures and drivers and identification of non-intuitive outcomes;
2) Increased efficiency and synergy across management actions through quantification of direct and indirect interactions and tradeoffs; and
3) Enhanced accounting for uncertainty in model projections of management performance that ensure desired resource management outcomes.

The direct outcomes of implementing this strategy are:

1) Improved uptake and application of EM results in management decisions,
2) Increased efficiency in delivery of EM results, and
3) More expansive/comprehensive EM capabilities that can support a diversity of needs.

Broader implications of implementing this strategy include:

- Streamlined and consistent operational EBM/EBFM advice provided to NOAA Fisheries' constituents – FMCs and other management bodies.
- An improved ability for NOAA Fisheries to integrate management advice across mandates and in support of multiple existing programs and initiatives (IEA, CFI, FIMS, Human Integrated EBFM, Forecasting, MSE Strategy, etc.).

- Enabling managers and other stakeholders who are engaged in using EMs to address an array of issues related to fisheries, other LMRs, climate, and habitat.
- More efficient use of data, software, and staff for developing models and transitioning them to operational implementation.
- Effective review processes and processes to ensure model software and applications are providing the best available science for managers.
- Adequate capabilities and capacity at each FSC to address major EBM/EBFM issues relevant to the regions under their purview.

Implementing this strategy will require:

- FSCs to establish a portfolio of models for their regional ecosystems using shared national software approaches relevant to issues in their ecosystems.
- Using existing and establishing new stakeholder engagement processes (through FMCs and other regional processes) to build out portfolios and identify new model needs as they arise.
- Developing end-to-end data toolchains to ensure data are available at timely intervals for operational model application.
- Supporting a programmer/software architect for the development of the Ecosystem Tools section of the FIT.
- Engagement with and regular use of the FIT to
    - apply existing model software to existing relevant management issues,
    - expedite dissemination of new software,
    - establish and implement software review protocols.
- Establishing clearer and routine expectations that ecosystem information and materials will be provided to managers and other stakeholders, which includes establishing clear standards and processes for development of models, model applications, model output visualization, and model review.
- Building capacity at each FSC and nationally through training and mentoring to ensure models are aptly executed and professionally developed and maintained.
- Instituting a national steering committee that fosters cross-regional capacity-building and gap-filling as well as leveraging international capabilities for EM development, application, and review.
- An understanding of the availability and applicability of regional data to support EM to make sure EM assumptions are reasonable for data.
- Greater coordination between EM and IT support to provide appropriate and secure IT resources.

Meeting these requirements is necessary so that FSCs have the necessary components of an operational EM team/program in place to meet the rising demand for EBM/EBFM. Meeting these requirements may also seem overwhelming; however, most FSCs have some of these components in place or under development. Existing initiatives and programs can be leveraged to help fulfill some of the requirements. The CFI seeks to build modeling capacity for connecting climate to ecosystems, so working in conjunction with the CFI will help to fill out model portfolios. The IEA program has supported model development and implemented stakeholder engagement processes in several regions. These can be expanded to provide iterative discussions on modeling needs, development, use, and review. IEA investment in automated data streams (to create ESRs) can also help support the dataflow to EMs. The FIT provides an existing outlet for model software collaboration and formal review. NEMoW and the NEMoW steering committee foster cross-collaboration on model development, application, and review. This steering committee could be given a broader charge and meet more regularly to expedite implementation of necessary components of an operational EM team/program across FSCs. Largely this strategy can be implemented with existing or minor additional resources and this strategy aims to develop efficiencies with data and software to minimize the need for new resources. However, some additional personnel may be needed to support engagement with management bodies and as needs for more ecosystem information in management arises.

To achieve the goals and objectives of this strategy, NOAA Fisheries ecosystem modelers need Leadership support:

- To work within existing programs and initiatives to implement the requirements of this strategy,
- To facilitate interactions with FMCs and other management bodies to support use of EMEM output and risk assessments, and
- To make resources available or use resources procured to conduct ecosystem modeling and to support the ongoing maintenance of operational EMs – e.g., capacity needs with respect to personnel.

Appendix A - Examples of Successful Application of Ecosystem Models that have Informed Fisheries Management and Other Resource Decision-Making

Atlantic Menhaden

In 2020, the Atlantic States Marine Fisheries Commission (ASMFC) approved the use of ecological reference points (ERPs) in the management of Atlantic menhaden. This is a major step towards operational EBFM. Their role as a forage fish supporting predatory fish, marine birds, and mammals has long been recognized but not well quantified – until now. ERPs expand on biological reference points by taking into account the ecological role a species plays. ERPs provide a quantitative tool to evaluate their ecological role and enable managers to explicitly account for trade-offs among fisheries stocks while considering stakeholder desires for the ecosystem. The ASMFC approach for setting ERPs uses a combination ecosystem and population dynamics model. Output from the EM allows stakeholders to visualize a range of options for fishing levels on menhaden and its key predators. Managers can then use the model output to set reference points that account for the stakeholders' desires and ecological constraints.

Modelers from the Southeast Fisheries Science Center and Office of Science and Technology worked in the ASMFC Atlantic Menhaden Technical Committee and Ecological Reference Point Workgroup to develop the stock assessment and EMs needed to develop ERPs.

Summary from Anstead et al. (2021)

Herring MSE

In 2016, a stakeholder-driven management strategy evaluation that incorporated a broad range of objectives for Atlantic herring was completed. Herring were linked to three sensitive predator types with adequate data to justify modeling; no existing model addressed all objectives. Three control rule types – constant catch, conditional constant catch, and 15% restriction on annual change – were rejected at the second stakeholder meeting for poor fishery and predator performance. Predators were not sensitive to the range of remaining harvest control rules because they were evaluated within FMSY for herring. Multispecies models of intermediate complexity were informative for managers and provide a foundation for future improvements.

Northeast Fisheries Science Center modelers were able to implement this Council-requested MSE in about a year, because they had a model portfolio and an institutional data system that enabled a rapid response to a model request.

Summary from Townsend et al. (2020)

EcoCast

The Southwest Fisheries Science Center (SWFSC) Environmental Research Division, Fisheries Resource Division, Fisheries Ecology Division, and the Marine Mammal and Turtle Division are using statistical habitat models to create maps of species distribution relative to anthropogenic threats and human activities. These efforts include a range of fish, sharks, mammal, and turtle species using generalized additive mixed models, boosted regression tree models, and Bayesian approaches to understanding species-habitat relationships, and using these relationships to predict habitat in space and time. These tools assume maintenance of the relationships to allow persistence through time and require ongoing validation when operationalized.

SWFSC is working with managers and fishers to make these nowcast products operational for informing fishers on how to avoid bycatch.

Summary from Townsend et al. (2020)

Gulf of Alaska Pacific Cod

The Gulf of Alaska experienced an unprecedented marine heatwave from 2014-2016, which caused persistent and widespread sea surface temperature increases of 1-2°C and extensive ecological responses. The North Pacific Fishery Management Council had been informed of the changes in the ecosystem during the heatwave, but Pacific cod was the first managed stock to show a steep decline that could be explained in part due to the heatwave. Collaboration among the stock assessment author and ecosystem scientists resulted in: 1) an explanation of the Pacific cod decline due to heatwave-related increased adult mortality and lack of recruitment in the stock assessment, and 2) an EM-based assessment of Pacific cod bioenergetics and diet limitations within the context of trophic-level wide negative impacts of the marine heatwave in the ecosystem assessment.

Summary from Townsend et al. (2019)

Hawai'i Coral Reefs

In Hawai'i, coral reef ecosystems are degrading in many regions due to land-based pollution, fishing, coastal development, and other local stressors combined with the devastating 2015 coral mortality from ocean warming. Though coral reefs can recover over decades, climate models project that coral bleaching related mortality may occur annually within the next 20-25 years. Changes in marine resource management are needed to improve recovery of ecosystem structure and services. The majority of Hawai'i's reefs are within state waters; however, under the Coral Reef Conservation Act, and specified in the EBFM road map, NOAA works with jurisdictions to support coral reef conservation and management. Hawai'i's coral reef management embraces an ecosystem-based approach to management to guarantee that ecosystem services such as fishing and a resilient ecosystem structure are maintained or improved. The Pacific Islands Fisheries Science Center worked with the state and University of Hawaii through its IEA process to develop models that evaluated stressor effects on reefs and reef ecosystems. Ecosystem modeling and analysis was used for strategic management decisions, i.e., to get insight in the socio-ecological tradeoffs in alternative marine and land-based management strategies.

The state management agency was confident that the use of the regional EMs will facilitate the ongoing discussion.

Summary from Townsend et al. (2019)

Gulf of Mexico Grouper

Severe red tides in this region frequently cause mass mortality events for fisheries. To aid in quantifying the effects of these events on reef fish population dynamics, multiple EMs were developed. Outputs from these models were used to inform the variability in natural mortality for stock assessment models. In the process of developing the multiple model ensemble (MME), stakeholders learned more about multispecies models approaches and the need for more data/research on red tides. Additional stakeholder involvement in model review and development should help build support for more robust use of the MME approach for this issue.

Scientists from the Southeast Fisheries Science Center and their partners were among the first groups to have collaborations between ecosystem modelers and stock assessors to provide operational EBFM advice.

Summary from Reum et al. (2021)

Connecting Ecosystem Models to Management Needs in the California Current

One of the significant challenges to using information and ideas generated through EMs and analyses for EBFM is the disconnect between modeling and management needs. Modelers from the Northwest and Southwest Fisheries Science Centers leveraged the stakeholder review of NOAA's annual ecosystem status report for the California Current Ecosystem established by the Pacific Fisheries Management Council's Fisheries Ecosystem Plan, to identify management priorities that require information from EMs and analyses. They then assessed potential EMs and analyses that could help address the identified policy concerns. They screened stakeholder comments and found 17 comments highlighting the need for ecosystem-level synthesis. Policy needs for ecosystem science included: 1) assessment of how the environment affects productivity of target species to improve forecasts of biomass and reference points required for setting harvest limits; 2) assessment of shifts in the spatial distribution of target stocks and protected species to anticipate changes in availability and the potential for interactions between target and protected species; 3) identification of trophic interactions to better assess tradeoffs in the management of forage species between the diet needs of dependent predators, the resilience of fishing communities, and maintenance of the forage species themselves; and 4) synthesis of how the environment affects efficiency and profitability in fishing communities, either directly via extreme events (e.g., storms) or indirectly via climate-driven changes in target species availability. They are working with existing management processes established in the U.S. West Coast to enable the structured, iterative, and interactive communication between managers, stakeholders, and modelers that is key to refining existing EMs and analyses for management use.

Summary from Tommasi et al. (2021)

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