A framework for incorporating species, fleet, habitat, and climate interactions into fishery management

A DRAFT white paper for the Mid Atlantic Fishery Management Council

January 2016

S. Gaichas, R. Seagraves, J. Coakley, G. DePiper, J. Hare, P. Rago, and M. Wilberg

Introduction

The Mid-Atlantic Fishery Management Council (Council) recently articulated objectives for the living marine resources under its management authority in its Strategic Plan. Foremost among these objectives is the need to advance ecosystem approaches to fisheries management in the Mid-Atlantic. This will be accomplished by moving beyond single species assessment and management to the development and implementation of assessments and management frameworks that incorporate, 1) environmental drivers, 2) habitat and climate change, 3) species interactions, and 4) fleet interactions, into fisheries management.

In June 2015, the Council convened a workshop with scientists and managers to discuss potential strategies to more fully consider species interactions and climate drivers in the stock assessment and management process (including determination of catch limits), and to build capacity within the region to conduct comprehensive management strategy evaluations (MSEs) as part of the Mid-Atlantic Council's Ecosystem Approach to Fisheries Management (EAFM). The workshop reviewed existing single species approaches as well as information and analytical tools available to address key interactions between species and their environment, between species within the food web, and between the ecosystem and fisheries, and between fleets due to technical or management issues. The workshop and this resulting white paper explore alternative pathways to incorporating species and fisheries interactions into the Council's fishery management policies and programs as part of the development of its EAFM Policy. Here, we develop a framework and process for defining key questions, evaluating the adequacy of information and analytical tools to address the questions, and developing analyses to evaluate management strategies to achieve Council management objectives.

In the first section, we briefly review information and analytical tools currently available to address climate, habitat, species, and fleet interactions in the Mid- Atlantic region. In the second section, we outline other tools which may help the Council address interactions more broadly. In the third section, we propose a potential framework for the Council to address these interactions in management, which would be tailored to specific questions to ensure the best management outcomes for the Council. In the final section, we outline example questions that the Council could address to illustrate how a structured decision making process within the framework could work.

1. Information available to address interactions in fishery management

Key Concepts

Definitions:

Predator-prey interactions: Predator: an animal that eats other animals. Prey: an animal that is eaten by other animals. Fishery managers are interested because managed fish eat each other at various life stages, and managed fish are eaten by protected species. Predator prey interactions are quantified with food habits or other diet data.

Competition: "Interaction between organisms, populations, or species, in which birth, growth and death depend on gaining a share of a limited environmental resource." Competition can be for food, space, or mates. Competition is difficult to quantify in the marine environment with current information and understanding.

Mutualism, symbiosis: Species interactions with mutually beneficial outcomes. Mutualism is difficult to quantify in the marine environment with current data.

Multifleet interactions: Vessels may participate in multiple target fisheries, and catch fish in different fishery management plans (FMPs). Commercial and recreational fleets target overlapping species. Fleets have varying footprints, gear configurations, catch compositions, and abilities to adapt to change. Quantified with landings, catch, observer, permit and other data.

Key questions:

Can our current management system adequately address these interactions?

- Can ecological and fleet relationships be addressed across FMPs?
- How do we address species and fleet interaction across multiple jurisdictions?
- Can we link ecological and fishery interactions with existing data?
- How will environmental changes alter interactions between habitats, species ranges, economic markets, and community conditions and the needs of the management system?

What tools can help managers look at the big picture?

- Model suites including single stock, multispecies, multifleet, and full ecosystem levels to address different questions
- Conceptual models linking key components, interactions, management objectives to see issues in the larger context
- Risk assessment methods for prioritizing issues to address
- Management Strategy Evaluation addressing specific questions
- Tracking indicator and proxies of the parameters and processes of interest
- Understand past and present regulations from a species, FMP, and ecosystem perspective

The Mid-Atlantic region has considerable available resources for addressing interactions, both in terms of available data and in terms of analytical tools. There is a wealth of environmental, ecological, and social and economic data that could potentially be integrated into analyses to support management decisions. An overview of available information (but not an exhaustive list) is synthesized in the NEFSC Ecosystem Status Report (ESR; available at http://www.nefsc.noaa.gov/ecosys/ecosystem-status-report/sitemap.html). Despite this wealth of data, information to address particular interactions may be sparse, such that information needs should be evaluated for each management issue, and uncertainties arising from missing information should be considered, as is current practice.

A spectrum of assessment and modeling methods are available to assist the Council with incorporating species, fleet, and climate interactions into management. Models range from conceptual to statistical and mechanistic mathematical models, from single species population dynamics to integrated ecosystem assessment, and from tactical to strategic. Ultimately, the Council will need to prioritize which interactions to deal with first, and risk assessment methods can contribute to this decision process. Similarly, the Council will need to evaluate management strategies to determine how they perform in achieving Council objectives, as well as evaluate tradeoffs between those objectives, which may be inevitable when considering a range of interactions and possible outcomes. A combination of these tools designed to address particular interactions can be developed for each management issue as with data above, as is also current practice.

Current state of the art

Single species stock assessments

In some ways, environmental, species, and fleet interactions are already accounted for in current stock assessments, depending on data inputs and model configuration. For example, single species stock assessments that use changing weight-at-age data over time as input are incorporating the effects of a changing environment and ecology on fish growth, although the sources of this variation cannot be identified. Further, some assessments incorporate changes in natural mortality (M) over time which can represent changing species interactions (most often, predation), but could also represent habitat or other environmentally mediated changes. Some effects of technical interactions between fisheries are included for individual species using the standardized bycatch reporting methodology (SBRM) to ensure that mortality from both directed fisheries and incidental catch are accounted for in assessments.

Successful fishery management can actually make the effects of interactions more important. As fishing mortality declines, natural mortality becomes a more important fraction of total mortality and therefore more influential on population dynamics. Reductions in fishing mortality also tend to increase lifespan and reveal traits obscured by high exploitation. To understand dynamics for rebuilding depleted stocks requires multiple disciplines, including population biology and ecology as well as bioeconomics, ecological and environmental change. Forecasting these changes can be challenging, but some key research at the interface of these disciplines can help.

Determination of absolute abundance is greatest challenge for single species, multispecies, and ecosystem models. To address this challenge, managers and scientists should foster an environment where there is increased interaction between gear technologists and stock assessment scientists (see e.g. Somerton *et al.*, 1999). Within a single species model, the ability to estimate changes in natural mortality (M) is dependent on ability to fix the quantity scaling the fishery independent index of population size to absolute population size (Q or survey catchability; Fig 1).

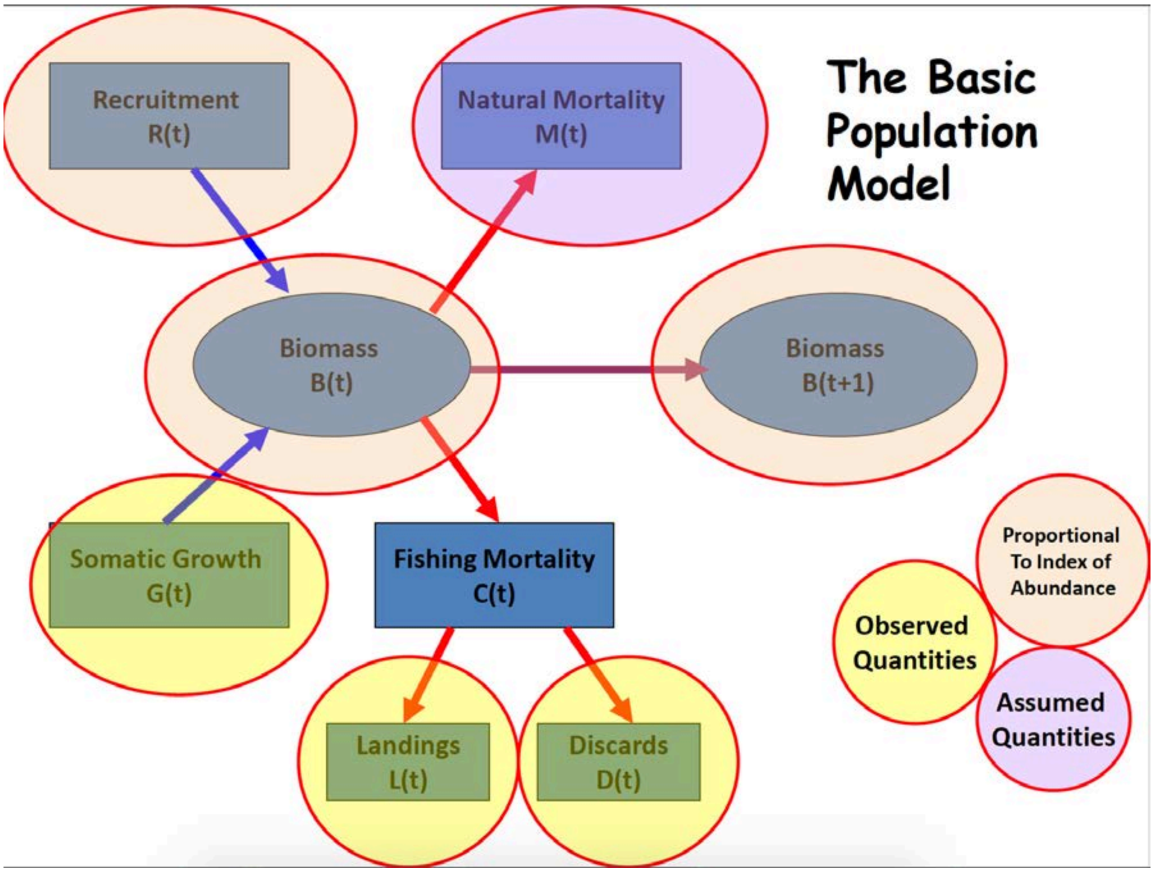

Figure 1. Mass balance in a basic population dynamics model, with sources of information. Considerable improvement in estimation of Fishing Mortality and other management reference points requires determination of scale, whether the model is of a single population or of interacting populations.

Determination of abundance is an essential ingredient of any model used for management, but there are multiple ways to determine scale and therefore several possible avenues for the Council to address this issue. Single species models currently in use to provide management advice are one method to estimate population abundance. Reliable estimates of total catch also provide a means of gauging the importance of other factors influencing stock dynamics. Catch is a measure of flux from the ecosystem to the economy—it is vital to measure catch with precision to analyze interactions properly. Stomach samples similarly provide a measure of potential energy fluxes between ecosystem components and a map of the links among species. However, the approach to scaling abundance requires measures of mass for at least some parts of the network.

Effective fisheries management also increases the need for research on the magnitude of natural mortality. Single species models summarize the joint effects of multiple factors on realized growth, recruitment, maturation, and total mortality, but cannot disentangle causative factors. The most recent butterfish assessment was improved by consideration of predation, but the major gain came from determination of the scale of abundance, which came about through and improved definition of survey catchability. The SBRM summarizes technical interactions among fleets and species. Major advances in assessments will come at interfaces among disciplines, especially for independent estimates of population scale.

The Northeast Trawl Advisory Panel (NTAP) was recently established to bring commercial fishing, fisheries science, and fishery management professionals together to identify concerns about regional research survey performance and data, to identify methods to address or mitigate these concerns, and to promote mutual understanding and acceptance of the results of this work among their peers and in the broader community. The NTAP is a joint advisory panel of the Mid-Atlantic and New England Fishery Management Councils. It is composed of Council members, fishing industry, academic, and government and non-government fisheries experts who will provide advice and direction on the conduct of trawl research. In addition, the Council has recently revised its research funding initiative (formerly the Research Set Aside Program) under the MAMFC Collaborative Research Program. The new Collaborative Research Program, in combination with advice and recommendations from the NTAP, offers an excellent venue to develop and conduct cooperative research with industry to address the critical issue of NEFSC survey catchability and to improve our understanding of the relationship between fishery independent indices of the abundance from the survey and true abundance in the ocean.

Trophic and multispecies interactions

In addition to the stock assessments currently used to provide management advice, information on predator-prey interactions can be derived from the extensive food habits databases maintained at NEFSC and VIMS. Food web models exist for 4 regions of the Northeast US shelf, including the Mid Atlantic, Southern New England, Georges bank, and Gulf of Maine (Link *et al.*, 2008, 2009). Updated models with more detail for individual species in each region and multi-fleet fisheries are currently under construction. Food web models are useful for estimating the relative proportion of fishing and predation mortality to evaluate whether assessments should consider including variable predation mortality. Food web models also quantify major prey for key species and can be used to evaluate whether assessments should consider including food-limited growth when prey fluctuate.

Multispecies models are in development for the Northeast US shelf to extend the suite of modeling tools available for assessment of species and fleet interactions. A suite of multispecies and ecosystem models already exist in this region, with several more currently in development. These include Atlantis (a spatially explicit bio-geochemical end-to-end ecosystem model), MS-PROD (a multispecies production model), MSVPA-X (an age structured multispecies model extended to include predators), several static mass-balance food web models, and several single species population dynamics models extended to include predators. Currently in development is a multispecies size structured assessment model and a set of linked static and dynamic food web models for each subregion. Another approach that has been used is to develop an index of predator abundance and use this index to scale natural mortality. While many of these models have an established role in providing strategic advice, the current challenge is to provide tactical management advice for fisheries in a multispecies context that can be readily used within the existing management framework. NEFSC is developing a system of simulation and assessment models to meet this challenge.

Models intermediate in scale between single stock and full ecosystem may be most promising in terms of providing tactical advice that incorporates species and fleet interactions as well as some environmental factors (Collie *et al.*, 2014; Plagányi *et al.*, 2014). Work is in progress by many research groups testing the capabilities of multispecies assessment models (e.g. Curti *et al.*, 2013; Van Kirk *et al.*, 2015). A prototype multispecies assessment project has been initiated for Georges Bank, which incorporates multispecies production models, multispecies delay difference models, and empirical nonlinear time series forecast models as assessment models within a multi-model inference framework. The multispecies assessment models were fit to simulated data, and assessment model estimates of biomass and catch trends were compared with "true" operating model values for each time series. This process both improves the multispecies models and informs managers of their strengths and weaknesses. Based on this work, multispecies models can be designed and evaluated for Mid-Atlantic stocks where appropriate.

Habitat and climate interactions

Fish require healthy surroundings to survive and reproduce. Habitat for a fish is the environment which supports it; this includes the benthic habitat, water column habitat, and ecological connections and linkages that occur throughout. The concept of habitat is simple and adaptable for describing a very complex system. Under MSA (16 U.S.C. 1802(10)), essential fish Habitat is, "those waters and substrate necessary to fish for spawning, breeding, feeding or growth to maturity". Fish habitat plays an essential role in the reproduction, growth, and sustainability of commercial and recreational fisheries and supports the biodiversity on which these ecosystems depend. Habitat can be described in different ways. One approach is a top-down stock-based approach to description, where you start with a species and then describe its associated habitat. The latter is a more landscape ecology type of approach from the bottom up, starting with the habitat and then associated species. Essential fish habitat for mid-Atlantic species uses the stock based approach of defining its habitat for individual species and life stages (eggs, larvae, adults, juveniles).

Some areas of the ocean are more productive for fish and shellfish than others. However, the importance of habitats in fish production and essential ecosystem services is poorly understood. A better understanding of habitat and its linkages to productivity is essential with the multiple demands and pressures on the ecosystem. Human activities have significantly altered coastal and marine habitat over time. Fish habitat continues to be degraded or lost due to a variety of factors, including coastal development, land-based pollution, fishing gear impacts, invasive species, dams and other blockages that restrict access for migratory fish species, and reduction in the amount and delivery of freshwater to estuaries. In addition, climate change and the demand for new sources of energy have the potential to cause wide-ranging impacts on fish and shellfish habitat. Given the continuing trend for coastal development, and projected impacts of climate change, the pressures on coastal and marine habitats will only increase.

Fleet interactions

Social and economic linkages across species are important due to the fact that they can bind species that otherwise have no strong biological interactions (for example, yellowtail flounder as a bycatch in the scallop fishery), or generate effects that either reinforce or dampen the signals from biological interactions. These fishery interactions have the potential to greatly impact fishing behavior, with implications for both human and marine communities. The linkages manifest themselves in seafood and other commercial markets for marine resources, technological interactions of the fishing gear themselves, management policies, and social networks, among others. In the context of EAFM, the currently available tools for assessing these interactions are high level, due to the complexity of the interactions, and generate indicators that can be tracked over time. More nuanced tools aimed at understanding drivers of fleet behaviors can be developed, but must be customized to answer specific questions.

As a brief introduction to the available tools, Figure 2 presents the revenue of MAFMC FMP species for the period 2005 – 2014, in 2014 equivalent dollar terms. The revenue peaks in at $250 million in 2006, with what seems to be a downward trend since then. Revenue is dominated by summer flounder, surf clam and ocean quahog, monkfish, and long-finned squid, and landed primarily in Massachusetts, New Jersey, and Rhode Island ports. Of interest is the fact that a relatively large number of ports in both New York and Maine have landed MAFMC FMP species historically, although the total revenue landed in these states is comparatively low.

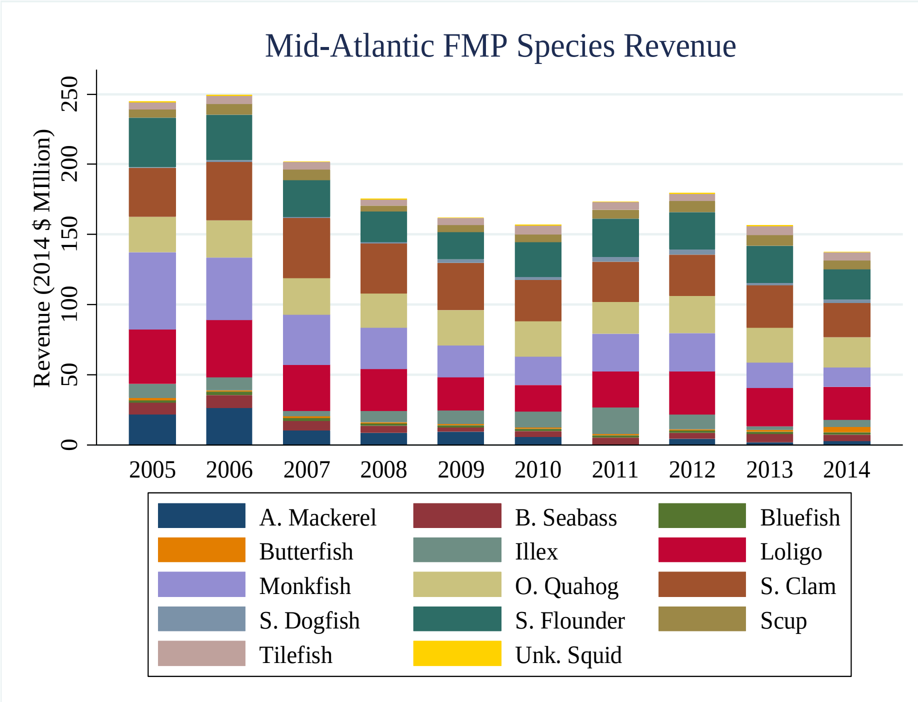

Figure 2. Revenue generated from MAFMC FMP species, by species.

Figure 3 presents the total revenue generated from permits that landed MAFMC FMP species in each year. Although the general trend is similar to Figure 2, the total revenue generated from these permits is roughly 4 times greater than the previous graphs. This means that the majority of the revenue generated from fishermen that catch MAFMC FMP species actually comes from species not managed by the MAFMC, and speaks to the scale of the fishery interactions faced by the MAFMC.

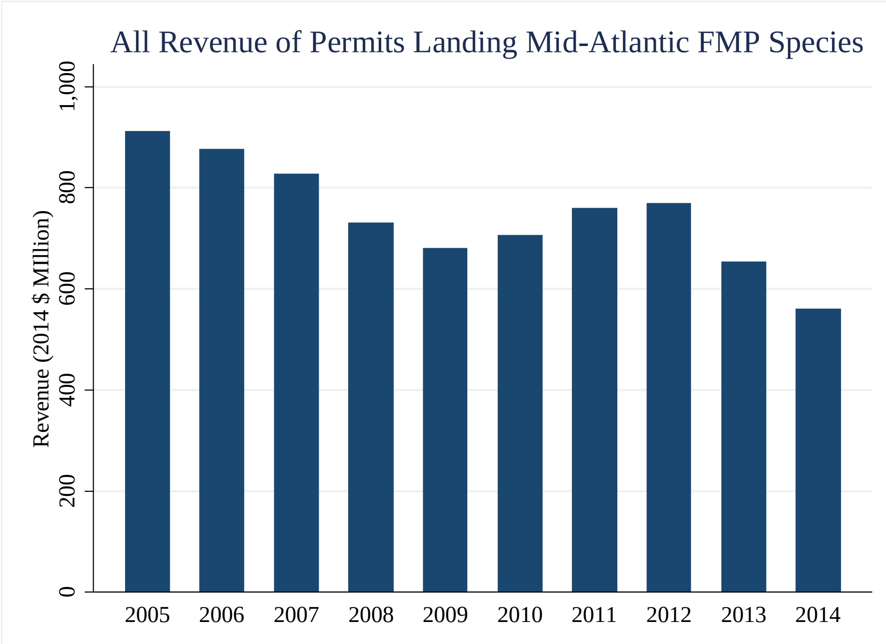

Figure 3. Total revenue generated by permits landing MAFMC species in that year.

Figures 4 and 5 present the predominant gear and vessel class associated with permits landing MAFMC FMP species. Bottom trawl serves as the dominant gear for much of the series, although in more recent years the number of permits for scallop dredge, hand gear, and gillnets are on par with the bottom trawl permit numbers. Conversely, the 30 to 50 ft. vessel class seems to have increased in proportion over the time series, primarily to the detriment of the largest vessel category (75 ft. and above).

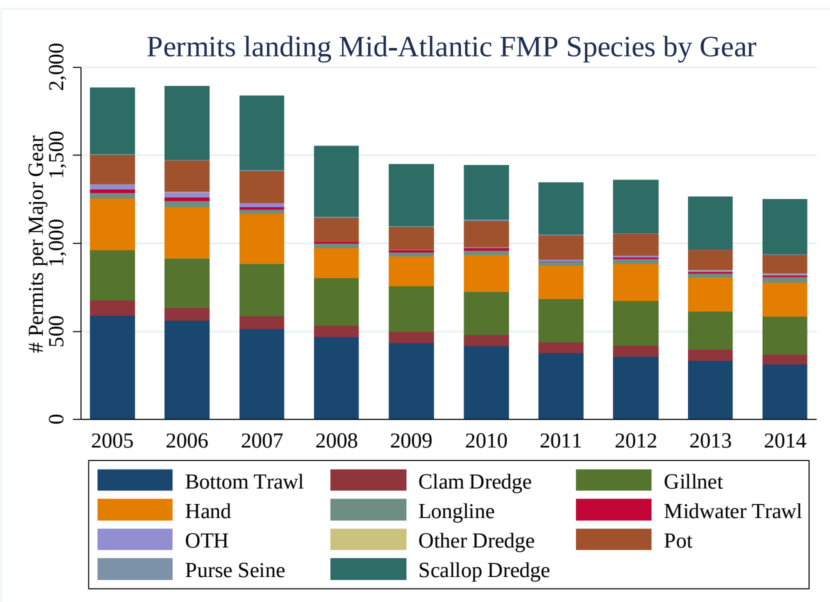

Figure 4. Number of permits landing MAFMC FMP species, by gear.

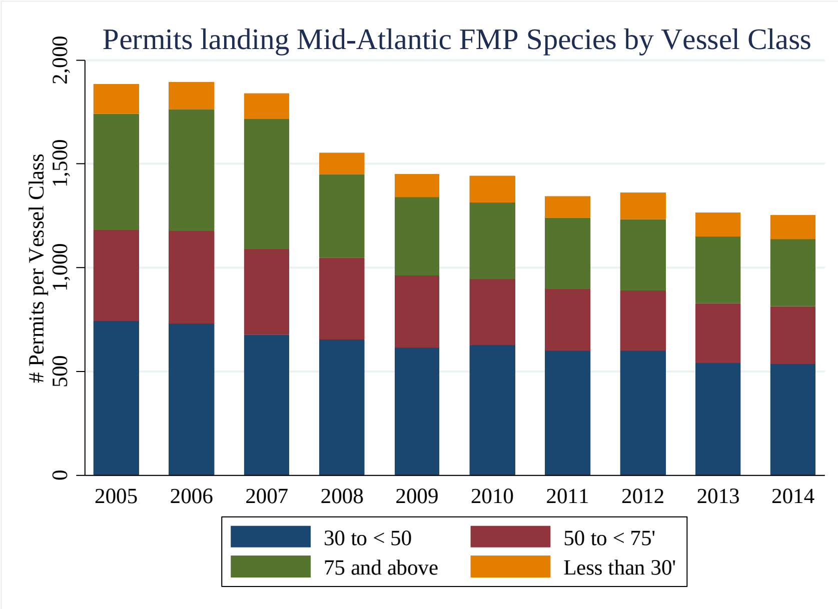

Figure 5. Number of permits landing MAFMC FMP species, by vessel class.

Estimates of diversity have been developed to better understand the dynamics embodied in Figures 2 – 5. These diversity estimates seek to understand whether specialization, or alternatively stovepiping, is occurring. Figure 6 presents the distribution of effective Shannon indices for species revenue at the permit level, for all permits landing MAFMC FMP species within a year. This index is calculated as $\exp(-\sum_{i=1}^{N} p_i \ln(p_i))$, with p_i representing the proportion of revenue generated by species i, and is a composite of richness (the number of species landing) and abundance (the revenue generated from each species). Although the exact value of the effective Shannon index is relatively uninformative, the distribution presented in Figure 6 indicates substantial heterogeneity in the diversity of species landed across permit holders. Further, this distribution is relatively constant across the time series, with no trend apparent. These results seem to indicate that specialization/stovepiping has not been a dominant force in the recent past.

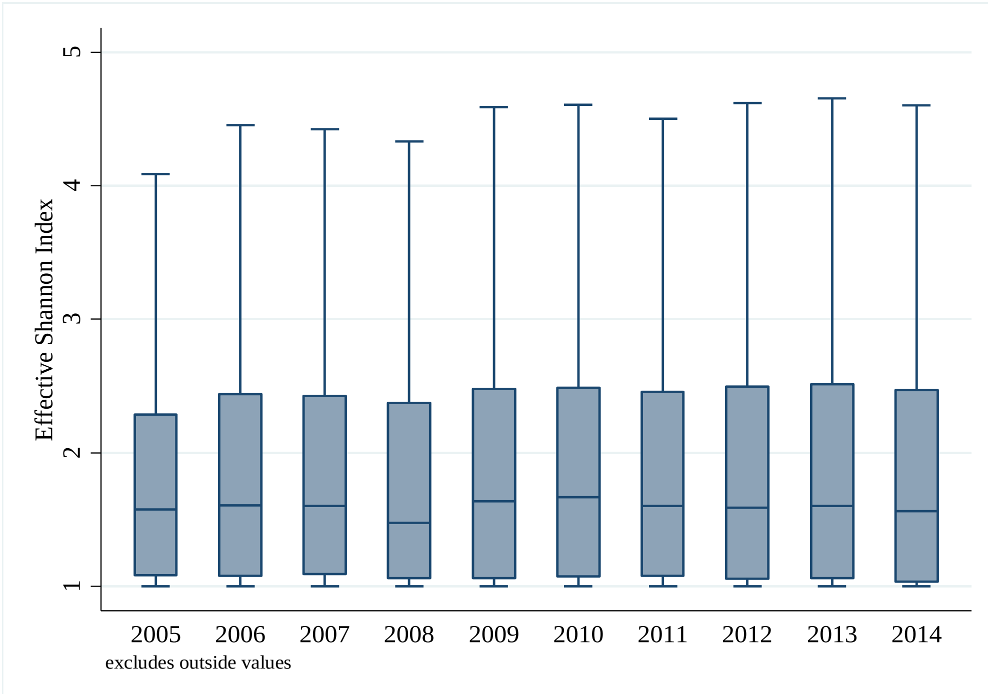

Figure 6. Distribution of effective Shannon indices for the diversity of species revenue at the permit level.

Figure 7 presents the effective Shannon index for fleet diversity, with diversity defined as the revenue generated by the combination of major gear and vessel class, as identified in Figures 4 and 5. This downward trend suggests that fleet diversity has decreased over time. Similar indices can been calculated to look at the diversity of ports landing MAFMC FMP species, to investigate the expansion or contraction of the suite of ports within the Mid-Atlantic, and better understand the dynamics within the system.

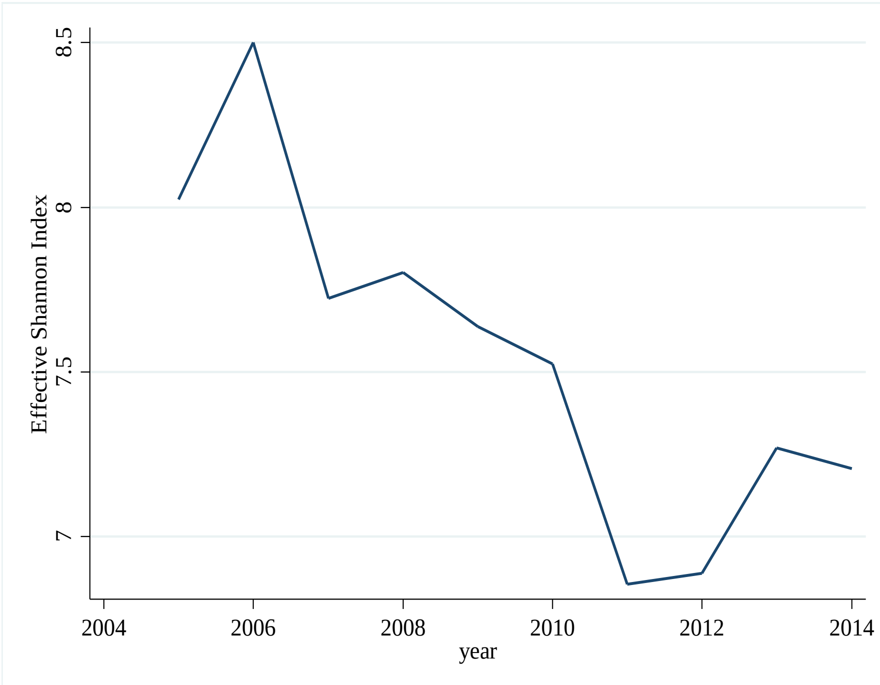

Figure 7. Fleet diversity, as measured by the revenue generated by each subfleet.

Regulatory Interactions

Regulations designed for one fishery, fleet, or issue may also interact with other fisheries or fleets, creating unintentional side effects or constraining fishing opportunities. For example, limits on the catch of one depleted species may cause it to act as a "choke" species, limiting the catch of other species caught in the same habitats to well below their allowable biological catch if the limiting species cannot be avoided. Similarly, time and or area management designed to meet an objective for a single species may also limit the catch of other associated species, causing fleets targeting the other species not to meet economic objectives. Fishery closures resulting from exceeding Total Allowable Catches under the Marine Mammal Protection Act are another example of regulatory interactions. These management-related interactions should be considered and analyzed prior to implementation of new management measures.

2. Additional comprehensive tools for addressing interactions

Integrated Ecosystem Assessments for Northwest Atlantic ecosystems

The NW Atlantic region has well-developed ocean observation systems, marine ecosystem surveys and habitat studies, though social and economic data collection systems are less well developed, and steps are being taken throughout the region to organize existing information and effectively communicate it to stakeholders and decision-makers. The Levin *et al.* (2009) IEA framework (Figure 8a) outlines the general process of integrated ecosystem assessment. Visualization of the IEA framework has evolved since then (Figure 8b), but its components remain the same.

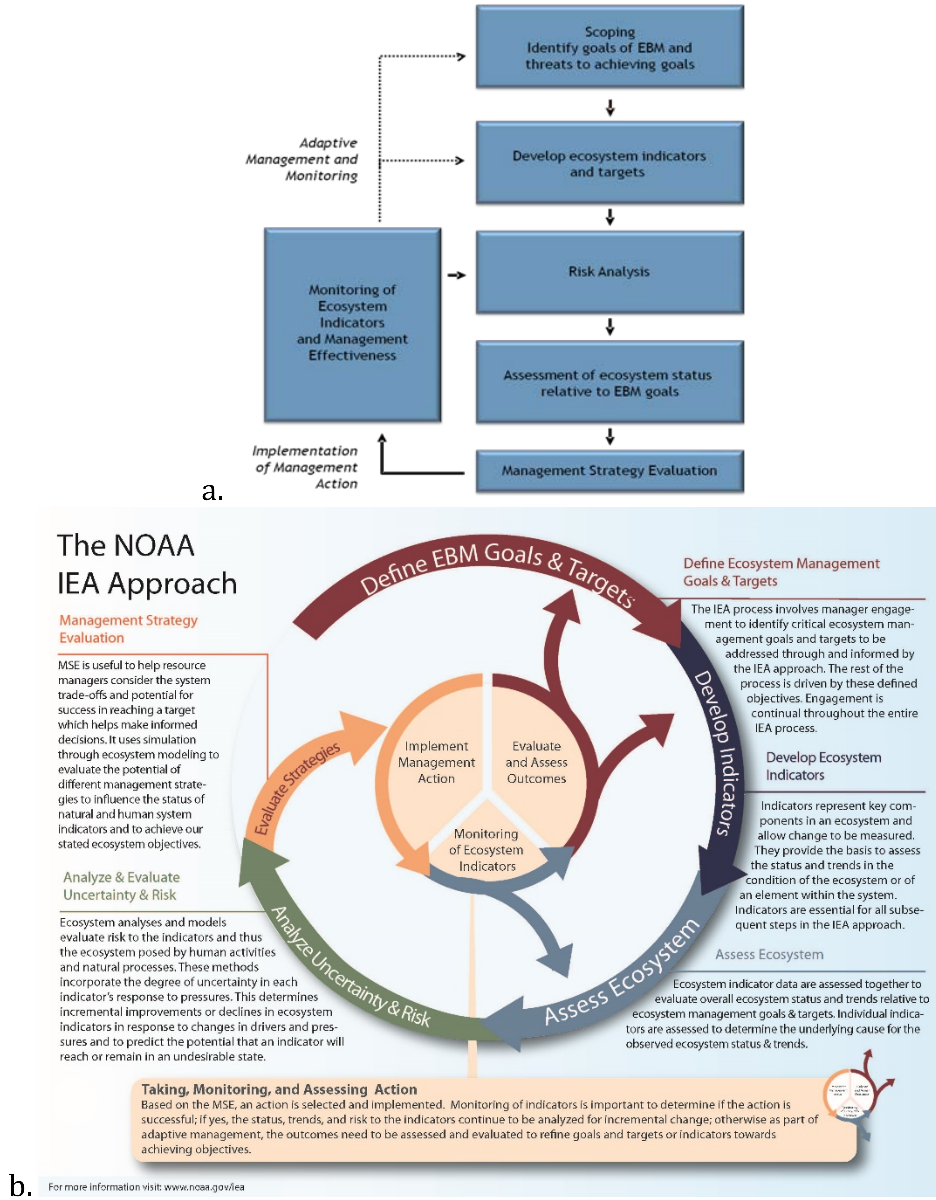

Figure 8. Visualizing IEAs. a. Levin et al (2009) b. Refined IEA representation.

Work is under way in a variety of contexts around the North Atlantic to develop Integrated Ecosystem Assessment (IEA) methods and approaches to support an Eco-system Approach to Management (EAM). For example, the International Council for the Exploration of the Seas Working Group on the Northwest Atlantic Regional Sea (ICES WGNARS) is comprised of scientists and managers from Canada and the US. The overarching objective of WGNARS is to develop Integrated Ecosystem Assessment (IEA) capacity in the Northwest Atlantic region to support ecosystem approaches to science and management. Considerable work has already been done compiling and reviewing ecosystem indicators across the themes of climate, biodiversity and habitat. Social sciences were integrated within the group early on, and the group continues to work on more fully integrated ecological and human dimensions in IEAs. Issues of spatial scale are important because the Northwest Atlantic

Regional Sea encompasses a variety of diverse ecoregions across a wide range of latitudes, physical oceanographic regimes, and habitats, as well as multiple administrative and management jurisdictions and boundaries, sociocultural groups and regional economies. Since 2013, WGNARS has been reviewing IEA component methods and applying them to test cases in the region. The 2013 sessions on IEA scoping, ecosystem indicator thresholds and performance testing, and risk analysis led to related peer-reviewed publications and established the context for development of a three-year workplan to address linked IEA components including assessment of ecosystem status relative to EBM goals and management strategy evaluation. Ultimately, WGNARS plans to continue to develop parallel products: (1) "worked examples" of linked IEA components, and (2) advice on developing processes for operational IEA implementation emphasizing the need for iteration between science, policy, and management.

NOAA's Integrated Ecosystem Assessment (IEA) program (www.noaa.gov/iea) continues to make progress in all 5 regions where it is currently being implemented (i.e. California Current, Gulf of Mexico, Northeast Shelf, Alaska Complex, Pacific Islands). On the Northeast Shelf, there is an updated Northeast US Ecosystem Status Report, an entirely web-based product (http://www.nefsc.noaa.gov/ecosys/). Relative to previous releases, this version features an expansion of human dimensions, stressors and impacts, status determination, and summary sections. The summary section can also be provided as a stand-alone printed annual "state of the ecosystem" report. Plans are in place to develop cumulative impact analysis and a marine ecosystem services assessment index, which would assign numerical scores for the status of delivery of a suite of ecosystem services that we've identified. Research continues into identifying regime shifts, and in multispecies and ecosystem modeling.

Conceptual Models

"Conceptual models" developed for the California Current IEA are being adapted for the Northeast US shelf, and could be a useful tool for Fishery Management Councils to address species and fleet interactions. Conceptual models are intended to provide a unifying framework that crosses disciplines, and clarifies system boundaries and any gaps in knowledge (Heemskerk *et al.*, 2003; Orians *et al.*, 2012). They are invaluable as a communication tool within an IEA working group, with other scientists, and with the public. This frame-work allows linking of indicators with elements of the conceptual models, as well as linking concepts across ecological and social components of a given system. The California Current IEA project worked for over a year to produce a set of linked conceptual models in December, 2014, as illustrated in Fig 9.

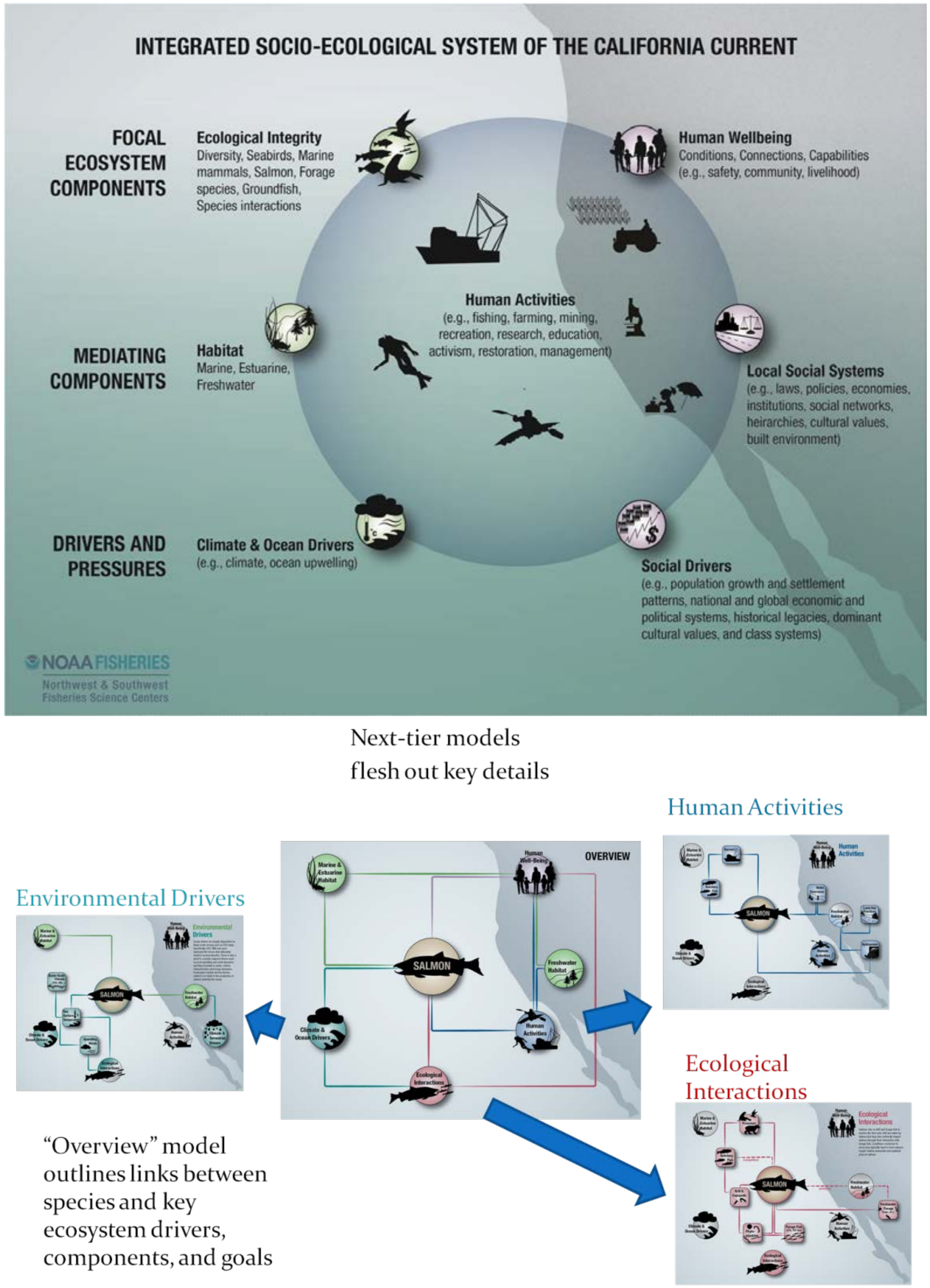

Figure 9. California Current conceptual models: overall system and detailed models linking environmental drivers, human activities, and ecological interactions for key ecosystem components. A set of models was developed for each focal component (salmon are shown here but others include coastal pelagics, marine mammals, etc).

In developing these conceptual models, the IEA team looked at each focal ecosystem component to develop links between ecological interactions (e.g. what are the strongest food web interactions), environmental drivers (what are the acknowledged drivers of abundance and community composition?), human activities (what are the strongest known human interactions or human risks posed to this focal ecosystem compoent?) and human wellbeing (what is the human dimensions context?). Detailed linkage models were developed for six ecosystem components: salmon species, coastal pelagic species, groundfish species, marine mammals, seabirds, biodiversity, and habitat. The California Current IEA project has used these conceptual models to improve communications with regional fishery management councils regarding key linkages between managed species and the environment, in groundfish stock assessment ecosystem considerations sections, and on their webpages for navigation by users to see linked information on status, trend, indicators, etc.

Risk Assessment

Risk assessment is a process to evaluate the potential, magnitude, and consequence of negative events occurring. This is a best practice adopted originally from business management fields and encoded by the International Standards Organization (ISO) standard 31000 (ISO, 2009a, 2009b, 2009c). The ISO standard bases risk management on a three-step risk assessment process: identification, analysis, and evaluation, which ultimately determines whether risk treatment is required to meet management objectives. Built into the standard are requirements for risk communication, consultation, review, and continued monitoring. The advantage of this approach is that it is consistent, transparent, and standardized. Furthermore, the approach has been adapted to evaluate a wide range of environmental issues (e.g. Cormier *et al.*, 2013; Standards Australia, 2012; US EPA, 1998) including some instances of risk assessment for fisheries stocks (e.g. Fletcher, 2005; Hobday *et al.*, 2011; Hollowed *et al.*, 2013; Martin-Smith, 2009; Patrick *et al.*, 2010; Smith *et al.*, 2007).

A simple ecosystem based risk assessment for the Aleutian Islands Fishery Ecosystem Plan in Alaska demonstrates how this tool can be used to prioritize key interactions within an region for further research, analysis, and or management strategy evaluation (AIFEP Team, 2007). In this application, expert opinion was used to first develop a set of key ecosystem interactions not currently assessed or monitored within the fisheries management system, and then to rate the probability of key ecosystem interactions occurring and the impact of the interaction to identify the highest risk interactions as those with high probability and high impact. Similar to the Australian Level 1 assessment, this risk assessment both identified high priority interactions and potential indicators suited to monitoring changes in the interactions. A quick assessment like this can form the basis for further development of management objectives. This contrasts with a more quantitative risk analysis that would be done once objectives are established, which would evaluate the risk of not meeting the management objectives, possibly under alternative management scenarios as in a management strategy evaluation.

Identifying climate risks to Mid Atlantic managed species

Climate vulnerability assessment has already been conducted for Mid-Atlantic managed fish species at both the general community (Gaichas *et al.*, 2014) and species specific (Hare *et al.*, 2016) levels. These analyses applied similar vulnerability assessment frameworks which used currently existing knowledge and expert opinion. Both used quantitative data when available, and qualitative information when data was lacking. In both analyses, "Vulnerability" was defined as the risk of changes in stock abundance or productivity in a changing climate. Stocks with ability to shift distributions in a changing climate may receive a "low vulnerability" ranking using these methods. Therefore, a subset of the attributes may be useful in identifying stocks that possess the ability to shift distributions, which is also important to fishery managers.

The community level analysis showed that the most vulnerable Mid-Atlantic stocks were commercially important and non-target benthic organisms, followed by commercially important demersal fish, with pelagic fish generally least vulnerable (Gaichas *et al.*, 2014). The species level analysis used model projections of climate conditions and evaluated individual species. This analysis also found that exposure to climate change throughout the Northeast US shelf is high to very high, and that climate sensitivity is higher for shellfish species and lower for groundfish and pelagics. Within the Mid-Atlantic region, 1 managed species received a very high vulnerability rating, 3 were rated high vulnerability, 3 were rated moderate, and only 6 was rated low (Figure 10). In addition, the NEVA (Hare et al. 2016) identifies which species are likely to shift distributions in response to projected climate patterns within the region: all but one managed species had high to very high distribution change potential (Figure 11). Finally, the NEVA evaluated the directional effect of climate change on fish and shellfish species. Three MAFMC managed species are likely to respond negatively, while six species are likely to respond positively (Figure 12).

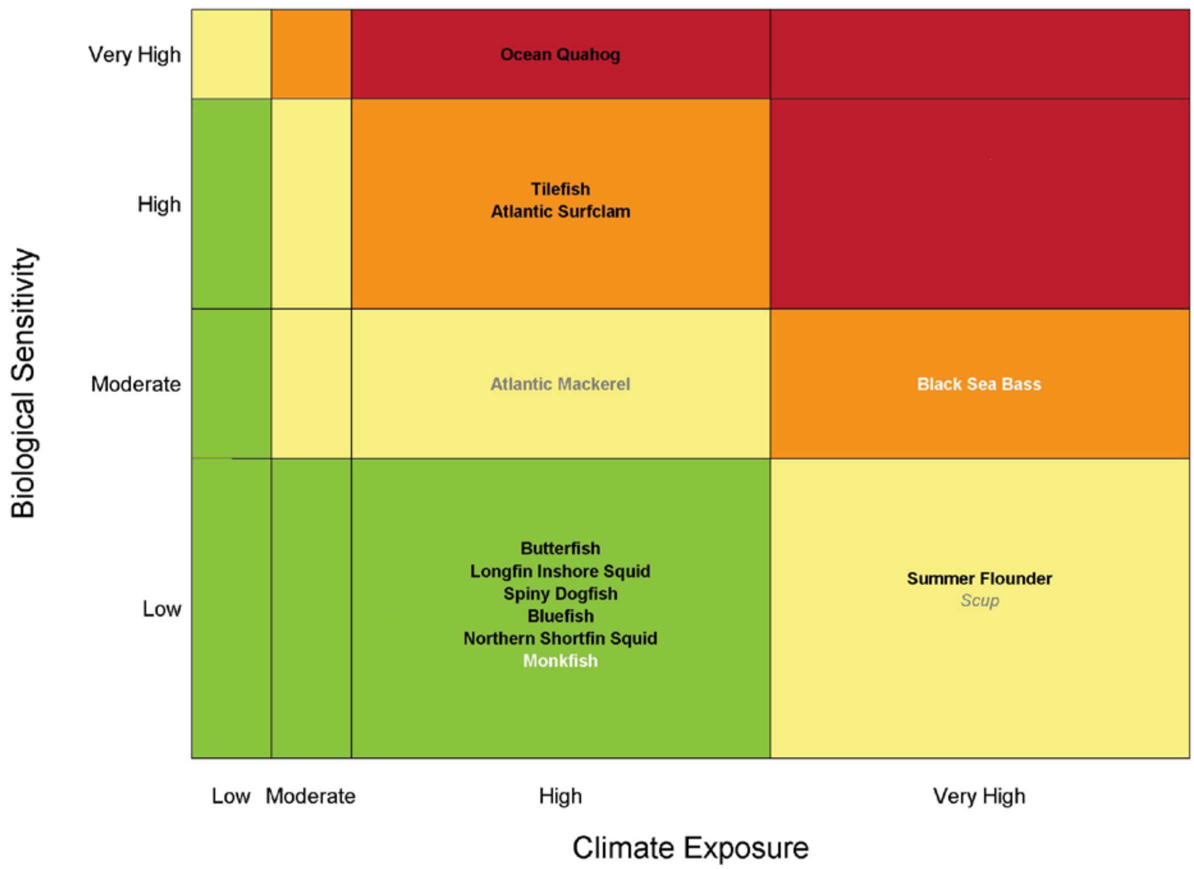

Figure 10. Summary of results from the Northeast Fisheries Climate Vulnerability Assessment (NEVA): First Implementation of a National Methodology for MAFMC managed species. Overall climate vulnerability is denoted by color: low (green), moderate (yellow), high (orange), and very high (red). Certainty in score is denoted by text font and text color: very high certainty (>95%, black, bold font), high certainty (90-95%, black, italic font), moderate certainty (66-90%, white or gray, bold font), low certainty (<66%, white or gray, italic font).

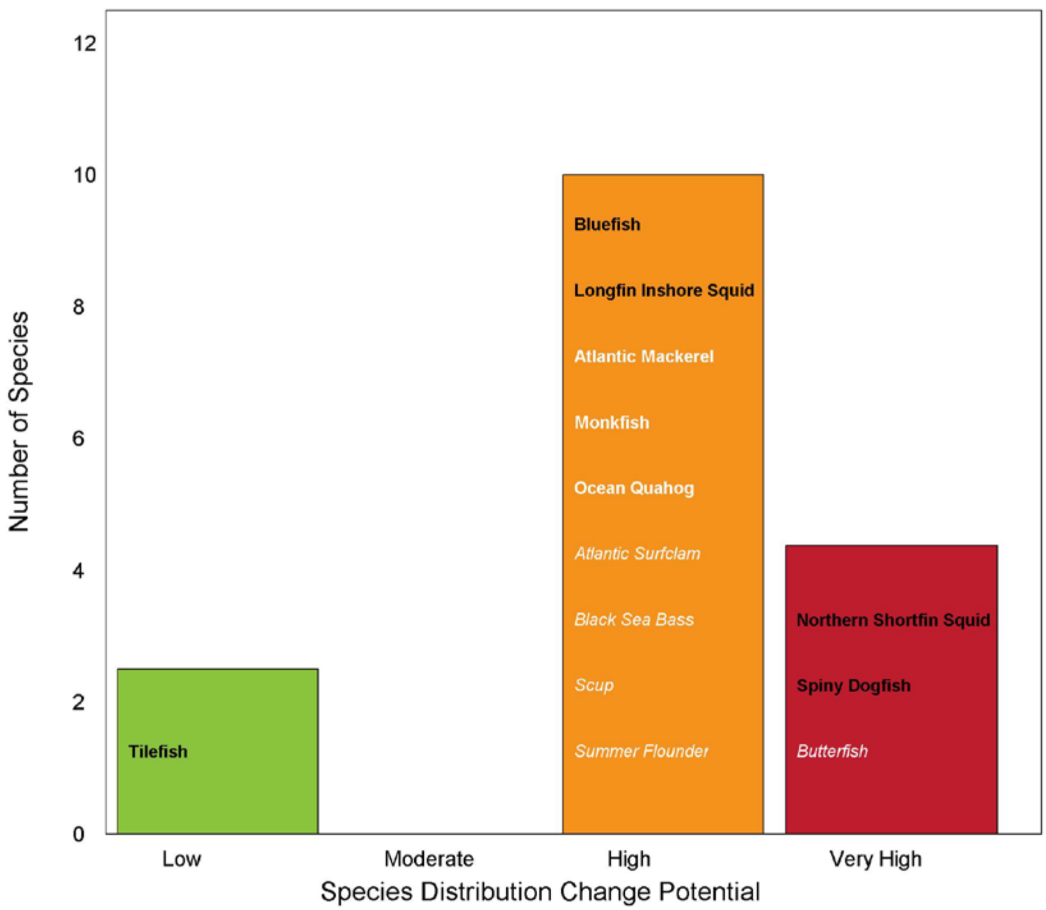

Figure 11. Potential for a change in species distribution. Potential was calculated using a subset of sensitivity attributes. Colors represent low (green), moderate (yellow), high (orange) and very high (red) potential for a change in distribution. Certainty in score is denoted by text font and text color: very high certainty (>95%, black, bold font), high certainty (90-95%, black, italic font), moderate certainty (66-90%, white or gray, bold font), low certainty (<66%, white or gray, italic font).

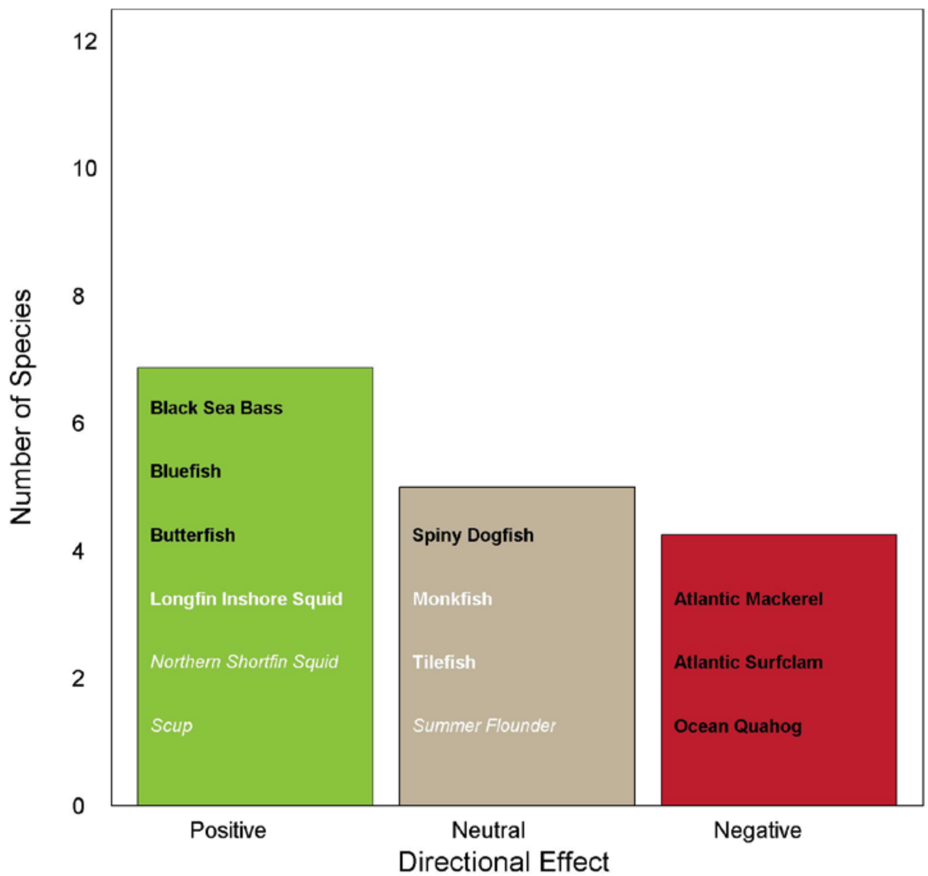

Figure 12. Directional effect of climate change. Colors represent expected negative (red), neutral (tan), and positive (green) effects. Certainty in score is denoted by text font and text color: very high certainty (>95%, black, bold font), high certainty (90-95%, black, italic font), moderate certainty (66-90%, white or gray, bold font), low certainty (<66%, white or gray, italic font).

This preliminary risk assessment, like any analysis, is not intended to answer all climate related questions for the Council, but is can be extremely helpful for making certain decisions. For example, it does not address magnitude of climate effects, it does not consider exposure or sensitivity as thresholds (cumulative), it does not evaluate harvest control rules or determine appropriate catch levels or replace mechanistic models, and it does not apply outside of the study area. Importantly, the NEVA does inform stakeholders as to the relative vulnerability of species. It identifies important climate exposure factors and sensitivity attributes. It informs data gaps and can contribute to setting research priorities. It identifies species where mechanistic models and/or MSE's that include climate change might be useful, and it does help identify species and issues that need more research attention. In short, this analysis could help the Council identify which species need integrated research on climate, habitat, species, and fleet interactions first.

Further information to guide the Council's future policy with respect to climate interactions will be forthcoming from the newly funded project by M. Pinsky and R. Seagraves, "Climate velocity over the 21st century and its implications for fisheries management in the Northeast U.S." The purpose of the proposed research is to inform the Council about the rate, magnitude, and uncertainty surrounding future distributional changes for managed and other important species likely to occur as a result of climate change over the next several decades and for the remainder of this century. This work will build upon the NEVA's initial work on likely range shifts to rank species by the rate and magnitude of range shift as well as the uncertainty in those values while also diagnosing the dominant source of uncertainty. In collaboration with the Council, this work will identify potential priority species for adaptation of fisheries management to climate. This would further clarify risks to the Council's management objectives and likely future issues arising from climate-driven distributional shifts.

Minimizing risks to economic returns in multispecies fisheries

The portfolio analysis developed in Jin *et al.* (2016), and following Sanchirico *et al.* (2008), provides an overview of the risk exposure associated with the mix of species managed by the Mid-Atlantic. Consideration of risk is weaved throughout the National Standards of the Magnuson-Stevens Fishery Conservation and Management Act. Portfolio theory allows the economic risk-reward trade-offs of multispecies fishery management to be assessed. Given elliptically-distributed returns, risk aversion entails choosing a mix of landings from species that minimizes the variance (risk) around an expected return (reward) from the system, subject to the biological constraints within the fishery. Put plainly, the portfolio approach identifies the mix of species that maximizes the probability of achieving the targeted returns to a system in any given year.

Portfolio analysis can be used to assess historical performance of the fisheries under MAFMC management by comparing the realized level of risk to the minimum risk that could have produced the same level of returns. Figure 13 is drawn from Jin *et al.* (2016), and presents an example of this historical analysis for Maine, Massachusetts, and Rhode Island, with the risk represented as the difference between the realized and optimal standard deviations divided by the realized returns. This analysis identifies the time periods in which the largest divergence from the risk-minimizing landings portfolio occurred. Further, because this analysis can be run at multiple spatial resolutions (from the full Northeast LME, to the Mid-Atlantic Ecological Production Unit, to individual ports), it can identify disproportional risk exposure across different geographic resolutions, and identify whether the risk propagates through or is balanced within the system as a whole.

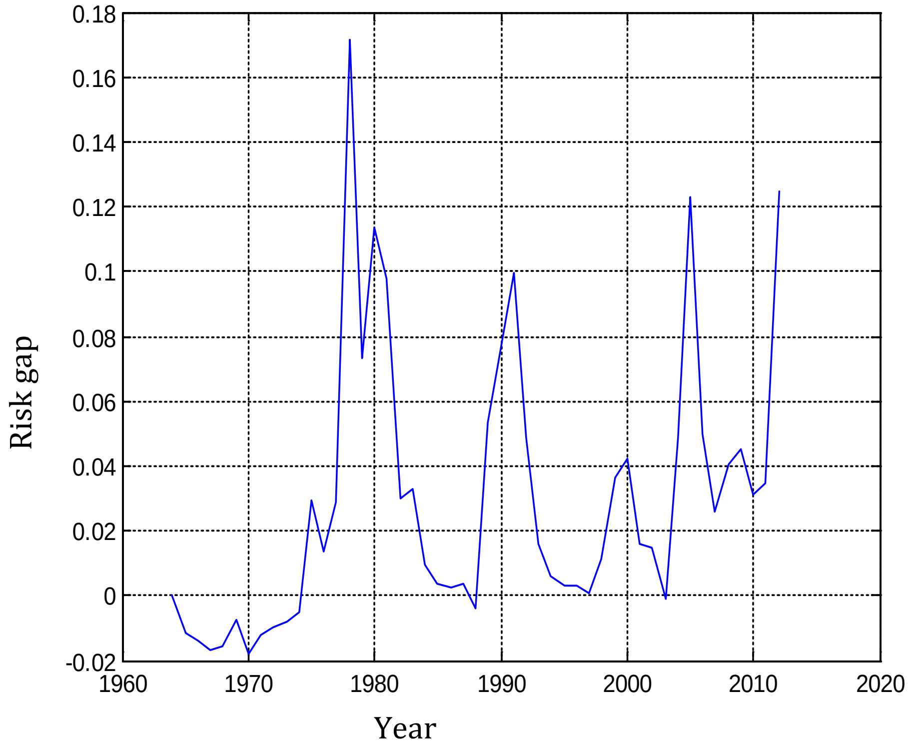

Figure 13. Risk inefficiency in ME, MA, and RI 1964 – 2012.

The portfolio model can also be coupled to the multispecies models currently under development at the NEFSC, and provide an explicit understanding of risk-reward trade-offs of future scenarios. Given that returns are not the only objective of management, the portfolio analysis would allow an understanding of the cost, in terms of additional economic risk, of achieving the suite of management objectives.

Management Strategy Evaluation

Management decisions are always made with substantial uncertainty. For example, there is uncertainty in the estimate of the status of the resource, the population dynamics of the resource, and the effects of the management decision on the resource and on the system as a whole. There is also uncertainty and risk associated with management choices. Management Strategy Evaluation (MSE) is an approach to determine if a method for making decisions is likely to achieve specified objectives (e.g., Butterworth, 2007; Punt *et al.*, 2014; Smith, 1994; Smith *et al.*, 2007). The MSE approach requires objectives be specified, performance metrics be identified, and management strategies, scenarios, and uncertainties to be specified clearly, and then uses a simulation model to test each management strategy's ability to meet the specified objectives (Fig 14).

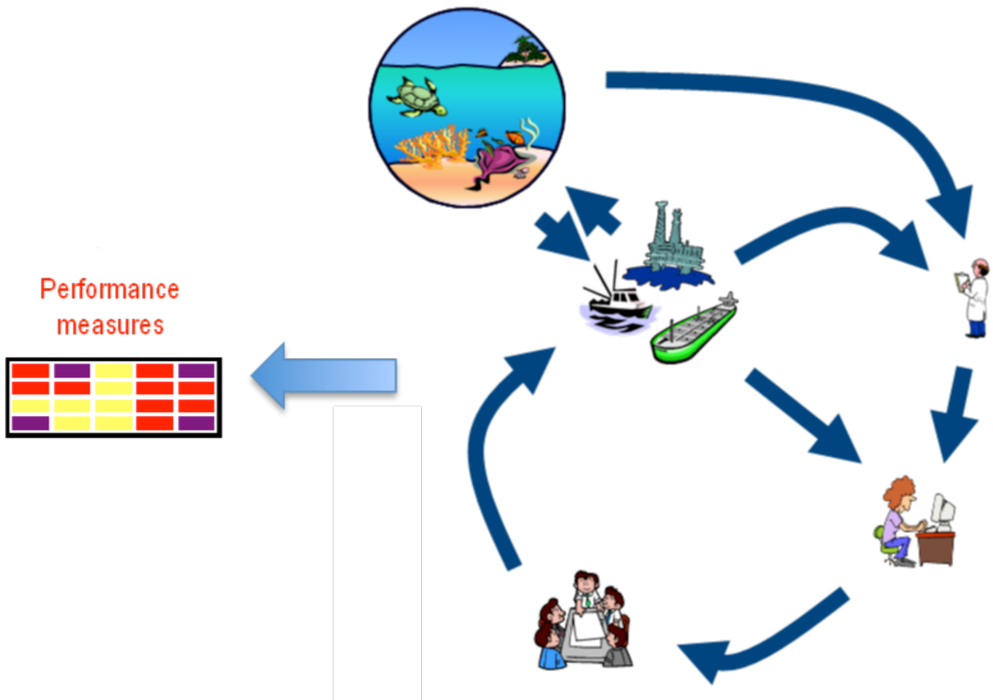

Figure 14. MSE simulation, courtesy Beth Fulton, CSIRO. Processes simulated within the "natural system" can include ecological, climate, habitat, fleet, economic, and social interactions. Data collection, assessment and management processes, as well as regulation of human activities with feedbacks into the natural system can also be simulated—this "closed loop" is a critical characteristic of MSE. Different management strategies are evaluated for performance against pre-determined performance measures.

The Council has already used MSE to inform decision-making. For example, the performance of alternative ABC control rules have been tested, as well as the performance of methods for implementing control rules. Similarly, MSEs have tested the performance of other characteristics of the management system (e.g., assessment frequency and management lag; data poor ABC estimation methods). Typically, the uncertainty in population dynamics (recruitment, fishery and survey size selectivity, and natural mortality) are included within the MSE, as well as uncertainty in fishery dependent and independent sampling and in stock assessment. However, many other uncertainties could be included in an MSE, depending on Council and stakeholder objectives. Examples of performance metrics used in MSEs can include average catch (short and long term), average biomass (short and long term), probability of overfishing, ability for populations to rebuild, and average annual variability of the catch. Again, many other performance metrics can be included in an MSE to measure performance against Council and stakeholder objectives related to fleet, species, habitat, and climate interactions.

An important aspect of MSE is that defining the objectives, performance metrics, and key uncertainties should be done within an inclusive stakeholder process. MSE is a simulation analysis, but to be helpful with management decisions, framing the analysis and the control rules or other management procedures to test must include managers, policy makers, fishermen, scientists, and other stakeholders. Overall, MSE allows the Council an opportunity to test management measures before implementation. MSEs can be particularly good for identifying strategies that will not work. MSE should be considered an investment rather than a quick fix, because the time requirement can be long and MSE is inherently an iterative process. Further, not all important uncertainties and objectives can be explicitly included, and MSE results can be highly dependent on the assumed dynamics. Therefore, investment in multiple simulation models with adequate alternative structures to evaluate the interactions of interest (species, habitat, climate and fleet) is a pre-requisite for effective MSE.

3. A potential framework for addressing interactions

To incorporate species, fleet, habitat, and climate interactions into management, the Council might consider a structured framework to first prioritize interactions, second specify key questions regarding high priority interactions, and third tailor appropriate analyses to address them. The primary tools for the initial steps in the framework are risk assessment and MSE. Finally, implemented management would be evaluated to ensure that objectives are being met, or to adjust measures as conditions change (Fig. 15).

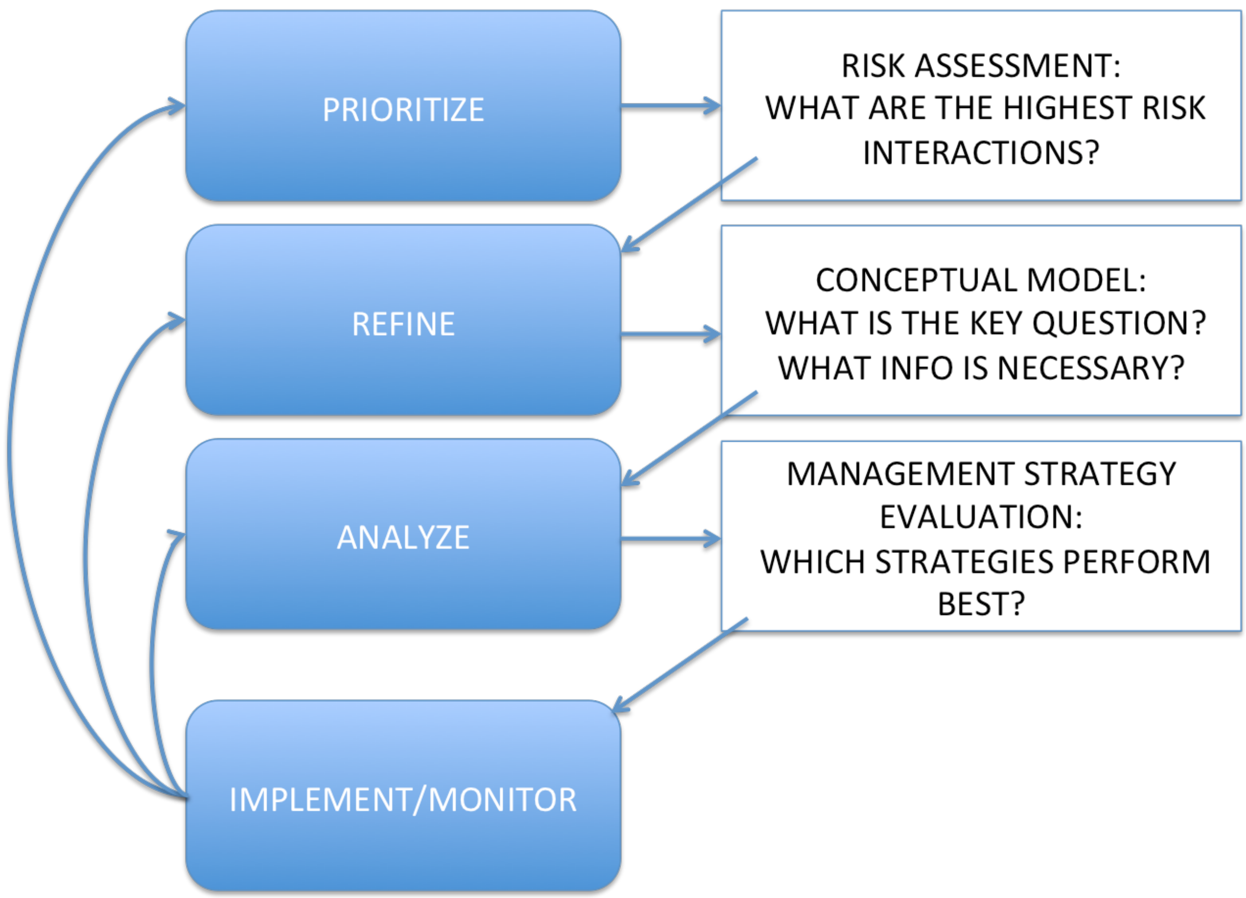

Figure 15. A potential framework for integrating interactions into management

Step 1: Prioritize with risk assessment tools

There are so many possible interactions in a fishery ecosystem that one analysis or tool cannot effectively address them all, so **risk assessment** is proposed as the initial step to identify a subset of high priority interactions for the Council to address first. The Council's goals and objectives would shape the assessment by first identifying risks and impacts of concern. Risk assessment is a critical nexus of science and management because this is where scientific information feeds directly into management decision making, in particular in developing risk criteria and consequences. Risk assessment helps managers to decide where to focus limited resources by clarifying priorities. These methods could be used much more often for screening out interactions of lesser importance that may currently have equal or more resources devoted to them than higher risk interactions.

For example, the NEVA described above has already identified which species are most likely to be vulnerable to climate/habitat change, so the Council could elect to evaluate whether species interactions pose further risks to meeting management objectives for the most climate-vulnerable species. Alternatively, climate-vulnerable coastal communities (e.g. Colburn et al., *in review*) and or fishing fleets could serve as a starting point, evaluating additional risks due to management, ecological, and other interactions.

Step 2: Refine key management questions for highest risk interactions
What are the Council's primary questions regarding a given high priority interaction? What are the Council's objectives for integrating the interaction into management? As the Council refines the question with stakeholders, scientists can evaluate data availability and gaps, and identify analytical tools to address the question. While much data and many tools exist for the Mid-Atlantic region, adequate time for data acquisition and quality control and tool refinement should be allocated to ensure a tailor-made, appropriate analysis.

Basic conceptual models can be developed for the particular question during this process to ensure that key ecological, climate, habitat, fleet, social, and economic interactions are addressed. Conceptual models help organize analyses and information, and clarify interactions for all stakeholders to work from a common understanding. For example, a question centered on climate impacts to a particular species might start with a conceptual model of known climate and habitat interactions for that species, but build in any critical interactions with other species, fishing fleets, fishing communities, regional and global economic markets, etc., as necessary to address the questions and management objectives.

This step is critically important in the framework, because it adds a point in the process where interactions are systematically considered. In particular, management interactions and inter-jurisdictional issues can be formally considered here (e.g. Council managed species discard in other regions; species moving into or out of the region due to climate and habitat change; land use practices altering nursery habitat for managed species). It may be necessary to consult with other management entities and involve them in further steps.

Step 3: Analyze management procedures with comprehensive MSE
The Council's questions and objectives identified in Step 2, along with available data, tools, and management strategies feed into comprehensive Management Strategy Evaluation employing performance measures across biological, ecological, management, social, and

economic outcomes. This iterative and stakeholder-driven process can evaluate the impacts of uncertainties in data collection systems, assessment methods, management decision processes, implementation of management measures, and other human activities as well as in the underlying climate, habitat, and ecology.

Some simulation models with capabilities to address species, habitat, climate, fleet, social, and economic interactions are available in the Mid-Atlantic region, although further development would be necessary for any particular MSE. Addressing questions with multiple simulation models and linking existing economic, single species, and ecosystem models expands analytical possibilities.

Step 4: Implement, monitor, adapt, and iterate as needed
Management measures designed to address interaction between species, habitats, fleets, and climate forcing may require additional or different monitoring to determine if objectives are being met. Careful consideration of performance measures and monitoring systems to be used in real time (as well as in MSE) needs to be part of this process. There is considerable potential to make better use of existing real time observing systems, in particular for climate and habitat interactions, as well as fishermen-based observation systems to evaluate management success.

4. Example questions to be addressed using the framework

What questions could the Council ask? These would each lead to a different analysis using different tools. These are only examples and not recommendations:

Question 1: "What management structure (i.e. licensing, allocations, etc.) provides the flexibility necessary to absorb the impacts of climate change, including shifting species distributions, and more broadly any large perturbation to the system."

Tools that could be used to answer question 1:

- Experimental economics can be used to understand the magnitude of both the intended and unintended consequences of management decisions. A good example of this would be the experiments investigating the point system that was proposed as part of scoping for Amendment 16 of the New England Fishery Management Council's Northeast Multispecies FMP (Anderson, 2010).
- Participatory modeling and management strategy evaluation with the Council and stakeholders could be used to inform potential outcomes of alternatives during the design of alternatives, for which historical data might not provide much insight (i.e., reallocation of stocks).

Question 2: "Under the current management system, what are the likely effects of inaction in the face of shifting species distributions and how quickly do they accrue?"

To address Question 2, exposure of species, fishermen, and communities to climate can be drawn together relatively quickly, given the current knowledge and models available.

However, specific models would need to be developed to assess the changes in welfare associated with future shifts.

- Economic models could be developed to assess which fishermen are likely to continue fishing, and what species would be caught.
- There are not currently off-the-shelf models to answer either question, and it would take time to generate the models/build up capacity. Therefore, having the Council identify priority questions is vital.

Similarly, for ecological interactions, priority questions could include:

- Are there strong interactions between managed species (high energy flow and/or mortality) that should be considered in setting ACLs or other fishery management measures??
- Are there strong interactions between managed and protected species which should be considered in setting ACLs or other fishery management measures?
- What is the status of key forage species supporting many managed and protected species, and should that be considered in setting managed species ACLs or other fishery management measures?? (raised in the Forage white paper)
- Are there key habitats for multiple species that require protection by the Council? How will the condition or extent of these key habitats be altered by projected climate change, and how should the Council consider this in setting ACLs or other fishery management measures?

Each of these requires a different supporting analysis and set of modeling tools, as noted above.

Conclusions

An ecosystem approach to fisheries management emphasizes a more integrated approach to habitat, sustainability, multi-species interactions, connectivity, and dynamic change. To address these ecosystem factors in terrestrial systems, there is high quality, easily collected data with a well mapped landscape, standard classification systems for habitat types and guilds of species (i.e., Southern Oak Pine Forest; Northern Peatland & Fens), and timely data collection systems. In the marine and aquatic environment there are none of these terrestrial advantages. The data is patchy in both space and time, and oceanographic data and biological data are incomplete. It is also very difficult to collect information in the very deep waters of the continental shelf.

So what do we do? Acknowledge we are in a transitional state and the incomplete nature of the data and science with which we have to work, and move forward both strategically and systematically. We first need to recognize that most of the Council's managed resources have strong nearshore and coastal linkages to habitat, and in many cases the nearshore and offshore environment for these managed resources is one continuum.

We need to start expanding how we describe Mid-Atlantic species habitat by focusing on the biological, physical-hydrographic, and ecological criteria. This should include taking tips from the landscape ecology approaches on land, which use the synecological/biotope approaches to describing habitat and associated species assemblages. As a first step this should include improving how EFH is designated.

Temperature can serve as a basic biological point to start mapping and modeling habitat. While salinity may set the biological boundaries between the freshwater, estuarine, and marine environment, temperature is a driving factors in a variety of biological processes. It plays a role in predator and prey migration (to onshore -offshore and vertical movements), light regimes, dissolved oxygen concentrations and fluctuations, and drives primary production, reproduction, survival, growth, and is a factor in ocean acidification.

To improve how we describe habitat, we need to prioritize the collection of data. This should include sampling both habitat types and use by species. The current fishery-independent trawl surveys and seine surveys actually sample trawl-able habitat and beaches often during migratory/transitional behaviors – we should be sampling across all habitat types seasonally to describe habitat characteristics and use by species. Under the current sampling, food habitat data and information may be biased for some species. We need to prioritize resources for habitat science to address these information gaps. Using technology and more efficient ways to collect and validate the information we need will be necessary given current sampling resources are limited.

To address habitat in the larger context, we must first:

1. Consider multi-stock assemblages and habitat use,
2. Define habitat by uniform and relevant biological, physical-hydrographic, and ecological criteria, and,
3. Address spatial and temporal scales in uniform way.

To address climate driven changes in productivity for some species

- Consider evaluating for changes in reference points
- Consider adjusting risk polices
    - Declining productivity ~ less risk
    - Increasing productivity ~ more risk

To address climate driven changes in distribution for many species

- Re-evaluate stock boundaries and data collection systems
- Re-evaluate spatial allocations (4 species)
- Re-evaluate time and space closures
- Food-web will change; evaluate impacts on consumption / natural mortality
- New species will come into area (e.g., BluelineTilefish, Chub Mackerel, others??)

To address Climate driven changes in productivity and distribution of forage species and protected species

- Consider effect of increase interaction with protected species
- Consider mechanisms to decrease interactions with protected species
- Consider effect of changes in forage fish

To address Climate driven change in fish and invertebrate populations will force changes in the socio-economics of fishing

- Community vulnerability to climate factors
- Changes in interactions with protected species or choke species
- Changes in markets
- Long-term economic decisions (individual and community)
- Consider other co-stressors (e.g., contaminants, habitat, invasive species)

To integrate trophic interactions into management, consider prioritizing:

- Strong interactions between managed species (high energy flow and/or mortality)
- Strong interactions between managed and protected species
- Key forage species supporting many managed and protected species (see Forage white paper)

To manage strongly interacting species, (in addition to forage recommendations)

- Consider conditional reference points for strongly interacting species (e.g. Species X Bmsy is dependent on Species Y F or B and or prevailing habitat volume/climate conditions)?
    - How would these be put through the management and regulatory process? Howe often would they need updating?

To manage fleet and any interactions,

- How would fishermen react to different management alternatives?
- What other options do they have from both a regulatory and ecological perspective?

Profit and production functions can provide much more detailed evaluation of fishery interactions at the level of the fishing business, and help answer questions surrounding fleet dynamics across numerous margins. For example, expected shifts in species distribution have the potential to affect fleet composition, species targeting and bycatch, fishing locations, and landing ports, among others. Each of these margins, in turn, provide understanding that help answer a different question, and although they all rely on a single underlying theoretical model, require a different specification of the empirical model to be estimated for tractability. Thus, the models are developed to answer specific questions which need to be defined as a first step, with specific guidance from the MAFMC.

References

AIFEP Team. 2007. Aleutian Islands Fishery Ecosystem Plan. North Pacific Fishery Management Council, 605 W. 4th Avenue, Suite 306, Anchorage, AK. http://www.fakr.noaa.gov/npfmc/PDFdocuments/conservation_issues/AIFEP/AIFEP12_07.pdf.

Anderson, C. M. 2010. An Experimental Analysis of a Points-Based System for Managing Multispecies Fisheries. Agricultural and Resource Economics Review, 39: 227–244.

Butterworth, D. S. 2007. Why a management procedure approach? Some positives and negatives. ICES Journal of Marine Science: Journal du Conseil, 64: 613–617.
Collie, J. S., Botsford, L. W., Hastings, A., Kaplan, I. C., Largier, J. L., Livingston, P. A., Plagányi, É., *et al.* 2014. Ecosystem models for fisheries management: finding the sweet spot. Fish and Fisheries: n/a–n/a.
Cormier, R., Kannen, A., Elliott, M., Hall, P., and Davies, I. M. (Eds). 2013. Marine and coastal ecosystem-based risk management handbook. ICES Cooperative Research Report No. 317. ICES Cooperative Research Report. International Council for the Exploration of the Sea, Copenhagen. 60 pp.
Curti, K. L., Collie, J. S., Legault, C. M., Link, J. S., and Hilborn, R. 2013. Evaluating the performance of a multispecies statistical catch-at-age model. Canadian Journal of Fisheries and Aquatic Sciences, 70: 470–484.
Fletcher, W. 2005. The application of qualitative risk assessment methodology to prioritize issues for fisheries management. Ices Journal of Marine Science, 62: 1576–1587.
Gaichas, S. K., Link, J. S., and Hare, J. A. 2014. A risk-based approach to evaluating northeast US fish community vulnerability to climate change. ICES Journal of Marine Science, 71: 2323–2342.
Hare, J., Morrison, W., Nelson, M., Stachura, M., Teeters, E., Griffis, R., Alexander, M., *et al.* 2016. A vulnerability assessment of fish and invertebrates to climate forcing on the Northeast U.S. Continental Shelf. PLOS ONE.
Heemskerk, M., Wilson, K., and Pavao-Zuckerman, M. 2003. Conceptual models as tools for communication across disciplines. Conservation Ecology, 7: 8.
Hobday, A. J., Smith, A. D. M., Stobutzki, I. C., Bulman, C., Daley, R., Dambacher, J. M., Deng, R. A., *et al.* 2011. Ecological risk assessment for the effects of fishing. Fisheries Research, 108: 372–384.
Hollowed, A. B., Planque, B., and Loeng, H. 2013. Potential movement of fish and shellfish stocks from the sub-Arctic to the Arctic Ocean. Fisheries Oceanography, 22: 355–370.
ISO. 2009a. Risk Management - Risk Assessment Techniques. International Standards Organization. IEC/ISO 31010. International Standards Organization.
ISO. 2009b. Risk Management Vocabulary. International Standards Organization. ISO GUIDE 73:2009(E/F). International Standards Organization.
ISO. 2009c. Risk Management Principles and Guidelines. International Standards Organization. ISO 31000:2009(E). International Standards Organization.
Jin, D., DePiper, G., and Hoagland, P. 2016. An Empirical Analysis of Portfolio Management as a Tool for Implementing Ecosystem-Based Fishery Management. North American Journal of Fisheries Management.
Levin, P. S., Fogarty, M. J., Murawski, S. A., and Fluharty, D. 2009. Integrated Ecosystem Assessments: Developing the Scientific Basis for Ecosystem-Based Management of the Ocean. PLoS Biol, 7: e1000014.
Link, J., Col, L., Guida, V., Dow, D., O'Reilly, J., Green, J., Overholtz, W., *et al.* 2009. Response of balanced network models to large-scale perturbation: Implications for evaluating the role of small pelagics in the Gulf of Maine. Ecological Modelling, 220: 351–369.
Link, J., Overholtz, W., O'Reilly, J., Green, J., Dow, D., Palka, D., Legault, C., *et al.* 2008. The Northeast U.S. continental shelf Energy Modeling and Analysis exercise (EMAX):

Ecological network model development and basic ecosystem metrics. Journal of Marine Systems, 74: 453–474.
Martin-Smith, K. 2009. A risk-management framework for avoiding significant adverse impacts of bottom fishing gear on vulnerable marine ecosystems. CCAMLR Science, 16: 177–193.
Orians, G., Dethier, M., Hirschman, C., Kohn, A., Patten, D., and Young, T. (Eds). 2012. Sound Indicators: A Review for the Puget Sound Partnership An assessment of the Puget Sound Partnership's progress in developing the scientific basis for monitoring and assessing progress toward achieving a vibrant Puget Sound. Washington State Academy of Sciences. http://www.washacad.org/about/files/WSAS_Sound_Indicators_wv1.pdf (Accessed 13 January 2016).
Patrick, W. S., Spencer, P., Link, J., Cope, J., Field, J., Kobayashi, D., Lawson, P., *et al.* 2010. Using productivity and susceptibility indices to assess the vulnerability of United States fish stocks to overfishing. Fishery Bulletin, 108: 305–322.
Plagányi, É. E., Punt, A. E., Hillary, R., Morello, E. B., Thébaud, O., Hutton, T., Pillans, R. D., *et al.* 2014. Multispecies fisheries management and conservation: tactical applications using models of intermediate complexity. Fish and Fisheries, 15: 1–22.
Punt, A. E., A'mar, T., Bond, N. A., Butterworth, D. S., Moor, C. L. de, Oliveira, J. A. A. D., Haltuch, M. A., *et al.* 2014. Fisheries management under climate and environmental uncertainty: control rules and performance simulation. ICES Journal of Marine Science: Journal du Conseil, 71: 2208–2220.
Sanchirico, J. N., Smith, M. D., and Lipton, D. W. 2008. An empirical approach to ecosystem-based fishery management. Ecological Economics, 64: 586–596.
Smith, A. D. M. 1994. Management strategy evaluation – the light on the hill. *In* Population dynamics for fisheries management, pp. 249–253. Ed. by D. A. Hancock. Australian Society for Fish Biology, Perth.
Smith, A. D. M., Fulton, E. J., Hobday, A. J., Smith, D. C., and Shoulder, P. 2007. Scientific tools to support the practical implementation of ecosystem-based fisheries management. ICES J. Mar. Sci., 64: 633–639.
Somerton, D., Ianelli, J., Walsh, S., Smith, S., Godø, O. R., and Ramm, D. 1999. Incorporating experimentally derived estimates of survey trawl efficiency into the stock assessment process: a discussion. ICES Journal of Marine Science: Journal du Conseil, 56: 299–302.
Standards Australia. 2012. Handbook: Managing Environmental Risk, HB 203:2012. http://infostore.saiglobal.com/store/details.aspx?ProductID=1516912.
US EPA. 1998. Guidelines for Ecological Risk Assessment. EPA/630/R-95/002F. U.S. Environmental Protection Agency, Washington DC. Published on May 14, 1998, Federal Register 63(93):26846-26924. http://www.epa.gov/raf/publications/pdfs/ECOTXTBX.PDF.
Van Kirk, K. F., Quinn, T. J., Collie, J. S., and A'mar, Z. T. 2015. Assessing Uncertainty in a Multispecies Age-Structured Assessment Framework: The Effects of Data Limitations and Model Assumptions. Natural Resource Modeling, 28: 184–205.