Accounting for Shifting Distributions and Changing Productivity in the Fishery Management Process: From Detection to Management Action

Melissa A. Karp, Jay Peterson, Patrick D. Lynch, and Roger Griffis (editors)

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U.S. Department of Commerce
National Oceanic and Atmospheric Administration
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U.S. Department of Commerce
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Executive Summary

Strong legislative mandates and investments in scientific programs have made the United States a world leader in sustainable fisheries management for seafood production, economic growth and outdoor recreation opportunities. NOAA Fisheries conducts targeted surveys, monitoring and research critical to tracking and understanding the physical, biological, and socio-economic conditions affecting fish stocks and fisheries. This information is essential for fisheries management and is used throughout the science-to-management process. However, changing climate and ocean conditions present new and growing challenges that affect the ability to understand and effectively manage fish stocks and fisheries. This report identifies the major challenges and possible solutions to addressing two of the main effects of changing climate and ocean conditions: shifts in stock distributions, and changing stock and ecosystem productivity.

Shifts in stock distributions and/or stock and ecosystem productivity can have significant implications for effective fisheries management. Traditionally a stock's life history parameters are assumed to be stationary, or constant, through time, and accurate estimates of these life history parameters are fundamental to establishing effective biological reference points. Changes in productivity can manifest through habitat alterations thereby affecting life history parameters, including growth, maturation rate, natural mortality, and stock-recruitment relationships. When productivity or distribution changes, the traditional assumption of stationarity is violated, with attendant implications for estimates of spawning stock biomass, biological reference points (e.g., maximum sustainable yield), and ultimately management actions, such as harvest recommendations and allocation decisions. Distributional shifts in response to changing climate and ocean conditions (e.g., temperature, habitat loss) can also alter the effectiveness of other management actions, such as time and area closures or bycatch reduction measures, as stocks may move out of designated protected areas and interact with different species and fishing gears.

In recognition of the numerous challenges facing fisheries management under changing climate and ocean conditions, NOAA fisheries has called for increasing the production, delivery, and use of climate and environmental information to fulfill the agency's living marine resource stewardship mandates. Addressing the growing challenges posed by changing conditions, and more formally including climate-informed decision making in the U.S. fisheries management process will require strengthening and adapting the current fisheries management framework, from improving detection and projection of changes, to better communication and use of climate-related information by resource managers. Incorporating climate-related information throughout the science-to-management process will help promote effective fisheries management in the face of current and projected changes in U.S. marine ecosystems.

This effort identifies six key steps (detailed in the following table) in the science-to-management process needed to better account for and respond to climate impacts on fisheries. The report identifies the main challenges and limitations associated with each step, and provides corresponding recommendations to address these issues. Implementation of these steps and recommendations will increase the development and application of climate-related science to support sustainable fisheries management in a changing world. The steps and actions recommended are not prioritized, nor were resource requirements or specific timelines identified. The capacity to implement these recommendations varies by region, and some initial efforts are already underway in some areas. Regional discussions and planning are warranted to identify priority actions and determine how to implement these steps and recommendations. The six-step process and associated actions should be reviewed in each region to determine a feasible implementation scale given current knowledge and resources. This report is an important step towards implementing and integrating key national strategies and fulfilling NOAA Fisheries' mission mandates in the face of changing climate and ocean conditions.

Step	Recommendations
1. Detect and anticipate changes	• Expand the spatial and temporal coverage of surveys and monitoring efforts through facilitating adaptive and flexible surveys, leveraging capacity of fishermen and other stakeholders, and expanding use of advanced sampling technologies • Develop early warnings and indicators of change • Facilitate coordination across jurisdictional boundaries to improve the integration of data streams and ability to track changes
2. Understand key drivers of change	• Design data collection and experimental approaches that evaluate fishery and survey catchability and selectivity in relation to ambient environmental and habitat conditions • Direct more research towards process studies to examine and understand key drivers of stock dynamics • Identify and address personnel and training needs to establish the staff capacity needed to address research needs
3. Evaluate risks and priorities	• Identify and prioritize the species and regions that are at greatest risk from current and future climate change using Climate Vulnerability and Risk Assessments • Use spatial analysis techniques and sensitivity analysis to identify and evaluate the relative importance and magnitude of distribution shifts and changes in productivity
4. Conduct assessments and develop forecasts	• Ensure that an ecosystem consideration component is included in the Terms of Reference for conducting and reviewing stock assessments • Incorporate spatial, temporal, multispecies, and economic data into stock assessment and other analyses where appropriate • Evaluate predictive skill associated with catch recommendations and other forecasts, and incorporate skill metrics into the characterization of uncertainty associated with scientific advice • Entertain multiple hypotheses regarding mechanisms and drivers of change through use of multi-model approaches (e.g., ensemble modeling) when competing hypotheses cannot be reconciled
5. Communicate scientific advice	• Develop standardized templates to report information on ecosystem dynamics, species distributions, and productivity to fishery managers • Facilitate communication among scientists, managers, and fisheries stakeholder groups through regular and open dialogue at workshops and/or debriefs to share and discuss issues and recommendations related to climate impacts on fisheries • Include decision support tools in stock assessment reports to quantify and present tradeoffs, risks, and uncertainties associated with various plausible management scenarios and states of nature
6. Manage fisheries under changing conditions	• Consider population resilience, age structure, and genetic diversity when making management decisions • Plan for future scenarios by using results from risk assessments and examining candidate management procedures using structured scenario planning, holistic ecosystem models, and/or Management Strategy Evaluation (MSE) • Use distribution analyses and projections to plan in advance for emerging fisheries • Evaluate time and area closures, adjusting where needed to reflect current and predicted distributions and habitat needs of managed stocks • Develop harvest control rules that are responsive to, and account for, changing conditions

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1.0 Introduction

Strong legislative mandates and investments in scientific programs have made the United States a world leader in sustainable fisheries management for seafood production, economic growth and outdoor recreation opportunities. NOAA Fisheries conducts targeted surveys, monitoring and research critical to tracking and understanding the physical, biological, and socio-economic conditions affecting fish stocks and fisheries management. However, changing climate and ocean conditions present a new and growing challenge affecting the ability of NOAA Fisheries and its management partners to understand and manage for the effects of the physical environment on fish stocks and fisheries (Figure 1).

In 2015, the *NOAA Fisheries Climate Science Strategy* (NCSS; Link et al. (eds.) 2015, Busch et al. 2016) was released to help increase the production, delivery, and use of climate-related information required to fulfill its mandates. Following this, the U.S. Government Accountability Office (GAO)[1] worked with NOAA Fisheries to assess the agency's efforts to develop actions the agency could take to incorporate climate information into fishery management decisions. One of the GAO's principal recommendations from that review was for NOAA Fisheries to develop guidance on incorporating climate information into the fishery management process.

In 2016, NOAA Fisheries released its *Ecosystem-Based Fisheries Management (EBFM) Road Map*[2] (Link et al., 2016) to ensure that NOAA Fisheries and its management partners; assess and account for major pressures affecting living marine resources and their habitats in the management process; execute the correct analytical level of assessment; address relevant ecosystem linkages; account for ecosystem-level features and cumulative impacts; and ensure that the frequency and scope of living marine resource assessments align with the broader ecosystem and fishing community dynamics. In 2018, NOAA Fisheries released *Implementing a Next Generation Stock Assessment Enterprise: An Update to the NOAA Fisheries Stock Assessment Improvement Plan*[3] (SAIP; Lynch et al. 2018). Building off the EBFM Road Map, the SAIP emphasizes the development of more holistic and ecosystem-linked stock assessments. The priorities and directions defined in the NCSS, GAO review, EBFM Road Map, and SAIP created the impetus for this report.

This report focuses on two effects of changing ocean conditions that are particularly challenging for fisheries management: shifting species distributions, and changing productivity, at both the stock and ecosystem levels (Nye et al. 2009; Lenoir et al. 2011; Pinsky et al. 2013; Lynch et al. 2015). Both shifting species distributions and changing productivity violate traditional stock assessment assumptions of stationarity, and have implications for estimates of spawning biomass, maximum sustainable yield, and for harvest recommendations and allocation. Distributional shifts in response to changing ocean conditions (e.g. temperature) can also alter the effectiveness of management measures, such as time and area closures or bycatch reduction measures, as species interact with different species and gears. Changes in productivity can manifest through habitat changes that affect a stock's life history parameters, including growth, maturation rate, natural mortality, and stock-recruitment relationships. Not accounting for changes in a stock's life history parameters can lead to significant error in estimates of stock biomass, biological reference

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[1] https://www.gao.gov/products/GAO-16-827

[2] https://www.fisheries.noaa.gov/topic/ecosystems#-science

[3] https://www.fisheries.noaa.gov/feature-story/up-dated-stock-assessment-improvement-plan-builds-past-success

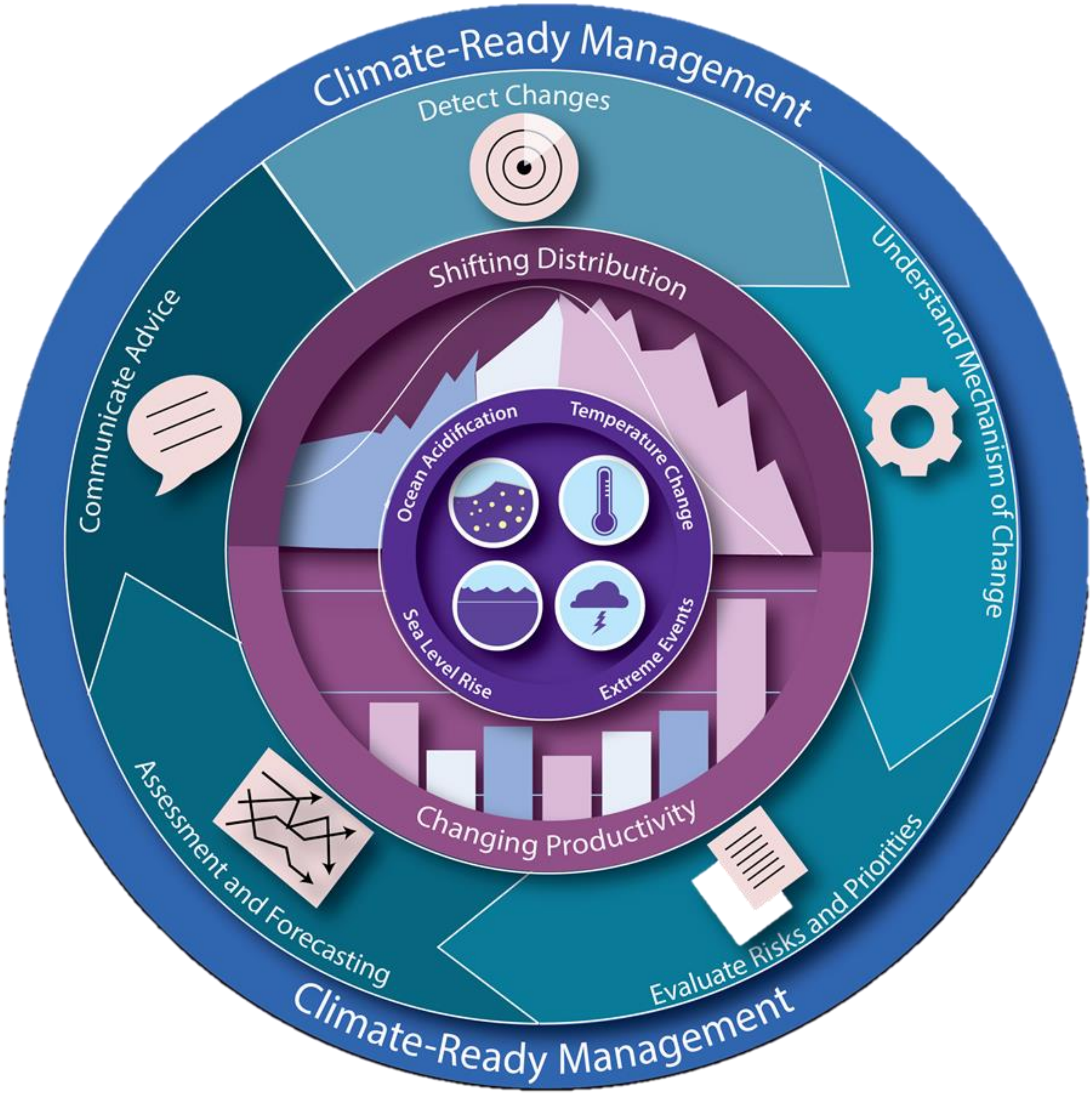

Figure 1: **Climate-ready fisheries management process.** Changing climate conditions is represented at the center of the diagram as ocean acidification, temperature change, sea level rise and extreme events. Those abiotic impacts of changing climate conditions cause changes in the biotic community such as shifting distributions and changing productivity, as indicated in the next ring out from the center. To enable managers to account for these changes and move toward climate-ready fisheries management (outermost ring), scientists and managers need to be able to detect changes, understand mechanisms of those changes, evaluate risks and priorities, conduct assessments and develop forecasts, and communicate results and advice to managers and stakeholders.

points, and maximum sustainable yield, which can affect not only stock status determinations, but also can affect sustainable catch recommendations and the achievability of rebuilding plans. Climate effects on species' distributions and productivity pose major challenges to living marine resource management; however, accounting for these effects in management decisions has remained limited.

To understand and address these challenges, this report evaluates the fisheries management process from the capacity to detect and understand changes, to communicating results to management and subsequent management actions (Figure 1). Recommendations are provided to address identified issues and ultimately increase the development and application of climate and ecosystem related science to support sustainable fishery management in a changing world. Section 2.0 of this report summarizes the effects of changing climate and ocean conditions on distributions and productivity of living marine resources. Section 3.0 describes key challenges and recommended actions under each of the following six important steps or components of a science-to-management process that is able to account for and respond to changing conditions:

1. Detect and anticipate changes
2. Understand key drivers of change
3. Evaluate risks and priorities
4. Conduct assessments and develop forecasts
5. Communicate scientific advice
6. Manage fisheries under changing conditions

Concluding thoughts are provided in Section 4.0, and references are provided in Section 5.0. An appendix provides case studies that illustrate how climate effects are being addressed in the fishery management process around the country.

2.0 Climate Effects on Fish and Fisheries

The potential effects of changing climate and ocean conditions are growing concerns for fishermen, managers, and coastal communities who rely on marine resources for food and economic security. The potential effects include increasing water temperature, ocean acidification, changes in atmospheric and ocean circulation, and more frequent and stronger weather events, and subsequent shifts in species distribution and productivity (IPCC 2014; The Royal Society 2005; Diaz and Rosenberg 2008; Hoegh-Guldberg et al. 2014; FAO 2016; Barange et al. 2010). The Intergovernmental Panel on Climate Change reported in 2014, there is "high confidence" that recent regional changes in ocean temperature have already had a "discernible impact" on some marine ecosystems and fisheries. Ocean temperatures are expected to increase an additional 2-4°C by the end of the century, increasing the effects to fish stocks and fisheries (Hoegh-Guldberg et al. 2014; IPCC 2014; Poloczanska et al. 2016).

2.1 Shifting Distributions

A distribution shift refers to a permanent, or at least multi-decadal to centennial, shift in the spatial distribution of a species or stock from its traditional region or habitat, to a new region or habitat. These shifts are often considered a result of changing climate or ocean conditions; although other factors (e.g., fishing, habitat degradation, trophic dynamics) may also cause shifts in distribution. Such shifts violate traditional assumptions of stationarity common to fish stock assessments, with attendant implications for estimates of spawning stock biomass, biological reference points, and ultimately harvest recommendations and allocation. Stocks are already on the move in response to oceanographic (e.g. temperature) and ecosystem (e.g. habitat loss, trophic dynamics) conditions (Nye et al. 2009; Lenoir et al. 2011; Pinsky et al. 2013; Bell et al. 2014; Lynch et al. 2015; Poloczanka et al. 2016), highlighting the importance of this issue.

How a distribution shift affects fish stock and resultant management actions depends on the type of shift that has occurred. Link et al. (2011) described the various scenarios of how stock distributions may respond to changing ocean conditions, and the different effects those scenarios have on management advice. Two main effects on stocks are that the apparent stock size within a given area may be quite different from the actual stock size, and stock structure may change (Figure 2). Both situations can lead to misspecification of stock status. For example, if a stock shifts northward across defined stock boundaries, there would be an apparent decline in abundance in the area that it is leaving, and an apparent increase in abundance in the area to which it is moving, while the true stock abundance may remain constant. If a stock is moving into an area in which it was not previously found, there is a risk that a fishery may develop in the new area before an appropriate monitoring program and fishery management plan can be implemented (Link et al. 2011).

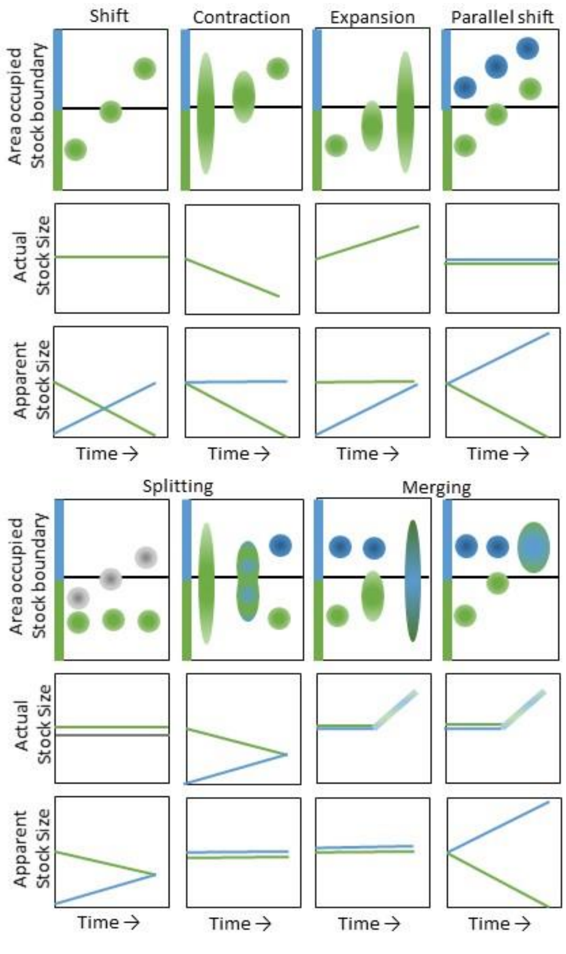

Figure 2: *Conceptualization of interaction between the type of stock distributional change and changes to actual and apparent stock size. Each of the 8 vertical sets of 3-panels depicts the type of movement of a stock or stocks across an assumed stock boundary (horizontal black line, top panel), the actual stock size (middle panel), and the apparent stock size (bottom panel) Figure adapted from Link et al. 2011.*

Shifting species distributions also will have consequences for access to the fish, particularly when stocks shift across management jurisdictions (state, federal, or international). Thus, such shifts may have direct economic impacts on fishing communities (see Box 1: Shifting Distributions and the Allocation of Fishing Rights). Additionally, management tools, such as catch limits, time or spatial closures, may lose their effectiveness as species shift in or out of those regions. Interactions, both between species and with fishing gear, may change as a result of distribution shifts, which could affect the performance of bycatch reduction measures. Additionally, The Magnuson-Stevens Act, which governs federal fishery management in the U.S., states in its National Standard 3 that “to the extent practicable, an individual stock of fish shall be managed as a single unit throughout its range, and interrelated stocks of fish shall be managed as a unit or in close coordination”. Geographic shifts in distribution may therefore result in fundamental changes to the structure of regional fishery management Council’s fishery management plans, and perhaps to the Councils themselves. At a minimum such shifts will require increased cross-jurisdictional coordination to manage stocks as they shift, expand, or contract their ranges.

2.2 Changing Productivity

BOX 1
SHIFTING DISTRIBUTIONS AND THE ALLOCATION OF FISHING

Allocation is defined by NOAA Fisheries as "a direct and deliberate distribution of the opportunity to participate in a fishery among identifiable, discrete user groups or individuals" (50 CFR 600.325; Morrison and Scott 2014). Allocation of fishery resources is one of the most challenging issues faced by fishery managers because of the economic value, history, and tradition associated with access to fishery resources and the perceptions of fairness that arise with allocation decisions. Allocation can be across jurisdictions (international, state, regional, etc.), across sectors (commercial, recreational, tribal, research, etc.), and within sectors (individual fishermen, gear types, etc.). To date, a large percentage of allocation decisions (80 percent of commercial/recreational allocations and 89 percent of catch share allocations) within the U.S. are based entirely or partially on

In 2016, NOAA Fisheries created an Allocation Policy to provide a mechanism to ensure that fisheries allocations are periodically evaluated and remain relevant to current conditions. The Policy defines roles and responsibilities for NOAA Fisheries and the eight regional fishery management Councils in reviewing allocations. The policy's first procedural directive outlines three categories that may trigger a Council to initiate an allocation review: public interest, time, or indicators. The Councils plan to identify one or more triggers for each fishery with an allocation by August 2019 (or as soon as practicable). The policy's second procedural directive outlines recommended practices and factors to consider when reviewing and updating allocations, and includes sections on planning for future conditions and on considering if the distribution of the species has changed.

Productivity in a fisheries context refers to the total biomass of fish, or the amount of yield, that a stock can support for removal (i.e., by fishing). Climate, ocean, and ecosystem conditions can greatly affect fish stock productivity by affecting habitat suitability, ecosystem-level productivity and dynamics (e.g., predator-prey interactions), and a stock's life history parameters, such as growth, maturation rate, natural mortality, and stock-recruitment relationships (Hare et al. 2010; Farley et al. 2016). For example, the recruitment of many cold-water and temperate species in the northwest Atlantic have been linked to the dynamics of the mid-Atlantic cold pool (Houghton et al. 1982, Miller et al. 2016). Warmer than average winter ocean temperatures cause Atlantic croaker recruitment to be higher than average (Hare et al. 2010), while Atlantic cod and Yellowtail flounder recruitment (Appendix D) is lower (Fogarty et al. 2008). These changes may occur concurrently with a stock's distribution shift, but also may affect stocks that remain within their historical ranges.

When stock productivity changes, it directly affects the assessment and management process. Errors in estimated life history parameters can lead to significant differences in inferred stock productivity (Whitten et al. 2013; Audzijonyte et al. 2016) and biological reference points, including estimation of the maximum sustainable yield (MSY). The effects of changing climate and ocean conditions on stock productivity affects the management utility of biological reference points, which are linked to historic conditions. In recognition of environmental (climate and ocean) effects on productivity, the national standard guidelines of the MSA states that "*if environmental changes affect the long-term productive capacity of the stock or stock complex, one* *or more components of the status determination criteria must be respecified."*

Changes in stock productivity may also affect the achievability of rebuilding plans if biological targets are no longer feasible under current or future conditions. Similar to the effect of shifting distributions, changing productivity may be unidirectional, so the affected stock would not be expected to return to its original state (as is expected with climate change). In other cases, productivity changes could occur in cycles that last for years to decades before shifting back to a previous productivity regime (as has been the case with decadal-scale climate and oceanographic oscillations). Therefore, NOAA Fisheries has developed, and should continue to improve, methods to detect and monitor for productivity changes, and evaluate whether biological reference points, status determination criteria, and harvest control rules reflect a stock's current productivity regime and are responsive and robust to changing conditions.

3.0 Six Step Process: Challenges and Recommendations

This section goes through each of the six general steps involved in a climate-informed science-to-management system: (1) detect and anticipate changes, (2) understand key drivers of changes, (3) evaluate risks and priorities, (4) conduct assessments and develop forecasts, (5) communicate advice to managers and stakeholders, and (6) manage fisheries under changing conditions. For each step the major challenges to accounting for shifting distributions and changing productivity are identified, followed by a description of recommendations to address those challenges. Recommendations and potential actions are summarized in a table at the end of each step's section. Addressing the challenges at each step in the process will strengthen NOAA Fisheries' ability to account for and respond to changing climate and ocean conditions in the sustainable management of living marine resources. Given regional variability in the capacity to implement this process, and the fact that some efforts are already underway in some regions, the steps themselves are not prioritized. Regional planning groups should walk through each step and associated recommendations, evaluate current knowledge, and determine when, where and how these steps can be implemented to facilitate a more "climate-informed" science-to-management system.

3.1 Detect and Anticipate Changes

For U.S. fisheries management to effectively address species distribution shifts and changing productivity, scientists and managers need to be able to: determine that a change has occurred in the past; detect that a change is currently occurring; and predict that a change is likely to occur in the near future. A crucial component of detecting changes is tracking and monitoring shifts in oceanographic conditions and stock characteristics in real-time. However, tracking changes and collecting data at the temporal and spatial scales necessary to provide real-time data and early warnings that a change may occur is challenging under current monitoring capacity.

NOAA Fisheries typically relies on fishery-independent and fishery-dependent sources to collect data and monitor changes in oceanographic and biological variables. For stock abundance monitoring, survey and catch rate data are often standardized over space and time (e.g., conducted within the same region and season) to the historic range of the species or to a jurisdictional domain. Historically, standardized sampling and analysis results in reduced sampling bias and facilitates spatial and temporal comparisons, yet standardization may introduce error and/or bias if changes in physical and oceanographic features affect stock distributions or life history parameters. Additionally, many of the geostatistical techniques underlying spatial models rely on extensive and accurate spatial data (Berger et al. 2017), increasing the need for data collection programs that accurately capture the spatial structure and movements of stocks and coinciding ecosystem information.

Movement of stocks across survey or jurisdictional borders poses an additional challenge for detecting changes in a stock's distribution or productivity. Surveys are not always consistent in design, timing, or gear type across jurisdictions. Survey inconsistency across regions can complicate the determination that productivity has changed, versus a species has shifted in or out of a region. It also makes it challenging to quantify the magnitude of changes in distribution or productivity. In fact, differences in survey design and methodology used to detect changes can have significant effects on the observed variability in the magnitude of stock distribution shifts in response to climate change (Brown et al. 2016).

Improvements and expansions in data collection, monitoring, and data-sharing programs are needed to develop early warnings and indicators that would help increase NOAA's capacity to detect changes when they occur and anticipate changes before they occur. Inevitably, these improvements will need to be prioritized and phased-in accordingly. Recommended actions to increase NOAA Fisheries' capacity to detect changes are described below and summarized in Table 1.

Recommendations

- **Develop early warnings and indicators of change using ecosystem or stock attributes that are relatively easy to track**

Important variables for tracking changing oceanographic conditions may include temperature, dissolved oxygen, pH, salinity, stratification, sea surface height, and circulation patterns. These variables are likely to change with changing climatic conditions and are potential drivers of fish stock dynamics. Other attributes that are important to monitor include catch histories and composition, centers of biomass, dispersion, guild or trophic structure, stock structure and connectivity, growth and size-at-age, and recruitment patterns (Rec 1.1, Table 1). Additionally, changes in habitat suitability may cause stocks to shift out of and into new regions; therefore, monitoring changes in important habitats (e.g. essential fish habitats) may serve as potential indicators and early warnings of change. A first step toward providing indicators of change is to analyze existing data for changes in the above mentioned attributes which could signal that a potential shift in distribution or productivity has occurred. Analysts can use and communicate this information to managers to provide initial indication that a change in the system has occurred.

- **Expand the spatial and temporal coverage of surveys**.

The SAIP (Lynch et al. 2018) recommends adjusting monitoring programs to track changes in species distributions, a recommendation reiterated here (Rec 1.2, Table 1). Facilitating survey flexibility and adaptability could greatly improve the detection and tracking of distribution shifts and changes in productivity, and ensure that the complete range of a stock is adequately sampled. Identifying how and when to adjust surveys should involve evaluating current survey domains and designs, particularly their relative abilities to detect changes and distinguish among changes in distributions, productivity, and abundance. Adapting surveys could involve both adjusting surveys in response to changing species behavior (e.g., Pacific sardine surveys, Appendix A) and expanding the spatial and temporal scope of surveys, which may be both a cost- and time-prohibitive endeavor in some regions. Therefore, the use of fishery catch data, citizen science, local ecological knowledge, and partnerships with fishermen should be encouraged to help expand the monitoring capacity of

NOAA Fisheries and provide information to help inform decisions to adjust surveys.

- **Use integrated ocean observing systems and advanced sampling technologies**

NOAA recently developed the Integrated Ocean Observing System (IOOS)[4], a national-regional partnership to maximize access to real-time data, generate information products, and improve habitat, ecosystem, and climate understanding. Fisheries monitoring and assessment teams could benefit from increasing coordination and use of the real-time data collected through this observing system. This system could provide information needed to track large scale oceanographic conditions and indicators of change at temporal and spatial scales not adequately captured by traditional fishery-independent surveys (see Manderson et al. 2011; Kohut et al. 2012). Increased use of advanced sampling technologies, such as sail drones and autonomous vehicles, can also help expand the collection of fish stock and oceanographic data.

- **Facilitate coordination across jurisdictional boundaries.**

TABLE 1

RECOMMENDATIONS AND POTENTIAL ACTIONS TO INCREASE CAPACITY TO DETECT AND ANTICIPATE CHANGES

Recommendation	Potential Actions
1.1 Develop indicators and early warning signs Utilize indicators and early warnings to detect and predict when stocks are exhibiting or may exhibit distribution or productivity changes	• Analyze survey and fishery catch data for changes in guild/trophic structure, species composition, location of catch, growth (e.g. catch-at-age), and recruitment patterns • Monitor changes in habitats and ecosystems through dedicated and opportunistic collection of oceanographic variables such as pH, dissolved oxygen, temperature, salinity, and bottom type • Evaluate the scale and rate of stock structure changes and spatial patterns in recruitment on a regular basis through tagging studies and genetic analysis
1.2 Expand spatial and temporal coverage of monitoring efforts Monitoring programs and surveys should be adjusted to track changes and reflect the current distribution and behavior of the stock	• Facilitate survey adaptability and flexibility • Engage and leverage the capacity of fishermen and other stakeholders, and use “citizen science” data collected by stakeholders and fishermen to inform monitoring programs • Use Ecosystem Status Reports to inform fish stock monitoring and assessments (e.g. to evaluate sampling designs and identify key stressors)
1.3 Use integrative ocean observing systems and advanced sampling technologies	• Increase the use of real-time data collected through the Integrated Ocean Observing System (IOOS) to help track large scale oceanographic conditions and indicators of change • Use and continue to develop advanced sampling technologies, such as sailing drones and autonomous vehicles
1.4 Facilitate coordination across jurisdictional boundaries Research and survey efforts should be coordinated across regions and jurisdictions to facilitate integrating data streams and improve the ability to track changes	• Evaluate ongoing surveys to prioritize intercalibration work and standardization of surveys across adjacent regions • Improve data-sharing through creation of publically available, machine-readable data warehousing that is compatible across NOAA regions and among data collection partners

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[4] https://ioos.noaa.gov/about/

Improving the coordination of research and survey efforts across regions and jurisdictions, including improved data-sharing across neighboring regions would improve each region's ability to track changes, as well as increase managers' awareness of the changes occurring in their, and neighboring, jurisdictions (Rec. 1.3, Table 1). However, this relies on having good communication and sharing of information between managers and scientists both within and between jurisdictions (see Section 3.5 for specific recommendations on improving communication). This information will be crucial for managers as they plan for future conditions and emerging fisheries (see Section 3.6)

3.2 Understand Key Drivers of Change

Not only is it important to identify that a change has occurred, but understanding the cause of the observed change is also key. For instance, an observed change in distribution or productivity could be related to a variety of factors, singly or in combination. These factors include natural variability in the system, changes in fishing practices, changing trophic dynamics and abundance of predators or prey, stock rebuilding plans, long-term environmental change, or some combination of drivers. The driving factors will affect how managers should respond.

Furthermore, understanding the underlying mechanisms of distributional and productivity changes may improve scientific advice and the ability to predict and develop forecasts of expected changes. For example, when stocks shift their distributions or movement patterns as a result of changing growth rates and/or oceanographic conditions, there can be resultant effects on the 'availability' (catchability, selectivity, sampling efficiency, etc.) of fish stocks to surveys or fisheries. This availability is important to quantify in stock assessments as it affects estimates of total abundance, productivity, and subsequently stock status and sustainable catch levels. Accounting for environmentally-driven and time-varying catchability and selectivity is therefore important, yet remains difficult due to limited mechanistic understanding.

Even when necessary data are available to provide information on key drivers of change, the time and personnel required to process and analyze these data can be a limiting factor. There are often an insufficient number of experts trained to work with the data, especially with regard to the zooplankton, secondary production, and food habits data that are useful for understanding changing stock and system productivity. The lack of trained personnel needed to process and work with the data in a timely manner can lead to a mismatch or lag between data collection and processing, resulting in not using the information in assessments to inform management decisions.

Therefore, increasing the collection of data (as noted in the previous section), process-oriented research efforts, and staff capacity are crucial to inform mechanistic understanding of observed changes. Recommendations to improve NOAA Fisheries understanding of key drivers of change are described below and summarized in Table 2, with some additional specific potential actions.

Recommendations

- **Institute collection of oceanographic, habitat, and multispecies information on all standard surveys.**

Collecting oceanographic, ecosystem, and habitat data concurrently with stock's biological information can provide indicators and early warnings of change as mentioned in section 3.1. Better coordination of data collection can also improve scientists' ability to determine potential drivers of change by matching up climate, ocean, and habitat conditions with resultant changes in stock dynamics.

Collecting multispecies and trophic information may help determine how different stocks respond to system-level changes. Some species may respond more strongly to changes in temperature while others respond more to changes in prey composition or habitat availability. Therefore, collecting a range of ecosystem data will provide necessary information to understand and evaluate various potential drivers of change (Rec 2.1, Table 2).

- **Evaluate stock availability to survey and fishing gear.**

  Data collection and experimental approaches should be designed to estimate catchability, availability, and selectivity in relation to ambient environmental and habitat conditions (Rec. 2.2, Table 2). Ways to evaluate these changes include paired acoustic-trawl surveys and video surveys of fish behavior around survey gear in concert with collecting environmental (habitat and oceanographic) information. Paired acoustic-trawl surveys can provide information on changes in vertical distribution of fish while enhanced sampling of fish behavior

TABLE 2
RECOMMENDATIONS AND POTENTIAL ACTIONS TO IMPROVE UNDERSTANDING OF KEY DRIVERS OF CHANGE

Recommendation	Potential Actions
2.1 Institute collection of oceanographic, ecosystem, and habitat information on all standard surveys. Ensure that appropriate ecological observations are collected on all standard surveys, and where opportunities exist, to enable direct linkage between species and environmental information	• Measure oceanographic variables, such as dissolved oxygen, temperature, salinity, and depth as standard procedure on surveys • Use acoustics and side-scan sonar to assess bottom and habitat type and zooplankton density • Use satellite and on-board sampling to collect information on primary productivity • Collect multi-species information, as a matter of sampling efficiency, but also to understand trophic dynamics
2.2 Evaluate stock availability to survey and fishing gears Design data collection and experimental approaches to estimate catchability, selectivity, and efficiency in relation to ambient environmental and habitat conditions	• Invest in process-oriented projects to characterize changes in catchability, selectivity, and gear efficiency and understand relationships between those changes and oceanographic conditions • Conduct paired acoustic-trawl sampling to estimate changes in vertical distribution
2.3 Identify key drivers of stock dynamics Conduct interdisciplinary process-oriented research that integrates across the physical, biological, and socioeconomic disciplines	• Conduct experiments to evaluate environmental effects on organisms' vital rates (i.e., growth, mortality, reproduction, etc.) • Establish and maintain ageing programs and food habits labs in all regions
2.4 Identify and address personnel and training needs Optimize staff capacity to address growing information challenges and needs	• Increase opportunities for scientific staff to receive training in topics such as plankton identification, gonad processing, genetic analysis, and diet analysis • Adjust staff performance plans to include dedicated time for interacting with and developing analysis and reports for fisheries managers, and conducting mechanistic research, stock structure studies, and catchability and calibration experiments

around survey gear would allow for improved understanding of how fish behavior and interactions with survey gear may change in response to changing environmental conditions.

- **Identify key drivers of stock dynamics.**

Process-oriented research on the effects of changing environmental conditions, particularly temperature, on organism vital rates such as growth, mortality, larval survival, maturity, fecundity and recruitment is important across all regions (see Stawitz et al. 2015, Boldt et al. 2015, Thorson et al. 2015b) (Rec 2.3, Table 2). Determining optimal management action under changing stock dynamics is contingent on a stock's life history (Thorson et al. 2015b, Barbeaux and Hollowed 2017); therefore, analysis of factors affecting a stock's vital rates throughout its life cycle should be prioritized to understand changes in productivity. Ageing programs and food habits labs are important for conducting much of this process research and should be supported in each region.

- **Identify and address personnel and training needs.**

Identifying and addressing personnel and training needs is essential to increasing staff capacity to confront the growing challenges facing fisheries management in a changing environment (Rec. 2.4, Table 2). Staff should be given opportunities and encouraged to: take training courses on topics such as plankton identification, gonad processing, and genetic analysis; interact with fisheries managers; and conduct research aimed at improving mechanistic understanding of changes.

3.3 Evaluate Priorities and Risks

Not all observed changes warrant a response in the science-to-management process. Ideally the decision to expand a stock assessment to include climate and ecosystem information, and/or to take management action, will consider the degree of change observed, the degree to which a stock is likely to respond (e.g., the stock's vulnerability to changing conditions), the relative importance of the stock, and if accounting for the change is likely to improve conservation and management overall. Recommended actions to help NOAA Fisheries evaluate risk and prioritize species for ecosystem considerations are provided below and corresponding specific potential actions are summarized in Table 3.

Recommendations

- **Evaluate the magnitude and relative importance of observed changes in distribution and productivity.**

The development and use of spatial-temporal models for fishery survey data has been increasing in the United States. These statistical techniques facilitate evaluation of changes in a stock's spatial distribution and incorporate spatial processes in stock assessments (e.g., Thorson et al. 2015a, 2016, Thorson and Wetzel 2015, Ianelli et al. 2016, Thorson and Barnett 2017). Assessment scientists should capitalize on advancements in geospatial statistics to help identify and evaluate the significance of distribution shifts and spatial changes in catch rates (Rec. 3.1, Table 3). Significant changes in either or both would provide support for including these factors in further analyses.

Sensitivity analysis is another useful tool that can help determine when shifting distributions or changing productivity should be accounted for in, and may improve, assessments and management advice. Sensitivity analyses are a routine part of stock assessments conducted to determine how modeling results are affected by perturbing the assumptions and uncertainties in the model (i.e., how "sensitive" is the model to these assumptions). These analyses can help identify factors that influence stock productivity and distribution, when observed changes in productivity (e.g. growth, mortality, recruitment) or distribution (e.g. catchability) have a meaningful effect on the scientific advice, and when explicitly accounting for the change may be warranted. For instance, assessment scientists can use sensitivity analyses to answer questions such as, what percentage change in growth, recruitment, or size results in a measurable effect on inferred stock size, stock status, or catch advice. Results of these analyses can also inform the development of thresholds and triggers that indicate when changes are large enough to warrant a management response.

- **Prioritize species at risk.**

The 2018 update to the Stock Assessment Improvement Plan, Implementing a Next Generation Stock Assessment Enterprise, proposes a three-step process for deciding when and how to expand a stock assessment to include climate and ecosystem information. The first step involves identifying stocks that are highest priority for expanded assessments. This would include, for instance, stocks that are most vulnerable to climate or ecosystem impacts. Ecological risk assessments identify major threats facing groups of species and their relative vulnerabilities to those threats, and can be used to help prioritize species for expanded assessments and/or management action.

Several different forms of ecological risk assessments exist. Hobday et al. (2011) proposed a hierarchical (tiered) ecological risk assessment approach for looking at the effects of fishing on species and ecosystems. Holsman et al. (2017) expanded this approach to include assessment of risk due to any natural or anthropogenic pressure. In the tiered approach analysts work through sequential steps where species identified as “at risk” in Level 1 analysis are further considered in Level 2 semi-quantitative analysis, and species identified as “medium risk” or “high risk” at Level 2 are further evaluated using quantitative model-based approaches in Level 3 assessments. Therefore, the approach allows analysts to focus and prioritize time and resources developing quantitative assessments for only those species identified to be most at risk. Additionally, the Level 1 qualitative assessment can provide a rapid and computationally inexpensive screening tool to identify key pressures that may be

TABLE 3
RECOMMENDATIONS AND POTENTIAL ACTIONS TO IMPROVE THE EVALUATION OF RISKS AND PRIORITIES

Recommendation	Potential Actions
3.1 Evaluate the magnitude and relative importance of distribution shifts and changes in productivity The magnitude and relative importance of an observed change should be evaluated prior to invoking a management response	• Use spatial analysis techniques to identify and evaluate the magnitude and relative importance of distribution shifts as well as spatial changes in fishery catch rates • Use sensitivity analyses to look at how accounting for climate change affects scientific advice and potential management responses
3.2 Prioritize species at risk Identify and prioritize the species and regions that are at greatest risk from current and future changes	• Apply the three-step process described in SAIP (Lynch et al. 2018) to prioritize stocks for ecosystem considerations • Conduct comprehensive risk assessments and climate vulnerability assessments to inform assessment and management priorities, in addition to science and research needs [Appendix G] • Run Tiered risk assessments (e.g. Hobday et al. 2011; Holsman et al. 2017; Hare et al. 2016) to rapidly screen potential climate and ecosystem effects for hundreds of species and habitats

affecting a wide range of species, habitats, activities, or social components and therefore be prioritized for more in-depth monitoring and analysis (Holsman et al. 2017).

Climate vulnerability assessment, another form of ecological risk assessment, is specifically designed to identify and prioritize fish stocks of greatest risk from climate change (Link et al. 2015). Results from these various risk assessment approaches can help determine where to focus efforts for inclusion of climate and ecological information into the fishery science-to-management process (Rec. 3.2, Table 3).

3.4 Conduct Assessments and Develop Forecasts

When there is a clear or anticipated effect of climate, ocean, and ecosystem conditions on fish dynamics, relying on fishing pressure as the sole, dynamic, extrinsic factor affecting fish populations may not be an effective management approach (Keyl and Wolff 2008). However, accounting for changing conditions within a stock assessment can be quite challenging. Presently, most stock assessment models assume that model parameters (e.g. catchability, growth, mortality, recruitment) either remain constant over time and/or space, or vary according to random processes. However, climate-induced changes may create sudden shifts in system states, or gradual drift in underlying conditions (as opposed to variability about a mean value); therefore, assumptions about stationary or randomly varying parameters will be violated. Overall, to better account for distribution shifts and changing productivity, external drivers need to be considered in stock assessment models, particularly in relation to catchability and vital rate parameters.

Catchability (Q) - Catchability or detectability relates to how susceptible an animal is to being caught or detected by fishing gear, including by fisheries and surveys. Surveys, fishery indices, and fishery assessments often assume that catchability for each fleet or survey is constant over time. However, environmental changes are likely to alter the probability of capturing or encountering many species, leading to real changes in catchability. Not addressing these changes in catchability in stock assessment models can result in biased assessment results. Fortunately, mechanistic, process-oriented studies that explicitly account for changes in catchability as a function of oceanographic conditions are possible and can greatly benefit the assessment process, e.g. yellowfin sole (Appendix B) and butterfish (Appendix C).

Recruitment (R) – Changing temperature, pH, dissolved oxygen, and other ocean conditions can also have direct effects on production, or the number of recruits produced by a given spawning stock size. The mechanisms underlying these linkages are complex and involve multiple factors throughout early life history. Considerable progress has been made in understanding these complex processes through using coupled biophysical hindcast models that track single or multiple species through the first year of life (Rose et al. 2015). However, identifying how information from coupled models of the early life history can be indexed for use in stock assessments remains challenging.

Growth (G) – In addition to recruitment, understanding the rate at which individuals in a stock grow is important for estimating a stock's productivity when size- or age-structured stock assessments are used. Growth is generally incorporated into stock assessments through the estimation of the relationship between size and age, often assumed to be constant through time. However, growth rates may change with changing environmental conditions. Bioenergetic models provide mechanistic explanations for how growth rates change as a function of diet, temperature, and other factor. These models can be valuable for evaluating how changes in growth can occur with environmental change (Holsman et al 2016). For example, growth rate is expected to increase with temperature to a certain point, then decline as temperature becomes too warm, leading to decline in aerobic performance (Audzijonyte et al. 2016).

Natural Mortality (M) - Natural mortality is the rate at which fish die due to natural causes, i.e., causes other than fishing, and may also be affected by changing oceanographic conditions. These changes could be due to both episodic events, such as harmful algal blooms (Appendix E), heat waves, cold spells, and other extreme weather events that create short-term spikes or drops in mortality, or slower, longer term changes in climate and ocean conditions. Additionally, climate may affect the abundance, size, or metabolisms of species that interact with the focal species, indirectly affecting the natural mortality of the focal species.

Despite the clear influence that oceanographic conditions can have on catchability and life history parameters, the value of including these effects in assessment models is often unclear, primarily because of limited understanding of the underlying mechanisms. Thus, the incorporation of ocean, climate, and ecosystem information in assessment models used for management advice is uncommon. As mentioned previously, there are numerous potential negative consequences of not integrating ocean and ecosystem information in the stock assessment models and/or advice to managers. Assessment scientists should explore ways to increase the incorporation of that information in assessments and forecasts. Recommended actions for scientists to move toward that goal are described below and corresponding specific potential actions are summarized in Table 4.

Recommendations

- **Include ecosystem considerations in Terms of Reference in the stock assessment process.**

To formalize the consideration of ecosystem drivers in a stock assessment, both the EBFM Road Map and the SAIP recommend that ecosystem considerations be included in stock assessment and assessment reviewer Terms of Reference (Link et al. 2016; Lynch et al. 2018), a recommendation that is re-iterated in this report (Rec 4.1, Table 4). These considerations are likely best addressed when improvements to stock assessment methodology are being considered (e.g., during “research” or “benchmark” assessments). However, there is opportunity to evaluate hypotheses about climate-related effects on fish stocks during routine operational assessments, which may help establish research priorities.

- **Capitalize on advancements in spatiotemporal and physical-ecosystem-economic models.**

It has been historically challenging to account for shifts in stock distribution or productivity when multiple drivers are plausible (e.g., temperature vs age-structured dynamics, vs. fishing mortality, e.g., Thorson et al. 2017). However, advancements in spatiotemporal and spatially explicit models can help address this challenge by statistical modeling techniques that can test different hypotheses regarding plausible drivers of change in the ecosystem. These modeling approaches allow for improved incorporation of spatial, multispecies, and oceanographic dynamics in assessments and should be further explored and developed.

- **Evaluate model diagnostics and the predictive skill of forecasts.**

Uncertainty in model forecasts can contribute to a lack of confidence in results from managers and stakeholders, limiting the use of potentially more accurate, but less certain, scientific advice. Therefore, there is a need for continued evaluation of the degree to which models with environmental and climate linkages are improvements over non-climate linked models. Practitioners should use various model diagnostics, including retrospective and sensitivity analyses, to evaluate the benefits and risks of including environmental covariates or time-varying parameters in models. Seasonal to decadal scale climate projections can be used to provide updates of predictive skill and inform forecasts for-models with mechanistic environmental linkages at scales relevant to fishery management (Tommasi et al. 2017). Additionally, regardless of whether environmental variables are included, the evaluation and quantification of model predictive skill should be a routine part of the stock assessment process.

TABLE 4

RECOMMENDATIONS AND POTENTIAL ACTIONS TO STRENGTHEN ASSESSMENT AND FORECASTING CAPABILITIES

Recommendation	Potential Actions
4.1 Include ecosystem considerations in Terms of Reference in the stock assessment process Terminology should be included in assessment TOR, assessment reviewer TOR, and there should be an expectation that management bodies consider climate effects when developing their catch recommendations	• "Research" or "benchmark" stock assessment TORs should consider including the following text: "Are there known or hypothesized: 1. Range shifts in the population 2. Changes in survey/fishery catch rates 3. Changes in productivity (e.g. growth, recruitment) 4. Episodic mortality events."
4.2 Capitalize on advancement in spatial-temporal and physical-ecosystem-economic models Spatial, oceanographic, multispecies, and economic data should be incorporated into stock assessments and other analyses where appropriate	• Utilize results from process-oriented research to understand environmental drivers of recruitment and other vital rates • Develop stock assessment models and test hypotheses related to: (1) including environmental covariates as drivers of catchability and vital rates, (2) changes to stock identification, characterization, or spatial dimensions, (3) regime shifts and extreme events (e.g., HABs), (4) climate-driven changes in trophic dynamics, and (5) forecast scenarios and prevailing environmental conditions.
4.3 Evaluate model diagnostics and the predictive skill of forecasts Selection of a final model, or set of models, should rely on comparing diagnostics and predictive skill of a plausible suite of models, including those with environmental linkages	• Employ probabilistic model evaluation techniques, such as retrospective bias analyses, forecast skill metrics for developing forecast ensembles, residual analysis to visualize error • Seasonal to decadal scale climate projections (Tommasi et al. 2017) can be used to provide rapid updates of predictive skill for models with environmental linkages, informing assumptions regarding uncertainty around longer-term projections • Results of diagnostic and skill tests should be communicated to managers and stakeholders to document the decision process and to fully characterize uncertainty around the scientific advice
4.4 Develop a suite of plausible hypotheses regarding stock assessment models and use multi-model inference when there is not a clear single best model	• When conducting research and development of operational models, consider and evaluate multiple hypotheses, including competing hypothesis regarding environmental drivers. • Develop scientific advice using multi-model inference or ensemble modeling techniques when a clear single best approach is not apparent.

- **Develop a suite of plausible hypotheses regarding stock assessment models and use multi-model inference when there is not a clear single best model**.

In cases where processes are not well understood, multiple hypotheses should be considered, wherein comparative assessments test alternative mechanistic formulations. Comparing diagnostics and predictive skill across a suite of plausible models can be helpful to determine which model, or suite of models, should form the basis of scientific advice. Results of these analyses should then be communicated to managers and stakeholders to document the decision process, and the results should be incorporated into the characterization of uncertainty around the final advice. Results from multiple models could also be potentially synthesized using multi-model and ensemble modeling techniques. Multi-model techniques are a useful tool that may enable assessment scientists to more fully evaluate alternative states of nature and mechanistic relationships to better characterize the uncertainty in the system and resultant forecasts (e.g., Ianelli et al. 2016; ACLIM project, Appendix F).

3.5 Communicate Scientific Advice to Management

To facilitate informed management decisions that respond to a dynamic and changing environment, scientific information needs to be communicated effectively and efficiently. There are numerous potential negative consequences to making management decisions that do not adequately or accurately account for shifts in distributions or changes in productivity. However, information on shifting distributions and changing productivity is often not used in management decisions partially as a result of how the information is communicated to managers leading to a lack of clarity on when and how the information could be used to adjust management actions.

In the U.S., the manner by which ecosystem information is communicated to managers during the stock assessment process is not consistent across regions. In some cases, such as with the North Pacific, Western Pacific, and Pacific Fishery Management Councils (NPFMC, WPFMC, and PFMC, respectively), the information is presented in dedicated ecosystem considerations chapters and/or scenarios within stock assessment reports. In the Gulf of Mexico, New England, and Mid-Atlantic Fishery Management Councils (GMFMC, NEFMC, and MAFMC, respectively), as well as the PFMC, short State of the Ecosystem reports, structured by general management objectives have been presented. Stock assessment scientists also present ecosystem information to Councils' Scientific and Statistical Committees (SSCs) during some regional SSC meetings. The lack of a standardized process or protocol for reporting on the ecosystem, including shifting stock distributions and productivity changes, hinders the ability to account for these changes during the stock assessment process.

This highlights the need to re-evaluate how climate change and ecosystem information is communicated to managers, and to identify ways to improve the communication and operationalization of this information. The goal is to provide evidence-based information in a transparent process in which management strategies are evaluated and the probable consequences of different management decisions under various states of nature are clearly demonstrated. Ensuring that environmental (climate and ecosystem) information, and how it may be used, is presented to managers and other stakeholders in a clear and understandable manner is a very important step towards this goal. Recommendations to improve the communication of climate and ecosystem information to inform management decisions are described below and specific potential actions are summarized in Table 5.

Recommendations

- **Standardize reporting and coordinate among ecosystem and stock assessment teams.**

Routine reporting and using standardized templates to communicate information on ecosystem dynamics, species distributions, and productivity, would improve the communication and delivery of assessment results to managers (Rec 5.1, Table 5). As part of this reporting, scientists should provide contextual information that changes are occurring with either positive or negative implications for management. Stock assessment and ecosystem science teams should work together to provide this contextual information in a coordinated fashion, drawing connections between ecosystem changes and stock assessments where appropriate and highlighting potential drivers of change. These interdisciplinary teams should work with management partners to determine the best format and timing for presenting Ecosystem Status Reports and other information to managers. A national initiative is underway to create a generic template that communicates stock-specific ecosystem considerations, referred to as Assessment Profile, Ecosystem Considerations, and Socioeconomics (APECS; Lynch et al. 2018). These APECS will provide two-page summaries of the important ecosystem and stock assessment information, thereby serving as a useful tool to improve communication and comparison of results across stocks and regions.

- **Use decision support tools to communicate assessment advice and associated uncertainties.**

Decision support tools (e.g., decision tables, decision trees) are useful to help communicate uncertainty, tradeoffs, and risks associated with various states of nature and management decisions (Rec 5.2, Table 5; Appendix E). To the extent practicable, decision support tools should be included in assessment reports and provide action-oriented information (i.e., communicate effects of trade-offs regarding metrics decision-makers care about, such as catch limits, gear restrictions, time and area closures, all associated with a probabilistic risk of overfishing). Results from sensitivity analyses that evaluate the level of change that results in measurable effects on a stock (see Section 3.3) can be used to inform the decision points and thresholds used in decision trees. Additionally, maps of changes in current and future projected species distributions, as related to management jurisdictions, can be a useful decision-support tool. Providing such maps during the decision making process can improve communication about changes and uncertainties around those changes and contribute to more informed decision making.

- **Facilitate communication between scientists and managers.**

Communication among scientists, managers, and stakeholders should be multidirectional, whereby all perspectives are heard and participants learn from each other. A critical component of this increased communication is regular engagement and coordination with managers and their various committees (e.g., Council SSCs, Plan Teams, and Advisory Panels) as well as with fisheries stakeholder groups (Rec. 5.3, Table 5). This can be achieved through regular and open dialogue at Council meetings, as well as workshops, and debriefs with stock and ecosystem assessment scientists. The goals of these engagements should include arrival at a clear understanding of whether there are action items or measures that managers should consider in response to changing systems. Additionally, establishing work teams that include NOAA Fisheries scientists who are monitoring and assessing a species' changing distribution and NOAA Fisheries management and regulatory staff would help ensure that scientists are aware of spatial management programs affecting species, and that managers are aware of changing scientific information on stock distributions and habitat use. Increased dialogue among all parties and a more collaborative and transparent decision-making process are important in building trust and scientific understanding, especially given the uncertainty and complexity of the

TABLE 5

RECOMMENDATIONS AND POTENTIAL ACTIONS TO IMPROVE COMMUNICATION OF SCIENTIFIC ADVICE ON SHIFTING DISTRIBUTIONS AND CHANGING PRODUCTIVITY

Recommendation	Potential Actions
5.1 Standardize reporting Use standardized templates to report information on ecosystem dynamics, species distributions, and productivity	• Provide managers with maps of species distributions over time and by life stage • Increase the use of Assessment Profile, Ecosystem Considerations, and Socioeconomics (APECS) to summarize key stock assessment advice • Determine best format and timing for presenting Ecosystem Status Reports to inform management decisions
5.2 Use decision support tools Quantify and present tradeoffs and risks associated with various states of nature and management scenarios	• Use decision tables to communicate the probabilistic risk of overfishing and other action-oriented information (e.g., fishing scenarios) associated with various states of nature and management scenarios • Develop and use decision trees to trigger specific management responses (e.g., if stock A moves X amount, revisit catch allocation procedure)
5.3 Facilitate communication between scientists and management partners Create mechanisms for regular and open dialogue between scientists, managers, and all fisheries stakeholder groups to support transparent decision-making, and ensure that the appropriate data are collected and used	• Conduct workshops where managers, scientists, and stakeholders discuss what information is needed to better inform decisions • Engage with stakeholders and managers throughout the entire science-to-management process • Conduct regular debriefs with interdisciplinary groups (e.g. ecosystem teams, Council subcommittees, stock assessment teams) following stock assessments to help interpret patterns and develop action items and research priorities • Form work teams between NOAA Fisheries scientists who analyze species distributions and NOAA Fisheries regulatory and management staff who implement spatial management programs

challenges posed by changing climate and ocean conditions.

3.6 Manage Fisheries under Changing Conditions

Fisheries managers increasingly face the daunting challenge of determining appropriate responses to current and predicted changes in stock distribution and productivity. As discussed in section 2.0, changing climate and ocean conditions and the resultant effects on species distributions and productivity can have significant effects on management decisions, such as allocation, spatiotemporal closures, stock status determinations, and catch limits. For instance, allocation issues can arise as the proportion of a species across regions changes due to shifts in its distribution. Basing allocation decisions on historical catch rates by region may not be appropriate, especially in the case of emerging fisheries. Both the fishermen who historically had fished the species and fishermen in the region into which it expanded will want to claim allocation rights. Historic fisheries do not want to experience reductions in their allocation, and emerging fisheries want a new or increased share of the quota.

Changing environmental and oceanographic conditions can also influence the identification of essential fish habitat (EFH) and the effectiveness of subsequent spatial management approaches by altering the distribution, spatial extent, and use of spawning, migration, and nursery habitats. Federal regulations specified in 50 CFR 600.815(a)(10) require that Councils review the EFH provisions of their fishery management plans (FMPs) and revise or amend those provisions as warranted based on available information, at least once every 5 years. However, this timeframe may be too long to adequately respond to changes. Therefore, regulatory regimes that manage through time and area closures to protect EFH or prohibit fishing during vulnerable parts of a stock's life history (e.g. spawning and juvenile stages) can see mismatches or lags between when change occurs in the water and when management actions can be implemented through the Council process.

Catch limits in the U.S. are usually arrived at through the use of harvest control rules (HCRs) that adjust fishing mortality or catch as a function of stock status relative to benchmarks and often provides precautionary buffers to account for associated scientific and management uncertainty (Brunel et al. 2010). Stock status determinations and HCRs are often developed under the assumption of fixed, or stationary, biological reference points over time. Many HCRs perform poorly when environmental conditions change stock productivity and reference points such that the HCR gets incorrect information on the true status of the stock or is unresponsive to changes (A'mar et al. 2009, Brunel et al. 2010).

Ideally, management should be prepared to quickly respond and adapt to naturally-induced and fishery-induced fluctuations to provide appropriate decisions on allocations, spatiotemporal closures, and catch advice. Strengthening and adapting the science enterprise to better detect, understand, assess, and communicate changes in the environment (Sections 3.1 – 3.5) inevitably will help managers determine appropriate courses of action. Some recommended actions for managers to take are described below and summarized in Table 6.

Recommendations

- **Consider population resilience, age structure, and genetic diversity when making management decisions.**

One of the most basic tools available to help build stock resilience to climate change is simply complying with the MSA's requirement to prevent overfishing, prevent stocks from being overfished, and rebuild overfished stocks. Since 1996, 44 fish stocks have been rebuilt in the United States, benefitting marine ecosystems and fishing communities.

Managers can also strengthen the adaptive capacity and resilience of stocks by protecting and enhancing the age structure and genetic diversity of a population. Genetic adaptation to climate change may be necessary, and management should aim to increase or preserve current genetic diversity as this provides the building blocks needed to adapt to a changing environment. Similarly, stocks that have maintained their age structure are more resilient to environmental change. Large females tend to have larger, healthier, and more abundant eggs (Planque et al. 2010). Large females also tend to spawn over a longer time period and depth gradient (Rouyer et al. 2011), and removal of these older fish can result in the loss of historical migration and spawning areas (Planque et al. 2010). Thus, removing large females can decrease the variety of conditions experienced by eggs and larvae, reducing the likelihood that some eggs and larvae encounter environmental conditions beneficial to growth and adaptation.

- **Evaluate management action under potential future scenarios.**

Managers should be able to proactively explore and plan for various future scenarios and evaluate the impacts and risks associated with different management actions under those scenarios (Rec 6.1, Table 6). Tools that can aid managers in this endeavor include: structured scenario planning, holistic ecosystem models, climate vulnerability and risk assessments, and management strategy evaluations (MSEs).

Structured scenario planning is a strategic planning method used to help visualize how alternative plausible futures might emerge, explore potential ways to prepare for those alternative futures, and evaluate how different actions or strategies would play out under the different plausible futures. Risk assessments and climate vulnerability assessments (CVAs; Morrison et al. 2015, Holsman et al. 2017) previously mentioned in Section 4 of this report can be useful tools to inform management actions by identifying species and ecosystems at most risk, and therefore in need of additional data, analyses, and management action (see Section 4 for more detail; Holsman et al. 2017). CVAs[5] are ongoing for finfish and invertebrate species nationwide, and are being expanded to address protected species. Managers should call for and use the results of such analyses to help prioritize limited resources for future actions [See Appendix G].

MSEs can be used to test the efficacy of various alternative management options in achieving predetermined management objectives. These analyses can be used to evaluate the robustness of alternative strategies under various states of nature (i.e., different climate change scenarios) by including climate change signals in developing alternative operating models.

- **Plan for emerging fisheries.**

The MSA provides an adaptive tool intended to give Councils better notification of, and potentially more authority over, emerging fisheries. Section 305(a) of the MSA requires that each Council develop a list of fisheries and gears used within its geographic area of authority. No person or vessel may employ fishing gear or engage in a fishery not included on this list without giving 90 days advance written notice to the appropriate Council, or to the Secretary of Commerce, where appropriate. This MSA provision is intended to give Councils time to develop, or ask the Secretary to develop, emergency regulations to address new fisheries as they arise to prevent the new fishery from compromising the effectiveness of conservation and management efforts under the MSA. A prudent and rudimentary management action to address potential movement of new species into fishery management areas would be for each Council to review and update its list of authorized fisheries and gear (Rec 6.2, Table 6).

When Councils prepare for emerging fisheries, they should develop and document a process for making allocation decisions when stocks change their distributions (Rec. 6.2, Table 6). A literature review (Morrison and Termini 2016) provides the following suggestions. Managers can negotiate prearranged management responses that articulate a set of indicators and responses to follow when adjusting allocations (Miller and Munro 2004). For example, allocations could be based on the proportional distribution of the stock across regions in a given year (Bailey et al. 2013. Additionally, Councils can use early warnings and spatial distribution projections to help identify species that may shift across jurisdictional boundaries to help prepare for potential emerging fisheries.

- **Evaluate time and area closures.**

Changing ocean and climate conditions may require more responsive and dynamic fisheries management. In dynamic ocean management near real-time biological, oceanographic, social and/or economic data (See section 3.1) are used to evaluate and adjust temporal and spatial management actions to better align with changes of the resources being managed (Maxwell et al. 2015, Hazen et al. 2018). The early warnings and indicators of change described in section 3.1 and distribution maps described in section 3.5 will be extremely important to enable such responsive ocean management. How a more dynamic and responsive management system would fit under the current MSA framework may need to be evaluated; however, in general, a combination of traditional and more responsive

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[5] https://www.fisheries.noaa.gov/national/climate/climate-vulnerability-assessment

TABLE 6

RECOMMENDATIONS AND POTENTIAL ACTIONS TO IMPROVE MANAGEMENT OF FISHERIES UNDER CHANGING CONDITIONS

Recommendation	Potential Actions
6.1 Consider population resilience, age structure, and genetic diversity when making management decisions Managers should consider the resilience and adaptive capacity of stocks when making management decisions.	• Continue to comply with MSA's requirement to prevent overfishing, prevent stocks from being overfished, and rebuild overfished stocks • Protect and enhance the age structure and genetic diversity of a population
6.2 Evaluate management actions under potential future scenarios Explore and plan for various future scenarios and evaluate impacts of different management actions under those scenarios	• Conduct structured scenario planning exercises to identify future scenarios and potential management options • As MSEs are conducted on harvest policies, include scenarios related to possible future climate-induced changes in species distributions and productivity, and use MSEs for more comprehensive analysis of management scenarios and associated risks and tradeoffs • Where possible, evaluate single species catch recommendations (ACLs) using a climate-linked ecosystem model (e.g. Atlantis) to assess potential integrated and cumulative impacts of management
6.3 Plan for emerging fisheries Councils should develop plans for how to respond to and coordinate with neighboring jurisdictions when distributions are shifting across management boundaries	• Evaluate current permitting systems for flexibility to account for shifting distributions and changes in productivity • Update and provide detailed descriptions of current fisheries and gears approved under MSA section 305(a). • Utilize early warning indicators and coordinate with neighboring jurisdictions to identify species which may shift into our out of a particular jurisdiction • Develop joint agreements between jurisdictions that describe the response to shifting distributions
6.4 Evaluate time and area closures Adjust closures to reflect a stock's current range, habitat needs, and phenology	• Use species and habitat distribution maps, and results of habitat suitability models to evaluate effectiveness of current and future conservation area boundaries • Use early warnings and indicators of ecosystem change to inform seasonal closures, gear restrictions, or bycatch reduction strategies, etc. • Facilitate collaboration between scientists and managers to develop management grids and spatial metrics that could inform decisions related to allocations, spatial management, and jurisdictions
6.5 Develop adaptive Harvest Control Rules Harvest control rules should be designed to be robust or responsive to changing ecosystems	• Design simulation-tested harvest control rules robust to climate-related uncertainty by incorporating this uncertainty into the buffer (catch reduction; e.g. P*) used to set catch limits that prevent overfishing • Develop and use decision trees (ideally through research and simulation) to help determine how, and at what scale, an environmental or ecosystem driver should adjust a harvest policy • Consider empirical management procedure-based harvest control rules that rely on simple, attainable, and responsive measures of living marine resource dynamics, particularly where mechanistic understanding is lacking

management procedures would potentially increase the speed and effectiveness of management decisions and their outcomes (Maxwell et al. 2015).

- **Develop adaptive and responsive harvest control rules.**

Developing HCRs that account for uncertainty and known changes in environmental conditions affecting productivity may increase the successful management of fish stocks influenced by environmental forcing (Rec 6.4, Table 6). Examples of HCRs that are adaptive or robust to changing conditions could take several forms. One possible approach is for a Council to adjust its risk policy to respond to concerns about changing ecosystems in determining its acceptable level of risk of overfishing. The benefit of this approach is that it can be used in cases in which a climate-induced effect on a stock is likely, but underlying mechanisms are not yet understood. As an example, if a standard control rule allows for a 40% chance of overfishing, then for stocks with high climate vulnerability scores, perhaps 35% is more appropriate.

Alternatively, HCRs that operate on empirical management procedures, such as indices of abundance, which implicitly and directly account for changing productivity may also be useful management considerations. Perhaps the most challenging and information intensive method is to explicitly estimate regime shifts or dynamic biological reference points, environmentally-driven stock-recruitment relationships, and forecasts that account for changes in stock or ecosystem productivity. Generally, these mechanistic approaches require relatively long time series of reliable observations to facilitate an acceptable level of prediction skill. They may require an FMP amendment, which could take up to a year to implement and perhaps another stock assessment cycle to conclude.

4.0 Conclusions

Changing climate and ocean conditions are affecting the Nation's managed fisheries in ways that are not routinely addressed in the science-to-management process. Traditional methods and assumptions used in the fishery management process need to be adapted to ensure effective stewardship of living marine resources. This involves addressing the challenges and gaps identified in this report – from detecting and understanding changes to analyzing and communicating results to the relevant decision-makers.

There are a variety of opportunities to consider and address changing ocean conditions in the science-to-fisheries management process. This report identifies six key steps and specific, actionable recommendations for how NOAA Fisheries and its partners can better prepare for and address climate effects on fish stocks and fisheries. The recommendations and related actions are intended to be applied broadly to support the full range of fishery management decisions in each region. However, resource and other limitations may require assessing how best to implement the recommendations in each region. NOAA Fisheries should partner with Councils and regional stakeholders to identify the most effective approach for implementing these recommendations in their region. This paper includes general recommendations and proposed actions to facilitate those discussions.

Faced with shifting species distributions and changing productivity, NOAA Fisheries, Councils and Interstate Commissions should explore future scenarios, plan for emerging fisheries, re-evaluate their spatial and temporal management procedures and develop responsive harvest control rules. Ultimately, all management approaches that account for changes in the environment as they occur depend on data collected from survey and monitoring efforts and process-oriented research. It is important that basic agency activities adapt to changing data needs to differentiate between changes in abundance and shifts in distribution or productivity. Opportunities exist to make better use of the current data collections, as well as to efficiently expand data collection through standardizing the type and frequency of data collected on existing surveys to allow better comparison across jurisdictions. Other key opportunities include leveraging the capacity of fishermen and citizen science programs, operationalizing advanced sampling technologies that can collect information at appropriate temporal and spatial scales, and using electronic technologies to more efficiently collect fishery-dependent data.

Each step in the science-to-management process benefits from close collaboration and communication among scientists, managers, and stakeholders. Regularly scheduled workshops, debriefs, meetings, or other mechanisms to allow open dialogue and engagement between scientists and managers, are essential for effective communication and collaboration. For instance, developing processes that allow scientists to provide timely information on ecosystem dynamics and species distributions to appropriate Council bodies can be important to inform management decisions. Regular meetings would also provide scientists with feedback from managers to help prioritize the types of analyses and evaluations that would be most beneficial to sustainable fisheries management.

The recommendations identified in this report, if enacted at appropriate regional and national levels, will better equip NOAA Fisheries to prepare for and respond to changing climate and ocean conditions, and thereby improving stewardship of the nation's living marine resources.

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6.0 Appendix

A. Flexible survey design, Pacific sardine off the west coast of North America

Pacific sardine (*Sardinops sagax*) are an important component of the coastal pelagic species (CPS) assemblage off the west coasts of Vancouver Island, Canada, the United States, and Baja California, Mexico. Sardine have a high caloric value per gram, tend to be preferred forage of many higher trophic level animals, and can greatly affect the reproductive success of predators (e.g., sea lions, McClatchie et al. 2016). Due to their high nutritional content, sardine are also economically valuable and harvested in the 3 countries primarily as a reduction fishery.

Sardine abundance varies massively at decadal scales (Zwolinski and Demer 2012). Sardine were very abundant in the 1930's and 1940's, but crashed in the 1950's to near non-detection levels decimating the economies of many coastal towns. Sardine abundances resurged in the 1980's and 1990's, and harvest resumed in the U.S. and Canada in the 1990s. Stock sizes declined in recent years and the commercial directed fishery was closed in 2016. Given the volatility and importance of Pacific sardine, estimating stock sizes and setting harvest guidelines is a major goal of NOAA Fisheries. Estimating stock size is complicated by sardine life history. During the spring, sardine generally congregate and spawn off central and southern California. In summer, larger individuals often migrate north to Oregon, Washington, and Canada to feed in these productive waters. Because sardine distributions have always been a moving target, NOAA Fisheries has developed sampling protocols that may be flexible enough to accommodate climate-induced shifting distributions. Sardine presence is well-predicted by satellite-derived measurements of sea surface temperature, chlorophyll *a*, and sea surface altitude, and relationships hold regardless of season or sardine spawning condition (Zwolinski et al. 2011). As such, NOAA Fisheries is able to define optimal, good, bad, and unsuitable sardine habitat (Zwolinski et al. 2011).

NOAA Fisheries conducts annual assessments of sardine stocks in the U.S. and Canada using acoustic-trawl (AT) sampling. AT methods involve searching for acoustic signals of CPS along predetermined transects during the day when CPS schools are at depth and then returning to locations where CPS were acoustically detected at night when they rise to the surface. Surface trawls are then run at night to evaluate which species characterized an acoustic signal. The sample frame and transect allocation is determined prior to the survey based on habitat classification based on the satellite-derived measurements. Greater sampling effort is apportioned in optimal and good than bad and unsuitable habitats. Stock estimates are then calculated within each habitat type in order to minimize overall CV. In a changing climate, it is possible that sardine and other CPS distributions will shift north. It is unlikely, however, that habitat suitability will change. Because sardine sampling is based on dynamic habitat rather than a fixed location, this type of design should remain viable in the future.

B. Yellowfin sole (*Limanda aspera*) – “time-varying q” and “regime shift”

Yellowfin sole are found along the Pacific coast of North America from British Columbia, Canada, to the Chukchi Sea, and south along the Asian Pacific coast to the South Korean coast in the Sea of Japan. They are the most abundant flatfish species in the eastern Bering Sea, and one of the largest flatfish fisheries in the world (BSAI SAFE report, 2011). Similar to many other fish species, bottom water temperature has been linked to changes in behavior and was addressed in several ways in the latest benchmark assessment.

The relationship between bottom water temperature and survey biomass was first explored in the 2001 assessment (Wilderbuer and Nichol 2001). In the 2011 benchmark assessment (Wilderbuer et al. 2011), this relationship was further explored by evaluating how bottom water temperature affects the catchability of yellowfin sole in the survey trawl. During cold years catchability and herding behavior are thought to decrease as fish become less active, and inshore migration timing may change, both of which may alter their availability to the survey area, impacting the survey estimates of stock biomass. To address this, catchability (*q*) was modeled as $q = e^{-a+\beta T}$, where e^{-a} is the time-independent estimate of *q*, and $e^{-\beta T}$ represents the time-varying (annual) *q*. The time-varying component is hypothesized to respond to the metabolic aspect of herding or distribution (availability) which can vary annually with bottom water temperature (Wilderbuer et al. 2011).

In addition to including a time-varying q based on bottom water temperature, new to this assessment was the examination of a “regime-shift” which occurred in 1977. They evaluated three different time-series to determine the stock-recruitment relationship: (1) full time series, 1955-2005, (2) pre-regime shifts, 1955-1977, and (3) post-regime shift, 1978-2005. These three time-series result in very different estimates of long-term sustainability of the stock. When scenario 1 or 2 were used, the stock was much more productive at low spawning stock biomass, which resulted in an F_{MSY} 1.2 times greater than the $F_{35\%}$, and relatively low B_{MSY}. Using the post-regime shift time series (scenario 3) resulted in lower F_{MSY} and higher B_{MSY}. Additionally, using time series scenarios 1 or 2 estimated F_{MSY} with less uncertainty; thus, the buffer between OFL and ABC would be smaller compared to scenario 3. However, if the stock was productive at low stock sizes in the past because of non-density dependent causes, such as environmental conditions, then fishing at high levels and reducing biomass to low levels could prove detrimental to the sustainability of the stock if the environmental conditions resultant productivity has changed in the recent (post-1977) period. Given the uncertainty in the stock-recruitment-environment relationship the panel ultimately went with the precautionary characterization of productivity and used scenario 3, the post-regime shift time series, to calculate biological reference points and determine stock status.

C. Butterfish (*Peprilus triacanthus*) – thermal habitat availability

Butterfish are considered a single stock throughout their range from Cape Hatteras to the Gulf of Maine, and are managed by the Mid-Atlantic Fishery Management Council. The most recent benchmark assessment conducted in 2014 included a TOR to "undertake novel approaches to investigate the impact of the environment on the available butterfish habitat and therefore butterfish availability in the NEFSC fall offshore survey over time". There was concern that recent changes in ocean temperature may have caused a shift in species range and migration dynamics that could affect survey catchability.

In the 2014, assessment a thermal niche model coupled with regional hindcast of bottom water temperatures was used to create a habitat-based estimate of availability (p_H) as the proportion of thermal habitat for butterfish available in the Northwest Atlantic sampled during the survey. More details on the modeling process can be found in the assessment report (NEFSC 2014), but a summary of the methods is presented here. The habitat-based availability index was developed in five steps. The first step was to develop a debiased bottom temperature hindcast for fishery independent surveys from 1973-2012. Daily bottom temperatures were hindcast using the Regional Ocean Modeling System (ROMS) numerical ocean circulation model (NEFSC 2014), and debiased using Mid-Atlantic Bight Ocean Climatological and Hydrographic Analysis (MOCHA). The daily bottom temperatures from the ROMS were interpolated onto the MOCHA grid. The second step was to develop a thermal niche response to temperature. This involved some data mining for an underlying temperature-survey catch response using a generalized additive model (GAM). The base GAM used swept area as an offset, with a bottom water temperature spline, and survey, season, and year as factors to estimate catch. Temperature explained 32% of the variance in catch. The closest known parametric temperature response function (The Johnson and Lewin response function) implied by the GAM was selected and fit to the data using maximum likelihood techniques. The third step was to evaluate the thermal niche model and projections of thermal habitat suitability using *in situ* temperature and catch data collected before 2008 and not included in the calibration. The model performed well, despite producing some false negatives. The fourth step was then to calculate a habitat availability index with uncertainty by using daily regional hindcasts of thermal habitat suitability sampled in the region during the survey periods. The final step was to evaluate the model based estimates of butterfish availability to the surveys by comparing them to empirical estimations (NEFSC 2014).

Assessment reviewers noted that this method was innovative and took a rigorous approach to understanding butterfish habitat preferences, particularly in the context of how those preferences may affect survey catchability (q). In the assessment model, catchability was parameterized as the product of available thermal habitat surveyed and an empirical estimate of net efficiency. The catchability estimate enabled more realistic scaling of butterfish population size than in previous assessments (NEFSC 2014). However, the time-varying estimate of availability was ultimately rejected by the review panel in favor of a more parsimonious time-series mean, although the thermal habitat suitability index was retained for use in future sensitivity analysis.

D. Southern New England-Mid Atlantic yellowtail flounder (*Limanda ferruginea*) – cold pools and stock-recruitment relationship

Yellowtail flounder is a small-mouthed flatfish (pleuronectid) found along the U.S. east coast. Historically, distribution of the Southern New England-Mid Atlantic yellowtail stock (hereafter referred to as the Southern New England stock) ranged from the Chesapeake Bay, but more recently from southern New England, to southern Labrador, Canada. There are three discrete stocks, or management units, for this species: Southern New England, Georges Bank, and Cape Cod/Gulf of Maine. The most recent benchmark assessment of the Southern New England stock in 2012 explored the use of an environmentally explicit stock-recruitment model based on the observed relationship between yellowtail recruitment and the mid-Atlantic cold pool, but did not successfully resolve the relationship between the cold-pool and the recent poor recruitment of the stock.

The recruitment of many cold-water and temperate species in the northwest Atlantic has been linked to the dynamics of the mid-Atlantic cold pool (Houghton et al. 1982, Miller et al. 2016). The linkage between Southern New England yellowtail flounder (YTF) recruitment and ocean temperatures has been hypothesized since the mid-1950s when Taylor et al. (1957) first proposed that the decline in southern New England yellowtail flounder in the 1940s was related to increasing ocean temperature. It was not until 2005, however, when Sullivan et al. (2005) made the connection between YTF recruitment and cold pool dynamics based on observations that YTF almost exclusively settle in the cold pool during summer.

The 2012 YTF benchmark assessment explored this relationship between recruitment and cold pool index by developing an alternative run of the stock assessment base model which modelled the cold pool index as a covariate in the Beverton-Holt stock-recruit relationship estimated internally within the stock assessment ASAP model. The cold pool index was negatively correlated with the variation in YTF recruitment as the cold pool index decreases (i.e., larger and colder pool) the predicted recruitment increases (NEFSC, 2012). The environmentally-explicit Beverton-Holt models that included the cold pool index tended to fit the data better than those based on spawning stock biomass SSB alone (NEFSC 2012; Miller et al. 2016). However, the inclusion of the cold pool index did not explain the step-like decline in YTF that occurred around 1990, and thus was ultimately not used in the final model. Instead, to determine biological reference points, two different recruitment scenarios were evaluated to account for this potential change in the ‘prevailing environmental conditions’ and the uncertainty in the causal mechanisms behind it. The first scenario used age-1 recruitment from 1990-2010, representing the “recent” period, recognizing the potential environmentally driven drop in productivity after 1990. The second scenario used the entire age-1 recruitment time series from 1973-2010, with “two stanzas” of recruitment determined by whether spawning stock biomass is either above or below 4,319 mt. This scenario is based on an alternate hypothesis that the low-recruitment may be due to a decrease in spawning stock biomass. The biomass reference points and conclusions regarding the overfished status of the stock depended greatly on the recruitment scenario employed. Spawning stock biomass at maximum sustainable yield (SSB_{msy}) and MSY were much lower under the “recent” low-recruitment scenario compared to the “two stanza” scenario, which lead to the conclusion that the stock was not overfished and that the stock had rebuilt.

Neither scenario could be ruled out with certainty; therefore, the panel suggested using a weight of evidence (Krimsky 2005) approach to decide whether a species productivity shift had occurred. The following criteria were considered (SARC 54 Panel Summary Report):

- A long period of observed above or below recruitment;
- A long period of above or below average recruitment residuals should be observed that cannot be corrected by simple re-specification of the stock-recruitment relationship;
- Error in estimated model inputs, such as total catch, abundance indices or catch age/size composition can be ruled out as a cause; and
- A plausible mechanism has been found that is based on environmental or ecological conditions.

The panel concluded that the weight of evidence appeared to support the notion of “recent” reduced recruitment of the stock. Although it was concluded that the stock was not overfished, and overfishing was not occurring, the biomass stock status determination remained uncertain due to the lack of strong evidence to support the mechanisms related to the changes in the stock productivity.

E. Quantifying risk from a change in ocean conditions: red-tide episodic event

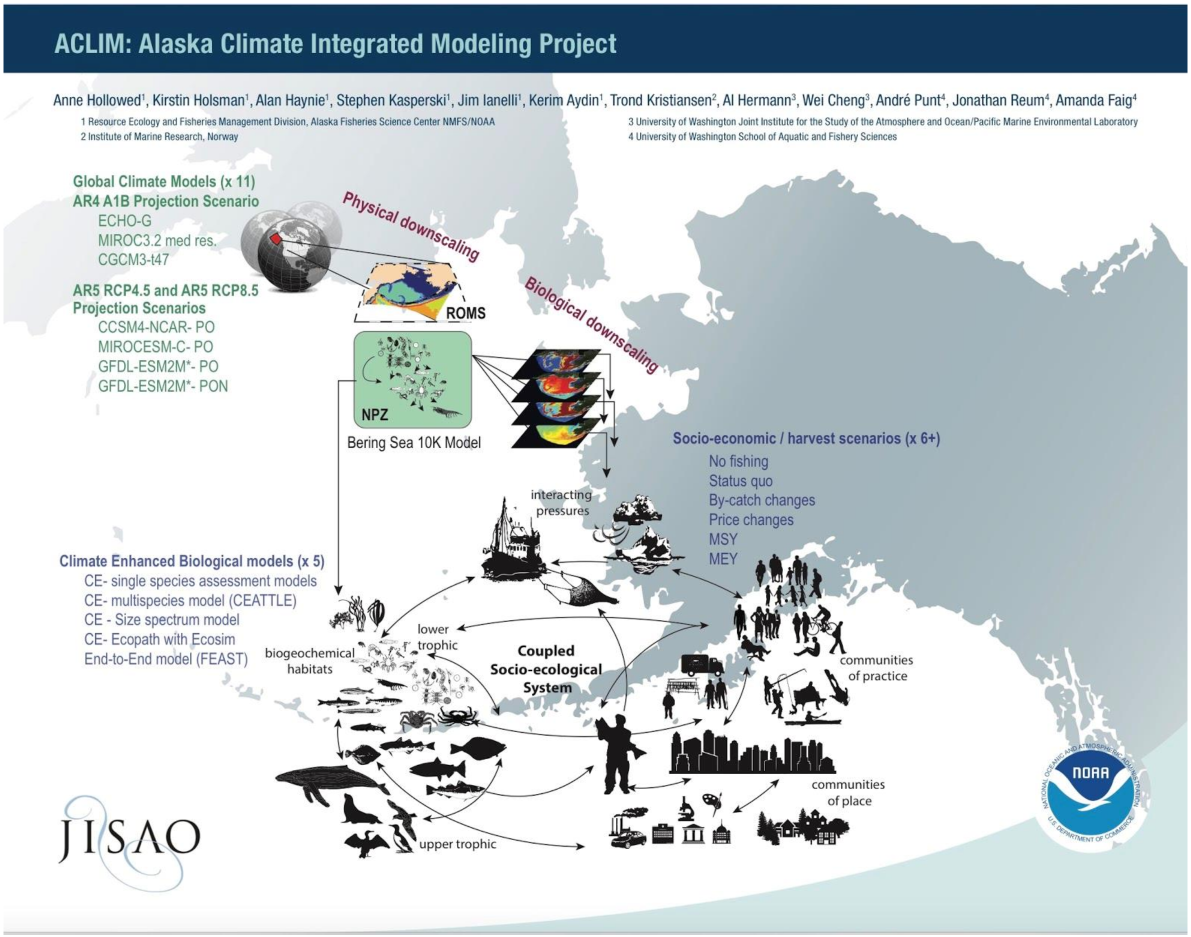
In the Gulf of Mexico, harmful algal blooms of the dinoflagellate *Karenia brevis* are responsible for major episodic mortality events of fish, such as red grouper (*Epinephelus morio*). Studies conducted since 2013 have been effective at quantifying red tide severity, understanding the effects of red tide mortality on groupers and on species which interact with groupers, improving fits to abundance indices, and refining estimation of management benchmarks (SEDAR 2014, 2015). However, questions remained on whether the management system was robust to red tide mortality events. Therefore, in 2014, the Gulf of Mexico Fishery Management Council passed a motion to "…evaluate the current red grouper harvest control rule to determine if it is robust to possible future changes in intensity and frequency of episodic events of non-fishing mortality" (GMFMC 2014). In response to management concerns, simulation testing was conducted to determine potential responses to these mortality events under two different harvest control rule designs; a reactive control rule which altered catch limits in response to red tide event occurrence and an unresponsive, yet precautionary catch limit aimed at buffering against future natural mortality events.

Management concerns revolved around determining (1) what the trade-offs are for different management approaches in terms of maintaining sustainable fisheries; (2) what considerations, if any, arise when mortality changes during stock rebuilding; and (3) how do precautionary approaches affect catches. Simulation tests were conducted focused on two components of the two harvest control rule designs: (1) decision-making reactivity and (2) the level of precautionary catch reduction used to buffer against episodic natural mortality events. The simulations tested several variants of each design considering different precautionary ACL reductions and decision frequencies (e.g., fixed 5-year intervals vs. 5-year reactive intervals where an ACL is newly calculated after a red tide mortality event). HCR performance was measured in terms of (1) avoiding minimum biomass, calculated as the frequency of years in a simulation run where biomass was greater than (1-M)/B_{MSY}, and (2) achieving optimum catch, calculated as the percentage of years in a simulation run where catches were greater than 0.75MSY. Simulations of management strategies were analyzed, and the performance outcomes were presented in the form of a decision tree. Presenting results in the form of decision trees enabled managers and stakeholders to play-out risk-averse or risk-prone approaches to HCR selection in circumstances where episodic natural mortality increases either materialize or fail to materialize. Overall, precautionary ACL reductions had a greater effect on management performance than did decision reactivity; however, in both cases there was a tradeoff between avoiding minimum biomass levels and achieving optimum catch. Reactive HCRs were also less likely to result in timely stock recovery compared with the precautionary ACL HCRs. Precautionary ACL reductions were also found to protect against multiple stochastic events (e.g., recruitment fluctuations and episodic natural morality events) that may be impacting a stock simultaneously.

This study highlights how MSE and structured management guidance can address uncertainty about future occurrences in episodic natural mortality events and can support rationale contrasts of management performance across a variety of scenarios (Harford et al. *submitted*).

F. Alaska Climate Change Integrated Modeling (ACLIM) project

The Alaska Climate Change Integrated Modeling (ACLIM) project represents a comprehensive, collaborative effort to characterize and project climate-driven changes to the Bering Sea ecosystem, from physics to fishing communities, and to understand how different fisheries management approaches might help promote adaptation to climate-driven changes and long-term sustainability in fish and shellfish populations. ACLIM strives to evaluate fishery management strategies under 10+ different climate change scenarios (spanning high and low CO_2 futures) in the Bering Sea. It connects research on scaling of climate models, climate-enhanced biological models, and socio-economic and harvest scenarios (Figure A1). ACLIM is a multi-year, interdisciplinary project, involving collaboration among 19 physical oceanographers, ecosystem modelers, socioeconomic researchers, and fishery management analysts from NOAA Alaska Fisheries Science Center (AFSC), NOAA Pacific Marine Environmental Lab (PMEL), and the University of Washington. A major focus of the project is to quantify scenario, parameter, and structural uncertainty through a multi-model projection suite which will aid in evaluating the performance of resource management strategies under different future scenarios.



ACLIM: Alaska Climate Integrated Modeling Project

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Global Climate Models (x 11)
AR4 A1B Projection Scenario
- ECHO-G
- MIROC3.2 med res.
- CGCM3-t47

AR5 RCP4.5 and AR5 RCP8.5 Projection Scenarios
- CCSM4-NCAR- PO
- MIROCESM-C- PO
- GFDL-ESM2M*- PO
- GFDL-ESM2M*- PON

Socio-economic / harvest scenarios (x 6+)
- No fishing
- Status quo
- By-catch changes
- Price changes
- MSY
- MEY

Climate Enhanced Biological models (x 5)
- CE- single species assessment models
- CE- multispecies model (CEATTLE)
- CE - Size spectrum model
- CE- Ecopath with Ecosim
- End-to-End model (FEAST)

Figure A1. Illustration of the multiple models and climate and fishing scenarios in the ACLIM project.

ACLIM uses output from global climate and earth system models (CGM and ESM, respectively) to project future boundary conditions for a regional ocean model. Dynamically coupled, regionally downscaled projections of the biogeochemistry of the eastern Bering Sea ecosystems are used to project the future of fish and fisheries in a region. Projections of the distribution, production and abundance of fish are used to estimate the future distribution and yield of commercial fisheries using a suite of population dynamics models with different levels of complexity. The approach of ACLIM is to integrate results from the diverse multi-model projection suite to provide a reasonable range of representative futures (with sufficient contrast in scenarios) that can be used to evaluate short- and long- term implications of management actions under future climate change. ACLIM is specifically designed to help NOAA Fisheries assess the science capacity and approaches needed in other regions to deliver and use projections of climate impacts on fisheries in management.

Operationalized ACLIM

AFSC has been moving towards operationalizing ACLIM. An operationalized ACLIM framework would be employed every 5 years (or more frequently if needed) to provide climate ready fisheries management advice. The generalized ACLIM approach for a new climate assessment is as follows: (1) global climate projections will be downloaded and used for initial and boundary conditions of regional high-resolution three-dimensional coupled physical circulation and lower trophic productivity models (ROMS-NPZ); (2) ROMS-NPZ models will be coupled to biological models (e.g., climate-enhanced stock assessment and/or climate-enhanced food web models); (3) with input from stakeholders and fisheries management councils, various harvest and management scenarios will be used to iteratively develop and refine management strategy evaluations (MSEs). This will enhance the global assessment of climate impacts on the world's oceans as well as regional management actions to ensure climate resilience for the Bering Sea ecosystem and the ~$2 billion/yr fishery industry it supports.

Identifying harvest strategies that perform well under non-stationary environmental conditions is a challenging endeavor (Szuwalski and Hollowed 2016). The proposed iterative ACLIM framework conducted on a ~5 year cycle is modeled after the highly successful annual stock assessment cycle in the region; the approach will ensure that fisheries management decisions account for climate-driven changes to fish production and distribution and that climate-ready fisheries management in the region reflects the most recent global climate and carbon emission projections and best available ecosystem and socioeconomic science. Results include projections of biological and physical conditions, species distribution and abundance, and fisheries harvest under various climate and management combinations. Initial results are regularly presented to fisheries managers, fishery dependent communities and other non-governmental organizations to seek feedback on the relative realism of proposed management and fisher responses to changing fish production. The suite of Representative Fishery Pathways are modified based on this input. Final results of the assessment will be distributed in the form of a climate assessment document and presented to regional stakeholders and fisheries councils in order to inform management decisions and tradeoff analyses under short- term and long-term variable conditions and contrasting ecological assumptions (inherent in each model).

G. Using comprehensive risk assessment to prioritize limited resources

Comprehensive risk analysis may be a useful tool to help Councils and other management bodies prioritize which actions to take with respect to incorporating climate and ecosystem factors into fisheries management. In 2016, the Mid Atlantic Fishery Management Council conducted a risk assessment in which sensitivity to climate driven distribution shifts and productivity shifts were considered along with single species status, food web, habitat, economic, social, and management factors to identify species and ecosystems at most risk due to changing climatic conditions (Gaichas et al. 2016).

For this risk assessment the Council selected a set of *risk elements* which are aspects that may threaten the ability to achieve Council social, biological, and economic objectives. The risk elements were evaluated at the managed species or sector level, or ecosystem region. Categorization for each risk element was evaluated using an associated set of indicators. Five risk element groups were identified:

- Ecological (assessment performance, fishing and biomass status, food web interactions (predator and prey), ecosystem productivity, climate, distribution shifts, estuarine habitat, offshore habitat);
- Economic (commercial/recreational revenue, commercial fishery resilience (revenue diversity), commercial fishery resilience (shoreside support));
- Social (fleet resilience, social-cultural) ;
- Food production (commercial, recreational); and
- Management (control, interactions, other ocean uses, regulatory complexity, discards, allocation).

Each sub-category within a risk element category was evaluated and the species or ecosystem given a risk score (low, low-moderate, moderate-high, high). The risk categorization for each subcategory was then summarized for each species, sector, and/or ecosystem and used to identify species, sectors, or ecosystems at most risk, and therefore highest priority for monitoring and management action. Information necessary to conduct the evaluations came from a multitude of sources. Ecological data came from NEFSC trawl surveys, food habits databases, remote sensing (e.g., satellites), and climate vulnerability analysis. Social and economic data were obtained from Quarterly Census and Employment and Wages statistics from the U.S. Census Bureau, Fisheries Economics of the US compiled by NMFS, and the NOAA Fisheries Community Social Vulnerability Indicators. Commercial and recreational seafood landings data were used to assess commercial and recreational seafood production. This effort is still in its initial stages; therefore, the risk assessments' benefits to management are still unclear.

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