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IMPLEMENTING A NEXT GENERATION STOCK ASSESSMENT ENTERPRISE

AN UPDATE TO NOAA FISHERIES' STOCK ASSESSMENT IMPROVEMENT PLAN

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Executive Summary

This new Stock Assessment Improvement Plan (SAIP) describes the advancements that have been made over the past 15 years under the direction of the 2001 SAIP. A key finding is that NOAA Fisheries has operationalized and largely achieved the SAIP's original goal of "Tier II" assessment capability – full assessments for all key stocks. The funding provided through the Expand Annual Stock Assessments budget line, now ~$70M, has supported growth of the research and the operational aspects of the stock assessment enterprise. Coupled with the implementation of a stock assessment prioritization process, NOAA Fisheries is now achieving a high tempo of high quality assessments across the country.

This new SAIP provides a strategic vision for enhancing the performance of NOAA Fisheries' stock assessment enterprise to the next generation level and complements other strategic guidance efforts to accomplish NOAA Fisheries' mission of sustainable fisheries through resource conservation and management. The plan's four sections include: Introduction and Accomplishments; Current State; Next Generation Stock Assessment (NGSA) Enterprise; and Summary, Recommendations, and Implementation.

<u>Introduction and Accomplishments</u> - Stock assessments can be considered both a process and a product that provide necessary information to fishery managers for implementing sustainable fisheries management. Data collection and monitoring, assessment modeling, peer-review, and communicating recommendations are all part of the stock assessment process that culminates in a stock assessment report that provides scientific advice to fishery managers. Stock assessments deliver advice on sustainable harvest policies, stock status relative to a harvest policy, and future catch levels, e.g. annual catch limits that will implement the harvest policy. Assessment advice is developed in strong coordination with the scientific and statistical committees of the fishery management councils. From 2001 to 2015, NOAA Fisheries expanded the capacity of each regional stock assessment program and created several national programs such as the NOAA Fisheries Toolbox and Advanced Sampling Technologies. Collectively, these investments increased the capacity for conducting stock assessments from near 50 assessments conducted in 2001 to near 190 assessments in 2015, a 217% increase in assessment output. Over this time period, NOAA Fisheries' assessments provided the information required to reduce the number of stocks experiencing overfishing by 30% and reduce the number of overfished stocks by 24%. Thus, the strategic direction provided by the 2001 SAIP helped NOAA Fisheries' stock assessment enterprise play a major role in establishing sustainable U.S. fisheries over the past 15 years.

<u>Current Status</u> - The second section of this new SAIP reviews the national stock assessment programs (Chapter 3), data types and collection methods to support stock assessment (Chapter 4), analytical tools used in stock assessment (Chapter 5), and quality assurance in the stock assessment process (Chapter 6). Stock assessments rely on data in three major categories: catch, abundance, and biology. Information to support contemporary stock assessments occurs through cooperative data collection from numerous

management organizations, academic institutions, and stakeholders. Data collected from commercial, recreational, or other fisheries are considered fishery-dependent and include catch, effort, bycatch, discards, and the biological characteristics of the catch. Scientific surveys are the main source of fishery-independent abundance data. They use collection methods that are consistent over time and space and consider the habitats and biological features of fish stocks in their natural environments. Additionally, stock assessments can be informed or improved using other sources such as ecosystem and environmental data. Assessment model complexity ranges from relatively simple, data-limited approaches for the many minor stocks for which the only data source is fishery catch, to highly flexible models termed integrated analysis, that are capable of simultaneously analyzing numerous data inputs, including environmental and ecosystem drivers. All assessment efforts strive to characterize the uncertainty in results such that precautionary management approaches can be implemented. The combination of limited data, model uncertainty, and demand for regulatory advice creates a high public profile for assessments. National guidance specifies that objective peer reviews of stock assessments are an important criterion for determining that the best scientific information available is being used as the basis for fishery management. Well established peer review processes are in place for each region and national guidance provides sufficient flexibility for the science centers and the respective councils to determine the appropriate scope for a stock assessment review.

Next Generation Stock Assessment (NGSA) Enterprise – This new SAIP provides an overview of the many challenges currently facing the stock assessment enterprise, and some of the innovative research and operations that will meet those challenges. One focus for improvement is to make the assessments more holistic in scope. This means that more **ecosystem and socioeconomic factors** that affect the dynamics of fish stocks and fisheries are directly taken into account, and more goals of fishery management are taken into account in the evaluation of sustainable harvest policies. Such expansion aligns with the "Tier III" goal of the 2001 SAIP and is now a principal goal of this new SAIP. This is critically important as we see shifting fish distributions and changing productivity regimes in some regions. Another focus is on **innovative technologies** to provide better data efficiently and quickly, and to use these data to maximum advantage with advanced modeling methods. Sonars, robotic camera systems, and automated image processing are among the many technologies being implemented. Advanced modeling systems range from Management Strategy Evaluation simulation tools to more fully investigate harvest policies, to spatial-temporal data assimilation models capable of more realistically representing the complex mosaic of species distributions and impacts. The third focus for improvement is in the **assessment process** itself so that NOAA Fisheries can efficiently update as many assessments as needed and deliver these assessment results effectively to fishery managers and the public. The goal being to achieve the best balance among the "4Ts" of throughput, timeliness, thoroughness, and transparency.

Summary, Recommendations, and Implementation – The concluding section summarizes the major recommendations that will achieve the NGSA enterprise. These are provided as goals, and are not prioritized or associated with resource requirements or specific timelines. Rather, the items provide a directional framework that NOAA Fisheries can use to ensure the quality and quantity of assessments that meet the growing demands of the fishery and management process.

Theme	Recommendation
Holistic & Ecosystem-Linked Assessment Paradigm	• More and routine consideration of ecosystem, environmental and socioeconomic drivers in research to develop operational assessments.
	• Coordinate stock assessments results and the advice being provided to managers across stocks; consider broader ecosystem and fishing community factors in a more holistic evaluation of harvest control rules; improve communication of stock assessment issues and gaps to inter-disciplinary researchers.
Innovative Science for Data Collection & Analysis	• Maintain and improve fishery-independent data collection capabilities. Include studies to directly calibrate fish abundance from surveys. Adjust coverage for shifting species distributions. Expand broad spectrum collection of ecosystem and environmental data.
	• Maintain and improve fishery-dependent data collection including electronic monitoring; develop low-cost fish and environmental survey methods deployable from fishing vessels.
	• Utilize advanced technologies, such as sonar, robotic camera systems, automated image processing, e-DNA, and others to lower costs, reduce stock impacts, and streamline data collection.
	• Improve the assessment modeling approach with a focus on advanced statistical methods such as spatial-temporal data-assimilation, expanding assessment model scope and broader use of management strategy evaluation simulations, and improving characterization of uncertainty, including the use of model ensembles. Improve professionalism of the assessment model development process.
Timely, Efficient, and Effective Processes to Deliver Assessments	• Prioritize stock assessment activity through implementing the new assessment data classification system and gap analysis.
	• Establish timely and efficient assessment processes by separating research from operational assessments; streamlining the operational process; expanding scope and inclusivity of the research process; and establishing a timely and efficient degree of peer-review focused on relevant issues.
	• Maintain effective stock assessments with standardized approaches and improve communication of data needs and assessment results through stakeholder engagement; improve training of current and future assessment scientists and improve opportunities for assessment scientists to engage in research.

SECTION I. INTRODUCTION TO THE STOCK ASSESSMENT IMPROVEMENT PLAN

Chapter 1—Background and Purpose

Chapter highlights:

- **This Stock Assessment Improvement Plan (SAIP) describes a vision for a Next Generation Stock Assessment Enterprise (NGSA) that improves timeliness and efficiency of assessments, prioritizes work, expands the scope of assessments, and uses innovative technologies and techniques to conduct assessments.**
- **Adaptive strategies need to be incorporated into the stock assessment process to account for changing ecosystems and a growing demand for assessments.**
- **Stock assessments provide necessary information to fishery managers and apply broadly to other aspects of coastal and ocean management and policy.**

In 2001, NOAA Fisheries published the SAIP. Effectively, this document sought to bolster NOAA's capacity and infrastructure for conducting assessments, and to expand the content and extent of these assessments. The SAIP also led to the development of important performance metrics that gauge progress in NOAA Fisheries' stock assessment enterprise. The 2001 SAIP provided a strategic vision that enhanced program performance in the years following the release of the SAIP (see Chapter 2 for an overview of accomplishments). Thus, the SAIP plays an important role in NOAA Fisheries' strategic efforts to advance the stock assessment enterprise, and the objectives of this SAIP update are to summarize the accomplishments and evolution of NOAA Fisheries' stock assessment enterprise since the release of the original SAIP in 2001, and to outline a vision for the next generation of NOAA Fisheries' assessments.

Although the SAIP focuses on stock assessments, it also complements many other strategic efforts that collectively help NOAA Fisheries best accomplish its overall mission (Fig. 1.1). In particular, this new SAIP responds to results of recent independent reviews of NOAA Fisheries' science programs and helps facilitate progress toward fishery management approaches that are more ecosystem-based and climate-smart. The following sections describe NOAA Fisheries' NGSA Enterprise.

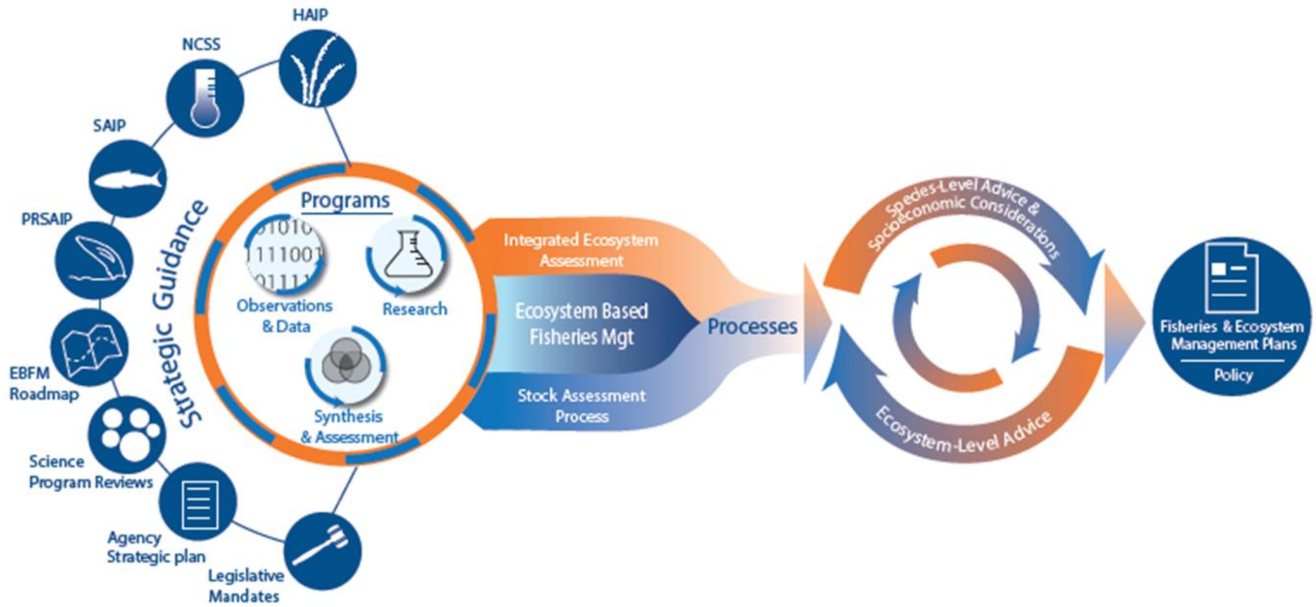

Figure 1.1. NOAA Fisheries' scientific programs are guided by numerous strategic efforts and products to provide advice to fishery managers under an interdisciplinary ecosystem-based approach to fishery management. Strategic guidance includes the Habitat Assessment Improvement Plan (HAIP), the National Climate Science Strategy (NCSS), the Stock Assessment Improvement Plan for fisheries (SAIP) and Protected Resources (PRSAIP), the Ecosystem-Based Fisheries Management Roadmap (EBFM Roadmap), Science Program Reviews, Agency Strategic Plans, and Legislative Mandates. Ultimately, this process results in scientific advice necessary for developing fishery management plans (FMPs) and fishery ecosystem plans (FEPs).

1.1. What is a stock assessment?

Stock assessments—These assessments provide the scientific underpinning of successful and sustainable fishery harvest management. A stock assessment is based upon the scientific processes of collecting, accessing, analyzing, and reporting species demographic information, and provides an evaluation which summarizes the effects of fishing (and other drivers) on fish[1] populations, quantifies uncertainty, and supports projections of future catch and stock status. The assessment process culminates in a scientific product (report) that provides fishery managers with a basis for implementing sustainable harvest policies. Thus, stock assessments can be considered both a product and a process. Further, a stock assessment is operational science and is more focused than general research on the population dynamics of a harvested fish stock: The assessment is conducted with the specific intent of using the results to provide the scientific basis for fishery management decisions.

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[1] The term "fish" is used throughout this document to collectively refer to all aquatic taxa affected by fishing in marine systems.

The three fundamental components of the stock assessment process include:

1. **Data collection and processing—**This information includes total catch from commercial, recreational, and subsistence fisheries; changes in abundance informed by scientific surveys and/or fishery catch rates; and biological data on fish stocks.
2. **Stock assessment modeling—**Mathematical models of stock and fishery dynamics are configured and then calibrated using analytical and statistical methods. These methods relate the models to patterns observed in the data used in the assessment.
3. **Developing and communicating recommendations—**Model results are summarized and bracketed by scientific uncertainty, then communicated as scientific advice for fishery managers.

Stock assessments provide advice on the following important aspects of a fish stock:

1. What are the biological limits to sustainable fishing and what fraction of the stock should be harvested each year? Addressing these questions generates **harvest policy** recommendations; i.e., control rules that provide a basis for determining an optimum harvest level that provides a sufficiently low risk of overfishing.
2. How hard have we been fishing and what is the current **stock status**? Is the stock **overfished** or undergoing **overfishing** (becoming overfished) relative to reference points that are linked to the harvest policy?
3. What short-term future catch level (**forecast**) would implement the harvest policy given the current stock status and prevailing environmental conditions?

Harvest policies—These policies are agreed-upon strategies for modulating catch to achieve a specified objective. In the United States, harvest policies are generally focused on the concept of maximum sustainable yield (MSY[2]), which is the maximum catch that can be harvested from a stock on a continuing basis. MSY is obtained when the fishing rate (*F*) is sustained for the foreseeable future at a level that provides the maximum average catch. Thus, MSY is a biologically based upper limit for harvest of a particular stock. However, various factors such as ecosystem and economic considerations, as well as uncertainty in the calculation of MSY and the capability of actually maintaining *F* at the F_{MSY} level, lead to recommendations for optimum yield that are somewhat less than MSY. Overall, stock assessments play an important role in the development and implementation of harvest policies. In addition to considering individual stock dynamics from assessments, these polices are an ideal place in the management process to infuse ecosystem and socioeconomic considerations.

Stock status—These determinations are based primarily on estimates of stock biomass and fishing intensity relative to established management objectives, such as the level of biomass and fishing intensity that produce the MSY (B_{MSY} and F_{MSY}). Fishing at a higher rate than F_{MSY} is considered

[2] Most stock assessments in the United States use proxies for MSY that are based on life history characteristics (e.g., natural mortality, growth, maturity, fecundity, and proportional harvest by age or size).

"**overfishing**," and if a stock falls below a specified fraction of B_{MSY}, the stock is considered to be "**overfished**." Stock assessments provide the scientific information necessary to determine stock status. Knowing a stock's status has helped fishery managers modify their harvest policies to reduce instances of overfishing and rebuild many previously overfished stocks.

Forecasts—Short-term predictions of annual harvest levels and stock status (under prevailing conditions) are used to help identify optimum yields and rebuilding strategies. There are uncertainties in these calculations, so stock assessments strive to provide a probability-based risk framework in which the chance of overfishing is balanced with the attainment of a large fraction of the maximum possible biological yield. Providing a probabilistic framework allows fishery managers, stakeholders, and other interested parties to make informed decisions in the face of uncertainty. The level of uncertainty in assessment forecasts is reduced in cases where high-quality data exists, particularly with respect to the reproduction (newly born or young organisms) that will support future harvest opportunities. Beyond prevailing conditions, a wide range of scenarios and strategies can be explored. These evaluations seek to define the range of reasonable harvest strategies and management options under varying conditions (e.g., ecosystem, socioeconomics) to identify a set of robust choices for achieving the goals of maximizing fishing opportunity and minimizing overfishing. Forecasts are a proactive result of stock assessments and offer another critical place to infuse ecosystem and socioeconomic information in the fishery management process.

1.2. What is the context for stock assessments?

Stock assessments are fundamental to sustainable fisheries management. Assessments use a quantitative framework to provide recommendations to fishery managers on how much biological catch can occur while preventing overfishing. In the U.S. system, fishery managers use these recommendations to set annual catch limits (ACLs), which represent targets for managed fisheries. By law, ACLs cannot exceed the levels recommended from the scientific process. To buffer against uncertainty, managers often set lower catch targets based on risk policies that take into account uncertainties in the stock assessment, ecosystem, and management processes. Thus, stock assessments play a key role in fishery management by setting scientifically based and legal upper bounds on annual harvest levels. Although assessments allow the agency to meet its fishery management mandates, they also support other aspects of NOAA Fisheries' mission, such as ecosystem-based fisheries management (EBFM) via integrated ecosystem assessments (IEAs). NOAA Fisheries leads the nation's efforts to evaluate the status and condition of a wide range of living marine resources. These resources include a broad array of marine taxa, and especially those targeted for commercial, recreational, or subsistence harvest. NOAA's stock assessment efforts are implicitly mandated by key sections of the Magnuson-Stevens Act (MSA), including the following:

- Status of stocks relative to established reference points
- Whether stock rebuilding needs to occur
- Annual quotas available for catch and the most suitable harvest rates

- Other impacts to these marine taxa
- Potential impacts to the food webs, habitats, and ecosystems associated with these marine taxa

Under the MSA, approximately 474 fishery stocks are managed by 8 regional fishery management councils[3] and the Highly Migratory Species Division of NOAA Fisheries[4]. The agency also provides various levels of support for the management of living marine resources found in state waters, international waters, and related jurisdictions. Further, other mandates merit consideration of the status of and impacts to marine stocks. Examples include:

- The cumulative effects to an ecosystem (National Environmental Policy Act – NEPA).
- Adequate forage for protected species (Marine Mammal Protection Act – MMPA Endangered Species Act – ESA).
- Effects of other activities on living marine resources and fishing (NEPA).
- Effects of fishing on other parts of marine ecosystems (NEPA).
- Effects of development and water quality on fish stocks (Coastal Zone Management Act – CZMA Clean Water Act – CWA).

These additional mandates are rely on knowledge of how the various ecosystem factors affect stock status. Facets of other mandated management activities, whether from system-level advice or protected species advice, inform and are informed by species-specific stock assessments. As such, stock assessments have wide utility, mandated need, and broad application within the full suite of scientific responsibilities executed by NOAA Fisheries and its partners to manage living marine resources in the United States.

Within NOAA Fisheries' scientific portfolio, extensive programs are executed to support and enhance stock assessments (Fig. 1.1). Data collection programs are fundamental to obtaining and processing the traditional data inputs used to inform stock assessments (Chapter 4). The agency strives to sustain and improve its data collection infrastructure, use of advanced sampling technologies, electronic technologies for data collection and data management, and analytical tools, education, and training for current and future professionals. This portfolio includes several programs that focus on population dynamics, where scientists work to develop and implement stock assessment models and conduct research to improve models. This research can consist of studies that seek to expand assessments by including ecosystem and socioeconomic factors.

NOAA Fisheries' suite of internal programs directs and funds crucial research and promotes the transition from research to operational science. The main project themes include exploring ecosystem linkages, climate change impacts, economic impacts, fisheries dynamics, and habitat dependencies. The agency also supports analytical methods development, management strategy evaluations, harvest control rule development, and operational improvements with innovative technologies. These funds are

[3] http://www.nmfs.noaa.gov/sfa/management/councils/
[4] http://www.nmfs.noaa.gov/sfa/hms/

distributed broadly throughout NOAA Fisheries and to agency partners to ensure that the most qualified individuals are addressing the most important problems. Further, many efforts not only have application to stock assessments but also cross-cut the agency by informing protected species science, habitat and ecosystem assessments, and other marine resource management considerations. As such, efforts to bolster stock assessments have been beneficial to a wide range of activities, just as the stock assessment process has benefited from the extensive suite of scientific efforts conducted by NOAA Fisheries. The interplay among the variety of strategic guidance (Fig. 1.1) and related programs clearly demonstrates the value of and need for coordinating related efforts across NOAA Fisheries' entire science enterprise. One aim of this document is to advocate for the continued integration and interchange across the full suite of NOAA Fisheries mandates and programs.

1.3. How are stock assessments conducted?

The stock assessment process consists of a full suite of efforts, including data collection and processing, stock assessment modeling, and developing and communicating recommendations (Fig. 1.2). Each step in the process requires technical expertise as well as substantial coordination and collaboration with multiple partners and stakeholders. The quantitative advice provided by assessments is generally derived from models that include mathematical representations of population and fishery dynamics, and are analyzed using statistical methods. Assessments rely on data collected from commercial, recreational, and subsistence fisheries; from NOAA research vessels and chartered vessels; and by academic and industry partners. Data crucial for stock assessments include a full and accurate accounting of the total catch (and discards) over time, measures that track changes in stock abundance, and stock-specific biological information. Where available and appropriate, additional data, such as information on ecosystem and socioeconomic trends, can be incorporated to make assessments more comprehensive.

In addition to data collection and sampling, models must be developed to integrate a wide range of information for a stock or group of stocks, model outputs must be reviewed, and ultimately management advice must be provided. For some, the term "stock assessment" invokes particular facets of the process, such as conducting scientific surveys or running assessment models. However, in this document we use the term "stock assessments" to mean the full process from data collection to the provision of advice.

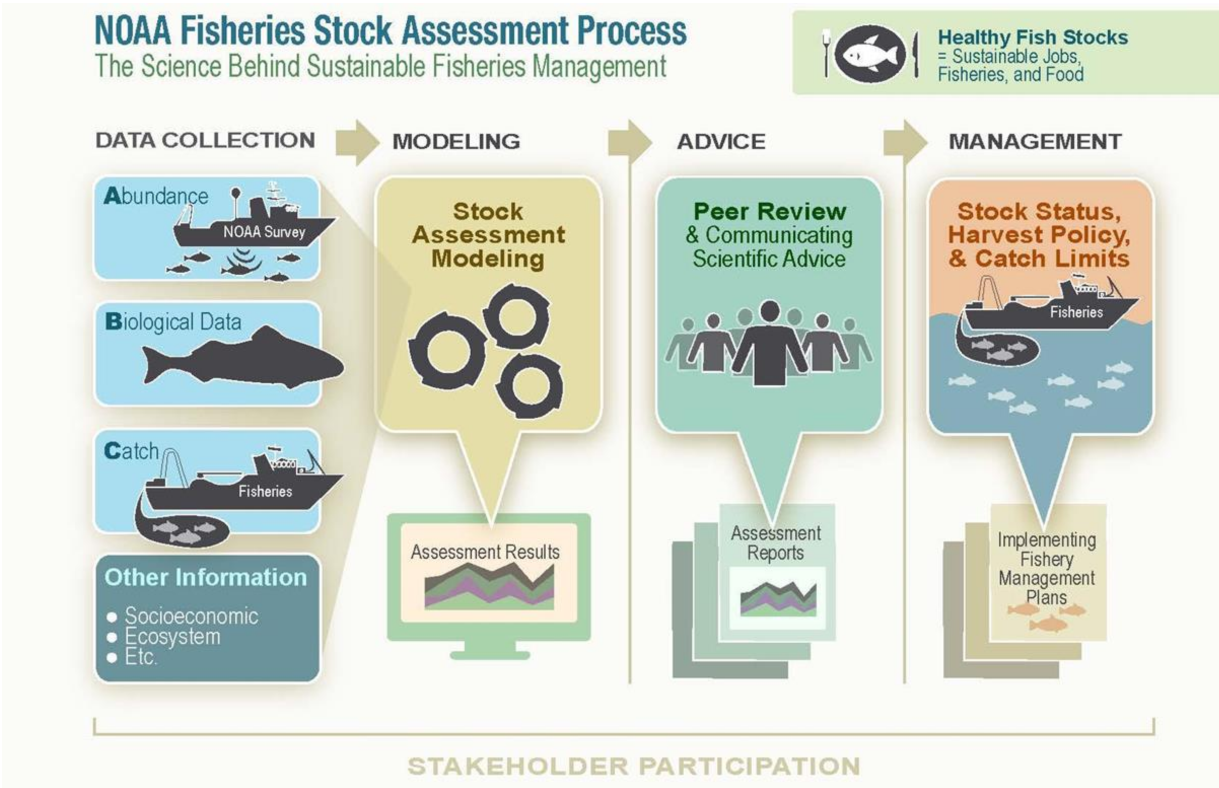

Figure 1.2. Overview of the stock assessment process from data collection through the provision of scientific advice to fishery managers. Stakeholders may participate in each step of the assessment process.

1.4. Why should stock assessments be improved?

There are three primary reasons to reevaluate NOAA Fisheries' stock assessment efforts, given the number of developments, advances, challenges, and opportunities that have occurred since the SAIP was published in 2001.

1. **Expanding the scope of stock assessments —**The scope of many stock assessments, which tend to focus on single-species population dynamics, needs to expand to better account for the direct impacts of changing conditions that affect overall productivity. For instance, stock productivity can be influenced by dynamics in habitats, oceanography, predators and prey, toxins, diseases, parasites, climate-scale factors, and other relevant variables. (Note that the term "ecosystem" is used from now on to refer collectively to these living and non-living dynamics that affect marine species.) The need to incorporate ecosystem dynamics is demonstrated indirectly by unexplained issues that can arise when running diagnostic tests on certain stock assessment models. For example, when observed patterns in data are not well represented by an assessment model's structure, the model may not account for crucial aspects of the ecosystem, which is necessarily a simplification of stock dynamics.

In addition, ecosystem information can improve assessments in cases where fishing intensity has been reduced and the natural variation in fish stocks makes it more difficult to estimate fishing rates when they are at a scale similar to natural processes. More direct evidence for the need to improve ecosystem linkages comes from studies that reveal the strength of interactions among species and between species and their environment. Biological factors that drive stock productivity, such as natural mortality, growth, and reproduction, are not strictly inherent properties of a species, but instead result from a species' interaction with its ecosystem. As fishing and other factors impact ecosystem dynamics, related shifts should be expected in the biological factors that form a basis for calculating sustainable fishery rates. In some cases, ecosystem changes may be small enough to justify the use of simpler approaches, and in other cases there are not sufficient data to look closely at ecosystem effects. Nevertheless, there is a clear need to evaluate the effects of ecosystem dynamics on stock productivity to the extent possible, and develop harvest control rules that are robust to these changes. These goals may be best accomplished by linking certain stock assessments to ecosystem dynamics.

The original SAIP recognized the need to improve linkages between stock assessments and ecosystem factors; however, the document did not explain these needs in depth. In fact, the original SAIP recommended initiating a dialogue between NOAA Fisheries and the public to determine how far-reaching and comprehensive these additional considerations should be. This dialogue has been ongoing, and now in this updated SAIP, the need for greater inclusion of ecosystem factors into stock assessments is paramount.

Further, as the collection and understanding of socioeconomic information has improved, there has been an increase in the ability to account for socioeconomic dynamics in the provision of management advice. Federal fisheries law requires fishery managers to optimize yield for fisheries while achieving an acceptably low risk of overfishing (as mandated in National Standard 1 of the MSA). One tool for conducting such investigations is a management strategy evaluation (MSE). NOAA Fisheries has the capability to conduct MSEs that characterize the performance of a science–management–fishery system. However, resources required for MSEs vary substantially depending on the type of analysis being conducted. To date, only a few MSEs have been used to inform fishery management decisions. Of these MSEs, most have addressed ecosystem effects while fewer have examined the economic consequences of addressing uncertainty in assessments. Reinforcing the use of and capacity to conduct MSEs is crucial for helping fishery managers make wise decisions that promote sustainable fisheries and resilient coastal communities.

2. **Prioritizing stock assessments—**Considering the number of demands on what are projected to be highly limited resources, the wise allocation of resources to conduct stock assessments increasingly requires that assessments are more formally prioritized. NOAA Fisheries' budget for

improving and expanding assessments has grown since the 2001 SAIP, and the number of assessments conducted per year has increased with the budget. However, in recent years the resources available and number of assessments conducted has essentially plateaued. However, there are still increasing demands to assess more stocks and conduct more frequent assessments of some stocks. One of the major gaps identified in the original SAIP was to conduct assessments of all managed stocks; therefore, there is a need to evaluate and prioritize stock assessment efforts during the next decade and beyond. Although advocating for more resources is warranted, the number, scope, extent, and focus of the full national stock assessment enterprise merits more thorough examination to balance resources to best meet assessment needs with limited capacity.

Additionally, there is tension among the rate at which stock assessments are conducted, the thoroughness of those assessments, and the degree of transparency throughout the process. Independent reviews of stock assessments are necessary to ensure that the best science information is being used to guide management and to gain the trust of the affected public. However, during the past 15 years, the increase in stock assessments has highlighted the need to balance the frequency of more rigorous, independent peer reviews of assessments with a streamlined review processes to ensure timely assessments for management decisions. The mandate to specify annual catch limits for all federally managed stocks suggests a demand for more frequent production of stock assessments. Certain assessments will always require thorough reviews, although streamlined processes should be explored where possible to increase assessment throughput.

3. **Utilizing innovative methodology and technology—**Most assessment models estimate stock abundance and mortality rates by calibrating the models with observed trends in fishing intensity and indices of relative abundance from fishery-independent sources (e.g., resource surveys). The models tend to perform better when there is a contrast in fishing intensity and abundance over time (i.e., periods of high and low fishing rates and abundance). However, as fishery management has become more effective at controlling fishing rates, the degree of contrast in the observations is diminishing for many stocks. Therefore, another source of calibration data may be required, and one potentially beneficial option may be the use of advanced sampling technologies to create surveys that directly measure absolute stock abundance, not just relative abundance. For instance, the use of acoustic and optical (photo and video) sampling technologies can be used to improve understanding of the degree to which traditional methods are sampling available fish, which simplifies the ability to better scale abundance measurements to actual abundance (rather than relative measures). Even if not estimated for every year in an assessment, these measures of absolute abundance would help anchor a stock assessment at reasonable levels of stock biomass. Additionally, advanced sampling technologies can be used to expand sampling efforts into areas that are not easily sampled with more traditional methods, thereby improving data for assessments.

Beyond sampling technologies, new analytical tools are needed to improve standard assessment models. Some important developments include advances in multispecies models and approaches that facilitate better connections between stock assessments and ecosystem dynamics, as well as improved analytical tools for data-limited stocks. Further, methodological advances could be adopted from other fields, such as infrastructural and analytical considerations associated with big data, risk analyses, financial forecasting, chaotic dynamics, and related quantitative approaches. The exploration of innovative methodologies warrants an evaluation of novel data needs. New approaches may rely on new sources of information, such as enhanced ocean observing systems for more efficient sampling, genomics, isotopes, fatty acids, and other chemical, electronic, or acoustic signatures of fish stocks and their ecosystems (Chapter 8).

Much of the theory on which the stock assessment enterprise is based has had a solid, multi-decade history of testing. However, to address current issues in fisheries science and management, the proposal, development, and evaluation of theoretical advancements should be pursued. Thus, NOAA Fisheries' NGSA Enterprise must provide the ability, expectation, venues, and time for the agency to play a leading role in expanding and advancing the stock assessment enterprise.

1.5. What is in this SAIP update?

Ultimately, the goals of this SAIP update are to summarize the accomplishments and evolution of NOAA Fisheries' stock assessment enterprise since the release of the original SAIP in 2001. In addition, this update outlines a vision for the next generation of NOAA Fisheries' assessments. With these goals in mind, the three fundamental components of this SAIP include the following:

- A recap of accomplishments from the original SAIP (Chapter 2)
- An updated description of the current stock assessment enterprise (Section II)
- A description of the NGSA Enterprise (Section III)

Chapter 2—Accomplishments of NOAA Fisheries' Stock Assessment Enterprise

Chapter highlights:

- **An increased quantity and quality of stock assessments in support of strong fishery management has greatly reduced overfishing and facilitated rebuilding of many overfished stocks.**
- **Stock assessment program funds have increased in response to the 2001 Stock Assessment Improvement Plan (SAIP), expanding the capacity for data collection, monitoring, and advancing stock assessment science.**
- **NOAA Fisheries has a national infrastructure for stock assessment programs.**
- **More is now known about stock dynamics. The increased attention has highlighted the importance of expanding many assessments to consider factors such as changes in the ecosystem.**

2.1. The 2001 Stock Assessment Improvement Plan

Generally, U.S. fisheries are recognized around the world as being successfully and sustainably managed (Food and Agriculture Organization (FAO), 2014). This success is due mainly to a scientifically driven management process that relies on the advice from the NOAA Fisheries stock assessment enterprise. Since the release of the SAIP in 2001, the subsequent expansion and advancement of the stock assessment program has drastically improved the quantity and quality of stock assessments being used to support fishery management. The 2001 SAIP defined three Tiers of Assessment Excellence to serve as milestones for NOAA's stock assessment enterprise (Fig. 2.1). The three tiers centered on assessment "levels" that were defined in the 2001 SAIP (not defined or used here), and the 2001 document recommended an initial effort to strive for Tier 2 at a minimum. Meanwhile, the 2001 SAIP also initiated a dialogue on the potential importance of taking more of an ecosystem approach to stock assessments. Although the original strategy was useful for expanding the scope and number of stocks assessed, Section III of this document describes a new strategy that shifts the focus from moving up the tiers for all stocks to setting stock-specific priorities.

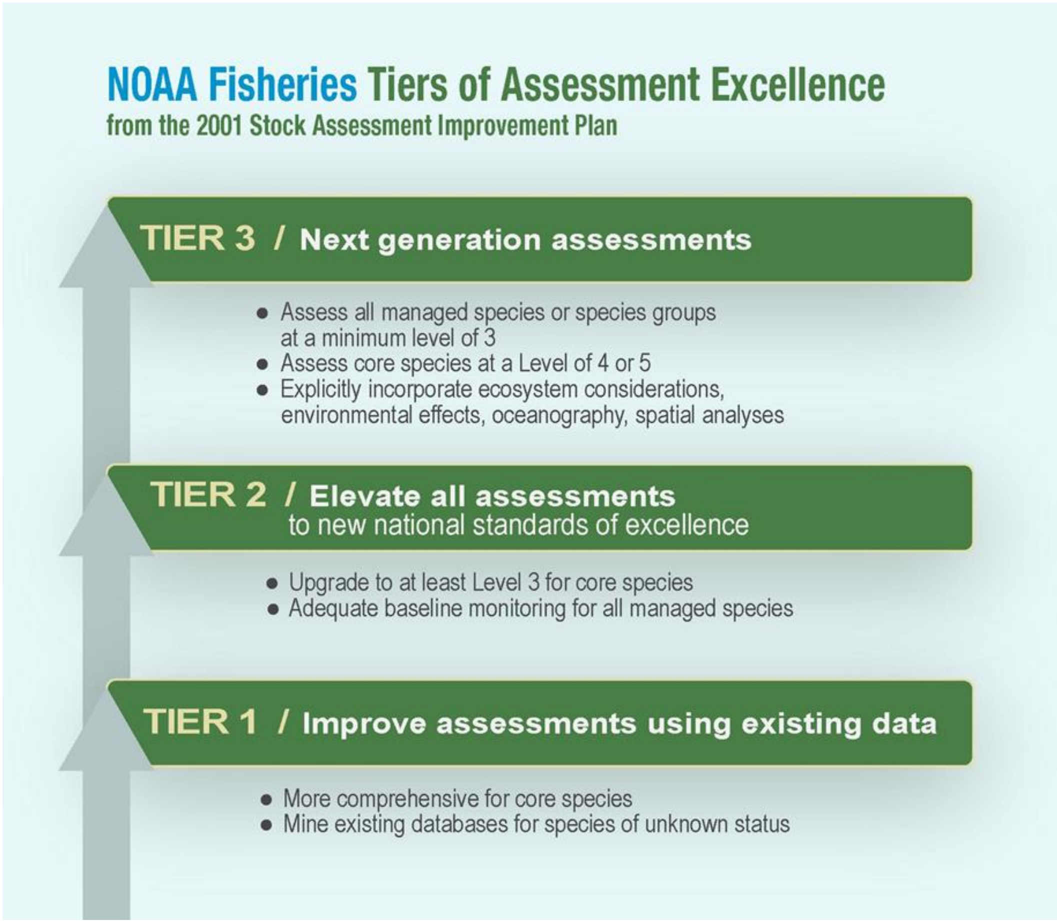

Fig. 2.1 Summary of the three Tiers of Assessment Excellence, as described in the 2001 Stock Assessment Improvement Plan (Mace et al., 2001). **Note**: The "levels" referenced in the figure were defined in the 2001 SAIP, but not defined here to avoid confusion with later chapters.

The 2001 SAIP concluded with 10 recommendations that set a strategic direction for NOAA Fisheries' stock assessment enterprise (NMFS, 2001). Those 10 recommendations can be combined into 6 general categories that served as new focus areas for NOAA Fisheries:

1. Increase overall budget and staff to expand data collection and stock assessment capabilities.
2. Enhance existing educational and training programs in quantitative fisheries and ecosystem science, fisheries economics, and social sciences to ensure an available pool of new federal fisheries scientists. In addition, develop comprehensive training programs to enhance the scientific skills of current federal scientists.
3. Improve stock assessments by enhancing partnerships and cooperative programs with other federal and state agencies, private foundations, universities, environmental groups, recreational and commercial fishing organizations, individual fishermen, and other stakeholders with an interest in data collection for stock assessments.

4. Increase federal and academic research to advance stock assessment methods.
5. Strengthen public awareness and credibility of NOAA Fisheries' stock assessment science by expanding internal and external outreach and communications efforts.
6. Create an overall strategic plan that provides comprehensive guidance toward achieving the mission of NOAA Fisheries.

NOAA Fisheries relied on the strategic direction put forth in the 2001 SAIP to improve the quality and quantity of its stock assessments by supporting advancements in data collection, research, workforce capacity, public messaging, and integrated strategic planning. In addition, a National Research Council report (NRC, 1998) identified gaps in NOAA Fisheries' stock assessment program, with emphasis on data collection, analytical methods, assessment processes, and education and training. To address federal mandates, the 6 focus areas identified from the 2001 SAIP, the 1998 NRC report, and other sources, NOAA Fisheries expanded its efforts toward building a robust and reliable stock assessment enterprise. These advances have created a strong foundation that aids the development and implementation of an NGSA Enterprise.

2.2. Improvements and Impacts of NOAA's Stock Assessments in the 21st Century

NOAA Fisheries' stock assessments have directly improved an overall understanding of the state of U.S. fisheries and have enhanced the science needed to manage for sustainability. With knowledge of stock status, fishery managers can make informed decisions to meet their management targets. From 2001 to 2014, NOAA Fisheries' capacity for conducting stock assessments increased substantially, with more than 50 assessments conducted in 2001 and almost 190 assessments in 2015, a 217% increase in assessment output (Fig. 2.2). During this period, NOAA Fisheries' assessments provided the information to reduce the number of stocks experiencing overfishing by 30% and reduce the number of overfished stocks by 24% (Fig. 2.3). Thus, NOAA Fisheries' stock assessment enterprise has played a major role in establishing sustainable U.S. fisheries during the past 15 years.

In 2005, NOAA Fisheries developed the Fish Stock Sustainability Index (FSSI), a performance measure that tracks the status and assessments of 199 core stocks identified according to regional priorities. Each stock tracked is awarded points if its status is known and if it is not considered overfished or undergoing overfishing. The FSSI combines this information into a single number by totaling the 199 FSSI stocks (the maximum possible value for the FSSI when summed across all categories and all stocks is 1,000). Significant effort has been dedicated toward conducting assessments of FSSI stocks in particular, and toward eliminating overfishing on all stocks. As a result, the FSSI has been steadily increasing since its inception toward its maximum value of 1,000 (Fig. 2.3). This trend is a simple and clear measure that emphasizes the success of a federal fishery management process that manages for sustainability.

The quantity and quality of stock assessments increased because of budget and staffing increases in NOAA Fisheries' core stock assessment budget lines (2001 SAIP, focus area 1). In particular, the 2001 SAIP supported growth of the Expand Annual Stock Assessments (EASA) budget line from $1.7 million in 2001 to $70.0 million in 2015 (Fig. 2.2). This growth in overall capacity enabled a range of investments that improved the national stock assessment program. Broadly, these investments included advances in data collection and monitoring programs, research in advanced sampling technologies and stock assessment methods, workforce capacity, and the stock assessment peer review process. Although the total number of stock assessments conducted each year has stabilized recently, the science behind the assessments has continued to improve.

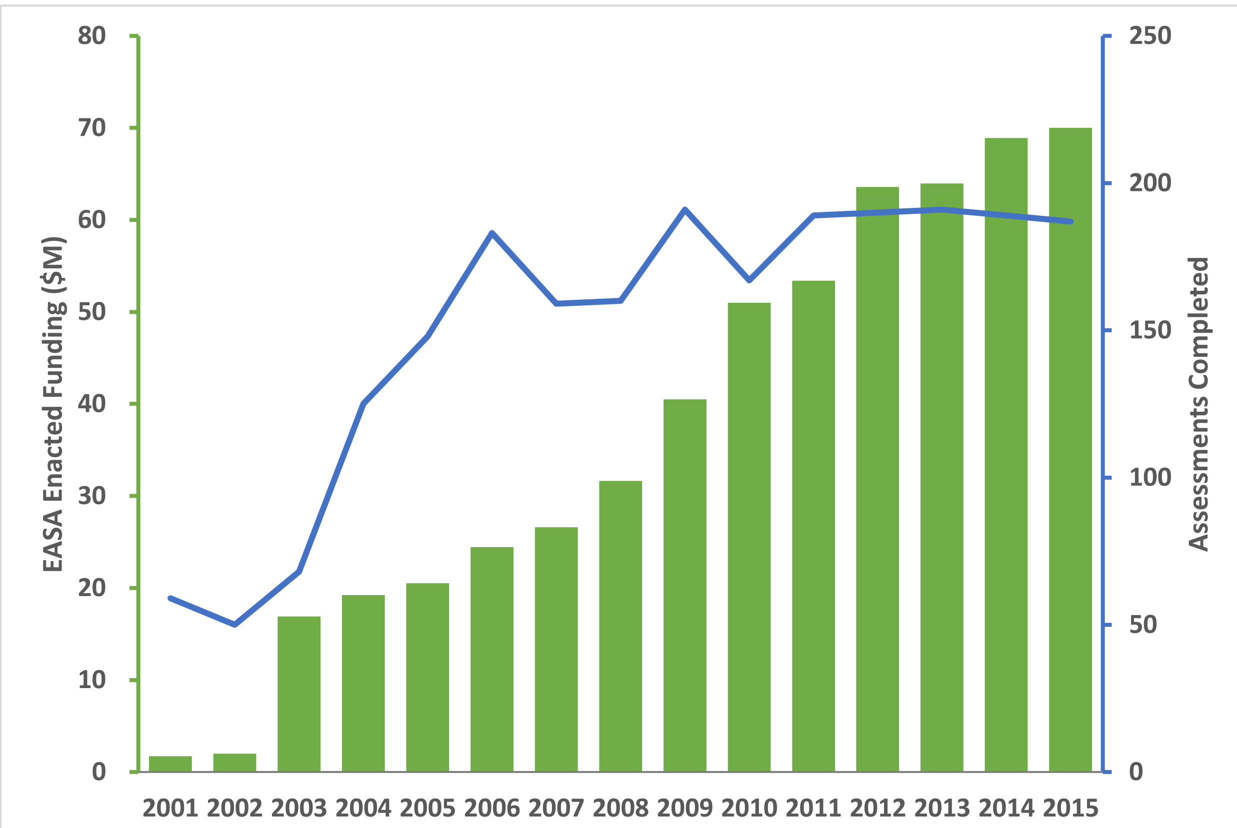

Figure 2.2. Comparison of the total number of stock assessments completed each year for federally managed stocks (right axis, blue line) and growth in the EASA budget line (left axis, green bars), 2001–2015. **Notes:** 1) Tracking of stock assessments before 2005 was less complete; 2) The FSSI was calculated retroactively for 2001–2004; 3) Budget lines other than EASA also contribute to stock assessments.

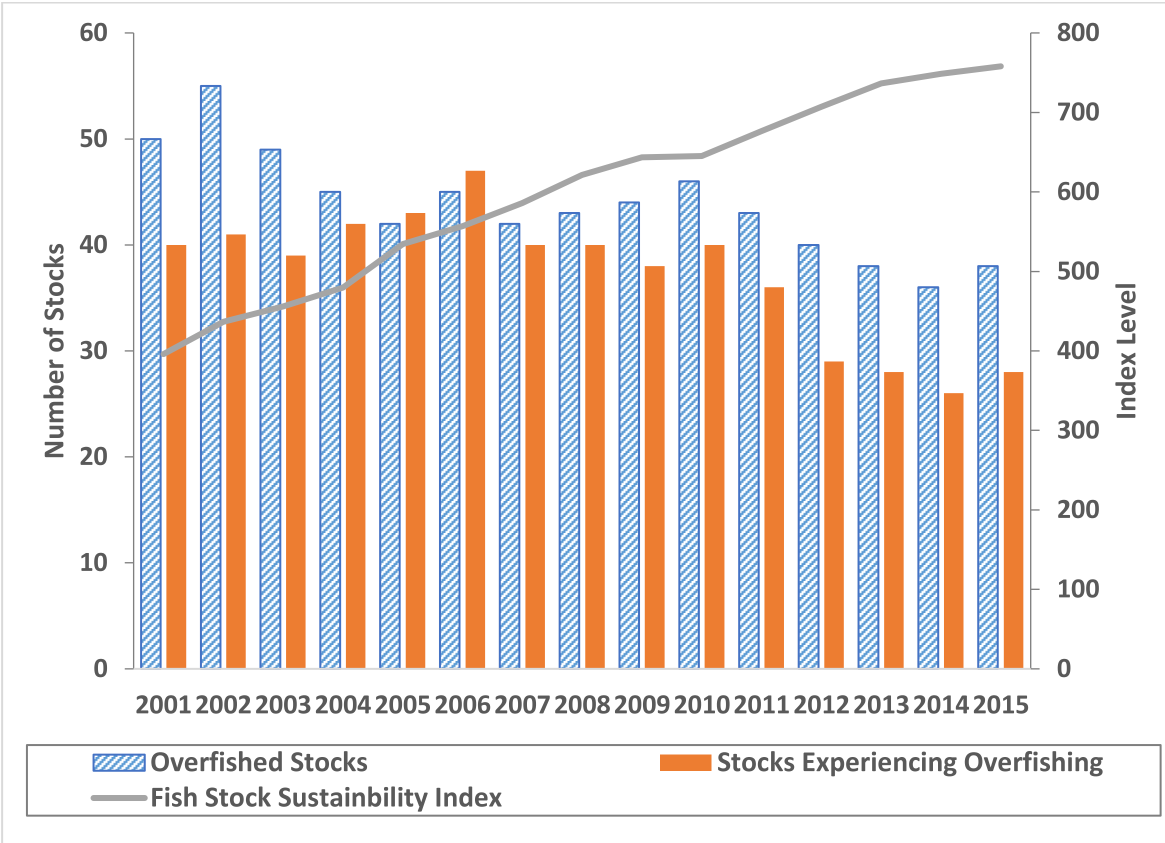

Fig. 2.3. Status of federally managed fish stocks (number of overfished stocks and stocks experiencing overfishing; left axis) over time compared with the NOAA Fisheries' Fish Stock Sustainability Index (right axis), 2001–2015.

2.2.1. Data Collection and Monitoring Capabilities

The data collection and monitoring capabilities of NOAA Fisheries' has expanded substantially. Improvements to catch monitoring programs have resulted in better coordination of data on commercial fishery statistics and better estimation of recreational statistics. The Fisheries Information System (FIS) program was established to coordinate fishery statistics and to facilitate public access to comprehensive, high-quality, and timely fisheries information. Another effort is the Marine Recreational Fisheries Statistics Survey (MRFSS), a long-standing program originating out of the Magnuson Fishery Conservation and Management Act of 1976 that has served as a foundational source of marine recreational fisheries information. With an increasing demand for improved stock assessments, it became clear that improvements to MRFSS were also needed. Therefore, in 2007, MRFSS was revised and renamed the Marine Recreational Information Program (MRIP).

Another investment made by NOAA Fisheries was to expand the regional fisheries observer programs that are coordinated under a National Observer Program (NOP). Funding for observers has tripled since

1999, resulting in an increase in the number of fisheries monitored by onboard observers from 17 to 48 (including 10 catch share fisheries) and the number of observer days from 55,000 to 80,210. This increase in fishery-dependent data collection has improved the accuracy of NOAA Fisheries' stock assessments, improved the characterization of fishery bycatch, and resulted in better overall fishery management. However, for many fisheries observer coverage remains low. In these cases, without further expansion, stock assessments will be challenging and may provide highly uncertain results.

In an effort to expand and improve fishery-dependent sampling, NOAA Fisheries has been evaluating and incorporating electronic monitoring and electronic reporting (EM/ER). Electronic reporting relies on digital data collection interfaces to allow reporting by fishermen, whereas electronic monitoring relies on video cameras to remotely observe fishery operations. These technologies can be used in a variety of fishery monitoring programs, and in fact strategic plans have been developed in each region to identify, evaluate, and prioritize implementation of these technologies[5].

In addition to expanding fishery-dependent data collection, NOAA Fisheries also invested in developing and/or improving scientific (fishery-independent) surveys. For instance, the West Coast Groundfish Bottom Trawl Survey expanded in spatial coverage, improving monitoring of approximately 90 commercially fished stocks along the coasts of Washington, Oregon, and California. Also, in collaboration with the South Carolina Department of Natural Resources' Marine Resource Monitoring and Assessment Program (MARMAP), NOAA Fisheries established the Southeast Fishery Independent Survey (SEFIS) program, which uses trap and video surveys to monitor reef fish in South Atlantic waters. This survey increased the accuracy, precision, and usefulness of data available for assessments and facilitated a greater than two-fold increase in the size of annual survey samples. Atlantic sea scallops also benefitted from improved survey capability by creating a habitat camera mapping system (HabCam) to augment the dragged dredge survey. This expansion significantly increased the number of scallops that could be observed by the survey, resulting in more accurate estimates of scallop abundance and habitat. Another example of expanded capacity is the Northeast Area Monitoring and Assessment Program (NEAMAP), a new survey that complements the NOAA Fisheries' bottom trawl survey by sampling shallower inshore habitat.

Although the development of new surveys has expanded total data collection capabilities, the overall cost of data collection has continued to increase. Scientific resource surveys are further limited by the availability of NOAA research vessels and funding to support chartering University–National Oceanographic Laboratory System (UNOLS) vessels and commercial industry vessels. Therefore, when considering the capacity required to provide management advice on all stocks under NOAA Fisheries' purview, there is a need to sustain NOAA's fleet infrastructure. Also required is improved survey coverage with integrated ocean observation systems. This coordination will help address information gaps and spatial uncertainties in stock assessments in a changing environment.

[5] http://www.st.nmfs.noaa.gov/advanced-technology/electronic-monitoring/index

2.2.2. Education and Training of Stock Assessment Scientists

The overall demand for more and improved stock assessments resulted in the realization that there were not enough stock assessment scientists in NOAA Fisheries to meet the growing assessment demand. Furthermore, as indicated by focus area 2 of the 2001 SAIP and NRC (1998), existing university programs were not capable of supplying enough stock assessment scientists to meet the expanding need. This awareness prompted investments in each fisheries science center to support educational efforts and connections among NOAA Fisheries and academia across the regions. One program that resulted from this initial investment is the West Coast Groundfish Stock Assessment Training and Mentoring program at the University of Washington, which is now considered one of the premiere institutions for training stock assessment scientists.. Another example is the Research Training and Recruitment (RTR) program in the southeast region. This program was designed to create a pipeline to introduce undergraduate students to stock assessment science, train graduate students, and recruit stock assessment scientists to NOAA Fisheries. Unfortunately, the RTR program has been discontinued due to budget cuts, but given the value and need for this pipeline, restarting the program could prove beneficial.

Following the 2001 SAIP, NOAA Fisheries and NOAA Sea Grant expanded their joint fellowship programs in population dynamics and marine resource economics. Initially supporting approximately 3 fellows per year, the fellowship program grew to fund 6 fellows on average with a maximum of 12 awarded in 1 year. Since the program's inception, more than 40% of fellows have gone on to work for NOAA Fisheries. Furthermore, to build capacity in ecosystem modeling, the NOAA Fisheries–Sea Grant fellowship program recently expanded to include quantitative ecology in general. NOAA also supports numerous other academic partnerships to facilitate education and training in mission-critical areas, including the Quantitative Ecology and Socioeconomics Training Program (QUEST), Cooperative Ecosystem Studies Units (CESUs), NOAA's 16 Cooperative Institutes (CIs), the Living Marine Resources Cooperative Science Center (LMRCSC), and many other programs coordinated by NOAA's Office of Education. Overall, the various educational programs have led to significant increases in the number of scientists with the quantitative skills necessary to provide scientific advice to fishery managers.

Despite initial investments in education and training, the need for qualified candidates has continued to exceed the number available. The gap in available stock assessment scientists was again illustrated in a 2008 report from the Departments of Commerce and Education, "The Shortage in the Number of Individuals with Post-Baccalaureate Degrees in Subjects Related to Fishery Science" (U.S. Dept. of Commerce and U.S. Dept. of Education, 2008). In recognition of the ongoing shortage, NOAA Fisheries continues to expand its QUEST program to increase the number of academic faculty in these disciplines. The QUEST program now provides dedicated support to seven faculty and additional support to three rotating faculty. As NOAA-supported faculties continue to train individuals, the identified gap in qualified candidates will continue to decrease, thereby addressing SAIP focus area 2.

2.2.3. Cooperative Research

To comply with focus area 3, cooperative research programs were established at national and regional levels to increase data collection capabilities. These programs also fostered communication, coordination, and mutual respect among NOAA Fisheries and its stakeholders. In addition, cooperative research has been shown to improve associations among fishers, scientists, and managers (Hartley and Robinson, 2006; Johnson and van Densen, 2007; Johnson 2010) by increasing opportunities for successful and sustainable management. Investments in cooperative research have also facilitated the development of innovative approaches to collecting, processing, and reporting information on stocks that were previously unavailable. A number of fishery-independent surveys previously conducted exclusively on NOAA ships were complemented or replaced by surveys from chartered industry vessels. For instance, NOAA Fisheries' Atlantic Surfclam–Ocean Quahog Survey began chartering an industry vessel in 2012. The NOAA-supported Northeast Area Monitoring and Assessment Program (NEAMAP) is also conducted by an industry vessel and augments existing surveys conducted on NOAA ships in the Northwest Atlantic. Additionally, the main groundfish trawl surveys conducted along the U.S. West Coast and Alaska are implemented through industry charters. NOAA Fisheries continues to expand collaborations with industry as well as other partner agencies (e.g., the previously mentioned SEFIS survey) to support sustainable fisheries management that engages stakeholders at all levels.

2.2.4. Advancements in Fisheries Science

NOAA Fisheries continues to support advancements in fisheries science (SAIP focus area 4) through the creation of several national working groups that focus on specific mission-critical topics. These programs are coordinated at NOAA Fisheries headquarters by the Office of Science and Technology, and many of these working groups manage internal funding to support regional projects that address high-priority issues, including improvements for stock assessments. In addition to supporting research, the funding opportunities foster collaboration and technology distribution throughout NOAA. Although the projects are led by NOAA scientists, collaboration with external groups is encouraged and results in partnerships with academics; commercial and recreational fishers; state, interstate, national, and international agencies; and non-governmental organizations. These partnerships have provided substantial improvements to NOAA Fisheries' stock assessment and monitoring capabilities.

Collectively in fiscal year 2015, almost $14 million in funding was distributed across programs to support innovative research in stock assessments and other aspects of fisheries science. Over time, these investments have resulted in major advancements, resulting in improvements in the science used to support fisheries management. For example, the Assessment Methods Working Group provides national oversight to facilitate direct improvements in the stock assessment enterprise. This group oversees the NOAA Fisheries Toolbox[6] , which provides a suite of standardized interfaces for implementing stock assessment analyses. Several Toolbox techniques were developed or improved through research

[6] http://nft.nefsc.noaa.gov/

projects funded by working groups and are now publicly available and applied in operational stock assessments. The Assessment Methods Working Group also facilitates NOAA's annual support of the AD Model Builder Project[7]. The ongoing support of this project has allowed open access to AD Model Builder, a software package that serves as the basis for a large percentage of NOAA Fisheries' stock assessments as well as stock assessments around the world. Other working groups focus on various aspects of fisheries science, including the incorporation of ecosystem and habitat information in the assessment process; improvements to the efficiency of data collection and survey operations with innovative technologies; and enhancements to cooperative research and international collaborations.

2.2.5. Peer Review Approaches

Notable improvements to the fishery management process have resulted from establishing rigorous peer review methods for stock assessments. Although various review processes were in place before 2001, substantial investments in stock assessment quality assurance have been made since the 2001 SAIP. In part, these investments were driven by legislative mandates to ensure that the best scientific information available was provided to fishery managers. Investments were also made to increase the credibility of NOAA Fisheries science products among stakeholders (SAIP focus area 5), and increase transparency and opportunities for public engagement in the fishery management process. A national peer review process, called the Center for Independent Experts (CIE), was established to provide a rigorous independent review of emerging scientific methods and influential science products. Various regional processes were either created or improved since 2001, including the Southeast Data, Assessment, and Review (SEDAR); Stock Assessment Workshop/Stock Assessment Review Committee (SAW/SARC) in the Northeast; Stock Assessment Review (STAR) in the Northwest; Western Pacific Stock Assessment Review (WPSAR); and the Plan Team process in the North Pacific. These regional processes all rely on the CIE when a higher degree of independence is required, particularly in the selection process of highly qualified reviewers. Overall, the level of quality assurance for stock assessments has vastly improved since the 2001 SAIP, resulting in a thorough and transparent fishery management process that uses high-quality advice as the basis for management decisions. Approaches to stock assessment quality assurance and peer reviews are covered in greater detail in Chapter 6.

2.2.6. Communication and Outreach

In the context of SAIP focus area 5, NOAA Fisheries has made a considerable effort to improve its communication and public outreach about stock assessments. Access to stock assessment reports has vastly improved, and the reports themselves have become comprehensive descriptions of the entire assessment. Although some of these reports can be difficult to understand, they offer a high degree of transparency. To improve access to assessment information, many reports now include upfront summaries of the primary results. NOAA Fisheries is continually improving its outreach and engagement strategy to convey information and maintain ongoing dialogues with a variety of audiences.

[7] http://www.admb-project.org/

Improvements have aimed to provide better information and engagement with stakeholders on the national stock assessment program and its performance, facilitate access to data used in stock assessments, improve communication within the national stock assessment program, and promote transparency in the assessment process and the resulting scientific advice. The Marine Resource Education Program (MREP), which is funded through a grant to the Gulf of Maine Research Institute, is a successful program designed to provide fishery stakeholders with an inside look at fisheries science and the management process.

Many new products have been developed to convey fishery stock assessment and management information to a variety of audiences. For instance, FishWatch[8] is a website designed by NOAA Fisheries to provide scientific information to consumers to encourage sustainable seafood choices. The Species Information System is a national database that stores stock assessment and fishery management information and offers access to summaries and results from assessments through a public portal[9]. NOAA Fisheries also generates several regular reports, such as annual reports to Congress on the status of stocks,[10] national stock assessment summary reports,[11] and annual summaries of commercial fishing statistics and economic impacts through Fisheries of the United States[12] and Fisheries Economics of the United States,[13] respectively. Completing these efforts provide broad access to the science that supports federal fisheries management.

Additionally, NOAA Fisheries welcomes opportunities to engage on assessment-related topics with various interested parties. These stakeholders include non-governmental organizations; NOAA and Department of Commerce leadership; Office of Management and Budget staff; Congressional representatives; and regional councils, both individually and nationally, through venues such as New Council Member Training, and the Council Coordination Committee and its Scientific Coordination Subcommittee. The incremental increases in appropriated funds, along with an improved public perception of NOAA Fisheries, suggest that overall expanded outreach and communication efforts have been effective in some areas. Nevertheless, communication and outreach efforts need to be expanded and improved. To achieve that goal, NOAA Fisheries will continue to seek funding and opportunities to improve strategies for communicating to and engaging with stakeholders on the stock assessment process.

2.2.7. Strategic Planning

Focus area 6 from the 2001 SAIP has been addressed through significant expansion of the extent to which NOAA Fisheries conducts and coordinates strategic planning efforts. The SAIP itself represents

8 http://www.fishwatch.gov/about/index.htm
9 https://www.st.nmfs.noaa.gov/sisPortal/sisPortalMain.jsp
10 http://www.nmfs.noaa.gov/sfa/fisheries_eco/status_of_fisheries/
11 http://www.st.nmfs.noaa.gov/stock-assessment/FishStockReports/index
12 http://www.st.nmfs.noaa.gov/commercial-fisheries/fus/fus13/index
13 http://www.st.nmfs.noaa.gov/economics/publications/feus/fisheries_economics_2012

one of many focused efforts that advance or report on a fundamental aspect of NOAA Fisheries' scientific portfolio. As portrayed in Fig. 1.1, other focused strategic efforts include the Marine Fisheries Habitat Assessment Improvement Plan (NMFS, 2010); the National Climate Science Strategy (Link et al., 2015); strategic documents related to assessing protected marine species (NMFS, 2004 and 2013); and annual peer reviews of NOAA Fisheries' scientific programs.[14] Additionally, a number of regular reports provide updates and opportunities for strategic evaluation of specific programs. For instance, the National Bycatch Report[15] provides a species-level accounting of bycatch by U.S. fisheries, and the Fisheries Information System Annual Report[16] describes the status of NOAA Fisheries data collection programs. Together, the various plans and reports are combined under the broad category of Ecosystem-Based Fishery Management (EBFM). Finally, the focused strategic planning efforts are synthesized and funneled through a number of national efforts. Several of these larger efforts include strategic plans and Annual Guidance Memoranda produced at multiple levels (office, agency, and department) and are used to guide agency and program operations.

2.3. Summary of the 2001 SAIP

The 2001 SAIP has been an invaluable strategic planning document that facilitated vast improvements in NOAA fisheries' stock assessment enterprise. Resulting increases in funds for stock assessment science allowed NOAA Fisheries to improve many stock assessments and address the six focus areas of the 2001 SAIP to varying degrees. As a result, the stock assessment programs and staff employed by NOAA Fisheries provide world-class scientific advice to resource managers. Despite the need for continuing advancements in the stock assessment enterprise (culminating in this new SAIP), it should not be overlooked that the U.S. fishery management system has been highly successful in achieving resource sustainability and community resiliency.

References

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U.S. Dept. Commer. and U.S. Dept. Educ. 2008. The shortage in the number of individuals with post-baccalaureate degrees in subjects related to fishery science. NOAA Tech. Memo. NMFS-F/SPO-91, 84 p.

[14] http://www.st.nmfs.noaa.gov/science-program-review/index
[15] https://www.st.nmfs.noaa.gov/Assets/Observer-Program/bycatch-report-update-2/NBR%20First%20Edition%20Update%202_Final.pdf
[16] http://www.st.nmfs.noaa.gov/Assets/FIS/documents/FIS%20Annual%20Report.pdf

SECTION II. THE CURRENT STATE OF NOAA FISHERIES' STOCK ASSESSMENT ENTERPRISE

Chapter 3. Overview of NOAA Fisheries' National Stock Assessment Programs

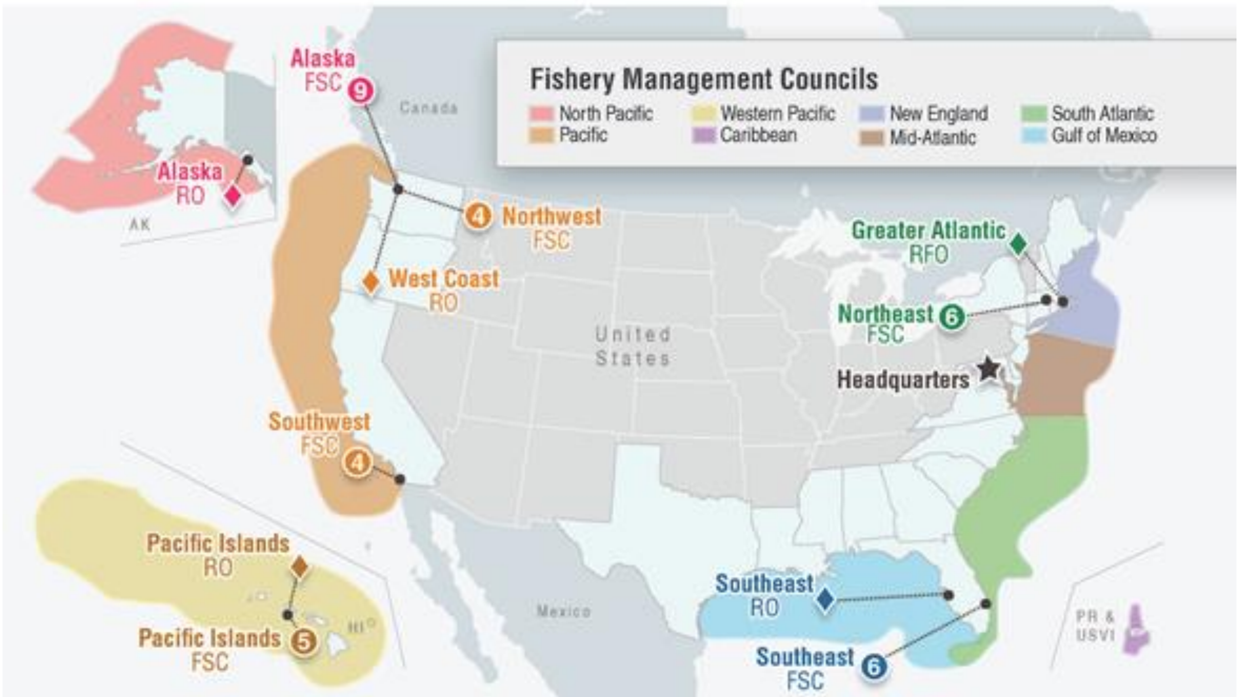
Chapter highlights:

- **NOAA Fisheries' stock assessments provide scientific advice for federal fisheries managed by regional fishery management councils and other fisheries managed by state, interstate, and international organizations.**
- **Regional assessment programs face diverse issues due to the nature of regional fisheries, species, ecosystems, and governances.**
- **Despite regional differences, patterns have emerged in the methods used to conduct assessments for federally managed fisheries.**

NOAA Fisheries' stock assessment programs provide global leadership in stock assessment science. The stock assessment enterprise is a combined system that operates through regional science–management partnerships and coordination, and national initiatives from headquarters offices. As described in Chapter 1, NOAA Fisheries is directed by federal law to provide scientific advice to eight Regional Fishery Management Councils and NOAA Fisheries' Atlantic Highly Migratory Species Division for more than 473 federally managed fish stocks, some of which are stock complexes that contain many individual stocks. NOAA Fisheries' science centers coordinate with their respective regional offices to provide scientific advice to federal fishery managers. Further, NOAA creates partnerships with state, interstate, and international fishery management organizations, and NOAA scientists work collaboratively with these groups to conduct or assist with assessments of stocks that do not fall under federal jurisdiction. Figure 3.1 shows the organization and responsibilities of NOAA Fisheries' stock assessment enterprise.

The types of stocks managed vary across regions. There are notable differences in the types of fisheries; stakeholders affected; jurisdictions and their respective assessment processes supported (see Chapter 6); and the natural ecosystems that support the productivity of fisheries. For example, many of the longest-standing and most lucrative commercial fisheries target groundfish and shellfish in temperate and cold waters (e.g., cod, pollock, scallops, crabs, and so on). In addition, several science centers conduct assessments of the nation's most economically and ecologically valuable groundfish and shellfish (especially the Alaska and Northeast Science Centers). Despite these differences, common characteristics among regions can be used to maximum advantage when designing strategies for NOAA's stock assessment programs.

NOAA Fisheries Science to Support Fisheries Management



° The Western Pacific FMC manages additional regions not depicted here.

NOAA Fisheries Organization

Regions	Regional Offices (RO)	Fishery Science Centers (FSC) (# Number of Fishery Management and/or Advisory Organizations supported by Science Center)	Labs / Field Stations / Facilities
Alaska	Alaska RO, Juneau, AK	9 Alaska FSC, Seattle, WA	AK | • Anchorage • Baranof Island • Dutch Harbor • Juneau • Kodiak • Pribilof Islands; WA | • Seattle; OR | • Newport
West Coast	West Coast RO, Seattle, WA	5 Northwest FSC, Seattle, WA	WA | • Manchester • Pasco • Seattle • Mukilteo; OR | • Hammond • Newport
		4 Southwest FSC, La Jolla, CA	CA | • Arcata • Granite Canyon • La Jolla • Pacific Grove • Piedras • Santa Cruz; Antarctica | • King George Isl. • Livingston
Pacific Islands	Pacific Islands RO, Honolulu, HI	5 Pacific Islands FSC, Honolulu, HI	HI | • Honolulu; U.S. Territories | • American Samoa • Guam • Northern Mariana Islands
Greater Atlantic	Greater Atlantic RFO*, Gloucester, MA * Regional Fisheries Office	6 Northeast FSC, Woods Hole, MA	ME | • Orono; RI | • Narragansett; NJ | • Highlands; MA | • Woods Hole; CT | • Milford
Southeast	Southeast RO, St. Petersburg, FL	6 Southeast FSC, Miami, FL	NC | • Beaufort; MS | • Pascagoula • Stennis; TX | • Galveston; FL | • Panama City • Miami; LA | • Lafayette

Fishery Management & Advisory Organizations

▲ *Advisory (not management) organization.*

Organization		Supported by NOAA Fisheries Science Center(s)	Managed Ecosystem	Managed Stocks
ADFG	Alaska Dept. of Fish & Game	AK	Gulf of Alaska & Bering Sea - Sub-Arctic	Numerous Alaska coast stocks
CCAMLR	Commission for the Conservation of Antarctic Living Marine Resources	SW	Antarctic	Toothfishes, Icefish, & Krill
CCSBT	Commission for the Conservation of Southern Bluefin Tuna	AK	Southern Hemisphere Oceans	Southern bluefin tuna
IATTC	Inter-American Tropical Tuna Commission	SW, PI	Eastern Pacific Ocean - Sub-Arctic to Tropical	Tunas, Billfish, Sharks
IPHC	Int'l Pacific Halibut Commission	AK	Pacific Coast - Temperate to Sub-Arctic	Pacific halibut
ISCTTS▲	Int'l Scientific Committee for Tuna & Tuna-Like Species in the Northern Pacific Ocean	PI	Northern Pacific Ocean	Tunas, Billfish, Sharks
NPFC	Northern Pacific FC	AK	Northern Pacific Ocean - Sub-Arctic to Sub-Tropical	Numerous groundfish, Pelagics, Invertebrates
NPFMC	Northern Pacific FMC	AK	Gulf of Alaska & Bering Sea - Sub-Arctic	Groundfish, Salmon, Crab, Scallops
PFMC	Pacific FMC	AK, NW, SW	California Current	Salmon, Groundfish, pelagics, HMS
PSC▲	Pacific Salmon Commission	AK, NW	Pacific Coast, Bays, Rivers, & Estuaries	Pacific salmon stocks
PSMFC▲	Pacific States Marine FC	AK, NW, SW	Pacific Coast, Bays, Rivers, & Estuaries	Numerous Pacific coast stocks
PWS	Pacific Whiting Treaty	NW	California Current - Temperate	Pacific whiting (Pacific hake)
SPRFMO	Southern Pacific Regional FMO	AK, PI	Southern Pacific Ocean	Jack mackerel, Chub mackerel, Squids
WCPFC	Western & Central Pacific FC	PI	Western & Central Pacific Ocean	Tunas, Billfish, Sharks
WPFMC	Western Pacific FMC	PI	Insular Pacific Hawaii - Tropical	Bottomfish, Reef fishes, HMS, Invertebrates
ASMFC	Atlantic States Marine FC	NE, SE	U.S. East Coast, Bays, & Estuaries	Coastal groundfish, Pelagics, Invertebrates, Anadromous fishes
CFMC	Caribbean FMC	SE	Caribbean Sea - Tropical	Reef fishes, Invertebrates, Migratory pelagics
GOMFMC	Gulf of Mexico FMC	SE	Gulf of Mexico - Tropical/Subtropical	Reef fishes, Invertebrates, Migratory pelagics
GSMFC	Gulf States Marine FC	SE	Coastal Gulf of Mexico - Tropical/Subtropical	Gulf menhaden, Blue crab, Many commercial/rec. stocks
ICCAT	Int'l Commission for the Conservation of Atlantic Tunas	SE	Atlantic Ocean - Sub-Arctic to Tropical	Tunas, Billfish, Sharks
MAFMC	Mid-Atlantic FMC	NE	Northeast U.S. Continental Shelf (Mid-Atlantic Bight)	Groundfish, Clams & quahogs, Pelagic fishes & squids
NAFO	Northwest Atlantic FO	NE	Northwest Atlantic Ocean	Groundfish, Squid, Shrimp
NASCO	North Atlantic Salmon Conservation Org.	NE	Northeast U.S. Continental Shelf (Georges Bank) - Temperate Climate	Georges Bank groundfish stocks shared by U.S. & Canada
NEFMC	New England FMC	NE	Northeast U.S. Continental Shelf (New England)	New England groundfish, Sea scallops, Red crab, Atlantic herring, Atlantic salmon
SAFMC	South Atlantic FMC	SE	Southeast U.S. Continental Shelf	Reef fishes, Invertebrates, Migratory pelagics
TMGC	Transboundary Mgmt. Guidance Committee	NE	Northeast U.S. Continental Shelf (Georges Bank) - Temperate Climate	Georges Bank groundfish stocks shared by U.S. & Cananda

Science Centers

AK Alaska · NW Northwest · SW Southwest · NE Northeast · SE Southeast · PI Pacific Islands

Geography

AK - Alaska | CA - California | CT - Connecticut
FL - Florida | HI - Hawaii | LA - Louisiana
MA - Massachusetts | ME - Maine | MS - Mississippi
NC - North Carolina | NJ - New Jersey | NY - New York
OR - Oregon | PR - Puerto Rico | RI - Rhode Island
TX - Texas | U.S. - United States
USVI - U.S. Virgin Islands | WA - Washington

Shorthand / Acronyms

Dept. Department
FC Fisheries Commission
FMC Fisheries Management Council
FMO Fisheries Management Organization
FO Fisheries Organization
HMS Highly Migratory Species
Int'l International
Isl. Islands
Mgmt. Management
Org. Organization
Rec. Recreational (fisheries)

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Figure 3.1. Summary of NOAA Fisheries' scientific programs that support fisheries management, including the location of regional offices, science centers and their associated field offices, and the various management jurisdictions supported.

In many cases, funding has supported decades-long survey monitoring programs of groundfish stocks and their fisheries, thus providing large quantities of information to support data-intensive and sophisticated approaches for conducting stock assessments. In contrast, many tropical-reef-associated fishes (e.g., snappers and groupers) that fall under federal jurisdiction have very limited data on which assessments and management decisions can be based; however, recreational fisheries for some of these stocks are among the most important fisheries in the country. The Southeast and Pacific Islands centers are responsible for many of the reef-associated stocks. Some of these stocks are subject to international harvests of unknown scale, further contributing to assessment and management challenges. Situations where there is little data for a fish stock may be due to limited ship time and resources, diverse species and life history patterns, and complex habitats that are not conducive to data collection. These data gaps substantially limit the types of analyses that can be conducted as well as the degree of certainty surrounding the resulting scientific advice. Although there is little data for some groundfish stocks and sufficient data for some tropical species, these species groups provide general "bookends": Most of the remaining categories of federally managed stocks fall along the range of data availability between these extremes.

Coastal mid-water (pelagic) stocks (e.g., sardines, hakes, mackerels, and squids) are assessed in nearly all centers, and several centers conduct assessments of anadromous fish that migrate between marine and freshwater systems, such as Pacific and Atlantic salmon. Stocks within these species groups vary greatly regarding the amount of data available for assessments. NOAA Fisheries also conducts assessments of highly migratory species (HMS; e.g., tunas, billfish, and sharks) in collaboration with international partners, although NOAA Fisheries manages U.S. stocks of Atlantic HMS and contributes to management of HMS in other oceans. Generally, assessments of these stocks rely heavily on fishery-dependent data, because scientific surveys that cover the distribution of wide-ranging species are cost-prohibitive.

Beyond species groups, other patterns emerge across regions. For instance, commercial catch may represent a high proportion of landings in some regions (e.g., Alaska, Pacific), whereas recreational interests dominate other regions (e.g., Southeast). The stakeholder group dynamics and complexity vary by region, with numerous state partners and diverse fishing interests along the east coast and generally fewer stakeholder groups along the west coast. In addition, each regional ecosystem has unique characteristics, although national similarities emerge in this area. For instance, cold-water and temperate ecosystems are experiencing a higher degree of warming due to climate change, potentially affecting the distribution and productivity of many valuable stocks (Nye et al., 2009; Pinsky et al., 2013). Warming in tropical regions has been less severe, but coral reef systems can be highly sensitive to small temperature fluctuations and ocean acidification, and localized effects on biodiversity have been observed. Although each stock faces many unique challenges within an assessment context, these regional similarities indicate that numerous issues rise to the national level. Consequently, a main objective of this document is to provide national guidance and potential solutions that may benefit assessments of many stocks across regions.

General issues facing the NOAA Fisheries stock assessment enterprise include the following:

- Centers increasingly require a comprehensive prioritization process to guide assessments and address information gaps. Despite growth in stock assessment capacity, the demand for stock assessments and scientific advice to guide fisheries management exceeds the capacity to meet that demand.
- After samples and data are collected, additional work is needed before they can be incorporated into assessments. These tasks include quality assurance, processing, and formatting to comply with assessment model requirements. These steps constitute significant bottlenecks that limit assessment throughput in many regions, especially where the input data for the assessment models must be compiled from diverse data sources.
- Historical stock depletions in U.S. fisheries resulted in many stocks being listed as overfished. Rebuilding an overfished stock takes time, and while a stock is on a rebuilding plan, frequent assessments are required. As a result, past actions have created a bottleneck in the assessment process, increasing the current demand for stock assessments.
- For certain stocks, the assessment and management process does not meet expectations. For instance, an increase in stock biomass might not be observed despite harvest reductions, or an assessment model may exhibit instability (Chapter 5). These issues can impact the credibility of the science, stakeholder engagement, and overall ability to manage for sustainable fisheries.
- NOAA Fisheries is responsible for providing scientific advice on numerous stocks for which there is little data. Although annual catch limits are required for all federally managed stocks, a high level of uncertainty exists around estimates of sustainable harvest levels when catches themselves are unknown.
- Due to their quantitative skills and familiarity with managed stocks, many NOAA assessment scientists are tasked with analyses to support evaluation of management alternatives, resulting in less time to devote to assessment research.
- The historical investment in fisheries and fishery-independent data has generally been lowest in regions with the highest diversity of fisheries and species. In many cases, the primary data collection programs began after certain target species were already overfished. Data from these programs are therefore highly uncertain and often contentious, and extensive investigations are often requested. As a result, more time, staff, and resources are required to complete assessments in these regions.

NOAA Fisheries; stock assessment enterprise successfully supports federal mandates and provides the scientific basis on which most U.S. fisheries have achieved sustainability. This science has helped support millions of jobs and generate hundreds of billions of dollars in economic activity annually. Although NOAA's current stock assessment enterprise functions well, challenges highlighted in this and subsequent chapters warrant attention to further improve long-term sustainability and opportunity for U.S. fisheries.

To that end, the remaining chapters in this section identify the primary issues facing NOAA Fisheries' stock assessment enterprise. These chapters describe the current status and challenges associated with the following specific aspects of the stock assessment process:

- Data collection (Chapter 4)
- Assessment modeling (Chapter 5)
- Quality assurance (Chapter 6)

This comprehensive evaluation is necessary for determining the highest priority issues.

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Chapter 4. Data collection to support stock assessments

Chapter highlights:

- Data collection for stock assessments is conducted in partnership with numerous management organizations, academic institutions, and stakeholders.
- Scientific surveys (also called "fishery-independent" surveys) use data collection methods that are tailored to the habitats and biological features of the species.
- Data collected in cooperation with commercial, recreational, and other fisheries (called fishery-dependent data) are used to monitor catch, effort, incidental catch (called "bycatch"), numbers of fish returned to the sea either dead or alive (called "discards"), and other stock and fishery dynamics.
- Fundamental data for stock assessments include abundance, biology, and catch (explained later in this chapter).
- Assessments can also be informed and improved using other data sources, such as ecosystem and socioeconomic data.

4.1. Data types and collection methods

NOAA Fisheries' stock assessments are conducted using a wide variety of data that are collected by numerous sources, including federal and state agencies; commercial, recreational, and other fisheries; academic partners; and other stakeholders. All data, regardless of the source, can be considered for inclusion in stock assessments (see Chapter 5 for information about how data are analyzed). As part of the stock assessment review process (Chapter 6), all data and their sources are evaluated to ensure that they are appropriate for an assessment model and were collected using a scientifically sound method.

Most contemporary stock assessments strive to include three main data types (Mace et al., 2001):

Abundance—changes in relative or absolute numbers or biomass over time
Biology—demographics and life history
Catch— fishing effort, bycatch, and discards

Increasingly, there is an effort to include other data in the stock assessment process: ecosystem data, such as environmental forcing factors and predator–prey dynamics; and socioeconomic data, such as market dynamics and human behavior)

Data for stock assessments are collected according to two primary strategies: fishery-dependent and fishery-independent. Fishery-dependent data, as the name implies, is collected as part of commercial, recreational, or subsistence/cultural/tribal fisheries. These data provide information on the landings and bycatch of the fishery as well as the biological make-up of the catch (i.e., age, size, sex). Fishery-independent data provide information on the abundance, distribution, and demographics of fish stocks in their natural environments. These data are collected using standardized scientific surveys, which use consistent methods over space and time to maintain objectivity and obtain an accurate perception of wild fish stock dynamics. Fishery-independent data can be collected in cooperation with the fishery and its vessels, but not during normal fishing operations.

The remainder of this chapter provides an overview of the specific types of data that are collected for and used in stock assessments of federally managed species, as well as challenges associated with the collection and use of those data. This information provides a baseline assessment to help identify data gaps and potential strategies for improved data collection (covered in detail in Chapter 8). A summary of the types of data used by NOAA Fisheries to support stock assessments is presented in Table 4.1, which is categorized by the geographic areas managed by the eight Fishery Management Councils (refer to Fig. 3.1).

Table 4.1. Summary of stock assessment data collection by regional fishery management council, source, and type of data collected. Fishery-dependent data is categorized into commercial and non-commercial sources, while fishery-independent data is categorized into extractive and non-extractive sources. Catch and effort data is typically compiled from all sources, and biological data is obtained from certain sources, including information on length (L), weight (W), age (A), reproduction (R), and genetics (G). An "X" indicates the collection of catch information only.

Summary Table			North Pacific	Pacific	Western Pacific	Gulf of Mexico	South Atlantic	Caribbean	Mid-Atlantic	New England
Fishery Dependent	Commercial	Port/Trip/Weighmaster Data		L,W,A,R	L,W	L,A	L,A	L	L,W,A	L,W,A
		Observer Data	L,W,A,R,G	L,W,A	L,W,A,R	L,W	L,W		L,W,A	L,W,A,R
		Market Data			L,W,A,R,G					
		Vessel Monitoring System	X		X	X	X	X	X	X
		Other (Aerial, Acoustic)	X		X					
		Self-Reported (Logbook, Trip Ticket, Cannery Reports, etc.)	X	X	L,W	X	X	X	W	W
	Non-Commercial	Intercept	W	L,W	L,W	L,W,A,R,G	L,W,A,R,G		L,W	L,W
		Observers		L,W					L,W	L,W
		Other (Tournament)				X	X	X		
		Self-Reported (Logbook, Phone or Mail survey, etc.)	X	X	X	X	X		X	X
Fishery Independent	Extractive	Trawl	L,W,A,R,G	L,W,A,R,G	X	L,W,R			L,W,A,R	L,W,A,R
		Longline	L,W,A,R,G	L,W,A,R,G	L,W	L,W,A,R	X			L,W,A,R
		Dredge							L,W,A,R	L,W,A,R
		Handline, Rod & Reel		L,W,A,R,G	L,W		L,W,A,R			
		Other (Trap, Gillnet)	X			L,W,A,R	X		L,W,A,R	
	Non-extractive	Acoustic	L,W,A,R,G	X	X				X	X
		Camera (stationary)			L	X				
		Camera (mobile)	X	L	L				L	L
		Other (Aerial, Diver, Mark-Recapture)	L		L	X	X	X		

4.1.1 Catch data

Catch refers to the removals due to fishing and, in some cases, research of all fish of a given stock (or stock complex. Catch includes the fish brought to shore for sale or consumption (i.e., landed) as well as fish released at sea that are either already dead or subsequently die (i.e., dead discards). Total catch is an important component of all stock assessments because it indicates the scale of fishing mortality imposed on a stock by commercial, recreational, or tribal fishing efforts. Approaches to estimating the different components of catch vary depending on the type of fishery, with landings typically more easily estimated than discards. The two main types of catch data are commercial and recreational (Table 4.1), although subsistence and tribal fisheries can also contribute to total removals for some stocks.

NOAA Fisheries' relies on data from commercial fisheries collected through self-reporting by fishermen, permit holders, or fish dealers, and through data collection and observer programs conducted by NOAA Fisheries, state agencies, tribes, and international partners. Through fishermen's logbooks, the commercial sector self-reports certain data related to catch, such as the total amount of a given species caught (typically in units of weight); catch locations (often following regional reporting areas or grids); and information on fishing techniques (e.g., fishing gear and vessel characteristics, and approaches used in fishing operations). Data on fishing techniques (e.g., gear measurements, fishing location, depth, time, and so on) can be used to estimate and standardize fishing effort across various fishing strategies. Tracking landings for many stocks can be relatively straightforward (e.g., a sum across all sales records), while tracking discards requires estimation.

An important approach for collecting fishery-dependent data is through the use of fishery observers, who are deployed on commercial fishing and processing vessels to monitor fishing activities. Fishery observers are crucial for tracking catch and discards, because they are placed on specific fishing vessels to record catch and discard rates by species and gear type. Those discard rates are expanded by the total amount of fishing effort within each gear type to generate total discard estimates. Fishery observer data are also used to validate self-reported discard rates from the commercial fleets. Studies can be conducted to determine the survival rate of discarded fish, with dead discards being added to the catch to determine the total. Observers may also sample the landings and discards to collect biological information, such as the size and age distribution of the catch.

Recreational fisheries can contribute a substantial portion of the total catch of certain stocks when there are large numbers of recreational fishermen, the recreational sector is allocated a large portion of the catch, and there are high levels of fishing effort. This is particularly the case in warmer regions of the U.S. and its territories, such as the southeast where landings from year-round recreational fishing often exceed commercial landings. The recreational sector is divided into three main subsectors: headboat, charter vessels, and individual private anglers. Both self-reporting and government programs collect data from all three subsectors.

The Marine Recreational Information Program (MRIP) is the national data collection program for recreational data (except in Alaska where the Alaska Department of Fish & Game coordinates this effort). To estimate the amount of recreational fishing effort in a region, MRIP conducts a telephone-based survey of registered recreational fishermen (although this survey is transitioning to a mail-based approach). Additionally, in-person shoreside surveys (called "intercept surveys") are conducted to estimate the catch and effort associated with individual trips. Finally, multiplying total effort estimated from the phone/mail surveys by the estimated average catch/effort for each trip provides estimates of the total recreational catch. Similar to the commercial sector, both landed and discarded fish are considered, with survival rates of the discarded fish applied to determine the total catch. Further sampling is also conducted to evaluate the biological characteristics of the fish caught in recreational fisheries.

When programs are in place, subsistence, cultural, and tribal data are incorporated through either standard reporting requirements or through specialized data collection systems. The amount of fish caught in this sector is often small compared with the commercial and recreational sectors. However, accounting for all catch is important to ensure accuracy in stock assessments. For some stocks, the subsistence, cultural, and tribal sectors are not sufficiently monitored; in these cases, the data are not used in assessments.

4.1.2 Abundance data

Data on stock abundance over time are important for evaluating a stock's response to fishing and effects due to other factors. Thus, abundance data directly influences estimates of stock productivity. With the exception of stocks for which little data are available (called "data-limited" stocks), abundance data are used in nearly all stock assessments. Abundance data may be relative (e.g., percentage changes in stock size over time) or absolute (total) abundance (e.g., measures of stock size in terms of total numbers or weight). When available, absolute abundance estimates are preferred, mainly because they provide a solid foundation for stock assessment analyses by anchoring the assessment model at a scale that reflects actual stock biomass. Trends in relative abundance are useful for characterizing fishing effects. However, estimating the actual scale of the stock can be challenging when using relative abundance, which can be quantified using numbers of fish as well as weight. Unfortunately, data on absolute abundance is uncommon because the approach used for calculating it requires information that is difficult to obtain (e.g., a stock's total habitat volume, proportion of a stock available to sampling gear, and the efficiency with which a survey samples the available stock). Despite these challenges, there are examples of surveys that provide absolute abundance estimates, including bottom trawl surveys for certain flatfish stocks in the Bering Sea, the yelloweye rockfish survey off southeast Alaska that uses observations from a remotely operated vehicle, and the sea scallop survey off New England that uses a towed camera system (HabCam).

Ideally, abundance trends or indices of relative abundance are obtained from scientific surveys. However, when survey observations are unavailable, fishery-dependent sources can be used. In a fishery-dependent survey, catch rates such as annual catch per unit of effort (CPUE) serve as substitutions for relative abundance. For example, catch rates in southeastern headboat fisheries[17] are used in assessments for multiple reef fish species managed by the South Atlantic Fishery Management Council (SAFMC) and Gulf of Mexico Fishery Management Council (GOMFMC). Also, because it is cost-prohibitive to conduct scientific surveys over the distribution of most highly migratory species, assessments of these stocks rely almost exclusively on fishery-dependent data. Although fishery-dependent data tends to be readily available as part of routine fishery monitoring, extra caution is needed when using these data because they are influenced by changes in fishing practices and therefore may not be objective. To remove potential biases, fishery-dependent CPUE trends are typically corrected or "standardized" (Maunder and Punt, 2003) before they are used as substitutes for stock abundance in an assessment.

Abundance trends generated from fishery-independent surveys are preferable to those from fishery-dependent sources. Fishery-independent surveys are standardized, using consistent methods over time and space that optimally cover the range of the stock, including areas of lower abundance. These surveys can be designed such that they balance sampling effort in accordance with regional stock density (e.g., via adaptive, data-guided approaches that distribute sampling by depth, longitude, latitude, and/or habitat type). As a result, changes over time in measures of stock abundance or density from well-designed scientific surveys are assumed to be proportional to changes in stock size. Nevertheless, scientific surveys do not provide a perfect depiction of stock dynamics: They often target

[17] http://www.sefsc.noaa.gov/labs/beaufort/sustainable/headboat/

multiple species and therefore may not follow a design that is ideal for certain species; they may have fixed designs that do not adapt to changing ecosystems; and they may be affected by changing priorities, resources, or unforeseen events (e.g., weather and mechanical delays). As a result, to maximize available resources and provide high-quality abundance data, NOAA Fisheries uses multiple fishery-independent survey techniques described in Table 4.1.

4.1.3 Biological data

Samples of fish collected to support stock assessments can provide information on age, length, weight, sex, reproduction (e.g., maturity and fertility or fecundity), genetic information, and natural mortality (i.e., not caused by fishing). Age and length data are used mainly to characterize growth, as well as the age and size distributions of the assessed stock (including the catch). Weight, sex, and reproductive data are used to calculate reproductive potential, which may include aspects of egg production and/or total weight of mature fish (i.e., fish that can breed). Genetic data typically are not used directly in stock assessments, but can be used to determine stock structure (i.e., the spatial boundaries of a stock) and evaluate whether the definition for a managed stock is consistent with the biological stock. Finally, natural mortality, which is difficult to estimate, can be informed by scientific research, such as tag-and-recapture studies. These studies can be done in advance to provide an estimate of natural mortality, or the data from the studies can be incorporated into a stock assessment model to help scientists estimate natural mortality within the assessment. In fact, for most of the biological information listed above, the samples collected require substantial processing and analysis before these data can be analyzed in a stock assessment. This step can actually be one of the major bottlenecks in the assessment process.

Fish samples are collected from both fishery-dependent and -independent sources (see Table 4.1). Samples from fishery-dependent sources are primarily collected by port samplers (intercept surveys at fishing ports) and at-sea observers. Age, length, and weight are the most common information collected from both fishery-dependent and -independent sources, with reproductive samples, genetic analyses, and natural mortality studies occurring less frequently.

It is relatively straightforward to measure a fish's size (length and weight), and these measurements can be taken at sea or wherever sampling is conducted (e.g., ports). There are multiple approaches to determining a fish's age, each of which requires substantial processing time in a laboratory. Most methods involve counting yearly rings found by examining hard parts extracted from fish, such as bones in the inner ear (otoliths) or, less commonly, fin spines, vertebrae, scales, or other structures.

Reproductive data can be collected from a visual examination, but there is also a need for microscopic tissue analyses to obtain detailed information on fertility and maturity. Genetic samples are collected mainly for research studies on fish stock structure than as routine samples collected for stock assessments. However, genetic studies occur periodically to determine whether management stocks are appropriately defined and whether data are being collected and analyzed accordingly (e.g., whether data from separate areas should be analyzed separately or in combination).

Similarly, natural mortality rates are often assumed in stock assessments rather than being influenced or estimated using assessment data. Thus, research studies that estimate natural mortality of managed stocks are another important activity that helps structure an assessment, but may only need to be conducted periodically rather than for every assessment. Within stock assessments, natural mortality is a simple but important parameter that captures many complex ecological processes that affect survival, such as predator–prey, disease, toxins, habitat, and other dynamics (except fishing). In fact, all biological parameters referenced here are affected by ecological processes. As a result, a strong connection exists between the collection and use of biological data and ecosystem data. In addition, there is a strong need to conduct research to better understand these relationships, particularly in ecosystems experiencing rapid change.

4.1.4. Ecosystem and socioeconomic data

Not only are there connections between stock biology, productivity, and ecological processes, but stock abundance data, and even fishery data, are affected by ecosystem and socioeconomic dynamics. For instance, the proportion of a stock sampled by a survey may be affected by environmental conditions. Similarly, the location and effectiveness of fishing may be influenced by changing ecosystems, market dynamics, and fishing strategies. Thus, as we continue to improve our understanding of the connections between fish, fisheries, and their ecosystems, a clear need emerges to improve assessments by expanding their scope to incorporate important ecosystem and socioeconomic connections. Our understanding of these connections is furthered through direct experience and studies that mimic actual conditions, both of which are based on observations (data) from marine ecosystems and communities. Although these environments are complex, dynamic, and often difficult to define, substantial progress has been made in recent decades to understand and describe the marine ecosystems that support federal fisheries. Nevertheless, significant work still needs to be done to fully characterize these ecosystems and communities and how they change over time; the data demand required to accomplish this work is large. Although additional data and research are needed to obtain a more complete understanding of how ecosystem and socioeconomic drivers affect fish and fisheries, the stock assessment process is flexible enough to adapt to include new features and data as they become available. In fact, certain stock assessments conducted by NOAA Fisheries already routinely incorporate ecosystem information (Chapter 5).

Because there is an increasing need and desire to include additional drivers in stock assessments, the necessary data are collected to both support routine use in existing assessments and to conduct research that expands overall knowledge and improves assessments in the future. The primary ecosystem data being collected (and projected) include diet information to capture predator–prey dynamics, and physical and chemical ecosystem properties such as temperature, salinity, oxygen concentration, pH, and seafloor structure. In many cases, existing surveys and research cruises have been expanded to include ecosystem data collection, thereby maximizing data collection opportunities. In other cases, cruises dedicated to ecosystem monitoring are conducted to collect key information. A wide range of data are being collected as part of the Global Ocean Observing System, both by NOAA and external partners, and these data can serve as key variables in stock assessments. In fact, the combination of ocean observation systems with survey designs will become increasingly important to better understand ecosystem and stock dynamics. Another source of ecosystem information that can be used in stock assessments is an ecosystem model that integrates data and draws conclusions from those observations to estimate ecosystem-level dynamics. Actually, aspects of ecosystem-level models are often constructed using the results from analyses of single stock dynamics (e.g., stock assessments). Therefore, a two-way connection between stock assessment and ecosystem modeling is occurring and is necessary to develop the science that supports fisheries management.

4.2.0. Strengths and challenges

Data collection for U.S. fish stock assessments has evolved into a far-reaching partnership that collects a high volume of a wide variety of data. Formal programs exist for collecting, processing, and preparing these data for analysis in stock assessment models. The use of these data in stock assessments is evaluated in a public forum (see Chapter 6) where all data, including those collected by stakeholders, are considered for inclusion in assessment models. Thus, the overall data collection process for stock assessments is sophisticated, transparent, and effective. However, several challenges remain that require attention:

- **It can be difficult to obtain accurate and timely catch data.**
  The accuracy and uncertainty surrounding catch and effort data varies considerably from stock to stock. Assessment models analyze historical catches to understand the impacts of fishing over time, and for stocks with fisheries that have been monitored since their beginning, catch histories may be fairly accurate. However, catch monitoring was commonly incomplete or nonexistent during a fishery's early years. Where historical data are lacking, reconstructions of catch time series can allow estimation of the full development of some fisheries, especially on the west coast, but reconstructions are difficult where fishing effort has been high for centuries. Even today, challenges exist in collecting accurate catch information. Monitoring of stocks that are harvested internationally can be hindered by jurisdictional issues. In addition, low observer coverage and lack of knowledge surrounding release mortality in some fisheries create challenges for characterizing bycatch and whether discarded fish survived. Fishery observer data are expensive to collect, but need to be increased in some regions of the country (e.g., observer coverage is approximately 2% for some fisheries in the southeast region). Recreational, subsistence, and artisanal fisheries are difficult to monitor because they are dispersed and have limited resources for reporting their catches (Cummings et al., 2015). Further, self-reported data from fisheries can contain errors, both unintentional and intentional, that require improvements in the data validation programs and quality assurance/quality control (QA/QC) systems.

Most stock assessment models treat catch information with a high degree of confidence, and inaccurate catch histories add uncertainty and bias to stock assessments. For fisheries with mandatory catch reporting that dates to the start of the fishery, it may be safe to assume that catch histories are fairly accurate. However, there are many instances where uncertainty surrounds catch estimates, so every effort is made to estimate the full extent of fishery removals. Where there is substantial uncertainty surrounding catch histories, assessment models may need enhanced functionality to account for this uncertainty.

One of the largest bottlenecks for assessments in almost every region of the country is related to the processing and delivery of fishery data to assessment modelers. These challenges extend the time required to conduct stock assessments, and may result in large gaps between the final year of data used in the assessment and when the assessment is completed. Increased electronic reporting by commercial fisheries could help create more efficient data access and potentially improve QA/QC. Similarly, the development of automated tools, such as video-based counting of discards by species, could improve the availability and accuracy of data in certain situations.

- **Abundance data is expensive to collect and challenging to extract from fishery catch rates.** Although fishery-independent surveys are preferred over fishery-dependent data sources for providing estimates of stock abundance, challenges also exist in the implementation and use of fishery-independent surveys. First, scientific surveys are often relatively expensive to conduct and require significant ship time, with vessel days typically ranging from approximately $2,500 per day for smaller, contracted vessels to more than $15-30,000 per day for larger NOAA ships. In addition to vessel costs, resources are also needed for equipment and supplies, and field, laboratory, and analytical personnel. As a result, annual costs for surveys often range from hundreds of thousands to millions of dollars per year when all costs are considered. Second, the efficiency of gear types used in fishery-independent surveys may vary with the size or age of specimens being caught (e.g., older and larger fish may be better at avoiding capture by trawls due to increased swimming ability or speed with size), or by habitat type (e.g., trawls may be more likely to collect fish over unstructured versus structured habitat). These differences in gear effectiveness, unless known and corrected for, increase the uncertainty around abundance estimates. Thus, to maximize the usefulness of fishery-independent data, gear-specific efficiencies must be assessed—potentially a time-consuming and costly undertaking. Third, surveys can be designed to make the most of information collected on specific species (e.g., dredge surveys for scallops, acoustic surveys for midwater schooling fish); however, most surveys capitalize on the opportunity to collect information on a group of species. This multi-species sampling approach means that data are collected on many more species than under a single-species approach, thereby allowing many more stock assessments to be conducted with minimal increases in resources. However, additional considerations are associated with multispecies surveys. For instance, the stocks collected may have different distributions, habitat preferences, daytime patterns, and/or availability to fishing gear. For such surveys, establishing a survey design that reduces uncertainty surrounding abundance estimates for certain target species may increase the uncertainty surrounding the abundance of other species. In other words, because distributions, habitat use patterns, and behaviors vary by species, it is impossible to design surveys that are ideal for all species sampled. Thus, choices will have to be made based on species-specific management importance, cost, and logistical considerations.

The primary challenge related to the use of fishery-dependent data for generating estimates of relative stock abundance is that multiple factors unrelated to stock abundance can affect fishery catch rates. For instance, changing management actions may alter catch rates due to varying harvest quotas, size restrictions, temporal and spatial management, and so on. Catch rates are also affected by fishery-driven changes in practices, such as changes in market prices, fuel prices, and so on; improvements in fishing strategies and techniques, such as new technologies that improve catch efficiency; and target species preferences, such as certain stocks may be targeted after quotas for other stocks are met. Additionally, changes in the completeness of reporting (e.g., enforcement and compliance with reporting requirements) will affect the data available on catch rates. Issues related to estimating abundance trends from fishery-dependent data require considerable attention, because fisheries can adapt their practices to maintain catch rates, and therefore profits, when stocks decline (e.g., if stock density declines in certain areas, fishing can be redirected to higher-density areas to maintain efficiency).

- **Research is needed to improve biological data.**

Because the types of biological data collected for stock assessments are diverse, so are the challenges associated with those data. Optimally, all biological data used in stock assessments should be collected to represent managed stocks as a whole. When only a portion of a stock's spatial distribution (or ages, sizes, or sexes) are sampled, the biological data must be interpreted with caution because it may not represent the entire stock. To avoid biased biological data, it is important to sample the entire stock as much as possible, and to research sampling strategies and efficiencies to understand which portions of the stock are represented by the data. In some cases, stock distributions extend across jurisdictional—state, federal, and international—boundaries, creating sampling and management challenges. However, if a managed stock is not consistent with a biological stock, then estimates of productivity, stock status, and harvest recommendations may be inaccurate.

When collecting biological data, it is important to understand the minimum number of samples needed to sufficiently estimate life history factors. For many stocks, studies to address sampling intensity have not been conducted, but this research is important for determining and prioritizing resources needed for data collection in stock assessments. There are potentially numerous cases of both under- and over-sampling of biological data, affecting not just the time and resources dedicated to collect the data, but also the time and resources assigned to processing the samples. In fact, due to limited capacity and substantial processing requirements, biological sample processing (e.g., counting age rings) is a primary bottleneck in the stock assessment process.

For aging analyses, species-specific studies are necessary to validate assigned ages; however, these studies are lacking for many managed stocks. Even when validation studies have occurred, the determination of an individual fish's age can be challenging, as is often the case for older individuals of long-lived species. As such, fish are typically aged by multiple analysts with a goal of reaching high levels (e.g., greater than 90% agreement) among analysts before data are judged useful for assessments (Campana, 2001).

For reproductive data, there are multiple areas where additional research could improve stock assessments. For example, more detailed understanding of reproductive capacity by size and age could result in more accurate assessment models and therefore biological reference points. Additionally, studies are needed to better understand the timing and duration of spawning seasons, as well as spawning frequency, particularly for stocks with individuals that spawn multiple times during a season, and stocks with individuals that do not spawn each season (Secor, 2008; Rideout and Tomkiewicz, 2011; Fitzhugh et al., 2012). Numerous species, especially tropical reef fishes, have both male and female reproductive organs (called "hermaphroditic"), often reaching maturity as one sex and then transitioning to the other. These species pose unique challenges to modeling reproductive dynamics, and more studies are needed to develop assessment methods and better understand ratios of males to females in the stock and how those ratios relate to productivity (Shepherd et al., 2013).

Natural mortality is a critical, although understudied, component of stock assessments. In fact, many assessments are conducted without any direct measures of natural mortality. Rather, natural mortality rates often emerge from using data and relationships with other life history data, other species, or without any supporting information. Thus, there is a clear need for more tagging studies and tag-and-recapture data to improve natural mortality estimates, as well as a link to predation and other sources of known, measurable mortality.

- **More ecosystem and socioeconomic data and research are needed.**
  Ultimately, to expand the scope of stock assessments, it is not enough that additional data are available. Scientists also need to understand more fully how fish stocks and fishery dynamics are affected by ecosystem and socioeconomic factors. For instance, because biological processes combine a number of ecosystem processes, more research on predator–prey, disease, toxins, and habitat dynamics would improve understanding of factors that affect stock productivity. Similarly, research into human and market dynamics is valuable to help understand and predict fisheries. Even without including ecosystem or socioeconomic data, many assessments already

account for change caused by these drivers, such as through variability in weight by age or changing fishing practices (e.g., selectivity patterns). However, further research will help improve an understanding of the key drivers to improve assessments and the resulting advice. Improving prediction skills is particularly important in the context of climate change, because a stock's historical responses to fishing, which are evaluated in an assessment, may not reflect future responses.

To expand assessments to be more holistic, researchers need to increase their collection of ecosystem and socioeconomic data. Although beneficial partnerships are in place, and many existing data collection efforts are being leveraged to collect these additional data, there simply is not enough data to fully characterize complex and multifaceted ecosystems and communities. Thus, additional data collection and research efforts are needed. However, the information currently available can be used and is being used in assessments now. With innovative science (Chapter 9) and strategic prioritization (Chapter 10), ecosystem and socioeconomic data can be incorporated where most needed.

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Chapter 5. Analytical tools

Chapter highlights

- **Stock assessment models are specifically designed to produce results needed by fishery managers.**
- **A range of models is available to suit the diversity in available data for each stock.**
- **Models that use limited data produce management advice by making strong assumptions; models that use more types of data can estimate the effects of more factors on a given fish population.**
- **Characterizing the uncertainty in model outputs is important for evaluating the risk associated with various management strategies.**

5.1. Introduction

This chapter provides an overview of the analytical tools used in NOAA's fish stock assessments. Many of these tools are highly technical, and therefore, this information is intended for those already familiar with these methods, or for those interested in an introduction to the mechanics of stock assessment modeling. The analytical work conducted by stock assessment scientists is designed to translate data from fisheries, surveys, and biological studies to characterize the status of a fish stock and to provide catch forecasts needed by fishery managers. These analyses consist of three principal stages:

1. Data preparation
2. Modeling and forecasting of fishery and population dynamics
3. Risk analysis and decision support

In stage one, the many samples collected each year from fisheries and surveys need to be processed and summarized by a few values (e.g., the age composition of the catch for a given year) that are input to a stock assessment model. During the second stage, development, calibration, application, and forecasting of these models are major activities for the stock assessment programs. Then, in the third stage, the uncertainty surrounding stock assessment results is explored to calculate tradeoffs and risks and communicate them to fishery managers and the affected public. In addition to these three stages of assessment analyses, which are described in more detail in this chapter, stock assessment modelers also conduct a wide range of research and perform management support activities that use their analytical skills. These activities range from investigations of ecosystem and habitat factors affecting fish stock dynamics, to analyzing bycatch patterns in fisheries. Opportunities to conduct research allow stock assessment scientists to remain creative, innovative, and at the forefront of stock assessment science. The distinction between stock assessments and general scientific research and investigations into fish population dynamics is that the results of stock assessment analyses are tailored for delivery to fishery managers. Thus, NOAA Fisheries' stock assessment scientists conduct world-class fisheries research while also participating in operational science (i.e., stock assessments) that deliver quality scientific advice to fishery managers.

5.2. Preparing stock assessment input data

As described in Chapter 4, a variety of data (i.e., samples) are collected to support stock assessments. However, the samples collected by these various programs may not be available as input into stock assessment models until they have been processed. This processing includes laboratory analysis of samples and organizing the data so they are appropriate for use in assessment models. For example, catch information recorded from thousands of fishing trips is combined into a measure of total (usually annual) catch by each fleet. Similarly, survey observations from hundreds of locations are totaled into a measure of stock abundance, again usually annual, throughout the range of the survey. This combination typically involves sophisticated statistical models often designed and implemented by stock assessment scientists (see review by Maunder and Punt, 2004).

Processing data for generating catch-age compositions (and catch-length compositions) requires analytical thoroughness and an incorporation of the sampling process (Kimura, 1989; Dorn, 1992). The fishery data on catch and its size and age composition can come from many sources including NOAA, commission or state-specific landings receipts, NOAA fishery observer programs, state-specific biological sampling, diverse recreational fishery sectors, and so on. Merging these raw data into statistically sound estimates of fleet-specific catch statistics can be difficult and time-consuming for stock assessment scientists and data analysts. The need to improve the efficiency of this process so that data are readily (and publicly) available for assessments was a major finding of NOAA's stock assessment program reviews in 2013[18]. In certain scenarios, standardized, immediately usable data systems could help relieve this drain on the assessment process and potentially result in more timely assessments for more stocks. However, frequent changes in fishery management and fishermen's behavior hinder the development of automated collection systems for fishery data.

Another major effort is developing methods to create a measure of stock abundance from raw fishery logbook or survey sample data. Here, statistical methods such as generalized linear models have been useful (Maunder and Punt, 2004), and the next wave of innovation in this area may be fully geostatistical methods (Thorson et al., 2015). Pre-processing data before using it in models also requires consideration of the appropriate observation uncertainties (Francis, 2011). Finally, statistical methods are used for estimating or reconstructing historical catches. The reliability of these methods can vary over time and by region (e.g., if the catch accounting method involves data collections at different spatial scales, assumptions about distributing can be critical).

5.3. Stock Assessment Models

5.3.1. Principles

Population dynamics models produce the main stock assessment results. Information fed into these models is obtained from the pre-processing models discussed earlier. Population dynamics models are

[18] https://www.st.nmfs.noaa.gov/science-program-review/program-review-reports/index

based on realistic, but simplified, representations of the factors affecting the productivity and mortality of fish stocks. In addition, these models are designed to produce estimates of current, historical, and future fish abundance and fishing mortality.

Population dynamics models are standardized using the time series of abundance, biological, and catch data. The quantity and quality of these data and the amount of variation (contrast) they show over time influences the types of models that are used and how well they can be expected to perform (Maunder and Piner, 2014). Each stock provides unique data for an assessment, including the research conducted to support assumptions underlying stock and fishery dynamics. Thus, the choice of stock assessment model and model configuration within the assessment framework is governed by a stock-specific, scientific, decision-making process that attempts to identify the most appropriate analytical approach. Implementing this process requires strong technical expertise and is a fundamental role of the stock assessment analyst. Numerous choices are available to assessment analysts, and Table 5.1 provides a general summary of the range of options.

Most stock assessment analyses are statistically based, so the general conceptual approach to running or "fitting" an assessment model follows basic statistical modeling practices. This process involves the following general steps:

1. Specifying mathematical equations (models) that are assumed to represent stock and fishery dynamics
2. Inputting relevant data pertaining to stock and fishery dynamics
3. Applying statistical methods that calibrate the mathematical models by comparing the processes defined by the equations to the patterns observed in the data.

The specific details about each step of the modeling process vary with the amount and type of data available for an assessment (Figure 5.1). For instance, most data-rich assessments are age (or length) based, and therefore provide a more detailed evaluation of the effects of fishing and other factors on the stock. To achieve this level of detail, the mathematical models need to be created to track cohorts (or length classes) over time, which results in a relatively large number of model parameters that need to be estimated (informed by data) or specified (i.e., assumed). This type of configuration requires age- (or length-) specific data, as well as relatively complex statistical methods capable of calibrating models with many parameters. One benefit of a more detailed model is that generally, there are fewer strong assumptions about stock dynamics required. With data-moderate assessments, there are typically observations of total catch as well as changes in abundance, but the data are aggregated across ages (sizes), so these assessments inherently assume that the dynamics apply to all ages and sizes of individuals in the stock equally. However, the benefits of a simple model include easier understanding, generally simpler statistical methods which can result in fewer complications during application (i.e., models that are easier fit), and often a straightforward calculation of key results. For instance, solutions for maximum sustainable yield (MSY) reference points which form the basis for stock status determinations and setting sustainable catch limits can be directly calculated with biomass dynamics models (see Section 5.3.2). With data-rich assessments, these reference points are often determined in a secondary step that involves simulation analyses based on the results obtained from fitting the assessment model.

Data-limited approaches are used for many U.S. stocks and may be used for a variety of reasons. The most common reason is when there is not enough data for more complete assessments. However, data-limited methods are also employed as a stop-gap for setting catch limits between more complete assessments and as a default approach when a more complete assessment has issues and is not deemed appropriate for management. There are numerous data-limited methods available that differ in their data requirements and underlying assumptions (Newman et al., 2014). Several methods rely only on catch data, while others incorporate life-history information or apply multipliers to trends in biomass. All data-limited approaches rely on fairly strong assumptions about stock dynamics (e.g., the amount that a stock has depleted over time) and therefore should not be considered a long-term approach to support sustainable management of important stocks.

5.3.2. Outputs and uses

Stock assessment models are designed to give fishery managers numerical estimates of relevant fishery management quantities. Common outputs and their uses include the following:

1) Reference Points:
   a) F_{MSY}—The average fishing rate, or suitable proxy (e.g., $F_{40\%}$), that would produce the maximum sustainable yield. This serves as the limit beyond which overfishing is considered to occur.
   b) B_{MSY}—The average stock abundance when fishing at F_{MSY} (the associated Minimum Stock Size Threshold (MSST) below which the stock is considered overfished is often a specified fraction of B_{MSY} or its proxies).
2) Stock Status Determination—The comparison of current stock abundance and fishing rates produced by an assessment model with the associated fishing and biomass reference points.
3) Harvest Control Rule—A formula that calculates a limit or target catch level and is based on a stock's abundance and other factors (e.g., scientific uncertainty, risk policy). Many control rules strive to attain a large fraction of MSY while keeping the risk of overfishing at an agreed level. National Standard 1 Guidelines require that scientific uncertainty be taken into account when calculating target harvest policies.
4) Harvest Recommendation—Level of catch recommended for achieving the objectives of the harvest policy, typically based on forecasts of abundance trends. For federal fishery managers, this value provides the technical input needed by a council's Scientific and Statistical Committee to recommend an acceptable biological catch (ABC) to its council.

As described in more detail in Section 5.4, the uncertainties surrounding outputs 1 through 4 should be characterized and measured as completely as possible to support effective and robust management decisions. Because stock assessment models are the foundation for determining stock status and setting catch limits, there is a high level of public scrutiny and strong peer review requirements (see Chapter 6). Additionally, assessment models and their outputs have broader applications (Section 1.2).

Many demands are placed on the stock assessment modeling community. Some managers and stakeholders want simpler methods that are quick to implement and transparent to a wider community, while others want methods that are more comprehensive and/or more heavily evaluated during each application. There is also interest in more spatial resolution to better match the on-the-water observations of local fishermen. Ideally, there is a preference for more complete measures of uncertainty to better implement precautionary approaches and avoid surprises as estimates change over time. No one modeling approach will satisfy all these demands, but progress is being made in several areas highlighted next and in chapter 9.

5.3.3. Categories

A range of stock assessment models has been designed to provide tools across a variety of scenarios, mainly related to data availability (Table 5.1). Where data are limited, or when simple analyses are used for monitoring between more comprehensive assessments, modeling approaches tend to be relatively simple and rely on fairly rigid assumptions about stock and fishery dynamics (Categories 1 and 2 from Table 5.1). In these cases, assumptions about important factors are often based on knowledge from stocks with similar attributes, so scenarios with limited data can still produce stock-specific results. Many stocks in U.S. managed fisheries do not have sufficient data for conducting stock assessments that provide typical management advice (i.e., stock status and catch limits/targets). However, the U.S. requirement to establish annual catch limits (ACLs) in all fisheries has forced a rapid response by stock assessment scientists to develop and advance methodology for data-limited stocks (Cummings et al., 2014; "Data-Limited" methods in Table 5.1). A study of methods for determining ACLs in the U.S. (Berkson and Thorson, 2015) indicated that 52% rely on methods that consider only catch data to provide management advice.

When a moderate amount of historical data are available, such as catches over time and an indicator of changes in stock abundance (or relative abundance) over time, then aggregate biomass dynamics models can be used (category 3 from Table 5.1). These models calculate how large the stock must have been to have exhibited the trends observed in the abundance data while the observed catch was being removed. These estimates are conditioned on population turnover rates indicated by available biological data.

Moving up the data availability spectrum, a third class of stage-based approaches uses the distributions of ages or lengths in the fishery harvests and/or surveys (categories 4 through 6 in Table 5.1). Age and/or size data are particularly useful because they facilitate estimates of total mortality rates for fish stocks (i.e., the proportional decline in fish abundance with age indicates the magnitude of fishing plus natural mortality). When eras of high and low mortality coincide with eras of higher and lower levels of catch, these methods can infer the size of the stock from which the catches were taken. When historical time series of age/size data are available, the models can also calculate, by age/size, the degree to which fish are available to (selected by) a fishery or survey. Further, age/size time series also allow for calculation of annual fluctuations in the amount of young fish entering the stock (i.e., recruitment) as well as annual fluctuations in body growth. Additional expansions and information, such as spatial model configurations and inclusion of ecosystem data, can be considered for any assessment model framework.

Table 5.1. Categories of stock assessment models with focus on the population dynamics structure (e.g., growth rates, mortality, reproductive characteristics), data requirements (minimum and data typically used), and types of management advice that can be provided with associated limitations. "Catch" refers to total catch (including discards to the extent feasible) in biomass or numbers but without information on age and/or length structure. "Abundance index" generally refers to a relative index assumed to be proportional to the abundance of a fish stock as modified by the assumed or estimated size and age selectivity of the fishery or survey that is the source of the data.

1. Data-Limited

- Example methods: Depletion-Based Stock Reduction Analysis (DBSRA; Dick and MacCall, 2011); Depletion Corrected Average Catch (DCAC;* MacCall, 2009); Surplus Production MSY (Martell and Froese, 2013); Egg-Escapement, Mean Length Estimation (Gedamke and Hoenig, 2006)
- Population dynamics: Typically not modeled, but some methods include basic assumptions and expert opionion on natural mortality, stock depletion, sustainability of recent catch, and others
- Data requirements: Total catch and/or other biological information as available
- Management advice: Catch recommmendations and sustainability of recent average catch
- Limitations: Results are a placeholder for management advice until direct information on stock status and/or trends can be obtained

2. Index-Based

- Example methods: Basic linear models and time series analyses, An Index Method (AIM; NOAA Fisheries Toolbox*)
- Population dynamics: Typically not modeled
- Data requirements: Time series of total catch and/or stock abundance
- Management advice: Mostly qualitative advice about stock trends and whether management action is triggered as part of a harvest control rule (e.g., abundance index goes below a prespecified threshold)
- Limitations: Does not provide estimates of stock biomass

3. Aggregate Biomass Dynamics

- Example methods: Schaefer or Pella-Tomlinson Production Models (ASPIC;* Prager, 1994); delay-difference models (Collie and Sissenwine ,1983; Deriso, 1990)
- Population dynamics: Aggregate biomass dynamics with minimal parameters (carrying capacity—*K*, intrinsic population growth rate—*r,* initial biomass—B_0, and a catchability coefficient—*q*, related to fishing mortality or survey abundance index); delay-difference models expand on this to include at least two life stages and assumptions about growth and natural mortality
- Data requirements: Time series of total catch and at least one index of stock abundance; delay-difference models typically have abundance indices for each life stage, and information on growth and natural mortality
- Management advice: Estimates of maximum sustainable yield (MSY), current biomass (*B*) relative to B_{MSY}, current fishing rate (*F*) relative to F_{MSY}, and the current catch that corresponds to F_{MSY}
- Limitations: Requires contrast in the data (i.e., periods of high and low catch and biomass, as well as variability in the abundance index over time); typically ignores biological information regarding individual body growth, maturity, and natural mortality rate; provides more detailed population dynamics but still aggregates dynamics within life stages

4. Virtual Population Analysis (VPA)

- Example methods: VPA and Dual Zone VPA (ADAPT & VPA-2BOX; NOAA Fisheries Toolbox[*])
- Population dynamics: Starting from the last year in the data and the oldest age for each cohort in that year, abundance-at-age is calculated backwards in time using catch-at-age and natural mortality; models are often tuned by fitting to age-specific abundance indices
- Data requirements: Complete, high-quality catch-at-age and weight-at-age data for every time step and at least one abundance index for calibration ("tuning" in a VPA context); age-specific abundance indices are often used
- Management advice: Time series of biomass and fishing rates are primary sources of advice; however, model output can be analyzed separately to evaluate stock-recruitment relationships; these additional analyses help provide complete advice on stock status and forecasts of catch limits and targets
- Limitations: Obtaining complete catch-at-age data that can be considered known without error at every time step is not realistic for many stocks; estimation techniques often use specific approaches that create challenges for characterizing uncertainty (e.g., confidence intervals); method performs best when the fishery is the dominant source of mortality (i.e., fishing mortality > natural mortality)

5. Statistical Catch-at-Length (SCAL)

- Example methods: Statistical Catch-At-LEngth (SCALE; NOAA Fisheries Toolbox[*]); Stock Synthesis (SS;[*] Methot and Wetzel, 2013); MultifanCL (Fournier et al., 1990); crustacean models (Zheng et al., 1995; Chen et al., 2005)
- Population dynamics: Length-structured, with a length-based transition matrix to update the stock's length composition between consecutive time steps; can incorporate natural mortality, growth, recruitment, and fishing mortality at length; the inclusion of size data from fishery or survey catches allows for the estimation of size selectivty patterns by fleets/surveys and the time sequence of recruitments
- Data requirements: Total catch by fleet, at least one abundance index, length composition data from fleets/surveys (some missing data allowed); may allow the catch data to be separated into landings and discards
- Management advice: Stock status and forecasts of catch limits and targets relative to management reference points (if stock-recruitment dynamics are embedded); otherwise advice is limited to estimated time series of biomass and fishing rates
- Limitations: Typically less informative about recruitment and mortality of older individuals than when age data are available

6. Statistical Catch-at-Age (SCAA)

- Example methods: Stock Synthesis (SS;[*] Methot and Wetzel, 2013); Age-Structured Assessment Program (ASAP;[*]Legault and Restrepo, 1999); Assessment Model for Alaska (AMAK[#]), Beaufort Assessment Model (BAM; Craig, 2012); MultifanCL (Fournier and Archibald, 1992; Fournier et al., 1990); C++ Algorithmic Stock Assessment Library (CASAL; Bull et al., 2012)
- Population dynamics: Age-structured, incorporating natural mortality, growth, recruitment and recruitment variability, fishing mortality, and selectivity
- Data requirements: Total catch by fleet, at least one abundance index, samples of age compositions by fleet/survey; missing data are allowed (in contrast to VPA); some implementations allow the catch data to be separated into landings and discards
- Management advice: Stock status and forecasts of catch limits and targets relative to management reference points (if stock-recruitment dynamics are embedded); otherwise advice is limited to estimated time series of biomass and fishing rates
- Limitations: Flexibility of software package to include additional factors is highly diverse and difficult to categorize; direct estimates of MSY-based quantities depend on whether stock-recruitment dynamics are included

***http://nft.nefsc.noaa.gov/index.html**

[#]https://github.com/NMFS-toolbox/AMAK

5.3.4. Application and choice

Assessment models use advanced statistical and computational methods to enable estimation of the parameters of the model, which can be as many as thousands in the most data-rich and flexible cases. When detailed, flexible models are applied to relatively simple data sets, some factors in the models need to be specified as constants or the models will need extra constraints/penalties on parameters for those factors to prevent the results from becoming highly uncertain or illogical. Conversely, when simpler model configurations are confronted with more detailed data, they may not adequately represent the processes that created some of the detailed patterns in the data. Therefore, they can produce biased results. In general, model choice is governed by data availability, but another important consideration relates to the *principal of parsimony*. The level of detail in the assessment relates to the scale of investment in data collection; thus, to maximize limited resources, assessments should be as simple as possible while achieving the management objectives. In many cases, age-structured data and other information are important for achieving optimum yield from fish stocks. However, for less important stocks, it may not be worth the investment to collect such detailed data.

Integrated analysis models, such as Stock Synthesis (Methot and Wetzel, 2013), provide flexibility to combine aspects of both age-structured and biomass dynamics models. These methods are frequently used in stock assessments because they can be adjusted to match a variety of data availability scenarios. Integrated analysis here refers to the ability to simultaneously include length and age, tag–recapture, and other data. Because these are flexible models, programs such as Stock Synthesis support a variety of configurations to implement many of the model categories in Table 5.1, particularly the SCAA and SCAL models. One potential drawback of integrated analysis models is that the flexibility may result in implementation errors or configurations that are too detailed given the data available. Drawbacks such as these emphasize the importance of documentation, best practices, and user guides for stock assessment methodology.

5.4. Assessment uncertainty and decision support

5.4.1. Characterizing scientific uncertainty

It is not possible to observe every process affecting every individual fish in a stock (without error); therefore, there will always be some degree of uncertainty surrounding stock assessment results. This uncertainty can be reduced by improving and expanding observing systems and by conducting research to understand processes. However, acknowledging and characterizing uncertainty is an integral part of fisheries management. Because information is not perfect and complete, the advice that results from analyzing that information may not be perfect either. Therefore, uncertainty is characterized and adjustments are made to buffer against negative outcomes, such as overfishing, when information is not perfect (Methot et al., 2014).

Six types of uncertainty that commonly receive attention in fisheries (Peterman, 2004; Link et al., 2012) include the following:

1. Process error (or uncertainty due to natural variability)
2. Observation error (or measurement or estimation uncertainty)
3. Structural complexity (or model uncertainty)
4. Communication uncertainty (issues related to interpretation and use of results)
5. Objective uncertainty (or lack of clarity on goals and objectives, often included with outcome uncertainty)
6. Outcome uncertainty (or management performance uncertainty)

From this list, 1–3 may be accounted for within stock assessments, where 4–6 are not typically addressed during analyses. For process and observation error, approaches that are likely to characterize uncertainty most appropriately are models that are explicitly statistical that allow for sufficient flexibility to capture both sources of error at the same time as. However, simpler models can provide reliable fisheries management advice, especially if they have been evaluated through simulation testing and/or decision support analyses (see Section 5.4.2).

Several statistical methods that are used frequently can help address and measure uncertainty in stock assessments. For instance, Bayesian statistics provide an opportunity to use prior knowledge about a certain process or model parameter to help with estimation in the assessment model. This method is especially useful when there is not enough information in the input data to estimate assessment parameters, and previous analyses do not provide enough certainty to specify the exact value of the parameters at the start of the assessment. The combined use of prior knowledge and information in the data supports an appropriate treatment of uncertainty in many assessments.

Another statistical approach that is becoming more common in stock assessments is the use of random effects, or state–space models. With this technique, assessment processes and parameters can be treated not only as fixed estimates, but also as parameters that change over time and/or space according to a random process. Previously, state–space techniques were too cumbersome to implement in relatively complex stock assessment models; however, recent developments in computing power and statistical software have made it possible to do so. Assessments can now account for shifts in population and/or fishery dynamics without a detailed understanding of the cause of those shifts. Thus, state–space models offer a sophisticated approach to addressing uncertainty that accounts for both observation and process errors and balances total uncertainty between these two components. Although full state–space stock assessments are not yet commonly used in the United States, these assessments provide a very active area of research and development.

A commonly used approach to account for process error in U.S. stock assessments is model sensitivity analyses. This technique evaluates the structural uncertainty of models. In other words, this approach tests to see how the results compare when other mathematical equations are used, data are added to or eliminated from the assessment, different values of parameters are selected, or different assumptions about model parameters are considered. Commonly this approach narrows the choice to one or a small set of plausible model configurations, thus arriving at what is considered a good model. However, resting on a single "base" model ignores the total uncertainty across the set of plausible models. In some cases, assessments try to average results across the suite of models, but more technical guidance is needed on how to do this in a stock assessment context. Although climate and weather forecasts rely heavily on ensemble modeling techniques, there are enough differences in the data and modeling approaches that the scientific basis behind their methods does not directly translate to a stock assessment application. Essentially, weather forecasts can evaluate model skill by direct comparison with observed events, but in stock assessments, the true occurrence (e.g., last year's total biomass) cannot be observed without uncertainty. Nevertheless, there is a growing preference to use multimodel inference for characterizing process errors in stock assessments, and quantitative approaches are currently being used for some stocks (Stewart and Martell, 2015).

Within a single assessment model configuration, several diagnostic tools can be used to evaluate the consistency and stability of a model. Retrospective analyses (such as Mohn, 1999) test for systematic inconsistencies, or patterns in the results, when the model excludes data year-by-year going back in time. If models do not perform well according to this diagnostic, then there is an issue with the assessment and alternative model configurations may be evaluated. Thus, retrospective analysis is useful for evaluating the extent of model mis-specification (Hanselman et al., 2013), which may help address process error. However, detecting and accounting for retrospective patterns is not straightforward and remains an area of active research (Deroba, 2014; Hurtado-Ferro et al., 2015; Brooks and Legault, 2016; Miller and Legault, 2017). Although other diagnostic tools can evaluate model stability, retrospective analyses are commonly used because when a model shows a pattern, researchers tend to be skeptical about the assessment results.

5.4.2. Decision support

Decision support analyses use the uncertainty surrounding the outputs of stock assessment models and other components of the management process to evaluate tradeoffs among options. The need to quantify uncertainty was reinforced under the National Standard 1 (NS1) Guidelines, which specify the requirement apply a risk policy that accounts for scientific uncertainty when setting catch limits (Methot et al., 2014). Assessment scientists from NOAA Fisheries provided important technical guidance for applying this aspect of the NS1 Guidelines (Shertzer et al., 2009) where they showed how the probability range (i.e., uncertainty) around an estimated overfishing level (OFL) could be used to set a catch target below the OFL that had a specified probability, P*, of allowing overfishing to occur. According to the NS1 Guidelines, the chance of exceeding the true OFL must not exceed 50%, and the approach from Shertzer et al. allows managers to specify the level of risk they are willing to tolerate (up to a 50% chance of overfishing). There are other acceptable approaches to account for uncertainty in catch recommendations, and these are typically more generic than P*. For example, the Pacific Fishery Management Council relies on a meta-analysis of the performance of past assessments to develop an overall level of assessment uncertainty to feed into the P* approach (Ralston et al., 2011).

Decision tables are another tool increasingly being used in stock assessments to show managers a range of outcomes if errors occur in certain aspects of the assessment. Decision tables contrast the effects of a range of possible management decisions (e.g., harvest levels) with a range of stock assessment scenarios. For example, this approach can show how a higher quota could quickly deplete a stock if the stock size is actually lower than the current estimate. Conversely, the table could show how a lower quota may result in missed fishing opportunity if stock biomass is actually higher than estimated.

Another, more comprehensive decision-support tool is termed Management Strategy Evaluation (MSE; de la Mare, 1986; Smith et al., 1999; Punt et al., 2014). An MSE takes the basic concept of the decision table and plays it out in computer simulations many times to reveal the performance characteristics of the entire fishery–science–management system. MSEs contribute to a transparent decision-making process because they include stakeholders in the earliest stages where objectives are defined. This approach helps improve management decisions, from data collection, to modeling approaches, to harvest control rules that have the most needed properties. Essentially, any decision point in the science–management process can be evaluated using MSE, such as optimizing between fishery-independent versus fishery-dependent data collection (Cummings et al., 2016). Because of the variety of uncertainties that can be addressed using the MSE technique, NOAA Fisheries has been expanding its capacity in this rapidly growing field by supporting projects and hiring staff dedicated to conducting MSEs.

5.5. Strengths and challenges

NOAA Fisheries is a world leader in the science of stock assessment modeling. With substantial modeling expertise and sophisticated software, the assessment models used by NOAA Fisheries are accurate and efficient and can accommodate a variety of stocks with different types and qualities of data. These models provide the quantitative advice that has supported a successful and sustainable U.S. fisheries management system. However, despite many decades of assessment model evolution, old challenges remain unresolved (Maunder and Piner, 2014), and new issues have come to the forefront.

- **More stock assessments should be linked to ecosystem or socioeconomic drivers.** All stock assessment models are simplifications of nature. They operate on less detailed spatial scales than the scale on which fish interact with fishing operations and their local habitats. The models tend to assume constant or randomly fluctuating rate processes that are rarely linked to specific ecosystem or socioeconomic causal factors. The standard assumption is that average, although variable, processes have been operating for the past decades, and these processes will continue to fluctuate around that same average in the future. However, as climate change and other mechanisms cause ecosystems to shift from recent average conditions, it may not be safe to assume that past conditions reflect the future. In fact, process errors (Section 5.4.1) may occur in some stock assessments when an assessment does not include important ecosystem effects.

  Thus, the scopes of certain stock assessments need to be expanded to incorporate factors other than fishing that influence the status and likely future direction of harvested stocks. Many important processes and dynamics operate within an ecosystem; consequently, there is a variety of approaches to account for ecosystem dynamics within assessments. For instance, assessment models are generally flexible enough to incorporate factors related to climate change, predator–prey dynamics, habitat effects, species distributions and movements, and others in a variety of ways. The primary challenges to expanding assessments are in understanding the relationship between ecosystems and fish stocks and obtaining data that capture these relationships. Through ongoing research efforts and advanced techniques, NOAA Fisheries has made good progress in expanding the scope of certain assessments. As described in Box 5.1, NOAA Fisheries incorporates ecosystem factors into assessments where there is a strong case for doing so and the appropriate data are available.

  Another important detail to consider regarding ecosystem and socioeconomic data and their incorporation in stock assessments is the ability to project those dynamics. Assessment models are used to develop forecasts of stock and fishery dynamics and predict future catches and stock status. These forecasts serve as the basis for developing recommendations regarding sustainable harvest levels. If features of the assessment model are linked to ecosystem or socioeconomic factors, then projections of those factors are needed. Certain ecosystem dynamics can be forecasted with much higher skill than others, and the resolution of the forecasts needs to match that of the assessment forecasts. Thus, in addition to increasing ecosystem data collection and process studies, there is a need to improve forecast skill for important ecosystem dynamics on time and space scales that are relevant to fisheries management. Although Box 5.1 demonstrates progress in this area, there is a definite need for continued advancement, and increased use of additional data and drivers in stock assessments will be contingent on three important factors:

1. Continued research to understand linkages between stock dynamics and ecosystem/socioeconomic drivers
2. Availability of relevant ecosystem/socioeconomic data (see Chapter 9)

3. Priority and capability for implementing expanded stock assessment models and forecasts (see Chapter 9 for a discussion of modeling capability and Chapter 10 for a prioritized approach to determining which assessments should be expanded) .

- **Guidance is needed for appropriately characterizing process errors.**
There is a long history in stock assessments of exploring a variety of model configurations and model types within assessments although, historically, scientific advice has typically been based on the results from one "best" model run. However, scientists and managers are becoming less comfortable with relying on a single model and are increasingly interested in capturing multiple theories about stock and fishery dynamics to form the basis for quantitative advice. Using a range of models offers appropriate treatment of the true process error and uncertainty surrounding the advice, but there are several important considerations in need of research and guidance:

    1. How should results from multiple stock assessment models be communicated and/or combined to provide advice to managers?
    2. What diagnostics and measures of model skill should be used when evaluating a suite of assessment models and selecting one or more model as the basis for management advice?
    3. How should the total uncertainty from a group of assessment models be appropriately characterized and used in the management process?

- **Research is still needed to inform basic stock assessment decisions.**
The current stock assessment process works well in most cases. However, stock assessment models are complex and diverse, so despite decades of development and application, continued work is still needed to address the basic features and assumptions of these models. For instance, there are often requests to use new data sources (or all available data) within assessments. Yet, not all data are necessarily appropriate for assessments because they may not

adequately represent stock dynamics, they may not be in a format that is compatible with a particular assessment model, or they are made available too late in the assessment process to be evaluated sufficiently. Assessment models tend to perform better when there is strong contrast in the data; that is, the observations cover a range of conditions from high to low stock abundance and from high to low levels of fishing. Unfortunately, most sampling programs were not in place throughout the several decades in which fisheries have impacted fish stocks. As a result, the data are more informative about recent trends but not about the absolute condition of the stock relative to historical conditions that predate fishing. Where fish abundance data can be adjusted to provide assessments with measures of absolute abundance, the assessment then contains a strong anchor point regarding total biomass. The availability of absolute abundance is a major step forward in knowledge for stock assessments. Unfortunately, fish are difficult to sample in a fully calibrated way, so most surveys and fishery-dependent indices of abundance reflect relative changes over time but not absolute measures of fish abundance.

Stock assessment teams, review panels, and management groups (e.g., council SSCs) play an important role in determining which data sources should be incorporated into specific assessments. After data are selected and prepared for a particular assessment model there still may be issues to resolve. For example, more than one data set may capture particular aspects of the stock, but conflict in the information being passed to the model. This conflict can inflate uncertainty or create instability with the assessment model and therefore can result in a debate about how to statistically "weight" various data sources. The following list highlights several areas where further research and development are needed to provide objective, standardized, and quantitative approaches to help guide several basic decisions within stock assessments:

1. Selection and processing of a variety of data sources for use in assessments
2. Weighting of data sources within assessments
3. Dealing with conflicting information and correlated or confounded model components

- **Data-limited stock assessment methods do not provide complete information to managers.** With limited information, researchers cannot obtain the same results or certainty available in stock assessments that use more complete data. Unfortunately, filling these gaps by collecting more data is not the only answer, because for many stocks, data collection is technically difficult or cost prohibitive. Data-limited methods give us tools to prioritize stocks into those for which full assessments appear unnecessary, and those for which relevant data needs to be collected to conduct a more complete assessment. Thus, there is a need to manage expectations with data-limited stock assessments (Cummings et al., 2014) and a need to develop strategies for addressing fishery management needs and mandates when data are not available to do so.

Box 5.1. NOAA Fisheries' stock assessments with ecosystem information

NOAA Fisheries conducts stock assessments to produce scientific advice for fishery managers. The main objectives of fishery stock assessments are to evaluate stock status relative to defined limits, and to recommend harvest levels that optimize yield, prevent overfishing, and rebuild depleted stocks as necessary. In most cases, assessments are conducted from a single-species perspective, where ecosystem and environmental factors are not drivers of stock dynamics, but are assumed to either be constant or to contribute to unexplained variation in stock abundance or biology. However, for a number of stocks, ecosystem information has been directly incorporated into assessment models, thereby providing fishery managers with stock-specific advice that accounts for changes in the ecosystem. Some West Coast salmon forecasts are incorporate numerous ocean and ecosystem indicators. Assessments of certain North Pacific groundfish stocks and West Coast small pelagic stocks incorporate water temperature, because this variable affects the number of fish encountered by abundance surveys. The assessment of the butterfish stock in the northeast Atlantic also accounts for habitat effects on availability to abundance surveys. In addition, for Atlantic herring, northern shrimp, and Gulf of Mexico groupers, the numbers of fish that die due to natural causes (i.e., natural mortality) are modeled using ecosystem indices. With herring, an important prey species in the northeast Atlantic, predator dynamics are incorporated into the stock assessment, and for groupers, fishermen and scientists have observed events where large numbers of fish die when substantial red tides occur (i.e., harmful algal blooms). Thus, a red tide index is incorporated in the grouper stock assessments.

The examples highlighted here refer to assessments that incorporated ecosystem data directly as drivers in the actual assessment models. However, ecosystem data can also be effectively considered when preparing assessment input data (or during other steps of the process not summarized here). The number of assessments that incorporate ecosystem data has continued to increase over time. In 2005, 4% of the stock assessments conducted by NOAA Fisheries included ecosystem factors, and by 2015 that number increased to 8%. As research and monitoring of stock and ecosystem dynamics continues to expand, the number of stock assessments and management measures that consider ecosystem variability and change will continue to increase.

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Chapter 6. Quality Assurance in the Stock Assessment Process

Chapter highlights

- **Objective peer reviews of stock assessments are necessary to help determine that the best scientific information available is used as the basis for fisheries management.**
- **Independent regional peer review processes improve the integrity, reliability, and credibility of scientific information used for fishery management.**
- **Stock assessment reviews vary in their extent in accordance with the "terms of reference" that guide a particular assessment peer review.**
- **The review process provides transparency and opportunities for stakeholder input.**
- **There is a trade-off between maintaining high standards for peer reviews and increasing the number of completed assessments.**

6.1.0. National guidance on science quality assurance

National Standard 2 (NS2) of the 2007 MSA specifies that conservation and management measures for federally managed fisheries should be based upon the best scientific information available (BSIA). The NS2 Guidelines were developed to ensure that the BSIA is used when providing advice to fishery management councils (NOAA, 2013; NOAA, 2016). This guidance includes the following criteria for evaluating BSIA: relevance, inclusiveness, objectivity, transparency and openness, timeliness, verification and validation, and peer review as appropriate. Scientific peer review is described as an important criterion in determining the BSIA, and for situations where rigorous, independent peer review is necessary, the NS2 Guidelines adopt many of the Office of Management and Budget (OMB) peer review standards (OMB 2004). These standards include balance in expertise, knowledge, and bias; lack of conflicts of interest; independence from the work being reviewed; and transparency of the peer review process. The NS2 Guidelines recognize that varying degrees of independence may be required for various reviews depending on the novelty, controversy, and complexity of the review. For example, an assessment update may be sufficiently reviewed with only regional expertise, while a review of emerging methods or controversial topics may require a more rigorous, independent peer review process. Deciding on an appropriate scope for the review is linked with how best to balance the need for a high quantity of assessments for timely management decisions with the need for rigorous peer reviews when necessary.

The NS2 Guidelines indicate that regional science centers and their respective councils have the discretion to determine the appropriate form of peer review needed for each stock assessment. The guidelines also clarify the role of the Fishery Management Councils' Science and Statistical Committees (SSCs) in the scientific review process. A peer review process is not a substitute for an SSC, but should work in conjunction with the SSC. The NS2 Guidelines also clarified the contents of the Stock Assessment and Fishery Evaluation (SAFE) report, which can consist of a set of documents that a council uses to make decisions. The overall objectives of the NS2 Guidelines are to ensure the highest level of integrity and strengthen public confidence in the quality, validity, and reliability of scientific information distributed by NOAA Fisheries to support fishery management actions.

6.2.0. Overview of the stock assessment review process for fisheries management

Well-established peer review processes are in place in each region (NOAA, 2016). Each peer review can vary based on the different stages of the review (e.g., review of the data collection, modeling methods, and assessment results); the form of the review; or the degree of thoroughness needed. Throughout these stages, reviews may be conducted internally by regional experts or they may be conducted by independent reviewers as coordinated by the Center for Independent Experts (CIE). Most often, review panels consist of a range of expertise including experts with regional knowledge and independent experts selected through the CIE process. NOAA Fisheries' Office of Science and Technology administers a contract for the CIE process but the deliverables of the CIE are handled independently. The CIE process autonomously selects highly qualified peer reviewers, and this rigorous CIE peer review process is most often used to evaluate benchmark assessments, emerging methods and science, or other potentially controversial topics (e.g., biological opinions or recovery plans). Typically, CIE reviews are conducted in person, but "desktop" reviews are also conducted when time and expenses need to be minimized, and the limitations of a remotely conducted review are acceptable.

The decision to establish a peer review, according to MSA section 302(g)(1)(E), is made jointly by the Secretary of NOAA Fisheries and a regional council (NOAA, 2016; NOAA 2013). Therefore, the scope of the review as defined by the review terms of reference (ToR) is established jointly among the pertinent NOAA Fisheries science center and relevant council(s). Accordingly, councils and science centers are given discretion to determine the form of peer review used for each stock assessment. For example, a science center and the relevant council(s) may determine the form of review needed (e.g., panel or desk review), establish the ToR for the review, and request the combination of expertise required, and whether independent CIE reviewers will participate on the review panel. Each regional peer review process incorporates this partnership among the science center and its respective council(s), and each process complies with the NS2 Guidelines (NOAA, 2016).

The overall review process and the NS2 guidelines provide sufficient flexibility for the science centers and their respective councils to determine when a peer review is needed, the form of review, and the degree of rigor needed in the peer review. However, these decisions must also consider the need to maintain a relatively high rate of completion of stock assessments to support timely management decisions. To meet this need, rigorous peer reviews should be reserved for products such as benchmark assessments, emerging methods, or potentially controversial topics (e.g., biological opinions and recovery plans). For these products, review panels are often balanced with both regional and independent perspectives in the review process, and stock assessments are often subject to a series of reviews involving NOAA Fisheries, SSCs, and external CIE review before the scientific information (e.g., SAFE report and peer review reports) is sent to the council's SSC advisory panel for its evaluation and recommendations. Other reviews, such as routine update assessments, do not require a high degree of independence, allowing for a more streamlined review process by regional experts and the council's SSC. NS2 Guidelines provide clarification that participation by the SSC in the peer review process is acceptable as long as their participation is compliant with the peer review standards and does not interfere with their primary role of providing an evaluation and recommendations to their council.

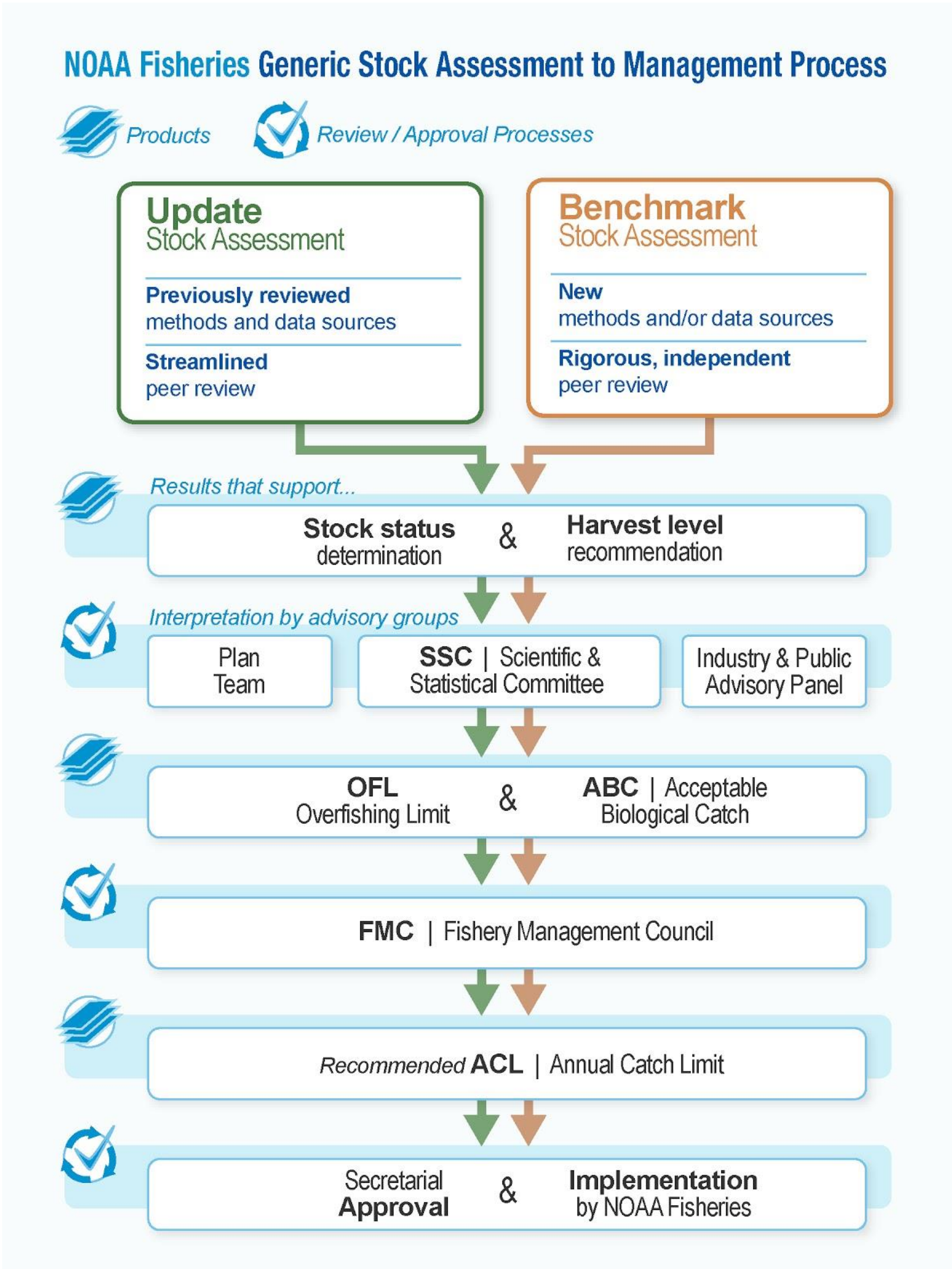

Figure 6.1. Generic overview of the process from a draft stock assessment to management decisions, including independent review, advisory bodies, council decisions, and final approval by NOAA Fisheries. While fishery management councils are responsible for recommending annual catch limits, NOAA Fisheries determines stock status for federally managed stocks and this action occurs in parallel to the

process depicted in this figure. (Note: This figure does not provide a detailed representation of each regional process.)

Overall, NOAA Fisheries' stock assessments are subject to appropriate levels of peer review before they are used as a basis for fishery management decisions. Figure 6.1 provides a generic representation of the process by which a stock assessment supports fishery management and is used to develop and implement catch limits. The details of the actual regional peer review processes vary across regions and do not strictly adhere to Figure 6.1. For federally managed (and certain interstate commission-managed stocks), the regional review processes are managed under regional entities, such as Southeast Data Assessment and Review (SEDAR), the Stock Assessment Workshop/Stock Assessment Review Committee (SAW/SARC), Stock Assessment Review (STAR), the Western Pacific Stock Assessment Review (WPSAR), and the North Pacific Plan Team stock assessment review process. Fishery Management Councils, in partnership with the science centers, use these regional processes in combination with their internal reviews and the independent CIE reviews. In all cases, review meetings are announced publicly and open to the public.

6.3. Regional stock assessment review processes

Each current regional review process is described briefly in the following sections and compared in Table 6.1. Although these processes encompass many federally managed stocks, NOAA Fisheries participates in a variety of other stock assessment review processes, particularly for stocks managed under transboundary and international agreements (i.e., authorities other than the MSA). Because these processes are quite diverse, and typically established through international partnerships, this section focuses on the review processes specific to federally managed stocks.

6.3.1. Southeast Data, Assessment, and Review (SEDAR)

The SEDAR process was jointly established in 2002 by the NOAA Fisheries' Southeast Fisheries Center (SEFSC) and Southeast Regional Office (SERO), Southeast Atlantic Fishery Management Council (SAFMC), Gulf of Mexico Fishery Management Council (GMFMC), and Caribbean Fishery Management Council (CFMC). The SEDAR process has improved the quality and transparency of fishery stock assessments in the Atlantic, Gulf of Mexico, and U.S. Caribbean regions. The SEDAR process also works in partnership with the Atlantic and Gulf States Marine Fisheries Commissions. The SEDAR Steering Committee, which consists of members from the SEFSC, councils, and Atlantic and Gulf States Marine Fisheries Commissions, determines the stocks that will be assessed and reviewed in a given year. Many stocks are assessed on a 3- to 5-year cycle, although higher priority stocks may be assessed more frequently. The SEDAR Steering Committee also determines the scope for each stock assessment (such as standard, benchmark, and update assessment). Stock assessment ToR are developed and reviewed by SSCs and SEFSC analytical staff prior to finalization, ensuring the ToR are appropriate for the species assessed.

The SEDAR process is organized around a series of workshops. In data workshops, datasets are documented, analyzed, and reviewed, and data for conducting assessment analyses are compiled. In assessment workshops, quantitative population analyses are developed and refined and stock assessment parameters are estimated. Finally, in review workshops, a panel of independent experts reviews the data and assessment analyses and recommends the most appropriate values of critical population and management quantities. The review workshops typically include a panel composed of CIE reviewers as well as council SSC appointees. The process takes approximately 6 to 9 months for a benchmark assessment and 3 to 5 months for an update. Current staffing levels at the SEFSC allow a total of five to seven SEDAR benchmark assessments per year in across the Gulf of Mexico, Atlantic, and U.S. Caribbean regions. Additional assessments are then possible if they are conducted as updates. All SEDAR workshops are open to the public, and SEDAR emphasizes constituent and stakeholder participation in assessment development, transparency in the assessment process, and a rigorous and independent scientific review of completed stock assessments. The relatively elaborate review process implemented by SEDAR, a high level of transparency at each step, and a typical need for compiling data from a wide variety of sources in the Southeast region creates several bottlenecks that limit the number of assessments produced in the Southeast.

6.3.2. Stock Assessment Workshop/Stock Assessment Review Committee (SAW/SARC)

Beginning in 1985, the SAW/SARC process was jointly established by the NOAA Fisheries' Northeast Fisheries Science Center (NEFSC), Greater Atlantic Regional Fisheries Office (GARFO), New England Fishery Management Council (NEFMC), Mid-Atlantic Fishery Management Council (MAFMC), and Atlantic States Marine Fisheries Commission (ASMFC). The SAW is a formal protocol designed to prepare and review assessments of fish and invertebrate stocks in the offshore U.S. waters of the northwest Atlantic, and facilitates federally led stock assessments for the New England and Mid-Atlantic Fishery Management Councils as well as state-led assessments for the Atlantic States Maine Fisheries Commission. Within the SAW, assessments are peer reviewed by an independent panel of stock assessment experts called the Stock Assessment Review Committee (SARC). The SAW/SARC process is overseen by the Northeast Regional Coordinating Council (NRCC), which includes directors and chairs of leading partner organizations. These committee members are responsible for developing a 2-year schedule for stock assessments and helping to develop and approve the stock assessment ToR with the councils and their SSCs. The SAW/SARC was primarily established for benchmark stock assessments, but other efforts such as update assessments, operational assessments, and data-limited evaluations are also facilitated.

The SAW/SARC process includes a series of meetings that are fully open to the public. There are industry meetings, data meetings, model meetings, and finally peer review meetings where the SARC is asked to determine the adequacy of the assessments in providing a scientific basis for management. The SARC panel may accept or reject an assessment, and each SARC panelist provides a written review approximately 5 weeks after the peer review meeting. The panel also provides an overall written summary of the proceedings. There are approximately two SARC meetings per year and within each, two or three stock assessments are typically reviewed. Additional assessments are conducted on stocks in the northwest Atlantic, but these are reviewed through other processes, such as internally through the council's SSC. Similar to SEDAR, the SAW/SARC process for benchmark assessments is relatively time-intensive and therefore limits the number of assessments produced. However, to improve the number of assessments conducted, the northeast region also produces update or "operational" assessments that rely on the council's SSC to offer a more streamlined review.

6.3.3. Stock Assessment Review (STAR)

The STAR process was established in 1998 to provide peer review of the scientific information (primarily stock assessments) used for management of Pacific groundfish and coastal midwater species. Thus, the STAR process is coordinated by the Pacific Fishery Management Council (PFMC), NOAA Fisheries' Northwest Fisheries Science Center (NWFSC), Southwest Fisheries Science Center (SWFSC), and West Coast Region (WCR). The PFMC oversees the process and involves its standing advisory bodies, particularly their SSC. Together, NOAA Fisheries and the PFMC consult with all interested parties to plan and prepare the ToR and develop a calendar of events with a list of deliverables for final approval by the council. NOAA Fisheries and the council share fiscal and logistical responsibilities and both strive to ensure that there are no conflicts of interest in the STAR process.

STAR panels include a chair appointed from the relevant SSC subcommittee (i.e., groundfish or coastal pelagic species) and three other experienced stock assessment analysts with knowledge of the specific modeling approaches being reviewed. Of these three members, at least one is typically appointed from the CIE and at least one should be familiar with west coast stock assessment practices. For groundfish, an attempt is made to identify one reviewer who can consistently attend all STAR panel meetings in an assessment cycle. Given these constraints, the pool of qualified technical reviewers is limited, and it can be difficult to meet all conditions when staffing STAR panels. Groundfish STAR panel meetings occur every 2 years, whereas reviews of Pacific sardine occur every 3 years and reviews of Pacific mackerel every 4. The resulting "off years" allow time for conducting research and improving stock assessments. Typically, three to five STAR panel meetings for groundfish are held during each assessment cycle ("on year") and one meeting for a coastal pelagic species (either Pacific sardine or Pacific Mackerel). The panels normally meet for 1 week, and the number of assessments reviewed per panel typically does not exceed two, except in extraordinary circumstances when the SSC and NOAA Fisheries agree that it is advisable, feasible, and necessary. For groundfish species, the SSC reviews the STAR panel report and recommends whether an assessment should be further reviewed at the so-called "mop-up" panel meeting, a meeting of the SSC's groundfish subcommittee that occurs after all of the STAR panels, primarily to review rebuilding analyses for overfished stocks. If an assessment is found unacceptable for use in managing coastal pelagic species, a full assessment would be conducted the following year. The entire STAR process is fully transparent, and all documents and meetings are open to the public with opportunity for public comment.

6.3.4. Western Pacific Stock Assessment Review (WPSAR)

The WPSAR process was established in 2010 to improve the quality and reliability of stock assessments for fishery resources in the Pacific Islands region. This region encompasses a range of fisheries and ecosystems, including the American Samoa Archipelago, Hawaii Archipelago, Mariana Archipelago, Pacific Remote Island Areas, and Pacific pelagic stocks. The Western Pacific Regional Fishery Management Council (WPRFMC), Pacific Islands Fisheries Science Center (PIFSC), and Pacific Islands Regional Office (PIRO) share responsibilities in implementing the WPSAR process. The WPRFMC, PIFSC, and PIRO provide a coordinator to work together to oversee and facilitate the review process, with direction from the WPSAR Steering Committee that consists of the directors (or their designees) of the science center, regional office, and council. The three coordinators work under the direction of the Steering Committee to plan and organize reviews, prepare ToR, and develop a schedule according to a multi-year planning cycle. Fiscal and logistical responsibilities are shared among the science center, regional office, and the council.

The WPSAR framework has been modified over time and currently uses two different approaches for the review and acceptance of stock assessment research products in the Pacific Islands region. For benchmark reviews, new stock assessment methods not previously used for management consideration and any major changes to a previous assessment (beyond inclusion of additional years of data) will undergo a panel review, most likely in person. This panel will have a chair who will also be a member of the council's SSC, and all other panel members will be external independent experts who will provide a review. For update reviews, where assessments have changed only by the addition of recent years of data, one to three experts will provide a review, most likely by desktop. These experts may consist of all PIFSC or SSC personnel. For any review, the WPSAR Steering Committee can decide to use CIE as the review mechanism. Any in-person reviews are open to the public to encourage constituent/stakeholder participation and ensure rigorous, transparent, and independent scientific review of completed assessments.

6.3.5. North Pacific Plan Team Stock Assessment Review Process

A variety of stocks fall under the jurisdiction of the North Pacific Fishery Management Council (NPFMC), including groundfish and invertebrates in the Gulf of Alaska (GOA), Bering Sea (BS), and the Aleutian Islands (AI). NOAA Fisheries' Alaska Fisheries Science Center (AFSC) is responsible for stock assessments for 22 species or species groups under the groundfish fishery management plan (FMP) for the Gulf of Alaska (GOA) and approximately 26 species or species groups under the Bering Sea/Aleutian Islands BS/AI Groundfish FMP. The Alaska Department of Fish and Game (ADF&G) is responsible for one stock assessment in the GOA groundfish FMP. The AFSC and ADF&G share assessment responsibilities for the 10 species in the BS/AI King and Tanner Crab FMP, and the ADF&G has responsibility for assessing scallops. The NPFMC, AFSC, Alaska Regional Office (AKRO), and the ADF&G collaborate on the preparation and conduct of the review of North Pacific stock assessments. The stock assessments and reviews are guided by generic ToR[19] rather than ToR specific to particular stocks. The review process in this region includes partnerships with federal and state agencies and academic institutions who participate in the stock assessment review and advisory process, such as the Council's Plan Teams, SSC, and Advisory Panel. Separate teams are appointed for the BSAI and GOA, comprising 12 members each. The teams meet twice a year (3 ½ days in September and 5 days in November). They meet jointly for 1½ days on issues of common interest, including information related to ecosystems, economics, management, research priorities, and so on. The teams meet separately to review survey data reports and stock assessments. Their recommendations on the stock assessments, overfishing limits (OFLs), and acceptable biological catch (ABC) levels are reviewed by the Council's SSC.

The review process has evolved over the past 2 ½ decades to become more streamlined than most regional processes. Essentially, all stocks managed by the NPFMC are evaluated and reviewed according to the frequency of the scientific survey upon which the assessment is based. The groundfish trawl survey in the Eastern Bering Sea (EBS) is conducted annually; therefore, most EBS stocks are assessed each year. Groundfish trawl surveys in the Gulf of Alaska (GOA) and Aleutian Islands (AI) alternate years (surveys in the GOA conducted during odd numbered years, and surveys in the AI during even numbered years). Despite this general schedule, certain stocks (e.g., walleye pollock, Pacific cod, and Atka mackerel) are assessed annually to prevent these groundfish fisheries from causing jeopardy of extinction of Stellar sea lions or adverse modification of their critical habitat. A combined GOA/EBS/AI assessment of sablefish occurs each year, timed with the annual frequency of the sablefish longline survey in the GOA, and alternating surveys for EBS and AI in odd and even years, respectively..

Typically, update assessments (termed "full assessments") are conducted for developing harvest advice for the following 2 years. The 2-year cycle allows for the use of the most recent biological information in the stock assessment while eliminating potential delays or gaps in setting the second year's limits. In the off years, partial update assessments ("executive summaries") are performed to reevaluate the scientific advice without conducting a full assessment. The stock assessment updates are compiled in a Stock Assessment and Fishery Evaluation (SAFE) report. After review and revision, the draft SAFE reports are released by the science center for pre-dissemination to the council's Plan Teams for review. Plan Teams review the SAFE reports and make recommendations to the SSC. The SSC then reviews the SAFE reports as well as the Plan Team recommendations and provides the NPFMC with an ABC and OFL recommendation for each stock. The council provides public notice of the meetings of its Plan Teams and SSC and when SAFE reviews are being conducted; procedures are in place to allow for public comment at these meetings. Although routine updates are necessary for a streamlined annual assessment and review cycle, recommendations for improving assessments are made and reviewed by the SSC during the year to allow for improvements without requiring a more comprehensive review process. However, in addition to the normal schedule of assessment updates and reviews, a separate

[19] http://www.npfmc.org/wp-content/PDFdocuments/membership/PlanTeam/Groundfish/GPT_TOR.pdf

review schedule is maintained, with the goal of obtaining an independent CIE review of each stock assessment about once every 5 years. These more involved reviews are scheduled so that they do not affect the relatively efficient annual cycle.

Table 6.1. Comparison of regional stock assessment and peer review processes used in the management of U.S. fisheries.

	Peer review process				
	SEDAR	SAW/SARC	STAR	WPSAR	North Pacific Plan Teams
Year initiated	2002	1985	1998	2010	1989
Region(s) covered	Southeast coast, Gulf of Mexico, Caribbean	Northeast coast	West coast	Pacific Islands	Gulf of Alaska, Bering Sea, Aleutian Islands
Council(s) supported	SAFMC, GMFMC, CFMC	NEFMC, MAFMC	PFMC	WPFMC	NPFMC
Other entities supported	ASMFC, GSMFC, HMS Sharks	ASMFC	-	-	-
Science center(s) participating	SEFSC	NEFSC	NWFSC, SWFSC	PIFSC	AFSC
Typical review panel	CIE and SSC	CIE and SSC	SSC, CIE, and other	SSC, PIFSC, CIE, and other	SSC, CIE (roughly every 5 years per stock)

6.4. Quality assurance of stock assessments for partner organizations

The United States has interests in numerous fisheries, not just the federally managed stocks that fall under the MSA. As a result, NOAA Fisheries contributes to assessments of many stocks managed by partner organizations, such as interstate commissions, state agencies, tribal organizations, international regional fishery management organizations (RFMOs), and organizations related to a variety of international treaties and agreements (Figure 3.1). The processes by which these assessments are reviewed are under the discretion of each partner organization. NOAA Fisheries works with these groups to comply with their respective review processes, but the processes are not bound to MSA mandates. In some cases, CIE reviewers are used, and NOAA Fisheries helps to facilitate these reviews. Also, certain partner organizations rely on the regional processes described in Sections 6.3.1 to 6.3.5. For example, the Atlantic States Marine Fisheries Commission uses the SEDAR and SAW/SARC processes for many of its stock assessments.

6.5. Strengths and challenges

NOAA Fisheries, the Fishery Management Councils, and many other partners and stakeholders ensure that high-quality scientific advice (i.e., BSIA) is provided to fishery managers by strictly adhering to MSA mandates and related guidance. The NS2 Guidelines of the MSA, which emphasize the importance of peer review, have helped to build confidence and trust among managers and stakeholders that the BSIA is used in the fishery management process. However, the peer review process presents strengths and challenges that must be considered to meet the increasing demand to provide timely assessments for management decisions. For this reason, more careful prioritization is needed when balancing reviews that require a more rigorous a peer review process (e.g., CIE peer review) and reviews that can be conducted in a more streamlined manner. Further, NOAA Fisheries facilitates and helps to improve stock assessment peer reviews through partnerships with numerous management agencies that are not governed by the MSA. Collectively, a substantial amount of attention is being dedicated toward quality assurance for stock assessments. These efforts have improved the credibility of the fishery management process and increased the quality and transparency of fishery management decisions. For federally managed fisheries, these improvements have contributed to nearly eliminating overfishing, rebuilding many important stocks, and ensuring the long-term sustainability of marine resources and resiliency of fishing communities. However, many challenges and tradeoffs associated with the current assessment review process remain that warrant consideration. The following list briefly describes these issues.

- **Comprehensive peer reviews create a bottleneck that affects the rate at which assessments can be completed.**
  Conducting an exhaustive independent peer review of a stock assessment requires substantial time, effort, and resources and should be used when appropriate. Thus, there is a tradeoff between the level of rigor dedicated to reviews and the number of assessments that can be conducted. The regional processes vary in how they prioritize assessment quantity versus review thoroughness. For example, the NPFMC conducts internal reviews of many assessment updates each year using council committees, whereas SEDAR coordinates fewer reviews that use a comprehensive process, particularly for "benchmark" assessments, that relies on the CIE. The actual review workshop organized by SEDAR lasts only 1 week, and that alone is not a bottleneck in the assessment completion rate. However, the assessment process coordinated by SEDAR for benchmark assessments involves multiple workshops (data, assessment, and review) with public participation and review at each. This multi-step process does limit the number of assessments completed in this region.

  Whether the reviews are comprehensive and independent, internal and smaller scale, or some combination of each, all current approaches comply with MSA mandates. Therefore, it is up to the various regional partners to determine what is most needed for successful fishery management in their region. Generally, comprehensive CIE reviews are not necessary when a stock assessment is not substantially different from an assessment that was previously deemed sufficient for management purposes (for a particular stock). A desktop CIE review is available when there is a need for fully independent peer review and a desire to minimize time and expenses dedicated to the review. However, desktop reviews can be challenging for reviewers to fully understand the scope and context of the review. Further, due to strict conflict of interest regulations and limited availability of independent CIE experts, considerable lead time is required for contracting and arranging travel for CIE reviewers (approximately 80% tend to be foreign nationals). Therefore, more rigorous reviews that require a high degree of independence (i.e., panel review with CIE reviewers) should be used sparingly. For example, these reviews could be reserved for benchmark assessments that are substantially different from a stock's previous assessment, assessments that include new or emerging methods, or for scientific information on potentially controversial issues.

- **Fully independent reviews may not always provide the best evaluation of the science.** NS2 provides guidance on balancing the perspectives of peer reviewers and the varying degree of independence needed for a review. Although the CIE tends to provide the highest degree of independence, there are drawbacks to using a CIE panel in addition to increased cost and time. Reviewers with a higher degree of independence (e.g., CIE reviewers) most often have little to no prior experience with the regional ecosystem or stock being assessed, and in certain instances, this might result in erroneous interpretation of the information under review due to the lack of familiarity with regional issues. Balancing a panel of reviewers with regional expertise may have benefits in this regard. Given variation in familiarity and the limited pool of CIE panelists, there also can be a lack of consistency across reviews. This inconsistency may cause some researchers to feel that the nature of the criticisms and potentially the rejection or acceptance of a particular assessment is driven more by the composition of the review panel than the quality of the science. This perception can create instability in the management process. The STAR process addresses this inconsistency by using a primary reviewer who participates in all its panel reviews during each review cycle (as well as reviewers with regional expertise such as SSC members).

- **There is a need for consistent documentation and transparent results in the peer review process.** Although the stock assessment peer review process offers a high degree of transparency and provides ample opportunity for stakeholder engagement, further improvements in the consistency and transparency can be made regarding the information used in the peer review process (e.g., SAFE reports) and the peer review results. All meetings are open to the public, and relevant documents, including assessment and reviewer reports, are generally provided and made available on publicly accessible websites. The CIE peer review reports are also made publicly available. However, there are instances where it is unclear in the final stock assessment report just how the peer review influenced the final product and improved the overall management advice. Because there is not a standard format across regions for reporting the conclusions of the review panel—and what, if any, adjustments or additional analyses were performed to address reviewer comments—this information can be difficult to locate or inconsistently reported. When stakeholders cannot find this information, they may perceive the process as less transparent than intended.

- **Well-defined ToR are critical for successful stock assessment reviews.**
  Establishing well-defined ToR can provide an appropriate scope for the review, define appropriate levels of expertise and independence for reviewers, ensure that reviewers focus on the key elements of the assessment, and describe how to document and respond to reviewer comments. Thus, the ToR for each regional peer review process and CIE review are established before the peer review is conducted (NOAA, 2016). To maintain successful peer review processes, improvements may be needed to ensure that future reviews are conducted appropriately and are most beneficial to the fishery management process. For this reason, it is beneficial for the science centers and their respective councils to jointly establish the ToR. In certain instances, reviewers have focused on aspects of the assessment that are less critical to ensuring high-quality advice. For example, reviewers may be tempted to focus on reviewing previously established methods, or previously reviewed data sets, rather than the way in which assessment methods were applied given the available data. Also, in some cases the number of additional analyses that can be requested by reviewers is unlimited. Issues such as these can result in a burdensome review process that may not improve the resulting scientific advice. The success of the review also depends on the chair who serves in the impartial facilitation of a panel review based on the ToR.

- **Externally provided stock assessments must be subject to the regional peer review process.**
  On occasion, entities other than NOAA Fisheries conduct assessments of federally managed stocks. These assessments may be well integrated into the management process or outside normal procedures. Typically, external assessments are commissioned by a stakeholder either to fill a data gap that is not being addressed or to provide an alternative perspective in an ongoing assessment. External assessments can be helpful when they provide advice for stocks that cannot be assessed in a timely fashion, thereby assisting with the assessment workload, or when they contribute additional analyses for consideration in an ongoing assessment. However, external assessments can also be disruptive, especially when they are provided late in the management process or without sufficient documentation to critically evaluate the approach. In these cases, the assessment tends to compete or conflict with the federal stock assessment without being subject to an equivalent level of peer review. Establishing well-defined ToR for peer review of externally provided stock assessments, as described earlier, helps to mitigate

some potential concerns. Unless the alternative analyses are contributed early in the assessment process and included in the peer review, these analyses should not have a strong influence on management decisions. As the contribution of external assessments continues to increase, many councils have developed or are developing protocols for including these assessments in the management process.

Although current approaches to stock assessment quality assurance address MSA mandates and result in high-quality scientific advice being provided to managers, there is room for improvement as discussed earlier, and recommendations for addressing these issues are provided in Section III. In particular, Chapter 10 describes a stock assessment process that strives to be timely and efficient while also maintaining thoroughness and transparency. These improvements rely on an objective approach to stock assessment prioritization that will optimize the completion rates of assessments by determining which stocks need assessments and the level at which those assessments should be conducted.

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Chapter 7—An Introduction to the Future of NOAA Fisheries' Stock Assessments

Chapter highlights:

- **Three primary objectives make up NOAA Fisheries' next generation stock assessment (NGSA) enterprise:**
    1. **Expand the scope of many stock assessments and support harvest policies that are more holistic and ecosystem-linked following a strategic approach that makes best use of available resources.**
    2. **Use innovative science and technological advancements to improve assessments and establish robust harvest policies to manage stocks between assessments.**
    3. **Create a more timely, efficient, and effective stock assessment process that prioritizes stock-specific goals and objectives.**

7.1. Summary of challenges and the need for improvement

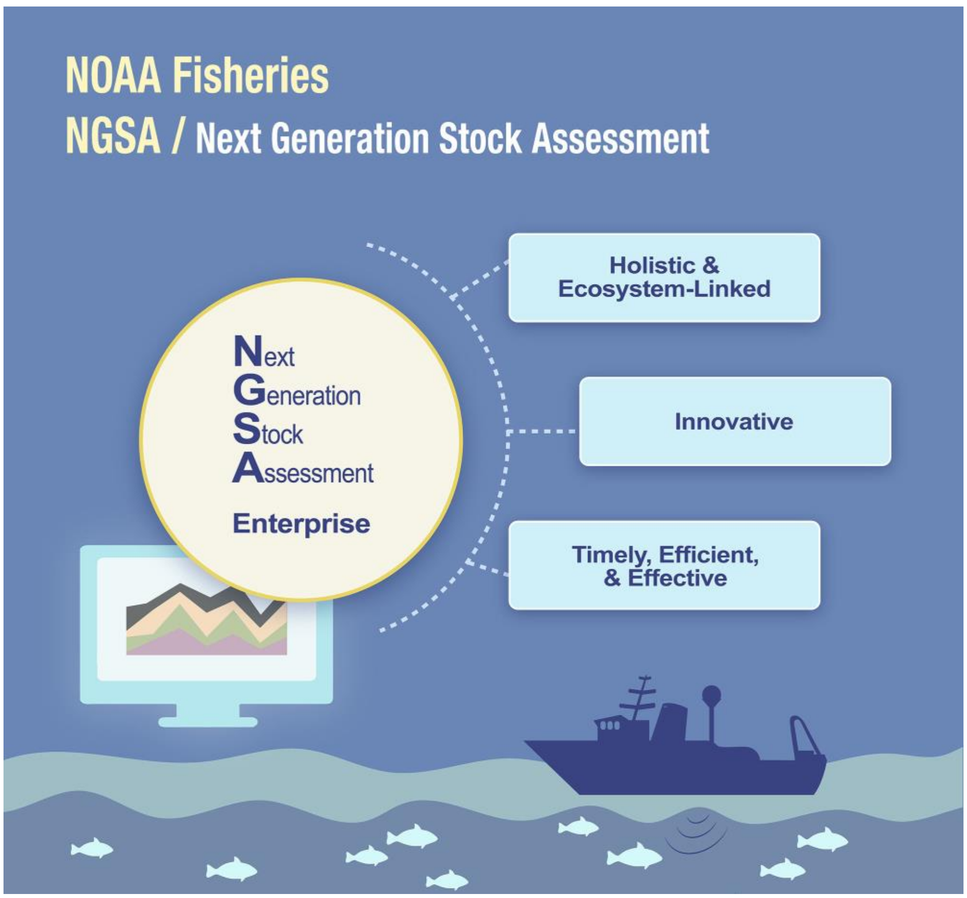
NOAA Fisheries' stock assessment enterprise faces numerous demands from federal operations, fishery managers, and interested parties. There are conflicting requests to make stock assessments simpler, more comprehensive, based on better data, ecosystem-linked, more transparent to affected parties, prioritized, updated using the latest data and model advancements, quicker to produce, and other demands. Many aspects of these demands are difficult to satisfy and some are mutually exclusive, as described in the following examples:

- Assessments could be simpler if they had access to reliable, basic data streams regarding the abundance of fish stocks. Much of the complexity of assessments is due to the advanced statistical efforts used to overcome various shortcomings in the data.
- Assessments could be updated more quickly if they used standardized, streamlined data systems and standard modeling methods. Improvements to assessment data and models could then be made by conducting research outside the normal management process, rather than attempting to develop new operational methods during a constrained management process.
- Assessments could be more comprehensive given that data and procedures to build in broader system-level mechanisms are available. Most assessments incorporate environmental and ecosystem changes indirectly and without including the actual mechanism driving the changes; hence, they have very little ability to project changes in future stock conditions that may occur as a result of future environmental and ecosystem changes.
- The effort to include all possible data in an assessment expands the assessment's complexity, obscures transparency, and reduces efficiency in the process because all data in an assessment require proper documentation, analysis, and review. Thus, this reduced efficiency is compounded by the preference for full transparency and comprehensive public review.

The NGSA framework is designed as a roadmap to address and balance the various demands on the stock assessment enterprise. There are three main themes to this framework (Figure 7.1):

a. Expanding the scope of stock assessments to be more holistic and ecosystem-linked (Chapter 8)
b. Using innovative science and advanced technologies to improve data and analytical methods (Chapter 9)
c. Establishing a timely, efficient, and effective stock assessment process (Chapter 10)

Figure 7.1. The three primary objectives that comprise NOAA Fisheries' NGSA.



7.2. Holistic and ecosystem-linked stock assessments

Today, fishery assessments are mainly designed to analyze a dynamic system in which fishing is the dominant force and ecosystem factors produce random changes that can be dealt with statistically. This approach has successfully guided fishery management toward preventing overfishing and rebuilding depleted fish stocks, but it lacks the ability to provide advice that directly accounts for expected changes in ecosystems. When faced with ecosystems that are shifting into previously unobserved states, which is an expected result of climate change, the quasi-equilibrium paradigm of contemporary stock assessments is ill-prepared to deal with shifts in stock productivity. Also, the single-species approach fails to account for the cumulative effects of fishing on multiple stocks in a regional ecosystem. Further, contemporary assessments do not account for socioeconomic drivers. Although fishery managers certainly address socioeconomic considerations when setting catch limits, this information may also be useful in configuring the sub-models of fishery dynamics within assessments.

Assessments can provide more accurate and comprehensive advice if they expand their scope. However, it is important to consider potential tradeoffs between expanding the scope of an assessment and the degree of uncertainty around assessment results. These expansions should be thoroughly vetted by conducting thoughtful research that facilitates the development and evaluation of expanded methods. There is a consequence to expanding assessments within the operational assessment process, because additional data sets can mean additional uncertainty that affects the final assessment results. Moreover, an expanded assessment scope may require increased resources to maintain the additional data inputs. Nevertheless, expansions should be routinely considered, and a prioritized approach should be used to determine which stock assessments should expand in scope and how expansive those assessments should be. Stock assessments should not necessarily expand to be as inclusive as Integrated Ecosystem Assessments,[20] which address all ocean uses in an ecosystem and take a much broader look at multiple forcing factors on an ecosystem and at multiple services provided by that ecosystem. However, stock assessments do serve a function within ecosystem-based fishery management (EBFM) by taking an ecosystem approach to fishery management to the extent feasible. For instance, assessments can incorporate ecosystem drivers of dynamic processes in the assessment model. Also, stock assessments provide important information regarding changes in major ecosystem components and processes, so these products are useful in the development of system-level advice. Chapter 8 provides a broader discussion and clearer pathway to achieving more holistic and ecosystem-linked stock assessments.

7.3. Innovative science

In general, stock assessments need to produce results with higher accuracy and precision. One way to achieve this goal is to strive for more highly calibrated data; that is, to "fine tune" a data series so it better represents true dynamics. This fine-tuning can be achieved through data calibration experiments, where more complete evaluations of certain assessment inputs are conducted so that the full data series of those inputs can then be adjusted to better reflect true dynamics over time. This approach may substantially improve assessments, such as those conducted with relatively simple assessment models that incorporate only the total catch history over time, and one or more time series of an indicator of stock abundance (see Table 5.1—Aggregate biomass dynamics models). These models are effective only if input data accurately capture stock and fishery dynamics, and when there is contrast in the data (i.e., high and low levels of fishing and abundance over time). In many cases, stock abundance indicators do not perfectly represent stock dynamics, especially when they are based on fishery catch rates, which are

[20] http://www.noaa.gov/iea/

particularly difficult to calibrate over time. Even the absolute knowledge of total catch is challenged as catch histories are being revisited using new approaches (recreational catches in particular), and as there is increased awareness of illegal, unreported, and unregulated (IUU) fishing. Contrast in the data is needed to understand how stocks respond to fishing and how they rebuild from low biomass levels. However, today's successful fishery management achieves stability, so relatively little contrast is being realized in recent time periods.

Advanced assessment models (e.g., statistical catch-at-age, see Table 5.1) provide a more complete description of the effects of fishing on a fish stock, but there are even more concerns about data calibration in addition to those associated with simpler methods. Advanced assessments incorporate information on individual growth and the sizes and ages represented in the catch to: 1) ascribe the catch to the actual age ranges of fish that are affected by the fisheries; 2) account for year-to-year fluctuations in body growth and the number of young fish entering the stock (i.e., recruitment); and 3) provide direct evidence of the level of total mortality as represented by the rate of decline in the numbers of older fish. With additional types of data, the assessment model contains more moving parts that interact and need simultaneous adjustment (e.g., accurate age, length, maturity, and other biological data is important). Further, these models also depend on external knowledge of the level of natural mortality and the possibility that older fish are not as available to fisheries and surveys. Finally, whether simple or advanced, all models are challenged by major shifts and high year-to-year fluctuations in fish productivity.

Given these challenges to the performance of modern assessment models, there is a clear need for more direct calibration of assessment data and more research to better understand and describe fish stock dynamics and the processes that drive those dynamics.

Chapter 9 describes new scientific and technological developments that may help advance stock assessments. In particular, there is a focus on achieving a higher calibration of stock abundance data, an expansion of the data collection and data delivery systems, and utilization of new statistical and mathematical modeling techniques. Collective investments in these promising areas could result in measurable improvements in the scientific advice being provided to fishery managers.

7.4.0 Timely, efficient, and effective stock assessment processes

To meet many of the increasing demands on NOAA Fisheries' stock assessment programs, there is a need to improve efficiency in the stock assessment process. Although increased efficiency would result in more timely advice, it is important that each assessment maintain an appropriate level of detail, transparency, and review. Each stock assessment should be conducted at a prescribed frequency and level (data and model richness) in a way that reduces as much as possible the time from data collection to management adjustment and is sufficiently transparent so that stakeholders have a high level of trust in the assessment results.

A data-rich assessment that is timely and transparent and occurs for as many stocks as needed is a substantial challenge. Fortunately, there are potential process-oriented changes that can help guide

NOAA Fisheries' stock assessment programs to best meet the demands associated with each stock. In particular, NOAA can improve the tracking of the types of data being used in each assessment; can use and expand the national stock assessment prioritization process to set goals for each stock; and can evaluate current assessment levels relative to target assessment levels to help identify stock assessment gaps and meet realistic expectations for each stock. Further, the process of conducting a stock assessment can be more streamlined. However, this approach should follow a simplified operational assessment track that relies on standard, reviewed, tested, and documented approaches to to generate scientific advice for fishery managers. Improvements to assessment data and methods can then be considered via a parallel research track that allows time for developing, testing, and reviewing new approaches before they are applied in a management setting. The level of review along the operational assessment track can be streamlined, allowing improvements to be fully vetted in the research track. Finally, standardized and streamlined reporting templates can be used to improve transparency in assessment results while reducing the time required to communicate those results. Chapter 10 describes proposed changes to the way stock assessments are tracked, conducted, and prioritized to improve the timeliness, efficiency, and effectiveness of stock assessments.

Chapter 8—Holistic and Ecosystem-Linked Stock Assessments

Chapter highlights:

- **The stock assessment approach should routinely consider ecosystem and socioeconomic drivers, and these drivers should be addressed as appropriate with a goal of improved understanding of stock dynamics and improved management advice.**
- **Stock assessment terms of reference (ToR), particularly those for research assessments that intend to improve an assessment, should formally consider ecosystem and socioeconomic information.**
- **Stock assessments should include multidisciplinary teams and coordinated access to ecosystem and socioeconomic reports and research.**
- **A general decision process is provided to guide the consideration of ecosystem and socioeconomic information in the stock assessment and fishery management process.**
- **There is a need for advancing the decision process and developing comprehensive criteria for determining the extent of qualitative and quantitative inclusion of ecosystem and socioeconomic linkages into the stock assessment and management processes.**

8.1 Introduction

Fishery scientists, managers, and stakeholders increasingly want to expand the scope of stock assessments to be informed by ecosystem drivers as well as the social and economic dynamics affecting fisheries. Stock assessments tend to account for these factors by either assuming that their effects occur at some constant average level over time, or to allow random variation in stock dynamics that is not directly guided by specific ecosystem or socioeconomic mechanisms. In many cases, these approaches are sufficient for achieving fishery management objectives; thus, it is not necessary to expand the scope of all stock assessments. However, there are stocks for which ecosystem and/or socioeconomic information may significantly improve the accuracy and precision of assessment results. For these priority stocks, expansion of the assessments should be supported by research as well as observations (e.g., ecosystem or socioeconomic data) available at scales appropriate for including in a stock assessment model. In most cases, substantial resources are required to conduct the research and data collection necessary to expand an assessment. Therefore, it is important that this work initially be directed to address the highest priority cases, while simpler approaches to dealing with ecosystem and socioeconomic factors can be explored for lower priority stocks.

There is no reason to "force" ecosystem or socioeconomic drivers into stock assessments when there is not clear evidence to support their inclusion. In fact, identifying drivers in such complex systems is very challenging. The purpose of these expansions is to improve the assessment and account for the major factors that drive productivity, but if there is not strong evidence for the expansion, the accuracy and precision of the assessment results may actually decrease. Regardless of whether ecosystem or socioeconomic information is included in the assessment, there are many options available to account for these additional drivers in fisheries management. In fact, evaluating ecosystem-level tradeoffs is a core feature of ecosystem-based fisheries management (EBFM).[21] This evaluation may best be accomplished through system-level simulation studies, such as management strategy evaluations (MSEs), and not stock assessments. However, system-level MSEs rely upon stock assessment results, so improved stock assessments remain fundamental to improving fisheries management. This chapter, with chapter 10, provides the context and vision for expanding the scope of more stock assessments to be linked to ecosystem and socioeconomic factors. Examples of stock assessments that incorporate ecosystem linkages are presented to demonstrate how understanding and advice are improved.

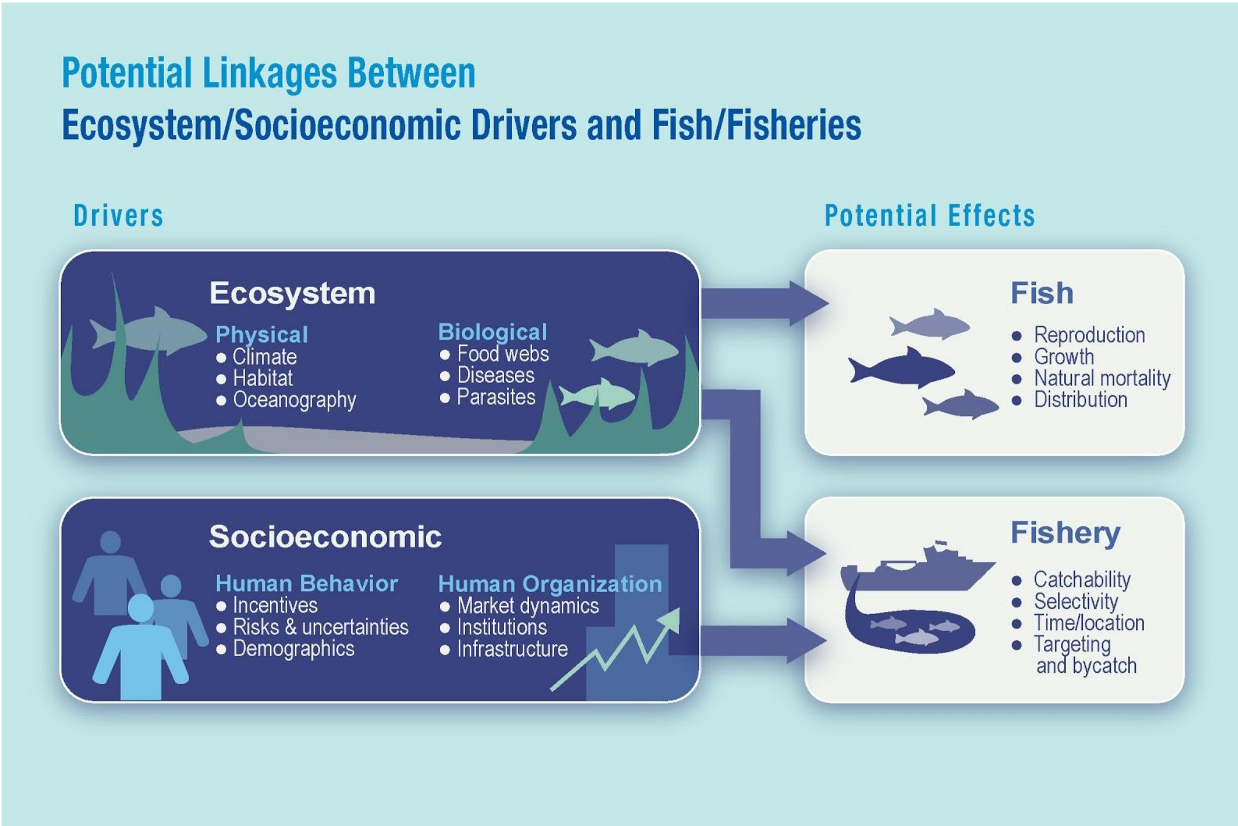
8.2 Why stock assessments should be expanded

The fishery stock assessment process uses biological reference points to support stock status determinations and the application of harvest control rules to support the development of short-term catch recommendations. In most cases, stock assessments use an historical analysis to determine biological reference points and then project models based on historical data to determine future catches. With climate change and other processes affecting marine ecosystems, a primary challenge facing stock assessment science is how to establish biological reference points and apply harvest control rules in complex environments that are experiencing constant change. In some cases, long-term sustainability may be fully understood and achieved by directly incorporating ecosystem and socioeconomic considerations into the process of determining stock status and developing catch recommendations. In other cases, it may be sufficient to ensure that robust control rules are in place and that they are adaptable to variations, such as those caused by climate change and ecosystem variability.

There are many features of an ecosystem and many socioeconomic factors that can affect both fish stock productivity and fishery dynamics (Figure 8.1). For example, predation mortality alone can considerably alter the status of a stock (Tyrrell et al., 2011), and changing thermal conditions impact the distribution, growth, recruitment, and productivity of numerous stocks (Keyl and Wolff, 2008). In some cases, these factors can be the dominant drivers of stock dynamics, especially as fishery management has reduced fishing pressure to sustainable levels. Yet those considerations are not often included in stock assessment models, assumed to be encapsulated in typical assessment model parameters, or included as random variation. Thus, in many instances, better incorporating these ecosystem linkages into the stock assessment process is warranted. Although assessment analysts are open and willing to include additional factors into the assessments, there can be hesitation when relationships with stock or fishery dynamics is not well understood, when data are not readily available in appropriate formats, or when it is unclear how best to include the information in an assessment model. These challenges emphasize the need for investing in research to support more holistic stock assessments.

Figure 8.1. Ecosystem and socioeconomic processes affecting fish and fisheries.

[21] http://www.nmfs.noaa.gov/op/pds/index.html



Part of the stock assessment process involves the use of diagnostic tools to evaluate how well a stock assessment model is configured. When assessment models exhibit poor diagnostics, one or more factors may be the cause. For example, an assumption about the population dynamics may be incorrect, a key factor may be missing from the model, or there may be unaddressed problems with the input data. If unresolved, poor diagnostics indicate that the model is not performing appropriately, and therefore the quality of the resulting scientific advice is questionable. Although models with questionable skill can still be used in a management context, the scientific uncertainty in the results should be characterized in a way that accounts for the poor model skill. Further, poor model diagnostics warrant a full investigation into the cause. In some cases, a simple fix within the assessment process can improve model diagnostics; in other cases, research studies are necessary to improve models outside the operational process (see Chapter 10 for more on research and operational assessment tracks). Regardless of the time and resources required for investigation, often poor model diagnostics are due to an assumption that some process is constant over time when in actuality the process changes appreciably. Thus, one common area that may improve model diagnostics is to more broadly explore ecosystem linkages in stock assessments models. However, because stock assessments are a simplification of very complex dynamics, the challenge lies in determining an appropriate level of linking assessments to the ecosystem without making the model too complex for the current goal.

8.3 When to expand stock assessments

Adding ecosystem or socioeconomic linkages to stock assessment models is not necessary in all cases. Doing so may not improve model diagnostics, may not provide a better representation of stock or ecosystem dynamics, and may not improve the management advice resulting from the modeling process (e.g., Punt et al., 2013). Yet a systematic, structured, decision-criteria approach based on first principles may help identify those situations that generally warrant closer examination of ecosystem or socioeconomic considerations and potential inclusion of such linkages in the stock assessment process.

Ideally, the decision to expand a stock assessment should be supported by thorough research into the drivers affecting a stock's dynamics combined with a full investigation (e.g., management strategy evaluation) of the costs and benefits of expanding the assessment. However, resources are not sufficient to support such a methodical approach for all stocks. Thus, a standard, cross-cutting triage exercise is needed to support the decision process for all stocks in a region. Conducting such exercises would not only serve to improve single-species assessments, but would also accomplish essential steps in the transition to EBFM. A relatively simple triage approach that integrates with the stock assessment prioritization process is described in Chapter 10. Numerous other methods have been developed (Levin et al., 2009; Link, 2010; Hobday et al., 2011) and examples have been applied in a fisheries context. These approaches are often termed "ecological risk assessment" and they serve to identify the major pressures and threats facing a group of species relative to their individual vulnerabilities to multiple threats. Any number of these methods could be used to inform decisions about the scope of a stock assessment as well as support the prioritization effort described in Chapter 10.

A stock's natural mortality is one component of a stock assessment that is inherently connected to ecosystem drivers. This value is challenging to estimate in stock assessments and is often estimated or assumed by including as a fixed input to an assessment model. Although it is often accepted that natural mortality varies over time and by age, it is common to assign it a constant value because there may not be enough data available to estimate the change, and typically there are not obvious theoretical or mechanistic linkages to ecological processes. In essence, natural mortality in a stock assessment model represents an integration of numerous complex and interacting processes. However, natural mortality of fishes that make up a substantial forage base for predators may be driven by the biomass of the key predator species. These stocks in particular represent good candidates for additional examination and exploration of predation mortality. Focusing on predator dynamics for forage species' natural mortality is an example of a simple triage approach to identify one important ecological process for a subset of stocks while eliminating species that do not experience significant predation mortality. The approach to examining predation mortality for a given stock could vary (see Section 8.5), but knowing that it could be an issue from the triage exercise would help highlight and prioritize the research.

Natural mortality represents one of many aspects to consider when triaging stocks to determine which assessments should be expanded to include ecosystem and/or socioeconomic factors. Figure 8.1 provides an overview of the many factors and effects that should be considered when constructing stock assessments. Although Figure 8.1 is a relatively simple diagram, there are numerous variations of potential interactions between drivers and stock and fishery dynamics. From these triage exercises, development of decision trees and recommended practices would naturally follow to delineate those conditions when ecosystem and/or socioeconomic linkages are high priority and which factors should be considered. Using criteria related to data availability, model diagnostics, model skill, model structure, known or hypothesized mechanisms, key processes and dynamics, key model parameterizations, and risk minimization would all be formulated to suggest particular approaches that could be used in the stock assessment process. For instance, decisions on creating ecosystem linkages in stock assessments are made in the context of several considerations:

1. Based on the stock's value, status, and biology, is there an incentive to expand its assessment to include ecosystem or socioeconomic factors?
2. Is there evidence to suggest that stock or fishery dynamics are tightly coupled with some variable ecosystem or socioeconomic feature?
3. Are data available to model this relationship within the assessment framework?
4. Can ecosystem or socioeconomic dynamics be incorporated in a way that maintains a manageable assessment model?
5. Can the relationship between stock, fishery, and ecosystem or socioeconomic dynamics be forecasted with at least a moderate degree of certainty?

Here, it is recommended that the stock assessment process include two steps:

1. Use Figure 8.1 as a framework for conducting a simple qualitative evaluation of potential ecosystem or socioeconomic linkages.
2. Evaluate the results of the target setting process described in Chapter 10 in combination with the previous considerations list to determine whether it is technically feasible, and worth the effort, to expand a particular assessment.

This systematic approach does not likely fit well into the operational stock assessment cycle, but should be developed in a parallel research assessment track (see Chapter 10) that is designed to improve operational assessments. Simply, research assessments should be guided by relatively generic, nationally consistent, standing terms of reference that include attention to ecosystem and socioeconomic considerations. The decision to expand assessments should not be based solely on the detection of correlations between factors, but rather through thoughtful consideration at each step and connection outlined earlier. Even if it is not deemed appropriate to expand an assessment to include ecosystem or socioeconomic linkages, the process of evaluating stock and fishery dynamics from a broader system-level perspective is generally beneficial. These evaluations should be well-coordinated with the implementation of EBFM. In particular, management councils will be developing more Fishery Ecosystem Plans (FEPs) and this process may provide a good opportunity to assemble an interdisciplinary group that evaluates various ecosystem processes and their effects on fish and fisheries. Thus, the FEP development process could provide direct guidance for research assessments.

8.4 How to expand stock assessments

The manner in which ecosystem and socioeconomic considerations can be included into the stock assessment process is broad and varied. This information can be used to provide context for interpreting stock assessment results and evaluating system-level effects of harvest recommendations; for diagnosing issues with stock assessment models; for forming hypotheses of how stock assessments could be improved; as leading indicators of potential change to prioritize assessment research and activities; or for adjusting or scaling the harvest advice that derives from a stock assessment. Finally, the information can be directly incorporated into stock assessment models as covariates and/or as new model components that describe ecosystem or socioeconomic mechanisms. Table 8.1 expands upon the processes described in Figure 8.1 to provide additional details on how stock assessments can include ecosystem or socioeconomic information. Thus, there are several ways in which additional information can be included in the stock assessment process, but what is appropriate for any given stock, ecosystem, or management plan dependents on several factors.

At one end of this spectrum are purely qualitative approaches. These include the strategic use of additional documents and information, including ecosystem status reports, ecosystem considerations already in stock assessments, socioeconomic reports, and relevant research products. This supplementary information can help shape management advice, such as guide the establishment of harvest rates that are responsive to changing conditions rather than assume equilibrium conditions; suggest the current productivity state of the environment, which is useful in guiding approaches to forecasting catch advice; and highlight possible upcoming changes that may warrant a reconsideration of future harvest levels or the frequency and approach by which assessments will be conducted. These qualitative approaches represent simple acknowledgments that changing ecosystems and socioeconomics affect fish and fisheries. They also fit well within current management approaches by helping to communicate uncertainty in stock assessment results and providing guidance on how harvest recommendations may be adjusted to account for this uncertainty.

At the other end of the spectrum are more formalized, quantitative approaches. Quantitative approaches generally seek to link stock assessment models to ecosystem and/or socioeconomic factors. This task can be completed either by directly adjusting selected model parameters or structures, or by providing an index that informs the model's estimation of particular parameters or trends in stock dynamics. The qualitative and quantitative methods are not mutually exclusive, and neither is superior to the other, but rather their appropriateness is situation specific.

It is not necessary to force ecosystem or socioeconomic information into every stock assessment. The important point in this chapter is that the stock assessment process should include a systematic approach to considering how stocks and fisheries are affected by changes related to ecosystems and socioeconomics, and where/how appropriate, those considerations should be included. Chapter 10 describes a simple approach to evaluating, across stocks, assessments that should be expanded to include ecosystem information. Then, Figure 8.1 combined with Table 8.1 and the considerations listed earlier, represent the generic thought process to determine how a stock's assessment could be expanded/improved. This decision process needs to be tested and improved, but the guidance provided here and in Chapter 10 is designed as a starting point.

Table 8.1. Level of ecosystem linkages and how they could inform the stock assessment process. 1 = context within which stock assessment results can be better interpreted, 2 = forming hypotheses of how the stock assessment model could be altered, 3 = a leading indicator of potential change, 4 = changing stock assessment model parameters to account for ecosystem conditions, 5 = inclusion of ecosystem data as a covariate in a stock assessment model, 6 = inclusion of ecosystem data as a mechanistically linked, directly modeled process, 7 = to direct inclusion in development of harvest control rules.

Pressures			Stock Assessment Factors	Linkage Levels
Ecosystem	Physical	Habitat (pelagic, benthic)	Distribution, abundance. selectivity, catchability, movement	1 through 6
Ecosystem	Physical	Climate (large-scale)	Distribution, maturity, growth, abundance, movement, consumption, reference points, projections, harvest control rules	1 through 7
Ecosystem	Physical	Winds (speed, upwelling)	Growth, abundance, catchability, recruitment, movement, projections	1 through 6
Ecosystem	Physical	Temperature/Salinity (surface, profile)	Distribution, maturity, growth, abundance, selectivity, catchability, recruitment, movement, consumption, reference points, projections	1 through 6
Ecosystem	Physical	Nutrients (nitrate, ammonium, iron)	Growth, recruitment, consumption	1 through 3
Ecosystem	Physical	Chemistry (acidification, hypoxia)	Maturity, abundance, harvest control rules	1 through 3
Ecosystem	Physical	Oceanography (current, height)	Distribution, growth, recruitment, projections	1 through 6
Ecosystem	Biological	Plankton (phyto, zoo, micro)	Recruitment	1 through 6
Ecosystem	Biological	Ichthyoplankton (eggs, larvae)	Recruitment	1 through 6
Ecosystem	Biological	Fish (juvenile, adult, spawning)	All Factors	1 through 7
Ecosystem	Biological	Diet (food web, competition)	Natural mortality, growth, abundance, recruitment, reference points	1 through 7
Ecosystem	Biological	Stress (predators, parasite, disease)	Natural mortality, reference points	1 through 6
Socioeconomic	Behavior	Incentive (food, job, tradition)	Catch, abundance	1 through 2
Socioeconomic	Behavior	Bycatch (avoidance, retention)	Distribution, catch, abundance, reference points, harvest control rules	1 through 7
Socioeconomic	Behavior	Social Impacts (non-catch, tourism)	Catch, abundance	1 through 2, 7
Socioeconomic	Behavior	Risk & Uncertainty (investment)	Harvest control rules	1 through 2, 7
Socioeconomic	Behavior	Demographics (fleet size, gear type)	Catch, selectivity, catchability	1 through 7
Socioeconomic	Organization	Market Dynamics (price)	Catch, selectivity	1 through 2, 7
Socioeconomic	Organization	Institutions (councils, certification)	Catch, selectivity	1 through 2, 7
Socioeconomic	Organization	Infrastructure (docks, plants, ports)	Catch, abundance, catchability	1 through 2
Socioeconomic	Organization	Navigation/Shipping	Selectivity, catchability	1 through 2

8.5. Multiple stocks in an ecosystem

In addition to expanding the scope of stock assessments by incorporating ecosystem or socioeconomic data, assessments can also be expanded through the coordinated evaluation of their results. For instance, the results from a collection of stock assessments within an ecosystem or fishing community may be combined to understand how stock dynamics are related and how communities are affected by variable harvests. This coordinated evaluation may facilitate the establishment of fishing levels across multiple stocks to conserve ecosystem functioning while optimizing fishing opportunity. Such an approach to fishery management is described in the revised NS1 Guidelines, which mention that harvest limits can be estimated for a group of stocks and these aggregate reference points can be used to optimize yield for the entire group. In fact, this approach is already in place in certain regions. For instance, a 2-million ton system-level cap is imposed on groundfish stocks in the North Pacific Ocean (Bering Sea-Aleutian Islands). This cap facilitates maximizing the catch of the most important stocks while reducing catches of other stocks to sustain biomass in the system. Overall, the coordinated evaluation of multiple stocks may enable the development of system or community-level harvest policies. In other words, harvest policies that account for interacting stocks, total fish production in a system, as well as cumulative or indirect effects of fishery or ecosystem dynamics. This system-level approach is an important component of NOAA Fisheries' EBFM Road Map[22] and represents a critical connection between fish population dynamics and ecosystem science. As described in the EBFM Road Map, an appropriate place for these system-level approaches is within the regional Fishery Ecosystem Plans.

Evaluating stocks and their assessments at the ecosystem or community level provides additional benefits beyond the establishment of coordinated harvest policies. By conducting multi-stock evaluations, certain features of an ecosystem or set of fishing practices may be highlighted as important drivers that affect multiple stocks simultaneously. For example, if a group of stocks exhibits a relatively drastic change in abundance at a certain time, there may be many potential causes worth evaluating, such as environmental shifts or changes in fishermen targeting behavior. It may then be efficient to address these issues in a way that is most beneficial to the whole system. Other benefits of coordinated evaluations relate to the assessment and management process. For instance, if issues arise, either with the data, analyses, or other step in the process, then it will be apparent if those same issues apply to multiple stocks. The issues may then be addressed so that they benefit the entire system/community. Along those lines, a multi-stock evaluation also facilitates a system-level gap analysis. If certain gaps apply to multiple stocks then there may be efficient ways to address those gaps and improve assessments for many stocks.

8.6. Conclusions

With changing ecosystems and complex socioeconomic factors driving stock and fishery dynamics, it is important that the scope of stock assessments expands to support more holistic approaches to fishery management. These expansions can occur by including ecosystem or socioeconomic factors in individual

[22] http://www.nmfs.noaa.gov/op/pds/index.html

stock assessments, or through the coordinated evaluation of single species assessments at the ecosystem or community level. At a minimum, it is important that the potential drivers and decision points discussed in this chapter be considered during the stock assessment process, potentially facilitated through the development and implementation of FEPs. The ultimate goal of these considerations is to improve assessments and the advice being provided to fishery managers in an attempt to prevent overfishing while achieving optimum yield for fisheries. Given the strong connection between system-level thinking and EBFM, this chapter emphasizes the fundamental connection between single-species stock assessments and EBFM. Thus, improving assessments through expanding their scope not only improves single species fisheries management, but is also important in achieving EBFM.

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Chapter 9—Innovative Science for Improving Stock Assessments

Chapter highlights:

- **Changing systems and mixed-stock fisheries warrant development, testing, and implementation of ecosystem-linked and multispecies assessment methods.**
- **Strategic investments in data collection and statistical and analytical assessment methods are needed to meet the demand for increasing the quantity and quality of stock assessments.**
- **Investments in advanced sampling technologies should be guided by stock and ecosystem assessment priorities, and should enhance NOAA's infrastructure with integrated survey and ocean observation systems.**
- **Advancing the research and development of advanced sampling technologies requires partnerships among academic institutions, industry, and other agencies.**
- **Calibration studies are necessary for enhancing ongoing data collection operations with new technologies, particularly when attempting to generate direct estimates of stock abundance.**
- **General modeling frameworks that facilitate ease of use, robust testing, community-level development, modular applications, and best practices are needed.**
- **Improved use of decision analysis tools and ensemble modeling techniques will better convey uncertainty for risk analysis in fishery management decisions.**

9.1. Introduction

Stock assessments are conducted via a multi-step interdisciplinary partnership (Chapter 1) to provide reliable, complete, and transparent advice to fishery managers. Many of the fundamental scientific achievements and evolution that form the basis for fisheries science and management today were realized in the twentieth century (Quinn, 2003). Contemporary stock assessments build upon these early accomplishments as well as new developments (Methot, 2009), thereby representing a synthesis of scientific achievements within each step of the process: data collection and processing, stock assessment modeling, and developing and communicating recommendations. Advancements in stock assessment science have not only been achieved within the field of fisheries science, but accomplishments in other disciplines are also being leveraged (e.g., mathematics and statistics, computer technology and programming, ecology, advanced sampling technologies, sample design, and risk management). Therefore, the stock assessments of today can benefit from data collected by a variety of technologies and in accordance with sound statistical designs, access to advanced computing power that facilitates the rapid execution of big data analysis using complex mathematical and statistical algorithms, and sophisticated approaches to visualizing and interpreting risk and uncertainty associated with a range of management scenarios.

Despite the numerous advances in stock assessment science during the past century, meeting current demands for an increased quality and quantity of assessments will require a stronger reliance on innovative science and technology. Chapter 4 provided an overview of the current state of data collection for fishery stock assessments, and Chapter 5 described the status of assessment models in NOAA Fisheries. This chapter offers several potential improvements related to new, innovative science that may apply to the entire stock assessment process. Many of the ideas in this chapter are not new, but are already in varying stages of development, testing, and/or use. Although suggestions described in this chapter could potentially improve stock assessments, they should not be adopted for all assessments, but rather through a thoughtful and strategic decision process, because there may be limited resources and/or tradeoffs to consider. These tradeoffs emphasize the overlapping and integrated nature of the elements of the next generation stock assessment enterprise described throughout Section 3. The following subsections provide detailed recommendations related to innovative science to benefit the stock assessment process, and they should be considered along with improvements to efficiency and prioritization (Chapter 10) and to expand the scope of stock assessments (Chapter 8).

9.2. Innovations in data collection and processing

The reliability of stock assessment results is directly related to the quality of available data. In other words, if data are not available, or if the information contained in the data is not informative with regard to stock or fishery dynamics, then stock assessment results should be interpreted with caution. Certainly, quantitatively characterizing the uncertainty in assessments became increasingly important after the adoption of uncertainty-based buffers between the overfishing level and a recommended catch level. Many of the recommendations in this section pertain to innovative science and technology that may expand and improve the data collected for stock assessments. However, there is also a need for recommendations and innovation related to the general processes and practices of data collection. For instance, changes and investments in data collection operations must be made strategically; therefore, a national group may be necessary to coordinate and prioritize those changes and investments. Establishing such a group within NOAA Fisheries is recommended here to conduct strategic planning for stock assessment data and to work with the gaps and recommendations resulting from the stock assessment prioritization exercise (Chapter 10) as well as with other relevant national working groups (e.g., advanced sampling technologies, stock assessment methods, and survey vessel coordinators). Although regional experts have the best knowledge of data gaps for particular species, changes in funding often occur nationally. Thus, a national group that is coordinated across regions and connected with other national strategic efforts is ideal for conducting a comprehensive gap analysis of stock assessment surveys to evaluate the sufficiency of sampling coverage and intensity across stocks, and to determine where new technologies and other investments can be considered to address data gaps. This group can coordinate across stock assessment data inputs with a goal of obtaining the appropriate level of sampling for each stock, implemented with methodologies and technologies to provide data for stock assessments in a way that best meets management objectives.

9.2.1 Fishery-independent data

As discussed in Chapter 4, fishery-independent data sources are important for understanding and monitoring fish stocks and provide fundamental inputs to assessments. Thus, maintaining and expanding (where necessary) NOAA's fish survey capabilities is crucial to improving stock assessments. The ongoing work to ensure a sufficient and functioning NOAA fleet, charter vessel arrangements, well-designed surveys, and integration of new technologies and ocean observing systems is necessary for maintaining these important data streams.

Opportunities for improving the data already being collected for stock assessments also exist. A primary focus of fishery-independent surveys is to estimate a time series of stock abundance that serves as input to the stock assessment model (Chapter 1). In most cases, abundance trends from surveys are relative; that is, they capture proportional changes in stock size but not absolute measures of abundance each year. The assessment models can infer absolute abundance from the trend information if the time series trend is long enough to provide contrast (i.e., show declines when catch is high and increases when catch is low). However, such contrast is not assured, and information on absolute stock abundance that comes directly from the survey is beneficial and easily included in contemporary assessment models. Obtaining measures of absolute biomass from surveys does not necessarily require new types of surveys, but can be achieved through research on existing surveys. For instance, if the surveys are calibrated to measure the proportion of the available biomass sampled (catchability) and the likelihood of sampling fish of a given age (selectivity), then absolute abundance can be estimated. Therefore, resources should be directed at research on survey catchability and selectivity to work toward better survey calibration and facilitate estimates of absolute abundance for priority stocks whose assessments would benefit most from this information (advanced sampling technologies [Section 9.2.3] may be helpful in conducting this type of research). The potential for improving stock assessments with better calibrated surveys is high, particularly in cases where other stock assessment data (e.g., catch and biology) are limited or highly uncertain.

Another issue affecting the quality of abundance data from stock assessment surveys is changing species distributions. Many stocks are responding to climate variability and climate change by shifting their distributions in a variety of ways (Nye et al., 2009; Pinsky et al., 2013). For surveys, particularly those with fixed sampling-designs, these shifts may compromise the ability to estimate abundance trends, particularly when stocks shift outside of the surveyed area. In other words, distribution shifts may cause survey catchability to vary over time, yet it is often assumed to be constant when estimating abundance. Thus, there is a relationship between species distributions and the recommendation calling for better understanding of survey catchability. Part of that work will be related to researching species distributions and habitat associations as related to survey designs. In some cases, it may be appropriate to alter and/or expand survey designs so they track and respond to shifting distributions. Ocean observation systems (autonomous and fixed platforms) are good options for supplementing the spatial coverage of surveys without increasing ship time. In other cases, it may be sufficient to calibrate surveys with respect to climate so that annual catchability for a particular species can be characterized (Adams et al., 2015).

9.2.2 Fishery-dependent data

Data collected from fisheries provide fundamental information for stock assessments on numerous factors (e.g., total catch, fishing strategies, catch composition—species, ages, sizes, sexes, and bycatch and discarding practices). Fishery catch rates are also occasionally analyzed to characterize changes in stock abundance over time, commonly for stocks that do not have dedicated abundance surveys. As described in Chapter 4, fishery-dependent abundance trends are necessary in certain scenarios, but these catch rates are hard to validate as a good indicator of stock abundance and must be treated carefully. Because many harvested stocks do not have dedicated surveys, it could be very beneficial to partner with fisheries to obtain more reliable estimates of abundance. Where there is a gap in survey coverage, and when funds are not available for establishing a scientific survey, the fisheries presence on the water represents a great opportunity for collaboration. The recommendation here is to establish more partnerships with the fishing industry and explore low-cost scientific work as part of normal fishing operations where some subset of fishing activity is conducted according to a sampling design. Such partnerships offer many benefits, such as filling critical data gaps, building stakeholder engagement and trust, and improving assessments and management. Overall, this approach would be less involved than surveys conducted with chartered fishing vessels but more standardized than the approaches currently used to extract abundance trends from fishery catch rates. In cases where fisheries cannot conduct scientific sampling, another option may be to impose a sampling design for a given stock and subsample catch rates from fishermen's logbook data according to that design. In this way, the fishery is retrofitted (roughly) as a survey.

Given that fisheries represent the primary sources of many key inputs to stock assessments, there is a general need to optimize the ways in which fisheries are monitored. For instance, fishery observers provide necessary information related to incidentally caught species ("bycatch"), catch composition, and fishing practices for commercial fisheries, yet many fisheries have little or no observer coverage. For recreational fisheries, phone, mail, and dockside surveys are typically used to generate estimates of catch, effort, fishing strategies, and discards. These surveys will never provide complete accounting of recreational catches, but in an effort to improve estimates for federally managed stocks, the Marine Recreational Information Program (MRIP) recently optimized its statistical sampling design. Commercial fishery observer programs, particularly in regions with limited observer coverage, may also consider revising and expanding their sampling strategies. The ultimate goal is to provide accurate information for stock assessment and management, but given limited resources in certain regions, the following questions are of importance:

- What is the effect of different levels of observer coverage?
- How should observers be distributed over time, space, and across vessels in a fishery?
- Which stocks are highest priorities for higher/lower observer coverage?

Answers to these questions are important and may be best addressed in a management strategy evaluation (MSE) context (Section 9.3.3), but they are central for optimizing the collection of critical fishery-dependent data.

Another recommendation to improve the collection and provision of fishery-dependent data for stock assessments is through an increased use of electronic monitoring and electronic reporting (EM/ER).[23] These electronic technologies allow fishermen to record their catches and fishing activities and make that information available in near real-time. There are also platforms, such as video camera systems, that can be used to monitor catches as they are brought onboard. Such systems could potentially offer an option for a low-cost expansion of observer coverage, as well as for catch accounting in Alaska. These technologies do not represent a viable replacement for observer programs, but they can be used enhance observer-collected data. NOAA Fisheries has already invested in research, development, and testing of EM/ER, and a small number of fisheries have implemented these innovative approaches to data collection and monitoring of commercial fisheries. In 2016, Congress appropriated $7 million for implementation of EM and ER in U.S. fisheries; these funds are expected to continue. Overall, these technologies may offer improvements to fishery-dependent data collection; therefore, the use of EM/ER will continue to be explored.

This section calls for increases in fishery-dependent data collection, but there are various costs to consider in doing so. A primary expense is the cost associated with expanded operations (i.e., new equipment and staff time for data collection and program management). However, there are added costs related to processing and analyzing more data. These costs cannot be overlooked, because in many cases, resource availability for data processing and preparation is a major factor that constrains the throughput of assessments. This issue is addressed in more detail in Section 9.2.5.

9.2.3 New data types

Chapter 8 described the need and approach for expanding the scope of stock assessments to consider the effects and inclusion of ecosystem and socioeconomic impacts. As consideration of these effects becomes more common in stock assessments, a broader collection of supporting ecosystem and socioeconomic data will become necessary. Not only will these data be important for the assessments that expand in scope, but as NOAA Fisheries progresses toward ecosystem-based fisheries management (EBFM), these data will be crucial for EBFM implementation as described in NOAA Fisheries' EBFM Roadmap.[24]

Fortunately, ecosystem and socioeconomic programs within NOAA Fisheries and its partners are actively collecting this information today. Additionally, ongoing work is being leveraged (e.g., stock assessment surveys that also collect ecosystem information) and many opportunities exist for further leveraging. For instance, fishery-independent data collection aboard NOAA ships and chartered vessels could be

[23] https://www.st.nmfs.noaa.gov/advanced-technology/electronic-monitoring/index
[24] http://www.nmfs.noaa.gov/op/pds/documents/01/120/01-120-01.pdf

expanded at a relatively low cost to collect more interdisciplinary data for ecosystem research. Also, coordinated and standardized ocean observations, as achieved through international collaborations such as the Global Ocean Observing System[25] and their coordination of Essential Ocean Variables, facilitates access to ecosystem data that may be useful in stock assessments. However, as mentioned previously, an important consideration in expanding data collection efforts is ensuring staff capacity for processing data and for conducting research to understand the ecosystem processes (Section 9.2.4). This consideration may explain the lack of ecosystem and socioeconomic data to support full evaluations of these drivers in all stock assessments.

Numerous socioeconomic and ecosystem factors must be considered under a holistic approach to managing living marine resources (Figure 8.1). Within an ecosystem, the key living and non-living features include information on food webs; diseases and parasites; oceanography (e.g., temperature, salinity, oxygen concentration, pH, and current dynamics); climate conditions; structural habitat; and toxins. Given the variety of factors, diverse and innovative approaches are needed to collect and characterize this information. Advanced sampling technologies, particularly from the following disciplines, will continue to enhance data collections: biotechnology (e.g., characterization of food webs using biosensors for sampling lipid, fatty acid, stable isotopes, genetics, and macroscopic analyses; and detection of diseases and parasites using genetic, macroscopic, physiological, and standard medical diagnostic analyses); remote sensing platforms and ocean observation systems (e.g., monitoring physical water conditions using satellites, autonomous vehicles, and standard oceanographic instrumentation); high-resolution and seasonal to decade-long climate models for forecasting climate conditions at scales relevant to most fishery management decisions; underwater sensor technologies (e.g., quantification and characterization of biological communities and their habitats using optics and sonar); and chromatography and other detection techniques for toxins.

There is a basic need to collect socioeconomic data to understand and manage fisheries in consideration of their community-level importance as well as their economic contributions. However, the recommendation for increasing the collection of this information is made here in the context of the stock assessment process. In addition to modeling stock dynamics, assessments also model fishery dynamics. Because fisheries support recreation, food, and livelihoods, their dynamics are driven largely by socioeconomic decisions. Although innovation and technology may enable the improved collection of socioeconomic data, the higher priority is to expand the collection of information related to fishermen's decision processes, sales, revenue, value-added impacts, and jobs. These data are collected mainly through on-the-ground outreach. However, some of this information may be well suited for collection using EM/ER (Section 9.2.2).

9.2.4 Advanced sampling technologies

[25] http://goosocean.org/

The previous section provided recommendations for expanding the types of data being collected for stock assessment purposes. Although many of the recommendations are related to technological advancements, the technologies discussed in this section focus largely on methods for monitoring stock abundance. NOAA Fisheries has long recognized the importance of advanced sampling technologies for enhancing survey data collection, improving abundance estimates, and minimizing uncertainties in measurements and estimates. The research and development in advanced sampling technologies include testing and calibration of the sampling tools, improving the efficiency of data processing, and evaluating the feasibility of transitioning technologies into operations (Chapter 4). Technology investments should be guided by stock assessment priorities and address information gaps to improve stock and ecosystem assessments (e.g., Chapter 10). In addition, these investments should benefit NOAA's next generation infrastructure with more efficient survey operations and integrated ocean observation systems.

For the research, development, and evaluation of advanced sampling technologies, NOAA will continue to rely on partnerships among academic institutions, industry, and other agencies. Promoting these partnerships with research and development of technology will be increasingly important, especially given that NOAA's limited pool of technology expertise will need to implement and sustain these technologies aboard its survey operations.

Sensing technologies continue to be integrated into ship survey operations to achieve multidisciplinary objectives, and this area holds significant potential for improving stock assessments. In particular, these technologies provide opportunities for calibrating ongoing abundance surveys by directly observing the area sampled by traditional gear (e.g., trawls) and the number, size, and type of species available to that gear. A recent upgrade of the northeast scallop survey included an advanced optical imaging system, which was calibrated and has facilitated estimation of absolute, rather than relative, abundance indices. Thus, advanced technologies facilitate the estimation of absolute stock abundance and therefore may be used to address recommendations in Section 9.2.1. Another benefit of sensor technology is the ability to deploy sampling gear in areas that have been difficult to survey with traditional gear (e.g., rocky and coral habitats). In most cases, data-limited stocks (e.g., fish groups associated with reef or rocky habitat) in federal fishery management plans lack data because of difficulties in sampling such habitats. Therefore, advanced sampling technologies offer exciting opportunities for improving the assessment and management of these important species.

With the implementation of advanced technologies, larger volumes of data are typically collected. This is particularly true for acoustic and optical surveys. For example, the next generation of fisheries acoustic systems will collect four times more data. In addition, using stereo video systems to enhance visual surveys will also drastically increase data collection. Although these large data streams need to be stored, this concern is minor compared with the need for rapid access to processed data for analysis and visualization. One approach NOAA Fisheries has taken to address this issue is to collaborate with the computer vision technology industry to develop tools for automated image analysis. This technology continues to evolve rapidly; therefore, continued investments in processing efficiencies are critical and expected to be beneficial.

Another promising, low-cost technique to explore for filling important stock assessment data gaps is environmental DNA (eDNA). This technology has typically been used to document the presence of a species in a given system by detecting the DNA of that species. However, more recently, eDNA has demonstrated potential for measuring abundance of a species under the theory that the concentration of a species' DNA in the environment is in proportion to the density of that species (Takahara et al., 2012). Given the simplicity of collecting water samples for later DNA analysis, it may be relatively cost-effective to collect this information on either new platforms or by leveraging ongoing fishing or survey operations.

Wise investments in advanced sampling technologies must be guided by stock assessment priorities to resolve key information gaps. Unmanned platforms (e.g., aerial systems, moorings, gliders, and autonomous and remotely operated underwater vehicles) will become relatively low-cost options for deploying acoustic and optical technologies, especially when compared to the cost of building, running, and staffing a traditional research vessel. However, ships remain the key infrastructure for conducting surveys and deploying technologies that augment and improve survey coverage. As technologies are implemented, calibrations are required at various levels, ranging from sensor, inter-vessel, and sampling gear performance, to changes in survey designs that are improved with technologies. Continued investment in these platforms and their calibration is necessary for expanding the coverage of stock abundance surveys and improving the assessment and management of data-limited species. Overall, these technologies provide an opportunity among NOAA programs, academic institutions, and industry to build an integrated survey and ocean observation infrastructure for NOAA's next generation stock assessment enterprise.

9.2.5 Improving data management, processing, and delivery

As emphasized throughout this document, data collection systems play a critical role for the success and improvement of stock assessments. In 2013, NOAA Fisheries conducted a series of independent reviews of its data collection and management systems for stock assessments.[26] It became clear from these reviews that comprehensive improvements are warranted. Additionally, the Open Data Initiative[27] formally calls on federal agencies, such as NOAA Fisheries, to offer public access to government information resources in a "computer readable" form. Thus, NOAA Fisheries is transitioning its data and information systems to be more secure, easier to access, and more readily understood by the public. These improvements offer opportunities, not only to address the Open Data Initiative, but also to improve the stock assessment process.

[26] http://www.st.nmfs.noaa.gov/science-program-review/
[27] https://www.data.gov/

Although the previous sections provide a vision for data types and collection techniques, this section specifically refers to data management in relation to stock assessment efficiency. As NOAA Fisheries creates data and information systems that comply with the Open Data Initiative, it is an opportune time to address data issues that lead to confusion and delay in the stock assessment process. For some assessments, analysts face challenges in obtaining all necessary data. These challenges arise because many sources of data are managed by individual programs and partners, data require varying degrees of processing before analysis, and the access and ability to process the data is limited. It is most efficient if stock assessment scientists can simply obtain all necessary data in the formats required as early as possible in the stock assessment process. There is a need to improve data management in NOAA Fisheries and with partner organizations that provide data to the stock assessment process (particularly within the networks used to compile fishery-dependent data). Stock assessments will become more streamlined, and in some cases, more accurate, by creating systems that are open and easily accessible, organized according to standard formats and data dictionaries, and that contain effective and automated error-checking and processing procedures to facilitate access to timely and accurate data. These technological and process-oriented improvements address objectives described in Chapter 10 related to improving the timeliness, efficiency, and effectiveness of the stock assessment process.

The development of streamlined systems for compiling and processing data (e.g. catch, abundance, composition) for assessment applications represents a first step toward improving assessment data delivery. For example, a web-based interface, such as the Alaska Fisheries Information Network[28] (AKFIN) simplifies data processing steps and ensures greater transparency in how the data were compiled. More regional systems such as AKFIN are nonetheless needed. Features should provide the user with ways to easily search and compile the information (e.g., through construction of maps, tables, and diagnostic figures) while also allowing easy documentation of the steps that were taken in the preparation of assessment input data. In the interest of transparency, routine retracing of these steps should be made feasible, and to facilitate thorough evaluation, interfaces should be designed that encourage users to examine data closely for characteristics such as incorrect data points and differences due to alternative processing techniques. For example, the ability to easily examine fishery data by sector, season, and spatial distribution can help users evaluate the number of fisheries that should be explicitly modeled in an assessment (and allow for the easy creation of alternative configurations for testing the sensitivity of an assessment). For situations where data from fishery-independent surveys are available, analytical tools for processing such data collections can benefit from applications that use innovative statistical techniques, such as better accounting for spatial dynamics (see the discussion in Section 9.3 on software developments).

[28] http://www.psmfc.org/program/alaska-fisheries-information-network-akfin

Box 9.1. Summary of Data Collection and Processing Recommendations

- **Establish a national working group in NOAA Fisheries focused on data collection for stock assessments.**
- **Conduct a gap analysis for stock assessment survey coverage and intensity in each region to facilitate survey prioritization.**
- **Conduct research to estimate survey catchability and selectivity to facilitate estimation of absolute abundance for key stocks.**
- **Adjust surveys to track shifting species distributions and conduct studies to calibrate surveys where distributions have changed.**
- **Partner with the fishing industry to conduct low-cost monitoring as part of normal fishing operations to fill data gaps and/or subsample fishery catch rates according to a sampling design.**
- **Increase use of cost-effective electronic monitoring and reporting to improve fishery-dependent data collection.**
- **Enhance broad spectrum sampling of ecosystem and socioeconomic data using new and existing platforms and technologies.**
- **Expand use of advanced sampling technologies (acoustics, optics, eDNA, and unmanned platforms) for tracking stock abundance by calibrating surveys and sampling in "untrawlable" habitat.**
- **Provide centralized open access to updated and processed stock assessment data.**
- **Utilize standardized and understandable data dictionaries and formats.**
- **Where possible, establish automated quality control and data processing procedures.**

9.3. Innovations in stock assessment modeling

Analytical tools available for conducting stock assessments are more powerful and more efficient than ever. This innovation has facilitated the integration of large amounts of data from diverse sources, comprehensive characterizations of statistical uncertainty, and the evaluation of multiple hypotheses about stock and fishery dynamics within an assessment. The tools themselves cannot "fix" issues in the data, but as tools develop, they contain enhanced functionality that allow for appropriate treatment of data and presentation of results and uncertainties. The recommendations in this section pertain mostly to technical advancements related to the functionality of analytical tools for stock assessments. These recommendations address many of the challenges raised in Chapter 5, offering a direction for improving stock assessment models. Some examples include new approaches for conducting data-limited assessments, promising statistical tools, and alternative strategies for evaluating risk in fishery management settings. The section concludes with a presentation of options for integrating ecosystem information into stock assessment models.

9.3.1 Improved software and advanced models

Advances in software have greatly facilitated application developments for fisheries stock assessments. The ability to develop open source software packages that focus on reproducibility of results and provide assistance with documenting those results has provided more time for assessment model developers and analysts to concentrate their efforts on prototyping and designing alternative models that account for a range of reasonable assumptions. This flexibility is important for providing an improved characterization of the true uncertainty surrounding assessment results (see Section 9.3.3).

The software package that continues to form the foundation of the majority of NOAA Fisheries' stock assessments is Auto Differentiation Model Builder[29] (ADMB; Fournier et al., 2012). The main advantage of ADMB is its ability to efficiently run complex nonlinear models with many estimated parameters, which is how most modern stock assessment models are configured. NOAA Fisheries continues to be the primary funding source for ADMB, providing global leadership in assessment model support and development. Unless assessments migrate to another platform, it is important for the entire stock assessment enterprise that this support continues at a level sufficient for ADMB to be able to adapt to ongoing advancements in assessment science. For example, in 2016 the ADMB project embraced a European-developed project, Template Model Builder[30] (TMB), which offers a substantial increase in speed for certain classes of model structures. NOAA Fisheries' scientists are significantly engaged in both ADMB and TMB.

Modern open source statistical programming languages such as R[31] represent another significant advancement for stock assessments. These programming languages improve the efficiency and rigor by which assessment data are evaluated, alternative assessment scenarios are conducted, and results are assimilated and presented. These languages are relatively accessible to analysts without formal training in computer programming, but they provide users with access to powerful programming tools (including C++ and FORTRAN libraries) within a common interface. Also, given the open source nature and global popularity, users also have access to tested and reviewed software packages that allow the

29 http://admb-project.org/
30 https://github.com/kaskr/adcomp/wiki
31 https://www.r-project.org/

implementation of common methods without the need to develop the methods from scratch. This access is particularly important for assessment analysts who are asked to evaluate numerous assumptions and configurations over shortened time periods, and NOAA Fisheries' scientists have contributed these software packages to the public domain (e.g., r4ss[32]).

A valuable opportunity available to assessment developers is the ability to coordinate with colleagues on projects via virtual and cloud-based platforms. This coordination has been enabled by modern online version control systems (e.g., git[33]), which provide easy access to develop code, write documentation, and facilitate model testing and exchange of ideas and methods. Many assessment platforms have been developed by single authors or small teams in independent settings. However, the community-level development option makes it easy to access a broad range of expertise, resulting in enhanced functionality and more thorough testing. Overall, the software packages, diversity of knowledge, and collaborative opportunities available to assessment model developers have matured to a point where NOAA Fisheries can now take a more professional approach to the development of general assessment tools. The assessment model, Stock Synthesis (Methot and Wetzel, 2013) has already migrated into NOAA's Virtual Lab[34] where git capabilities allow access to NOAA and invited external developers. The recommended approach to tool development will be to start with professional software architecture and to create modular applications to facilitate the rapid incorporation of new features as needed. This approach is an important component of the next generation stock assessment framework, because it allows for standard models that improve efficiency and transparency, as well as easy expansion of models (including more holistic options) driven by needs identified through prioritization.

The cutting edge of assessment model development lies in the ability to treat certain model components (e.g., natural mortality) not as fixed constants, but rather as factors that vary randomly over time, age, and/or space in a way that is informed by available data and constrained by an estimated statistical distribution. This technique has many names, including state-space models, random effects models, mixed-effects models, and hierarchical models, among others. The use of this statistical technique helps to address several challenges in the assessment process. In particular, the characterization of uncertainty may be improved by accounting for variation in the model structure (i.e., process error). This approach relates to improved risk assessment (Section 9.3.3) as well as an ability to indirectly account for ecosystem and socioeconomic effects (Chapter 8 and Section 9.3.4). Even when there is not a clear understanding of the mechanisms that cause stock and fishery dynamics to drift over time, and when data are unavailable to model those mechanisms, allowing for a random but informed variation of a model component may sufficiently account for these external drivers in some cases. Although these techniques are not yet common in U.S. stock assessments, many European stocks are assessed using the State-space Assessment Model (SAM[35]), which does allow for random effects. Recent

32 https://cran.r-project.org/web/packages/r4ss/index.html
33 https://git-scm.com/
34 https://vlab.ncep.noaa.gov/group/stock-synthesis/home
35 https://www.stockassessment.org/

development of TMB, which allows for efficient estimation of complex statistical models with numerous random effects, now opens the door to implementing this technique more broadly in stock assessments. It is recommended here that many stock assessments capitalize on this opportunity to better characterize changes in processes and better account for spatial dynamics.

A specific technical challenge for modern assessment methods relates to "data weighting." This term refers to the appropriate specification (or estimation) of variances associated with different data components. This term also includes how to elicit and apply prior information, particularly for data-limited situations, and how to specify process error variances where estimation is presently difficult or impractical. In general, data weighting requires some degree of subjectivity. However, recent developments to estimate variances of composition data hold some promise for objective approaches (e.g., Francis, 2014; Thorson, 2014). Tests for these approaches and how they may apply to data-limited situations require simulation testing (e.g., Deroba et al., 2014). Furthermore, approaches that augment information on a particular stock based on data from similar species and regions are a clear, cost-effective way forward (for example applications see Punt et al., 2011; Punt and Dorn, 2013;). As noted in Bentley (2014), models for management face the challenge to balance opposing risks of inappropriate management "action" due to assessment inaccuracy, and inappropriate management "inaction" due to assessment uncertainty.

9.3.2 Using multiple models to generate advice

Methods that combine results from multiple alternative models are generally referred to as "ensemble modeling." This approach involves generating multiple projections of future system states using a range of assumptions about how to configure the assessment. Therefore, ensemble modeling has the potential to capture structural uncertainty in addition to the observation uncertainty that is typically quantified. This approach is widely used in climate modeling where uncertainty is reflected in the accuracy of the approximations to the well-known and accepted physical principles of climate and the inherent variability of the climate system. For the purposes of weather forecasts (e.g., predicting a hurricane track), model ensembles are created from a suite of models whose performance is updated (with precise data) at regular intervals and monitored to provide probability statements on near- and medium-term predictions. The past predictions of each model can be evaluated relative to known storm tracks and used to weight its contribution to the ensemble for future predictions.

Fish stocks and fishery management operate at a slower pace than weather predictions. The challenges with fisheries, however, are that the observations are rarely precise; many drivers affecting fish stocks (other than fishing) typically go unobserved (e.g., the impact of tides, food availability, predation, and so on); and there is less opportunity for validating past predictions (e.g., hurricane forecasts can be compared with the actual hurricane track, but the true abundance of a fish stock is seldom known). In these settings, more formal methods of combining model alternatives, such as Bayesian Model Averaging, (e.g., Buckland et al., 1997; Durban et al., 2005; Hoeting et al., 1999; Kass and Raftery, 1995; Raftery et al., 2005; Chimielechi and Raftery, 2011) or bootstrapping approaches (Stewart and Martell,

2015) can be applied. Critical simulation testing has shown that model averaging approaches outperformed methods that generated advice based on a "best" model (Wilberg and Bence, 2008). It is recommended that stock assessments capitalize on these advances in ensemble modeling to generate management advice with more complete characterizations of uncertainty. However, it is important to stress that each model included in the final ensemble should be considered plausible according to the assessment analysts and reviewers (at least). Further, all models should be well documented and contributed early enough in the assessment to be included in the assessment review process. Thus, every model in an ensemble should have consistent levels of review and transparency.

9.3.3 Risk assessment for fisheries management decisions

The evaluation of risk and accounting for uncertainty are clear requirements for setting annual catch limits (ACLs) as specified in the MSA (e.g., to provide a sufficiently low chance of overfishing while maximizing catch; Methot et al., 2014). These actions involve estimating scientific uncertainty (Chapter 5) and evaluating management uncertainty (Patrick et al., 2013). Approaches are outlined later to evaluate uncertainty in the implementation of management actions with a goal of satisfying this and other objectives for fishery managers and stakeholders. Such methods should be shown to be robust to management objectives (i.e., low probability of leading to an overfished state while optimizing yield). For management purposes, a key for new analytical tools will be to balance research models and operational management tools that are used as a basis for setting catch limits and determining status.

The field of decision theory provides useful analytical methods for finding optimal solutions in the assessment of risk. However, these approaches suffer from a lack of transparency, and simpler methods are often preferred by fishery managers. An example where a risk-averse, decision-theoretic approach was replaced by a more straightforward method has been adopted for certain ("Tier 1") stocks managed under the Bering Sea/Aleutian Islands Groundfish Fishery Management Plan (Amendment 56). In this example, the risk-averse approach to developing a catch recommendation (i.e., Acceptable Biological Catch, ABC) was found to be equal to an approach that simply used a certain type of averaging (i.e., the harmonic mean) of the estimate of the overfishing limit (F_{MSY}). An appealing characteristic of this approach is that the harmonic mean is some percent reduction from F_{MSY}, and when uncertainty in the assessment (particularly around F_{MSY}) is high, the recommended catch is decreased as one might expect in a precautionary harvest control rule. This approach has proven useful for accounting for scientific uncertainty, but fishery managers must also consider other factors, such as management uncertainty and socioeconomic factors, when optimizing yield.

Another management measure that attempts to account for assessment uncertainty related to risk of exceeding an overfishing limit is known as the P* approach (Shertzer et al., 2008). This method relates the probability that a projected future catch would exceed the overfishing (F_{MSY}) level and allows the policy makers to establish the level of risk related to a catch limit selection. For example, if P* was set to 0.4, then this would represent a 40% chance that the corresponding catch limit would exceed the true overfishing limit. Although effective at addressing specific sources of uncertainty, the P* and decision-theoretic approaches do not account for considerations related to interactions among fisheries and multiple species within an ecosystem.

An important advancement for evaluating risk in fishery management is the growing application of simulation-tested management strategy evaluations (MSEs; Butterworth et al., 1996; Butterworth, 2007; Punt et al., 2014). A distinct advantage of this decision analysis tool is that models used for developing catch recommendations (i.e., the actual management strategies or control rules) are designed to be transparent and relatively simple. Also, the approach can incorporate any number of considerations, including biological, ecosystem, and socioeconomic factors. This aligns well with the NS1 Guidelines, which suggest that a council can consider the socioeconomic and ecological tradeoffs between being more or less risk averse. Further, by conducting simulation testing, there is a certain amount of confidence in the results. In a well-designed MSE, stakeholders are engaged throughout the process to ensure that the performance metrics that directly relate to management objectives are easy to understand (Punt et al., 2014). The challenges for this approach include developing defensible operating model configurations, particularly for testing control rules in data-limited situations. Borrowing from related species and stocks from other areas could help establish plausible estimates for biological parameters (e.g., Smith et al., 2015).

The MSE approach benefits from using disparate sources of information and models (including multispecies and ecosystem considerations) to devise plausible realities for testing management options. Looking forward, recent developments in statistical programming languages such as R (Section 9.3.1) have made it easier for stakeholders to participate in MSEs. For instance, by having access to tools that are designed to work within a specific assessment framework, such as the ss3sim[36] package for Stock Synthesis (Methot and Wetzel, 2013), more time can be spent on developing objectives and performance metrics with stakeholders than on coding simulation analyses. Other R packages specialize in user-friendly interfaces to evaluate policy choices given uncertain states of nature, such as mseR (Kronlund et al., 2012) and the MSE tool developed for the International Pacific Halibut Commission.[37] It is recommended here that NOAA Fisheries continues to invest in the development of MSE tools and the resources necessary for development and expansion of MSEs to inform management decisions in the face of uncertainty.

9.3.4 Holistic stock assessment models

Ecosystem information is beginning to form a more integral part of modern stock assessments. Effective marine conservation and management requires an understanding of how ecosystem drivers (e.g., temperature changes) can affect assessment results (in particular, biological reference points). As these broader applications become a more integral part of the stock assessment process, any number of management decisions can account for this information, including catch levels. Stock-specific ecosystem

[36] https://github.com/ss3sim/ss3sim
[37] http://shiny.iphc.int/sample-apps/mseapp/

considerations within an assessment can help prioritize factors most likely to affect processes related to the stock. In addition, these considerations can provide further specifics on future productivity and potential management actions that may be needed (e.g., Shotwell et al., 2014).

Chapter 8 provided a full discussion of holistic approaches to stock assessments that consider ecosystem and socioeconomic factors. Most current stock assessment models can incorporate many of these factors today, but there remains a need for research and development. With mixed-stock fisheries and climate change forcing systems into unobserved states with consequences for fisheries (e.g., Ianelli et al., 2011; Meuter et al., 2011; Holsman et al., 2016), it is imperative that next generation stock assessment models have straightforward options for accounting for ecosystem and/or socioeconomic factors, and that the effects of these additional factors be easily understood and tested. Example model features that would facilitate more holistic assessments include capabilities for spatial structure and connectivity, options to incorporate multispecies dynamics, state-space implementations that allow efficient models with random change and variability, the ability to apply multiple model configurations/types, and standard diagnostic and reporting features for rapid dissemination of results. The recommendation here to develop assessment tools with these capabilities could result in more efficient, but also more comprehensive (holistic), stock assessment models.

9.3.5 Expanding and improving process studies

Many of the recommendations provided in this chapter are challenging to implement without a more complete understanding of key processes. For instance, in order to expand the scope of a stock assessment to include ecosystem and socioeconomic factors, it is not only important to collect the necessary data (Section 9.2.3) and to have assessment tools capable of incorporating those data (Section 9.3.4), it is also necessary to understand the main processes that drive stock and fishery dynamics. These process studies will provide guidance on how to configure expanded models. This research is also useful in helping to select plausible models for ensembles (Section 9.3.2) and to design and implement MSEs (Section 9.3.3). Thus, process research has an important role in improving the basis on which models of fish population dynamics and ecosystem dynamics are built. It is recommended here that NOAA continue to invest in these efforts and, in particular, that these investments be guided by stock assessment priorities (Chapter 10). Key areas for process studies that would address stock assessment priorities include the following research areas:

- Habitat and environmental factors affecting the distribution of fish, fisheries, and the design of sampling programs
- Factors constraining the physiology of fish in a changing environment
- Flow of energy through marine food webs
- Connection between changes in the marine environment and fluctuations in birth and growth rates of young fish

9.4. Conclusions

Although stock assessment science has benefited from numerous advancements during the past century, continued research and development is still required. A series of research initiatives within NOAA Fisheries allow federal researchers to develop projects that specifically tackle these objectives. These nationally run programs fund priority projects across the regions that improve stock assessments.

Another path for improving assessments is through coordinated workshops and symposia that specifically address theories, estimators, and assumptions within particular aspects of stock assessment. These workshops provide the opportunity to synthesize current research and develop guidelines and best practices; examples include NOAA Fisheries' National Stock Assessment Workshops and the workshops being organized by the Center for the Advancement of Population Assessment Methodology.[38] The next generation stock assessment framework described in this document is attainable given the current state of the science, ongoing prioritized investments in research, and opportunities to collaborate broadly throughout the stock assessment community.

Box 9.2. Assessment Modeling Recommendations

- Utilize advancements in statistical techniques, such as state-space, geo-statistics, sample weighting, auto-correlated processes, and so on.
- Provide a more complete characterization of uncertainty and utilize ensemble modeling and decision analysis tools to convey structural uncertainty and inform fishery management decisions.
- Improve professionalism of model development (professional architecture, thorough testing and publication of test results, thorough documentation and user guides, community development, and cloud-based computing).
- Expand the scope of assessment models where appropriate to include spatial dynamics, multispecies and ecosystem processes, and/or socioeconomics.
- Rely on stock assessment priorities to guide investments in innovative science and technology and the resources necessary to implement these advancements.

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[38] http://www.capamresearch.org/

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Chapter 10—An Efficient and Effective Stock Assessment Enterprise

Chapter highlights:

- **The demand for increasing the quantity and quality of stock assessments has overloaded NOAA's stock assessment enterprise.**
- **The completion rate of stock assessments is affected by varying requirements regarding the complexity of data sources, and how timely, thorough, and transparent assessments need to be to support effective management.**
- **A national method for categorizing and prioritizing stock assessments is proposed to balance stock-specific needs, better use assessment resources, and identify gaps in NOAA's stock assessment enterprise.**
- **Stock assessments should use more standardized processes regarding data preparation and delivery, assessment modeling, peer review, and communication.**
- **Research is necessary to continue improving stock assessments, and the standardized operational process must be adaptable to incorporate advancements.**

10.1. Introduction

NOAA Fisheries' national stock assessment enterprise consists of several regional assessment programs that provide scientific advice to regional fishery management organizations (Chapter 3). Overall, this federal fishery management system operates in accordance with the MSA; however, the regional assessment programs and management organizations have developed independently over time. Thus, the processes by which MSA mandates are addressed can vary by region. Although the science–management interface has successfully achieved its goals for federal fisheries (Chapter 2), the demands and challenges surrounding the provision of best scientific information are substantial, conflicting, and broadly applicable. These issues can be classified according to the "4Ts" (Figure 10.1).

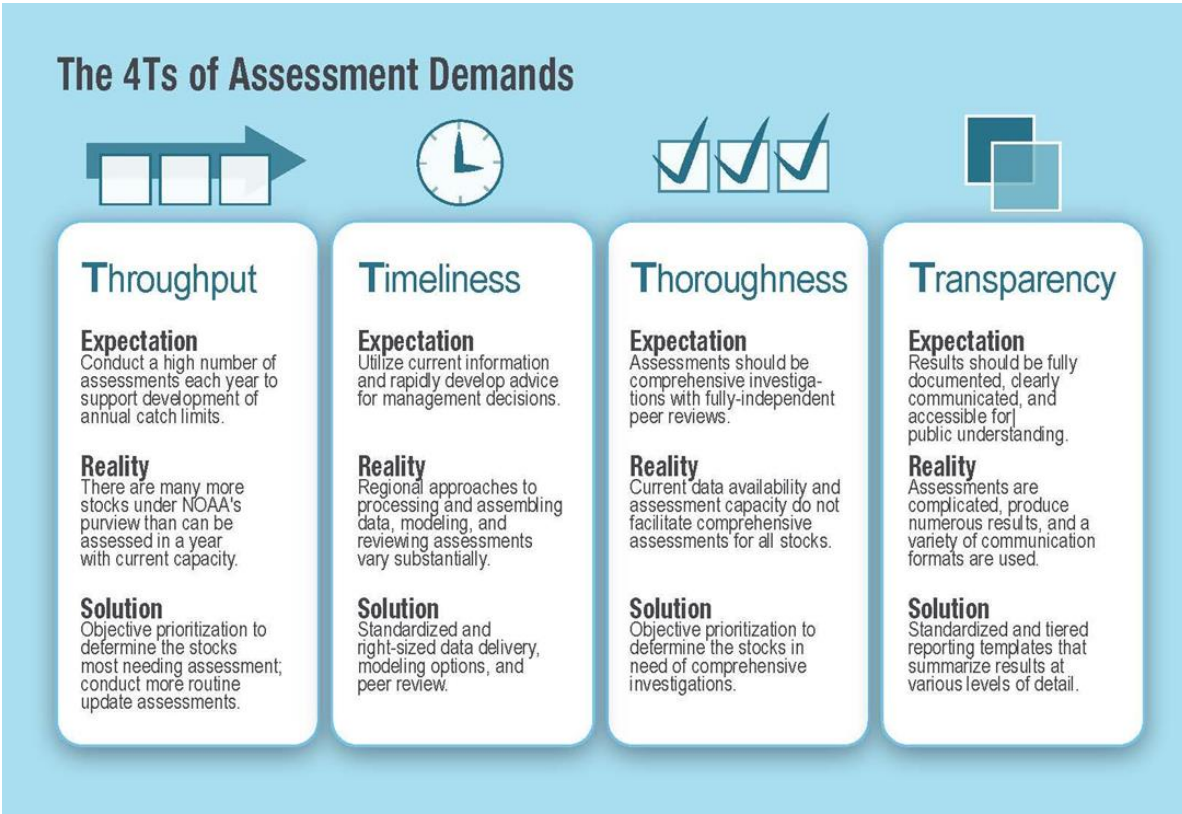

Figure 10.1. The major demands and challenges facing NOAA Fisheries' stock assessment enterprise summarized by 4Ts (throughput, timeliness, thoroughness, and transparency).

There are unrealistic expectations surrounding the 4Ts and it is not possible to simultaneously achieve high grades for each T. Figure 10.1 summarizes expectations and realities for the current stock assessment enterprise while also offering solutions to better meet expectations. These solutions do not intend to meet all expectations, but rather offer a balanced approach that manages expectations and suggests improvements where feasible. Thus, in this chapter, the range of improvements provided will achieve a more efficient and effective stock assessment process.

Nationally, there are many more federally managed fish stocks than can be assessed in a single year with NOAA Fisheries' current stock assessment capacity. The annual stock assessment demand in a given region typically exceeds the number of assessments that NOAA scientists can complete. However, annual assessments may be unnecessary for stocks that are not highly valued commercially, recreationally, or for other reasons. Also, stocks that do not exhibit substantial fluctuations in abundance from year to year may not require annual assessments. Because it is unnecessary to revise catch recommendations for certain stocks every year, and because NOAA Fisheries has limited stock assessment capacity, it is essential to determine which stocks are most in need of assessment. For high-priority stocks, it is also important to set the frequency at which assessments should be conducted in following years, and determine how comprehensive each assessment should be (i.e., the key data sources that should be used to calibrate the assessment as well as the nature of peer review that should occur). This chapter describes an objective national approach for establishing an assessment portfolio and offers suggestions for developing more efficient regional assessment processes.

This portfolio approach is fundamental to maximizing available stock assessment resources, guiding future investments, and achieving sustainable fisheries and resilient communities to the maximum extent possible. The main components of the portfolio approach include the following:

1. Classifying the stock assessments conducted by NOAA Fisheries
2. Establishing stock-specific targets for assessment frequency and the level (types of data used) of each assessment
3. Developing annual prioritized lists of stocks to assess in each region
4. Conducting gap analyses that compare classified assessments against their target levels
5. Using the resource assessment to right-size the stock assessment enterprise and seek funding as needed

A similar approach to strategic planning was introduced in the 2001 Stock Assessment Improvement Plan (Mace et al., 2001), which included an assessment classification system and strategic guidance outlined by the Three Tiers of Assessment Excellence (Chapter 2). Overall, this system provided guidance and justification for expanding and improving the stock assessment program. However, with the increasing demand for stock assessments, and the evolution of legal mandates, scientific knowledge and capability, and assessment processes, it is clear that a new portfolio approach is needed. In the following sections, we describe each of the three components of this new approach with reference to the existing system.

10.2. Classifying stock assessments

Not all stock assessments are created equal. In Chapter 1, stock assessments were defined as being a process that results in a product. However, both the process and the product vary across the United States. See Chapter 6 for a description of the various regional assessment review processes (Table 6.1), and Chapter 5 for the range of stock assessment modeling approaches and their data requirements (Table 5.1). Thus, the type of product produced and degree of effort required for each assessment varies substantially. Further, the fishery management process may rely on analyses to support decisions, such as establishing annual catch limits, which use assessment science but do not assess the status of the stock and therefore are technically not stock assessments. For example, one approach to adapting catch regulations without conducting a full stock assessment is to rely on estimates from a previous assessment to forecast stock abundance and catch recommendations using updated catch data. These approaches are very useful analyses that support management between more complete stock assessments; however, they should not be considered stock assessments. Additionally, stock assessment research is conducted outside the operational assessment process to improve stock assessment methods. This work can be just as involved (if not more) than an operational assessment, but is not immediately used to provide management advice.

To offer a consistent language on the various types of assessment-related analyses conducted by NOAA Fisheries, the following general categories are recommended:

- **Research stock assessment**—development or revision of a stock assessment data type or method, typically subjected to the regional assessment review process. If the activity both produces a substantial revision to the assessment method and applies that method to produce management advice, then the activity is labelled as both a research assessment and an operational assessment (next category).
- **Operational stock assessment (or "stock assessment")**—analyses conducted to provide scientific advice to fishery managers with particular focus on determining stock status and recommending catch limits. These are the predominant assessment activities and include assessments using any of the methods described in Table 5.1, updated with the most recent data. Within the range of operational assessments will be first time applications of previously researched methods ("new" or "benchmark" assessments); applications with updated data streams and minor revisions to methods within the scope of previously researched themes; and applications that simply update the model with the most recent data. However, if only catch data are updated then the activity falls into the next category.
- **Stock monitoring update**—methods used to provide stock-level advice to fishery managers between stocks assessments. These analyses include the methods described in Table 5.1, but only when they are updated using the most recent catch information to develop new catch advice. These are sometimes called partial updates. Because there are no changes in the methods or data series in stock monitoring updates, just updated catch data, the conduct and review of these analyses should be very routine and intense scrutiny is not warranted.

Because a major focus of this plan is to set priorities for conducting assessments at frequencies and levels that are most appropriate for each stock, there is a need to establish a consistent approach to tracking and classifying assessments (i.e., everything captured in the "operational stock assessment" category). A stock assessment classification system was described in the 2001 SAIP (Mace et al., 2001). This system is currently used by NOAA Fisheries to classify individual assessments according to five categories, three of which capture the input data used in each assessment, and two for describing the assessment approach. The input data are categorized according to catch, abundance, and life history data, and the assessment approach is described in terms of the modeling technique used and frequency at which the stock is assessed. Overall, this system has proven useful for tracking stock assessments, evaluating assessment capacity, and addressing program gaps. For instance, as the preference to incorporate ecosystem dynamics into the assessment process has continued to increase, the classification system has been used to summarize which stocks already include such information (Box 5.1).

However, the current assessment classification system has limitations. The level of detail captured in the categories is not sufficient to fully summarize assessments. Model configurations are largely driven by the available input data, so an expansion of the original data categories is warranted. Also, the original assessment model category blends modelling approaches and data inputs. For example, the highest level in this category refers to a model that incorporates ecosystem, environmental, spatial, and/or seasonal information. However, these types of data can be included using many assessment techniques from simple to comprehensive.

A new Stock Assessment Classification System is proposed and summarized in Table 10.1. This system includes the high-level model categorization described in Chapter 5 (Table 5.1), tracks the age of the assessments, and expands the categorization of available input data. Appendix A provides a detailed description of the levels of each category in Table 10.1.

Table 10.1. NOAA Fisheries' Stock Assessment Classification System. Seven attributes will be used to classify individual stock assessments. Quantitative levels are defined for input data attributes to support gap analyses.

	Attribute	Level
Assessment Application	**Model Category**	• Data-Limited • Index-Based • Aggregate Biomass Dynamics • Virtual Population Analysis • Statistical Catch-at-Length • Statistical Catch-at-Age
	Age	• Years since assessment conducted
Input Data	**Catch**	0. None 1. Major gaps preclude use 2. Major gaps in some sector(s) 3. Minor gaps across sectors 4. Minor gaps in some sector(s) 5. Near complete knowledge
	Size/Age Composition	0. None 1. Major gaps preclude use 2. Support data-limited only 3. Gaps, but supports age-structured assessment 4. Support fishery composition 5. Very complete
	Abundance	0. None

		1. Uncertain or expert opinion 2. Standardized fishery-dependent 3. Limited fishery-independent 4. Comprehensive fishery-independent 5. Absolute abundance
	Life History	0. None 1. Proxy-based 2. Empirical and proxy-based 3. Mostly empirical estimates 4. Track changes over time 5. Comprehensive over time and space
	Ecosystem Linkage	0. None 1. Informative or used to process input data 2. Random variation, not mechanistic 3. Direct linkage(s) 4. Linkage(s) informed by process studies 5. Fully coupled

Overall, the Stock Assessment Classification System will improve national tracking of NOAA Fisheries' stock assessments and will provide a clear picture of the data available for each assessment. Further, the new categories specific to ecosystem linkages and size and age data will provide a more comprehensive understanding of how these key aspects of fish stock dynamics are being incorporated into stock assessments.

10.3. Prioritizing stock assessments

Historically, fish stock assessment prioritization has been conducted following independent regional processes. Each of the eight Regional Fishery Management Councils, in conjunction with their corresponding NOAA Fisheries science centers and regional offices, establish stock assessment schedules for the stocks under their management purview. These organizations utilize independent processes to identify and prioritize stocks in need of assessment. For instance, essentially all stocks managed by the North Pacific Fishery Management Council are assessed annually or biennially. By contrast, due to limited data availability, assessments are infrequent or yet to be conducted on stocks managed by the Caribbean Fishery Management Council. Within these extremes, most regional processes are informed by a multitude of factors when selecting the stocks to be assessed in a given year. Additionally, NOAA Fisheries supports and conducts assessments of stocks managed by state, interstate, or international organizations. In many cases, the assessment schedules for these stocks are established by the partner agencies.

Given that the socioeconomics, fishery dynamics, and species harvested are unique for each region, regional processes must determine assessment schedules. However, using a range of independent approaches among the regions is challenging for stakeholders that need to understand why certain assessments are conducted in a given year. If each region follows a unique protocol, it is difficult to track how assessment schedules are determined. This limits NOAA Fisheries' ability to evaluate stock assessment capacity from a national perspective, because the overall demand for stock assessments can be unpredictable when various approaches to scheduling are used. For federally managed stocks, annual catch limits are a required component of fishery management plans. Yet, NOAA Fisheries' current stock assessment capacity is not sufficient to support assessments of all federally managed stocks each year. For stocks that are relatively stable over time, it may be unnecessary to conduct annual stock assessments; however, to achieve optimum yield for fisheries, many stocks may need annual assessments. Using an objective process to establish the list of stocks in need of assessment and the frequency at which those assessments should be conducted would provide important guidance for NOAA Fisheries to determine how best to allocate federal resources to address regional needs. Thus, maintaining a transparent and predictable prioritization process is crucial for maximizing the usefulness of overall assessment capacity to meet national mandates.

10.3.1 A national protocol for prioritizing stock assessments

The national prioritization process for stock assessments is based on the concept that it is not necessary to conduct the most data-rich, ecosystem-linked assessment for every stock every year. That level of effort is not needed to achieve good management of fisheries. Stable stocks and their fisheries get little benefit from frequent reassessment. Minor stocks may be of less overall importance relative to the cost of an assessment, but they can be managed well enough if they occur in a complex with other, well-assessed and well-managed stocks.

NOAA Fisheries has developed a standard protocol for prioritizing fish stock assessments (Methot, 2015). The purpose of this protocol is to provide an objective framework that will help guide regional decisions about which stocks require assessment and the level at which those assessments should be conducted. This framework can be adapted to best suit regional needs and is expected to continue to evolve. For each region, this national protocol represents one of many potential factors to consider when determining assessment schedules. However, by using this standardized approach, there will be an objective basis against which difficult or controversial decisions can be evaluated.

This section, along with Tables 10.2 and 10.3, provide a brief summary of the prioritization protocol. Section 10.3.2 then expands upon the protocol by describing a process for setting target assessment levels for each stock. Thus, this document should be used along with Methot (2015) to fully understand and implement the national prioritization process.

A summary of the five main elements of the prioritization protocol are provided in Table 10.2. NOAA Fisheries is pursuing full implementation of the prioritization protocol, and this process is a crucial piece of the NGSA enterprise described in this document. The original process described by Methot (2015) uses 14 factors (Table 10.3) and combines them using formulas that identify target assessment frequencies for each stock, as well as scores and ranks that establish relative priorities for stocks needing assessments. Additionally, the factor concerning the presence of new information can guide decisions about whether an assessment should be conducted as a routine update, a more involved benchmark assessment, or addressed separately in a research assessment track (10.5.2).

Overall, regional planners should aim to achieve a feasible workload that addresses the highest priorities. For example, a mix that includes a few new and/or benchmark assessments and many more routine updates is likely manageable under current assessment capacity. Conducting assessments at a higher frequency than is proposed or on stocks that can be managed with minimal baseline monitoring is unnecessary and represents an inefficient use of assessment and management resources.

Table 10.2. Overview of the national protocol for prioritizing fish stock assessments.

1. Who	• NOAA Fisheries in collaboration with regional experts and managers conduct prioritization in each region
2. What	• Determine and include the stocks that require assessments versus those that can be sufficiently managed through baseline monitoring
3. When	• Intended to inform the scheduling of annual assessments • Total annual effort required for the prioritization process will decrease after initial implementation
4. How	• Regional experts develop scores for 14 factors • 9 factors establish target assessment frequencies • Managers develop weights for 12 factors, including assessment frequency, to reflect regional priorities • Calculate and rank weighted scores for 12 factors • Use results as objective guidance for scheduling assessments

Table 10.3. The 14 factors used in NOAA Fisheries' national stock assessment prioritization protocol, 9 of which are used for determining target assessment frequency and 12 are used to establish priority for assessments.

Factor	Scoring Range	Scoring Based On	Target Assessment Frequency	Determine Annual Priorities
Commercial Fishery Importance	0 to 5	National catch and value databases; calculated as $\log_{10}$(1 + landed catch value)	X	X
Recreational Fishery Importance	0 to 5	Regional recreational fisheries expert opinion	X	X
Importance to Subsistence	0 to 5	Regional fisheries expert opinion	X	X
Rebuilding Status	0 or 1	National stock status database	X	X
Constituent Demand	0 to 5	Regional fisheries expert opinion	X	X
Non-Catch Value	0 to 5	Regional fisheries expert opinion	X	X
Relative Stock Abundance	1 to 5	Most recent spawning biomass and target/threshold levels, as available from SIS database		X
Relative Fishing Mortality	1 to 5	Most recent fishing mortality estimates and limit levels, as available from SIS database		X
Key Role in Ecosystem	1 to 5	Maximum of bottom-up and top-down components; assigned by regional fisheries expert opinion	X	X
Unexpected Changes in Stock Indicators	0 to 5	Regional fisheries expert opinion, where indicators are available		X
New Type of Information	0 to 5	Regional fisheries expert opinion		X
Years Assessment Overdue	0 to 10	Calculated as: year for setting priorities - year of last assessment - target assessment frequency + 1 year		X
Mean Age in Catch	value	Recent average of mean age; direct measurement or assessment estimates	X	
Stock Variability	-1 to +1	Coefficient of variation (CV) for recruitment from assessment estimates	X	

*SIS = Species Information System

10.3.2. Stock assessment targets—an expansion of the national prioritization protocol

As described in *Prioritizing Fish Stock Assessments* (Methot 2015), elements of the national prioritization process require further development. In general, there is a need to stress that the prioritization process is one of several decision-making tools being used in federal fisheries management, including already established regional prioritization processes (the national process can provide additional information). To maintain consistency and capitalize on multiple efforts, it is important that the results of other national exercises, such as the climate vulnerability analyses recommended in the National Climate Science Strategy (Link et al., 2015) be officially included in the stock assessment prioritization process. These results can be used to help guide expert opinion in developing scores for several existing factors (e.g., "Unexpected changes in stock indicators" and "New type of information") and in the new steps described below.

A primary focus in the prioritization document (Methot 2015) was to describe a process for setting target assessment frequencies. This process can be summarized as follows:

1. Begin with mean age in catch (or proxy)
2. Multiply by a regional scaling factor (default = 0.5)
3. Adjust for recruitment variability
    a. -1 year: Recruitment CV > 0.9
    b. +1 year: Recruitment CV < 0.3
4. Adjust for fishery importance
    a. -1 year: Stock in top 33% of regional fishery importance
    b. +1 year: Stock in bottom 33% of regional fishery importance
5. Adjust for ecosystem importance
    a. -1 year: Stock in top 33% of ecosystem importance
    b. +1 year: Stock in bottom 33% of ecosystem importance
6. Results will be between 1 and a maximum of 10 years

There is no need to refine the process for setting target assessment frequencies here, but what follows are several new steps in the prioritization process that serve as guidance for setting target assessment levels. These new steps were developed because the prioritization document indicated that this aspect of prioritization would be developed in this revised SAIP. By expanding the process here, stock assessment prioritization will be aligned with the design of a next generation stock assessment (NGSA) enterprise.

The assessment level essentially reflects the types of data included in an assessment, so in effect a target assessment level establishes priorities for data collection and analytical techniques. The Stock Assessment Classification System (Table 10.1) describes how comprehensive each assessment was conducted according to five data input categories. Thus, to align the national prioritization protocol with the NGSA enterprise, the process for setting target assessment levels described next directly corresponds to the five categories of the classification system. This approach will facilitate a comprehensive gap analysis that compares current assessment levels to target levels.

The following guidance is proposed to describe how the national prioritization protocol can be used to establish targets for each of the five stock assessment categories. This guidance serves as an addendum to Methot (2015) and should be implemented as part of that process. The process described here is for setting baseline target assessment levels that should be evaluated and considered in the context of other existing information. For example, the results of other strategic efforts, such as NOAA Fisheries' Climate Vulnerability Analyses (Link et al., 2015), may be used to adjust baseline targets. Also, decision analysis tools, such as management strategy evaluations, represent comprehensive approaches that can be used to evaluate data tradeoffs and determine target assessment levels. When available, the results of more thorough research and decision analyses should serve a primary role in establishing target assessment levels. Adjustments to this approach to target setting will become apparent as testing and implementation develop in each region. However, after a consistent approach is fully implemented, it is anticipated that targets will remain relatively stable over time. Significant shifts in targets will most likely be a result of notable changes, such as emerging fisheries, substantial changes in market dynamics, major ecosystem shifts, or the development of groundbreaking technologies and/or research.

Target catch level: Because most stock assessment models assume a high degree of certainty, if not complete certainty in the amount of fish removed by the fishery, it is important to strive for complete knowledge of catch when stocks are being assessed with traditional statistical methods. However, when a stock is subject to little or no fishing, limited catch monitoring may be appropriate. Given these fairly stark needs regarding catch monitoring, the following describes a simple framework for establishing target catch levels. The target levels for catch and all following attributes correspond to the levels described in Table 10.1. Various levels for the factors in Table 10.1 were not considered to be appropriate targets; thus, there may not be a scenario in the following tables that corresponds to each level in Table 10.1 (i.e., certain levels are skipped).

Target Catch Level	Stock Scenario
0	• Stocks not caught as target or bycatch in any fishery
2	• Stocks subject to very minimal catch so that fishing-induced mortality most likely does not have measurable effects on stock dynamics
5	• All other stocks

Target size and/or age composition level: Stock assessments that include size or age composition data produce more complete descriptions of the effects of fishing on fish stocks than assessments that do not include this information. Also, if natural mortality is estimated within a stock assessment model, including composition data may improve the ability to estimate this mortality (Magnusson and Hilborn, 2007). However, collecting and processing composition data requires significant allocation of resources, so it may be unnecessary to include this information in assessments of lower profile stocks. Three of the four factors that determine target assessment frequency from the prioritization protocol (recruitment variability, fishery importance, and ecosystem importance) represent metrics that, together, are useful for determining the importance of age/size composition data. The remaining assessment frequency factor (mean age in the catch) is not as useful. Thus, to establish target levels for size and/or age composition data, the following formula is recommended to calculate an importance metric, which adjusts the target assessment frequency equation from Methot (2015) by excluding the scaled mean age in the catch:

Calculating Size/Age Importance

1. **Set Size/Age Importance = 0**
2. **Adjust for recruitment variability (using the coefficient of variation – CV)**
   a. -1 when recruitment CV > 0.9
   b. +1 when recruitment CV < 0.3
3. **Adjust for Fishery Importance**
   a. -1 when stock is in top 33% of regional fishery importance
   b. +1 when stock is in bottom 33% of regional fishery importance
4. **Adjust for Ecosystem Importance**
   a. -1 when stock is in top 33% of regional ecosystem importance
   b. +1 when stock is in bottom 33% of regional ecosystem importance

Possible values range from -3 to 3

Target Size/Age Composition Level	Stock Scenario
0	• Stocks that are not a priority for assessments
2	• Stocks with Size/Age Importance > 1
4	• Stocks with Size/Age Importance from -1 to 1
5	• Stocks with Size/Age Importance < -1

Target abundance level: When stock assessments incorporate indices of abundance or biomass, the indices are used as observed changes over time (i.e., input data about abundance or biomass patterns). Thus, assessment results can be biased when observed trends do not reflect actual dynamics, and it has been shown that fishery catch rates can be misleading about abundance (Cooke and Beddington, 1984). In some cases, estimates of absolute abundance should be included in an assessment rather than indices of relative abundance. Further, in the absence of stock assessments, abundance trends serve as useful indicators of stock dynamics for baseline monitoring. The usefulness of abundance data and the limitations associated with fishery catch rates suggest that fishery-independent monitoring of abundance should be in place for most managed stocks. Thus, in the following scenario we recommend high targets for abundance levels, except for stocks not subject to fishing mortality.

Target Abundance Level	Stock Scenario
0	• Stocks not caught as target or bycatch in any fishery and in the bottom 33% of regional ecosystem importance
3	• Stocks subject to very minimal catch so that fishing-induced mortality most likely does not have measurable effects on stock dynamics
4	• Stocks subject to fishing-induced mortality and not in the top 33% of regional fishery or ecosystem importance
5	• Stocks in the top 33% of regional fishery or ecosystem importance • Stocks subject to measureable fishing-induced mortality, but with uncertain catch data (Catch Level < 3) • Stocks for which absolute abundance estimates are feasible

Target life-history level: High-quality information about a stock's life history facilitates the ability to isolate and evaluate fishing impacts, and improves overall assessment accuracy and precision. The highest levels of life-history data should be reserved for stocks that require more complete evaluations of the effects of fishing, while stocks with relatively lower importance can be successfully managed with less detailed life-history information. The approach to determining size/age composition levels is useful here, and in fact, there are strong connections between the role of life history and size/age composition data in an assessment model. Therefore, the approach to setting target life-history levels mimics that for size/age composition.

Target Life History Level	Stock Scenario
0	• Stocks that are not a priority for assessments
2	• Stocks with Size/Age Importance > 1

4	• Stocks with Size/Age Importance from -1 to 1
5	• Stocks with Size/Age Importance < -1

Target ecosystem linkage level: Determining when and how to directly account for ecosystem dynamics within a stock assessment is not a straightforward process. In some cases, unexplained drifts in assessment results (e.g., retrospective biases) indicate that additional factors should be included, but often there is not sufficient information to identify the specific drivers that were overlooked. In other cases, research studies have described connections between specific ecosystem dynamics and stock productivity, but the ability to model and/or forecast the relationship may be limited. Further, it has been shown in certain scenarios that including ecosystem factors may not always improve the ability to achieve management objectives (Punt et al., 2013). In many cases, empirically based approaches that use ecosystem information to guide management decisions may be more appropriate than to directly include that information in the analytical framework. As mentioned in Chapter 8, decisions on creating ecosystem linkages in stock assessments are made in the context of the following range of decisions:

1. Based on the stock's value, status, and biology, is there an incentive to expand its assessment to include ecosystem or socioeconomic factors?
2. Is there evidence to suggest that stock or fishery dynamics are tightly coupled with some variable ecosystem or socioeconomic feature?
3. Are data available to model this relationship within the assessment framework?
4. Can ecosystem or socioeconomic dynamics be incorporated in a way that maintains a manageable assessment model?
5. Can the relationship between stock, fishery, and ecosystem or socioeconomic dynamics be forecasted with at least a moderate degree of certainty?

In general, the standard for including ecosystem information is lowest for Decision 2 above, but raises through Decision 5, which itself presents a substantial challenge to linking assessments to dynamic ecosystem features. However, if the answer to Decision 2 is "yes," but there is not sufficient data or capabilities to meet Decisions 3, 4, or 5, then gaps have been identified, which then may be addressed to improve the assessment.

Given the complexity of marine systems, the challenges associated with creating and forecasting reliable mechanistic ecosystem linkages in stock assessments, and variable benefits to incorporating these linkages into assessments, decision analysis tools (such as MSEs) should be used for evaluating when and how to expand single-species stock assessment models to include ecosystem features. When available, the results of these analyses should serve as default advice for guiding target levels for the ecosystem linkage category. In general, stocks that are good candidates for linking assessments to ecosystem dynamics include those that serve as key forage, that rely heavily on a specific habitat during one or more life stages, and that are particularly sensitive to fluctuations or shifts in environmental conditions (e.g., temperature). Further, higher profile stocks warrant strong consideration of ecosystem linkages to maximize economic opportunity while being responsive to potential changes or shifts in dynamics, thereby ensuring long-term resiliency. The role of ecosystem variability and change should be at least considered in the development or improvement of every stock assessment. However, in the absence of results from more complete decision analyses, we offer the following approach that uses an Ecosystem Linkage Index (ELI) that builds mainly off the information already being assembled for stock assessment prioritization.

Calculating Ecosystem Linkage Index (ELI)

1. **Set ELI = 0**
2. **Adjust for recruitment variability (using the coefficient of variation – CV)**
    a. -1 when recruitment CV > 0.9
    b. +1 when recruitment CV < 0.3
3. **Adjust for Fishery Importance**
    a. -1 when stock is in top 33% of regional fishery importance
    b. +1 when stock is in bottom 33% of regional fishery importance
4. **Adjust for Ecosystem Importance**
    a. -1 when stock is in top 33% of regional ecosystem importance
    b. +1 when stock is in bottom 33% of regional ecosystem importance
5. **Adjust for Habitat Association**
    a. -1 if it is clear that a stock relies on a particular habitat niche that is sensitive to ecosystem change during one or more life stages (e.g., anadromous species)
    b. +1 if stock is thought to easily adapt to changes in physical properties of the ecosystem
6. **Adjust for Model Issues**
    a. -1 if current assessment model exhibits issues that may be appropriately addressed by including ecosystem dynamics (e.g., retrospective or residual patterns)

Possible values range from -5 to 4

Target Ecosystem	**Stock Scenario**

Linkage Level	
0	• Stocks that are not a priority for assessments
1	• Stocks with ELI > 2
2	• Stocks with ELI from -3 to 1
4	• Stocks with ELI = -4
5	• Stocks with ELI = -5

***NOTE: This approach should be used only when more complete research or decision analyses, such as MSEs, are not available to guide decisions about creating ecosystem linkages.**

If the ELI suggests a certain stock is a high priority for building ecosystem linkages into the assessment, but there is not the capability to do so, then this may indicate a need for additional research, data collection, and management strategy evaluations to determine how to address the potential gap.

10.4.0 Establishing a right-sized stock assessment enterprise

The new Stock Assessment Classification System (Table 10.1, Appendix A) and expanded assessment prioritization protocol provide a national framework that will inform strategic decisions regarding the national stock assessment enterprise. The classification system will be used to identify how stock assessments are currently being conducted, and the expanded prioritization protocol will be used to set target levels for each assessment. This national framework is meant to enhance, not replace, ongoing regional approaches to determining assessment priorities, which involve important collaborations among NOAA Fisheries, management organizations, and stakeholders. Discussions among these regional expert groups will necessarily remain the primary source of input for setting assessment objectives, but the framework described here offers a consistent planning tool that supports discussions about target levels. By comparing existing levels to targets, regional stock assessment gaps can be identified and prioritized. The majority of these gaps will concern data for assessments, but some will be related to research and modeling improvements. Because there are ongoing regional processes and multiple strategic efforts underway at NOAA Fisheries (Figure 1.1), the stock assessment gaps identified through this process will be evaluated alongside the results of these other efforts.

The initial work needed to collect the information for each stock is substantial, but after it is collected and a data management infrastructure is established, updating and maintaining stock-specific details should be fairly straightforward. The intention is that information will be reviewed and updated annually, if necessary, to inform near-term assessment scheduling and investments. The process will likely evolve in the initial years as it is tested and implemented until it produces objective results that are most useful to regional planners.

10.5. Standardized approaches

The process of conducting stock assessments in NOAA Fisheries has developed somewhat independently by region and management jurisdiction. Also, many assessment processes have expanded in scope over time to include more data as enhanced data collection programs and research studies have become available, involved more participants, and included more thorough, independent, scientific reviews of the assessments. As regional processes developed and expanded, they became associated with varying degrees of efficiency. In most cases, differences in efficiency across regions can be attributed to regional attributes, such as the number of states and partners involved in monitoring catches, number and types of fisheries, and diversity of species and habitats. This variability across regions limits the degree to which assessments can be standardized. Nevertheless, establishing and using more standardized approaches may improve efficiency overall and contribute to a more transparent and understood process.

A high throughput of assessments cannot be accomplished if lead assessment scientists must be engaged in building input data sets from raw fishery and survey data, and if the assessment methods themselves are in constant flux. A mature assessment enterprise needs to separate research efforts where innovations can be freely explored from operational efforts where assessment results are delivered to fishery managers. Standardized data systems can keep a wide range of indicators updated and can deliver processed data in a form ready to be used in assessment models. Standardized models make it easier for less experienced analysts to complete assessments, easier for fuller development of the model itself, easier for reviewers of model results, and easier to communicate to constituents and managers. Yet, standardization cannot stand in the way of innovation. There needs to be a parallel track for conducting research on population dynamics, statistics, and other fields; and a deliberate process by which good research is transitioned into the operational models. Also, standardized processes should not be completely rigid so they can accommodate the high diversity of stocks, fisheries, jurisdictions, and so on.

10.5.1 Stock assessment analytical tools

Over the past several decades, the analytical tools and approaches used in fishery stock assessments have evolved rapidly. These advances have been a benefit to sustainable fisheries management, and growth in this field will only continue. Development of stock assessment software and tools, including those for data processing, running assessment models, and developing forecasts, are typically performed by stock assessment and fishery scientists (as opposed to software developers). It is crucial that assessment scientists be involved in these developments, because not only do they need complete conceptual and practical understanding of the tools, they also have the knowledge necessary to design tools that are applicable in specific assessment scenarios. However, because fishery assessment and management systems have developed according to a regional design, many regions have produced tools with very similar features. NOAA Fisheries has numerous scientists with a wide variety of expertise and capabilities for developing assessment tools, and development often may draw from a vast professional network that extends outside NOAA. With a capacity at this scale, tremendous efficiency could be gained by a unified, community approach to sharing expertise and developing assessment tools. This approach would also facilitate increased use of fewer standard tools, which would improve efficiency in both conducting analyses and in understanding and reviewing the assessments. Additionally, partnering with professional software developers could facilitate enhanced functionality, maintenance, stability, and also free up time for NOAA scientists to engage in important assessment and fishery-related research projects. The recommendations presented in Box 10.1 relate to the development, provision, and use of stock assessment analytical tools.

Box 10.1. Recommendations for Development of Analytical Tools

1. **Provide national coordination of stock assessment tools and use professional software development practices.**
2. **Develop tools in community and cloud-based environments to capitalize on diverse expertise from a variety of collaborators.**
3. **Use standardized, tested, verified, and fully documented tools in operational assessments to facilitate efficient and well-understood analyses.**
4. **Increase opportunities for NOAA scientists to conduct research related to assessment analyses.**

10.5.2 The stock assessment process

Fishery stock assessments represent an applied operational science that provides fundamental information to fishery managers for setting harvest regulations. Industries, small businesses, and individuals plan around these management decisions; thus, it is imperative that the scientific advice be timely, transparent, and reliable. Further, to facilitate planning, many stakeholders value long-term stability in regulations. Given the role of stock assessments in fishery management, it is important that consistent, well understood, and thoroughly reviewed methods be used to conduct operational assessments. The process by which assessments are conducted currently varies by region, which is suitable given that fisheries management is an inherently regional process. However, some assessment processes can further be improved in regard to one or more of the preferred qualities (timeliness, transparency, and/or stability).

The framework for conducting and reviewing stock assessments described in Table 10.4 is recommended as a general structure for regions to use and adapt according to their needs. The driving concept behind this framework is to provide a streamlined approach to updating scientific advice for managers using *operational assessments*. Major changes to model configurations, data sources, etc. would then be evaluated in *research assessments* that do not produce the scientific advice that is being used for management. The operational assessments then use methods that have already been independently reviewed. These assessments can be applied to develop scientific advice for fishery managers without the additional scrutiny of the methods and would be reviewed with a focus on the application of those methods. The research assessments are evaluated for their usefulness to consider in future operational assessments.

Table 10.4. Recommended process for conducting operational and research stock assessments.

	Operational Assessment	Research Assessment
Preparation	• Stocks selected for assessment based on results of national assessment prioritization protocol. • Streamlined, integrated data systems provide efficient access to data in formats needed for assessments and are publicly accessible and transparent to facilitate additional investigations. • General tools provide timely public access to data summaries and figures. • The suite of analytical tools used in the assessment is accessible, documented, tested, and independently reviewed prior to use.	• Occur as needed to improve operational assessments. • Scoped to evaluate, test, document, and review potential changes to operational assessments (not to provide advice to managers). • Connected to research recommendations from previous operational assessment; evaluated soon after completion to prioritize importance and feasibility of addressing recommendations in a research assessment. • Broad interdisciplinary engagement upfront is encouraged so a range of expertise can be used to inform assessment improvements. • Stakeholder involvement is also encouraged so outside data, analyses, and ideas can be evaluated, and trust in potential changes is built from the beginning.
Conduct	• Designated analysts use a suite of previously reviewed procedures and data sets. • Assessment model or suite of models configured according to previously accepted specifications.	• New procedures, data sets, and configurations are made available to address issues with operational assessments and/or make general improvements. • The scope of improvements may include ecosystem and socioeconomic drivers and considerations, and

	• Minor changes to previous approaches are acceptable, especially to account for issues that may arise as a result of additional years of data. • A full exploration of model sensitivity is not necessary as that should have been conducted during the research assessment (the accepted suite of models is used to characterize observational and structural uncertainties). • Primary objectives are to update stock abundance forecast and provide probability distributions of future catch based on the harvest control rule and characterize recent and projected overfishing and overfished statuses.	management strategy evaluations represent one framework recommended for use in these investigations. • Improvements may include harvest policy investigations and/or use of simpler methods to achieve management objectives and/or use as interim approaches between more involved assessments. • Research assessments should be applied to particular stocks and evaluated against the recent operational assessment (using the actual assessment data at some point) to determine the influence of the proposed improvements (both long-term and short-term effects should be evaluated). • For research assessments to be accepted into the next operational assessment there must be a long-term commitment to collect and provide the accepted data and methods.
Documentation and Review	• Documentation of results should be concise with information relevant for fishery management summarized clearly upfront. • Analytical techniques should be summarized very briefly with reference to original descriptions. • Data sources can also be referenced and do not need full descriptions, just depiction of major trends. • Uncertainty should be characterized for all results, and decision tables should be used to summarize uncertainty and risk associated with a range of management decisions. • Anomalies, concerns, and research recommendations documented for future consideration.	• New procedures, data, and findings with application to particular stocks should be fully documented to support use and serve as reference in future operational assessments. • Documentation may be prepared as an assessment report, technical memorandum, and/or peer-reviewed publication equal to the scope and novelty of changes. • Unresolved issues and additional research recommendations should be documented to inform future research assessments. • Independent, comprehensive review is conducted to provide objective evaluation of proposed changes. • Review panels may include some regional expertise, but should be independent of analysts and should include fully external reviewers (such as through the CIE) equal to the degree of controversy and novelty of the proposed changes.

	• Review is streamlined for quality assurance by a standing committee of regional experts. • Review is not intended to make harvest-level recommendations, determine stock status, or declare whether the best scientific information available was used, but rather to evaluate whether the previously approved approach was applied correctly. • If the new application of an operational assessment is not deemed appropriate for management, a default approach to generating catch advice should be established and agreed to upfront.	• Review panels should focus on the scientific merits and feasibility of implementing proposed changes relative to current operational assessments with less of a focus on interpretations, applications, and consequences of assessment results. • Review panels should not expect all issues to be resolved and therefore should not be asked to accept/reject the entire assessment, but rather should evaluate each component to facilitate future use of one or more proposed changes. • Major changes identified by review panels should not be expected to be addressed immediately but should be considered as additional research recommendations.

Completion of a technically accurate assessment is not the final step of an effective assessment. The results must be communicated to a diverse range of constituents to achieve success.

Because the operational assessment process is intended to be as efficient as possible, there is a need for standardized approaches to documentation. Yet, to trust the results, affected constituents must get enough information about the assessment and the data and methods supporting it. Fishery managers also must receive assessment products that clearly describe the risks and benefits of possible controversial decisions. Fellow scientists must have access to detailed results in order to conduct meta-analyses and other comparative studies. Deliberate development of the right communication product for each audience is needed. A succinct and standard reporting template can reduce the time required for compiling results and facilitate access of results to fishery managers and other interested parties, not just regionally, but nationally as well. Further, by using a standardized template, the primary assessment results can be compared and evaluated across stocks. This step may be particularly important for making management decisions within a fishery management plan that contains multiple stocks. Managers and stakeholders may also benefit from easy access to other information and analyses, not just the primary stock assessment results (e.g., the prioritization results and stock-specific targets described previously, summaries of important stock indicators, and climate vulnerability analyses). Appendix B provides a recommended template (completed with a case study) that attempts to summarize the results of an operational stock assessment as well as additional information. This template attempts to provide brief organized access to the primary information for which most assessments are accessed, and its use would provide consistent national representation of NOAA Fisheries' stock assessment results.

Finally, regardless of whether operational or research assessments are conducted, scientific products used to support fishery management should have a level of review that corresponds with the degree of novelty of the work, and the controversy and importance of the resulting management action. Extensive review processes have been developed in all regions (Chapter 6), and some have become so intensive that the throughput of assessments is constrained. Effective certification that the best scientific products are being used can be attained with a modified review approach built around the separation of research from operations and the use of standardized data and methods. The most extensive and intensive review involving highly independent external reviewers should be focused on the research products that are designing and developing new methods. Here the alternative experiences and backgrounds of the external reviewers can make the greatest contribution to improved methods. Then, application of these accepted standardized methods to the most recent standardized data can receive sufficient quality assurance when reviewed by knowledgeable regional experts, including council's Scientific and Statistical Committees, who have good knowledge of regional data sources and assessments for other stocks in that region.

Whether comprehensive and fully independent, or streamlined through standing committees, reviews are most beneficial when guided by clear terms of reference (ToR). These terms should ensure that reviews focus on the science conducted to support fisheries management given the information available at the time. Although reviewers can provide important research recommendations, those recommendations should be reserved for future research assessments, and current reviews should not be contingent on incorporation of those recommendations. Further, it is not appropriate for review panels to perform management actions, such as determining stock status, harvest recommendations, or formal declarations about the assessment representing the best scientific information available. The focus of the review is to determine which, if any, major issues may limit the usefulness of the assessment for fishery managers relative to what is already available. Along those lines, reviews should be conducted in a way that facilitates use of components of the stock assessment, rather than a simple accept/reject of the entire package. To promote an effective and efficient review of operational stock assessments, Box 10.2 includes a suite of generic statements that are recommended for inclusion in review terms of reference. These statements intend to help focus reviews so that they are most helpful to the assessment–management process. For research assessments, there is less of a need to constrain the peer review ToR because the scope of potential changes to an assessment are broad and can be evaluated in a variety of ways. However, it should be very clear in ToR for research assessments that the review is focused on the proposed changes and whether they would result in an improved operational stock assessment.

10.6. Conclusions

In this chapter, a number of process-oriented changes are recommended that may affect NOAA Fisheries' stock assessment programs as well as our fishery management partners and stakeholders. These recommendations have been carefully vetted with the overall goal of creating a timelier, more efficient, and more effective stock assessment enterprise. Although adoption of these recommendations may require an investment of time and resources from NOAA Fisheries and our partners, the long-term gains will offset the short-term costs.

Box 10.2. Recommended statements to include in operational stock assessment review terms of reference (ToR)

- Determine, according to the best of your knowledge, if all data considered for use in the stock assessment were made available with sufficient time to review and evaluate their utility to the assessment. If not, please explain.
- Of the data considered for inclusion in the assessment, determine if final decisions on inclusion/exclusion of particular data were appropriate and justified. If not, please explain.
- Determine whether the final data that were included in the stock assessment were prepared and processed appropriately, and potential sources of bias were addressed and/or documented appropriately. If not, please explain.
- Given the data selected for use in the assessment, determine if the methods used to analyze those data and characterize uncertainty were appropriate and sufficient for accomplishing the following:
  (For each category, if you feel the methods were not appropriate or if previous analyses are more appropriate, please explain.)
    - Estimating biological reference points related to stock size
    - Estimating biological reference points related to fishing intensity
    - Estimating stock size in the final assessment year
    - Estimating fishing intensity in the final assessment year
    - Estimating an historical time series of stock size
    - Estimating an historical time series of fishing intensity
- If applicable, please review the methods used for forecasting, including the characterization of uncertainty, to determine whether they were appropriate and sufficient for the following:
  (For each category, if you feel the methods were not appropriate or if previous analyses are more appropriate, please explain.)
    - Developing harvest recommendations for the next 1–4 years
    - Developing harvest recommendations beyond 4 years
    - Projecting biomass relative to corresponding biological reference point(s)
    - Projecting fishing intensity relative to corresponding biological reference point(s)

*Note: The structure of ToR in review of research stock assessments should be less constrained than ToR for operational assessments, and should be designed to focus the review on any changes to the assessment that are being proposed and whether these changes would likely improve the next operational assessment.

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SECTION IV. SUMMARY, RECOMMENDATIONS, AND IMPLEMENTATION

PLACEHOLDER, TO BE COMPLETED

Acronyms

ABC – Acceptable Biological Catch
ACLs – Annual Catch Limits
ADMB – Auto Differentiated Model Builder
AFSC – Alaska Fisheries Science Center
AKFIN – Alaska Fisheries Information Network
AKRO – Alaska Regional Office
ASMFC – Atlantic States Marine Fisheries Commission
BSIA – Best Scientific Information Available
CESUs – Cooperative Ecosystem Studies Units
CFMC – Caribbean Fisheries Management Council
CIE – Center for Independent Experts
CIs – Cooperative Institutes
CPUE – Catch Per Unit Effort
CWA – Clean Water Act
CZMA – Coastal Zone Management Act
EBFM – Ecosystem-based Fisheries Management
ELI – Ecosystem Linkage Index
EM/ER – Electronic Monitoring and Electronic Reporting
ESA – Endangered Species Act
FIS – Fisheries Information System
FMC – Fisheries Management Council
FMO – Fisheries Management Organization
FO – Fisheries Organization
FSC – Fisheries Science Center
FSSI – Fish Stock Sustainability Index
GARFO – Greater Atlantic Regional Fisheries Office
GMFMC – Gulf of Mexico Fisheries Management Council *****
HAIP – Habitat Assessment Improvement Plan
HMS – Highly Migratory Species
IEAs – Integrated ecosystem assessments
IUU – Illegal, Unregulated, and Unreported fishing
LMRCSC – Living Marine Resources Cooperative Science Center
MAFMC – Mid-Atlantic Fishery Management Council
MARMAP – Marine Resource Monitoring and Assessment Program
MMPA – Marine Mammal Protection Act
MREP – Marine Resource Education Program
MRFSS – Marine Recreational Fisheries Statistics Survey
MRIP – Marine Recreation Information Program
MSA – Magnuson-Stevens Act
MSE – Management Strategy Evaluation
MSY – Maximum Sustainable Yield
NCSS– NOAA Fisheries Climate Science Strategy
NEAMAP – Northeast Area Monitoring and Assessment Program (Note: This is used twice, page 21 and 23, and both times the full thing was spelled out as well)
NEFMC – Northeast Fisheries Management Council
NEFSC – Northeast Fisheries Science Center
NEPA – National Environmental Policy Act
NGSA – Next Generation Stock Assessment
NPFMC – North Pacific Fisheries Management Council
NRC – National Research Council
NRCC – Northeast Regional Coordinating Council
NS1 – National Standard 1
NWFSC – Northwest Fisheries Science Center
OFL – Overfishing Level
PFMC – Pacific Fishery Management Council
PIFSC – Pacific Islands Fisheries Science Center
PIRO – Pacific Islands Regional Office
PRSAIP – Protected Resources Stock Assessment Improvement Plan

QUEST – Quantitative Ecology and Socioeconomics Training Program
RFMOs- Regional Fishery Management Organizations
RO – Regional Office
RTR – Research Training and Recruitment
SAFE – Stock Assessment and Fishery Evaluation
SAFMC – Southeast Atlantic Fishery Management Council
SAIP – Stock Assessment Improvement Plan
SAM – State-space Assessment Model
SAW/SARC – Stock Assessment Workshop/Stock Assessment Review Committee
SCAA – Statistical Catch-At-Age
SCAL – Statistical Catch-At-Length
SEDAR – Southeast Data, Assessment, and Review
SEFIS – Southeast Fishery Independent Survey
SEFSC – Southeast Fisheries Science Center
SERO – Southeast Regional Office
SSC – Scientific and Statistical Committee
STAR – Stock Assessment Review
SWFSC – Southwest Fisheries Science Center
TMB – Template Model Builder
ToR – Terms of Reference
UNOLS – University National Oceanographic Laboratory System
VPA – Virtual Population Analysis
WCR – West Coast Region
WPFMC – Western Pacific Fishery Management Council
WPSAR – Western Pacific Stock Assessment Review

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	Level					
Attribute	**0**	**1**	**2**	**3**	**4**	**5**
Catch	No quantitative catch data	Some catch data, but major gaps for some fishery sectors or for historical periods such that their use in assessments is not supported	Enough catch data establish magnitude of catch and trends in catch for a major fishery sector in order to apply a data-limited assessment method. This includes fisheries that are closed and it is known that negligible catch is occurring	Catch data is generally available for all fishery sectors to support quantitative stock assessment, but some gaps exist such as low observer coverage, high levels of self-reported catch, weak information on discard mortality	No data gaps substantially impede assessment, but catch is not without uncertainty (e.g., recreational catches estimated from surveys)	Very complete knowledge of total catch
Size and/or age composition	No composition data collected	Some size or age composition data has been collected, but major gaps in coverage, not used in assessment, or historically preclude use in assessments	Enough size or age composition data has been collected to enable data-limited assessment approaches	Enough size or age composition data is collected over a sufficient time series to be informative in age/size structured assessment models	Enough age composition data has been collected over a sufficient time series to enable assessments methods that need age composition data from the fishery	Very complete age and size composition data, including, as needed on stock-specific basis, knowledge of ageing precision, spatial patterns or other issues

Abundance	No indicator of stock abundance or trend in stock abundance over time	Fishery-dependent catch rates (CPUE) are available, but high uncertainty about their standardization over time; or expert opinion on degree of stock depletion over time	Fishery-dependent catch rates (CPUE) are sufficiently standardized to enable their use in full assessments	Limited fishery-independent survey(s) provide estimates of relative abundance; however, the temporal or spatial coverage of the stock is limited or the sampling variability is high	Complete fishery-independent survey(s) provide estimates of relative abundance, and the survey(s) cover a large proportion of the spatial extent of the stock with several years of tracking at a level of precision that supports assessments	Calibrated fishery-independent survey(s) or tag-recapture provide estimates of absolute abundance
Life history	No life history data	Estimates of most life history factors not based on empirical data; instead derived using proxies, meta-analyses, borrowed from other species, or without scientific basis	Estimates of some life history factors based on stock-specific empirical data, but at least one derived using life history proxies, meta-analyses, borrowed from other species, or without scientific basis. Generally supports data-poor assessments that use life history information	Estimates of most life history factors based on stock-specific empirical data	Data are sufficient to track changes over time in at least growth	No major gaps in life history knowledge, including detailed stock structure, spatial and temporal patterns in natural mortality, growth, and reproductive biology

Ecosystem linkage	No linkage to ecosystem dynamic or consideration of ecosystem properties (environment, climate, habitat, predator-prey, etc.) in configuring the assessment (i.e., equilibrium conditions assumed for ecosystem)	Ecosystem-based hypotheses inform the assessment model structure (e.g., defining the stock boundaries and/or spatial or temporal features) and/or are used for processing assessment inputs (e.g., abundance index), but no explicit linkage to any ecosystem drivers (environment, climate, habitat, predator-prey, etc.)	The assessment includes some form of variability or effect to explicitly account for unidentified ecosystem dynamic(s) (e.g., time/space "regimes", random variation, or other approaches to changing features without direct inclusion of ecosystem data)	One or more assessment features is linked to a dynamic (i.e., data) from at least one of the following categories: environment, climate, habitat, predator-prey data (e.g., covariate)	The assessment model is linked to at least one ecosystem dynamic, and one or more process studies directly support the manner in which environmental, climate, habitat, and/or predator-prey dynamics are incorporated (e.g., consumption rates measured and covariate informed by results)	The assessment approach is configured to be coupled or linked with an ecosystem process (e.g., multispecies, coupled biophysical, climate-linked models)

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