Atlantic States Marine Fisheries Commission

Management and Science Committee

October 29, 2019
8:30 a.m. – 5:00 p.m.
New Castle, New Hampshire

Draft Agenda

The times listed are approximate; the order of items is subject to change; other items may be added as necessary.

1.	Welcome & Introductions *(K. Knowlton)*	8:30 a.m.
2.	Approval of Agenda	8:40 a.m.
3.	Review Committee Roles and Past Projects *(M. Armstrong)*	8:45 a.m.
4.	Discuss Measuring Success in Rebuilding and Sustaining Stocks	9:15 a.m.
5.	Discuss Climate Change Impacts to Fisheries Resources	10:15 a.m.
6.	Overview of Management Strategy Evaluations *(J. McNamee)*	10:30 a.m.
	LUNCH	**12:00 p.m.**
7.	Overview of New MRIP Survey Data *(R. Andrews)*	1:15 p.m.
8.	Discuss Offshore Wind Development and Fisheries Interactions	2:30 p.m.
9.	Overview of USGS Scientific Support to ASMFC *(S. Faulkner)*	3:00 p.m.
10.	Review ASMFC Research Priorities	3:45 p.m.
11.	Other Business	4:30 p.m.
12.	Public Comment	
13.	Adjourn	5:00 p.m.

The meeting will be held at Wentworth by the Sea, 588 Wentworth Road, New Castle, NH; 603.422.7322

Fisheries Science Program Overview

Management and Science Committee

Committee Name: Management and Science Committee (MSC)

Purpose: The MSC is an oversight committee providing advice to the Commission, Executive Committee, or the Interstate Fisheries Management Policy Board on matters spanning coastal fisheries science and fisheries management. The MSC also carries out specific assignments requested by Commissioners. Its major duties are to:

1. Serve as the senior review body for the Commission, Executive Committee, and ISFMP Policy Board
2. Provide oversight to the Commission's Stock Assessment Peer Review Process
3. Upon request of the ISFMP Policy Board for any Management Board/Section, review and provide advice on species-specific issues
4. Evaluate the state of science regarding species interactions and provide guidance to fisheries managers on multispecies and ecosystem issues. Evaluations and/or recommendations focus on modifying the single-species approach in development of Commission fishery management plans and/or stock assessments
5. Evaluate and provide advice on cross-species issues, including tagging, ageing, invasive species, fish health, and protected species issues
6. Coordinate Commission technical and scientific workshops and seminars, when requested.

Membership: The MSC is comprised of one representative from each member state, the NMFS Northeast and Southeast Regions, and the USFWS Regions 4 and 5 who possess scientific as well as management and administrative expertise.

Codifying Document: ISFMP Charter

Type & Frequency of Meetings: MSC meets twice in person per year during the Commission's Spring and Annual Meetings.

Primary activities:

- Improving the peer review process through:
  - Updating the Benchmark Stock Assessment and Peer Review Process
  - Developing Terms of Reference for Peer Reviews
  - Identifying scientists to serve on Peer Reviews
  - Providing instructions to Peer Reviewers

- Identifying and prioritizing Research Needs for Stock Assessments and Fisheries Management
- Developing a Fish Ageing Manual to achieve consistent ageing methods among the states
- Identifying forage fish species of importance to management along the Atlantic Coast
- Provide direction and oversight to the Multispecies TC and Ecosystem Reference Points WG on predator-prey and ecosystem models for management advice

Major accomplishments:

Climate Change, Stock Distributions, and State Quota Allocations (2014)

- MSC investigated whether climate change and warming coastal water temperatures are causing shifts in the geographic distributions of several ASMFC managed fish stocks; where shifts are occurring, MSC created options for reconsidering the state-by-state allocation structure and need for adjustments.
- MSC collaborated with Northeast Fisheries Science Center (NEFSC) scientists to summarize the state of knowledge for focal species and to demonstrate distribution shifts for stocks where climate-induced changes are occurring.
- The MSC created a number of reallocation options to define the methods for adjusting state-by-state allocations. To determine the feasibility of each option, the Committee distributed a survey to ASMFC Commissioners. Based on Commissioner responses, the MSC compiled a set of reallocation option recommendations for the Policy Board.
- The MSC also recommended that the ISFMP Policy Board task individual species technical committees (TCs) with creating scenarios to explore how reallocation options might function for each stock.

Research Priorities in Support of Interjurisdictional Fisheries Management (2013)

- MSC assisted in compiling research needs that were prioritized by Commission stock assessment subcommittees and technical committees.
- MSC also developed a list of Critical Research Needs (2009) derived from the prioritized research needs document, to highlight the most pressing needs for each ASMFC managed species. Furthermore, a Comprehensive Research Needs list was derived from the critical research needs, to identify projects which would cover multiple species in a coordinated effort to address common research needs.
- Subsequent to updating and evaluating Research Priorities, MSC developed a multispecies fisheries observer proposal that was funded by ACCSP from 2010-2013

Fishing Gear Technology Work Group: Gear Evaluations in Priority Fisheries (2008)

- MSC provides oversight and tasks the FGTWG with evaluating gear issues (bycatch, habitat impacts) and new gear technology in fisheries impacting ASMFC species.
- The FGTWG completed an evaluation of gear technology for 10 Atlantic coast fisheries to define bycatch and discard impacts, and promote innovative technology to reduce finfish bycatch as well as protected species interactions

The Impacts of LNG and Alternative Energy Development on Fishery Resources Workshop (October 2006)

- Workshop to determine the most effective role for the Commission to assist the states in protecting fishery resources and fish habitat throughout the energy policy, development, permitting, and/or monitoring process in state coastal waters.

- Recommendations included: an ASMFC permit review policy, appoint a staff member to serve as a point of contact for energy related issues, develop a source document as guidance on energy related issues, advocating for more time on energy issues

Observer Program Workshop (July 2006)

- The MSC held a workshop to review state observer programs, to discuss opportunities for improved state-federal coordination of observer programs, and to identify and evaluate common issues across programs.

Power Plants publication: Assessing Coastwide Effects of Power Plant Entrainment and Impingement on Fish Populations: Atlantic Menhaden Example (April 2006)

- A method was developed for assessing coastwide effects of power plant impingement and entrainment on managed fish stocks.

Circle Hook Definition and Issues (July 2003)

- The ISFMP Policy Board called for an analysis of release mortality issues and the development of an enforceable definition of a circle hook. A Management and Science Committee (MSC) Workgroup comprised of hook manufacturers, ASMFC Commissioners, law enforcement representatives, recreational stakeholders, and technical personnel, was formed to address these charges.

Guidance Relative to Development of Responsible Aquaculture Activities in Atlantic Coast States (November 2002)

- In September 1998, the National Marine Fisheries Service (NMFS), in cooperation with the Commission and its member states, conducted a state-federal Atlantic coastal aquaculture workshop (NMFS 1998). The workshop developed recommendations on several different areas, including strategic planning, fishery management plan integration, aquaculture data collection, and integration of mandates related to aquaculture. Several recommendations focused on potential future work in coordination of aquaculture activities.

Workshop on the Introduction of Asian Oysters (*Crassostrea ariakensis*) to the Chesapeake Bay (June 2002)

- Two-hour workshop to review information concerning the potential introduction of the Asian oyster in Virginia and Maryland waters of the Chesapeake Bay. The workshop also identified potential ecological risks over a broader geographical region since an introduced species could potentially spread throughout the Atlantic and Gulf coasts. This workshop was focused on obtaining information from ASMFC Commissioners and other agency personnel.

Conservation Equivalency Workshop (October 17, 2001)

- Two-hour workshop was held in conjunction with the ASMFC annual meeting to allow commissioners and advisors an opportunity to address the issues surrounding the application of conservation equivalency.
- Initiated the process for developing a clear policy to address the procedures for submitting plans, time lines for review and approval, and standards by which the plans will be evaluated to address many of the identified problems.

History of Chairmanship:

Current Chair & Vice-Chair (4/16 – present): Jim Gartland, VA; Kathy Knowlton, GA

5/14 – 4/16: Joe O'Hop, FL

5/12 – 4/14: Mike Armstrong, MA

6/10 – 11/11: Pat Geer, GA

5/08–5/10 : Harley Speir MD

10/06–10/07 : Doug Grout NH

10/04–10/06 : Linda Mercer ME

11/02–5/04 : Chris Bonzek VA

4/01–5/02 : Charlie Lesser DE

10/96–10/00 : Dale Thieling SC

10/94–10/96 : Mike Street NC

Staff Lead: Sarah Murray, Fisheries Science Coordinator, smurray@asmfc.org

ASMFC Stock Status Overview

This document provides an overview of stock status for the Commission's 27 managed species or species groups. Graphs contain the most recent information available and have been vetted through the relevant species technical committee. Where biomass data is lacking, other fishery indicators are used (i.e., landings, fishing mortality rates). Time frames differ based on data availability.

July 2019

Sustainable and Cooperative Management of Atlantic Coastal Fisheries

Quick Guide to ASMFC Species Stock Status

(Current as of July 2019)

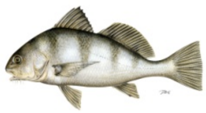
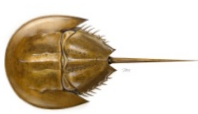
√ = Rebuilt/Sustainable ↑/⇔ = Recovering/Rebuilding ↓ = Depleted ? = Unknown * = Concern

STATUS/ TRENDS	SPECIES		OVERFISHED	OVERFISHING	REBUILDING STATUS & SCHEDULE
↓		American Eel	Depleted	Unknown	2017 stock assessment update indicates resource remains depleted
√	American Lobster 	Gulf of Maine/ Georges Bank (GOM/GBK)	Not Depleted	N	GOM/GBK stock abundance has increased since the 1980s. SNE stock has collapsed and is experiencing recruitment failure.
↓		Southern New England	Depleted	N	
↓		American Shad	Depleted	Unknown	Depleted on coastwide basis; Amendment 3 established 2013 moratorium unless river-specific sustainability can be documented; benchmark assessment scheduled for 2020
?		Atlantic Croaker	Unknown	Unknown	Status unknown; TLA indicates relatively low harvest in 2017; no management action triggered
*		Atlantic Herring	N	N	2018 stock assessment indicates declines in total biomass, SSB, and recruitment over the past 5 years
√		Atlantic Menhaden	N	N	2018 & 2019 TACs set at 216,000 mt
↓		Atlantic Striped Bass	Y	Y	Overfished and overfishing occurring on a coastwide basis; Board has initiated management action to reduce fishing mortality
↓		Atlantic Sturgeon	Depleted	N	40+ year moratorium implemented in 1998; listed in 2012 under the ESA; 2017 benchmark assessment indicates stock is depleted coastwide though slow recovery has been occurring since 1998 and total mortality is sustainable

Quick Guide to ASMFC Species Stock Status

(Current as of July 2019)

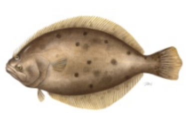
√ = Rebuilt/Sustainable ↑/⇔ = Recovering/Rebuilding ↓ = Depleted ? = Unknown * = Concern

√		Black Drum	N	N	FMP approved in 2013; status based on 2015 benchmark assessment, which found 2012 median biomass well above median biomass that produces MSY
√		Black Sea Bass	N	N	Improved recruitment and declining fishing mortality rates since 2007 have led to steady increases in SSB; operational assessment scheduled for 2019
√		Bluefish	N	N	Biomass above threshold but below target; operational assessment scheduled for 2019
*		Coastal Sharks	Varies by species & species complex		
√		Cobia	N	N	FMP approved in 2017; SEDAR research track assessment scheduled for 2019 and SEDAR operational stock assessment scheduled for 2020
*		Horseshoe Crab	Unknown	Unknown	2019 benchmark assessment found Northeast region and DE Bay stocks are neutral; the New York region stock is poor; and the Southeast region stock is good. Coastwide abundance has fluctuated, with many surveys decreasing after 1998 but increasing in recent years. ARM Framework has been used since 2013 to set harvest levels for horseshoe crabs of DE Bay origin
?		Jonah Crab	Unknown	Unknown	No range-wide assessment; Interstate FMP adopted in August 2015
↓		Northern Shrimp	Depleted	N	2018 benchmark assessment indicates biomass has declined precipitously since 2010 and recruitment in recent years has been low; fishery moratorium in place since 2014 to protect remaining spawning population

Quick Guide to ASMFC Species Stock Status

(Current as of July 2019)

√ = Rebuilt/Sustainable   ↑/⇔ = Recovering/Rebuilding   ↓ = Depleted   ? = Unknown   * = Concern

STATUS/ TRENDS	SPECIES		OVERFISHED	OVERFISHING	REBUILDING STATUS & SCHEDULE
⇔	Red Drum 	Northern Region	Unknown	N	sSPR above target and threshold SPRs
		Southern Region	Unknown	N	sSPR above target and threshold SPRs, though high uncertainty
↓		River Herring	Depleted	Unknown	2017 assessment update indicates stock remains depleted on coastwide basis; Amendment 2 established 2012 moratorium unless river-specific sustainability can be documented
√		Scup	N	N	Rebuilt
√		Spanish Mackerel	N	N	Rebuilt
√		Spiny Dogfish	N	N	Rebuilt since 2008
?		Spot	Unknown	Unknown	Status unknown; TLA indicates relatively low harvest in 2017; no management action triggered
?		Spotted Seatrout	Unknown	Unknown	Omnibus Amendment includes measures to protect spawning stock & establishes 12" minimum size limit
*		Summer Flounder	N	Y	2016 assessment update shows biomass trending downward since 2010; benchmark stock assessment scheduled for release in 2019
*	Tautog 	Massachusetts – Rhode Island	N	N	Amendment 1 establishes regional stock units and reference points
		Long Island Sound	Y	Y	
		New Jersey – New York Bight	Y	Y	
		Delaware – Maryland – Virginia	Y	N	

Quick Guide to ASMFC Species Stock Status

(Current as of July 2019)

√ = Rebuilt/Sustainable ↑/⇔ = Recovering/Rebuilding ↓ = Depleted ? = Unknown * = Concern

STATUS/ TRENDS	SPECIES		OVERFISHED	OVERFISHING	REBUILDING STATUS & SCHEDULE
↓		Weakfish	Depleted	N	6-year rebuilding period if spawning stock biomass < threshold level; restricted harvest since 2009; Stock assessment update scheduled for 2019
*	Winter Flounder 	Gulf of Maine	Unknown	N	Stock biomass is unknown; unknown why stock is not responding to low catches and low exploitation rates
↓		South New England/ Mid-Atlantic	Y	N	Current biomass at 18% of SSB target based on 2017 operational assessment

What Does a Status Mean?

Rebuilt/Sustainable - Stock biomass is equal to or above the biomass level established by the FMP to ensure population sustainability. When between benchmark assessments, a stock can still be considered rebuilt/sustainable if it drops below the target but remains above the threshold.
Recovering/Rebuilding - Stocks exhibit stable or increasing trends. Stock biomass is between the threshold and the target level established by the FMP.
Unknown - There is no accepted stock assessment to estimate stock status.
Depleted - Reflects low levels of abundance though it is unclear whether fishing mortality is the primary cause for reduced stock size
Concern – Those stocks developing emerging issues, e.g., increased effort, declining landings, or impacts due to environmental conditions.
Overfished - Occurs when stock biomass falls below the threshold established by the FMP, significantly reducing the stock's reproductive capacity to replace fish removed through harvest.
Overfishing - Occurs when fish are removed from a population at a rate that exceeds the threshold established in the FMP, which over the long-term will lead to declines in the population. A stock that is experiencing overfishing is having fish removed at a rate faster than the population can sustain in the long run, which will lead to declines in the population.
Stable/ Unchanged - Stock biomass has been consistent in recent years.
Benchmark stock assessment - A full analysis and review of stock condition, focusing on the consideration of new data sources and newer or improved assessment models. This assessment is generally conducted every 3-5 years and undergoes a formal peer review by a panel of independent scientists who evaluate whether the data and the methods used to produce the assessment are scientifically sound and appropriate for management use.
Stock assessment update - Incorporates data from the most recent years into a peer-reviewed assessment model to determine current stock status (abundance and overfishing levels)

Atlantic States Marine Fisheries Commission

Annual Performance of the Stocks: 2019 Review

July 2019

Objective: – Support the ISFMP Policy Board's review of stock rebuilding performance and management board actions and provide direction to management boards for 2020 Action Plan.

A. Validate status/rate of progress (acceptable/not acceptable)
B. If not acceptable, identify appropriate corrective action

Species Groups: – Species are grouped under five major categories (1) rebuilt/sustainable; (2) recovering/rebuilding; (3) concern; (4) depleted; and (5) unknown, as defined below.

Rebuilt/Sustainable – Stock biomass is equal to or above the biomass level established by the FMP to ensure population sustainability. When between benchmark assessments a stock can still be considered rebuilt/sustainable if it drops below the target but remains above the threshold.

Recovering/Rebuilding – Stocks exhibit stable or increasing trends. Stock biomass is between the threshold and the target level established by the FMP.

Concern – Those stocks developing emerging issues, e.g., increased effort, declining landings, or impacts due to environmental conditions.

Depleted – Reflects low levels of abundance though it is unclear whether fishing mortality is the primary cause for reduced stock size

Unknown – There is no accepted stock assessment to estimate stock status.

Status as of 2019

Rebuilt/Sustainable:
American Lobster (GOM/GBK)
Atlantic Menhaden
Black Drum
Black Sea Bass
Bluefish
Horseshoe Crab (Southeast)
Cobia
Scup
Spanish Mackerel
Spiny Dogfish

Recovering/Rebuilding:
Horseshoe Crab (Delaware Bay)
Red Drum
Summer Flounder
Tautog (MA/RI)

Concern:
Coastal Sharks
Winter Flounder (GOM)

Depleted:
American Eel
American Lobster (SNE)
American Shad
Atlantic Herring
Atlantic Striped Bass
Atlantic Sturgeon
Horseshoe Crab (New York)
Northern Shrimp
River Herring
Tautog (LIS, NJ/NY Bight, DelMarVa)
Weakfish
Winter flounder (SNE/MA)

Unknown:
Atlantic Croaker
Horseshoe Crab (New England)
Jonah Crab
Spot
Spotted Seatrout

Status as of 1998

Rebuilt/Rebuilding
Atlantic Herring
Atlantic Striped Bass
Bluefish
Black Sea Bass
Spanish Mackerel
Summer Flounder

Concern/Depleted
American Lobster (SNE)
Atlantic Menhaden
Northern Shrimp
Red Drum
Scup
Spiny Dogfish
Tautog
Weakfish
Winter Flounder (SNE/MA and GOM)

Unknown
American Eel
American Shad
Atlantic Croaker
Atlantic Sturgeon
Horseshoe Crab
River Herring
Spot
Spotted Seatrout

Overview of Species of Concern

Winter Flounder - GOM: Concern

2017 Groundfish Operational Stock Assessment

Overfished Unknown

- Assessment is based on 30+ cm area-swept biomass estimated directly from the surveys.
- B_{MSY} and F_{MSY} are unknown, and consequently the fishing mortality (F) and SSB targets could not be generated.
- The primary source of uncertainty for the estimate of biomass is the survey gear catchability (q).

Overfishing Not Occurring

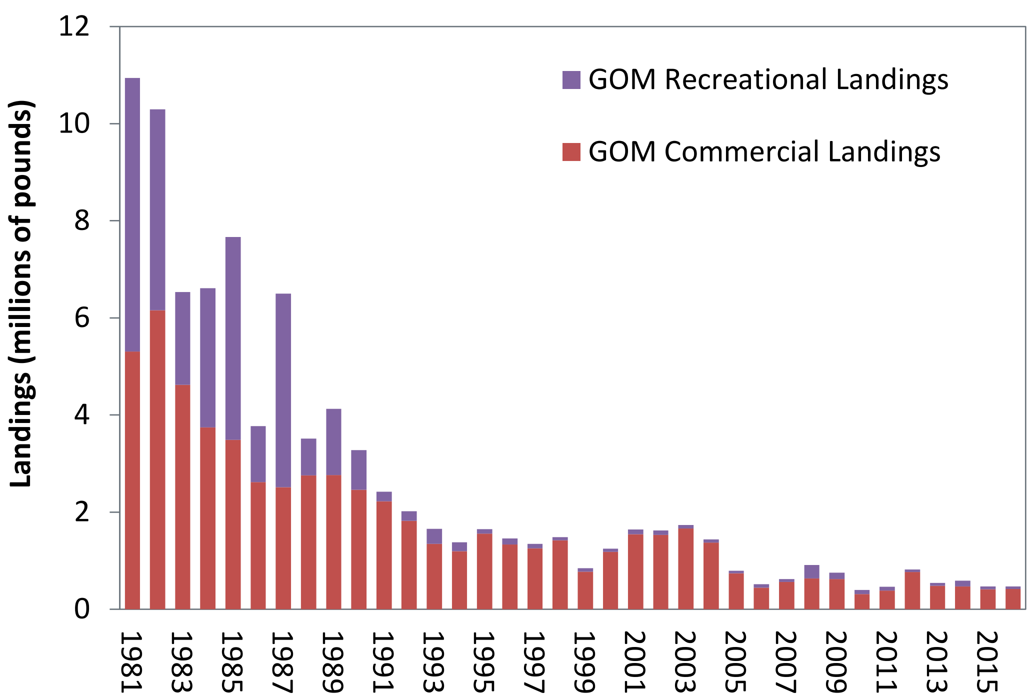
- The 2016 30+ cm exploitation rate is estimated to be 0.086, which is 37% of the overfishing exploitation threshold proxy.
- It is unknown why large declines in recreational and commercial catch have had little impact on the GOM winter flounder survey indices, which are relatively flat and show minimal change in size structure.

Board Adherence to Scientific Advice

- Addendum I measures, implemented in 2009, reduced recreational and commercial harvest by an estimated 11% and 31%, respectively
- In response to the 2011 stock status, NOAA Fisheries increased the 2012 state water sub-component to 272 mt (a 450% increase from 2010 levels) based on the overfishing status.
- Following this federal action, the Commission's Winter Flounder Board approved Addendum II in October 2012 to increase the maximum possession limit for non-federally permitted commercial vessels from 250 pounds to 500 pounds.
- In 2017, NOAA Fisheries reduced the state waters sub-component to 67 mt (from 122 mt in 2016) and reduced the total stock-wide annual catch limit to 428 mt (from 776 mt in 2016).
- The Commission's Board has maintained the trip limits and size limits in GOM winter flounder fishery since 2012.

Winter Flounder GOM Commercial & Recreational Landings

NEFSC Operational Assessment of 19 Groundfish Stocks, 2017



Next Assessment: Unknown

Rebuilding Trajectory: Flat at low levels

Timeline of Management Actions: FMP & Addendum I ('92); Addendum II ('98); Amendment 1 ('05); Addendum I ('09); Addendum II '12); Addendum III ('13)

Overview of Depleted Species

American Eel: Depleted

2017 Stock Assessment Update

Depleted: Trend analyses and model results indicate American eel has declined in recent decades and the prevalence of significant downward trends in multiple surveys across the coast is cause for concern.

Overfishing Determination: No overfishing determination can be made at this time.

Assessment Findings

- In recent decades, there has been neutral or declining coastwide abundance.
- Decreasing trends in yellow eels were seen in the Hudson River and South Atlantic regions.
- Although commercial fishery landings and effort in recent times have declined in most regions from historical levels, current fishing effort may still be too high given the additional stressors affecting the stock, such as habitat loss, passage mortality, and disease, as well as potentially shifting oceanographic conditions.
- Management efforts to reduce mortality on American eels in the U.S. are warranted.

Board Adherence to Scientific Advice

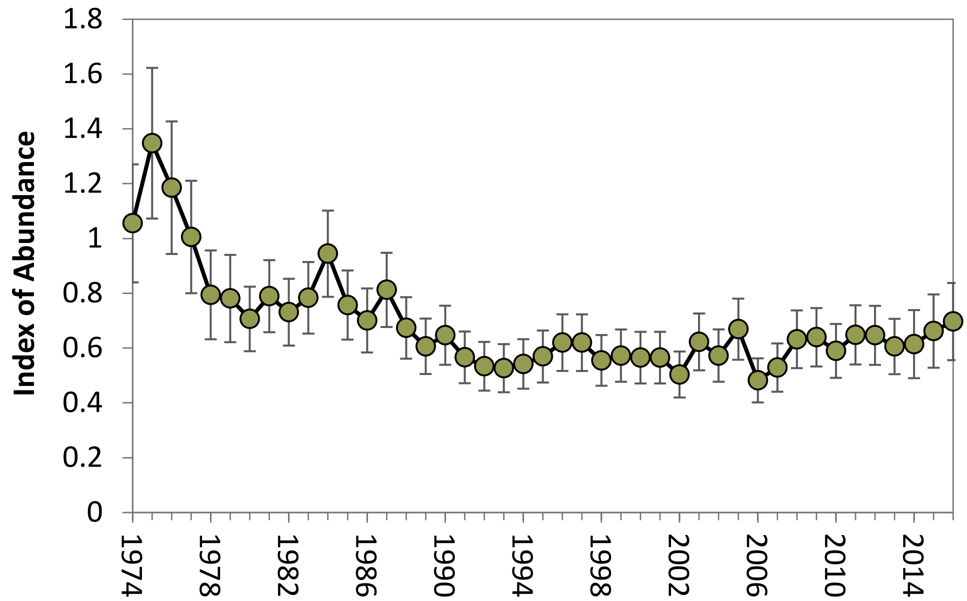
- Based on results of the 2012 benchmark assessment, the Board implemented two Addenda (III and IV) to reduce fishing mortality on American eels through size and possession limits for yellow eel, prohibiting most silver eel fisheries, establishing a 907,671 pound coastwide quota for yellow eel fisheries, and reducing Maine's glass eel quota to 9,688 pounds.
- The Board approved Addendum V in August 2018, which slightly increases the yellow eel cap, inconsistent with the advice of both the Technical and Stock Assessment Committee. The Addendum also adjusts the management trigger and response should the cap be exceeded.

Next Assessment: Unknown

Rebuilding Trajectory: Unknown

40+ Year Index of Abundance of Yellow American Eel along the Atlantic Coast, 1974 - 2016

Source: ASMFC American Eel Stock Assessment Update, 2017



The error bars represent the standard errors about the estimates.

Timeline of Management Actions: FMP ('99); Addendum I ('06); Addendum II ('08), Addendum III ('13); Addendum IV ('14); Addendum V ('18)

Overview of Depleted Species

Trend Analysis of Regional and Coastwide Indices of American Eel Abundance by Young-of-the-year (YOY) and Yellow Eel Life Stages

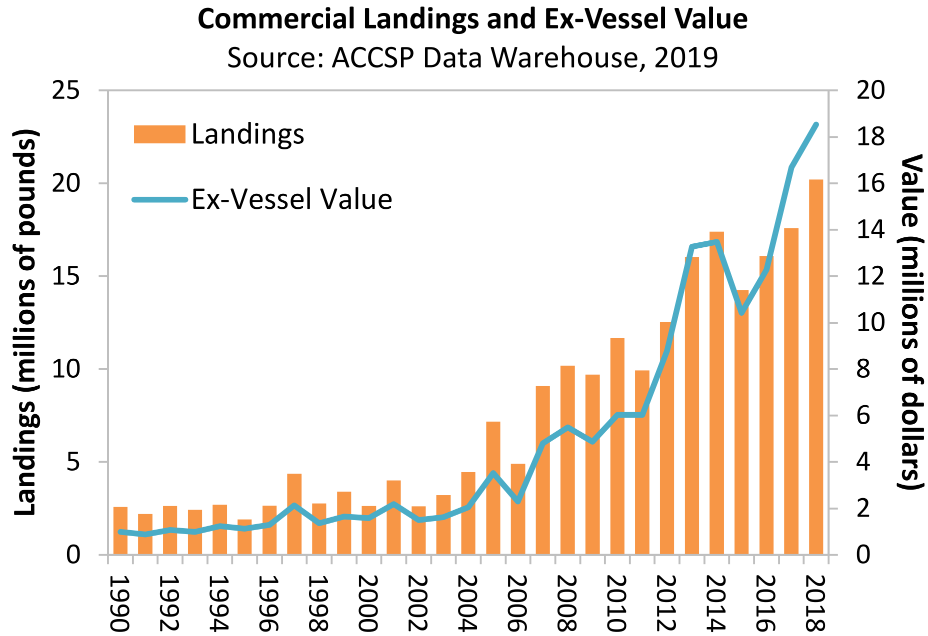
Region	Life Stage	Time Period	2012 Trend	2017 Trend
Gulf of Maine	YOY	2001–2016	NS	NS
Southern New England	YOY	2000–2016	NS	NS
	Yellow	2001–2010	NS	-
Hudson River	YOY	1974–2009	↓	-
	Yellow	1980–2016	↓	↓
Delaware Bay/ Mid-Atlantic Coastal Bays	YOY	2000–2016	NS	NS
	Yellow	1999–2016	NS	NS
Chesapeake Bay	YOY	2000–2016	NS	NS
	Yellow	1990–2009	↑	↑
South Atlantic	YOY	2001–2015	NS	↓
	Yellow	2001–2016	↓	↓
Atlantic Coast	YOY (short-term)	2000–2016	NS	NS
	YOY (long-term)	1987–2013	NS	NS
	Yellow (40+ year)	1974–2016	NS	↓
	Yellow (30-year)	1987–2016	↓	↓
	Yellow (20-year)	1997–2016	NS	NS

Overview of Species of Unknown Stock Status

Jonah Crab: Unknown

Available Information

- Landings have increased 6.48 fold since the early 2000s, with over 17 million pounds of crab landed in 2014. These high landings have continued with 20.2 million pounds of Jonah crab landed in 2018.
- The status of the Jonah crab resource is relatively unknown and there is currently no data on juvenile recruitment.
- Bottom trawl surveys conducted by the Massachusetts Division of Marine Fisheries found an exponential increase in Jonah crab abundance since 2010, particularly in the spring.
- The Northeast Fisheries Science Center 2014 surveys showed record high abundance in the Georges Bank and Gulf of Maine regions. The spring survey in Southern New England has been fairly stable.



Timeline of Management Actions: FMP ('15); Addendum I ('16); Addendum II ('17); Addendum III ('18)

Needed Information/Data

- Conduct age-at-maturity studies in U.S. waters.
- Investigate the extent and motivation of annual migration patterns.
- Research the timing and rates of maturity at different regions along the coast.
- Determine Jonah crab growth rates, including the frequency of molting and molt increments.

Management and Monitoring Measures

- Following the recommendations of the Jonah Crab Fishery Improvement Project, the Board approved an Interstate Fishery Management Plan in August 2015 which included a 4.75" minimum size and a prohibition on the retention of egg-bearing females.
- To address concerns about bycatch in the fishery, the Board approved Addendum I in May 2016, setting a 1,000 crab limit for non-trap gear and non-lobster traps. Addendum II built upon this management measure by defining bycatch based on the composition of catch, by weight. Addendum II also established a coastwide standard for claw landings in the fishery.
- In 2018, the Board approved Addendum III, which expanded the required harvester reporting data elements, established a timeline for increased harvester reporting, and improved the spatial resolution of harvester data.

Next Assessment

No assessment is currently scheduled due to a lack of data.

Atlantic States Marine Fisheries Commission

Management, Policy and Science Strategies for Adapting Fisheries Management to Changes in Species Abundance and Distribution Resulting from Climate Change

February 2018

Climate change is already having impacts on the fishery resources the Commission manages. As average temperatures rise, mobile marine species are moving toward the poles and/or deeper water to stay cool. Shifts in the distributions and productivity of stocks can cause ecological and economic disruptions, such as predators becoming separated from their prey impacting food webs, or fishermen no longer catching a species their livelihood relies on. In the face of climatic shifts, change is likely to be the only constant. Accordingly, managers will need to learn how to respond to and manage these changes. Managers will likely need to focus on sustaining ecological functions, rather than historical abundances. As conditions change, current conservation goals and management objectives may no longer be feasible. Successful climate adaptation will depend not only on adjusting management strategies, but also in reevaluating and revising, as necessary, the underlying conservation goals and objectives of fishery management plans.

The Climate Change Work Group was tasked with developing science, policy, and management strategies to assist the Commission with adapting its management to changes in species abundance and distribution resulting from climate change impacts. This is document is intended to be a guidance document that will evolve as additional information becomes available. Work Group discussions resulted in five main outputs: A) a proposed approach for working through climate related fishery management issues; B) a list of management options for stocks at persistent low biomass; C) a list of management options for stocks with changing spatial distributions; D) a recommendation to consider inclusion of a climate change terms of reference for stock assessments; and E) a recommendation to create a list of climate change data available for inclusion in analyses. For outputs B and C, the Work Group listed options that could be considered when evidence suggests a changing environment could be impacting species' biomass levels or distributions. However, none of the options have been analyzed to clarify their pros and cons, and there are options included that may not be consistent with current federal law or the fisheries management goals identified in the Interstate Fisheries Management Program Charter. **The lists are thus intended to provide a starting point for managers as they discuss the management options.**

A. A Stepwise Approach

Carrying out effective management strategies in the face of climate change can seem complex. By clarifying a process and demonstrating how the various parts of this process fit together, implementing adaptive management can be less daunting. A generalized framework can break the process down into discrete steps designed to help managers understand how the pieces of the process fit together, and how to recognize when various methods and approaches may be appropriate. The following stepwise approach is detailed in a resource document from the *National Wildlife Federation: Climate Smart Conservation* was modified slightly for marine resource management.

Step 1. Define planning purpose and scope. This includes: articulating a purpose; clarifying existing management goals; identifying management targets; specifying a scope and time frame; engaging key stakeholders; and determining resource needs and availability.

Step 2. Assess climate impacts and vulnerabilities. Understanding climate vulnerabilities is crucial for designing effective adaptive management strategies, and the specific components of vulnerability—exposure, sensitivity, and adaptive capacity—can provide a useful framework for linking actions to impacts.

Step 3. Review/revise management goals and objectives. Because goals serve as the basis for subsequent strategies and actions, they should be climate-informed and forward looking. Reevaluation of goals and objectives may either validate their continued relevance, or indicate a need for refinement or modification.

Step 4. Identify possible adaptive management options. What are possible approaches for reducing key climate-related vulnerabilities or taking advantage of newly emerging opportunities? At this stage, a broad array of alternative strategies and actions should be identified, with particular attention to creative thinking in crafting possible management actions.

Step 5. Evaluate and select adaptive management options. The array of possible adaptation options can now be evaluated to determine which are likely to be most effective from a biological/ecological perspective, and most feasible from implementation, social and economic perspectives.

Step 6. Implement adaptive management options. Successfully implementing adaptation requires individual leadership as well as institutional commitment and resources, and often depends on engaging diverse partners early on, and emphasizing benefits to multiple sectors of society.

Step 7. Track action effectiveness and ecological responses. Monitoring helps provide context for understanding climate-related impacts and vulnerabilities and for informing adaptive management. Monitoring approaches should be carefully designed to ensure they are capable of guiding needed adjustments in management strategies.

B. Managements Options for Stocks at Persistent Low Biomass

There are two main questions that should be addressed for stocks with persistent low biomass: 1) what, if any, is an appropriate harvest level, and 2) how many resources should be committed to continue monitoring and managing the species.

Approaches

1. Status Quo: Following the current status quo addresses the first question (appropriate harvest level) but does not address questions related to continuation of monitoring and management. The current harvest strategies include allowing landings that target a rebuilding fishing mortality (F) with a biomass target based on historic assessment information with the assumption that the stock will eventually respond to a low F. If biomass continues to decline, there are two harvest options:

a. Continue the above scenario with further reductions in F
b. Put a harvest moratorium in place for a period of time based on the life history of the species

2. Evidence of a Change in Productivity: As with the status quo option, the monitoring and management would be retained at historical levels. The harvest level would be adjusted as reference points are redefined based on evidence the stock will likely not recover to previous biomass targets because of a change in productivity from environmental causes. The reference points will target a sustainable yield from a biomass that is much lower than previously targeted. The actual yield will be much reduced from historic levels, leading to a very small fishery with presumably much fewer participants. This approach may also entail a rebuilding period. The rebuilding period would be reflective of the new reference points based on an expected lowered productivity level of the stock.

3. Evidence the stock has a low to no productivity; recovery to sustainable levels is highly unlikely

a. Management: A permanent moratorium is put in place or harvest continues until it becomes economically unfeasible. Decision between these options could be based on confidence in prediction of no recovery and consideration of genetic diversity that is often high at the tail end of a species range (Nowack et al., 2013). It may be more beneficial to protect the remaining genetically diverse stock, or it may be more beneficial to allow economic harvest of the species.

b. Monitoring: Determine what level of monitoring would occur: increased, current, or reduced

4. Management and monitoring cease and harvest does not continue because it becomes economically unfeasible.

Science requirements
Each of the options places great demands on the science. Questions to be answered before choosing among the options would include:

1. What is the mechanism of decline/loss of productivity?
2. What evidence is there that the stock will likely not come back to its former productivity?
3. How is sustainable yield determined and at what level of biomass will a harvest be permitted?
4. Are there ecological/genetic considerations to be considered before taking any of these approaches to manage a stock or population?
5. What are the economic and ecological tradeoffs of continuing to harvest at lower levels vs. a moratorium?

C. Management Options for Stocks with Changing Spatial Distributions:

1. Maintain current state-by-state or regional allocations.
    - Quota sharing by fishery or within fishery: Under state-by-state management without quota reallocation it is necessary to allow for transfer of quota between states in order to have a mechanism to respond to changing distributions of stocks. But under regional or coastwide quota management, sharing of quota becomes less important when

responding to distributional changes in stocks; although sharing between two regions may still be needed.

- Add a minimum allocation for states with low quotas or states that are on the edge of stocks that are moving north or south
- Include an episodic events approach (quota set aside) for species that are moving northward
  - A certain percentage of the coastwide quota would be set aside for use by specified states/regions. The set aside is designed to allow for harvest of fish that episodically move in and out of a region

2. Maintain regional or state-by-state allocations and develop a Commission policy to revisit allocation based on identified triggers (see NMFS Allocation Policy).
   - Triggers could be based on time, an indicator of change, or a threshold of public comment.
     a) For time based triggers, triggers could be a set number of years or could be related to the life history of the species. Allocation reviews may not automatically result in a re-allocation, but they would require the Board to "revisit" the state or regional allocations periodically and decide whether to initiate management action to change allocation or vote to reaffirm current allocation. Alternatively, the board could include a provision in the FMP where the state or regional allocations would "sunset" on a prescribed date so the Board must initiate management action to either reinstitute current allocation or modify allocation.
   - Options for who makes the final decision regarding reallocation could be internal or external to the Commission:
     a) Species management boards know the fishery the best but could be open to strong political pressure from impacted states.
     b) Australia has used independent panels to determine allocations as they can take the pressure off managers and allow fairer compromises. For more information, see section 9.2 in Morrison and Scott 2014.
   - Potential options for adjusting allocations:
     a) Use distribution and abundance data from certain fisheries independent surveys that cover extended geographical areas to help determine the state or regional quota allocation percentages (e.g NEAMAP surveys; NEFSC bottom trawl survey, etc.)
     b) Use a combination of historical allocations and current distribution that adjusts through time: 75% historical allocations years 1-2, 65% historical allocations years 3-4, etc.
     c) Use Management Strategy Evaluation (MSE) to determine allocation using 4 evaluators:
        - Catch distribution
        - Recruitment
        - Productivity
        - Total yield across years

    d) Use it or lose it provisions: revisit a state's quota after X number of years of not utilizing quota.

3. Change management away from state-by-state allocations. Ideas include:
    - Change management from species focus to area focus. Allow for area allocations where industry can be permitted for multiple species at once where they can move from stock to stock as they rise and fall
        - For example, an area could be GOM; species could be lobster, herring, groundfish, menhaden, black sea bass, dogfish, others?
        - Allocations would be set based on the health of the ecosystem overall. Every 1-3 years do assessments on an area to determine what level of harvest is feasible for stocks. Look at more than just species assessment to determine allocations. Also look at ocean environment to help make predictions of the direction of stock levels.
        - This would be a significant change to how we manage stocks
    - Allocation by timeframe (e.g., calendar quarters)
        - Quotas could be allocated by seasons and open to all fishermen when the season opened (e.g., 4 seasons: spring, summer, fall, winter each with a specified percentage of the quota each season. All fishermen would have access to the quota each season).
        - Seasonal quota could be further broken out by area (e.g., the summer quota could be divided into a northern and southern allocation).

D. Including a Climate Change Terms of Reference

Work Group discussions resulted in a recommendation that stock assessment committees consider including a terms of reference (TOR) to evaluate whether climate change impacts on the species of interest are evident. Climate change recommendations were reviewed by the Commission's Assessment Science Committee (ASC). The ASC supported a process where assessment committees consider including new climate TORs when starting new stock assessments. If a TC/SAS thinks there may be climate impacts on a stock and related analyses are possible, a climate TOR is to be added. If a TC/SAS does not think there are climate impacts, a TOR does not need to be added. TCs will then have the option to include a brief assessment report section describing why climate impact analyses on a stock were not conducted.

The following are options related to climate for TCs to consider when devising the full set of TORs at the outset of a stock assessment.

- Describe the thermal habitat and its influence on the distribution and abundance of species X, and attempt to integrate the results into the stock assessment.
- Consider the consequences of environmental factors on the estimates of abundance or relative indices derived from surveys.
- Characterize oceanographic and habitat data as it pertains to species X distribution and availability. If possible, integrate the results into the stock assessment.

- Evaluate new information on life history such as growth rates, size at maturation, natural mortality rate, and migrations. Explore possible impacts of environmental change on life history characteristics.
- Present the survey data available for use in the assessment, evaluate the utility of the age-length key for use in stock assessment, and explore standardization of fishery-independent indices. Characterize the uncertainty and any bias in these sources of data, including exploring environmentally driven changes in availability and related changes in population size structure. Explore the spatial distribution of the stock over time, and whether there are consistent distributional shifts.
- Provide best estimate of population parameters (fishing mortality, biomass, and abundance) through assessment models. Evaluate model performance and stability through sensitivity analyses and retrospective analysis, including variation in life history parameters. Include consideration of environmental effects where possible. Discuss the effects of data strengths and weaknesses on model results and performance.
- Update or redefine biological reference points (BRPs; point estimates or proxies for B_{MSY}, SSB_{MSY}, F_{MSY}, MSY). Evaluate stock status based on BRPs. If possible, develop alternative MSY-based reference points or proxies that may account for changing productivity regimes.

E. Climate Change Data Availability and Gap Analysis

Climate change is affecting a number of aspects of the environment which may affect abundance, distribution, and productivity of various species. Besides warming waters, changes to other aspects of the marine environment (such as salinity, pH and currents – Table 1) may also be occurring. To assist the assessment committees in this work, the Work Group recommended the creation of a coastwide database summarizing the types of climate related data various state, federal, and university programs collect. The database would not store the actual data, but provide metadata on the programs (i.e., the database would contain a summary of the types of environmental data collected, temporal and spatial aspects of the data, sample design, and contact information). The database would be a central repository of information for the species assessment committees to identify and request available climate data appropriate for the species and area of interest. The decision to house the metadata and contact information and not the actual environmental data was to avoid:

- Needing to annually update the data
- duplication of datasets
- adapting the data inappropriately, and
- ensuring the most recent information is used

Development of the database will be a collaborative coastwide effort to ensure all known programs that collect environmental data are included. In addition to the numerous ocean observing buoys, data portals, and state and federal monitoring programs, the database should include power plant monitoring data and smaller-scale programs conducted by counties, towns, and universities for a variety of purposes. The ASC noted that some data sources may need to be converted to usable format.

Two levels of gap analysis will be conducted after development of the environmental metadata database:

1. Review to ensure all known programs that collect environmental data are included
    a. Verify that all appropriate information is included
        i. The review should be conducted by each state and federal agency to assure completeness coordinated by the ASC and reviewed by the Management and Science Committee.
2. Review the types of environmental data collected and temporal and spatial scale of the information
    a. Determine if there are temporal and/or spatial gaps in data necessary to investigate the effects of climate change on species
        i. Task species TC and SAS for review
    b. Determine relative importance of filling individual data gaps
    c. Prioritize data gap filling and identify strategies to address the important gaps

Table 1. Climate Data Types

- Temperature
    - Annual, seasonal, daily
    - days above threshold (need daily data)
    - timing of ice melt
- Salinity
    - Temporal/spatial changes
    - Temporal/spatial changes of estuarine salt wedge
- pH (ocean acidity)
- Precipitation
    - River currents
    - Temporal/spatial salinity changes
- Wind
    - Changes to local wind patterns
    - Frequency of storm events – spatial and temporal patterns
- Currents
    - Strength and location of local currents
    - Location of basin wide currents (i.e. – Gulf Stream, Labrador currents)
- Global climate measures
    - North Atlantic Oscillation (NAO)
    - Atlantic Multidecadal Oscillation (AMO)
    -

Resources to Assess How Species and Environments are Being Impacted by Climate

The following are potential resources managers could use to determine if a stock has reached a point that necessitates change in a fisheries management strategy to adapt to climate change impacts

- Northeast Fish and Shellfish Climate Vulnerability Assessment developed by NOAA

- Ecosystem status reports/Ecosystem indicators- large scale requires significant resources would need to partner with NOAA
- Ocean Adapt – analysis of changing distributions by NMFS and Rutgers
- NOAA National Center for Environmental Information – hosts and provides public access to archives of climate data
- Stock predictions
    - Climate predictions
    - Species distributions
    - Species abundance (climate velocity)
- Citizen Science—create venue for watermen to report changes they are seeing on the water as an advanced warning to managers.
- Triggers defined by fishermen: seek public input on triggers for when management would adapt due to changes in the resource from climate change

References:

Pauls, S., C. Nowak, M. Balint, and M. Pfenninger. 2013. The impact of global climate change on genetic diversity within populations and species. Molecular Ecology 22:925-946.

FISH and FISHERIES

FISH and FISHERIES, 2016, **17**, 303–334

Management strategy evaluation: best practices

André E Punt[1,2], *Doug S Butterworth*[3], *Carryn L de Moor*[3], *José A A De Oliveira*[4] *& Malcolm Haddon*[2]

[1]School of Aquatic and Fishery Sciences, University of Washington, Seattle, WA, 98195, USA; [2]CSIRO Oceans and Atmosphere, GPO Box 1538, Hobart, TAS, 7001, Australia; [3]Marine Resource Assessment and Management Group (MARAM), Department of Mathematics and Applied Mathematics, University of Cape Town, Rondebosch, 7701, South Africa; [4]CEFAS Lowestoft Laboratory, Pakefield Road, Lowestoft, Suffolk, NR33 0HT, UK

Abstract

Management strategy evaluation (MSE) involves using simulation to compare the relative effectiveness for achieving management objectives of different combinations of data collection schemes, methods of analysis and subsequent processes leading to management actions. MSE can be used to identify a 'best' management strategy among a set of candidate strategies, or to determine how well an existing strategy performs. The ability of MSE to facilitate fisheries management achieving its aims depends on how well uncertainty is represented, and how effectively the results of simulations are summarized and presented to the decision-makers. Key challenges for effective use of MSE therefore include characterizing objectives and uncertainty, assigning plausibility ranks to the trials considered, and working with decision-makers to interpret and implement the results of the MSE. This paper explores how MSEs are conducted and characterizes current 'best practice' guidelines, while also indicating whether and how these best practices were applied to two case-studies: the Bering–Chukchi–Beaufort Seas bowhead whales (*Balaena mysticetus*; Balaenidae) and the northern subpopulation of Pacific sardine (*Sardinops sagax caerulea;* Clupeidae).

Keywords Fisheries management, management procedure, management strategy evaluation, simulation, stakeholders, uncertainty

Correspondence:
André E Punt, School of Aquatic and Fishery Sciences, University of Washington, Seattle, WA 98195, USA
Tel.: +1 (206) 221-6319
Fax: +1 (206) 685-7471
E-mail: aepunt@uw.edu

Received 26 Jun 2014
Accepted 22 Oct 2014

 DOI: 10.1111/faf.12104

Introduction

Management strategies (also referred to as management procedures; Butterworth 2007, 2008a,b) are combinations of data collection schemes, the specific analyses applied to those data and the harvest control rules used to determine management actions based on the results of those analyses. Management strategy evaluation (MSE),[1] the evaluation of management strategies using simulation, is widely considered to be the most appropriate way to evaluate the trade-offs achieved by alternative management strategies and to assess the consequences of uncertainty for achieving management goals. Butterworth *et al.* (2010a) list three primary uses for MSE:

1. development of the management strategy for a particular fishery;
2. evaluation of generic management strategies; and
3. identification of management strategies that will not work and should therefore be eliminated from further consideration.

One specific use for MSE, particularly in the United States where the forms of the harvest control rules for federal fisheries management are constrained by the Magnusson–Stevens Act (MSA), is to quantify the impacts of uncertainty associated with management strategies adopted at present, and to identify the 'realizable' performance which can be achieved given the quality of the data available and the types of uncertainties which are inherent in the system being managed.

Butterworth (2007) contrasts MSE with the traditional approach to providing management advice, which involves conducting a 'best assessment' of the resource, evaluating uncertainty using confidence intervals and sensitivity tests, and providing a recommendation for a management action based on applying some harvest control rule or by conducting constant catch or constant fishing mortality projections. That paper explains how MSE overcomes many of the concerns with the traditional approach, including that the full range of uncertainty can be taken into account and that decision-makers consider longer term trade-offs among the management objectives, instead of focusing on short-term considerations only.

For the purposes of this paper, a MSE must address the fact that the data and models on which management strategies are based are subject to uncertainty. Consequently, analyses in which fishing mortality can be set and implemented exactly (e.g. Punt and Butterworth 1991) are not considered to be MSEs, even though such analyses may be useful in terms of understanding the dynamical properties of exploited ecosystems.

Management strategy evaluation has been used extensively to understand the expected behaviour of management strategies, but is increasingly being implemented to select management strategies for implementation in actual fisheries. The earliest use of MSE for such selection occurred in South Africa, where the control rules used to set total allowable catches (TACs) for the anchovy *Engraulis encrasicolus*, Engraulidae, and later the sardine *Sardinops sagax*, Clupeidae, fisheries were selected using what has since become known as MSE (Bergh and Butterworth 1987; Geromont *et al.* 1999; De Oliveira and Butterworth 2004). MSE has also been used in South Africa to select management strategies for the Cape hake *Merluccius paradoxus* and *M. capensis*, Merlucciidae (Rademeyer *et al.* 2008), rock lobster *Jasus lalandii* and *Palinurus gilchristi*, Palinuridae (Johnston and Butterworth 2005; Johnston *et al.* 2008) and most recently horse mackerel, *Trachurus trachurus capensis*, Carangidae (Furman and Butterworth 2012) fisheries. The use of management strategies that have been tested using simulation has been routine for the major fisheries in South Africa for some 20 years.

Management strategy evaluation has been used extensively by the International Whaling Commission (IWC) since the late 1980s to select management strategies to calculate potential catch limits for commercial whaling and determine actual strike limits for aboriginal subsistence whaling

[1] A term introduced into the fisheries lexicon by Smith (1994). To the extent possible, the nomenclature for MSE outlined by Rademeyer *et al.* (2007) is followed throughout.

(Punt and Donovan 2007). The use of MSE accelerated internationally following a 1998 ICES Symposium on Confronting Uncertainty in the Evaluation and Implementation of Fisheries-Management Systems, which included several papers illustrating the methods underlying MSE and then current applications (Butterworth and Punt 1999; Cooke 1999; Smith *et al.* 1999).

Management strategy evaluation has been used by the Commission for the Conservation of Southern Bluefin Tuna (CCSBT) to select a management strategy for southern bluefin tuna *Thunnus maccoyii,* Scombridae (Kurota *et al.* 2010; Anonymous 2011). The Potential Biological Removals method, used to determine upper limits on anthropogenic removals of marine mammals in the USA, was also developed using MSE (Wade 1998). Similarly, MSE was used to evaluate a by-catch management control rule for seabirds (Tuck 2011). Outside of South Africa and the IWC, MSE has been applied most extensively in Australia where it has been used to compare and select management strategies for the Southern and Eastern Scalefish and Shark Fishery, SESSF (Punt *et al.* 2002; Wayte and Klaer 2010; Little *et al.* 2011), the Queensland spanner crab *Ranina ranina*, Raninidae fishery (Dichmont and Brown 2010), the Northern Prawn Fishery (Dichmont *et al.* 2008, 2013), the fishery for southern rock lobster *Jasus edwardsii*, Palinuridae off South Australia (Punt *et al.* 2012a) and the Tasmanian abalone fishery (Haddon and Helidoniotis 2013). The management strategies used to recommend catch limits for southern rock lobster off New Zealand have also been selected using MSE (Starr *et al.* 1997; Breen and Kim 2006).

Management strategy evaluation has been applied extensively to European fisheries to explore the performance of management strategies theoretically (Kell *et al.* 2005a,b, 2006), but few applications have resulted in strategies being formally implemented. The International Council for the Exploration of the Seas (ICES) provides a list of 18 management plans for North East Atlantic stocks that have been evaluated using MSE approaches since 2008 (ICES 2013). As an advisory body to the governments of ICES member countries and the European Commission, ICES bases its advice on these management plans if advice recipients have agreed that they can be used as a basis for that advice and provided the MSEs have shown them to fulfil ICES' precautionary criteria (ICES 2012). If this does not apply, ICES reverts to its own MSY framework, and if there is no basis for giving MSY-related advice, takes account of precautionary considerations (ICES 2012). The European Commission has its own advisory body, the Scientific, Technical and Economic Committee for Fisheries (STECF, established to advise on matters pertaining to the conservation and management of living aquatic resources) that performs impact assessments of proposed management plans, and may make use of MSEs for this purpose (STECF 2011a).

In North America, MSE has been applied to evaluate management strategies for the fishery for the northern subpopulation of Pacific sardine *Sardinops sagax caerulea*, Clupeidae, and the control rule used for this fishery from 1998 until 2012 was based on a MSE (PFMC 1998), as was the 2014 revision to this control rule (Hurtado-Ferro and Punt 2014). A revision to the management strategy adopted became necessary when the estimated relationship between recruitment success and environmental factors changed given new information. MSE has also been used to establish a management strategy for sablefish *Anoplopoma fimbria*, Anoplopomatidae off British Columbia (Cox and Kronlund 2008), for West Greenland halibut *Reinhardtius hippoglossoides*, Pleuronectidae (Butterworth and Rademeyer 2010; NAFO 2010) and for pollock *Pollachius virens*, Gadidae off eastern Canada (Rademeyer and Butterworth 2011).

Management strategy evaluation has recently been used to evaluate alternate management strategies for Tristan rock lobster (*Jasus tristani*) for three of the islands that form the Tristan da Cunha group of islands (Johnston and Butterworth 2013, 2014; Butterworth and Johnston 2014).

The focus for most previous MSEs has been single-species systems. However, MSE has also been used to evaluate management strategies to achieve multispecies or ecosystem objectives (Sainsbury *et al.* 2000; Fulton *et al.* 2007; Dichmont *et al.* 2008, 2013; Plagányi *et al.* 2013).

Management strategy evaluation is at the interface between science and policy. While it would be desirable to keep science and policy separate, there is a link. Decision-makers need to identify the desirable outcomes that any management strategy adopted should aim to achieve, while scientific analyses (the MSE) can inform the decision-makers on the feasible ranges of trade-offs. A well-structured MSE will utilize the links between policy and science, but ensure that a 'wall of science' remains whereby decision-makers do not decide scientific issues and scientists do not make policy decisions (Field *et al.* 2006).

While MSE is widely acknowledged to be the most appropriate way to compare management strategies, and the basic approach has been summarized in many publications, actual uses can differ markedly with regard to the likelihood that the resulting management strategy actually provides the best trade-off amongst the management objectives and is robust to uncertainty. Furthermore, it is well recognized that poorly conducted MSEs are likely to be less useful for management purposes than using the traditional best assessment approach coupled to essentially *ad hoc* advice (Rochet and Rice 2009; Butterworth *et al.* 2010b; Kraak *et al.* 2011). This paper therefore outlines the process of conducting MSEs and identifies a set of 'best practice' guidelines (Table 1). These proposed best practices for MSEs should assist in facilitating that MSEs are conducted in the most appropriate manner so that the resulting management strategies are best able to achieve their goals. The focus of the paper is on single-species applications of MSE, although applications that consider multispecies and ecosystem aspects are also considered. The extent to which these guidelines have been followed in practice is illustrated for two case-studies: the management strategy for the northern subpopulation of Pacific sardine and that for bowhead whales, *Balaena mysticetus* Balaenidae, in the Bering Sea, Chukchi Sea and Beaufort Sea.

MSE – the basics

The basic steps that need to be followed when conducting a MSE (Fig. 1) are as follows:

1. identification of the management objectives in concept and representation of these using quantitative performance statistics;
2. identification of a broad range of uncertainties (related to biology, the environment, the fishery and the management system) to which the management strategy should be robust;
3. development of a set of models (often referred to as 'operating models') which provide a mathematical representation of the system to be managed; an operating model must represent the biological components of the system to be managed, the fishery which operates on the modelled population, how data are collected from the managed system and how they relate to the modelled population (including the effect of measurement 'noise'); in addition, an implementation model is required that reflects how management regulations are applied in practice; note that more than a single operating model is nearly always required because of the need to cover the range of the ever-present uncertainties, which include the imprecision of the values of parameters estimated from fits to data, as well as structural uncertainties such as how many reproductively separate stocks of a species are present in the region considered;
4. selection of the parameters of the operating model(s) and quantifying parameter uncertainty (ideally by fitting or 'conditioning' the operating model(s) to data from the actual system under consideration);
5. identification of candidate management strategies which could realistically be implemented for the system;
6. simulation of the application of each management strategy for each operating model; and
7. summary and interpretation of the performance statistics; this may lead to refinement of the relative weighting of the management objectives as the simulation process develops and continues to provide more refined results to inform the quantitative trade-offs among competing goals.

The feedback loop between the management strategy and the operating model(s) is a fundamental aspect of MSE and is the particular feature, which distinguishes it from simple risk assessment where the implications of unchanging management regulations (e.g. constant TAC) are evaluated by use of projections. Simple risk assessment overestimates risk through failing to take account of management reactions to the information provided by future data.

Management strategy evaluation is not the same as conducting projections from a stock assessment, although a stock assessment may form the basis for the operating model(s) which are core to a MSE. Specifically, MSE takes feedback control into account, that is it takes account of the collection and use of future data on the status of the managed system. In addition, stock assessments usually involve selecting a single model structure and estimating the parameters of the model.

Table 1 Summary of the best practice guidelines.

Selection of objectives and performance metrics

- Involve decision-makers and stakeholders (e.g. using workshops) throughout the process to ensure the performance statistics capture the management objectives and are understandable.
- At a minimum, report statistics related to average catches, variation in catches and the impact on stock size.

Selection of uncertainties

- Consider a range of uncertainties, which is sufficiently broad that new information collected after the management strategy is implemented should generally reduce rather than increase this range.
- Include trials for each potential source of uncertainty (unless there is clear evidence that the source does not apply) and for the factors considered in Table 3.
- Consider the need for spatial structure, multiple stocks, predator-prey interactions and environmental drivers on system dynamics; modelling the last by imposing trends on the parameters of the operating model is often sufficient to understand its implications.
- Include predation effects using minimum realistic models and examine the potential for technical interactions amongst major fished species, especially in multispecies fisheries.
- Divide the trials into ‘reference’ and ‘robustness’ sets.
- Use Bayesian posterior distributions to capture the parameter uncertainty for each trial if possible.

Identification of candidate management strategies

- This should be the primary responsibility of the stakeholders/decision–makers, but with guidance from the analysts given the limitations of the management strategy evaluation (MSE). Care needs to be taken that the management strategy can be implemented in practice.
- Evaluate the entire management strategy. In cases in which the management strategy is complex, this may be impossible computationally, in which case a simplification of the assessment method is needed – the nature of the simplification should be based on simulation analyses.

Simulation of the application of the management strategy

- Check that operating model and management strategy are consistent with reality; projections into the future should generate quantities, such as past assessment errors and levels of variability in biomass and recruitment, on the same scales as those estimated to have occurred in the past.
- Conduct tests of the software, for example using ‘perfect’ data before conducting actual analyses.
- Base recommendations for management actions in management strategies only on data which would (with near certainty) actually be available.
- Document any assumptions regarding parameters assumed known when applying the management strategy.

Presentation of results and selection of a management strategy

- Develop a process, so that the decision-makers understand the results of the MSE and the range of trade-offs which are available to them.
- Use effective graphical summaries which are developed collaboratively with the stakeholders.
- Identify whether there are ‘performance standards’ which must be satisfied to eliminate some possible management strategies immediately and hence simplify the final decision process.
- Select a method for assigning a plausibility rank to each trial and take these ranks into account when making a final selection among candidate management strategies.

Other

- Include ‘Exceptional Circumstances’ provisions which specify the situations under which a management strategy’s recommendations may be over-ridden.
- Include a schedule for when formal reviews of the implemented management strategy will take place.

Although an aim of a stock assessment is to quantify uncertainty, it is rarely possible to capture all the key sources of uncertainty within the confines of a stock assessment, in particular ‘outcome uncertainty’ (see below), and to carry uncertainty forward fully into the provision of management advice. MSE can also be used when it is not possible to apply standard methods of stock assessment, as is common in data-poor situations.

Although not the focus of the present paper, Marasco *et al.* (2007) observe that the results from a MSE may be used not only to choose amongst the candidate management strategies, but also to identify future research and monitoring goals. In addition, the results of a MSE can be used to evaluate how well existing monitoring and data analysis methods are able to reflect the true status of the system with reasonable accuracy (see e.g. Ful-

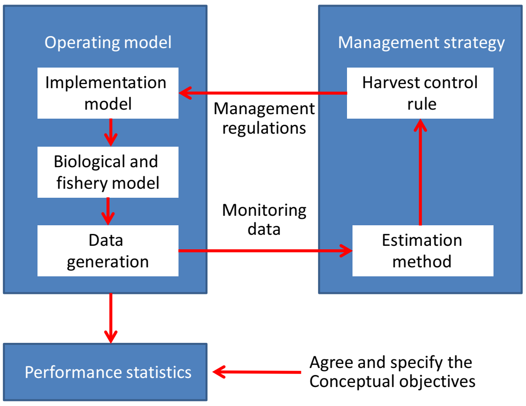


Figure 1 Conceptual overview of the management strategy evaluation modelling process.

ton *et al.* 2004; for an evaluation of ecosystem indicators). Marasco *et al.* (2007) also emphasize the need to continue to monitor the system following the implementation of a management strategy. Consistent with practice in, for example, the IWC and South Africa (Butterworth 2007; Punt and Donovan 2007), they stress the need to review and revise the MSE periodically, as consolidated outcomes from future monitoring and research become available.

Overview of the case-studies

Bering–Chukchi–Beaufort Seas bowhead whales

Bowhead whales in the Bering, Chukchi and Beaufort Seas are considered to be a single stock, separate from the stocks in the Okhotsk Sea, the Davis Strait and Hudson Bay, and off Spitsbergen. This stock, often referred to as the Bering–Chukchi–Beaufort (or BCB) Seas stock of bowhead whales, has been subject to hunting by aboriginal peoples off Alaska (USA) and Russia for centuries. In common with other stocks of bowhead whales, it was severely depleted by commercial whaling, which occurred between 1848 and 1914 in the case of the BCB stock. Commercial whaling on the BCB bowhead stock ceased once whaling there became economically non-viable, but aboriginal whaling continues at low levels.

Management of bowhead whales is challenging because individuals can live beyond 100 years (George *et al.* 1999). In addition, the location of the population and the fishery makes monitoring difficult (it involves ice platform sighting surveys of bowhead whales as they migrate through leads which open as the ice thaws). The aboriginal hunt of bowhead whales off Alaska and Russia is managed under the IWC. Management for aboriginal whaling is based on strike limits, which are the number of strikes of whales permitted within a season. Management advice is based on the number of strikes rather than numbers of whales landed because of the need to account for mortality when animals are struck but subsequently not landed ('lost').

Each country wishing to take whales for aboriginal subsistence purposes must provide the IWC with a 'Need Statement' which documents the number of annual strikes needed to satisfy the requirements of aboriginal peoples in terms of nutrition and culture. Management advice in the context of the BCB bowhead whales relates to whether the need requested can be satisfied without impacting the ability to achieve conservation-related management goals; this contrasts with commercial whaling, where the aim is to maximize the catch subject to the same constraint. The development of a management strategy for aboriginal subsistence whaling, and in particular for the BCB bowhead whales, commenced in 1995 after a management strategy for commercial whaling was adopted in 1994 (IWC 1994). A 'Strike Limit Algorithm' (SLA) was later adopted as the management strategy for the BCB bowhead whales in 2003 (IWC 2003). Prior to the use of the SLA, evaluation of whether the need requested was consistent with the IWC's conservation-related objective involved comparing the proposed need in terms of strikes with an estimate of a lower percentile (usually the lower 5th percentile) of a distribution for the replacement yield (the number of animals removed from the population each year which will keep the population at its current level; Givens *et al.* 1995).

The development of the SLA involved the IWC identifying management objectives for aboriginal subsistence whaling, obtaining a 'need envelope' from hunters and their scientific representatives (the range of possible maximum need levels by year over the next 100 years), developing operating models tailored to the dynamics of the BCB bowhead whale population, and simulating the application of candidate SLAs (equivalent to management strategies). The operating models for the BCB bowheads were case-specific, rather than generic as was the case for commercial whaling, because this was considered likely to lead to an improved ability to satisfy the management goals and because there are only a few aboriginal whaling fisheries. The development process was competitive, with several sets of 'developers' 'competing' to best satisfy the management goals. However, as it happened, the final selected SLA was none of these individual SLAs, but rather an average of the best two.

Northern subpopulation of Pacific sardine

The northern subpopulation of Pacific sardine is harvested off Mexico, the USA (including Alaska) and Canada. The population dynamics of Pacific sardine, in common with those of many small pelagic fish species, are characterized by large changes in abundance, driven primarily by environmental conditions. The long-term nature of these fluctuations has been confirmed for Pacific sardine using samples of fish scales from sediment cores in the Santa Barbara basin (Soutar and Isaacs 1969, 1974; Baumgartner *et al.* 1992). Sardine populations in the Santa Barbara basin are estimated to have peaked at intervals of approximately sixty years. The biomass and catch of Pacific sardine increased rapidly during the 1930s until the mid-1940s, and declined thereafter. The decline was likely due to a combination of environmental conditions leading to poor recruitments and very high fishing mortality rates.

The biomass of Pacific sardine began to rebuild during the 1980s, and by 1991 a directed fishery was re-established. The Pacific sardine fishery was managed by the State of California until 2000 when management authority was transferred to the Pacific Fishery Management Council (PFMC; Hill *et al.* 2011). Harvest Guidelines for Pacific sardine between 1998 and 2012 were set using a harvest control rule of the form (PFMC 1998):

$$\text{HG} = (\text{BIOMASS} - \text{CUT-OFF}) * \text{FRACTION} * \text{DISTRIBUTION}$$

where: HG (Harvest Guideline) is the allowable catch for each management year; BIOMASS is the estimate of the biomass of Pacific sardine aged 1 and older obtained from an age-structured stock assessment model; CUT-OFF is 150 000 mt and is the escapement threshold below which fishing is prohibited; FRACTION is a temperature-dependent exploitation fraction which ranges from 5 to 15%; and DISTRIBUTION is the average proportion of the coastwide biomass in USA waters, estimated at 0.87. In addition, there is a maximum allowable catch regardless of biomass such that HG ≤ MAXCAT, where MAXCAT is 200 000 mt. The purpose of CUT-OFF is to protect the stock when biomass is low. The purpose of FRACTION is to specify how much of the stock is available to the fishery when BIOMASS exceeds CUT-OFF. The DISTRIBUTION term recognizes that the stock ranges beyond USA waters and is therefore subject to foreign fisheries. In PFMC (1998), FRACTION was determined on the basis of a 3-year running average of the temperature at Scripps Pier, La Jolla, USA.

The overarching management plan for all coastal pelagic species (CPS) managed by the PFMC was modified in 2011 to be consistent with the 2006 reauthorization of the MSA. This involved formally introducing how the overfishing limit (OFL, the annual catch amount consistent with an estimate of the annual fishing mortality that corresponds to maximum sustainable yield) is calculated, as well as the acceptable biological catch (ABC, a harvest limit set below the OFL that incorporates a buffer against overfishing to take account of scientific uncertainty).

The specifications of the harvest control rule adopted in 1998 were determined using simulations in which the population dynamics were represented by a production model where productivity was related to an environmental variable (PFMC 1998). Results of assessments conducted after 1998 were analysed during a workshop in February 2013 (PFMC 2013) which suggested that the temperature at Scripps Pier no longer exhibited the same trends as most other measures of temperature for the offshore waters to the west of North America (McClatchie *et al.* 2010). Rather, the relationship between recruitment, spawning biomass and temperature was strongest when temperature was based on sea surface temperature obtained from CalCOFI samples (PFMC 2013).

The results from the February 2013 workshop formed the basis for developing a set of operating models for the northern subpopulation of Pacific sardine, as well as an initial set of candidate management strategies (PFMC 2013). The process of selecting the operating models and the candidate management strategies was iterative, involving presentations by the analysts to the PFMC as well as its Scientific and Statistical Committee, Coastal

Pelagic Species Advisory Panel and Coastal Pelagic Species Management Team. The PFMC took advice from these advisory bodies as well as from members of the public, including industry and environmental non-governmental organizations (ENGOs), and then directed the analysts. Hurtado-Ferro and Punt (2014) summarize the most recent MSE results, along with the specifications for the operating models and candidate management strategies.

Best practices for MSE

Establishing objectives and performance statistics

One of the main strengths of MSE is that the decision-makers clarify their objectives. Objectives for fisheries management can be categorized as either 'conceptual' ('strategic') or 'operational' ('tactical'). Conceptual objectives are generic, high-level policy goals. For example, the conceptual objectives for CPS off the USA west coast (i) promote efficiency and profitability in the fishery, including stability of the catch; (ii) achieve 'Optimum Yield' (OY); (iii) encourage cooperative international and interstate management of CPS; (iv) accommodate existing fishery sectors; (v) avoid discards; (vi) provide adequate forage for dependent species; (vii) prevent overfishing; (viii) acquire biological information and develop a long-term research programme; (ix) foster effective monitoring and enforcement; (x) use resources spent on management of CPS efficiently; and (xi) minimize gear conflicts (PFMC 2011). These goals are largely self-consistent, but this need not always be the case. For example, the conceptual objectives for aboriginal subsistence whaling (i) ensure that risks of extinction are not seriously increased by whaling; (ii) enable native people to hunt whales at levels appropriate to their cultural and nutritional requirements (i.e. satisfy their 'need'); and (iii) move populations towards and then maintain them at healthy levels. Objective (ii) may be in conflict with objectives (i) and (iii) for some populations.

To be included in a MSE, the conceptual objectives need to be converted into operational objectives (expressed in terms of the values of performance measures or performance statistics). This usually involves translating each conceptual objective into one or more operational objective(s) and performance statistic(s). For example, the conceptual objective of 'avoid overfishing' could be represented operationally as 'the annual probability that the stock drops below 20% of the unfished level should not exceed 5%'. However, some conceptual objectives may link to multiple operational objectives. For example, the conceptual objective 'achieve OY' could be quantified by the operational objectives 'maximize catch in biomass', 'minimize the interannual variation in catch' and 'maximize the economic rent to the fishing industry', amongst others.

The operating model(s) should be developed so that performance statistics can be calculated. For example, when there are explicit ecosystem and economic objectives, the operating model(s) may need to include a fleet dynamics model (Ulrich *et al.* 2007) or models of how fishing impacts ecosystem components other than the target species (Schweder *et al.* 1998), as well as related performance statistics.

It is inevitable that some of the objectives will be in conflict to some extent, and one aim of MSE is to highlight trade-offs among the objectives as quantified using performance statistics. For example, increased monitoring efforts may allow higher catches for the same level of risk (see Fig. 2), but the increased monitoring will come at a financial cost. The more common trade-offs are between risk to the resource and benefits to the fishery, and between average catch and variation in catch (the less variability in catch permitted, the lower the average catch needs to be able to accommodate catch reductions needed at times the resource might be at a low abundance). It is critical to ensure that the decision-makers are aware of these trade-offs. One way to achieve this is to use a utility function which balances the various factors in providing a single number. However, efforts to base MSEs on utility functions have generally been unsuccessful because decision-makers (and stakeholder groups) wish to see how well each candidate management strategy achieves each objective and how they trade off.

The difficulties associated with conflicting objectives become more challenging when management strategies are developed for fisheries which target multiple species, or when there are multiple stakeholder groups which fish using different gears or may have markedly different objectives (e.g. commercial and recreational sectors within a fishery). This is because what is seen as the 'optimal' state of the system will differ among stakeholders. Few management strategies that have been

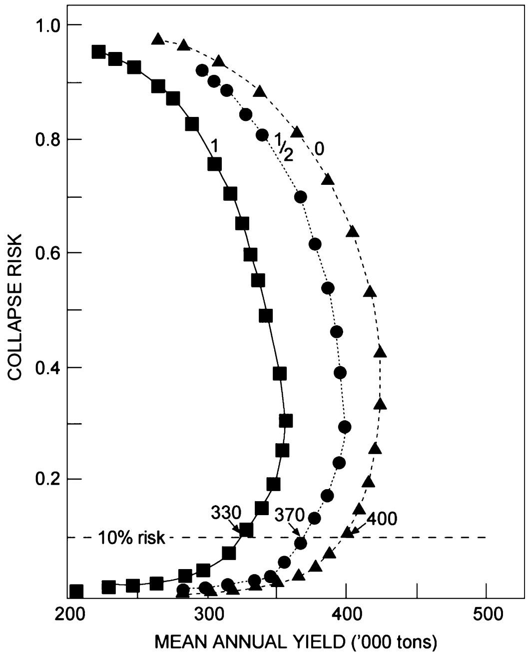


Figure 2 Relationship between risk and reward for South African anchovy ('collapse' is defined here as the spawning biomass falling below 10% of its average unexploited level, and risk reports the probability of that happening at least once during a 20-year period). Each line indicates a different level of survey precision (1: current precision; ½: double the survey effort; 0: perfect information; reproduced from Bergh and Butterworth 1987).

implemented have addressed the issue of between-species trade-offs. One notable exception is the South African fishery for anchovy and sardine. Here, there is a trade-off between anchovy and sardine catches because of an unavoidable by-catch of juvenile sardine with anchovy, which decreases the TAC possible for the more valuable adult sardine. This multiple species allocation problem was addressed over one period by allowing each company with rights to each of the two species to choose its preferred trade-off. First, the TACs that would follow under each company's desired trade-off were calculated; next quotas were allocated to that company which were computed by multiplying the TACs related to its trade-off by the proportional right to the combined (sardine and anchovy) fishery as a whole that it had been awarded; finally, the TACs themselves were calculated by summing the quotas awarded to each company for each species (De Oliveira 2003; Butterworth *et al.* 2012).

Best practice in terms of specifying objectives, particularly operational objectives, is through the use of inclusive workshops (Cox and Kronlund 2008; Mapstone *et al.* 2008; PFMC 2013). Workshop participants need to be representative of the decision-makers and other stakeholders, and efforts should be made to ensure that the decision-makers are fully aware of which decisions are theirs (weighting objectives, and selecting management strategies to be tested) and which decisions are primarily technical. Progress in such workshops may be facilitated by providing draft specifications that can be criticized, expanded upon or rejected outright.

The statistics used to evaluate the performance of alternative candidate management strategies should be chosen, so that they are easy for decision-makers and stakeholders to interpret (Francis and Shotton 1997; Peterman 2004). Butterworth and Punt (1999) comment that standard deviations or coefficients of variation of catch limits are difficult for many stakeholders to understand. Experience suggests that stakeholders find it much easier to relate to statistics such as the fraction of years in which the catch is less than some desirable level. Care should be taken to avoid having too many performance statistics. While it may seem desirable to have, for example, a number of performance statistics to quantify catch variation (IWC 1992), the final decision process is made considerably easier if the number of performance statistics is small, so that they can easily be summarized graphically. In any case, experience suggests that such catch variation statistics are often highly correlated with each other.

It is common to include performance statistics such as the probability of dropping below some threshold level [such as the minimum stock size threshold (MSST) defined in the USA MSA, or 20% of the estimated unfished biomass, B_0]. However, while dropping below MSST has implications in the USA (leading to the requirement for a rebuilding plan), the use of a metric such as the probability of dropping below a fixed fraction of B_0 can be criticized both because any such level is somewhat arbitrary, and because there is seldom evidence for threshold or depensatory effects. Nevertheless, in relation to answering questions of direct interest to decision-makers, such policy-related performance statistics may need to be included in the set reported. ICES (2013) notes that there are three ways to define the probability of dropping below a threshold: (i) the average probability (over simulations and years) of being below the threshold; (ii) the probability (over simulations) of dropping below the threshold at least once during each projection; and (iii) the maximum annual probability (over simulations) of being below the threshold over the projection period. Other ways to summarize these probabilities exist, including, for example, the probability in a given year. de Moor *et al.* (2011) comment that the probability of dropping below a threshold depends on the extent of process error, and define a performance statistic that evaluates risk in terms of the extent to which this probability increases with fishing, relative to its value in the absence of fishing.

A complicating factor with performance statistics that pertain to population size relative to B_0 or the MSY level is how these are to be defined in a changing environment and when there is time-varying predation (A'mar *et al.* 2009a,b, 2010). Usually, this problem has been resolved by replacing carrying capacity in these statistics by the population size which would have occurred had there been no catches (IWC 2003). However, for multispecies operating models, this can lead to counter-intuitive results where the unfished level is actually lower than the fished population size (Mori and Butterworth 2006).

Although most operational objectives relate to the fishery and the conservation of the species on which it depends, increasingly these objectives include ones pertaining to ecosystem impacts of fishing (Dichmont *et al.* 2008) and economic objectives (Dichmont *et al.* 2008; Anderson *et al.* 2010). Performance statistics can also relate to the management system itself. For example, in a MSE to evaluate management strategies for overfished USA west coast groundfish stocks, Punt and Ralston (2007) considered performance statistics such as when rebuilding was estimated to have occurred compared to how long this had been anticipated to take when the rebuilding plan was developed, and how often a rebuilding plan failed. This was because these were issues of interest to the decision-makers, which also related to the confidence stakeholders and the public have in the management system.

In the context of BCB bowheads, the conceptual objectives were selected by the IWC (i.e. the Commissioners). The operational objectives (and related performance statistics) were selected by the Scientific Committee of the IWC to reflect the intent of the conceptual objectives. These included statistics related to (i) the proportion of the nutritional and cultural need requested by aboriginal communities which could be satisfied, (ii) the delay in rebuilding to the population size corresponding to MSY caused by the mortality permitted and (iii) measures of the variation in the number of strikes permitted. No performance statistics specifically related to extinction risk were considered because none of the management strategies explored led to an appreciable risk of extinction – indeed the probability of extinction was zero for all management strategies and (plausible) simulations. The performance statistics related to the delay in rebuilding were hard to interpret, so that the final conservation-related statistics were based on simpler concepts such as the lowest ratio of population size to carrying capacity and the ratio of population size to carrying capacity after 100 years of simulated management.

The performance statistics for the Pacific sardine MSE were initially proposed during a workshop with stakeholders (PFMC 2013); these statistics were then refined based on input from the PFMC and its advisory bodies. The final set of performance statistics included conventional statistics related, for example, to average catches and variation in catches. However, the performance statistics also included quantities such as the proportion of times that the fishery was closed or its catch was <50 000 t, the average number of consecutive years the fishery was predicted to be closed, and the proportion of years that the biomass of animals aged 1 and older was <400 000 t. The last statistic was a proxy for indications of whether the biomass is sufficiently low that predators may be impacted.

Selection of uncertainties to consider and selection of operating model parameter values

Ideally, the range of uncertainties considered in a MSE should be sufficiently broad that new information collected after the management strategy is implemented should reduce rather than increase the range (Punt and Donovan 2007; IWC 2012a). However, in practice, it is seldom the case that it is possible to come close to incorporating all the pertinent uncertainties fully for any given situation, and choices are needed as to which uncertainties are the most consequential and reflect more plausible alternative hypotheses. Several attempts (Francis and Shotton 1997; Haddon 2011a) have been made to characterize sources of uncertainty. For the purposes of this paper, five sources of uncertainty are distinguished.

1. Process uncertainty: variation (usually assumed to be random, though sometimes incorporating autocorrelation) in parameters often considered fixed in stock assessments such as natural mortality, future recruitment about a stock–recruitment relationship and selectivity.
2. Parameter uncertainty: many operating models are fit to the data available, but the values estimated for the parameters of those operating models (e.g. fishery selectivity-at-age, the parameters of the stock–recruitment relationship and historical deviations in recruitment about the stock–recruitment relationship) are subject to error.
3. Model uncertainty: the form of relationships within an operating model will always be subject to uncertainty. The simplest type of model uncertainty involves, for example, whether the stock–recruitment relationship is Beverton–Holt or Ricker, whether a fixed value for a model parameter is correct, or whether fishery selectivity is asymptotic or dome-shaped. However, there are other more complicated types of model structure uncertainty such as how many stocks are present in the area modelled, the error structure of the data used for assessment purposes, the impact of future climate change on biological relationships such as the stock–recruitment function, and ecosystem impacts on biological and fishery processes.
4. Errors when conducting assessments, which inform the catch control rule that is being evaluated using the MSE: management advice for any system is based on uncertain data. Consequently, the data that inform catch control rules need to be generated in a manner which is as realistic as possible. Uncertainty arises when the model used for conducting assessments and providing management advice differs from the operating model, or the data are too noisy to estimate all key parameters reliably.
5. Outcome (or 'implementation') uncertainty: the impact of fishers and other players in the management system on the performance of management strategies has long been recognized (Rosenberg and Brault 1993; Rosenberg and Restrepo 1994). The most obvious form of this type of uncertainty is when catches are not the same as the TACs – typically more is taken or the decision-makers do not implement the TACs suggested by the management strategy. However, there are many other sources of outcome uncertainty, such as that associated with catch limits set for recreational fisheries and regulating discards. In some cases, this source of uncertainty has been found to dominate all the others (Dichmont *et al.* 2008; Fulton *et al.* 2011a).

In general, the evaluation of management strategies proceeds by first identifying the set of factors which are perceived to contribute the most to the uncertainty for the case in question. There will usually be factors for each of the five sources of uncertainty listed above. For example, factors could be 'the extent to which carrying capacity changes into the future', or 'the variation in realized catches about those intended'. Each factor will have a number of levels: for example, different rates of change in carrying capacity or variations in realized catch about the intended catch. Trials would then be constructed by selecting a level for each factor and thereby represent the range of uncertainty about a hypothesis to be considered in the evaluation. Best practice for a specific case involves explicitly addressing each of these uncertainties, or at least indicating how the uncertainties reflected were selected. Minimally, a MSE should consider (i) process uncertainty, in particular, variation in recruitment about the stock–recruitment relationship; (ii) parameter uncertainty relating to (a) productivity and (b) the overall size of the resource; and (iii) observation error in the data used when applying the management strategy. Which uncertainty is most important will be case-specific. For example, process uncertainty is unlikely to be very important for the management of large whale populations, whereas this uncertainty could be very consequential for a short-lived species such as Pacific sardine; the uncertainty factors considered in the MSEs for the two case-studies unsurprisingly differed markedly (Table 2).

Best practice is to divide MSE trials into a 'reference' (or 'base case') set of trials and a 'robustness' set of trials (Rademeyer *et al.* 2007). The reference trials are considered to reflect the most plausible hypotheses (see below for further comments on assigning plausibility to trials) and hence form the primary basis for identifying the 'best' management strategy, while the robustness trials are used to determine whether the management strategy behaves as intended in scenarios that are fairly unlikely, even though they are still plausible. While it is clearly desirable to conduct trials for all combinations for the levels for each factor (Kurota *et al.* 2010), this is often computationally impossible except when the management strategies being evaluated are fairly simple (Carruthers *et al.* 2014), and even then, conducting a MSE could be very computer-intensive depending on how many trials are run. Although partial factorial designs can be used to address this difficulty (Schweder *et al.* 1998), it is more common to select 'base' levels for each factor (in some cases multiple 'base levels'), and then to develop trials which involve varying each 'base' level in turn, perhaps also adding a few trials in which multiple factors are changed from their 'base' levels.

Table 2 Factors related to uncertainties considered in the simulation trials developed to test the management strategies for the Bering–Chukchi–Beaufort (BCB) Seas bowhead whales and the northern subpopulation of Pacific sardine.

BCB bowhead whales	Pacific sardine
Population dynamics	
• Inherent productivity	Extent of variation in recruitment
• Shape of the production function	Time-varying natural mortality
• Process error in calving rate	Time-varying productivity[1]
• Time trends in carrying capacity	Changes in selectivity spatially
• Time trends in productivity	Time-varying selectivity
• Occasional catastrophic mortality or recruitment events	Time-varying weight-at-age
• Time lags in the density dependence function	
• Alternative stock structure hypotheses[2]	
Data related	
• Survey frequency	Extent of auto-correlation in biomass estimates
• Average bias of survey estimates	Extent of variation in biomass estimates
• Trends in bias of survey estimates	Biomass estimates non-linearly related to true abundance
• Survey CV	
• Bias in reported catches	
Implementation related	
• Survey conducted to maximize strike limits	Only the USA follows the control rules

1All trials allowed for some variation in productivity due to environmental effects, but the manner in which productivity was related to the environment was varied in these trials.
2Conducted during the 2007 *Implementation Review* (International Whaling Commission 2008a,b, 2009, 2014).

Kraak *et al.* (2011) assert that the choice of sources of uncertainty included in MSE simulations often is quite arbitrary, and the uncertainties chosen do not necessarily reflect the key sources of uncertainty. They note that some MSEs conducted in Europe ignore spatial structure and whether egg production rather than spawning biomass drives recruitment. If these were indeed key uncertainties for the resources concerned, the scientists conducting those MSEs would clearly have been in error in ignoring them.

Best practice would involve trials based on at least a standard set of factors (Cooke 1999), so that the simulations extend over the set of uncertainties found to have had a large impact on the performance of management strategies for other systems (a list is given in Table 3). Most early operating models considered a single stock, ignored climate drivers of recruitment, growth and natural mortality, and treated the area being managed as a single homogeneous region. Each of these limitations can be overcome, particularly given the availability of sufficient computing resources. For example, although Butterworth and Punt (1999) commented that there were very few operating models which accounted for spatial structure when they conducted their review in 1998, subsequently Punt *et al.* (2005), IWC (2008a,b, 2009, 2014), Punt and Hobday (2009) and Carruthers *et al.* (2011) have all developed operating models which can, to some extent, account for spatial structure.

Climate and environmental variation is increasingly recognized as factors which often need to be included when evaluating management strategies. Two basic approaches have been adopted. The first is to include these factors in end-to-end models which represent entire ecosystems from physical processes to high trophic levels and fisheries, such as Atlantis (Fulton *et al.* 2011b) and Ecopath-with-Ecosim (Gaichas *et al.* 2012). The second is to relate environmental change to values of parameters empirically (Punt *et al.* 2014). Under the latter approach, environmental change can be

Table 3 List of factors, whose uncertainty commonly has a large impact on management strategy performance, which should be considered for inclusion in any management strategy evaluation.

Productivity	*Data-related issues*
• Form and parameters of the stock–recruitment relationship.	• CVs and effective samples sizes of data.
• Presence of depensation.	• Changes in the relationship between catchability and abundance.
• Extent of variation and correlations in recruitment about the stock–recruitment relationship.	• Changes in survey bias (fishery-independent data).
• Occasional catastrophic mortality or recruitment events.	• Survey and sampling frequency.
	• Ageing error.
	• Historical catch inaccuracy (bias).
Non-stationarity	*Outcome (Implementation) uncertainty*
• Changes in the stock–recruitment relationship.	• Decision-makers adjust or ignore management advice.
• Time-varying natural mortality (potentially a multispecies operating model).	• Realized catches differ from total allowable catches due to mis-reporting, black market catches, discards, etc.
• Time-varying carrying capacity (regime shift; linked to environmental variables or multispecies effects).	
• Time-varying growth and selectivity.	
Other factors	
• Spatial and stock structure.	
• Technical interactions.	
• Time-varying selectivity, movement and growth.	
• Initial stock size (unless it is estimated reliably when conditioning the operating model).	

modelled by linking environmental variables to the parameters that determine the dynamics of the population represented in the operating model (A'mar *et al.* 2009a; Ianelli *et al.* 2011; Punt 2011), or regime shift changes in parameters can be modelled (A'mar *et al.* 2009b; Wayte 2011; Szuwalski and Punt 2013). Most studies in which biological parameters are driven by environmental effects are conducted in circumstances where the relationships between the environment and the population dynamics are largely unknown (Hurtado-Ferro and Punt 2014). Most previous MSEs have allowed only one parameter of the operating model to exhibit time trends. However, it is possible to force a number of operating model parameters to do so. For example, Kell and Fromentin (2010) explored the performance of a VPA-based management strategy where both recruitment and migration varied as a function of the environment, while Punt *et al.* (2013) investigated the robustness of a management strategy for rock lobsters off Victoria, Australia, to time trends in natural mortality, catchability and growth.

Ecosystem effects, in particular biological and technological interactions, can be addressed within the context of end-to-end models such as Atlantis and Ecosim. However, most current investigations of the impacts of ecosystem effects on the performance of management strategies have been based on models of intermediate complexity for ecosystems (MICE; Punt and Butterworth 1995; Schweder *et al.* 1998; Plagányi 2007; A'mar *et al.* 2010; Howell *et al.* 2013), primarily because it is possible to parameterize these types of models by fitting them to monitoring data, although this renders the conclusions case-specific (Plagányi *et al.* 2014).

Technical interactions are probably easier to include in operating models given that there are usually direct data on catches and by-catches by fleet. Such interactions have been included in the MSEs conducted by De Oliveira and Butterworth (2004) for South African sardine and anchovy, by Dichmont *et al.* (2006a) for two prawn species off northern Australia, by Punt *et al.* (2005) for two shark species of southern Australia and by Kraak *et al.* (2008) for the flatfish complex in the North Sea. Dichmont *et al.* (2006a) and Kraak *et al.* (2008) model effort allocation based on economic incentives that lead to technical interactions among species.

How realistically the data are generated will directly impact the performance of any assessment method, and therefore also of any management strategies which depend on the results of the assessment. For example, most simulation studies generate age/length composition data from the survey or fishery catch in a way that matches the distributions assumed when fitting the assessment model (Bence *et al.* 1993; Sampson and Yin 1998; Radomski *et al.* 2005). However, this means that even very small sample sizes can appear to be extremely informative. In contrast, the residual patterns for actual stock assessments are often suggestive of both overdispersion and model misspecification. It is important to ensure that a number of plausible relationships between indices and true abundance are considered when assessments rely on fishery-dependent index data.

Best practice for parameter uncertainty for a given model structure is to sample parameters values from a Bayesian posterior distribution, or less ideally to use bootstrap samples or to sample parameter vectors from the asymptotic variance–covariance matrix for the parameters. Constructing Bayesian posterior distributions or developing bootstrap distributions for parameters can, however, be very intensive computationally.

Although the ideal is to evaluate management strategies using a trial structure which has been developed for a given stock or system, this may be impossible to achieve for data-poor situations. Nevertheless, it remains important to evaluate management strategies for data-poor situations, especially when the management strategies use proxies for measures of biomass; consequently, extensive testing of management strategies for data-poor situations has been undertaken, particularly in Australia (Haddon 2011b; Little *et al.* 2011; Plagányi *et al.* 2013, in press) and New Zealand (Bentley and Stokes 2009a,b). In these cases, there is a value in developing management strategies which can be applied generically. Naturally, generic management strategies would not be expected to perform as well as a management strategy that has been developed for a specific case (Butterworth and Punt 1999). When an evaluation of generic management strategies is to be undertaken, it is necessary to ensure that a broad range of species life histories are explored, along with a broad range of hypotheses regarding the quality of past and future data, and the state of the stock when the management strategy is first applied (Wiedenmann *et al.* 2013; Carruthers *et al.* 2014; Geromont and Butterworth in press-a). The values for the operating model parameters in this case would be selected based on generic considerations, and values for species which are characteristic of those to which the management strategy is to be applied.

Finally, it would be naive to believe that it is possible to identify all key uncertainties correctly, and it should not come as a surprise that some potential uncertainties not taken into account during the development of a management strategy turn out to be consequential. Kolody *et al.* (2008) drew attention to a key uncertainty (underestimation of historical catches) that was not initially considered during the development of a management strategy for southern bluefin tuna (*T. maccoyii*). They also questioned whether analyses of historical data, for example, as part of the process of conditioning the operating model(s) to data will capture the full extent of uncertainties. This problem should not imply that it is not worthwhile to conduct a MSE, but rather emphasizes that the earlier view that management strategies can be developed to run on 'autopilot' for a large number of years is likely flawed. Thus, the value of management strategies including 'Exceptional Circumstances' provisions and conducting regular *Implementation Reviews* (see final section) is high and justified, even if it entails additional work. Butterworth (2008a) emphasizes that the operating models considered in MSE analyses should remain 'broadly comparable' with the data. In practice, this means that use of, for example, strict model selection criteria to weight trials should be considered very carefully; in particular, use of, for example, AIC-weighting or the analytic hierarchy process (Merritt and Quinn 2000) should only be considered when there is confidence that the likelihood function is reliable (which is often not the case because the data inputs are not completely independent, as is usually assumed). Best practice in cases when the data used to parameterize the operating model are in conflict, for example when the various indices of abundance exhibit different trends, is to develop alternative operating models which represent each data set (Butterworth and Geromont 2001).

Identification of candidate management strategies which could realistically be considered for implementation

Ultimately, the management strategy chosen should reflect the policies developed by the decision-makers. Management strategies can be divided roughly into those that are model-based and those that are empirical, although some management strategies could be considered to be a mixture of the two types of strategies (Starr *et al.* 1997). Broadly, model-based management strategies usually involve two stages (see below), although some management strategies such as the IWC's Revised Management Procedure (IWC 1994) integrate the two stages to the point that it is impossible to distinguish them. For southern bluefin tuna, the model-based part of the management strategy is in effect a biologically plausible smoother of the two abundance indices used, with the actual harvest control rule having more in common with empirical harvest control rules than the more traditional model-based versions (Anonymous 2011).

The first stage in a model-based management strategy involves applying a stock assessment method (which may be much simpler than the methods used to develop the operating models that provide the basis for the MSE simulation testing process), and the second involves taking the results from that stock assessment model as the input for a harvest control rule. Several jurisdictions, including the USA and Australia, apply complex model-based management strategies, at least for their 'data rich' stocks. Despite the process being very intensive computationally, these types of management strategies have been evaluated using simulation (Dichmont *et al.* 2006b; A'mar *et al.* 2008, 2009a,b, 2010; Anonymous 2011; Fay *et al.* 2011; Punt *et al.* 2013). Model-based management strategies tend to lead to lower variation in terms of, for example, TACs than empirical approaches that do not constrain the estimated dynamics using population models (Butterworth and Punt 1999; Anonymous 2011), although this effect may be alleviated by imposing constraints on the extent of interannual change permitted in catch limits (see below).

In contrast to model-based management strategies, empirical management strategies do not utilize a population model to estimate biomass, fishing mortality or related quantities for use in harvest control rules. Rather, they set regulations such as TACs directly from monitoring data, usually after some data summary methods have been applied (e.g. CPUE standardization for catch and effort data). For example, the empirical harvest control rule used to recommend annual catch limits for the South African sardine involves setting catch limits as a constant proportion of the resource abundance estimated from the most recent hydro-acoustic survey. This rule is then subject to a number of constraints, or meta-rules, such as a maximum TAC and a maximum amount by which the TAC can decrease interannually. By removing this latter constraint during years of high TACs, the rule was designed to be flexible enough to allow the industry to take advantage of the occasional 'booms' that are a feature of this highly variable resource, without increasing the risk of the resource dropping to an undesirably low level (de Moor *et al.* 2011).

Rademeyer *et al.* (2007) remark that empirical management strategies are easier to test and are often easier to explain to decision-makers, but have the disadvantage that there might not be a clear basis for determining the target at which the resource will eventually equilibrate (Little *et al.* 2011). Examples of management strategies implemented which are empirical are those for hake, rock lobster, horse mackerel, anchovy and sardine off South Africa, for rock lobsters off South Australia and Tristan da Cunha, for West Greenland halibut and for pollock off eastern Canada. Most empirical management strategies base management decisions on trends in an index of abundance. However, there is a move towards 'target'-based rules, where TAC changes depend on the difference between the most recent level and the target for some abundance-related index (Little *et al.* 2011; Rademeyer and Butterworth 2011; Geromont and Butterworth in press-b), because the resultant catch limits tend to show less variability without impacting performance on other statistics such as average catch and risk to the resource. An example of an empirical 'target'-based rule is that used to recommend annual catch limits for the South African south coast rock lobster: the annual TAC is adjusted up or down from that recommended for the previous year according to whether the most recent measure of standardized CPUE is above or below a target value, with the extent of TAC adjustment proportional to the magnitude of the difference between the recent CPUE and the target value (Johnston *et al.* 2014). Management strategies can also be based on changes in metrics defined from age and size compositions (Butterworth *et al.* 2010b; Wayte and Klaer 2010; Fay *et al.* 2011).

Many management strategies impose constraints on how much catch limits can vary from 1 year to the next. For example, the management strategies for Australia's SESSF include 10 and 50% rules, which state that no change in TAC up or down will be larger than 50% of the current TAC; similarly, if a predicted change is <10% of the current TAC, then no change is made. In South Africa, both the hake and rock lobster management strategies include maximum TAC changes of either 5 or 10%, although these are over-ridden if appreciable declines in abundance become evident from the indices monitoring resource abundance. These minimum change rules have the advantage of smoothing out what might be noise from the management strategy output arising from noise in its data inputs.

Most of the management strategies considered in MSEs have been based on the conventional data used for stock assessments (e.g. catches, indices of abundance, age/length composition information). However, it is possible to develop management strategies, particularly for data-poor situations, using non-conventional data. For example, McGilliard *et al.* (2010) and Babcock and MacCall (2011) developed management strategies that use the ratio of the density inside and outside of marine protected areas to adjust limits on catch and effort in fished areas. Wilson *et al.* (2010) extended these approaches to use data on the proportion of old fish in the population. Christensen (1997) defined (and evaluated) a management strategy in which limits on effort are a function of the economic rent from the fishery, while Pomarede *et al.* (2010) evaluated one based on estimates of total mortality. The management control in most management strategies changes based on the data collected (feedback strategies), although some management strategies for data-poor situations are effectively non-feedback, setting management controls based, for example, on historical catch only. The performance of non-feedback strategies is, however, generally poor (Carruthers *et al.* 2014).

While the candidate management strategies which could be adopted should be identified by the decision-makers (or their advisers), best practice for MSE is also to evaluate additional management strategies to better understand the behaviour of the strategies identified by the stakeholders and decision-makers. In particular, it is a valuable exercise to apply variants of a management strategy in which the state of the stock is known exactly by the management strategy because this provides an upper limit to the 'value of information'. In addition, having results for 'reference' strategies, such as the strategy which maximizes average catch, can be useful for determining whether or not differences in performance statistics among management strategies are meaningful.

Most management strategies involve changes in the values of traditional management instruments such as catch limits, the total amount of effort or the length of the fishing season. However, MSE can also be used to evaluate novel management strategies such as that of Kai and Shirakihara (2005) that involves changing the size of a closed area based on the results of monitoring data.

It is essential that the management strategies being tested or compared are fully specified and can be implemented both for the operating models and in reality. Best practice is to simulate the management strategy exactly as it would be applied in reality, and this is commonly done when the management strategy is empirical (De Oliveira and Butterworth 2004; Little *et al.* 2011; Punt *et al.* 2012a; Carruthers *et al.* 2014), or the assessment method is not very demanding computationally (Kell and Fromentin 2009). It is becoming easier to evaluate complex management strategies given the increased availability of, for example, distributed computing including cloud computing. However, simulating very complicated management strategies such as those that involve fitting a statistical catch-at-age model can still require considerable computation (e.g. a single set of 100 simulations of 45 years to evaluate the actual management strategy for Gulf of Alaska walleye pollock took over 3 weeks on a fast desktop computer) and run the risk that fully automated fitting procedures may not find the global minimum that would be detected in the comprehensive searches typical of 'best assessment' approaches. Consequently, it is common to approximate application of a management strategy, for example by assuming that the estimates of biomass are log-normally distributed about the true biomass, perhaps with autocorrelated errors (DiNardo and Wetherall 1999; Hilborn *et al.* 2002; Anderson *et al.* 2010; Punt *et al.* 2012b).

However, ICES (2013) comments that it is generally not sufficient to simply add random noise to quantities derived from the operating model, and express concern that only 4 of the 18 MSEs which they reviewed had simulation tested the actual assessment. Failing to simulate application of the actual assessment method allows a broader set of hypotheses to be explored quickly, but the risk is that the actual error distribution associated with assessments does not match that assumed, and hence the values of the performance statistics are incorrect. In the extreme, the resultant relative ranking of management strategies may become incorrect. The justification for using an approximation to a management strategy may be examined by running a few simulations for the actual management strategy and the approximation, and comparing the results to ascertain whether the approximation is adequate. For example, ICES (2008) compared a 'full' and 'shortcut' MSE and found that the ranking of the performance of the harvest control rules evaluated changed when conducting a shortcut MSE compared to a full MSE (i.e. the best performing harvest control rule was different for the two evaluations).

The management strategy adopted for the BCB bowhead whales is based on averaging the strike limits from two SLAs (IWC 2003): (i) an empirical relationship between the strike limit and estimates of carrying capacity, the replacement yield predicted for the year for which a strike limit is needed, and the current stock size (Johnston and Butterworth 2000; Givens 2003); and (ii) a control rule based on the concept of adaptive Kalman filtering (a combination of Kalman filtering and Bayesian methodology; Dereksdóttir and Magnússon 2003). Both SLAs included ways to restrict interannual variation in strike limits, a factor considered very important during the selection process for a SLA. In particular, the component SLAs included a 'snap to need' feature which sets the strike limit equal to the need if the strike limit indicated by the algorithm is very close to the need.

The management strategy used for Pacific sardine is based on a set of control rules (Fig. 3) that are applied to an estimate of age 1+ biomass from a stock assessment model. The value for the FRACTION parameter may depend on the value of an environmental variable. The MSE for Pacific sardine (Hurtado-Ferro and Punt 2014) did not simulate application of the actual stock assessment process, but instead generated estimates of biomass directly from the operating model. Nevertheless, the extent of the errors

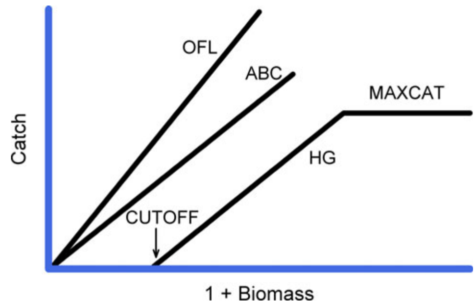


Figure 3 Harvest control rules applied to the northern subpopulation of Pacific sardine. The OFL is the overfishing level, which is based on the fishing mortality corresponding to maximum sustainable yield. The ABC is the acceptable biological catch, computed as the overfishing limit (OFL) reduced to account for scientific uncertainty. CUT-OFF determines the 1+ biomass at which the harvest guideline (HG) is zero, and MAXCAT is the maximum catch possible under the control rule.

associated with the biomass estimates for Pacific sardine was selected using a simulation evaluation of the actual stock assessment method (Hurtado-Ferro *et al.* 2014) in an attempt to ensure realism.

Simulation of application of each management strategy for each operating model

The actual process of linking the data generation phase of the operating model with the management strategy is generally straightforward, even if the process of conducting the simulations and summarizing the results can be very time-consuming. The difficult issues with MSE at this stage are primarily related to software development. There are several ways to minimize the chances of errors due to software coding, and use of these methods is best practice for MSE.

1. Base the operating model(s) and the management strategy on software that has been developed for broad application and has been tested extensively, such as Stock Synthesis (Methot and Wetzel 2013; Anderson *et al.* 2014; Maunder 2014), or use tools specifically developed to evaluate management strategies (Kell *et al.* 2007; Hillary 2009). However, in many instances, it is necessary to develop software for a specific case given the nature of the management strategy being evaluated and the hypotheses considered plausible – capturing the full range of uncertainty and of potentially

appropriate candidate management strategies should take priority over using available software.

2. Conduct simulations in which the system dynamics are deterministic, the operating model matches the estimation component of the management strategy, and the data are generated without error. In this situation, it should be possible for an analyst to heuristically predict the state of the system in the future fairly accurately (e.g. the stock should equilibrate at B_{MSY} if a strategy is based on a target fishing mortality of F_{MSY}, while if a strategy has a target level based on CPUE the stock should equilibrate at this level unless there are response-delay factors that induce oscillations) and compare this with where the MSE predicts the system will be. This provides a basic test to ensure that the coding of the operating model and of the management strategy is correct.
3. Conduct simulations in which the system dynamics are deterministic, the assessment model underlying the management strategy (if required) matches the operating model, and the data are generated with random error. Again, this provides a case where it is relatively straightforward to predict the results of the analyses.

The second and third of these steps also provide a way to eliminate poor management strategies from further consideration; it is virtually certain that a management strategy will not perform adequately in complex trials if it performs poorly when the data are not subject to error or there is no process error in the system.

The number of simulations for each trial (10 000 in the case of Pacific sardine and 100 in the case of the BCB bowheads) should be selected to ensure that the percentiles of the distributions on which performance statistics are based can be calculated with the precision required for the decisions to follow. The number to achieve a particular precision for probability-based statistics can be calculated taking into account that the simulations are independent (ICES 2013), and probability measures based on counts are therefore binomially distributed. Note that a very (perhaps prohibitively) large number of simulations may be needed if the decision-makers wish to draw conclusions based on very precise estimates of the lower fifth or first percentile of the distribution for some output from the operating model(s).

The number of years for which the operating model is projected will depend on the life history of the species under consideration. The number should be chosen, so that it is possible that the management strategy can impact the dynamics of the system and should cover 1–2 generations at minimum to allow for transients arising from response delays linked, for example, to the age at maturity. For example, the number of years for short-lived species such as sardine can be quite low while this number will be much higher for species such as bowhead whales.

It is essential, and hence best practice, that the management strategy bases recommendations for management actions only on data which would actually be available, and any assumptions regarding parameters assumed known when applying the management strategy need to be clearly documented (e.g. that natural mortality is assumed to be known exactly). One way to achieve this goal is to have separate segments of software for the operating model and for the management strategy, and to pass information (and management recommendations) between the operating model and management strategy using input and output files or their software equivalent.

The same set of random numbers should be used for all simulations for each trial, so that differences between candidate management strategies reflect the differences between the strategies themselves and not the consequences of different sets of observation and process errors.

Most management strategies assume that the data needed to apply them are always available (e.g. surveys are conducted at the expected frequency). However, this assumption might not be met in practice (e.g. a survey may not take place because of mechanical problems), and Butterworth (2008b) highlights that a management strategy should ideally also include specifications for how to provide management advice in circumstances in which anticipated data are not available. A related aspect is that the management strategy should ideally reward the provision of extra data and penalize the reverse situation. For example, the IWC's Revised Management Procedure reduces whale fishery catch limits to zero if new survey estimates do not become available within a specified time period (IWC 2012b).

Presentation of results and selection of a management strategy

Ultimately, the selection of a management strategy is not a scientific enterprise, but involves addressing trade-offs. This task lies primarily within the purview of decision-makers and policy. In principle, the selection of a management strategy could be automatic if a utility function was selected, which reflects the desired trade-offs amongst the objectives, and probabilities could be assigned to each alternative operating model configuration. However, this is rarely possible, and the authors know of no examples where a management strategy which has actually been implemented was selected this way.

There are almost always trade-offs among the management objectives. Consequently, it is desirable to provide results for a number of candidate strategies. Evaluation by the decision-makers of the trade-offs amongst the management objectives achieved by each candidate strategy may lead to a better understanding of what is possible, and even to changes to the relative ranking of management objectives. However, the results of management strategy simulations can be extensive and complicated, and the entire MSE process may be difficult for non-experts to comprehend. In South Africa, the details of the assumptions and sources of uncertainty were communicated, but statistics such as probability distributions were found hard to interpret (Cochrane *et al.* 1998). A better understanding of some of the trade-offs, particularly that between catch and catch variation, can be achieved by 'real-time gaming' of the MSE, which involves the decision-makers managing simulated populations where they are provided with the data which would actually be available on an annual basis. Walters (1994) provides an overview of the use of gaming to compare management options, including some best practices. Gaming has been used successfully in the South African fisheries (Butterworth *et al.* 1993). However, many MSE analyses are very computationally intensive, making real-time gaming impractical.

Stakeholders need to be involved in the decision process. However, more than that, they also need to be integrated within the entire MSE development process, including problem formulation, and even perhaps selecting the assumptions on which projections are based. This is, however, seldom easy and can be very time-consuming. Pastoors *et al.* (2007) describe an instance where stakeholders evaluated a MSE based on the extent to which hindcasts of the operating model could reproduce the observed dynamics of how TACs were set and whether the trends in stocks and catches proceeded 'logically'. Their advice was to present results relative to reference levels rather than in absolute terms, so as to reduce some of the concerns which stakeholders expressed.

As emphasized by Rademeyer *et al.* (2007), the basis for selecting a management strategy has to be clear to all stakeholders and should be made as simple as can be justified. Although much of the literature has focused on trade-offs among the objectives, some systems have fixed constraints. For example, the USA MSA effectively prohibits fishing mortality exceeding F_{MSY} for long periods, while adoption of a management strategy that would lead to high probabilities of decline of BCB bowhead whales would be considered unacceptable. Miller and Shelton (2010) identify an approach to selecting a management strategy based on 'satisficing', in which there are certain minimum standards for any candidate strategy, and only those candidates who satisfy these standards can be considered for possible adoption. Care should be taken not to require management strategies to meet performance statistic targets defined in terms of extreme tail probabilities, for example implementing a standard such as 'the probability of overfishing on an annual basis should not exceed 0.1%', because such probabilities are likely to be very poorly determined (Rochet and Rice 2009; Kraak *et al.* 2011). In cases in which the decision-makers require high certainty about a particular outcome, it is imperative that the analysts convey the likely level of precision possible from a MSE and that the major strength of a MSE lies in comparing the relative performance of alternative management strategies.

The first step in the process of selecting a management strategy should be explaining all of the options to the decision-makers, and placing the management strategies evaluated in the context of current management arrangements (Dowling *et al.* 2008). The value of effective graphical summaries cannot be over-emphasized. Some simple rules for constructing graphical summaries of results (see Figs 4 and 5 for examples) are to define 'best' performance for all operational objectives to be a high value for the associated performance statistics, and not to display too many performance statistics or management strategies on a single plot (contrast Figs 4 and 5 in this regard).

Perhaps most importantly, graphical approaches to summarizing performance statistics should be selected in collaboration with the decision-makers who need to understand and use them. For example, the axes in Fig. 5 were defined to report on the major areas of concern for stakeholders. 34 performance measures were identified by fishers, processors and local community, as well as given legislated fisheries and conservation objectives to across social, economic and ecological aspects (Fulton *et al.* 2014). For transparency, all of these measures were reported on, but it was not until the outcomes were aggregated and summarized around the major topic areas (using Fig 5 and other similar plots) that the relative performance and trade-offs between the objectives were clear. The axes represent natural groupings of the performance measures, but also highlight key concerns of the various stakeholders. Note that the industry and management efficiency axes used inverted performance scores, so that a larger score reflected better performance for all axes.

A key step in selecting a management strategy is dealing with the fact that not all of the trials reflect equally plausible hypotheses. This is partially addressed by assigning some trials to a reference set and the remaining trials to a robustness set (see above). However, other approaches are possible. For example, the IWC has adopted a set of guidelines for interpreting the results of trials to evaluate management strategies for commercial whaling. Specifically, trials are assigned to one of three categories ('high plausibility', 'medium plausibility' or 'low plausibility') by the Scientific Committee of the IWC (2012a). The required conservation performance of acceptable management strategies, expressed in terms of the values for performance statistics, is pre-specified for each

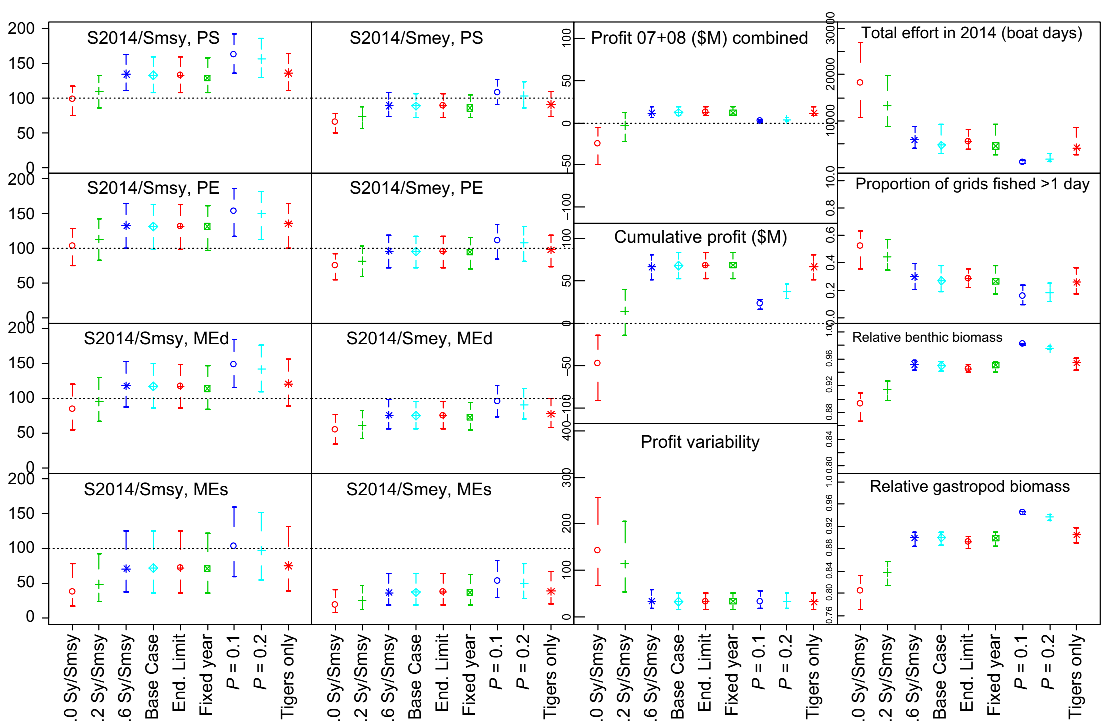


Figure 4 Biological, economic and ecosystem performance measures for a variety of management strategies for Australia's Northern Prawn Fishery (reproduced from Dichmont *et al.* 2008). The symbols indicate distribution medians, and the bars cover 95% of the simulation distributions. The performance statistics relate to spawning biomass relative to that at which MSY and maximum economic yield are achieved for four species (first two columns) and profit and its variability (third column). The right-most column shows the total effort in 2014, the proportion of grids fished for more than 1 day in 2014, the total benthic biomass relative to unfished levels, and the biomass of gastropods in 2014 relative to unfished levels. The management strategies differ in terms of the target biomass, the extent of precaution, and whether assessments for only two of the species form the basis for changes to effort limits.

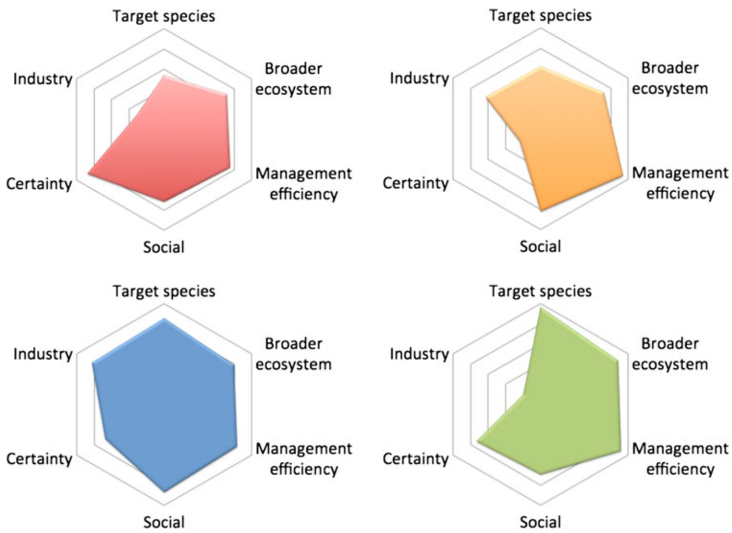


Figure 5 Example of plots which qualitatively compare four management strategies across six general areas of mean performance for a large multisector, multispecies fishery in southeastern Australia (E. Fulton, CSIRO, personal communication). A better result for a performance statistic is indicated by a vertex which is further from the centre of each hexagon.

category, which essentially (though not entirely – see IWC 2012a, for details) automates the process of selecting a 'best' management strategy. The assignment of plausibility for a trial is based on assigning a plausibility ranking to the level for each factor on which the trial is based ('high', 'medium', 'low' or 'no agreement'), with levels for which there is no agreement being treated as 'medium'. The ranking of a trial reflects the lowest rank assigned to each level of the factors on which it is based (thus to be categorized as a 'high' plausibility trial, the levels of all the factors included in the trial need to be considered to be of 'high' plausibility). Any trials considered to be 'low' plausibility are assigned a 'low' rank and ignored. This approach has been applied to select management strategies for the western North Pacific minke whales (IWC 2014), the western North Pacific Bryde's whales (IWC 2010) and the North Atlantic fin whales (IWC 2009).

In an effort to provide an improvement to simply selecting plausibility ranks based on expert judgement, Butterworth *et al.* (1996) proposed four sets of criteria with which plausibility ranks might be assessed:

1. how strong is the basis for the hypothesis in the data for the species or region under consideration?
2. how strong is the basis for the hypothesis in the data for a similar species or another region?
3. how strong is the basis for the hypothesis for any species? and
4. how strong or appropriate is the theoretical basis for the hypothesis?

Although this approach was presented to the Scientific Committee of the IWC, it was never adopted, and in general weights are almost always assigned based on expert judgement.

An alternative approach to addressing plausibility in selecting a management strategy is to assign weights to each trial and to compute integrated values for the performance statistics. However, this involves selection of quantitative weights upon which it is likely to be even more difficult to reach agreement than on assigning trials to categories of plausibility. Moreover, integrated performance statistics may obscure low plausibility trials for which performance is very poor (Rademeyer *et al.* 2007). Those authors also comment that stakeholders may benefit from being shown results of individual catch and population trajectories, as these tend to give a better impression of variation than statistics such as CVs and variances, which may be difficult for some stakeholders to understand.

Assignment of quantitative weights for plausibility becomes necessary if decision-makers wish to draw conclusions based on some percentile of the distribution of a performance statistic and the MSE is being conducted over a reference set of operating models. This was the case in the CCSBT, where the use of this set, rather than working only with a single reference case operation model, rendered consensus much more easily achieved in the Scientific Committee. Subsequently, the Commission requested its Scientific Committee to report results for reaching a target recovery level of 20% of the estimate unfished abundance by 2035 with 70% probability [see final agreed management strategy specifications reflected in CCSBT (2011)]. To provide such results, integration across the reference set became necessary.

While providing percentile results for a single operating model is a relatively objective process, as the statistical basis to take account of the associated stochastic effects is well established, extending to a reference set creates some difficulties. This is because the results will depend on the choice of which models are included in the set and how they are weighted, which is much less straightforward. Given that balance (between more optimistic and more pessimistic scenarios) is usually seen as a desired feature of a reference set of operating models, estimates of the medians of performance statistics would be expected to remain relatively robust and reliable. However, care should be taken in the interpretation of high and low percentiles of distributions for a reference set, as these will not be as firmly established as in the case of a single reference case operating model.

In the BCB bowhead case, the Chair of the group tasked with developing and testing alternative SLAs briefed the IWC as well as representatives of the hunting communities. In particular, as a key objective of the SLA was to satisfy the nutritional and cultural needs of aboriginal communities rather than to maximize catch, an important input to the analyses was the 'Need Envelope'. This function was obtained through discussion with the hunters and their scientific representatives, and formed the basis for specifying performance statistics such as the fraction of total need over 100 years which could be satisfied.

In contrast to the bowhead case-study, the MSE for Pacific sardine was developed in the context of a USA Regional Fishery Management Council process. This allows for input by stakeholders, state and federal analysts, and the public during the development of management decisions. The structure of the MSE was initially developed during a workshop (PFMC 2013) which included biologists familiar with Pacific sardine and its relationship with the environment, modellers (including assessment biologists and ecosystem modellers), representatives of the advisory bodies of the PFMC, and stakeholders (conservation and industry). The MSE structure was then subjected to peer review through the PFMC's Scientific and Statistical Committee on several occasions. Input from stakeholder groups included interpretation of the results of the simulations in the context of the objectives which each such group considered most important (Parrish 2014).

Did the case-studies follow 'best practice'?

The two case-studies highlighted in this paper followed best practice to different extents. Both case-studies involved stakeholders and decision-makers at various points in the development and selection process, and included default performance statistics. The range of uncertainties was wider in the bowhead case-study, and there are some uncertainties which are likely important for Pacific sardine which were not explored (such as that the USA fishery operates at some times on the southern as well as the northern subpopulation). Such omissions were due to limited time being made available to conduct the MSE. In actual development and implementation, limited time frames are common and constitute a constraint on achieving best practice.

Neither of the case-studies explicitly considered predator-prey interactions as these were not seen as likely to have large impacts; the sardine case-study did however explore environmental impacts on recruitment, and both case-studies accounted for spatial structure to some extent. The bowhead case-study represented parameter uncertainty by sampling parameter vectors from a posterior distribution, whereas the sardine case-study explored this uncertainty through sensitivity testing.

The candidate management strategies for Pacific sardine were selected by the stakeholders and the decision-makers, whereas these were identified by the competing teams of 'developers' in the bowhead case. In contrast to the bowhead SLA, the actual management strategy for sardine was not simulated exactly because it was not the assessment itself (which is based on a statistical catch-at-age analysis) that was simulated. Rather, this assessment was approximated by true biomass from the operating model plus autocorrelated log-normal error. However, an attempt was made to assess the likely level of assessment error.

Both case-studies applied standard programming techniques to attempt to ensure that the code implementing the operating model(s) and management strategies was correct, but only in the sardine case were deterministic analyses undertaken. The code implementing the operating models for the bowhead case was developed by a member of the staff of the IWC and independently checked by one of us (AEP). Neither case-study conducted a thorough comparison of whether the operating model and management strategy produced results of projections consistent with reality through, for example, comparing variability in assessment outcomes with historical results, although some checks were carried out for sardine. Neither of the management strategies adopted included 'Exceptional Circumstances' provisions, although *Implementation Reviews* are mandated and have been conducted for the bowheads. The SLA for the BCB bowheads was subject to an *Implementation Review* in 2007 (IWC 2008a,b, 2009, 2014) and 2013 (IWC 2013). The 2007 *Implementation Review* focused on the possibility that the BCB stock may actually consist of two stocks as well as that different age and sex classes migrate differently. However, it did not lead to a change to the SLA developed for the BCB stock because the performance of this SLA was not markedly impacted by the multi-stock scenarios examined.

Both case-studies relied on graphical and tabular summaries, and both involved trying to educate the decision-makers on how to interpret the results from the MSE. Performance standards were adopted for interpreting the results of the trials for bowheads (IWC 2003), but the comparison of alternatives for Pacific sardine was based primarily on finding an acceptable trade-off among the performance statistics. The trials for the bowhead case were divided into 'reference' and 'robustness' trials, with most focus during selection given to the 'reference' set.

In summary, the application of MSE for bowheads followed the proposed best practice guidelines to the largest extent possible, while that for sardine took several short cuts, owing primarily to the need to complete the analyses in time for management decision-making.

Final comments

Management strategy evaluation arose from the desires to deal more systematically with the issue of uncertainties and to identify management strategies that are adaptive given the collection of new data. Although the benefits of active adaptive management strategies, that is management strategies which select management actions to increase 'contrast' and hence improve the information content of the available data, have long been known (Walters 1986), few jurisdictions have been able or willing to implement such strategies (Sainsbury *et al.* 1997 being a noteworthy exception, although in that case the 'experimental unit' was primarily a foreign fishery off Australia's northwest shelf). Consequently, MSE has in practice generally involved evaluation of passive adaptive management options, that is learning about the system dynamics through ongoing monitoring but without attempting to deliberately manipulate the system to learn more about it, although the strategy developed for the mid-water fishery for horse mackerel in South Africa is an exception to this (Furman and Butterworth 2012).

Management strategy evaluation has been applied most widely in relation to fisheries and cetacean conservation and management. However, it has also been applied to explore the performance of ballast-water management options (Dunstan and Bax 2008), and recently there have been calls for MSE to be applied to terrestrial systems, including in the development of conservation plans for threatened species (Milner-Gulland *et al.* 2010; Bunnefeld *et al.* 2011; Moore *et al.* 2013). Most fisheries applications have focused on single-species cases. However, MSE can be applied to identify management strategies to achieve ecosystem and multiuse objectives. The applications in this area remain few, in particular because of the computational requirements associated with fitting and projecting models such as Atlantis. However, one would expect that the number of these applications will increase rapidly as computational constraints become less of an issue.

Management strategy evaluation has generally been used to evaluate management strategies in terms of their ability to satisfy management goals, either generically or for a specific situation, with a view to possible formal adoption and implementation. However, an additional key reason for conducting a MSE is to identify when management strategies are likely to fail, and either to identify new data collection schemes to detect when failure might occur or to revise an existing management strategy appropriately. Finally, evaluation of the management strategies on which a fishery is based is part of several eco-certification systems, including that of the Marine Stewardship Council (MSC). In the case of Tristan da Cunha rock lobster, the MSE was conducted specifically to satisfy one of the performance indicators for MSC certification.

Smith *et al.* (1999) outline the roles for the various participants in the MSE development process, including those of decision-makers, industry, conservation agencies and groups, fishery scientists and MSE analysts. As noted above, the involvement of as many of these groups as possible enhances the likelihood that the results of the MSE will be considered credible and hence the strategy actually implemented throughout the period for which it is intended to apply. Although inclusion of stakeholders in the development of management strategies is emphasized by Smith *et al.* (1999) and in many other publications, the actual number of MSEs for which there is direct evidence that stakeholders were involved throughout the entire process is rare. ICES (2013) outlines the roles of stakeholders (and decision-makers) in the MSE process as it is typically applied in Europe. The MSE developed for Australia's SESSF was guided by a steering committee of stakeholders from all sectors of the fishing industry, an ENGO, decision-makers and representatives of two key funding agencies (Smith *et al.* 2007). In South Africa, the process is taken forward in the species-specific scientific working groups of the Fisheries Branch of the Government Department responsible; these groups include observers from both industry and ENGOs who participate actively.

The establishment of a management strategy is a critical part of effective management. However, it is only one part. There still needs to be a formal process for reviewing the appropriateness of a management strategy given information collected following adoption. In Europe, apart from performing impact assessments of proposed management plans, the European Commission's advisory body, STECF, also evaluates the performance of existing management plans in relation to their original objectives (STECF 2011b; Kraak *et al.* 2013). In South Africa, reviews of management strategies are planned for every 4 years, while reviews of the CCSBT management strategy are planned for every 9 years, with the latter commonly adjusting TACs only every 3 years (Butterworth 2008b). The IWC has established a formal process for the regular (usually 5-year) review of the basis for specific management strategies, termed *Implementation Reviews* (IWC 2012a, 2013; Punt and Donovan 2007).

A management strategy is tested for the set of hypotheses considered plausible when it was first developed. However, subsequent research could indicate that those hypotheses did not include the entire plausible range. Consequently, rules have been developed (IWC 2013) for when it is necessary to temporarily stop applying the management strategy and rely on *ad hoc* adjustments to management regulations or to initiate an *Implementation Review* before one is due. The management strategies for South African fish stocks include some formal 'Exceptional Circumstances' provisions (Butterworth 2008b), as do those for southern bluefin tuna, west Greenland halibut and east Canadian pollock, but most other management strategies do not. 'Exceptional Circumstances' are generally defined to apply when the future data fall outside of the range indicated for the projections considered in the MSE. The inclusion of such provisions should be considered a standard component of best practice.

We have identified 'best practices' for conducting MSE (Table 1). The 'best practices' should be followed as closely as possible, particularly when the intent is to use the MSE to develop a management strategy for a particular fishery. However, as we illustrate for the two case-studies, a MSE can be useful even if not all of the best practices are followed strictly. This is particularly the case when the aim of the MSE is to evaluate generic management strategies rather than to propose a management strategy for implementation to a specific stock. Most critical perhaps is that the primary aim of a MSE is to identify which uncertainties are most important in terms of achieving management objectives. What is the minimum that can be done for the process still to be considered as a MSE? We would propose this to be that a MSE *considers* all sources of influential uncertainty, even if they are not all represented in the operating models, *considers* all the management objectives, even if they cannot all be reflected in the operating models, and minimally allows for uncertainty in the information on which management advice is based.

Finally, the practice of MSE continues to develop, and so, just as management strategies should be adapted under changing circumstances, MSE best practice is expected to continue to become further articulated as more experience is gained.

Acknowledgements

This paper benefited from comments by Tony Smith, Eva Plaganyi and Geoff Tuck (CSIRO Wealth from Oceans Flagship), Kelli Johnson (UW), two anonymous reviewers and the editor. This publication is [partially] funded by the Joint Institute for the Study of the Atmosphere and Ocean (JISAO) under NOAA Cooperative Agreement No. NA08OAR4320899 Contribution No. 2370.

References

A'mar, Z.T., Punt, A.E. and Dorn, M.W. (2008) The management strategy evaluation approach and the fishery for walleye pollock in the Gulf of Alaska. In: *Resiliency of Gadid Stocks to Fishing and Climate Change* (eds G.H. Kruse, K. Drinkwater, J.N. Ianelli, J.S. Link, D.L. Stram, V. Wespestad and D. Woodby). Alaska Sea Grant College Program, University of Alaska, Fairbanks, pp. 317–346.

A'mar, Z.T., Punt, A.E. and Dorn, M.W. (2009a) The evaluation of management strategies for the Gulf of Alaska walleye pollock under climate change. *ICES Journal of Marine Science* **66**, 1614–1632.

A'mar, Z.T., Punt, A.E. and Dorn, M.W. (2009b) The impact of regime shifts on the performance of management strategies for the Gulf of Alaska walleye pollock fishery. *Canadian Journal of Fisheries and Aquatic Sciences* **66**, 2222–2242.

A'mar, Z.T., Punt, A.E. and Dorn, M.W. (2010) Incorporating ecosystem forcing through predation into a management strategy evaluation for the Gulf of Alaska walleye Pollock (*Theragra chalcogramma*) fishery of ecosystem changes on the management of the fishery for walleye pollock in the Gulf of Alaska. *Fisheries Research* **102**, 98–114.

Anderson, B.S., Vermard, Y., Ulrich, C., Hutton, T. and Poos, J.J. (2010) Challenges in integrating short-term behaviour in a mixed-fishery Management Strategies Evaluation frame: a case study of the North Sea flatfish fishery. *Fisheries Research* **102**, 26–40.

Anderson, S.C., Monnahan, C.C., Johnson, K.F., Ono, K. and Valero, J.L. (2014) ss3sim: an R package for fisheries stock assessment simulation with Stock Synthesis. *PLoS One* **9**, e92725.

Anonymous. (2011) Report of the 16th meeting of the Extended Scientific Committee for the Commission for the Conservation of Southern Bluefin Tuna. CCSBT.

Babcock, E.A. and MacCall, A.D. (2011) How useful is the ratio of fish density outside versus inside no-take marine reserves as a metric for fishery management control rules? *Canadian Journal of Fisheries and Aquatic Sciences* **68**, 343–359.

Baumgartner, T., Soutar, A. and Ferriera-Bartrina, V. (1992) Reconstruction of the history of pacific sardine and northern anchovy populations over the past two millennia from sediments of the Santa Barbara Basin, California. *CalCOFI Reports* **33**, 24–40.

Bence, J.R., Gordoa, A. and Hightower, J.E. (1993) Influence of age-selective surveys on the reliability of stock synthesis assessments. *Canadian Journal of Fisheries and Aquatic Sciences* **50**, 827–840.

Bentley, N. and Stokes, K. (2009a) Moving fisheries from data-poor to data-sufficient: evaluating the costs of management versus the benefits of management. *Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science* **1**, 378–390.

Bentley, N. and Stokes, K. (2009b) Contrasting paradigms for fisheries management decision making: how well do they serve data-poor fisheries? *Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science* **1**, 391–401.

Bergh, M.O. and Butterworth, D.S. (1987) Towards rational harvesting of the South African anchovy considering survey imprecise and recruitment variability. *South African Journal of Marine Science* **5**, 937–951.

Breen, P.A. and Kim, S.W. (2006) Development of an operational management procedure (decision rule) for CRA 4. New Zealand Fisheries Assessment Report 2006/53, 46 pp.

Bunnefeld, N., Hoshino, E. and Milner-Gulland, E.J. (2011) Management strategy evaluation: a powerful tool for conservation? *Trends in Ecology and Evolution* **26**, 441–447.

Butterworth, D.S. (2007) Why a management procedure approach? Some positives and negatives. *ICES Journal of Marine Science* **64**, 613–617.

Butterworth, D.S. (2008a) A commentary on: salvaged pearls: lessons learned from a floundering attempt to develop a management procedure for Southern Bluefin Tuna. *Fisheries Research* **94**, 351–354.

Butterworth, D.S. (2008b) Some lessons from implementing management procedures. In: *Fisheries for Global Welfare and Environment, 5th World Fisheries Congress 2008* (eds K. Tsukamoto, T. Kawamura, T. Takeuchi, T.D. Beard Jr and M.J. Kaiser). TERRAPUB, Tokyo, pp. 381–397.

Butterworth, D.S. and Geromont, H.F. (2001) Evaluation of a class of possible simple interim management procedures for the Namibian hake fishery. *South African Journal of Marine Science* **23**, 357–374.

Butterworth, D.S. and Johnston, S.J. (2014) Recommendations on rock lobster TACs for the Tristan outer group of islands for the 2014/15 season. MARAM Document: MARAM/2014/JUL/10, 6 pp. Available at: http://www.mth.uct.ac.za/maram/pub/2014/MARAM_TRISTAN_2014_FEB_03.pdf (accessed 10 November 2014).

Butterworth, D.S. and Punt, A.E. (1999) Experiences in the evaluation and implementation of management procedures. *ICES Journal of Marine Science* **56**, 985–998.

Butterworth, D.S. and Rademeyer, R.A. (2010) Greenland halibut MSE results for updated SCAA reference case and robustness test operating models. NAFO Document: FCWGMSE WP 10/13, 18 pp. Available at: http://www.mth.uct.ac.za/maram/pub/2010/wgmsewp 10-13_MSE_update.pdf (accessed 26 June 2014).

Butterworth, D.S., De Oliveira, J.A.A. and Cochrane, K.L. (1993) Current initiatives in refining the management procedure for the South African anchovy resource. In: *Proceedings of the International Symposium on Management Strategies for Exploited Fish Populations (Anchorage, Alaska, October 1992)* (eds G. Kruse, D.M. Eggers, R.J. Marasco, C. Pautzke and T.J. Quinn II). Alaska Sea Grant College Program AK-SG-93-02, Fairbanks, AK, pp. 439–473.

Butterworth, D.S., Punt, A.E. and Smith, A.D.M. (1996) On plausible hypotheses and their weighting, with implications for selection between variants of the Revised Management Procedure. *Reports of the International Whaling Commission* **46**, 637–640.

Butterworth, D.S., Johnston, S.J. and Brandáo, A. (2010a) Pretesting the likely efficacy of suggested approach to data-poor fisheries. *Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science* **2**, 131–145.

Butterworth, D.S., Bentley, N., De Oliveira, J.A.A. *et al.* (2010b) Purported flaws in management strategy evaluation: basic problems or misinterpretations? *ICES Journal of Marine Science* **67**, 567–574.

Butterworth, D.S., De Oliveira, J.A.A. and de Moor, C.L. (2012) Are South African administrative law procedures adequate for the evaluation of issues resting on scientific analyses. *South African Law Journal* **129**, 461–477.

Carruthers, T.R., McAllister, M.K. and Taylor, N. (2011) Spatial surplus production modeling of Atlantic tunas and billfish. *Ecological Applications* **21**, 2734–2755.

Carruthers, T.R., Punt, A.E., Walters, C.J. *et al.* (2014) Evaluating methods for setting catch limits in data-limited fisheries. *Fisheries Research* **153**, 48–68.

Christensen, S. (1997) Evaluation of management strategies – a bioeconomic approach applied to the Greenland Shrimp Fishery. *ICES Journal of Marine Science* **54**, 412–426.

Cochrane, K.L., Butterworth, D.S., De Oliveira, J.A.A. and Roel, B.A. (1998) Management procedures in a Fishery based on highly variable stocks and with conflicting objectives: experiences in the South African pelagic fishery. *Reviews in Fish Biology and Fisheries* **8**, 177–214.

Commission for the Conservation of Southern Bluefin Tuna (CCSBT) (2011) Report of the Eighteenth Annual Meeting of the Commission. Available at: http://www.ccsbt.org/userfiles/file/docs_english/meetings/meeting_reports/ccsbt_20/report_of_SC18.pdf (accessed 11 November 2014).

Cooke, J.G. (1999) Improvement of fishery-management advice through simulation testing of harvest algorithms. *ICES Journal of Marine Science* **56**, 797–810.

Cox, S.P. and Kronlund, A.R. (2008) Practical stakeholder-driven harvest policies for groundfish fisheries in British Columbia, Canada. *Fisheries Research* **94**, 224–237.

De Oliveira, J.A.A. (2003) *The development and implementation of a joint management procedure for the South African pilchard and anchovy resources*. PhD thesis, University of Cape Town, [iv] + 319 pp.

De Oliveira, J.A.A. and Butterworth, D.S. (2004) Developing and refining a joint management procedure for the multispecies South African pelagic fishery. *ICES Journal of Marine Science* **61**, 1432–1442.

Dereksdóttir, E.H. and Magnússon, K.G. (2003) A Strike Limit Algorithm based on Adaptive Kalman Filtering with an application to aboriginal whaling of bowhead whales. *Journal of Cetacean Research and Management* **5**, 29–37.

Dichmont, C.M. and Brown, I.W. (2010) A case study in successful management of a data-poor fishery using simple decision rules: the Queensland spanner crab fishery. *Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science* **2**, 1–13.

Dichmont, C.M., Deng, R., Punt, A.E., Venables, W. and Haddon, M. (2006a) Management strategies for short lived species: the case of Australia's Northern Prawn Fishery. 1. Accounting for multiple species, spatial structure and implementation uncertainty when evaluating risk. *Fisheries Research* **82**, 204–220.

Dichmont, C.M., Deng, R., Punt, A.E., Venables, W. and Haddon, M. (2006b) Management strategies for short lived species: the case of Australia's Northern Prawn Fishery. 3. Management strategy scale and complexity. *Fisheries Research* **82**, 235–245.

Dichmont, C.M., Deng, A., Punt, A.E. *et al.* (2008) Beyond biological performance measures in Management Strategy Evaluation: bringing in economics and the effects of trawling on the benthos. *Fisheries Research* **94**, 238–250.

Dichmont, C.M., Ellis, N., Bustamante, R.H. *et al.* (2013) Evaluating marine spatial closures with conflicting fisheries and conservation objectives. *Journal of Applied Ecology* **50**, 1060–1070.

DiNardo, G.T. and Wetherall, J.A. (1999) Accounting for uncertainty in the development of harvest strategies for the Northwestern Hawaiian Islands lobster trap fishery. *ICES Journal of Marine Science* **56**, 943–951.

Dowling, N.A., Smith, D.C., Knuckey, I. *et al.* (2008) Developing harvest strategies for low-value and data-poor fisheries: case studies from three Australian fisheries. *Fisheries Research* **94**, 380–390.

Dunstan, P.K. and Bax, N.J. (2008) Management of an invasive marine species: defining and testing the effectiveness of ballast-water management options using management strategy evaluation. *ICES Journal of Marine Science* **66**, 841–850.

Fay, G., Punt, A.E. and Smith, A.D.M. (2011) Impacts of spatial uncertainty on the performance of age structure-based harvest strategies for blue-eye trevalla (*Hyperoglyphe antarctica*). *Fisheries Research* **110**, 391–407.

Field, J.C., Punt, A.E., Methot, R.D. and Thomson, C.J. (2006) Does MPA mean "Major Problem for Assessments?" Considering the consequences of place-based management systems. *Fish and Fisheries* **7**, 284–302.

Francis, R.I.C.C. and Shotton, R. (1997) "Risk" in fisheries management: a review. *Canadian Journal of Fisheries and Aquatic Sciences* **54**, 1699–1715.

Fulton, E.A., Smith, A.D.M. and Punt, A.E. (2004) Which ecological indicators can robustly detect effects of fishing? *ICES Journal of Marine Science* **62**, 540–551.

Fulton, E.A., Smith, A.D.M. and Smith, D.C. (2007) Alternative management strategies for Southeastern Australian Commonwealth Fisheries: Stage 2: Quantitative Management Strategy Evaluation. Report to the Australian Fisheries Management Authority and the Fisheries Research and Development Corporation. CSIRO Marine and Atmospheric Research.

Fulton, E.A., Smith, A.D.M., Smith, D.C. and van Putten, I.E. (2011a) Human behavior: the key source of uncertainty in fisheries management. *Fish and Fisheries* **12**, 2–17.

Fulton, E.A., Link, J.S., Kaplan, I.C. *et al.* (2011b) Lessons in modelling and management of marine ecosystems: the Atlantis experience. *Fish and Fisheries* **12**, 171–188.

Fulton, E.A., Smith, A.D.M., Smith, D.C. and Johnson, P. (2014) An integrated approach is needed for Ecosystem Based Fisheries Management: insights from ecosystem-level management strategy evaluation. *PLoS One* **9**, e84242.

Furman, L.B. and Butterworth, D.S. (2012) Proposed Catch Control Rules for Horse Mackerel Bycatch in the Small Pelagics fishery and Directed Catch in the Midwater Trawl Fishery. Department of Agriculture, Forestry and Fisheries Report No. FISHERIES/2012/OCT/SWG-DEM/23, 33 pp. Available at: http://www.mth.uct.ac.za/maram/pub/2012/FISHERIES_2012_OCT_SWG-DEM_23_Horse_mackerel_juvenile_PUCL.pdf (accessed 11 November 2014).

Gaichas, S., Gamble, R., Fogarty, M. *et al.* (2012) Assembly rules for aggregate-species production models: simulations in support of management strategy evaluation. *Marine Ecology Progress Series* **459**, 275–292.

George, J.C., Bada, J., Zeh, J. *et al.* (1999) Age and growth estimates of bowhead whales (*Balaena mysticetus*) via aspartic acid racemisation. *Canadian Journal of Zoology* **77**, 571–580.

Geromont, H.F. and Butterworth, D.S. (In press-a) Generic management procedures for data-poor fisheries: forecasting with few data. *ICES Journal of Marine Science.*

Geromont, H.F. and Butterworth, D.S. (In press-b) Complex assessments or simple management procedures for efficient fisheries management: a comparative study. *ICES Journal of Marine Science.*

Geromont, H.F., De Oliveira, J.A.A., Johnston, S.J. and Cunningham, C.L. (1999) Development and application of management procedures for fisheries in southern Africa. *ICES Journal of Marine Science* **56**, 952–966.

Givens, G.H. (2003) Empirical estimation of safe aboriginal whaling limits for bowhead whales. *Journal of Cetacean Research and Management* **5**, 39–43.

Givens, G.H., Zeh, J.E. and Raftery, A.E. (1995) Assessment of the Bering–Chukchi–Beaufort Seas stock of bowhead whales using the Baleen II Model in a Bayesian synthesis framework. *Reports of the International Whaling Commission* **45**, 345–364.

Haddon, M. (2011a) *Modelling and Quantitative Methods in Fisheries*, 2nd edn. Chapman & Hall, CRC Press, 449 pp.

Haddon, M. (2011b) Management Strategy Evaluation testing of the Management Strategies used with South-Eastern Scallop Fisheries. Report prepared for the Department of Agriculture, Fisheries and Forestry (DAFF) as part of the Reducing Uncertainty in Stock Status Project, 100 pp.

Haddon, M. and Helidoniotis, F. (2013) Legal minimum lengths and the management of abalone fisheries. *Journal of Shellfish Research* **32**, 197–208.

Hilborn, R., Parma, A. and Maunder, M. (2002) Exploitation rate reference points for West Coast rockfish: are they robust and are there better alternatives? *North American Journal of Fisheries Management* **22**, 365–375.

Hill, K.T., Crone, P.R., Lo, N.C.H. *et al.* (2011) Assessment of the Pacific sardine resource in 2011 for U.S. management in 2012. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-SWFSC-487, 260 pp.

Hillary, R. (2009) An introduction to FLR fisheries simulation tools. *Aquatic Living Resources* **22**, 225–232.

Howell, D., Filin, A.A., Bogstad, B. and Stiansen, J.E. (2013) Unquantifiable uncertainty in projecting stock response to climate change: example from North East Arctic cod. *Marine Biology Research* **9**, 920–931.

Hurtado-Ferro, F. and Punt, A.E. (2014) *Revised Analyses Related to Pacific Sardine Harvest Parameters*. Pacific Fishery Management Council, Portland, OR.

Hurtado-Ferro, F., Punt, A.E. and Hill, K.T. (2014) Use of multiple selectivity patterns as a proxy for spatial structure. *Fisheries Research* **158**, 102–115.

Ianelli, J.N., Hollowed, A.B., Haynie, A.C., Mueter, F.J. and Bond, N.A. (2011) Evaluating management strategies for eastern Bering Sea walleye pollock (*Theragra chalcogramma*) in a changing environment. *ICES Journal of Marine Science* **68**, 1297–1304.

ICES. (2008) Report of the Working Group on Methods of Fish Stock Assessments (WGMG), 7–16 October 2008, Woods Hole, USA. ICES CM 2008/RMC:03, 147 pp.

ICES. (2012) Report of the ICES Advisory Committee 2012. ICES Advice, 2012. Book 1, 156 pp.

ICES. (2013) Report of the Workshop on Guidelines for Management Strategy Evaluations (WKGMSE), 21–23 January 2013, ICES HQ, Copenhagen, Denmark.

International Whaling Commission (IWC) (1992) Report of the Third Comprehensive Assessment on Management Procedures. *Reports of the International Whaling Commission* **42**, 271–304.

International Whaling Commission (IWC) (1994) Report of the Scientific Committee, Annex H. The Revised Management Procedure (RMP) for Baleen Whales. *Reports of the International Whaling Commission* **44**, 145–152.

International Whaling Commission (IWC) (2003) Report of the Scientific Committee, Annex E. Report of the Standing Working Group (SWG) on the Development of an Aboriginal Subsistence Whaling Management Procedure (AWMP). *Journal of Cetacean Research and Management* **5**(Suppl), 154–225.

International Whaling Commission (IWC) (2008a) Report of the Scientific Committee, Annex E. Report of the Standing Working Group (SWG) on the Aboriginal Subsistence Whaling Management Procedure (AWMP). *Journal of Cetacean Research and Management* **10**(Suppl), 121–149.

International Whaling Commission (IWC) (2008b) Report of the Scientific Committee, Annex D. Report of the Sub-committee on the Revised Management Procedure. *Journal of Cetacean Research and Management* **10** (Suppl), 84–92.

International Whaling Commission (IWC) (2009) Report of the Scientific Committee, Annex D. Report of the Sub-committee on the Revised Management Procedure. *Journal of Cetacean Research and Management* **11**(Suppl), 91–144.

International Whaling Commission (IWC) (2010) Report of the Scientific Committee, Annex D. Report of the Sub-committee on the Revised Management Procedure. *Journal of Cetacean Research and Management* **12**(Suppl), 89–116.

International Whaling Commission (IWC) (2012a) Requirements and Guidelines for Implementations under the Revised Management Procedure (RMP). *Journal of Cetacean Research and Management* **13**(Supplement), 497–505.

International Whaling Commission (IWC) (2012b) The Revised Management Procedure (RMP) for Baleen Whales. *Journal of Cetacean Research and Management* **13**(Supplement), 485–494.

International Whaling Commission (IWC) (2013) Report of the Scientific Committee, Annex E. Report of the Standing Working Group (SWG) on the Aboriginal Subsistence Whaling Management Procedure (AWMP). *Journal of Cetacean Research and Management* **14**(Suppl), 137–171.

International Whaling Commission (IWC) (2014) Report of the Scientific Committee, Annex D1. Report of the Working Group on the *Implementation Review* for Western North Pacific Common Minke Whales. *Journal of Cetacean Research and Management* **15**(Suppl), 112–188.

Johnston, S.J. and Butterworth, D.S. (2000) Examination of a potential Strike Limit Algorithm for the Bering–Chukchi–Beaufort Seas stock of bowhead whales. Paper SC/52/AWMP6 presented to the IWC Scientific Committee, June 2000, in Adelaide, Australia (unpublished).

Johnston, S.J. and Butterworth, D.S. (2005) Evolution of operational management procedures for the South African West Coast rock lobster *(Jasus lalandii)* fishery. *New Zealand Journal of Marine and Freshwater Research* **39**, 687–702.

Johnston, S.J. and Butterworth, D.S. (2013). An operational management procedure for the Tristan da Cunha rock lobster fishery. Document MARAM/TRISTAN/2013/OCT/14, 11 pp. Available at: http://www.mth.uct.ac.za/maram/pub/2013/MARAM_Tristan_2013_OCT_14.pdf (accessed 10 November 2014).

Johnston, S.J. and Butterworth, D.S. (2014). Initial OMP candidates for the Inaccessible and Gough island fisheries. Document MARAM/TRISTAN/2014/FEB/03, 33 pp. Available at: http://www.mth.uct.ac.za/maram/pub/2014/FISHERIES_2014_SEP_SWG-SCRL_07.pdf (accessed 10 November 2014).

Johnston, S.J., Butterworth, D.S. and Glazer, J.P. (2008) OMP 2008 for the South Coast Rock Lobster Resource. Marine and Coastal Management Report No. MCM/2008/AUG/SWG-SCRL/30, 8 pp. Available at: http://www.mth.uct.ac.za/maram/pub/2008/MCM_2008_AUG_SWG_SCRL_30.pdf (accessed 10 November 2014).

Johnston, S.J., Butterworth, D.S. and Glazer, J.P. (2014) South Coast Rock Lobster OMP 2014: Initial Specifications. Department of Agriculture, Forestry and Fisheries Report No. FISHERIES/2014/SEP/SWG-SCRL/07, 14 pp.

Kai, M. and Shirakihara, K. (2005) A feedback management procedure based on controlling the size of marine protected areas. *Fisheries Science* **71**, 56–62.

Kell, L.T. and Fromentin, J.-M. (2009) A management strategy evaluation framework for Mediterranean Atlantic bluefin tuna. *Collective Volume of the Scientific Papers – ICCAT* **64**, 633–646.

Kell, L.T. and Fromentin, J.-M. (2010) Evaluation of the robustness of maximum sustainable yield based management strategies to variation in carrying capacity or migration pattern of Atlantic bluefin tuna (*Thunnus thynnus*). *Canadian Journal of Fisheries and Aquatic Sciences* **64**, 837–847.

Kell, L.T., Pastoors, M.A., Scott, R.D. *et al.* (2005a) Evaluation of multiple management objectives for Northeast Atlantic flatfish stocks: sustainability vs. stability of yield. *ICES Journal of Marine Science* **62**, 1104–1117.

Kell, L.T., Pilling, G.M., Kirkwood, G.P. *et al.* (2005b) An evaluation of the implicit management procedure used for some ICES roundfish stocks. *ICES Journal of Marine Science* **62**, 750–759.

Kell, L.T., Pilling, G.M., Kirkwood, G.P. *et al.* (2006) An evaluation of multi-annual management strategies for ICES roundfish stocks. *ICES Journal of Marine Science* **63**, 12–24.

Kell, L.T., Mosqueira, I., Grosjean, P. *et al.* (2007) FLR: an open-source framework for the evaluation and development of management strategies. *ICES Journal of Marine Science* **64**, 640–646.

Kolody, D., Polacheck, T., Basson, M. and Davies, C. (2008) Salvaged pearls: lessons learned from a floundering attempt to develop a management procedure for Southern Bluefin Tuna. *Fisheries Research* **94**, 339–350.

Kraak, S.B.M., Buisman, F.C., Dickey-Collas, M. *et al.* (2008) The effect of management choices on the sustainability and economic performance of a mixed fishery: a simulation study. *ICES Journal of Marine Science* **65**, 697–712.

Kraak, S.B.M., Kelly, C.J., Codling, E.A. and Rogan, E. (2011) On scientists' discomfort in fisheries advisory science: the example of simulation-based fisheries management-strategy evaluations. *Fish and Fisheries* **11**, 119–132.

Kraak, S.B.M., Bailey, N., Cardinale, M. *et al.* (2013) Lessons for fisheries management from the EU cod recovery plan. *Marine Policy* **37**, 200–213.

Kurota, H., Hiramatsu, K., Takahashi, N., Shono, H., Itoh, T. and Tsuji, S. (2010) Developing a management procedure robust to uncertainty for southern bluefin tuna: a somewhat frustrating struggle to bridge the gap between ideals and reality. *Population Ecology* **52**, 359–372.

Little, L.R., Wayte, S.E., Tuck, G.N. *et al.* (2011) Development and evaluation of a cpue-based harvest control rule for the southern and eastern scalefish and shark fishery of Australia. *ICES Journal of Marine Science* **68**, 1699–1705.

Mapstone, B.D., Little, L.R., Punt, A.E. *et al.* (2008) Management strategy evaluation for line fishing in the Great Barrier Reef: balancing conservation and multi-sector fishery objectives. *Fisheries Research* **94**, 315–329.

Marasco, R.J., Goodman, D., Grimes, C.B., Lawson, P.W., Punt, A.E. and Quinn, T.J. II (2007) Ecosystem Based Fisheries Management: some practical suggestions. *Canadian Journal of Fisheries and Aquatic Sciences* **64**, 928–939.

Maunder, M.N. (2014) Management Strategy Evaluation (MSE) implementation in Stock Synthesis: Application to Pacific bluefin tuna. IATTC Document SAC-05-10b. Available at: http://www.iattc.org/Meetings/Meetings2014/MAYSAC/PDFs/SAC-05-10b-Management-Strategy-Evaluation.pdf (accessed 11 November 2014).

McClatchie, S., Goericke, R., Auad, G. and Hill, K. (2010) Re-assessment of the stock-recruit and temperature-recruit relationships for Pacific sardine (*Sardinops sagax*). *Canadian Journal of Fisheries and Aquatic Sciences* **67**, 1782–1790.

McGilliard, C.R., Hilborn, R., MacCall, A., Punt, A.E. and Field, J. (2010) Can information from marine Protected Area be used to inform control rule-based management of small-scale, data-poor stocks? *ICES Journal of Marine Science* **68**, 201–211.

Merritt, M.F. and Quinn, T.J. II (2000) Using perceptions of data accuracy and empirical weighting of information: assessment of a recreational fish population. *Canadian Journal of Fisheries and Aquatic Sciences* **57**, 1459–1469.

Methot, R.D. and Wetzel, C.R. (2013) Stock Synthesis: a biological and statistical framework for fish stock assessment and fishery management. *Fisheries Research* **142**, 86–89.

Miller, D.C. and Shelton, P.A. (2010) "Satisficing" and trade-offs: evaluating rebuilding strategies for Greenland halibut off the east coast of Canada. *ICES Journal of Marine Science* **67**, 1896–1902.

Milner-Gulland, E.J., Arroyo, B., Bellard, C. *et al.* (2010) New directions in management strategy evaluation through cross-fertilization between fisheries science and terrestrial conservation. *Biology Letters* **6**, 719–722.

de Moor, C.L., Butterworth, D.S. and De Oliveira, J.A.A. (2011) Is the management procedure approach equipped to handle short-lived pelagic species with their boom and bust dynamics? The case of the South African fishery for sardine and anchovy. *ICES Journal of Marine Science* **68**, 2075–2085.

Moore, J.E., Curtis, K.A., Lewison, R.L. *et al.* (2013) Evaluating sustainability of fisheries bycatch mortality for marine megafauna: a review of conservation reference points for data-limited populations. *Environmental Conservation* **40**, 329–344.

Mori, M. and Butterworth, D.S. (2006) A first step towards modelling the krill-predator dynamics of the Antarctic ecosystem. *CCAMLR Science* **13**, 217–277.

NAFO (2010) Report of the FC Working Group on Greenland Halibut Management Strategy Evaluation (WGMSE), 16–17 September 2010, Halifax, Nova Scotia, Canada. FC Doc 10/30, 60 pp. Available at: http://www.nafo.int/publications/frames/publications.html (accessed 26 June 2014).

Parrish, R. (2014) *Comments on the Sardine Re-Analysis*. Pacific Fishery Management Council, Portland, OR.

Pastoors, M.A., Poos, J.J., Kraak, S.B.M. and Machiels, M.A.M. (2007) Validating management simulation models and implications for communicating results to stakeholders. *ICES Journal of Marine Science* **64**, 818–824.

Peterman, R.M. (2004) Possible solutions to some challenges facing fisheries scientists and managers. *ICES Journal of Marine Science* **61**, 1331–1343.

PFMC (1998) *Amendment 8 (to the Northern Anchovy Fishery Management Plan) Incorporating a Name Change To: The Coastal Pelagic Species Fishery Management Plan*. Pacific Fishery Management Council, Portland, OR. Appendix B. Available at: http://www.pcouncil.org/wp-content/uploads/a8apdxb.pdf (accessed 26 June 2014).

PFMC (2011) *Coastal Pelagics Species Fishery Management Plan as Amended Through Amendment 13*. Pacific Fishery Management Council, Portland, OR. Available at: http://www.pcouncil.org/wp-content/uploads/CPS_FMP_as_Amended_thru_A13_current.pdf (accessed 26 June 2014).

PFMC (2013) *Report of the Pacific Sardine Harvest Parameters Workshop*. Pacific Fishery Management Council, Portland, OR. Available at: http://www.pcouncil.org/wp-content/uploads/I1b_ATT1_SARDINE_WKSHP_RPT_APR2013BB.pdf (accessed 26 June 2014).

Plagányi, É.E. (2007) Models for an ecosystem approach to fisheries. *FAO Fisheries Technical Paper* **477**, 108.

Plagányi, É.E., Skewes, T.D., Dowling, N.A. and Haddon, M. (2013) Risk management tools for sustainable fisheries management under changing climate: a sea cucumber example. *Climatic Change* **119**, 181–197.

Plagányi, É.E., Punt, A.E., Hillary, R. *et al.* (2014) Models of intermediate complexity for ecosystem assessment to support tactical management decisions in fisheries and conservation. *Fish and Fisheries* **15**, 1–22.

Plagányi, É.E., van Putten, I., Hutton, T. *et al.* (In press) Integrating indigenous livelihood and lifestyle objectives in managing a natural resource. *Proceedings of the National Academy of Sciences*.

Pomarede, M., Hillary, R., Ibaibarriaga, L., Bogaards, J. and Apostolaki, P. (2010) Evaluating the performance of survey-based operational management procedures. *Aquatic Living Resources* **23**, 77–94.

Punt, A.E. (2011) The impact of climate change on the performance of rebuilding strategies for overfished groundfish species of the U.S. west coast. *Fisheries Research* **109**, 320–329.

Punt, A.E. and Butterworth, D.S. (1991) On an approach for comparing the implications of alternative fish stock assessments, with application to the stock of Cape Hake, Merluccius spp. off Northern Namibia. *South African Journal of Marine Science* **10**, 219–240.

Punt, A.E. and Butterworth, D.S. (1995) The effects of future consumption by the Cape fur seal on catches and catch rates of the Cape hakes. 4. Modelling the biological interaction between Cape fur seals *Arctocephalus pusillus pusillus* and Cape hakes *Merluccius capensis* and *M. paradoxus*. *South African Journal of Marine Science* **16**, 255–285.

Punt, A.E. and Donovan, G. (2007) Developing management procedures that are robust to uncertainty: lessons from the International Whaling Commission. *ICES Journal of Marine Science* **64**, 603–612.

Punt, A.E. and Hobday, D. (2009) Management strategy evaluation for rock lobster, *Jasus edwardsii*, off Victoria, Australia: accounting for uncertainty in stock structure. *New Zealand Journal of Marine and Freshwater Research* **43**, 485–509.

Punt, A.E. and Ralston, S.V. (2007) A Management Strategy Evaluation of rebuilding revision rules for overfished rockfish species. In: *Biology, Assessment and Management of North Pacific Rockfishes* (eds J. Heifetz, J. DiCosimo, A.J. Gharrett, M.S. Love, V.M. O'Connell and R.D. Stankey). Alaska Sea Grant College Program, University of Alaska Fairbanks, Anchorage, pp. 329–351.

Punt, A.E., Smith, A.D.M. and Cui, G. (2002) Evaluation of management tools for Australia's South East Fishery. 3. Towards selecting appropriate harvest strategies. *Marine and Freshwater Research* **53**, 645–660.

Punt, A.E., Pribac, F., Taylor, B.L. and Walker, T.I. (2005) Harvest strategy evaluation for school and gummy shark. *Journal of Northwest Atlantic Fisheries Science* **35**, 387–406.

Punt, A.E., McGarvey, R., Linnane, A., Phillips, J., Triantafillos, L. and Feenstra, J. (2012a) Evaluating empirical decision rules for southern rock lobster fisheries: a South Australian example. *Fisheries Research* **115–116**, 60–71.

Punt, A.E., Siddeek, M.S.M., Garber-Yonts, B. *et al.* (2012b) Evaluating the impact of buffers to account for scientific uncertainty when setting TACs: application to red king crab in Bristol Bay, Alaska. *ICES Journal of Marine Science* **69**, 624–634.

Punt, A.E., Trinnie, F., Walker, T.I. *et al.* (2013) The performance of a management procedure for rock lobsters, *Jasus edwardsii*, off western Victoria, Australia in the face on non-stationary dynamics. *Fisheries Research* **137**, 116–128.

Punt, A.E., A'mar, T., Bond, N.A. *et al.* (2014) Fisheries management under climate and environmental uncertainty: control rules and performance simulation. *ICES Journal of Marine Science* **71**, 2208–2220.

Rademeyer, R.A. and Butterworth, D.S. (2011) Technical details underlying the Management Strategy Evaluation process leading to selection of a management procedure for Western Component (4Xopqrs5) pollock. DFO Canadian Scientific Advisory Secretariat Research Document 2011/nnn.

Rademeyer, R.A., Plagányi, É.E. and Butterworth, D.S. (2007) Tips and tricks in designing management procedures. *ICES Journal of Marine Science* **64**, 618–625.

Rademeyer, R.A., Butterworth, D.S. and Plagányi, É.E. (2008) A history of recent bases for management and the development of a species-combined Operational Management Procedure for the South African hake resource. *African Journal of Marine Science* **30**, 291–310.

Radomski, P., Bence, J.R. and Quinn, T.J. II (2005) Comparison of virtual population analysis and statistical kill-at-age analysis for a recreational, kill-dominated fishery. *Canadian Journal of Fisheries and Aquatic Sciences* **62**, 436–452.

Rochet, M.-J. and Rice, J.C. (2009) Simulation-based management strategy evaluation: ignorance disguised as mathematics? *ICES Journal of Marine Science* **66**, 754–762.

Rosenberg, A.A. and Brault, S. (1993) Choosing a management strategy for stock rebuilding when control is uncertain. In: *Risk Evaluation and Biological Reference Points for Fisheries Management* (eds S.J. Smith, J.J. Hunt and D. Rivard). Canadian Special Publication in Fisheries and Aquatic Sciences **120**, 243–249.

Rosenberg, A.A. and Restrepo, V.R. (1994) Uncertainty and risk evaluation in stock assessment advice for U.S. fisheries. *Canadian Journal of Fisheries and Aquatic Sciences* **51**, 2715–2720.

Sainsbury, K.J., Campbell, R.A.Lindholm.R. and Whitelaw, A.W. (1997) Experimental management of an Australian multispecies trawl fishery: examining the possibility of trawl induced habitat modification. In: *Global Trends: Fisheries Management* (eds E.L. Pikitch, D.D. Huppert and M.P. Sissenwine). American Fisheries Society Symposium 20, Bethesda, Maryland, pp. 107–112.

Sainsbury, K.J., Punt, A.E. and Smith, A.D.M. (2000) Design of operational management strategies for achieving fishery ecosystem objectives. *ICES Journal of Marine Science* **57**, 731–741.

Sampson, D.B. and Yin, Y. (1998) A Monte Carlo evaluation of the Stock Synthesis assessment program. In: *Fishery Stock Assessment Models* (eds F. Funk, T.J. Quinn II, J. Hiefetz, J.N. Ianelli, J.E. Powers, J.F. Schweigert, P.J. Sullivan and C.-I. Zhang). Alaska Sea Grant College Program Report No. AK-SG-98-01, pp. 315–318.

Schweder, T., Hagen, G.S. and Hatlebakk, E. (1998) On the effect on cod and herring fisheries of retuning the Revised Management Procedure for minke whaling in the greater Barents Sea. *Fisheries Research* **37**, 77–95.

Smith, A.D.M. (1994) Management strategy evaluation – The light on the hill. In: *Population Dynamics for Fisheries Management, Australian Society for Fish Biology Workshop Proceedings, Perth 24–25 August 1993* (ed. D.A. Hancock). Australian Society for Fish Biology, Perth, pp. 249–253.

Smith, A.D.M., Sainsbury, K.J. and Stevens, R.A. (1999) Implementing effective fisheries-management systems – management strategy evaluation and the Australian partnership approach. *ICES Journal of Marine Science* **56**, 967–979.

Smith, A.D.M., Fulton, E.J., Hobday, A.J., Smith, D.C. and Shoulder, P. (2007) Scientific tools to support the practical implementation of ecosystem-based fisheries management. *ICES Journal of Marine Science* **64**, 633–639.

Soutar, A. and Isaacs, J.D. (1969) History of fish populations inferred from fish scales in anaerobic sediments off California. *CalCOFI Reports* **13**, 63–70.

Soutar, A. and Isaacs, J.D. (1974) Abundance of pelagic fish during the 19th and 20th Centuries as recorded in anaerobic sediment off the Californias. *Fishery Bulletin* **72**, 257–273.

Starr, P.J., Breen, P.A., Hilborn, R.H. and Kendrick, T.H. (1997) Evaluation of a management decision rule for a New Zealand rock lobster substock. *Marine and Freshwater Research* **48**, 1093–1101.

STECF. (2011a) Impact Assessment of Baltic cod multi-annual plans (STECF 11-05) (ed. J. Simmonds). EUR 24899 EN–2011, 231 pp.

STECF. (2011b) Evaluation of multi-annual plans for cod in Irish Sea, Kattegat, North Sea, and West of Scotland (STECF-11-07) (eds J. Simmonds and S. Kraak). EUR 24901 EN–2011, 358 pp.

Szuwalski, C. and Punt, A.E. (2013) Fisheries management for regime-based ecosystems: a management strategy evaluation for the snow crab fishery in the eastern Bering Sea. *ICES Journal of Marine Science* **70**, 955–967.

Tuck, G.N. (2011) Are bycatch rates sufficient as the principal fishery performance measure and method of assessment for seabirds? *Aquatic Conservation: Marine and Freshwater Ecosystems* **21**, 412–422.

Ulrich, C., Andersen, B.S., Sparre, P.J. and Nielsen, J.R. (2007) TEMAS: fleet-based bioeconomic simulation software to evaluate management strategies accounting for fleet behaviour. *ICES Journal of Marine Science* **64**, 647–651.

Wade, P.R. (1998) Calculating limits to the allowable human-caused mortality of cetaceans and pinnipeds. *Marine Mammal Science* **14**, 1–37.

Walters, C.J. (1986) *Adaptive Management of Renewable Resources*. Macmillan, New York.

Walters, C.J. (1994) Use of gaming procedures in evaluation of management experiments. *Canadian Journal of Fisheries and Aquatic Sciences* **51**, 2705–2714.

Wayte, S.E. (2011) Management implications of including a climate-induced recruitment shift in the stock assessment for jackass morwong (*Nemadactylus* *macropterus*) in south-eastern Australia. *Fisheries Research* **142**, 47–55.

Wayte, S.E. and Klaer, N.L. (2010) An effective harvest strategy using improved catch-curves. *Fisheries Research* **106**, 310–320.

Wiedenmann, J., Wilberg, M.J. and Miller, T.J. (2013) An evaluation of harvest control rules for data-poor fisheries. *North American Journal of Fisheries Management* **33**, 845–860.

Wilson, J.R., Prince, J.D. and Lenihan, H.S. (2010) A management strategy for sedentary nearshore species that uses Marine Protected Areas as a reference. *Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science* **2**, 14–27.

MRIP PSE MSE Summary

The ACCSP PSE Steering Committee oversaw the development of a computational model to evaluate how different levels of Percent Standard Error (PSE) affect the stock assessment and management of fisheries. The management strategy evaluation (MSE) model was completed in January 2014. In this model there were 189 scenarios run at seven PSE levels, three life histories, three sizes of recreational fishery and three levels of fishing intensity. In general, model estimates are more reliable (unbiased) for input data with PSEs up to 40-60%. Higher values (>=60%) of recreational data precision were tolerated for species with a shorter life history and smaller recreational fishery component.

PSE MODEL TERMS OF REFERENCE:

1. Develop a statistical catch at age assessment model to examine fisheries management risk of using recreational data with various levels of precision
2. Simulate data for theoretical species of slow, medium, and fast life histories
3. Evaluate sensitivity of fisheries with Recreational/Commercial splits at 30%, 60%, and 90% recreational fishery removals
4. Evaluate sensitivity of assessments on stock units for various PSE levels from 10-100% (10,20,30,40,50,60,100)
5. Evaluate sensitivity of fisheries management for various PSE levels (One scenario fishing at target fishing mortality rate)

a. Project model 12 years into future
b. Assessment performed every 2 years

Data generated in the operating model are used in a statistical catch-at-age (SCAA) assessment model to determine stock status, with harvest-at-age from both fisheries and an index of abundance at age being the primary inputs. Additional inputs, such as natural mortality and weight- and maturity-at-age were fixed at the true values in the model. Estimation of parameters was done using a maximum likelihood approach. The parameters estimated were the mean and annual deviations in recruitment and fishing mortality, the selectivity parameters in the recreational and commercial fisheries and survey, and the catchability coefficient in the survey. Parameter estimates were then used to calculate biological reference points (BRPs), either using the stock-recruit relationship to generate MSY-based BRPs, or using a spawning biomass per-recruit approach to generate proxies (e.g. $F_{35\%}$).

Discards were not considered in this model, so the catch for a fishery is equal to the landings.

Each model run spans 58 years divided into two periods, denoted the initial and management periods (Figure 2). The initial and management periods cover 40 and 18 years, respectively.

This work only explored the uncertainty in annual, coastwide harvest estimates on the assessment process, and ignored the implications of PSEs at smaller spatial scales. While the coastwide landings estimates for a stock may have a low PSE, estimates for particular states for the stock in a given year may be considerably higher. State-specific data are often used to set regulations in the recreational fishery for a given stock, and large amounts of uncertainty can impact the effectiveness of the state-specific regulations, which can potentially impact the larger population. Such an analysis was beyond the scope of this work, but has potentially important implications in the management of some recreational fisheries.

For a full description of the MSE methods and results, see Wiedenmann (2014) report to ACCSP, *Evaluation of the Effects of Uncertainty in Recreational Harvest Estimates on Fisheries Assessment and Management*.

Evaluation of the Effects of Uncertainty in Recreational Harvest Estimates on Fisheries Assessment and Management

Final Report to the Atlantic Coastal Cooperative Statistics Program
January 20th, 2014

John Wiedenmann
Institute of Marine and Coastal Science
Rutgers University

EXECUTIVE SUMMARY

Estimates of harvest in many recreational fisheries are often associated with a high degree of uncertainty. Accurate estimates of harvest in recreational fisheries are important for the effective assessment and management of species of recreational importance. For this study, a simulation model was developed to evaluate the effects of uncertainty in recreational harvest estimates on the assessment and management processes, and how these effects depend on the relative size of the recreational harvest for a stock. The model was run for three different species life histories ("fast", "medium", and "slow"), three sizes of the recreational fishery (with landings comprising 30, 60 and 90% of the total, on average), and even levels of uncertainty in recreational landings estimates (PSEs of 0.2, 0.3, 0.4, 0.5, 0.6, 0.8, and 1.0). Results of this work suggest that PSEs above 0.6 produce unreliable estimates of population status, such that inclusion of catch estimates with this level of uncertainty in an assessment may result in a biased estimate from the assessment, which may impact the management process for a stock. In general, model estimates are more reliable (unbiased) for PSEs at or below between 0.4 and 0.6, with the specific upper limit dependent on the scenario being explored. Finally, the selection of a particular threshold PSE based on this study requires having clear objectives and specified levels of risk to effectively interpret the broad range of performance measures calculated.

TABLE OF CONTENTS

INTRODUCTION

Estimates of harvest in many recreational fisheries are often associated with a high degree of uncertainty. For many species, the uncertainty of harvest estimates from the Marine Recreational Information Program (MRIP) is high, with proportional standard errors (PSEs) sometimes in excess of 0.5. Accurate estimates of harvest in recreational fisheries are important for the effective assessment and management of species of recreational importance, and may be particularly important for populations where the recreational harvest comprises a sizeable fraction of the total harvest.

Estimates of total harvest from recreational fisheries are used in the assessment of stock status, which in turn informs the determination of the sustainable harvest for a stock. Error in harvest estimates from the recreational fishery can propagate throughout the assessment and management process, resulting in catch limits being set that are too conservative or too high. While uncertainty in recreational harvest estimates can have a large impact on the assessment and management of a stock, it remains unclear how much uncertainty is tolerable. That is, it is unknown if there is a threshold amount of uncertainty (measured as the PSE of the harvest), above which output from an assessment model is unreliable, and how this threshold may depend upon the size on recreational fishery for a particular stock.

For this study, a simulation model was developed to evaluate the effects of uncertainty in recreational harvest estimates on the assessment and management processes, and how these effects depend on the relative size of the recreational harvest for a stock. The model was developed to be flexible enough to explore a range of scenarios, and for the current report, the model was run for three different life histories (“fast”, “medium”, and “slow”), three sizes of the recreational fishery (with landings comprising 30, 60 and 90% of the total, on average), and seven levels of uncertainty in recreational landings estimates (PSEs of 0.2, 0.3, 0.4, 0.5, 0.6, 0.8, and 1.0).

METHODS

Overview of Model Structure

The simulation model was developed in AD Model Builder (Fournier, 2011), and contains three main components (Figure 1). The foundation of the simulation is the operating model, which determines the population dynamics of the stock and how data are generated. Data generated in the operating model are based on the "true" dynamics within the model with some specified amount of error. The operating model generates data on the recreational and commercial harvests, as well as a fishery-independent index of abundance. These data are then used in the assessment model to estimate stock status and biological reference points. The assessment model is a statistical catch-at-age (SCAA) model, and output from the assessment is used in the management model to determine the catch limit using a set harvest policy. The catch limit estimated in the management model is removed from the population, with some implementation error, and the simulation loop continues for a set number of years. This process is repeated many times for each model specification (e.g. amount of error in the data, relative size of the recreational fishery) to account for the variability in the data generation and population dynamics. At the end of each run, the performance of the model is measured for comparison across different model specifications (called scenarios).

Operating, Assessment and Management Models

The operating model used age-structured population dynamics with the equations governing these dynamics in Table 1 and variable definitions in Table 2. Equations used in the model are referenced by their number in Table 1, such that the numerical abundance-at-age is referred to as equation T1.1. Annual abundance of recruited ages was determined from the abundance of that cohort the previous year, decreased by continuous natural and fishing mortality (equation T1.1). Recruitment to the population followed the Beverton-Holt stock-recruit relationship, with bias-corrected lognormal stochasticity (equation T1.2). Parameters for the Beverton-Holt model were derived from the unfished spawning biomass, unfished recruitment, and the steepness parameter (equation T1.3), where steepness represents the fraction of unfished recruitment that results when the spawning biomass is reduced to 20% of the unfished level (Myers et al. 1999). Total spawning biomass in a given year was calculated by summing the product of the proportion mature, weight at age and abundance at age over all recruited age classes (equation T1.4). Weight at age was an allometric function of length at age, which followed a von Bertalanffy growth function (equations T1.5 and T1.6). The proportion mature at age was calculated using a logistic function (equation T1.7). Length, weight, and maturity at age were fixed for a given life history.

The model contains both commercial and recreational fisheries, with selectivity at age calculated using a logistic (saturating) function (equation T1.8). Because both natural (*M*) and fishing mortality (*F*) occurred continuously throughout the year, catch was calculated using the Baranov catch equation (Quinn and Deriso 1999; equation T1.9).

Discards were not considered in this model, so the catch for a fishery is equal to the landings. Thus the terms catch, harvest, and landings are used interchangeably throughout this report.

Each model run spans 58 years divided into two periods, denoted the initial and management periods (Figure 2). The initial and management periods cover 40 and 18 years, respectively. During the start of the initial period, the population is in the unfished state. Both recreational and commercial fisheries develop at this time, and a fixed pattern of total fishing mortality (*F*) is applied to the population. Example patterns in *F* during the initial period are shown in Figure 3, but all results shown herein are for the model run where *F* plateaus during the initial period. The intensity of fishing (e.g., light, moderate, or heavy exploitation) during this period determines the population abundance at the start of the management period. The total *F* in each year is allocated between the commercial and recreational fisheries so that the recreational landings are a fixed proportion of the total landings in each year (0.3, 0.6, and 0.9; herein called the recreational ratio), on average.

At the end of the initial period (year 40) the population is first assessed using data generated during the initial period. The data are generated starting in year 10 of the initial period, representing close to 30 years of data when the population is first assessed. This length of time was selected as it approximates the length of time that recreational landings data have been collected along the eastern U.S. There is a 1-year lag between the data and the assessment, such that for an assessment that is done in year 40, data from years 10 through 39 are used. The data that are generated annually are the catch from each fishery (both total and at-age) and a fishery-independent survey-derived index of abundance (both total and at-age). These data are generated based on the true value and some observation error (equations T1.10 - T1.13). The amount of observation error is fixed across years in the creation of data from the commercial fishery (PSE = 0.1) and the survey (0.25), with PSEs of 0.2, 0.3, 0.4, 0.5, 0.6, 0.8 and 1.0 explored for the recreational fishery (Figure 4). For a given PSE, the standard deviation in the data-generating model is calculated with $\sigma = (\log(\text{PSE} + 1)^2)^{0.5}$. To generate abundance at age data, a multinomial distribution was used, which requires specifying the number of samples to be drawn to generate the random values. Larger values result in the random sample being closer to the true value. For the commercial and survey data, samples sizes of 200 were used. For the recreational fishery, the sample size decreased with increasing PSE. The assumption here is that as PSEs increase, the error in classifying the age structure also increases. Within both the operating and assessment models, sample sizes of 200, 185, 170, 155, 140, 130, and 120 with corresponding PSEs of 0.2, 0.3, 0.4, 0.5, 0.6, 0.8 and 1.0, respectively.

The time series of catch and survey data are input into the SCAA model to estimate the abundance at age and fishery-specific exploitation rates in each year. The specific parameters estimated in the SCAA are the initial abundance at age (in year 10), recruitments and fishing mortality rates (across years), fishery selectivity parameters, and the survey catchability. Parameters are estimated using a maximum likelihood approach and the objective function shown in Table 3. All other required SCAA inputs (i.e., natural mortality, and maturity and weight at age; Table 2) are set to the true values specified in the operating model (Bence et al. 1993; Wilberg and Bence 2006). The SCAA model also estimates the spawning potential ratio (SPR) – based reference points (NEFSC 2002). The limit fishing mortality rate that defines overfishing (F_{lim}) depends on the assumed level of steepness for the species life history, as Punt et al. (2008) have shown a direct relationship between steepness and the SPR that produces MSY. Thus, different SPR% values were selected as the proxies for F_{MSY} for the different life histories (Table 2.). Estimates of F_{lim} are used to define overfishing in the model, and therefore calculate the overfishing limit, or OFL (the catch at F_{lim}). The target fishing mortality rate (F_{targ}) is set at an SPR% above the limit value (Table 2), and is used to estimate the ABC (which is set as the target catch). The spawning biomass reference point and MSY-proxy are calculated by multiplying the SPR and yield-per-recruit (YPR) from fishing at F_{lim}, respectively, by the mean estimate of recruitment over the time series. Because most of the inputs are fixed at the true values, the SPR-based reference points vary across assessments based on the estimated selectivities in each fishery and the estimated mean recruitment. Due to the 1-year lag in the data collection and stock assessment, the OFL and ABC that are calculated are based on a 1-year projection of population biomass. This projection uses the terminal estimates of abundance at age and fishing mortality, and the mean recruitment to predict abundance in the current year to calculate the OFL and the ABC.

The estimated ABC is divided between the recreational and commercial fisheries (based on a specified recreational ratio), and there is sector-specific amount of implementation error (CV = 0.1 for the commercial fishery and 0.2 for the recreational fishery), such that the actual catch fluctuates around the target across years. The ABC is fixed for 2 years, as this time period represents the interval between assessments. Every 2 years the population is re-assessed (using new data that are collected) and the target catch is updated. Note the model contains a fixed-F control rule, with the $F_{\text{targ}} < F_{\text{lim}}$. The management model does not adjust F_{targ} if the population is estimated to be overfished (i.e., there is no specific management response for rebuilding).

Based on the error in the assessment estimates in a given year and the uncertainty in recruitment dynamics, it is possible for the ABC to exceed to the total exploitable biomass in a given year. In such cases, the actual catch is set to 60% of the exploitable biomass, thus preventing the fishery from removing all individuals in a given year.

Performance Measures

At the end of each 58-year period, a range of performance measures is calculated to determine the effects of uncertainty in recreational estimates on the assessment and management of the population. Performance measures can be grouped into 2 categories; those that summarize the status of the population and the fishery, and those that summarize the accuracy of the assessment model (Table 4). Performance measures that summarize population / fishery status were calculated using the true values over the management period. For example, the ratio of spawning biomass to the MSY reference point (S_{MSY}) was calculated as the mean spawning biomass over the management period (years 41 – 58) relative to S_{MSY}. Other performance measures are calculated as the proportion of years when something occurs during the management period. For example, the proportion of years when overfishing occurs is calculated by determining the frequency of years in which the total fishing mortality ($F_{tot} = F_{com} + F_{rec}$) exceeds F_{lim}.

For performance measures summarizing assessment accuracy (Table 4), the relative error (RE) in each assessment-estimated quantity in the terminal year (biomass, recruitment, harvest rates, OFL) is calculated as

$$RE = \frac{estimated - true}{estimated} \times 100$$

Since there are 10 assessments that are conducted in the management period, there are 10 estimates of RE of a particular model estimate. For the purposes of summarizing assessment accuracy over the years for a single model run, the median of the relative error (MRE) is calculated (Wilberg and Bence, 2006). If the MRE of a quantity (such as biomass) equals 0, it means that half of the terminal assessment estimates are above and half are below the true value. Herein, the term unbiased is used to indicate MREs that are near 0. In addition to the MRE, the median of the *absolute* relative error (MARE) is also calculated. Estimates of MARE measure the width of the distribution of the REs. For example, an MARE of 20 indicates that half of the estimates are within ± 20% of the true value, while half are in excess of ± 20%. MRE an MARE were used in place of the mean relative error or the root mean square error to reduce the influence of extreme values of RE (Wilberg and Bence, 2006).

Parameterization and Model Runs

The model was run for three different life histories, which are labeled 'slow', 'medium' and 'fast'. The slow life history has slow growth, late maturation, and low productivity. In contrast, the fast life history has rapid growth, early maturation, and high productivity. The medium life history is between the slow and fast life histories. Rather than use parameters from real species, a number of generalizations were made across life histories. Both steepness and the growth rates increased going from the slow to the fast life history, while age at maturity and recruitment to the population and fisheries decreased going from the slow to the fast life history. Unfished recruitment (R_0) and the parameters controlling the length-weight relationship were identical for each stock.

Running the Model

The model was run for 3 life histories (slow, medium, and fast), three recreational fisheries comprising 30, 60, and 90% of the total landings (herein the term recreational ratio is used to denote the size of the fishery, with a value 0.3 = 30%), and 7 levels of uncertainty in recreational landings (PSEs = 0.2, 0.3, 0.4, 0.5, 0.6, 0.8, and 1.0). For these scenarios, all other parameters (e.g., PSE of the commercial catch and survey index) were fixed. For each of these scenarios, 1,000 model iterations were conducted. The fishing mortality during the initial period was also varied for a given scenario, such that maximum level of F shown in Figure 3 was set to 0.5, 1.0, and 2.0 x F_{lim}. This resulted in the population being lightly, moderately, and heavily exploited at the start of the management period. Thus, 1/3 of the 1,000 model iterations represented the light-, moderate-, and heavy exploitation scenarios. As a result, 189 different scenarios were run (3 x 3 x 3 x 7), with ~ 333 model runs for each scenario.

In addition to the scenarios run above, a sensitivity run was conducted to explore the effects of model uncertainty. For this run, natural mortality was allowed to vary across years (around the true mean) in the operating model, but it was fixed across years at the mean value shown in Table 2 in the assessment model (similar to the approach of Deroba and Schueller, 2013). This scenario exploring an incorrect model assumption was run for the medium life history that was moderately exploited.

Results

Performance measures were summarized primarily using boxplots for each scenario, with the bold horizontal line representing the median of the performance measure and box representing the interquartile range. In addition, contour plots were used to summarize the interactions between the recreational ratio and the PSE of the catch estimates across scenarios. Plots were qualitatively examined for trends across scenarios (c.f. Deroba and Schueller, 2013).

In Figures 5- 7, the RE in spawning biomass estimates is shown across scenarios for the entire time period (initial + management period; based on output from the final stock assessment conducted in year 58) for the fast, medium, and slow life histories, respectively. From these figures, a number of patterns appear. First, the range of RE in biomass estimates (based on the 95% confidence intervals) remains relatively constant for much of the time series, but expands as towards the end of the time period. Thus, the uncertainty in estimates increases approaching the most recent year. Second, as the PSE increases, the median biomass estimate becomes biased over all years, with the estimates being above the true value. For the largest PSEs, the median estimates of spawning biomass RE are as large, or larger than the upper 95% confidence interval for the lowest PSEs (Figures 5-7).

Estimates of spawning biomass RE shown in in Figures 5-7 are for the entire time series from a single output stock assessment. However, the most important estimates from an assessment are in the final (terminal) year, as these estimates have management implications. Terminal assessment estimates determine the target catch in subsequent years, and also determine if the population is currently overfished and / or experiencing overfishing. In such cases, costly measures may need to be taken to reduce fishing mortality and rebuild the stock. Therefore, many of the performance measures calculated are based on the RE in terminal estimates from repeated assessments of many important quantities. Both the median RE (MRE) and median of the absolute RE (MARE) are calculated using terminal estimates of spawning biomass (Figures 8 - 13), recruitment (Figures 14 - 19), recreational fishing mortality (Figures 20 - 25), total fishing mortality (Figures 26 - 31), and the OFL (Figures 32 - 37). In addition, the proportion of years when the terminal estimates of spawning biomass and the OFL were within ± 20% of the true value was also calculated (Figure 38 – 43). Terminal assessment estimates of total fishing mortality are also used to determine the frequency of overfishing false negatives (when overfishing occurs in the terminal year but is not identified by the assessment; Figures 44 - 46) and false positives (when the assessment incorrectly estimates that overfishing occurred; Figures 47 – 49). These figures are boxplots showing the range of the estimates for the performance measures over the iterations for a single model scenario. The median values for each scenario (the bold horizontal line within each box) are also listed in Tables 5 – 7. All plots shown are for the base model run where natural mortality is fixed on both the operating and assessment models. Results from the sensitivity run where natural mortality varies in the operating model but is assumed fixed in the assessment model, are summarized in Tables 8 and 9.

Due to the large number scenarios explored, a detailed description of the dynamics of each Figure is impractical. Therefore, only broad patterns of assessment accuracy are described here. For a given life history, exploitation history, and recreational ratio, as the PSE increases, the MRE in spawning biomass (Figure 8 -10) and recruitment (Figures 14 - 16) becomes positively biased, with terminal assessment estimates being generally higher than the true value. The effect of this positive bias is that the fishing mortality rates are underestimated (negative bias; Figure 20-22 and 26-28) and the OFL is overestimated (Figures 32 – 34).

There appears to be a threshold PSE, above which the estimates go from unbiased (median of the MRE estimates near 0) to biased, but the specific PSE where this occurs is dependent upon the life history, exploitation history, and size of the recreational fishery. For biomass and recruitment estimates, biased estimates occur for PSEs of 0.6 and above for nearly all scenarios, but in some cases estimates become biased for PSEs as low as 0.4. In general, this threshold PSE decreases going from the heavy to the light exploitation cases. That is, assessment estimates are generally more robust for higher PSEs for the heavily exploited population. In addition, higher PSE thresholds (between 0.5 and 0.6) generally occur when the recreational fishery is small (30% of total landings). The threshold level decreases for the larger recreational fisheries, but there appears to be a saturating effect, as the differences between the larger recreational fisheries (60 and 90% of the total) are generally small.

Estimates of the OFL, in contrast, show more instances of positive bias at lower PSEs. Across life histories, bias in the OFL estimates increases going from the light exploitation to the heavy exploitation scenarios (Figures 32 – 34). In fact, for the heavy exploitation case, the OFL estimates exhibit positive bias for all PSEs. Similar to the biomass and recruitment estimates, there appears to be a threshold effect where the magnitude of the bias (i.e., the size of the deviation from 0) increases rapidly at or above PSEs of 0.5.

The MRE performance measures help identify directional bias in estimates from the stock assessment, but they do not characterize the overall variability in the estimates well. For example, there can be two distributions for the MRE in biomass that are centered at 0, but with very different levels of variability in the estimates (i.e., the box and whiskers of the boxplot span a larger range of values). In both cases, estimates have an equal chance of being above or below the true value, but with increased variability, more extreme levels of error are possible. Therefore, it is important to evaluate the magnitude of the variability, and this magnitude is captured by the median of the absolute value of the relative error (MARE). For example, if the median of the distribution of MARE in biomass estimates is 0.2, it means half of the estimates are within ± 20% of the true value, and half are outside ± 20%. A similar performance measure also calculated is the proportion of years when an estimate is within ± 20% of the true value.

For biomass, recruitment, and the OFL, estimates of the MARE show similar patterns to the estimates of the MRE, with the magnitude of error increasing for PSEs typically above 0.5 (Figures 11-13, 17-19, 35-37). For biomass and the OFL, the MARE is similar across life histories, whereas for recruitment, it is lower for the fast life history.

It is perhaps easiest to identify the threshold PSE values by looking at the proportion of years when estimates of biomass are within ± 20% of the true value (Figures 38 – 43). From these Figures it becomes clear when the assessment estimates begin to fall outside of this range. For biomass estimates, at lower PSEs the baseline level is around 0.7, 0.8, and between 0.7 and 0.9 for the fast, medium and slow life histories respectively. These values rapidly decline at PSEs at or above 0.5, with terminal biomass estimates being within ± 20% of the true value in as few as 10 – 20% of assessments in extreme cases. For the OFL, baseline proportions are 0.4, 0.6, and between 0.5 and 0.7 for the fast, medium and slow life histories, respectively, and rapidly decline at PSEs at or above 0.5. While the proportion of years when estimates are within ± 20% varied across life histories (with the fast life history having estimates within this range less frequently), the PSE thresholds are consistent across life histories for a given recreational ratio and exploitation history.

Assessment estimates of total fishing mortality and the overfishing level (F_{lim}) are used to determine if overfishing is occurring. Incorrectly declaring that a stock is experiencing overfishing when it is not (a false positive) can have a negative impact on the fishery as unnecessary penalties may imposed. Alternatively, not identifying overfishing (a false negative) can have a negative impact on the population, as unsustainable harvest rates are not reduced. The proportion of years with overfishing false negatives and false positives were calculated across scenarios and are shown Figures 44 – 49. Generally, the rate of false positives is consistent across PSEs (between 10 – 20% of the time). In contrast, false negatives increase with increasing PSEs from a baseline occurrence in 10% of the years for lower PSEs, to as high as 40% for the highest PSEs (Figures 44-46).

Error in the assessment process will impact the population and fishery though estimates of the catch limit (or ABC) that is set each year. With increasing PSEs, the estimates of OFL from the assessment became higher than the true value, resulting in the population biomass being lower for runs with higher PSEs relative to lower PSEs (Figures 50 – 52). The magnitude of these differences can be very large, and depends on the exploitation history. For example, for the medium life history that was moderately exploited, the spawning biomass ranged from about 10% above S_{MSY} for a PSE of 0.2 to about 30% below S_{MSY} for a PSE of 1.0.

Similarly, the rate of population growth (or decline) was impacted by the PSE. Because the target catch is set at a fishing mortality rate near F_{lim}, the biomass of should trend towards S_{MSY}, so the change in biomass over the time period depends on the biomass before the management model was initiated. Thus, a decline, no change, and an increase in biomass are expected for the lightly, moderately, and heavily exploited populations, respectively. Increasing PSEs affect the magnitude of the change in biomass, with greater declines in the light exploitation scenario, and less increases in the heavy exploitation scenario (Figures 53 – 55). Interestingly, there is little to no effect on the amount of yield for a given scenario across PSEs. While the biomass is lower for higher PSEs, the positive bias in the OFL results in catches being similar or slightly higher at higher PSEs for the fast and medium life histories (Figures 56 – 57), and much higher for the largest PSEs for the slow life history (Figure 58). Running the model for a longer time period would likely alter these trends, as continued decreases in biomass would ultimately result in lower yields to the fishery, on average.

Inflated OFL estimates can result in increased instances of overfishing, and increased risk of the population becoming (or remaining) overfished. Figures 59 – 64 show the probability of the population being overfished, and the probability that overfishing occurs (calculated as the proportion of years over the management period where each event occurs). Increasing the PSE results in increased probabilities of being overfished and experiencing overfishing. For the fast life history, the population can become overfished for all exploitation histories explored (Figure 59). For the medium and slow life histories, the population generally only becomes overfished for the light and moderate exploitation scenarios when PSEs are 0.8 or higher (Figures 60 and 61). Across life histories, instances of overfishing occur for all exploitation scenarios. The probability of overfishing begins to exceed 0.5 (where overfishing is more likely to occur than not) at PSEs of 0.6 and above (Figures 62-64).

The final performance measure calculated is the probability that the ABC exceeds the available biomass in a given year (Figure 65 – 67). Such an occurrence could result from an erroneous assessment, a very low recruitment event, or both. This occurred very infrequently for the medium and slow life histories (Figures 66 and 67). For the fast life history under certain scenarios, the ABC exceeded the population biomass between 5 and 20% of the time, with more frequent occurrence resulting from the highest PSEs.

For the performance measures described thus far, the boxplots are split across exploitation histories and life histories. While this separation is useful for identifying patterns across these scenarios, it obscures the relationship between the PSE and the recreational ratio for a given performance measure. To make this relationship more clear for a subset of the performance measures, contour plots were crated by combing the data across all exploitation history scenarios, and the median value was selected for each PSE / recreational ratio combination. From these plots the threshold effect is apparent, as the MRE and MARE of biomass and recruitment rapidly become more extreme (contour lines closer together) at PSEs between 0.5 and 0.6 for a given sized recreational fishery (Figures 68 – 70). Similar patterns result for the MRE and MARE in estimates of fishing mortality and the OFL. (Figures 71 – 73).

For a given PSE, the interaction with the recreational ratio can be identified by looking at the slope of the contour line across the recreational ratios. A downward slope for the MRE / MARE estimates shown indicates that values become more extreme as the size of the fishery increases (for a given PSE), an increasing slope indicates values become less extreme, and no slope indicates that that size of the fishery does not at that PSE for a particular performance measure. In general, for the MRE / MARE in biomass and recruitment, values become more extreme going from a recreational ratio of 0.3 to 0.6. This trend levels off above a recreational ratio of 0.6, indicating the size of the recreational fishery has an effect up to this point. In some cases at the highest PSEs, the lines slope upward, indicating performance measures become less extreme for the largest fishery. This pattern exists for both the MRE and MARE of the OFL, but only for the

MRE of fishing mortality estimates, which has downward sloping contour lines for all recreational ratios (Figure 71 - 73). For the plots showing the proportion of years with estimates of biomass and the OFL within ± 20% (Figures 74 - 76) the interpretation of trends in the contour lines is similar, although in these instances "more extreme" values indicate that model estimation becomes worse, with fewer estimates (and thus a lower proportion) within this range. For these measures, the effect of the recreational fishery is most apparent at smaller ratios. Patterns are opposite for the overfishing false negative and false positive performance measures. Overfishing false negative occurrence is influenced at smaller recreational ratios (between 0.3 and 0.6), but not higher ratios. In contrast, false positives are not affected by lower ratios, but increase rapidly between 0.6 and 0.9 (Figure 74 – 76).

Error in assessments estimates in this simulation study result from uncertainty in the survey and catch data (i.e. data uncertainty). Another important source of uncertainty is model uncertainty, where specific assumptions made in the assessment model about the underlying population dynamics are incorrect. In base scenarios explored in this simulation model, all assessment inputs (excluding the survey and catch data) were fixed at the true values used in the population dynamics model (Table 2). Estimates of natural mortality, maturity-, and weight-at-age used in the stock assessment were set at the values used in the operating model (Table 2). Thus, the assessment estimates in this model may exhibit less bias for a given PSE than may occur in cases when erroneous assumptions are made in the stock assessment. A sensitivity run was conducted where the true natural mortality rate fluctuates annually (around the mean value in Table 2 but with no trend), but the assessment assumes a fixed value across years. This sensitivity run was conducted for the medium life history that experienced moderate exploitation. Output from this run is shown in Table 8, and a comparison of select performance measures with the base model (where natural mortality is fixed over time) is shown in Table 9. Many of the performance measures show similar values at PSEs at or below 0.6. For higher PSEs, the estimates from the sensitivity run are more extreme. An exception to this trend across PSEs is for the probability of overfishing, which increases rapidly above PSEs of 0.3.

Conclusions

The results of this work can be used to help determine threshold levels of uncertainty in recreational harvest estimates. It is clear from these model runs that assessment estimates become biased for PSEs at or above 0.6 across all scenarios explored. Furthermore, the amount of bias increases greatly for PSEs of 0.8 and 1.0. Thus, using PSEs of this magnitude will likely have a large impact on the assessment accuracy and management of a stock. While such high PSEs are ill advised, the question remains as to how much uncertainty is tolerable for the assessment and management of a population.

In general, assessment estimates were unbiased below PSEs between 0.4 and 0.6, with the particular threshold level depending upon the specific scenario (life history, exploitation, history, and recreational ratio). Threshold PSE values were typically higher for heavily exploited populations relative to lightly exploited populations. However, care is needed in trying to select a particular PSE threshold based on exploitation history, as an accurate determination of population status from a stock assessment is required to do so. In other words, trying to select a threshold amount of data uncertainty for an assessment based on exploitation history requires that the exploitation history can be accurately classified, which typically requires a reliable assessment (which may not be available in such cases). Threshold PSE levels tended to decrease between recreational ratios of 0.3 and 0.6, but were relatively consistent above a ratio of 0.6. Therefore, similar threshold may be selected for moderate and large recreational fisheries.

Determining a specific threshold level of uncertainty in landings estimates will depend on the specific objectives that managers are trying to achieve, and how much risk managers are willing to accept. For example, for the fast life history that is moderately exploited with a recreational ratio of 0.9 (Figure 8), estimates of biomass become biased at a PSE of 0.5, but the amount of bias for this PSE is small relative to PSEs of 0.6 and higher. Managers who want to avoid bias altogether may therefore set a threshold PSE of 0.5, whereas managers who are willing to accept a small amount of bias may opt for a threshold of 0.6.

As another example of using specific objectives to determine the threshold PSE, the revised Magnuson Act aims to prevent overfishing, and this has been interpreted to mean that the probability of overfishing is below 0.5. Many Fisheries Management Councils have adopted policies to achieve lower probabilities of overfishing, such as 0.4. To achieve a particular probability of overfishing, the output shown in Figures 62 – 64 can be used to inform this decision. However, the probability of overfishing calculated here is specific to the harvest policy used (fishing at an $F_{\text{targ}} < F_{\text{lim}}$) in this analysis. Higher probabilities would result for less conservative harvest policies, and vice-versa.

It is important to emphasize that the model results presented are based only on runs with data uncertainty. In other words, error in the assessment estimates results only from error in the catch and survey data, as all other inputs to the assessment model are fixed at the true values used in the operating model (e.g., weight and maturity at age). It is likely that model error (i.e., incorrect assumptions in the assessment) will also impact the assessment estimates. A sensitivity run was conducted to explore model error, where natural mortality varied annually around the mean (with no trend), but was assumed fixed across years in the assessment. The effect of this model error was small at lower PSEs, but became more pronounced at higher PSEs (Table 9). However, it is likely different types of model error will impact estimates differently. Exploration of alternative sources of model error is warranted, and a possible example is to include time-varying selectivity in the recreational fishery that is ignored in the assessment.

The assessment process in the model was automated, with the output from the assessment treated as the best available estimates and used in the management process. In the model, there are no checks and balances throughout this process, which might otherwise identify erroneous data or model estimates. For example, certain estimates of catch may be thrown out or modified during the Data Workshop. The assessment model may also be modified by an assessment scientist, by adjusting likelihood weights, for example, if initial runs produce questionable estimates. Including such checks is not feasible in such a model, but it is important to acknowledge that the error in assessment estimates might get reduced in an actual assessment through various approaches. Also, an assessment might be rejected in the review process, which would mean results could not be used for management purposes. In such cases data-poor methods might be relied upon, but such methods require "reliable" catch estimates such that error in recreational landings might have a larger effect of management of the stock (c.f., Wiedenmann et al. 2013).

This work only explored the uncertainty in annual, coastwide harvest estimates on the assessment process, and ignored the implications of PSEs at smaller spatial scales. While the coastwide landings estimates for a stock may have a low PSE, estimates for particular states for the stock in a give year may be considerably higher. State-specific data are often used to set regulations in the recreational fishery for a given stock, and large amounts of uncertainty can impact the effectiveness of the state-specific regulations, which can potentially impact the larger population. Such an analysis was beyond the scope of this work, but has potentially important implications in the management of some recreational fisheries.

In summary, the results of this work suggest that PSEs above 0.6 produce unreliable estimates of population status, such that inclusion of catch estimates with this level of uncertainty in an assessment may result in a biased estimate from the assessment, which may impact the management process for a stock. In general, model estimates are more reliable (unbiased) for PSEs at or below between 0.4 and 0.6, with the specific upper limit dependent on the scenario being explored. Finally, the selection of a particular threshold PSE based on this study requires having clear objectives and specified levels of risk to effectively interpret the broad range of perform measures calculated.

References

Bence, J. R., A. Gordoa, and J. E. Hightower. 1993. Influence of age-selective surveys on the reliability of stock synthesis assessments. Canadian Journal of Fisheries and Aquatic Sciences 50: 827-840.

Deroba, J. J., and A. M. Schueller. 2013. Performance of stock assessments with misspecified age- and time-varying natural mortality. Fisheries Research. 146: 27-40.

Fournier, D. 2011. An Introduction to AD Model Builder for Use in Nonlinear Modeling and Statistics. Version 10. http://admb-project.org/documentation/manuals/admb-user-manuals.

Myers, R. A., K. G. Bowen, and N. J. Barrowman. 1999. Maximum reproductive rates of fish at low population sizes. Canadian Journal of Fisheries and Aquatic Sciences 56:2404-2419.

Quinn, T. J., and R. B. Deriso. 1999. Quantitative Fish Dynamics. Oxford University Press, New York.

Punt, A. E., M. W. Dorn, and M. A. Haltuch. 2008. Evaluation of threshold management strategies for groundfish off the U.S. West Coast. Fisheries Research. 94: 251-266.

Wiedenmann, J., Wilberg, M., and T. Miller. Evaluation of harvest control rules for data poor fisheries. 2013. North American Journal of Fisheries Management. 33: 845-860.

Wilberg, M. J. and J. R. Bence. 2006. Performance of time-varying catchability estimators in statistical catch-at-age analysis. Canadian Journal of Fisheries and Aquatic Sciences 63:2275-2285.

.

Table 1. Equations characterizing the age-structure population and fishing dynamics in the operating model (see Quinn and DeRiso 1999 for more details on age-structured dynamics).

	Equation	Description
	Population dynamics	
1	$N(a,t)=\begin{cases} R(t) & a=a_R \\ N(a-1,t-1)e^{-Z(a-1,t-1)} & a_R<a<a_{\max} \\ N(a-1,t-1)e^{-Z(a-1,t-1)}+N(a,t-1)e^{-Z(a,t-1)} & a=a_{\max} \end{cases}$	Numerical abundance at age
2	$R(t)=\dfrac{S(t-a_R)}{\alpha+\beta S(t-a_R)}e^{\theta_R-0.5\sigma_R^2}$ $\alpha=\dfrac{S_0\left(1-h\right)}{4hR_0} \qquad \beta=\dfrac{5h-1}{4hR_0}$	Stock-recruit relationship
3	$S(t)=\sum_{a=a_R}^{a_{\max}} m(a)w(a)N(a,t)$	Spawning biomass
4	$Z(a,t)=M+\sum_f s(a,f)F(t,f)$	Total mortality
	Life history	
5	$L(a)=L_\infty\left(1-e^{-k(a-a_0)}\right)$	Length at age
6	$w(a)=bL(a)^c$	Weight at length
7	$m(a)=\dfrac{1}{1+e^{-\left(\frac{a-m_{50\%}}{m_{slope}}\right)}}$	Maturity at age
	Fishing dynamics	
8	$s(a,f)=\dfrac{1}{1+e^{-\left(\frac{a-s_{50\%}(f)}{s_{slope}(f)}\right)}}$	Selectivity at age in fishery *f* (or in the survey, denoted $s(a,v)$)
9	$C(a,t,f)=\dfrac{s(a,f)F(t,f)}{Z(t,a)}w(a)N(a,t)\left(1-e^{-Z(a,t)}\right)$ $C(t,f)=\sum_a C(a,t,f)$ $C(t)=\sum_f C(t,f)$	Total catch

Data-generating dynamics

10	$C_{obs}(t,f) = C(t,f)e^{\varepsilon(t,f)-0.5\sigma^2(f)}$ $\varepsilon(t,f) \sim N(0,\sigma^2(f))$	Observed catch
11	$I(a,t,v) = q(v)s(a,v)N(a,t)$ $I(t,v) = \sum_a I(a,t,v)$	True index of abundance
12	$I_{obs}(t,v) = I(t,v)e^{\varepsilon(t,v)-0.5\sigma^2(v)}$ $\varepsilon(t,v) \sim N(0,\sigma^2(v))$	Observed index of abundance
13	$\mathbf{p}_{obs}(t,f) = \frac{1}{n(f)}\mathbf{\Theta}(t,f)$ $\mathbf{\Theta}(t,f) \sim Multinomial\left(n(f),\mathbf{p}(t,f)\right)$ $\mathbf{p}(t,f) = \frac{1}{C(t,f)}\left(C(a=1,t,f),...,C(a_{\max},t,f)\right)$	Observed vector of proportion-at-age in fishery *f*

Table 2. Parameter values for the slow, medium, and fast life histories for the simulation. Important quantities derived from these parameters used in the analyses are also listed.

Parameter	Description	Life History Slow	Medium	Fast
Specified				
a_r	Age at recruitment (to population)	3	1	1
a_{max}	Maximum age	15	10	7
M	Natural mortality rate	0.12	0.2	0.4
R_0	Virgin recruitment	$1x10^6$	$1x10^6$	$1x10^6$
h	Steepness	0.45	0.65	0.85
a_0	Age at length=0	0	0	0
L_∞	Maximum length	105	90	50
k	Growth rate	0.15	0.25	0.35
b_1	L-W scalar	$2.98x10^{-7}$	3.0×10^{-6}	3.0×10^{-6}
b_2	L-W exponent	3	3	3
m_{50}	Age at 50% maturity	4	2.5	1.25
m_{slope}	Slope of maturity function	1	0.5	0.25
s_{50}	Age at 50% selectivity (commercial, recreational, survey)	5.5, 5.5, 3.5	3.25, 3.25, 1.75	2, 2, 1
δ	Slope of selectivity function	0.5	0.5	0.5
SPR_{lim}	Limit SPR % that defines overfishing	0.45	0.4	0.35
SPR_{targ}	Target SPR% used to set the ABC	0.5	0.45	0.4
Derived				
S_{MSY}	Spawning biomass that produces *MSY*	4,032,260	1,326,560	94,127
S_{targ}	Spawning biomass when fishing at F_{lim}	4,663,130	1,216,650	91,635
F_{MSY}	Fishing mortality that produces *MSY*	0.07	0.2	0.54
F_{lim}	Fishing mortality that defines overfishing	0.08	0.22	0.56
MSY	Maximum sustainable yield	284,565	201,599	28,870
F_{lim} / M	Ratio of F_{lim} to M	0.8	1.1	1.4

Table 3. The negative log-likelihood function used to estimate the parameters in the statistical catch-at-age (SCAA) model.

1	$L=\sum_f \ell_C(f)+\sum_f \ell_{p_C}(f)$ $+\sum_f \ell_I(v)+\sum_v \ell_{p_I}(v)$	Objective function
2	$\ell_C(f)=0.5n(f)\log(\sigma^2_{est}(f))+\frac{1}{2\sigma^2_{est}(f)}\sum_t\left(\log(C_{obs}(t,f)-\log(C_{est}(t,f))\right)$	Fishery catch
3	$\ell_I(v)=0.5n(v)\log(\sigma^2_{est}(v))+\frac{1}{2\sigma^2_{est}(v)}\sum_t\left(\log(I_{obs}(t,v)-\log(I_{est}(t,v))\right)$	Survey index
4	$\ell_{p_C}(f)=-g(f)\sum_t\sum_a p_{obs}(a,t,f)\log(p_{est}(a,t,f))$	Fishery proportion-at-age
5	$\ell_{p_C}(v)=-g(v)\sum_t\sum_a p_{obs}(a,t,v)\log(p_{est}(a,t,v))$	Survey proportion-at-age

Table 4. Performance measures calculated for each model iteration for each scenario. MRE and MARE refer to the median relative error and median absolute relative error in terminal estimates from each stock assessment. Measures in the Population and Fishery Dynamics category are calculated using the final 18 years of the model run. Measures in the Assessment Estimates category are calculated comparing terminal assessments from 10 assessments to the true value in that year.

Category	Performance Measure
Population and Fishery Dynamics	Mean spawning biomass ratio (S / S_{MSY})
	Proportional change in biomass (ΔS)
	Mean catch / MSY
	Proportion of years when the population is overfished
	Proportion of years with overfishing occurring
	Proportion of years when the ABC > exploitable biomass
Assessment Estimates	MRE / MARE in terminal S estimates
	MRE / MARE in terminal R estimates
	MRE / MARE in terminal OFL estimates
	MRE / MARE in terminal F_{rec} estimates
	MRE / MARE in terminal F_{tot} estimates
	Proportion of years when overfishing not identified (false negative)
	Proportion of years when overfishing incorrectly declared (false positive)
	Proportion of years with S estimates within ± 20% of the true value
	Proportion of years with OFL estimates within ± 20% of the true value

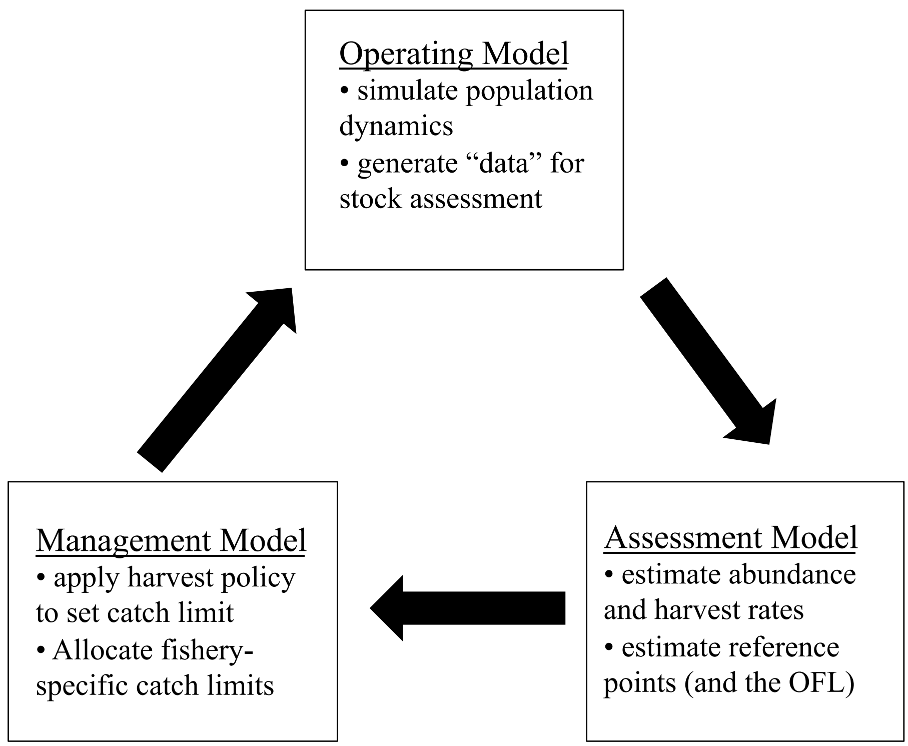


Figure 1. The individual model components linked together in the simulation. This loop is repeated over a set number of years for each run, and a total of 1,000 runs are conducted for each scenario of the simulation.

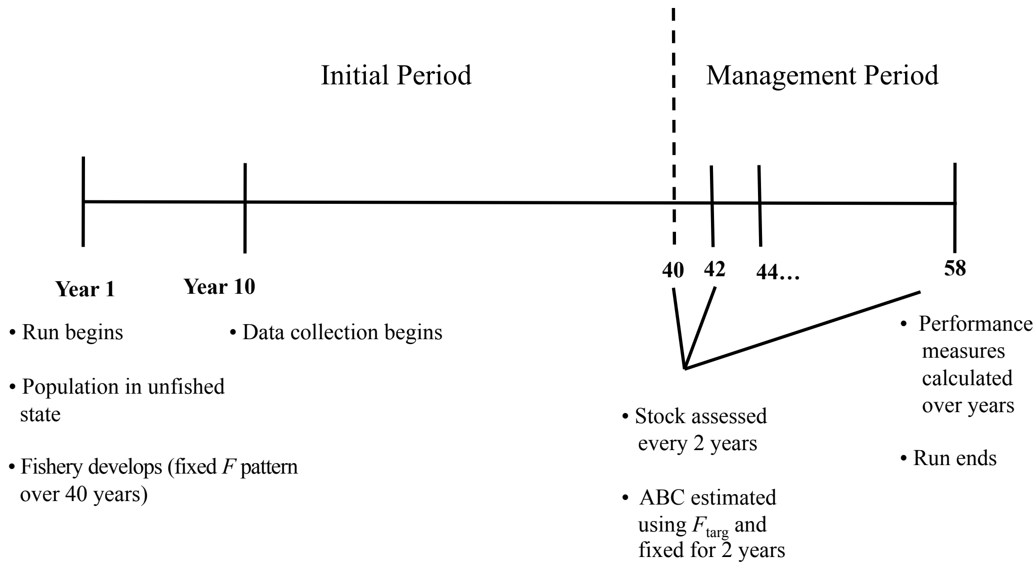


Figure 2. Timeline of the dynamics in the simulation model.

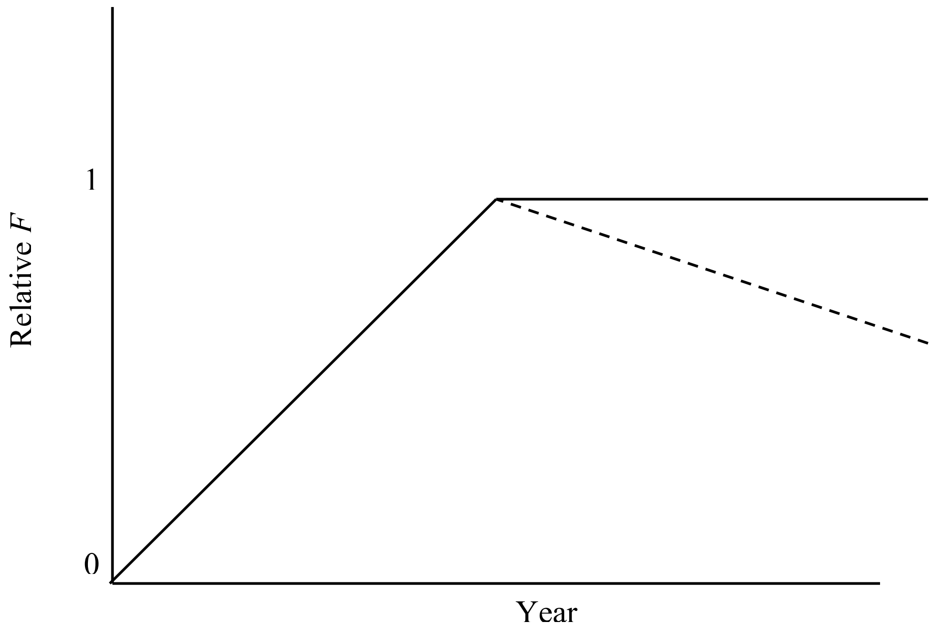


Figure 3. Example patterns of relative total fishing mortality (commercial + recreational) during the initial period. The fishery-specific estimates of F are estimated in the model and are dependent upon the exploitation scenario and the relative size of the recreational fishery. The maximum total fishing mortality in the initial period was set at 0.5, 1.0 and 2.0 x F_{MSY} for the light, moderate and heavy exploitation scenarios, respectively. Results are shown for the model with fishing mortality plateauing.

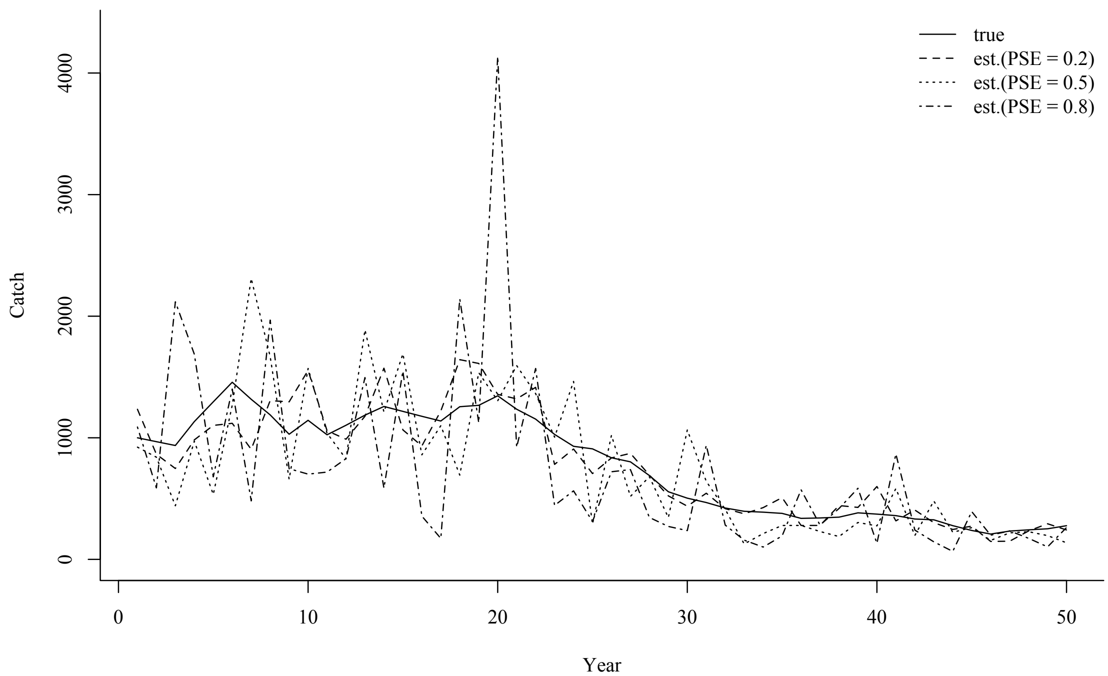


Figure 4. An example time series of true and observed catch levels for a single run of the simulation illustrating the effects of the proportional standard error (PSE) on the estimated values

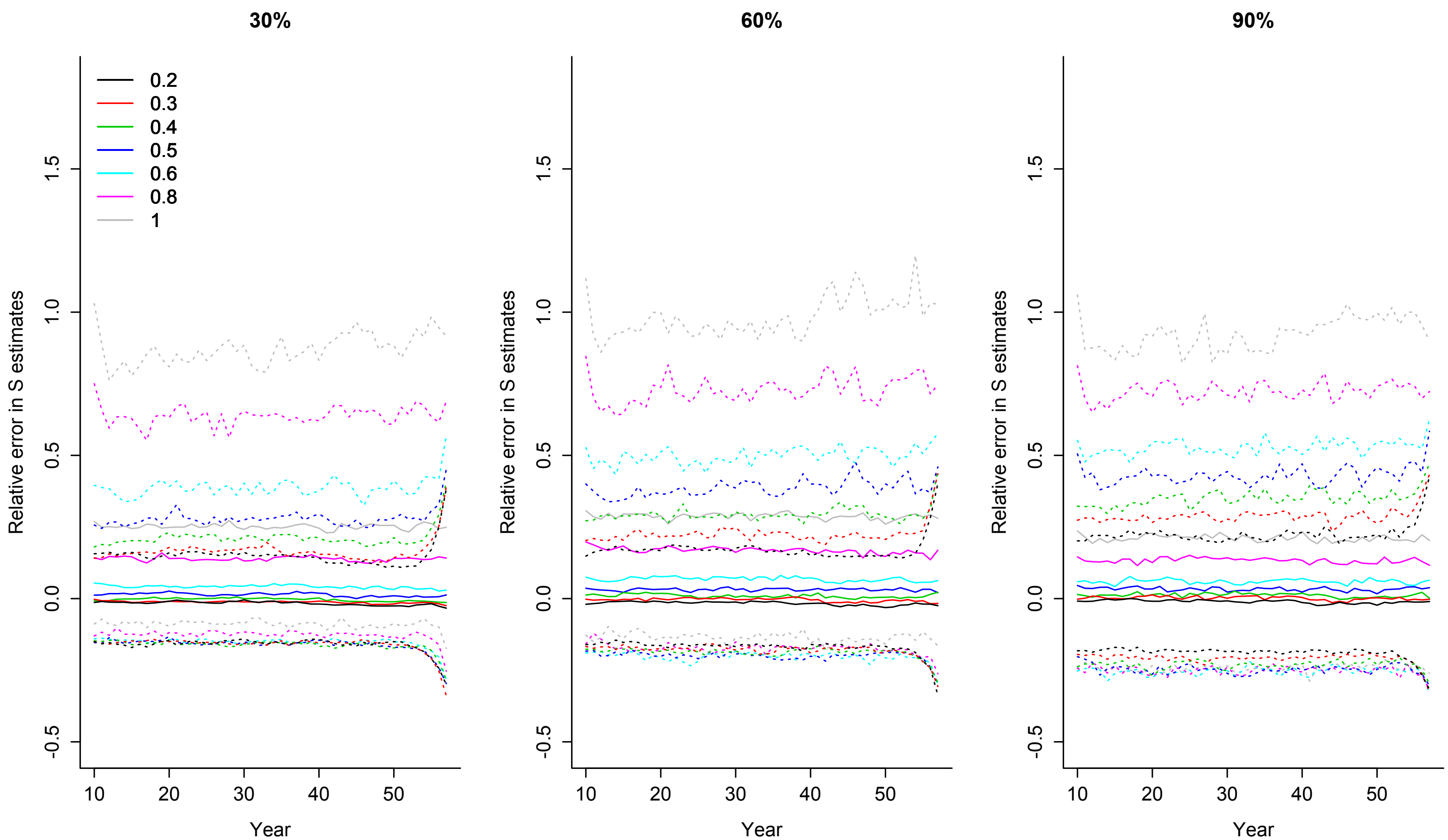


Figure 5. Time series of estimates of relative spawning biomass (estimated value / true value) for different sized recreational fisheries (30, 60, and 90% of total landings) for the fast life history. Colored lines denote the different PSE runs, with solid lines representing the median value across model iterations, and dashed lines representing the 95% confidence intervals.

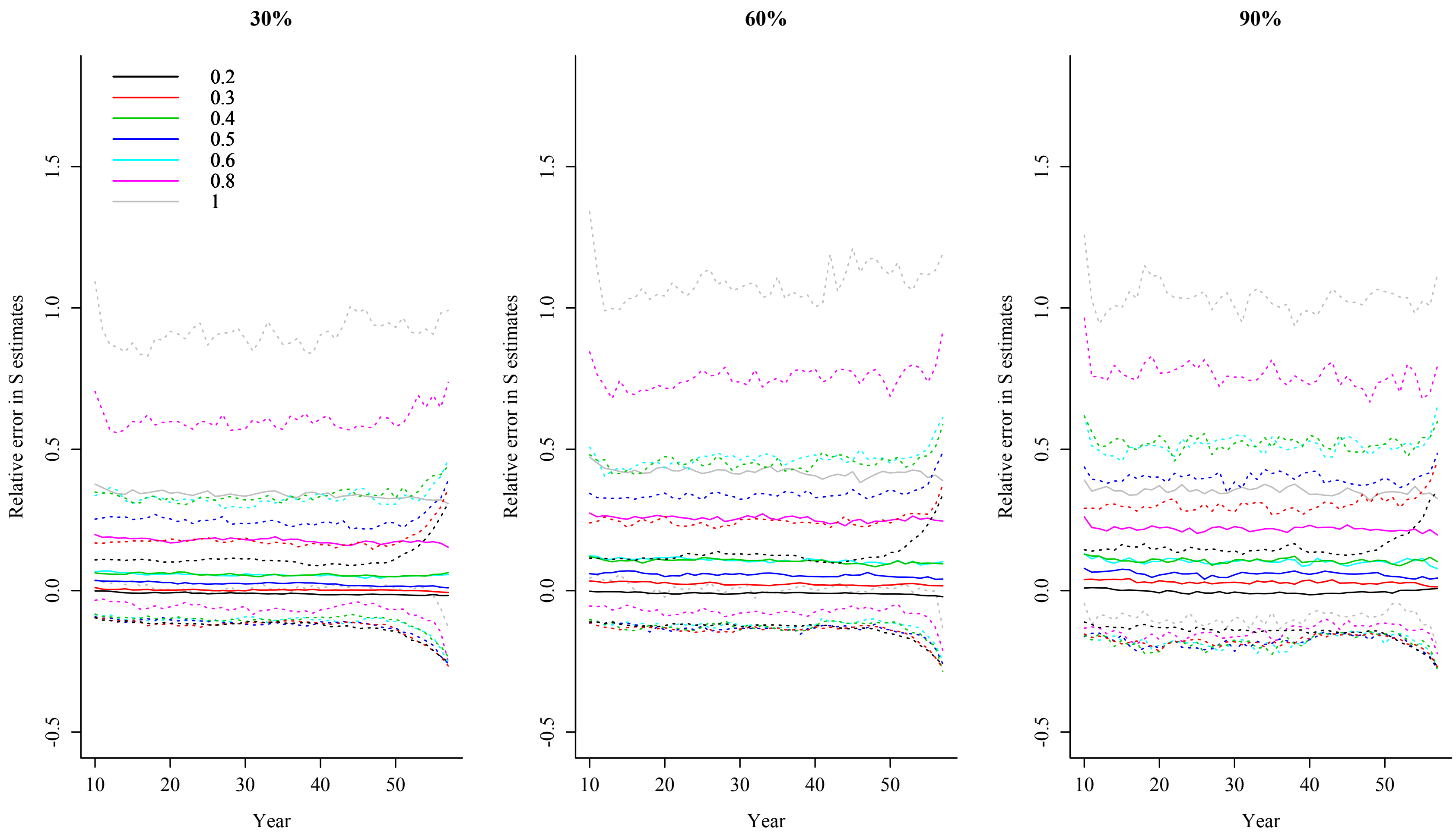


Figure 6. Similar to Figure 5, but for the medium life history.

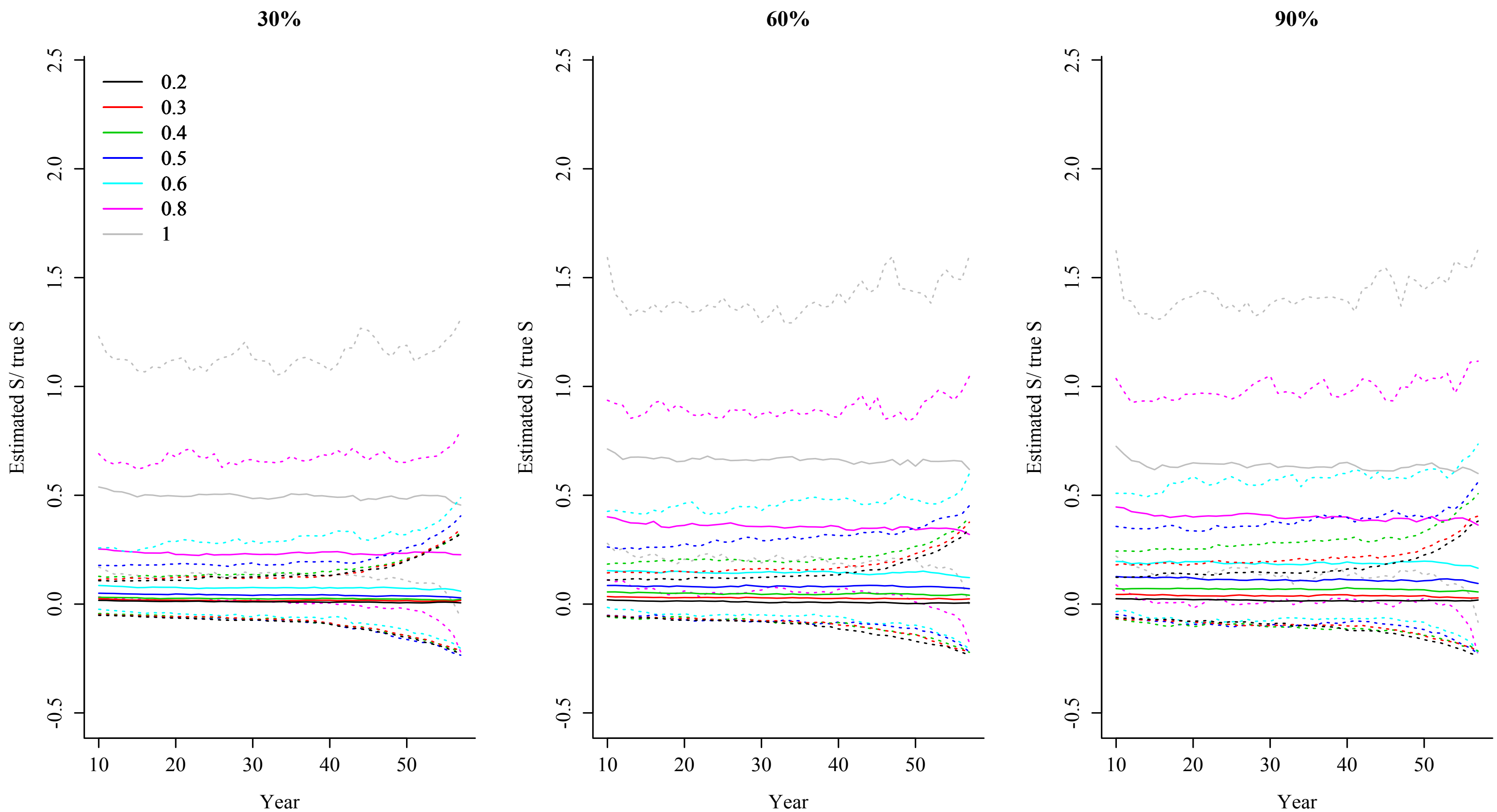


Figure 7. Similar to Figure 5, but for the slow life history.

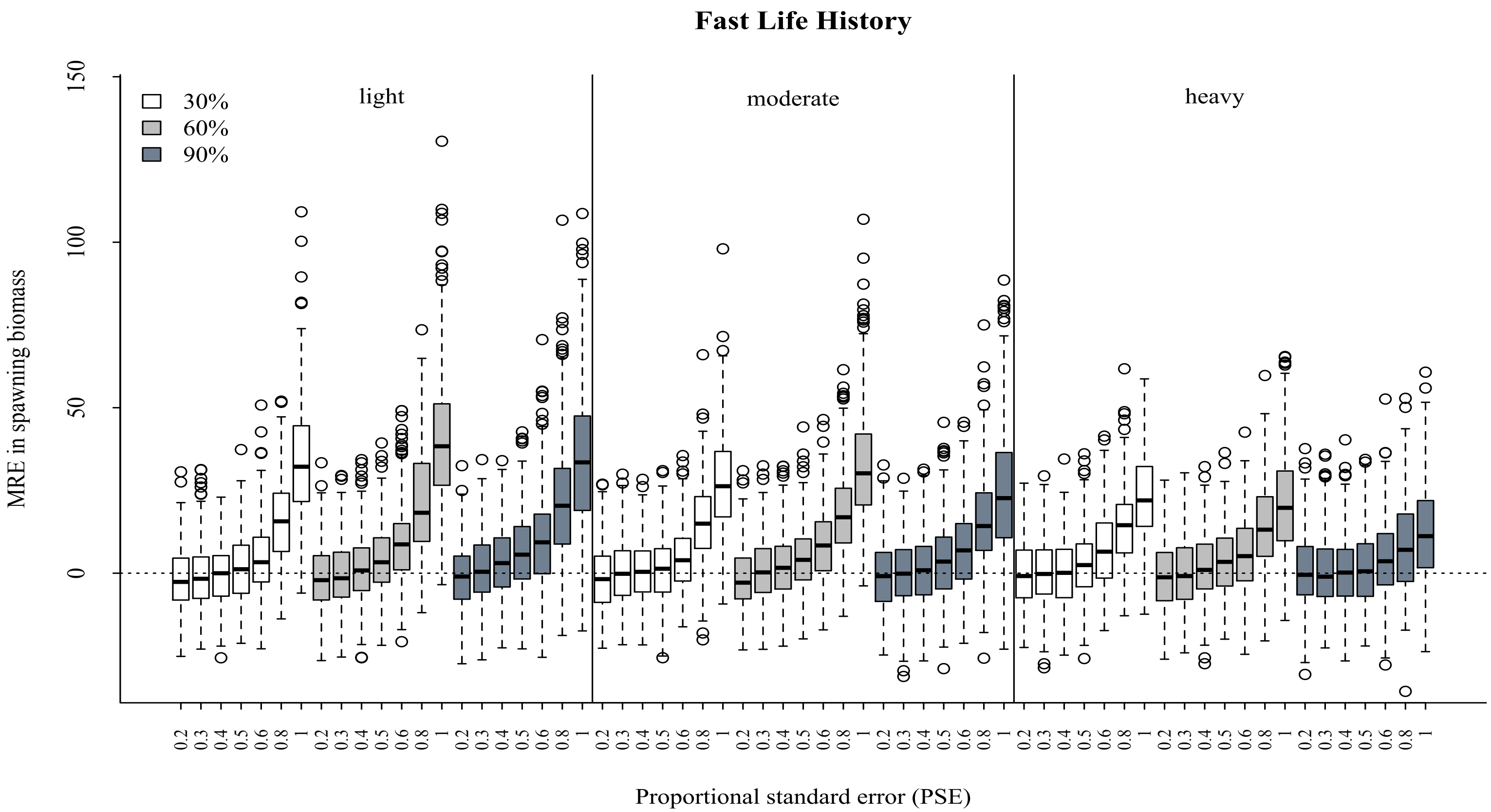


Figure 8. Boxplot of the median relative error (MRE) in terminal estimates of spawning biomass as a function of the proportional standard error (PSE) in recreational catch estimates across model runs for each scenario for the fast life history. Model runs for different exploitation scenarios are separated by the solid vertical lines, while runs for the different sized recreational fisheries (where the recreational fishery comprises 30, 60 and 90% of the total landings) are separated by color. Each box represent the interquartile

range on the estimates, with the median being the horizontal line within each box. The whiskers are ± 1.5 x the interquartile range, and the circles are observations outside the whiskers. The dashed line at 0 is added as a reference, with values below indicating the MRE is below the true value, and vice-versa.

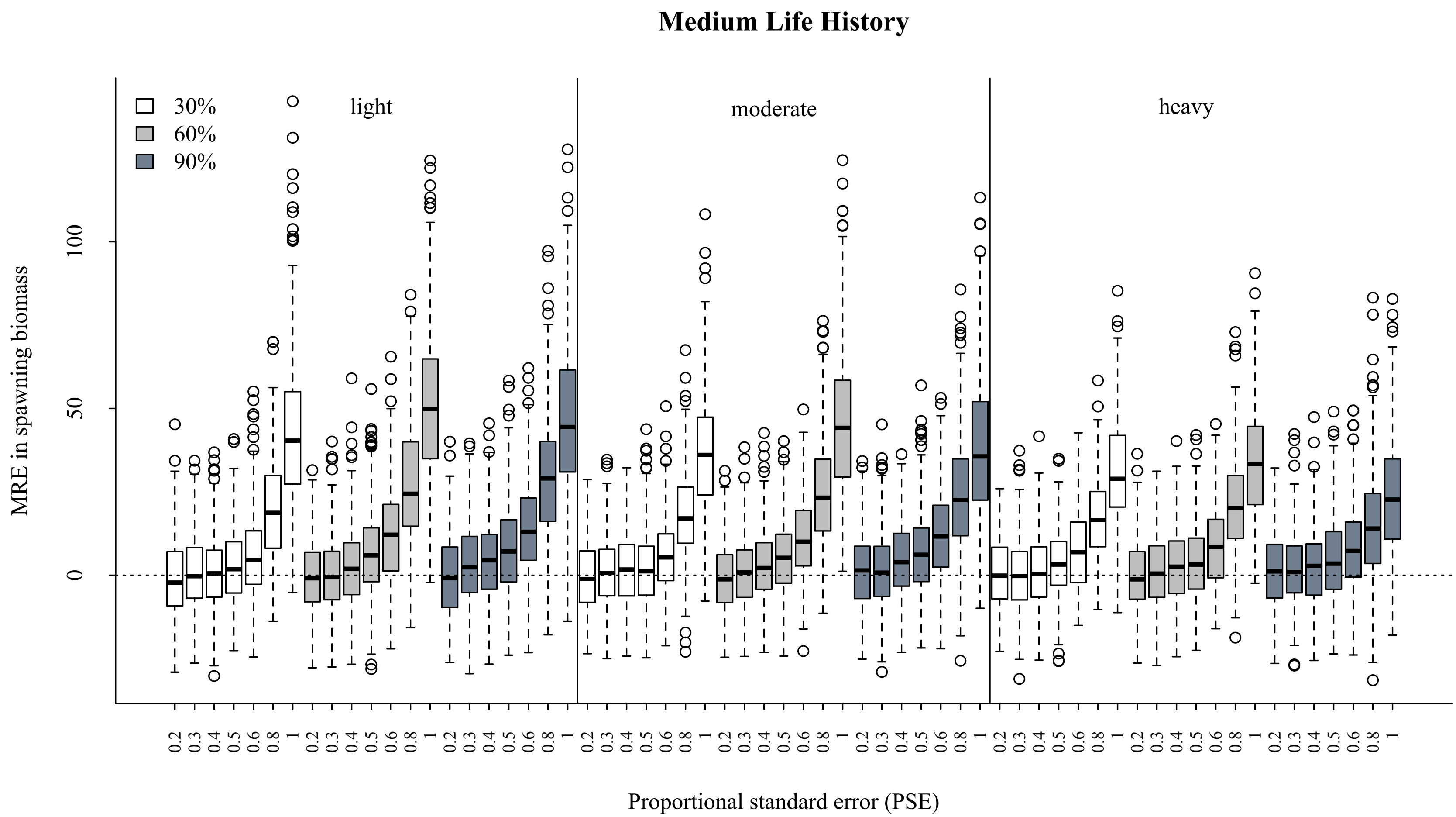


Figure 9. Similar to Figure 8, but showing the MRE in spawning biomass estimates for the medium life history.

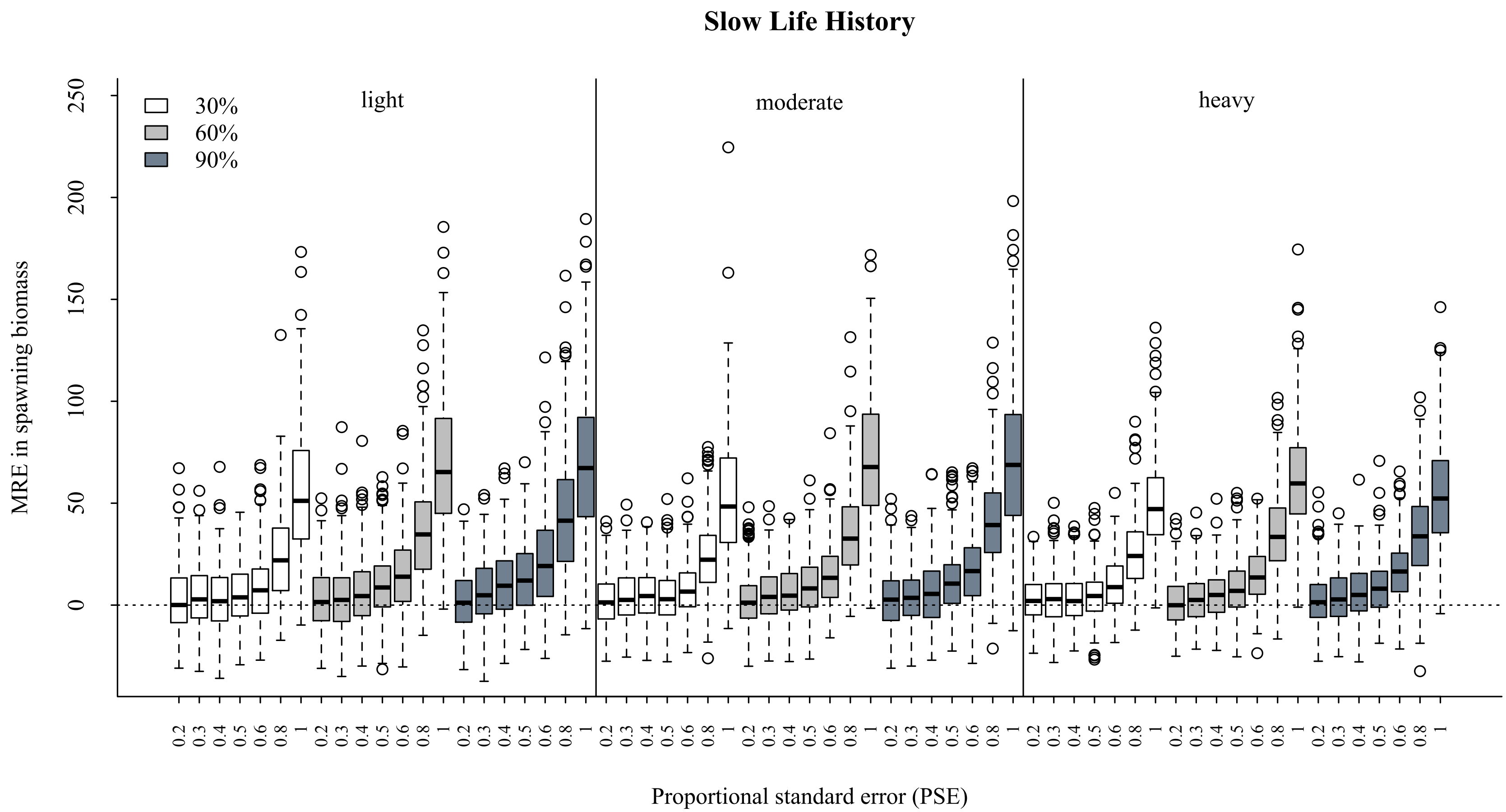


Figure 10. Similar to Figure 8, but showing the MRE in spawning biomass estimates for the slow life history.

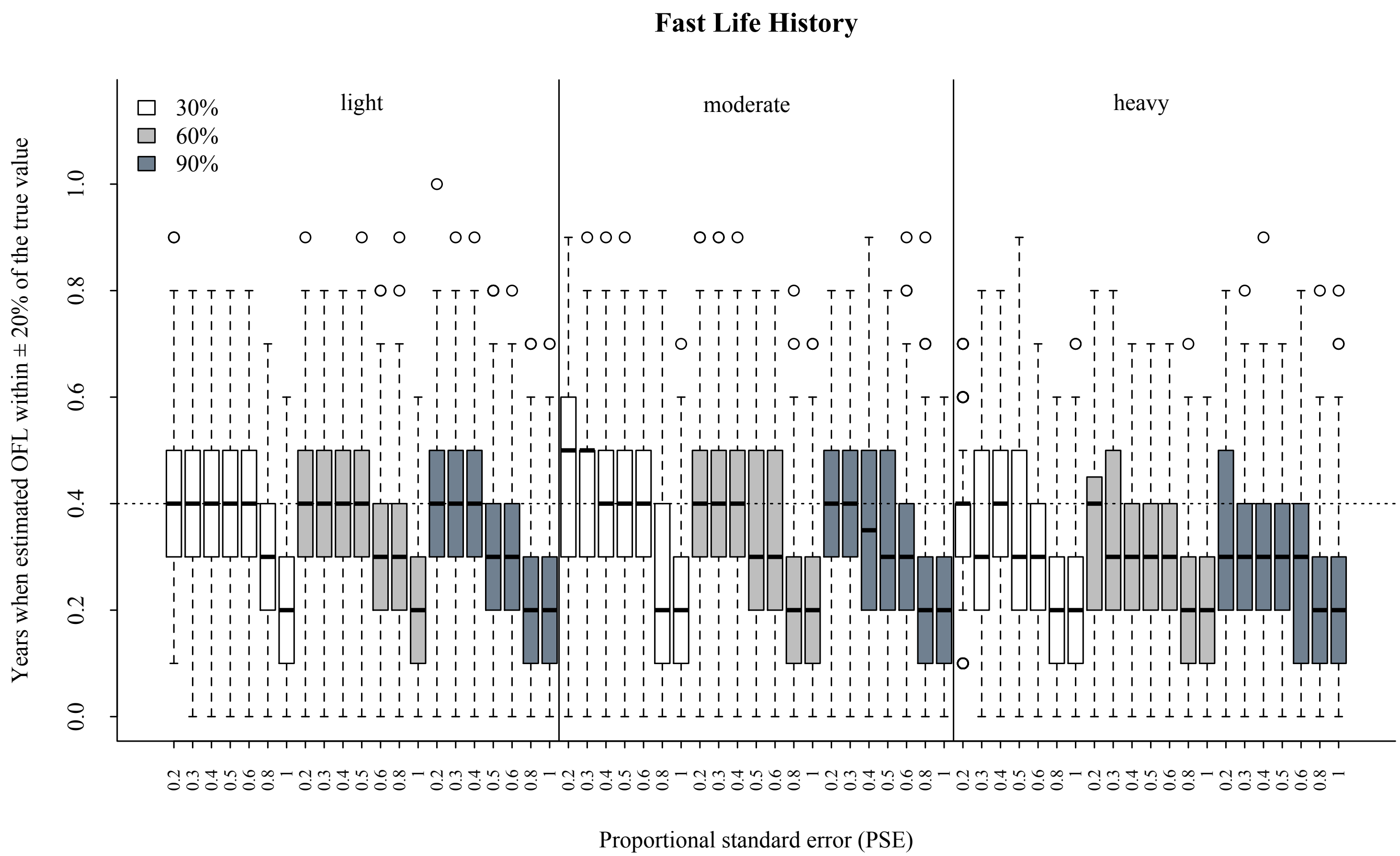


Figure 41. Similar to Figure 8, but showing the proportion of years when terminal estimates of the OFL are within ± 20% of the true for the fast life history. The horizontal line at 0.4 is added as a reference to compare estimates across scenarios.

Medium Life History

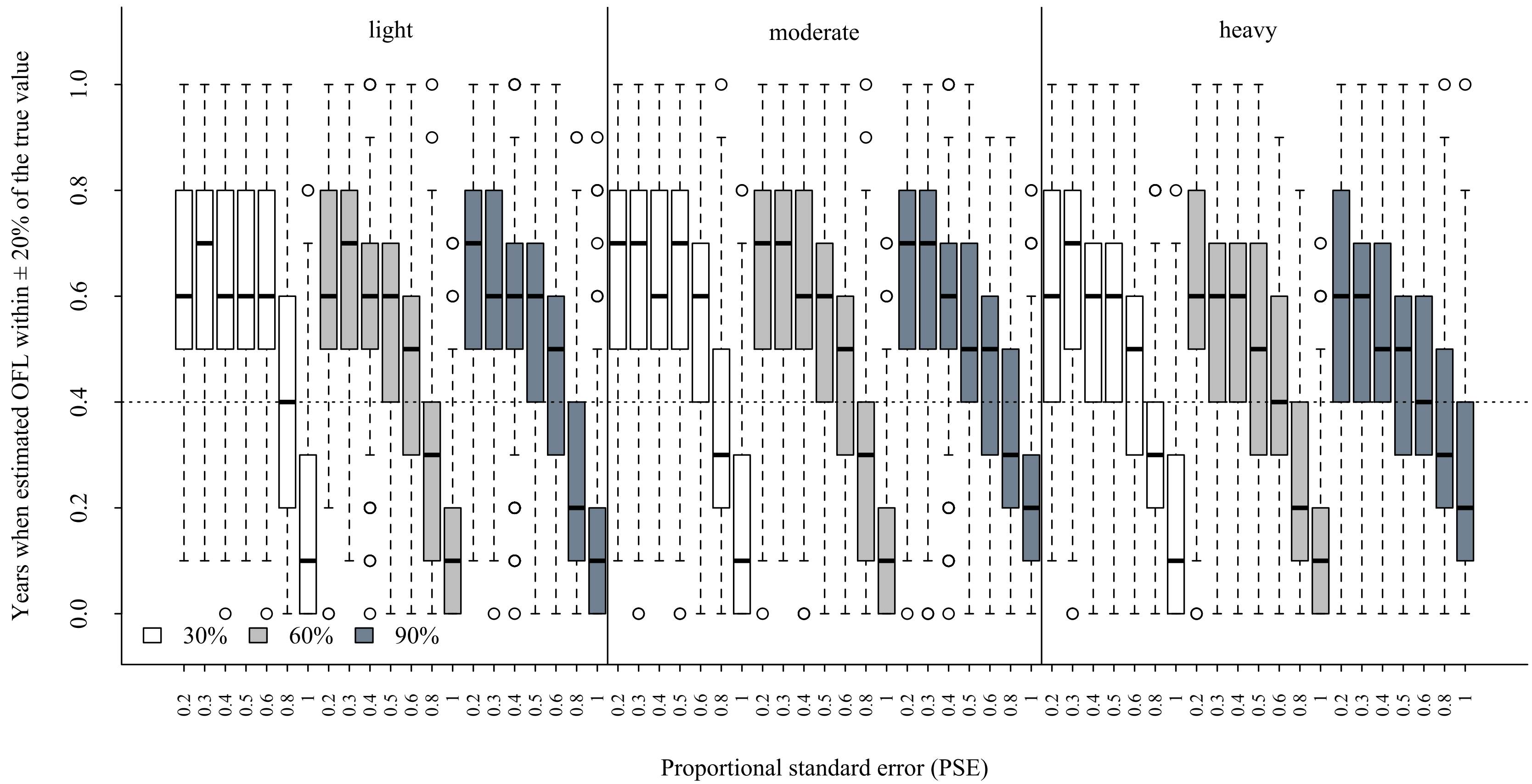


Figure 42. Similar to Figure 8, but showing the proportion of years when terminal estimates of the OFL are within ± 20% of the true for the medium life history. The horizontal line at 0.4 is added as a reference to compare estimates across scenarios.

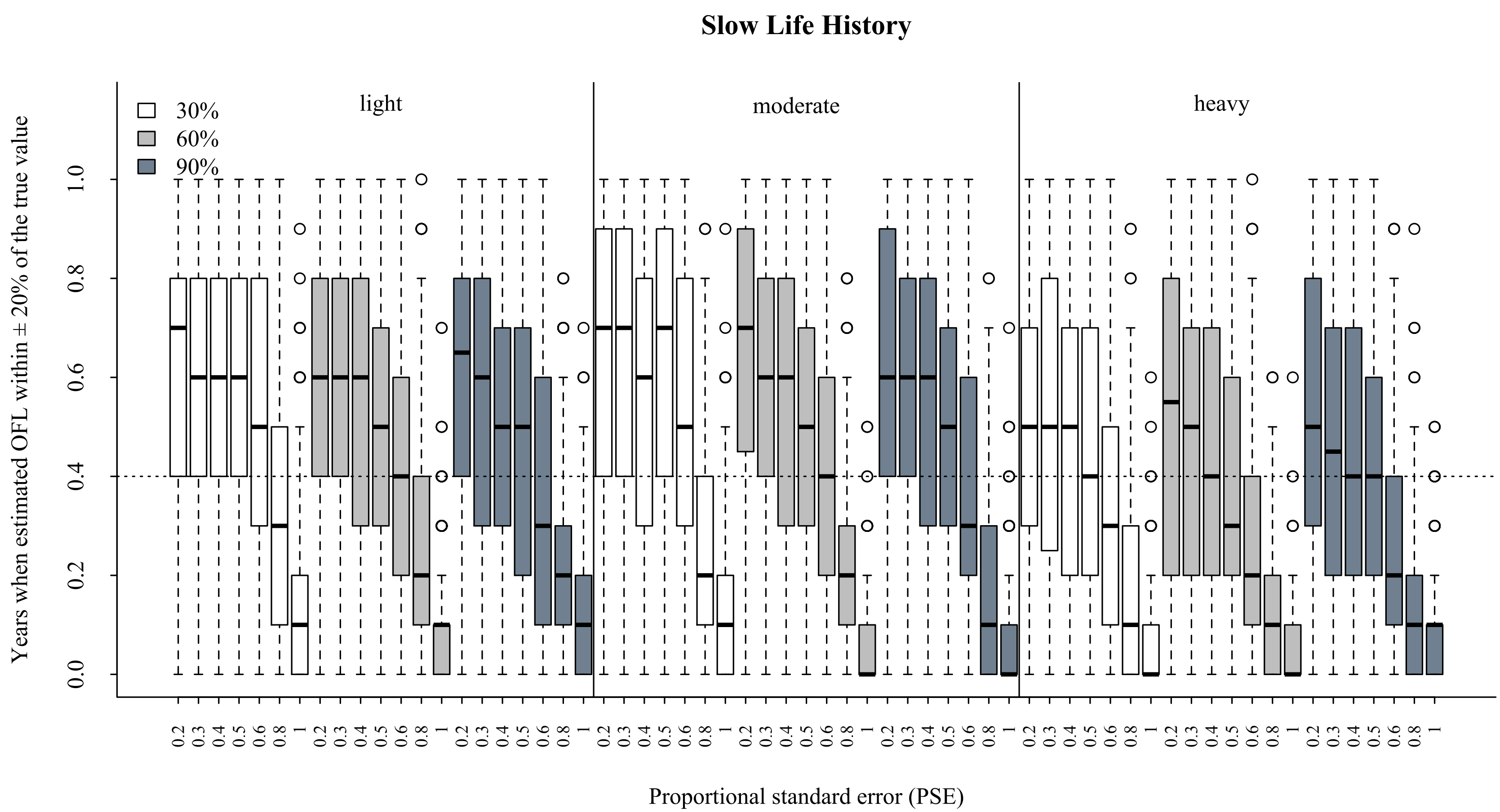


Figure 43. Similar to Figure 8, but showing the proportion of years when terminal estimates of the OFL are within ± 20% of the true for the slow life history. The horizontal line at 0.4 is added as a reference to compare estimates across scenarios.

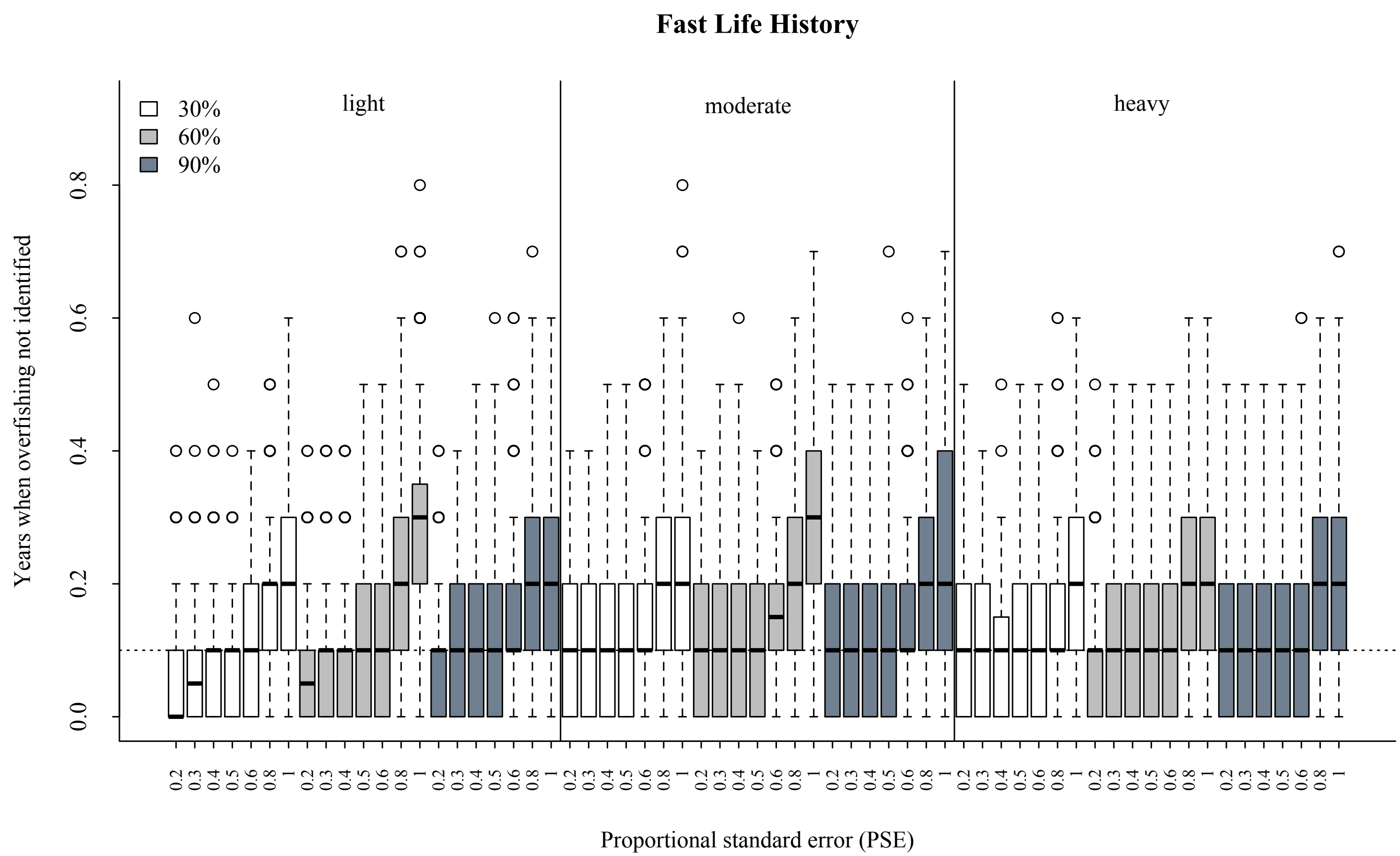


Figure 44. Similar to Figure 8, but showing the proportion of years when overfishing occurs in the terminal year but is not identified in the assessment for the fast life history. The horizontal line at 0.1 is added as a reference to compare estimates across scenarios

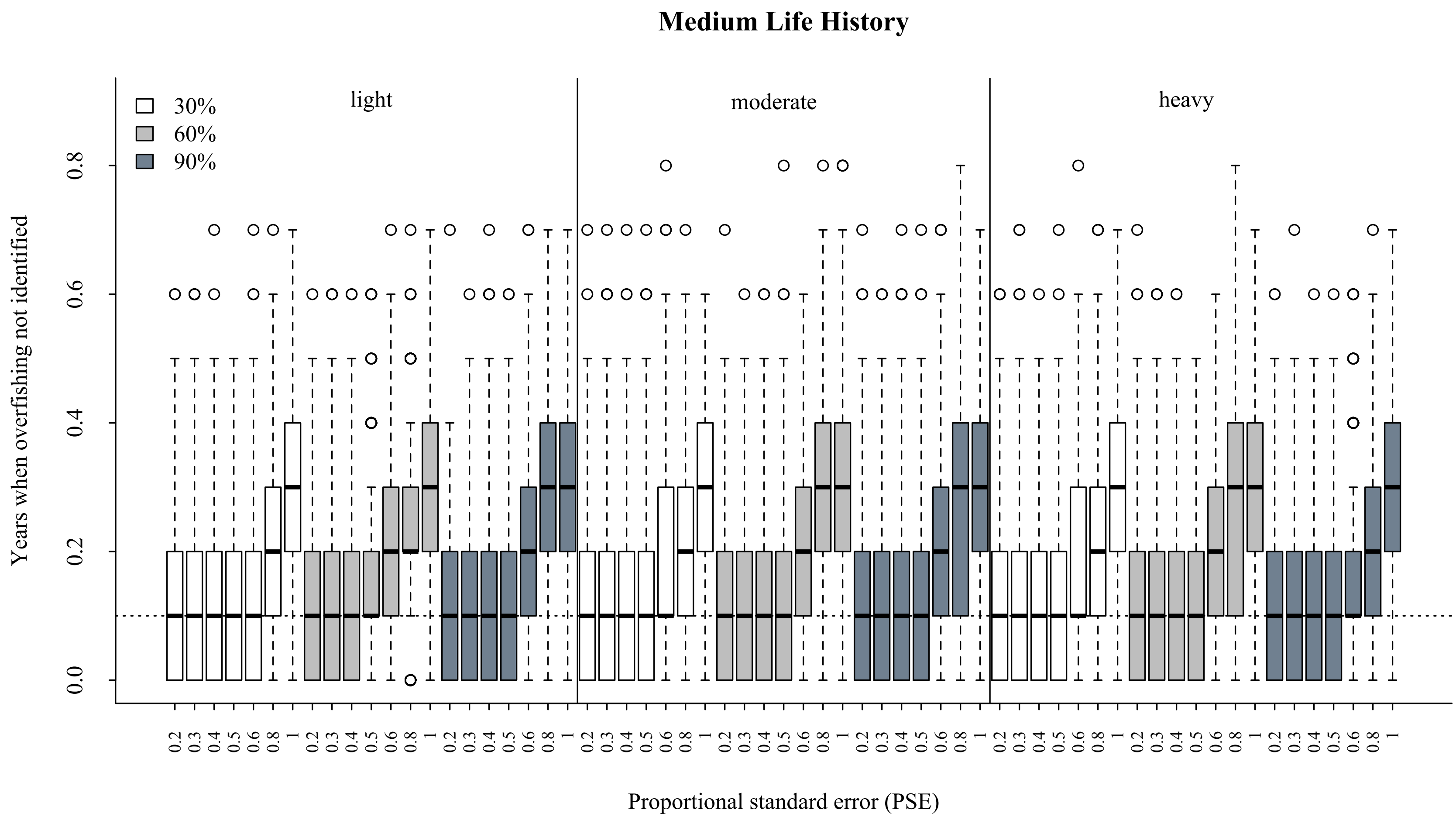


Figure 45. Similar to Figure 8, but showing the proportion of years when overfishing occurs in the terminal year but is not identified in the assessment for the medium life history. The horizontal line at 0.1 is added as a reference to compare estimates across scenarios

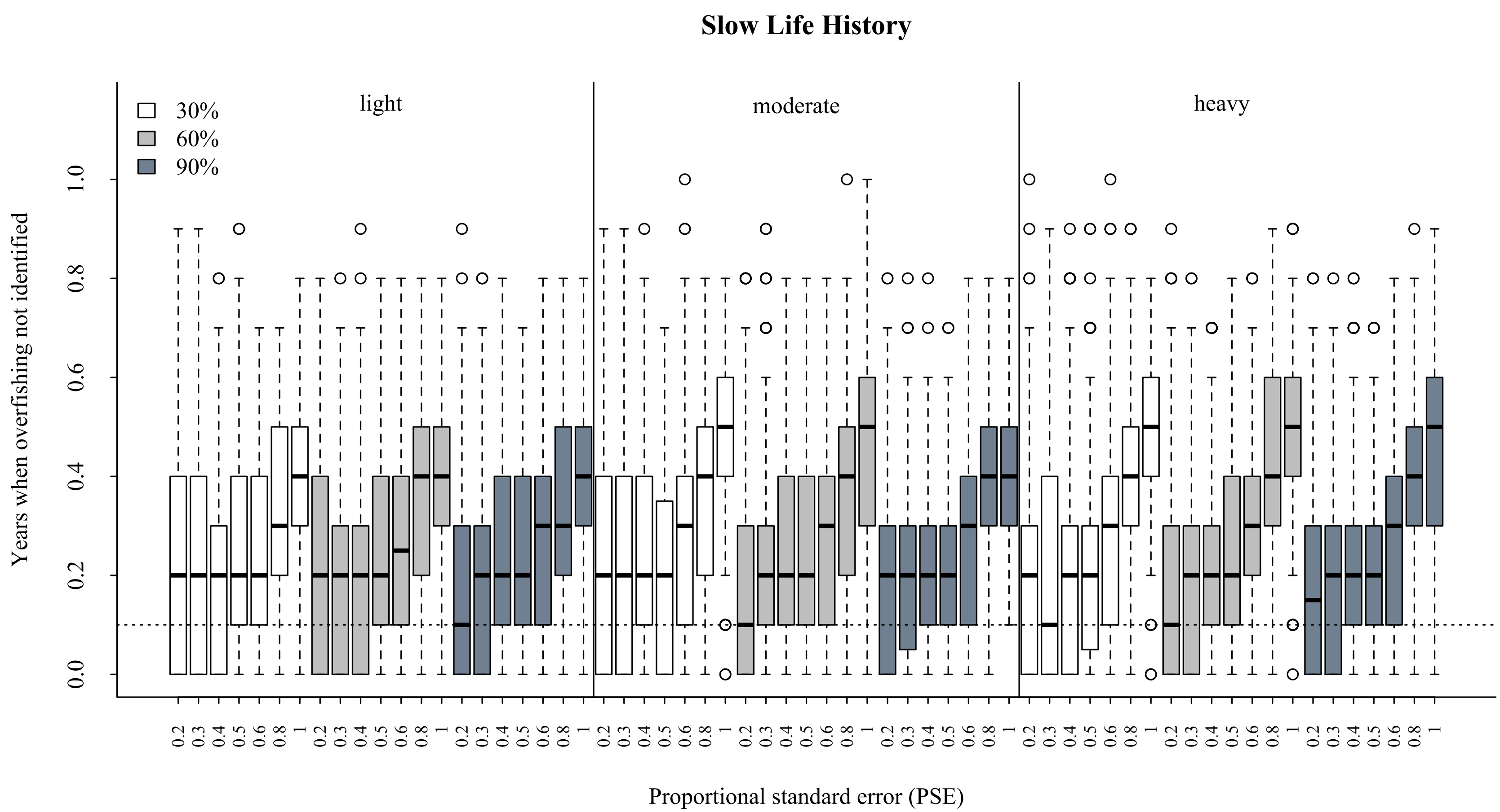


Figure 46. Similar to Figure 8, but showing the proportion of years when overfishing occurs in the terminal year but is not identified in the assessment for the slow life history. The horizontal line at 0.1 is added as a reference to compare estimates across scenarios

United States Department of the Interior

United States Geological Survey
Leetown Science Center
11649 Leetown Road
Kearneysville, WV 25430

BACKGROUND: The Department of Interior's (DOI) U.S. Geological Survey (USGS) is responsible, along with NOAA Fisheries and the U.S. Fish and Wildlife Service (FWS), under the Atlantic Coastal Fisheries Cooperative Management Act (1993) to serve as a research agency of the Atlantic States Marine Fisheries Commission (ASMFC). DOI's responsibility is also stated in the ASMFC Compact signed by Congress in 1950 and the Atlantic Striped Bass Act in 1984.

USGS leadership recently (2017) became aware of this Congressional responsibility. While USGS Leetown Science Center (LSC) and some USGS Cooperative Research Units have provided science support to ASMFC, the effort was minimal and not at a level needed or desired by ASMFC. As a result, the USGS Ecosystem Mission Area (EMA) provided LSC an additional $100,000 in both FY2018 and FY2019 to address priority research needs of ASMFC. The USGS Northeast Region has also provided $60,000 to LSC in FY2019 to further support ASMFC science needs.

In FY2018, the LSC submitted 25 research ideas to ASMFC based upon their science priorities document. ASMFC science and technical committee members comprising of ASMFC, FWS, NOAA Fisheries and State agencies reviewed and provided a prioritized list. Based upon this review, the LSC funded the follow four projects with FY2018 funding.

Project Title for New EMA Funded ASMFC Science Support	**ASMFC Technical Committee (Includes US FWS) Review Priority**	**LSC PI(S)**	**FY2018 Budget**
Eel migration and chemical attractants	High	Pis: Heather Galbraith and Carrie Blakeslee	$35,000
Estimation of regional survival and inter-embayment movement through analysis of the US FWS horseshoe crab tagging database	High	PI: David Smith and Dan Fitzgerald	$30,000
Scoping Project on the Development of American eel GIS-type habitat assessment model	High	Pis: John Young, Heather Galbraith, Carrie Blakeslee and Alex Haro	$10,000
Improving Downstream Passage for American Eels at Hydro and Other Dams	High/Medium	Pis: Alex Haro and Kevin Mulligan	$25,000
		Total	$100,000

LSC scientists also successfully pursued multiple external funding opportunities in FY2018 to address research priorities of ASMFC that aligned with DOI/USGS priorities totaling more than $1.1 million. Recent shifts in LSC's Chesapeake Bay Science Program is providing LSC additional funding to support a watershed habitat and health assessment in collaboration with NOAA building off of the National Fish

Habitat Partnership's Mid-Atlantic Region assessment is also of significant interest and benefit to ASMFC. Lastly, LSC scientists has increased representation on ASMFC's scientific and technical committees including new additions to the Habitat Committee and Atlantic Coastal Fish Habitat Partnership.

- Department of Defense (DOD) funding Fishway Entrance Pallisade study ($300K);
- U.S. Navy funding Atlantic sturgeon telemetry project in New England ($30,000);
- Corps funding an Atlantic sturgeon project in the Delaware River to examine the potential impacts of channel dredging and determine family structure and reproduction ($84,000);
- NOAA funding for maintaining the Atlantic Coast Sturgeon Tissue Research Repository and associated genetic analyses related to sturgeon incidental take/research permit samples ($118,000); and
- NOAA funding to expand genetic baseline and improve stock assessments for Atlantic sturgeon coastal waters of the southeastern U.S. ($99,996).
- BOEM Understanding of Atlantic Sturgeon Migratory Patterns – Integrating Telemetry and Genetics ($500K)

PROGRESS REPORT FOR EMA FY2018 FUNDING PROJECTS: Funded projects are at different stages of completion given funding was not received until late in FY2018 after which fish collection was no longer available. PIs have been strongly encouraged to establish and maintain frequent communications with ASMFC species technical leads in an effort to foster relationship trust, obtain regular feedback on project progress and facilitate science product delivery.

Improving Downstream Passage for American Eels at Hydro and Other Dams (LSC S.O. Conte Anadromous Fish Research Laboratory (CONTE), Alex Haro): $25,000

Level of coordination with ASMFC Species Technical Leads (Steve Gephard/Jeff Kipp): Initially contacted Gephard (CTDEEP) and Kipp (ASMFC) in September 2018 to refine scope of possible studies; turbine mortality and bypass technology for eels were discussed as possible topics. No opportunity to initiate any new study in 2018; not enough time before eel runs would begin. Agreed to pursue possible new field projects in 2019. Worked with Gephard in September/October 2018 on design for a new deep airlift bypass at a reservoir in Clinton, CT (Connecticut Water Company); construction ongoing. Data collected from 3rd year of operation of the Groton, CT airlift from September to November 2018; data currently being analyzed. Additionally, developed a program to analyze existing downstream eel passage data from a previous USGS/Conte telemetry study (Shetucket River, CT) to assess bypass effectiveness at three consecutive dams and physical/operational effects on bypass effectiveness. Recruited postdoctoral associate (Elsa Goerig) to analyze the Shetucket data and draft 1-2 publications from the results; $15K of funding will go to pay Goerig. Project timeline: Clinton airlift project technically started September 2018; initial trials of Clinton airlift will begin August-September 2019; study complete by November 2019. Analysis of Shetucket data will begin March-April 2019. Shetucket data analysis complete by July 2019; publication draft by September 2019. Anticipated products: journal manuscript for Shetucket project; technical report (to CTDEEP and ASMFC) on Clinton and Groton airlift performance by December 2019.

June 2019 Update: The new deep airlift bypass at Clinton, CT is now constructed; operational tests are planned for July 2019 and eel collection monitoring planned for September-November 2019. Additional

2018 data from Groton, CT airlift acquired; analysis in progress with previous years' data. Analysis from Shetucket River (CT) eel downstream passage telemetry data by E. Goerig (LSC) underway. Discussions ongoing to initiate a potential new project to evaluate exclusion of eels from a water supply reservoir (migratory dead-end) using underwater lighting at Aspetuck Reservoir, CT via PIT telemetry; fieldwork to tentatively begin September 2019. Anticipated products: delay in processing supplemental funding for Shetucket project will push back analysis completion date to December 2019, journal manuscript in January 2020. Report on Clinton and Groton airlift performance (and possibly Aspetuck telemetry study) in December 2019.

Eel migration and chemical attractants (LSC Northern Appalachian Research Laboratory (NARL), Heather Galbraith): $35,000

The goal of this study is to continue work on juvenile American eel chemical communication in support of ASMFC research needs to improve passage of eels at migration barriers. Results of completed studies at USGS LSC Northern Appalachian Research Laboratory (NARL) suggest that chemical cues may be useful for enhancing juvenile upstream American eel passage at dams. In combination with other fish passage technologies (e.g., fish ladders, electrical guidance, attraction flows), chemical cues may provide an effective and sustainable method for American eel restoration. Due to the timing of American eel migratory patterns, this study has not yet begun, but instead must be timed to coincide with the period when juvenile American eels arrive at the Atlantic Coast in early spring (March/April). Study objectives include: evaluating eel behavioral response to bile acids shown to be potential chemical attractants; determine whether groups of migrating glass eels exhibit a similar behavioral response to individual glass eels to determine if odorant detection is affected by the presence of conspecifics; and evaluate odorant detectability above natural background odorants by completing laboratory assays using river water. To date, NARL researchers have been in communication with ASMFC species technical leads and points of contact; have purchased necessary software for tracking movement and behavior of groups of eels along with supplies needed for two-choice maze construction; and have begun drafting a study plan amendment to complete this work. Behavioral experiments are anticipated to be completed by June 2019 with data analysis and manuscript submission to follow (estimated date Dec. 2019).

<u>March 2019 Update</u>: Researchers at the LSC NARL obtained incoming migrating glass eels in March to continue their research on the roles of putative chemical attractants in American eel migration.

Development of American eel GIS-type habitat assessment model (Scoping of model framework with ASMFC) (LSC Aquatic Ecology Lab (AEL), John Young, and NARL, Heather Galbraith): $10,000

Conversations between USGS-LSC and ASMFC began in the fall of 2018 to scope the possibility of incorporating GIS-based habitat variables into an American eel stock assessment. USGS-LSC researchers John Young and Heather Galbraith began the task of conducting a literature review and reached out to selected researchers to explore habitat requirements of American eel. ASMFC queried the American eel Stock Assessment Sub-committee (SAS) on project concepts and prepared a list of objectives and desired products that was provided to USGS on November 30, 2018 for feedback and comment. The goal was for John Young and Heather Galbraith to prepare a response to the ASMFC concept document and to brief the ASMFC in January of 2019 via a conference call with members of the SAS. Due to the lengthy US Government shutdown in January 2019, the conference call was postponed, eventually occurring in March 2019.

March 2019 Update:

USGS-LSC Scientists (Young, Galbraith) conducted a literature review and scoping activity to assess American eel habitat associations and to prepare a response to ASMFC's stated objectives and desired products. USGS-LSC researcher Alex Haro was requested to join the effort to consult and contribute due to his long history of American eel research and his international outreach to other eel species assessments, including in Canada and New Zealand. USGS-LSC presented findings from the scoping effort to the ASMFC American eel Stock Assessment Sub-Committee on March 13, 2019. USGS-LSC prepared a thorough, point-by-point response to ASMFC objectives and desired products. Literature reviews revealed recent GIS-based habitat assessments in Canada (Cairns et al. 2017, Cairns et al. 2012), New Zealand (Graynoth and Booker 2009, Hoyle 2016, Beentjes 2016), and France (Briand et al. 2018) for eel congeners that could serve as models for American eel assessments, given appropriate and available data from eel specific or fishery independent surveys. Additional examples of relating GIS-based physical habitat metrics into density and carrying capacity estimates were also explored for other anadromous species (i.e. Pacific salmon). In response to post-call follow-up from the ASMFC, the USGS-LSC additionally provided a summary of input data requirements and response variable types for modeling eel density or biomass in ways similar to Canadian, French, and New Zealand efforts that incorporated GIS-based habitat assessments. USGS-LSC proposed a phased approach moving forward that would entail 1) inventory and data compilation, 2) focused pilot studies in data sufficient areas, and 3) (ultimately) a range wide-assessment. Cairns et al. (2017) and Cairns (personal communication) suggested that the Delaware Bay and Chesapeake Bay regions as the best candidates for areas on the US east coast with enough data to pilot GIS-based habitat assessment approaches. Discussions since with the ASMFC staff have led to preliminary outreach to states in these areas.

Estimation of regional survival and inter-embayment movement through analysis of the US FWS horseshoe crab tagging database (LSC AEL, Dave Smith): $30,000

This work has been coordinated with the current benchmark stock assessment lead by Kristen Anstead (kanstead@asmfc.org) and Mike Schmidtke (mschmidtke@asmfc.org)

Dave has started the tagging analyses and some preliminary results on regional (NE, NY bight, Del Bay, SE) estimates of survival and effect of biomedically bleeding on survival have been included in the assessment report for peer review. An analysis on rates of inter-embayment movement between Del Bay and Coastal MD to VA has been started, but will not be included in assessment report. The next steps are to 1) finalize the analyses by accounting for capture method and disposition and 2) write up the work into journal publications. This project will be completed by the end of FY19.

Update (21 June 2019): Regional survival estimates were finalized, included in the benchmark stock assessment, and the stock assessment was peer-reviewed and presented to the management board. The survival estimates from the tagging data were a key piece of information in the benchmark stock assessment. The analysis of long-term effect of LAL bleeding on annual survival based on tagging data analysis was also included in the benchmark stock assessment and was presented at the 4th International Workshop on Science and Conservation of Horseshoe Crabs in Qinzhou City, PR China. A manuscript on the tagging data analysis is being prepared for publication.

STATUS of FY2019 FUNDING AND PROJECTS: The $100,000 of FY2019 funding from the USGS Ecosystem Mission Area was provided to the Leetown Science Center in June 2019. Based on conversations with ASMFC and the results of the FY2018 American eel GIS habitat assessment model scoping project, FY2019 funding will be used to support this project which is described below. Additionally, ASMFC identified a science support need for updating the program code and operational effectiveness of the horseshoe crab adaptive resource management model and leading/assisting a management evaluation effort of ASMFC FMPs. After discussing how to support this need by examining USGS capabilities and exploring additional funding sources, the LSC has agreed to provide this support. Discussions between USGS and USFWS also resulted in funding on research to developing the next generation of fish-passable stream gaging weirs with a focus in Delaware River Basin to improve fish passage and aquatic connectivity. The LSC also worked with MD DNR, ASMFC and NOAA to leverage partner funds to co-design an invasive blue catfish study in the Patuxent River, MD on distribution, movements, abundance and diets to from freshwater tidal to the mesohaline area. This study will improve understanding of ecological and socio-economic impacts, and design an effect harvest control strategy via a targeted commercial fishery.

Development of an American eel habitat model to support stock assessment needs of the ASMFC: A pilot effort in the Delaware and Chesapeake Bay watersheds (LSC AEL, John Young; CONTE, Alex Haro; and NARL, Heather Galbraith)

The Atlantic States Marine Fisheries Commission (ASMFC) conducts periodic stock assessments for American eel (*Anguilla rostrata*) in support of their fisheries management responsibilities for Atlantic coastal states. Recently the ASMFC requested assistance from the USGS Leetown Science Center (USGS-LSC) to scope if and how geographic information system (GIS) based habitat assessments could aid stock assessment activities, particularly if habitat information could inform estimates of eel population size, sex ratios, and/or biomass. At the conclusion of the scoping effort (see above), USGS-LSC proposed to conduct a two-phase pilot assessment (data inventory and compilation; GIS modeling) in the Delaware and Chesapeake Bay watersheds in FY19-20 to develop methodologies and test models for including habitat in American eel stock assessments in support of expressed ASMFC research priorities. This work aligns with existing USGS-LSC research in the Chesapeake Bay and Delaware Bay watersheds on fish habitat assessment, American eel life history characteristics, bathymetric habitat modeling, fish passage, and other fisheries related research. Using USGS-LSC provided guidance, staff of ASMFC have begun requesting data from the States that could serve as input response variables for density models, and some states have responded with metadata summaries or with data records of American eel surveys or fishery independent surveys where eels were captured.

Updating the ASMFC Horseshoe Crab ARM Model by Incorporating CSM Estimation and Converting Optimization Software from ASDP to MDPSolve (LSC AEL, Dave Smith (lead) and Dan Fitzgerald; USGS Coop Unit Auburn; Conor McGowan, US FWS John Sweka; Delware DF&W, Rich Wong; and NCSU, Paul Fackler): $130,000 for 2 years ($65K each year)

BACKGROUND: Since 2012 (Addendum VII to the Fishery Management Plan), the Atlantic States Marine Fisheries Commission (ASMFC) has relied on the adaptive resource management (ARM) framework to set harvest for the Delaware Bay horseshoe crab population. The ARM framework was designed to set harvest while accounting for the migratory shorebirds that use Delaware Bay as a stopover (McGowan et al. 2015). The horseshoe crab ARM framework has been very effective at managing harvest in an explicit and transparent way consistent with the DOI's principle framework for managing the Nation's resources in the face of uncertainty (DOI Adaptive Management Initiative, Williams et al. 2007).

In the ARM framework, the future abundance levels or states are predicted using species population dynamics models for shorebirds and horseshoe crabs (McGowan et al. 2011). Also, swept-area estimates from a trawl survey provide the observed abundance states for adult horseshoe crabs even though the swept-area estimates are known to be biased low due to imperfect catchability (Hata and Hallerman 2009). The recently completed ASMFC benchmark assessment demonstrated the use of the catch survey model (CSM; Collie and Sissenwine 1983) to estimate abundance and the peer-review panel endorsed its use to estimate stock size (Sweka et al. 2019). Thus, incorporating the CSM estimates into the ARM would be a significant advance.

The ARM framework currently uses the software ASDP to implement stochastic dynamic programming (Probert et al. 2011) to optimize state-dependent harvest decisions. However, ASDP is outdated and cannot be used with current operating systems; thus, limiting its operation. Recently developed software (MDPSolve), which runs in MATLAB, is a significant advance in methodology, can operate under multiple platforms and greatly improves user accessibility (Fackler 2011).

OBJECTIVES: The proposed project will result in improved science-based conservation of the Delaware Bay ecosystem by

1) incorporating the CSM estimates into the ARM framework and
2) translating and testing the conversion of the ASDP code into MDPsolve.

APPROACH

1) Translate the ASDP code into MDPSolve
2) Run simulation tests to ensure compatible and consistent output and results from ASDP and MDSolve
3) Code the CSM into MDPSolve
4) Generate decision matrices using MDPSolve
5) Train ASMFC committees on use of MDPSolve for ARM

PRODUCTS: Peer-reviewed publications on the technical aspects and application of the project will result. Reports (oral and written) will be presented to Atlantic States Marine Fisheries Commission, which will impact how horseshoe crabs and red knots are managed.

BENEFITS: Results from this project will prepare the ARM for continued implementation, which will influence a wide-range of adaptive management applications because the horseshoe crab ARM serves as an important example of multi-species adaptive management. Science-based management of horseshoe crabs and shorebirds bears directly on national and regional conservation priorities, most notably the USFWS Strategic Habitat Conservation Initiative and the DOI Adaptive Management Initiative. This project contributes to meeting high priority needs in the Endangered Species Act, National Shorebird Plan, BCR 30 Draft Plan, and State Wildlife Action Plans.

Developing the next generation of fish-passable stream-gaging weirs (LSC Conte, Alex Haro; USGS NJ Water Science Center, Tom Suro): $75,000, year 1 funding.

BACKGROUND: The USGS cooperative stream-gaging program dates back to the late 1800s and is a major component of providing accurate streamflow data for drinking-water supplies, protecting the environment, aquatic habitat and human life and property. USGS operates and maintains over 9000 continuous-record stream gaging stations nationwide to monitor surface water flow. For many of these stream gages, low-head (<1 m height) gaging weirs function to provide a stable low flow control and site conditions facilitating the computation of streamflow to help manage water resources. However, resource agency (NOAA/NMFS, USFWS, States) and NGO programs frequently consider potential removal of low-head gaging weirs to provide freer passage of migratory fishes and other aquatic species that cannot pass these weirs due to their structural height, high water velocities, or low water flow depths over the face of the weir, especially during low river flows.

The ability to modify or replace a non-passable stream-gage weir with new stream-gaging technology that maintains sensitivity to small changes in streamflow and stability of the stage-discharge relationship while also providing improved fish passage would be a major accomplishment for USGS to provide both ecological connectivity and accurate stream-gaging. Some existing modifications to a traditional weir that create passable conditions include: retrofitting the weir with a fishway or fish bypass channel, notching the weir, or backwatering the weir, among other methods. However, many of these methods have a negative impact on the stage-discharge relationship and/or the weir's ability to control flow while remaining sensitive to incremental changes in streamflow. New technologies such as continuous ADCP profiling in an open river channel may eliminate the need for a physical weir altogether, which may significantly facilitate fish passage, but may also result in substantial increased costs to the cooperator funding the stream-gage. A new hybrid design that incorporates aspects of a weir and a flume may provide a novel "next generation" solution for locations where some type of in-stream structure is necessary. If proven to work, the next generation hybrid weir and advanced stream-gaging technologies will need to be incorporated into new stream-gages and retrofit/repair of older weirs that need to be modified to allow better fish passage or have reached the end of their functional life. As we move into the next generation of data collection and analysis, evaluating impacts to our environment from factors like pollution and climate change will likely result in more investigation and analysis of trends in our data. Utilizing a new hybrid weir design as a low-flow streamflow control at long term stream-gages may also provide an opportunity to minimize potential bias added to the data when a long-term stable control structure like a stream-gaging weir is removed. These new or modified designs could reduce unnecessary costs while increasing fish passability and maintaining streamflow accuracy and stability at USGS stream-gages.

Relevance to NGWOS/Delaware Program:

The USGS Next Generation Water Observing System (NGWOS) pilot program, focused on the Delaware River Basin, provides an ideal opportunity to integrate both modernization of stream-gaging sensing systems and telemetry and facilitate passage of migratory fishes. The Delaware River Basin affords many potential test sites for such systems and has several ongoing migratory fish restoration programs that could benefit from the research.

Study Objectives:

1) Establish performance guidelines and operational criteria for stream-gages that can maintain required flow sensitivity and effective fish passage.
2) Identify and prioritize existing stream-gages in the Delaware River Basin that could benefit from modification or replacement to improve fish passage.
3) Design and test a "next generation" hybrid or modified weir design and other new designs/technologies than can be built and evaluated in the USGS Conte Fish Lab Hydraulic Laboratory (CARFL) Flume Facility for both measured stage and streamflow and fish passage performance, at full scale under controlled conditions and using live, actively migrating fish.

4) Publish alternative design options for new weirs and retrofit designs for existing weirs that would improve fish passability while maintaining a stable and sensitive stage-discharge control.

Characterize seasonal distribution, abundance and movement patters and diets for invasive catfish in Patuxent River, MD to better understand ecological and socio-economic impacts and guide effective population control strategies (LSC Christine Densmore, Deb Iwanowicz, Chris Ottinger, Dave Smith, Dave Kazyak, Ben Letcher; co-designed with MD DNR in coordination with ASMFC and NOAA NMFS): $118K.

BACKGROUND: Blue catfish (*Ictalurus furcatus*) is an invasive fish predator in Chesapeake Bay watershed with an increasing distribution. Its populations have grown to nuisance-level abundances in the past three decades. Early records of blue catfish in Potomac River were "random and sporadic" in the 1980s (Sauls et al. 1997) and there was no evidence of reproduction. At that time the occurrence of invasive catfishes in the upper Chesapeake Bay were considered temporary, the result of wet years in 1993 and 1994. Since then, blue catfish reproduction in Potomac River has led to high abundances that support a Potomac River, commercial fishery contributing over a million pounds per year. The species has also spread to adjacent rivers such as Patuxent River, rivers of the upper Chesapeake Bay, and has become noticeably abundant in eastern shore rivers such as Nanticoke River. Over the past 40 years, work has been done to learn about the abundance (Fabrizio et al. 2016) and diets of blue catfish (Schmitt et al. 2018) in Virginia. Early forecasts of extrapolated values from Virginia rivers suggested that over a million blue catfish could exist in the Chesapeake Bay. However, it is unlikely that blue catfishes are uniformly spread throughout the watershed because of habitat differences among and within rivers, and affection for certain habitats by blue catfish. Research has shown that the species achieved high abundances in Virginia rivers and consumed both fishes and macroinvertebrates, having a penchant for the latter and foraging more commonly at lower trophic levels. Additionally, blue catfish were observed to forage on blue crabs in the lower portions of rivers (Schmitt et al. 2018), which could complicate management of that highly prized natural resource in Maryland. Diet work conducted in Potomac River by Maryland biologists supported omnivory by blue catfishes (Graham 1999), also consuming egg chains of yellow perch from shallow water areas and fishes (unpublished data, M. Groves). Opportunistic feeding and omnivory could suggest that ecosystem impacts from this invasive species differ over space and time. Spatiotemporal differences in diet may not only exist among streams within a river, but also among rivers within Chesapeake Bay watershed. The recent spread of the species into habitats occupied by striped bass during their spawning season, as well as co-occurrence with American shad in Potomac River, has also given rise to additional concerns regarding feeding success of this very abundant predator. Because of the recent spread of blue catfish throughout the Chesapeake Bay, a robust understanding of movement patterns and consumption impacts at greater spatial and temporal scales will require studies across the range of the species in the watershed. Results from this work will identify overwintering (November – February) and spawning habitats (May – July) for the sole purpose of efficiently lowering densities during periods when densities are expected to be at their greatest. They will also help establish expectations for managing other resources, such as blue crabs, striped bass, and yellow perch, that are possibly threatened by the expansion of blue catfish in the Chesapeake Bay.

Study Objectives

1) learn where blue catfish reside during winter and the spawning season.
2) learn their abundance in those areas.
3) determine the percentage likely to stay in those areas year-round.
4) learn what blue catfish are eating across different seasons from freshwater and mesohaline habitats.

This work will be conducted in Patuxent River, which has a growing population of blue catfish, offers a relatively pristine environment, and can serve as a model study for other rivers of the Chesapeake Bay. We lack a comprehensive study of diet from mesohaline areas, as well as many rivers in the Chesapeake

Bay, which muddies an understanding of ecological relationships in the Bay watershed. Achieving objectives of this project will inform management actions for control by: 1) guiding efficient harvesting of blue catfish by agencies and watermen when fish are in overwintering and spawning habitats; and 2) informing managers on possible additive increases in natural mortality of recreationally and commercially valued species (e.g., blue crabs, yellow perch, and striped bass).

For More Information Contact:

Tom O'Connell, Director, Leetown Science Center, 304-724-4401; toconnell@usgs.gov

Atlantic States Marine Fisheries Commission

Research Priorities and Recommendations to Support Interjurisdictional Fisheries Management

April 2018

Sustainably Managing Atlantic Coastal Fisheries

Acknowledgments

The Atlantic States Marine Fisheries Commission (Commission) would like to thank all state, federal, and academia representatives who contribute information for this document. Identification and prioritization of research needs is provided by members of various Commission committees, including species stock assessment subcommittees, technical committees, advisory committees, plan development and review teams, and management boards.

Input is also provided by the Commission's Habitat Committee, Committee on Economics and Social Sciences, and Management and Science Committee. The research topics listed in this publication are consistent with those developed by the National Marine Fisheries Service Northeast Fisheries Science Center for organization and classification of Stock Assessment Workshop/Stock Assessment Review Committee (SAW/SARC) research recommendations. The Commission extends its appreciation to the members of the Management and Science Committee for providing oversight to the effort to identify and prioritize Commission research needs.

This publication should be cited as: Atlantic States Marine Fisheries Commission. 2018. Research Priorities and Recommendations to Support Interjurisdictional Fisheries Management. ASMFC, Arlington, VA. 93pp.

This is a report of the Atlantic States Marine Fisheries Commission pursuant to U.S. Department of Commerce, National Oceanic and Atmospheric Administration Award No. NA15NMF4740069.

Table of Contents

Preface

Research priorities listed in this document were identified from Atlantic States Marine Fisheries Commission (Commission) fishery management plans and amendments, annual plan reviews, special reports conducted by the Commission on species technical and stock assessment issues, Commission external peer reviews, and Stock Assessment Workshop (SAW) documents by the Stock Assessment Review Committee (SARC, since 1996) in the Northeast US and SouthEast Data, Assessment and Review (SEDAR, since 2002) process in the Southeast US in collaboration with the National Marine Fisheries Service. This publication is a living version of Special Report #89 Research Priorities and Recommendations to Support Interjurisdictional Fisheries Management published by the Commission in 2013. Updates are completed after each new assessment via the Commission's website at www.asmfc.org.

Research priorities were prioritized by Commission stock assessment subcommittees and technical committees under the purview of the Plan Development/Review Teams. Additional input to priorities is provided periodically by Advisory Committees, Management Boards, the Habitat Committee, the Committee on Economics and Social Sciences, and the Management and Science Committee.

It is the intent of the Commission to continually update this document as research priorities are either met or as new research needs are identified. The overall purpose of this document is to encourage state, federal, and university research programs to develop projects to meet the research priorities of Commission-managed species and thereby improve the overall management of these fisheries. It is also hoped that state, federal, and non-profit organizations will utilize this document in prioritization of research projects for future funding programs.

Abbreviations and Acronyms

ACCSP	Atlantic Coastal Cooperative Statistics Program
ASMFC	Atlantic States Marine Fisheries Commission
ASPIC	A Stock Production Model Incorporating Covariates
ASPM	Age structured production model
BMP	Best management practice
BRD	Bycatch reduction device
CAA	Catch-at-age analysis
CFD	Computer fluid dynamics
CPUE	Catch per unit effort
CSA	Collie-Sissenwine Analysis; also Catch Survey Analysis
DFO	Department of Fisheries and Oceans (Canada)
DO	Dissolved oxygen
EFH	Essential Fish Habitat
F	Instantaneous fishing mortality rate
FERC	Federal Energy Regulatory Commission
FMP	Fishery Management Plan
GIS	Geographic Information Systems
GLM	Generalized linear model
GLOBEC	Global Ocean Ecosystems Dynamics
GPS	Global Positioning System
HAPC	Habitat areas of particular concern
IPN	Infectious pancreatic necrosis
LPUE	Landings-per-unit-effort
M	Instantaneous natural mortality rate
MARMAP	Marine Resources, Monitoring, Assessment, and Prediction
MCMC	Markov chain Monte Carlo
MEDMR	Maine Department of Marine Resources
MRIP	Marine Recreational Information Program
MSE	Management Strategy Evaluation
MSVPA	Multispecies virtual population analysis
MSY	Maximum sustainable yield
NEAMAP	Northeast Area Monitoring and Assessment Program
NEFSC	Northeast Fisheries Science Center
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NPDES	National Pollutant Discharge Elimination System
NRCC	Northeast Regional Coordinating Council
PCB	Polychlorinated biphenyl
PIT	Passive integrated transponder
PRFC	Potomac River Fisheries Commission
SARC	Stock Assessment Review Committee

SCA	Statistical catch-at-age
SCDNR	South Carolina Department of Natural Resources
SEAMAP	Southeast Area Monitoring and Assessment Program
SEDAR	SouthEast Data, Assessment, and Review
SS	Stock Synthesis
SSB	Spawning stock biomass
TAL	Total allowable landings
TIP	Trip Interview Program
TOR	Terms of Reference
TRAC	Transboundary Resources Assessment Committee
USFWS	United States Fish and Wildlife Service
VPA	virtual population analysis
VT	Virginia Tech University
VTR	Vessel Trip Reporting
YOY	Young-of-the-year
YPR	Yield-per-recruit

Annual Monitoring Programs

Annual monitoring programs are a critical component of stock assessments and resource management. These programs include both fishery-dependent monitoring, such as catch and effort reporting and biological sampling, and fishery-independent monitoring, such as surveys that track abundance and biological characteristics (e.g., growth, maturity) that vary over time. Without annual monitoring, stock assessment scientists' ability to detect and account for this variability is degraded and assessment results will be less certain.

In the species-specific research priorities that follow, for species where the current level of annual monitoring is inadequate, recommendations to increase sampling levels, develop new surveys, etc. are provided. However, the Atlantic States Marine Fisheries Commission stresses that maintaining current levels of annual monitoring is vital for all species.

Fishery-dependent monitoring programs provide essential information for stock assessments every year. While knowing how many fish are removed by the commercial and recreational fisheries is important, annual biological sampling from the catch provides information on growth, reproduction, mortality, and the size, age, and movement of fish. For example, annual age-length keys remain the standard for age-based assessments. However, pooling data across years to fill gaps when annual monitoring is not conducted should be avoided. For example, interannual variability in year-class strength results in differing proportions of age-at-length keys from year to year, therefore, when data are pooled across years, the keys will not be able to accurately separate age-classes in the catch, making strong year-classes appear weaker and weak year-classes appear stronger. This makes the estimates of fishing mortality, recruitment, and abundance from age-structured models less reliable. For similar reasons, it is important to collect length frequency data on the catch every year and to provide the most accurate annual data on what components of the population are being harvested and/or being subjected to discard mortality.

Fishery-independent monitoring should also be conducted every year and maintained over time. Fishery-independent surveys provide information on annual year-class strength, which is important to monitor every year given the interannual variability of recruitment in marine and anadromous populations. Fishery-independent monitoring also allows us to track changes in abundance from year to year, compare that to trends in annual harvest, and assess the impact of fishing on the population annually. In addition, fishery-independent monitoring is an important source of biological data, especially for very small and very large fish that are not well-represented in the catch sampling and for fisheries where collecting hard parts is expensive or time-consuming. As a result, fishery-independent monitoring helps supplement fishery-dependent sampling to develop more complete age-length keys. Fishery-independent monitoring can also provide data on species with closed fisheries (or low quotas). It can provide data for areas closed to commercial fishing regulations, which are data that would not be obtained at all or in a large enough sample size by fishery-dependent monitoring.

As the focus of fisheries management expands from single-species to ecosystem-based fisheries management, the need for information that fisheries-independent monitoring provides has also increased significantly. For example, in addition to the ongoing baseline data required for effective management of recreational and commercial fisheries, improved information is needed on predator and prey species' life histories and interactions, essential fish habitat needs, and environmental conditions. This information is vital to enhancing fisheries management and is captured by annual fisheries-independent monitoring programs.

In addition to enhancing fisheries management, question-specific research projects can build on and/or compliment these monitoring programs. While annual monitoring programs are a significant investment of time and money, they are the cornerstone of reliable assessments and management decisions, and are a high research priority for the Commission.

Research Priorities by Species/Species Complex

AMERICAN EEL

Fishery-Dependent Priorities

High

- Monitor catch and effort in bait fisheries (commercial and personal-use) and in personal-use fisheries that are not currently covered by MRIP or commercial fisheries monitoring programs.
- Improve knowledge of the proportion of the American eel population and the fisheries occurring south of the US that may affect the US portion of the stock.
- Require standardized reporting of trip-level landings and effort data for all states in inland waters. Data should be collected using the ACCSP standards for collection of catch and effort data (ACCSP 2004).
- Compare buyer reports to reported state landings.
- *Moderate*
- Collect site specific information on the recreational harvest of American eel in inland waters, potentially through expansion of MRIP to riverine/inland areas.
- Monitor discards in targeted and non-targeted fisheries.
- Require states to collect fishery-dependent biological information by life stage, potentially through collaborative monitoring and research programs with dealers. Samples should be collected from gear types that target each life stage.[1]
- Review the historical participation level of subsistence fishers and relevant issues brought forth with respect to those subsistence fishers involved with American eel to provide information on the changing exploitation of American eels.
- Investigate American eel harvest and resource by subsistence harvesters (e.g., Native American tribes, Asian and European ethnic groups).

Fishery-Independent Priorities

High

- Maintain and update the list of fishery-independent surveys that have caught American eels and note the appropriate contact person for each survey.
- Request that states record the number of eels caught by fishery-independent surveys. Recommend states collect biological information by life stage including length, weight, age, and sex of eels caught in fishery-independent sampling programs; at a minimum, length samples should be routinely collected from fishery-independent surveys.
- Encourage states to implement surveys that directly target and measure abundance of yellow and silver stage American eels, especially in states where few targeted eel surveys are conducted.
- Develop a coastwide sampling program for yellow and silver stage American eels using standardized and statistically robust methodologies.

[1] SASC is developing a draft protocol for sampling fisheries.

- Continue the ASMFC-mandated YOY surveys; these surveys could be particularly valuable as an early warning signal of recruitment failure. Standardize sampling across all surveys. Develop proceedings document for the 2006 ASMFC YOY Survey Workshop. Follow-up on decisions and recommendations made at the workshop.

Moderate

- Develop standardized sampling gear, habitat, and ageing methods and conduct intensive age and growth studies at regional index sites to support development of reference points and estimates of exploitation.

Modeling / Quantitative Priorities

High

- Perform periodic stock assessments (every 5-7 years) and establish sustainable reference points for American eel required to develop a sustainable harvest rate in addition to determining whether the population is stable, decreasing, or increasing. Investigate if a longer time interval (8-10 years) between assessments will improve population trend estimates. Longer time periods may better reflect eel generation time.
- *Moderate*
- Develop new assessment models (e.g., delay-difference model) specific to eel life history and fit to available indices.
- Develop GIS-type model incorporating habitat type, abundance, contamination, and other environmental factors.

Life History, Biological, and Habitat Priorities

High

- Monitor non-harvest losses due to barriers such as impingement, entrainment, spill, and hydropower turbine mortality.
- Develop, investigate, and improve technologies for upstream and downstream American eel passage at various barriers for each life stage. Identify effective low-cost alternatives to traditional passage designs. Develop design standards for upstream passage devices.[2]
- Evaluate the impact, both upstream and downstream, of barriers to eel movement with respect to population and distribution effects. Determine relative contribution of historic loss of habitat to potential eel population and reproductive capacity.
- Implement large-scale (coastwide or regional) tagging studies of eels at different life stages to determine growth, passage mortality, movement and migration, validated ageing methods, reporting rates, and tag shredding/tag attrition rates.[3]

[2] An ASMFC Eel Passage Workshop occurred in 2011 reviewing details on passage design.
[3] Current tagging studies are ongoing in the St. Lawrence River system. A tagging study to examine local and regional movement has been completed by a graduate student at Delaware State University.

- Identify the mechanism driving sexual determination and the potential management implications.
- Identify spatially explicit, sex specific, triggering mechanism for metamorphosis to mature adult and silver eel life stage, with specific emphasis on the size and age at onset of maturity. A maturity schedule (proportion mature by size or age) would be extremely useful in combination with migration rates.
- Improve understanding of the effects of contaminants on fecundity, natural mortality, and overall health (non-lethal population stressors). Research the effects of bioaccumulation with respect to impacts on survival and growth by age and effect on maturation and reproductive success.[4]
- Conduct research on the prevalence, incidence of infection, and effects of the swim bladder parasite *Anguillicola crassus* on American eel growth and maturation, migration to the Sargasso Sea, and spawning potential. Investigate the impact of the introduction of *A. crassus* into areas that are presently free of the parasite.

Moderate

- Recommend monitoring of upstream and downstream movement at migratory barriers that are efficient at passing eels (e.g., fish ladder/lift counts). Data that should be collected include presence/absence, abundance, and biological information. Provide standardized protocols for monitoring eels at passage facilities, coordinate compilation of these data, and provide guidance on the need and purpose of site-specific monitoring.
- Evaluate eel impingement and entrainment at facilities with NPDES authorization for large water withdrawals. Quantify regional mortality and determine if indices of abundance could be established at specific facilities.
- Assess available drainage area over time to account for temporal changes in carrying capacity and sex ratio. Develop GIS of major passage barriers.
- Assess characteristics and distribution of American eel habitat and value of habitat with respect to growth and sex determination. Develop GIS of American eel habitat in US. This will have to be a habitat-specific analysis based on past studies that show high habitat-specific variability in sex ratios within a drainage system.
- Improve understanding of within-drainage behavior and movement and the exchange between freshwater and estuarine systems.
- Improve understanding of predator-prey relationships, behavior and movement of eel during their freshwater residency, oceanic behavior, and movement and specific spawning location of adult mature eel in the Sargasso Sea. Determine if larger females have a size refuge during the freshwater phase.
- Examine the mechanisms for exit from the Sargasso Sea and transport across the continental shelf to determine implications for recruitment. Examine migratory routes and guidance mechanisms for silver eel in the ocean.
- Research mechanisms of recognition of the spawning area by silver eel, mate location in the Sargasso Sea, spawning behavior, and gonadal development in maturation.

[4] USFWS currently has a project examining maternal transfer of contaminants in American eel.

- Continue investigation of the length and weight specific fecundities of American eel.
- Examine age-at-entry of glass eel into estuaries and freshwater to determine time lag between spawner escapement and glass eel recruitment.
- Improve understanding of all information on the leptocephalus and glass stages of eel, including mode of nutrition and transport/recruitment mechanisms.
- Develop a monitoring framework to collect and provide coastwide information on the influence of environmental factors and climate change on recruitment for future modeling.

Additional Habitat Research Recommendations

- Research the behavior of silver eels at downstream passages; determine specific behavior of eels migrating downstream, and research how they negotiate and pass hydropower facilities.
- Research the behavior of American eel approaching hydropower dams to determine searching behavior and preferred routes of approach to confirm best siting options for upstream passage.
- Investigate how river flow, lunar phase, water temperature, and behavior near artificial lighting impact the behavior of American eel, and influence the amount of time that the eels spend at a dam.
- Investigate the impact of stream velocity/discharge and stream morphology on upstream migration of glass eel and elvers.
- Research the factors that cause American eel to initiate downstream migration and affect their patterns of movement.
- Examine the environmental conditions required for the hatching success of American eel.
- Research the changes in ocean climate and environmental quality that might influence larval and adult eel migration, spawning, recruitment, and survival, including oceanic heat transport and interactions with the atmosphere and greenhouse gas warming.
- Determine the importance of coastal lakes and reservoirs to American eel populations.
- Investigate the impact of seaweed harvesting on American eel.

Management, Law Enforcement, and Socioeconomic Priorities

High

- Implement a special permit for use of commercial fixed gear (e.g., pots and traps) to harvest American eels for personal use. Special-use permit holders should be subject to the same reporting requirements for landings and effort as the commercial fishery.
- Coordinate monitoring, assessment, and management among agencies that have jurisdiction within the species' range.
- Perform a joint US-Canadian stock assessment.
- Improve compliance with landing and effort reporting requirements as outlined in the ASMFC FMP for American eel.

Moderate

- Continue to require states to report non-harvest losses in their annual compliance reports.

- Conduct socioeconomic studies to determine the value of the fishery and the impact of regulatory management.
- Develop population targets based on habitat availability at the local level.

American Eel Research Priorities Identified As Being Met

- ✓ Accurately document the commercial eel fishery so that our understanding of participation in the fishery and the amount of directed effort could be known. *Trip-level reporting of catch and effort became mandatory in 2007.*
- ✓ Evaluate the use of American eel as a water quality indicator.
- ✓ Investigate practical and cost-effective methods of re-establishing American eel in underutilized habitat.

AMERICAN LOBSTER

Outstanding 2009 Lobster Stock Assessment Peer Review Research Recommendations Updated with Responses (in italics) from 2015 Benchmark Stock Assessment

HIGH PRIORITY: While improvements such as mandatory dealer reporting have been made, the 2009 Panel feels commercial landings and fishing efforts continue to be recorded piecemeal over the stock range. We recommend that they be standardized. The Panel recommends a statistically-designed survey (rather than current ad hoc approach) be implemented for collection of biological characteristics of the catch. The Panel commends the improvement in the spatial coverage of sea and port biological sampling from commercial landings since the last stock assessment, but stresses the need to continue this sampling so as to achieve representative coverage of all segments of the fishing fleet. These data were especially helpful in evaluating Georges Bank stock status in the 2009 stock assessment. In particular, the Panel recommends annual reporting by state agencies of the data needed for the assessment model be implemented so that data are readily available for annual updates of stock indicators to be presented to the Lobster Management Board and for assessment model updates every five years.

- *Additional funds are needed to address the staffing needed to complete annual data reporting due to the scale and complexity of the fishery.*
- *A first cut of sampling power was attempted in this assessment, and has identified statistical areas in need of sampling and others that are adequately sampled.*

MEDIUM PRIORITY: While growth and mortality are key factors influencing population dynamics, recruitment often is the driver behind population resilience. The lobster stock assessment models define recruitment as entry into the fishery and thus bypass the early life stages. Nevertheless, we think research into larval mortality and distributions should be carried out. In particular, the biophysical coupled modeling approach (Xue et al. 2008) that simulates the patterns of egg production, temperature-dependent larval growth, stage-explicit vertical distributions of larvae, and mortality in a realistically simulated physical environment should be extended to other areas to understand recruitment sources for the U.S. lobster stocks. It will likely provide insight for the assessment team with regard to stock connectivity and shed some light on the conundrum of unusual stock resilience. In particular, the Panel recommends use of the model to understand whether larval sources are the same for below average and strong year classes. Identifying sources of recruits may provide managers with options to help ensure the continued resilience of this stock.

- *A long-term stock-wide larval study would be necessary to complete this, which requires funding and research.*

HIGH PRIORITY: Include an option to estimate a stock-recruitment relationship within the length-based model.

- *This research recommendation was not completed in the 2015 assessment because attention was focused on implementing recruit covariates to deal with environmental effects on recruitment, which appear more important in all stock areas during recent years. Interested users can use preliminary spawning biomass estimates as recruit covariates until these modifications are made to achieve nearly the same effect.*

HIGH PRIORITY: Examine the implications of varying the weightings on components of the overall likelihood on model fits. Such exploration is considered good practice in assessment modeling. With respect to model output presentation, the Panel also would have liked to have seen the actual likelihood values from the base case and alternative model runs, rather than just relative differences.

- *The 2015 assessment team used relative differences which are presented in the report and neglected to provide absolute values as requested.*

LOW PRIORITY: Allow more surveys as input.

- *The structure of the current code prevents reprogramming to allow an arbitrary number of surveys. It would be easier to reprogram the model than to make this type of change to the existing code. For the 2015 assessment, the model was modified to accommodate up to sixteen surveys which can be broken down by sex and season for efficient use of the available slots. The updated model sufficed for this assessment but the model should be reprogrammed for the next assessment.*

HIGH PRIORITY: The success of MSE relies heavily on the assumed stock-recruitment relationship. The Panel recommends completing a meta-analysis of stock-recruitment relationships for long-lived crustaceans so that some reasonable parameter estimates for the stock-recruitment relationship may be identified for the lobster stock, and then be implemented in the MSE.

- *Funding and research is needed to complete a MSE.*

Outstanding 2010 CIE Review Recommendations of the TC Report on SNE Recruitment Failure Updated with Responses (in italics) from 2015 Benchmark Stock Assessment

- Lobster recruitment surveys should be continued into the future, and if possible their sampling intensity should be increased to enhance their power to detect changes in larval or young-of-year abundance. New surveys are also recommended to give a spatially comprehensive picture of spawning patterns across SNE. Deployment of passive postlarval collectors is a promising methodology for such surveys. These surveys should be used (a) to improve understanding of recruitment processes, (b) to provide early feedback on the success of management measures aimed at protecting spawning potential, and (c) to allow forecasts of recruitment and landings for both inshore and offshore area.

  - *MA has added 4 new YOY sampling stations; RI has done additional sampling at 2 existing YOY stations. Additional sampling requires more funding, current state fiscal resources are limiting.*

- It is recommended that the UMM model and the model used in the report be investigated to determine which estimates of female abundance are most likely.
  - *This recommendation was not directly addressed in the 2015 assessment but female abundance estimates and trends for SNE were similar in the basecase and a range of sensitivity analyses.*

- It is recommended that the MA survey be relocated to a region where it is a better prediction of abundance and CPUE in the MA region.

- It is recommended that more reliable effort data is routinely collected from the fishery and that CPUE replace landings in assessing the fishery.
  - *Since the previous assessment most states have moved to 100% harvester reporting but the largest landing state still only collects 10% harvester reporting with 100% dealer reporting. This is an issue for the management to address.*

- It is recommended that effort be reduced in the fishery to a level equivalent to the 1980s and that a socio-economic study be implemented to determine the economic viability of effort reductions.
  - *This is an issue for the management board.*

- It is recommended that a study be undertaken to investigate the longer term future of the fishery. This could be achieved by using the downscaled IPCC climate models.
  - *Additional funds are necessary to apply IPCC modeling to the lobster fishery.*

- It is recommended that a decision rule process be considered that involves both government and industry and that incorporates both fishery independent (e.g. YOY) and fishery dependent (e.g. regional CPUEs) indices.
  - *This is an issue for the management board.*

- It is recommended that several low recruitment scenarios be determined and included in the projections. Each scenario needs to define what the recruitment value is compared to a base case (e.g. the BH-R).

- Further studies are undertaken to attempt to separate F from M.
  - *Additional funds are necessary to meet this objective.*

- It is recommended that the ASFMC adopts a definition of recruitment failure that is consistent with the criteria used to determine the threshold reference point that is used to assess whether the lobster stock is overfished.
    - *This is an issue for the management board.*

- It is recommended that, if and when exploitation of the SNE lobster stock is permitted, male lobster are preferentially exploited and female lobster are protected to the extent that is possible, *e.g.*, through use of a V-notch program or male-only fishery. It is also recommended that, if male lobster are preferentially exploited, monitoring programs are established to detect whether such exploitation produces a significant reduction in the number of females that are mated, or a significant reduction in the fecundity of females of different lengths.
    - *This is an issue for the management board.*

- It is recommended that managers impose a five-year moratorium on exploitation of the SNE lobster stock.
    - *This is an issue for the management board.*

2015 Lobster Stock Assessment Research Recommendations

Model Recommendations
Examine the use of a hierarchical modeling technique (Conn, 2010) to aggregate survey information for the different stock areas as an alternative to internally weighting indices in the model or using area-swept information.

Program Research
New research and expansion of existing monitoring programs in the following areas would provide information needed to improve future stock assessments.

FISHERY-DEPENDENT INFORMATION

- Accurate and comparable landings are the principal data needed to assess the impact of fishing on lobster populations. The quality of landings data has not been consistent spatially or temporally. Limited funding, and in some cases, elimination of sea sampling and port sampling programs will negatively affect our ability to characterize catch and conservation discards, limiting the ability of the model to accurately describe landings and stock conditions. It is imperative that funding for critical monitoring programs continues, and increased monitoring efforts for offshore areas, particularly those from which a large portion of landings originate, are necessary. These types of programs are essential for accurate lobster assessments and must have dedicated funding.

- There are some indications that lobster harvest may be under-reported and this under-reporting may be significant during some periods in the time series examined for this assessment. It is recommended that future research examine this potential under-reporting, and this examination should include simulation testing of these potential periods of under-reporting. One particular area that can be examined is the period prior to the implementation of the 100/500 possession rule for non-pot gear, as landings by non-pot gear may have been a significant source of under-reporting.

- A thorough investigation of methods for determining optimal biological sampling intensity based on variability in catch and spatial/temporal landings information should be undertaken. This investigation should explore other metrics that may be more variable than length composition (i.e. conservation discards, sex ratio, legal proportions), as well as an examination of the importance of the different Statistical Areas to the assessment and how this may interplay with the needed level of sampling from those areas.

FISHERY-INDEPENDENT INFORMATION

- ***Ventless Trap Survey-*** **(*High priority*)** Calibration work to determine how catch in the ventless trap surveys relates to catch in the bottom trawl surveys would be a useful topic of research. It is likely that at low densities, when trawl survey indices have dropped to near zero, ventless trap surveys will still catch lobsters due to the attractive nature of the gear and the ability to fish the gear over all habitat types. Conversely, it is possible that trawl surveys may be able to detect very high levels of lobster abundance, if trap saturation limits the capacity of the ventless traps. Ventless traps may be limited in their ability to differentiate between moderately high and extremely high abundance, and calibration with bottom trawl surveys may help to clarify how q might change with changes in lobster density.

- Now that funding for long-term ventless trap surveys appears to be more secure, there are some outstanding questions regarding this survey method that would benefit from further research. Namely, understanding trap saturation, in terms of high lobster densities and the capacity of the traps, along with the ensuing behavioral interactions that affect trapping of particular individuals, is a prime topic of interest to understand how density might impact the segment of the population represented in the survey catch. Also, the efficiency of the standardize survey gear could be explored in relation to effective fishing circles.

MATURITY AND GROWTH

- **(*High priority*)** Increases in water temperatures over the past several decades (see Section 2.2) have likely resulted in changes to size at maturity and growth patterns, since temperature has such a strong influence on these vital processes (see Section 2.1). Maturity data used in this assessment are more than 20 years old, making it likely that changes have since occurred. Evidence to suggest that decreases in the size at which females reach maturity exists in both the GOM stock (see Pugh et al. 2013) and the SNE stock (see DNC 2013, Landers et al. 2001). Changes in sizes at maturity will subsequently affect growth, since female molting frequency decrease after reaching sexual maturity. Additionally, growth is directly influenced by water temperatures, and evidence exists in SNE for increased molt frequency and decreased molt increments (DNC 2013). It is critical to collect updated information on maturity and growth in order to appropriately assign molt probabilities to lobsters in the U. Maine length-based model.

AGE

- If a definitive age-length relationship can be developed, a research recommendation will be to confirm the transition matrices used in the University of Maine model and improve the current assessment.

- In 2013 the Maine Department of Marine Resources contracted with the University of Maine for a five year $250,000 project designed to apply Kilada et al.'s (2012) approach to ageing for lobster. This work will focus on lobsters ranging in size from newly settled lobsters to fully recruited sizes. Regional temperature regimes will be tested as well as differences between laboratory and field scenarios. Anticipated deliverables should be directly applicable to future assessment and will include size-at-age estimates, molt increments and molt frequency.

ENVIRONMENTAL INFLUENCE ON LOBSTER LIFE HISTORY PROCESSES

- Examine methods for determining age- or length-varying natural mortality, as well as looking at more rigorous ways of determining time-varying natural mortality for lobster, which may be driven by climactic shifts and changing predator fields. Additionally, interplay between natural mortality and the potential for underreported harvest should be examined to determine how these factors may impact assessment outcomes.

- Continue exploring relationships between environmental drivers (temperature) and recruitment. Develop techniques to enhance predictive capabilities of YOY indices used together with temperature time series. Improve methods to incorporate environmental data into population modeling.

- Examine post-larval settlement dynamics in relation to movement/re-distribution of spawning stock. Develop habitat suitability models for spawning stock and settling post-larvae. Integrate climate projections into habitat suitability models for lobster.

- The Maine Department of Marine Resources conducted a three year study (2010-2013) where settlement was measured in randomly selected sites, based on depth and substrate, and compared to standardized sentinel locations in Mid-Coast Maine. Mid-Coast Maine is the region with the longest time series for settlement, dating back to

1989. For this reason, it was important to investigate the patterns of settlement from fixed and randomly selected sites. Initial results indicate fixed and random stations have similar magnitude and trend with respect to settlement density for this region.

In other regions in Maine, there may be evidence that thermal conditions may have changed, providing additional habitat for settlement. Annis et al. (2013) suggest that small differences in water temperature may shape settlement patterns through either behavioral avoidance of colder settlement sites or elevated post-settlement mortality of postlarvae settling at colder sites. Wahle et al. (2013) observed young-of-year lobsters as deep as 80 m. If available substrate has increased in eastern/northern Maine, simply as a result of increasing water temperatures, then fixed sentinel sites in shallow water may miss a broader pattern of settlement in the region. As such, deep water settlement should be investigated, using an appropriate number of passive settlement collectors (see Wahle et al. 2009) to detect anticipated settlement in conditions where the lack of thermal stratification would tend to distribute postlarvae evenly with depth.

- With the high prevalence of shell disease in the SNE stock, particularly in ovigerous females, some exploration of the potential sub-lethal effects of disease should be examined. These effects could include negative impacts to larval quality, fecundity issues in females who need to re-direct physiological resources to dealing with the disease, and male sperm quality (see Comeau and Benhalima 2009). Any sub-lethal effects of shell disease could further impede the potential for the SNE stock to rebuild.

POPULATION DYNAMICS AND MATING SUCCESS

- With the SNE stock in such poor condition, questions arise regarding how the population functions at some basic levels. In particular, because of the nature of the American lobster mating system (wherein males establish mating shelters and females seek out and choose to mate with dominant males; see Atema 1986, Atema and Vogt 1995 for reviews), low population abundance may be causing a mate-finding Allee effect (Stephens et al. 1999, Gascoigne et al.2009). There is some evidence indicating that larger, presumably reproductively mature females have not mated in some inshore regions (Pugh et al. 2103, Pugh 2014). In order to understand the potential the SNE stock has to rebuild, it is important to know whether current stock conditions have disrupted the mating system. Additional work to examine female mating activity and success should be initiated.

  Due to the continuation of female-skewed sex ratios observed in the GBK stock (on-going since the previous assessment), questions regarding the reproductive capacity of these large females should be considered. Recent laboratory work showed that females who mated with smaller males, or who mated under female-skewed sex ratios, did not have completely filled seminal receptacles, and may have been sperm-limited (Pugh 2014). As such, information regarding the location and timing of the female molt (thus mating) would be required to determine whether the skewed sex ratios and larger female size structure might impact female reproductive output. Additionally, sampling of the large females to determine whether they have mated would also be informative with regards to reproductive activity, as preliminary data indicated some large females had not mated (Goldstein et al. 2014).

STOCK CONNECTIVITY

- **(*High priority*)** There is need for a comprehensive large scale tagging study to examine stock connectivity between the Gulf of Maine and Georges Bank. Historical tagging studies demonstrate movement from the inshore Gulf of Maine to locations east of Cape Cod in the inshore portions of Georges Bank, from the Scotian Shelf to Georges Bank, and from inshore areas east of Cape Cod to inshore Gulf of Maine (see Section 2.9). What is lacking is a tagging study of lobsters in the fall/winter on Georges Bank proper, prior to seasonal migrations which occur in the spring. This information would be extremely valuable to help complement other data used to justify the combination of the Gulf of Maine and Georges Bank stock and to confirm the connectivity of the Gulf of Maine and Georges Bank.

AMERICAN SHAD AND RIVER HERRING

Fishery-Dependent Priorities

High

- Expand observer and port sampling coverage to quantify additional sources of mortality for alosine species, including bait fisheries, as well as rates of bycatch in other fisheries to reduce uncertainty.[5]

Moderate

- Identify directed harvest and bycatch losses of American shad in ocean and bay waters of Atlantic Maritime Canada.

Low

- Identify additional sources of historical catch data of the US small pelagic fisheries to better represent earlier harvest of river herring and improve model formulation.

Fishery-Independent Priorities

Moderate

- Develop demersal and pelagic trawl CPUE indices of offshore river herring biomass.

Modeling / Quantitative Priorities

High

- Conduct population assessments on river herring, particularly in the south.[6]
- Analyze the consequences of interactions between the offshore bycatch fisheries and population trends in the rivers.
- Quantify fishing mortality for major river stocks after ocean closure of directed fisheries (river, ocean bycatch, bait fisheries).
- Improve methods to develop biological benchmarks used in assessment modeling (fecundity-at-age, sex specific mean weight-at-age, partial recruitment vector/maturity schedules) for river herring and American shad of both semelparous and iteroparous stocks.
- Improve methods for calculating M.

Moderate

- Consider standardization of indices with a GLM to improve trend estimates and uncertainty characterization.
- Explore peer-reviewed stock assessment models for use in additional river systems as more data become available.

Low

- Develop models to predict the potential impacts of climate change on river herring distribution and stock persistence.

Life History, Biological, and Habitat Priorities

---

[5] A prior statistical study of observer allocation and coverage should be conducted (see Hanke et al. 2012).

[6] A peer reviewed river herring stock assessment was completed in 2012 by the ASMFC.

High

- Conduct studies to quantify and improve fish passage efficiency and support the implementation of standard practices.
- Assess the efficiency of using hydroacoustics to repel alosines or pheromones to attract alosines to fish passage structures. Test commercially available acoustic equipment at existing fish passage facilities. Develop methods to isolate/manufacture pheromones or other alosine attractants.
- Investigate the relationship between juvenile river herring/American shad and subsequent year class strength, with emphasis on the validity of juvenile abundance indices, rates and sources of immature mortality, migratory behavior of juveniles, and life history requirements.
- Develop an integrated coastal remote telemetry system or network that would allow tagged fish to be tracked throughout their coastal migration and into the estuarine and riverine environments.
- Verify tag-based estimates of American shad.
- Continue studies to determine river herring population stock structure along the coast and enable determination of river origin of catch in mixed stock fisheries and incidental catch in non-targeted ocean fisheries. Spatially delineate mixed stock and Delaware stock areas within the Delaware system. Methods to be considered could include otolith microchemistry, oxytetracycline otolith marking, genetic analysis, and/or tagging.[7]
- Validate the different values of M for river herring and American shad stocks through shad ageing techniques and repeat spawning information.
- Continue to assess current ageing techniques for river herring and American shad, using known-age fish, scales, otoliths, and spawning marks. Conduct biannual ageing workshops to maintain consistency and accuracy of ageing fish sampled in state programs.[8]
- Summarize existing information on predation by striped bass and other species. Quantify consumption through modeling (e.g., MSVPA), diet, and bioenergetics studies.
- Refine techniques for tank spawning of American shad. Secure adequate eggs for culture programs using native broodstock.

Moderate

- Determine the effects of passage barriers on all life history stages of American shad and river herring. Conduct studies on turbine mortality, migration delay, downstream passage, and sub-lethal effects.
- Evaluate and ultimately validate large-scale hydroacoustic methods to quantify river herring and American shad escapement in major river systems.
- Conduct studies of egg and larval survival and development.
- Conduct studies on energetics of feeding and spawning migrations of American shad on the Atlantic coast.
- Resource management agencies in each state shall evaluate their respective state water quality standards and criteria and identify hard limits to ensure that those standards,

[7] Genetic research currently underway in combination with otolith chemistry.
[8] River herring ageing workshop to occur in 2013.

criteria, and limits account for the special needs of alosines. Primary emphasis should be on locations where sensitive egg and larval stages are found.
- Encourage university research on hickory shad.
- Develop better fish culture techniques, marking techniques, and supplemental stocking strategies for river herring.

Low
- Characterize tributary habitat quality and quantity for Alosine reintroductions and fish passage development.
- States should identify and quantify potential shad and river herring spawning and nursery habitat not presently utilized, including a list of areas that would support such habitat if water quality and access were improved or created, and analyze the cost of recovery within those areas. States may wish to identify areas targeted for restoration as essential habitat.[11]
- Investigate contribution of landlocked versus anadromous produced river herring.

Additional Habitat Research Recommendations
- When considering options for restoring alosine habitat, include study of, and possible adjustment to, dam-related altered river flows.
- Ascertain how abundance and distribution of potential prey affect growth and mortality of early life stages of alosines.
- Determine factors that regulate and potentially limit downstream migration, seawater tolerance, and early ocean survival of juvenile alosines.
- Determine if chlorinated sewage effluents are slowing the recovery of depressed shad stocks.
- Determine if intermittent episodes of pH depressions and aluminum elevations (caused by acid rain) affect any life stage in freshwater that might lead to reduced reproductive success of alosines, especially in poorly buffered river systems.
- ASMFC should designate important shad and river herring spawning and nursery habitat as HAPC.[9]
- When populations have been extirpated from their habitat, coordinate alosine stocking programs, including: reintroduction to the historic spawning area, expansion of existing stock restoration programs, and initiation of new strategies to enhance depressed stocks.
- When releasing hatchery-reared larvae into river systems for purposes of restoring stocks, synchronize the release with periods of natural prey abundance to minimize mortality and maximize nutritional condition. Determine functional response of predators on larval shad at restoration sites to ascertain appropriate stocking level so that predation is accounted for, and juvenile out-migration goals are met. Also, determine if night stocking will reduce mortality.

---

[9] River-specific habitat recommendations for American shad can be found in: Atlantic States Marine Fisheries Commission. 2007. American shad stock assessment report for peer review, volumes II and III. Atlantic States Marine Fisheries Commission Stock Assessment Report No. 07-01 (Supplement), Washington, D.C.

Management, Law Enforcement, and Socioeconomic Priorities

High

- Develop and implement monitoring protocols and analyses to determine river herring and American shad population responses and targets for rivers and tributaries, particularly those undergoing restoration (passage, supplemental stocking, etc.).
- Determine the impact of directed fisheries on American shad and river herring stocks and reduce F.
- Mandate FMPs for rivers with active restoration plans for American shad or river herring.
- Improve spatial and gear specific reporting of harvest.

Low

- Conduct and evaluate historical characterization of socioeconomic development (potential pollutant sources and habitat modification) of selected shad rivers along the east coast.[5]
- Develop appropriate Habitat Suitability Index Models for alosine species in the fishery management plan. Possibly consider expansion of species of importance or go with the most protective criteria for the most susceptible species.

ATLANTIC CROAKER

Short-term

HIGH PRIORITY

- Increased observer coverage for commercial discards, particularly the shrimp trawl fishery. Develop a standardized, representative sampling protocol for collection of individual lengths and ages of discarded finfish.
- Describe the coast-wide distribution, behavior, and movement of croaker by age, length, and season, with emphasis on collecting larger, older fish.

MEDIUM PRIORITY

- Conduct studies of discard mortality for recreational and commercial fisheries by each gear type in regions where removals are highest.
- In the recreational fishery, develop sampling protocol for collecting lengths of discarded finfish and collect otolith age samples from retained fish.
- Encourage fishery-dependent biological sampling, with proportional landings representative of the distribution of the fisheries. Develop and communicate clear protocols on truly representative sampling.

Long-term

HIGH PRIORITY

- Continue state and multi-state fisheries-independent surveys throughout the species range and subsample for individual lengths and ages. Ensure NEFSC trawl survey continues to take lengths and ages. Examine potential factors affecting catchability in long-term fishery independent surveys.
- Quantify effects of BRDs and TEDs implementation in the shrimp trawl fishery by examining their relative catch reduction rates on Atlantic croaker.
- Continue to develop estimates of length-at-maturity and year-round reproductive dynamics throughout the species range. Assess whether temporal and/or density- dependent shifts in reproductive dynamics have occurred.
- Re-examine historical ichthyoplankton studies for an indication of the magnitude of estuarine and coastal spawning. Pursue specific estuarine data sets from the states (NJ, VA, NC, SC, DE, ME) and coastal data sets (MARMAP, EcoMon).

MEDIUM PRIORITY

- Investigate environmental covariates in stock assessment models, including climate cycles (e.g., Atlantic Multi-decadal Oscillation, AMO, and El Nino Southern Oscillation, El Nino) and recruitment and/or year class strength, spawning stock biomass, stock distribution, maturity schedules, and habitat degradation.
- Use NMFS Ecosystem Indicators bi-annual reports to consider folding indicators into the assessment; identify mechanisms for how environmental indicators affect the stock
- Encourage efforts to recover historical landings data, determine whether they are available at a finer scale for the earliest years than are currently reported.

- Collect data to develop gear-specific fishing effort estimates and investigate methods to develop historical estimates of effort.
- Develop gear selectivity studies for commercial fisheries with emphasis on age 1+ fish.
- Conduct studies to measure female reproductive output at size and age (fecundity, egg and larval quality) and impact on assessment models and biomass reference points
- Develop and implement sampling programs for state-specific commercial scrap and bait fisheries in order to monitor the relative importance of Atlantic croaker. Incorporate biological data collection into program.
- Investigate the relationship between estuarine nursery areas and their proportional contribution to adult biomass. I.e., are select nursery areas along Atlantic coast ultimately contributing more to SSB than others, reflecting better quality juvenile habitat?

ATLANTIC MENHADEN

Many of the research and modeling recommendations from the last benchmark stock assessment (SEDAR 2015)[10] remain relevant for this update stock assessment. Research recommendations are broken down into two categories: data and modeling. While all recommendations are high priority, the first recommendation is the highest priority. Each category is further broken down into recommendations that can be completed in the short term and recommendations that will require long term commitment. Notes have been added for this report regarding work that has been addressed or initiated since SEDAR 2015.

<u>Annual Data Collection</u>

Short-term (next 3-6 years):

1. Continue current level of sampling from bait fisheries, particularly in the Mid-Atlantic and New England. Analyze sampling adequacy of the reduction fishery and effectively sample areas outside of that fishery (e.g., work with industry and states to collect age structure data and biological data outside the range of the fishery). **NOTE**: Work to assess the sampling adequacy of the bait and reduction fisheries has been initiated by Genevieve Nesslage's research group at the University of Maryland Center for Environmental Science.
2. Ageing:
    a. Conduct ageing validation study (e.g., scale:otolith comparison), making sure to sample older age classes. Use archived scales to do radio isotope analysis.
    b. Ageing precision: conduct an ageing workshop to assess precision and error among readers (currently planned for January 2015). **NOTE**: A workshop was completed and described in ASMFC 2015[11] and Atlantic menhaden scales have been added to the annual ASMFC QA/QC Fish Ageing Workshop (ASMFC 2017)[12] to address an ongoing need for information on ageing precision and error.
3. Conduct a comprehensive fecundity study. **NOTE**: This work has been initiated and is ongoing with Rob Latour's research group at Virginia Institute of Marine Science.
4. Place observers on boats to collect at-sea samples from purse-seine sets, or collect samples at dockside during vessel pump-out operations (as opposed to current top of hold sampling) to address sampling adequacy.
5. Investigate relationship between fish size and school size in order to address selectivity (specifically addressing fisher behavior related to harvest of specific school sizes).
6. Investigate relationship between fish size and distance from shore (addressing selectivity).

---

[10] Southeast Data, Assessment, and Review (SEDAR). 2015. SEDAR 40 - Atlantic menhaden stock assessment report. SEDAR, North Charleston SC. 643 p.

[11] Atlantic States Marine Fisheries Commission (ASMFC). 2015. Atlantic Menhaden Ageing Workshop Report. ASMFC, Arlington, VA.

[12] Atlantic States Marine Fisheries Commission (ASMFC). 2017. Report of the Quality Assurance/Quality Control Fish Ageing Workshop. ASMFC, Arlington, VA.

7. Evaluate alternative fleet configurations for the removal and catch-at-age data.

Long-term (6+ years):

1. Develop a menhaden specific coastwide fishery-independent index of adult abundance at age. One possible methodology is an air spotter survey complemented with ground truthing for biological information (e.g., size and age composition). In all cases, a sound statistical design is essential (involving statisticians in the development and review of the design; some trial surveys may be necessary). **[Highest Priority] NOTE:** Design of a winter pelagic survey of adult Atlantic menhaden in the Mid-Atlantic has been initiated by Genevieve Nesslage's research group at the University of Maryland Center for Environmental Science.
2. Conduct studies on spatial and temporal dynamics of spawning (how often, how much of the year, batch spawning, etc.)
3. Conduct studies on productivity of estuarine environments related to recruitment. **NOTE**: Anstead et al. 2016[13] and 2017[14] used otolith chemistry to evaluate the proportional contribution of each nursery area along the US Atlantic coast for recruits for 2010-2012.
4. Investigation of environmental covariates related to recruitment. **NOTE**: Buchheister et al. 2016[15] evaluated coast wide recruitment patters from 1959-2013 and found the Atlantic Multidecal Oscillation was the best predictor of regional recruitment. Simpson et al. 2016[16] evaluated several environmental covariates for an effect on larval survival and found temperature had the greatest effect on early life survival which was more related to recruitment than larval supply.

<u>Assessment Methodology</u>

Short term (3-6 year):

1. Conduct management strategy evaluation (MSE). **[Highest Priority] NOTE:** This work has been initiated and is ongoing with Amy Schueller's research group at the Southeast Fisheries Science Center in Beaufort, North Carolina.
2. Conduct multi-objective decision analysis (MODA). **[Highest Priority] NOTE:** This will be addressed through the ongoing BERP WG activities.
3. Continue to develop an integrated length and age based model (e.g., SS3).
4. Continue to improve methods for incorporation of natural mortality (e.g., multi-species

---

[13] Anstead, K. A., J. J. Schaffler and C.M. Jones. 2016. Coast-wide nursery contribution of new recruits to the population of Atlantic Menhaden. Transactions of the American Fisheries Society, 145(3): 627-636.
[14] Anstead, K. A., J. J. Schaffler and C.M. Jones. 2017. Contribution of Nursery Areas to the Adult Population of Atlantic Menhaden. Transactions of the American Fisheries Society 146(1): 36-46.
[15] Buchheister, A., T. J. Miller, E. D. Houde, D. H. Secor, and R. J. Latour. 2016. Spatial and temporal dynamics of Atlantic menhaden (Brevoortia tyrannus) recruitment in the Northwest Atlantic Ocean. ICES Journal of Marine Science: Journal du Conseil, fsv260.
[16] Simpson, C. A., M. J. Wilberg, H. Bi, A. M. Schueller, G. M. Nesslage, and H. J. Walsh. 2016. Trends in Relative Abundance and Early Life Survival of Atlantic Menhaden during 1977–2013 from Long-Term Ichthyoplankton Programs. Transactions of the American Fisheries Society, 145(5): 1139-1151.

statistical catch-at-age model). **NOTE**: This work will be addressed by McNamee's doctoral thesis (*in prep*)[17] and through current BERP WG activities.

5. During the next benchmark stock assessment process (scheduled for 2019), the SAS recommends that the following items be considered during modeling workshops:
    a. Re-examine the methodology and surveys used for the development of the NAD index.
    b. Explore the likelihood component for the length composition data.
    c. Examine the age composition of the bait fishery.

Long term (6+ years):

1. Develop a seasonal spatially-explicit model, once sufficient age-specific data on movement rates of menhaden are available.

[17] McNamee, J. E. *in prep*. A Multispecies statistical catch-at-age (MSSCAA) model for a Mid-Atlantic species complex. Doctoral dissertation for University of Rhode Island.

ATLANTIC SEA HERRING

Fishery-Dependent Priorities

High

- Develop (simple) methods to partition stocks in mixed stock fisheries.
- Investigate bycatch and discards in the directed herring fishery through both at sea and portside sampling.
- Continue commercial catch sampling of Atlantic herring fisheries according to ACCSP protocols.

Fishery-Independent Priorities

High

- Conduct more extensive stock composition sampling including all stocks (i.e., Scotian Shelf).
- Expand monitoring of spawning components.

Low

- Continue to utilize the inshore and offshore hydroacoustic and trawl surveys to provide an independent means of estimating stock sizes. Collaborative work between NMFS, DFO, state agencies, and the herring industry on acoustic surveys for herring should continue to be encouraged.
- Consider alternative sampling methods such as HabCam.

Modeling / Quantitative Priorities

High

- Evaluate use of length based models (Stock Synthesis and Chen model).
- Develop statistical comparison of consumption estimates and biomass from model M.

Moderate

- Develop indices at age from shrimp survey samples.
- Conduct simulation studies to evaluate ways in which various time series can be evaluated and folded into the assessment model.
- Develop new approaches to estimating recruitment (i.e., juvenile abundance) from fishery-independent data.
- Examine the possible effects of density dependence (e.g., reduced growth rates at high population size) on parameter estimates used in assessments.

Low

- Develop an industry based LPUE or some other abundance index (Industry Based Survey).
- Conduct a retrospective analysis of herring larval and assessment data to determine the role larval data plays in anticipating stock collapse and as a tuning index in the age structured assessment.
- Investigate the M rate assumed for all ages, the use of CPUE tuning indices, and the use of NEFSC fall bottom trawl survey tuning indices in the analytical assessment of herring.
- Develop objective criteria for inclusion of novel data streams (consumption, acoustic, larval, etc.) and how this can be applied.

Life History, Biological, and Habitat Priorities

High

- Consider information on consumption from other sources (i.e. striped bass in other areas) and predators inshore of the current surveys.

Moderate

- Continue tagging and morphometric studies to explore uncertainties in stock structure and the impacts of harvest mortality on different components of the stock. Although tagging studies may be problematic for assessing survivorship for a species like herring, they may be helpful in identifying the stock components and the proportion of these components taken in the fishery on a seasonal basis.
- Analyze diet composition of archived mammal and sea bird stomachs. Improve knowledge on prey size selectivity of mammals and sea birds.
- Evaluate prey field to determine what other prey species are available to predators that could explain some of the annual trends in herring consumption.
- Investigate why small herring are not found in the stomachs of predators in the NEFSC food habits database.

Low

- Research depth preferences of herring.

Management, Law Enforcement, and Socioeconomic Priorities

High

- Evaluate the current herring spawning closure design in terms of areas covered, closure periods, catch-at-age within (before fishing prohibition in 2007) and outside of spawning areas to determine minimal spawning regulations (Maine DMR).
- Continue to organize annual US-Canadian workshops to coordinate stock assessment activities and optimize cooperation in management approaches between the two countries.

Moderate

- Develop a strategy for assessing individual spawning components to better manage heavily exploited portion(s) of the stock complex, particularly the Gulf of Maine inshore spawning component.
- Develop socioeconomic analyses appropriate to the determination of optimum yield.

Low

- Develop economic analyses necessary to evaluate the costs and benefits associated with different segments of the industry.

ATLANTIC STRIPED BASS

Fishery-Dependent Priorities

High

- Continue collection of paired scale and otolith samples, particularly from larger striped bass, to facilitate development of otolith-based age-length keys and scale-otolith conversion matrices.

Moderate

- Develop studies to provide information on gear specific discard morality rates and to determine the magnitude of bycatch mortality.[18]
- Improve estimates of striped bass harvest removals in coastal areas during wave 1 and inland waters of all jurisdictions year round.
- Evaluate the percentage of fishermen using circle hooks.[19]

Fishery-Independent Priorities

Moderate

- Develop a refined and cost-efficient, fisheries-independent coastal population index for striped bass stocks.

Modeling / Quantitative Priorities

High

- Develop a method to integrate catch-at-age and tagging models to produce a single estimate of F and stock status.[20]
- Develop a spatially and temporally explicit catch-at-age model incorporating tag based movement information.[21]
- Develop a fully sex-disaggregated model that accounts for differences in survivorship and growth.
- Review model averaging approach to estimate annual fishing mortality with tag based models. Review validity and sensitivity to year groupings.[22]
- Develop methods for combining tag results from programs releasing fish from different areas on different dates.
- Examine potential biases associated with the number of tagged individuals, such as gear specific mortality (associated with trawls, pound nets, gill nets, and electrofishing), tag induced mortality, and tag loss.[23]

---

[18] Literature search and some modeling work completed.

[19] Work ongoing in New York through the Hudson River Angler Diary, Striped Bass Cooperative Angler Program, and ACCSP elogbook.

[20] Model developed, but the tagging data overwhelms the model. Issues remain with proper weighting.

[21] Model developed with Chesapeake Bay and the rest of the coast as two fleets. However, no tagging data has been used in the model.

[22] Work ongoing by Striped Bass Tagging Subcommittee to evaluate the best years to use for the IRCR and the periods to use for the MARK models.

[23] Gear specific survival being examined in Hudson River.

- Develop field or modeling studies to aid in estimation of natural mortality or other factors affecting the tag return rate.

Moderate

- Explore issues related to exploitation rate and management targets surrounding sexually differentiated migration, possibly through a two-area simulation model.
- Develop maturity ogives applicable to coastal migratory stocks.
- Examine methods to estimate annual variation in natural mortality.[24]
- Develop reliable estimates of poaching loss from striped bass fisheries.
- Improve methods for determining population sex ratio for use in estimates of SSB and biological reference points.
- Evaluate truncated matrices and covariate based tagging models.

Low

- Examine issues with time saturated tagging models for the 18 inch length group.
- Develop tag based reference points.

Life History, Biological, and Habitat Priorities

High

- Continue in-depth analysis of migrations, stock compositions, etc. using mark-recapture data.[25]
- Continue evaluation of striped bass dietary needs and relation to health condition.[26]
- Continue analysis to determine linkages between the mycobacteriosis outbreak in Chesapeake Bay and sex ratio of Chesapeake spawning stock, Chesapeake juvenile production, and recruitment success into coastal fisheries.

Moderate

- Examine causes of different tag based survival estimates among programs estimating similar segments of the population.
- Continue to conduct research to determine limiting factors affecting recruitment and possible density implications.
- Conduct study to calculate the emigration rates from producer areas now that population levels are high and conduct multi-year study to determine inter-annual variation in emigration rates.

Low

- Determine inherent viability of eggs and larvae.
- Conduct additional research to determine the pathogenicity of the IPN virus isolated from striped bass to other warm water marine species, such as flounder, menhaden, shad, and largemouth bass.

---

[24] Ongoing work by the Striped Bass Tagging Subcommittee

[25] Ongoing through Cooperative Winter Tagging Cruise and striped bass charter boat tagging trips. See Cooperative Winter Tagging Cruise 20 Year Report.

[26] Plans for a stomach content collection program in the Chesapeake Bay by the Chesapeake Bay Ecological Foundation.

Additional Habitat Research Recommendations

- Passage facilities should be designed specifically for passing striped bass for optimum efficiency at passing this species.
- Conduct studies to determine whether passing migrating adults upstream earlier in the year in some rivers would increase striped bass production and larval survival, and opening downstream bypass facilities sooner would reduce mortality of early emigrants (both adult and early-hatched juveniles).
- All state and federal agencies responsible for reviewing impact statements and permit applications for projects or facilities proposed for striped bass spawning and nursery areas shall ensure that those projects will have no or only minimal impact on local stocks, especially natal rivers of stocks considered depressed or undergoing restoration.[27]
- Federal and state fishery management agencies should take steps to limit the introduction of compounds which are known to be accumulated in striped bass tissues and which pose a threat to human health or striped bass health.
- Every effort should be made to eliminate existing contaminants from striped bass habitats where a documented adverse impact occurs.
- Water quality criteria for striped bass spawning and nursery areas should be established, or existing criteria should be upgraded to levels that are sufficient to ensure successful striped bass reproduction.
- Each state should implement protection for the striped bass habitat within its jurisdiction to ensure the sustainability of that portion of the migratory stock. Such a program should include: inventory of historical habitats, identification of habitats presently used, specification of areas targeted for restoration, and imposition or encouragement of measures to retain or increase the quantity and quality of striped bass essential habitats.
- States in which striped bass spawning occurs should make every effort to declare striped bass spawning and nursery areas to be in need of special protection; such declaration should be accompanied by requirements of non-degradation of habitat quality, including minimization of non-point source runoff, prevention of significant increases in contaminant loadings, and prevention of the introduction of any new categories of contaminants into the area. For those agencies without water quality regulatory authority, protocols and schedules for providing input on water quality regulations to the responsible agency should be identified or created, to ensure that water quality needs of striped bass stocks are met.[28]
- ASMFC should designate important habitats for striped bass spawning and nursery areas as HAPC.
- Each state should survey existing literature and data to determine the historical extent of striped bass occurrence and use within its jurisdiction. An assessment should be conducted of those areas not presently used for which restoration is feasible.

[27] Ongoing in New York.

[28] Significant habitat designations completed in the Hudson River and New York Marine Districts.

Management, Law Enforcement, and Socioeconomic Priorities
Moderate

- Examine the potential public health trade-offs between the continued reliance on the use of high minimum size limits (28 inches) on coastal recreational anglers and its long-term effects on enhanced PCB contamination among recreational stakeholders.[29]

[29] Samples collected from two size groups ($\geq$ 28 inches and 20-26 inches) in Pennsylvania and processed by the Department of Environmental Protection to compare contamination of the two size groups.

ATLANTIC STURGEON

Benchmark Assessment Recommendations (TC/SAS)

Research recommendations have been categorized as future research, data collection, and assessment methodology and ranked as high or moderate priority. Recommendations with asterisks (**) indicate improvements that should be made before initiating another benchmark stock assessment.

Future Research

High Priority

- Identify spawning units along the Atlantic coast at the river or tributary and coastwide level.
- **Expand and improve the genetic stock definitions of Atlantic sturgeon, including developing an updated genetic baseline sample collection at the coastwide, DPS, and river-specific level for Atlantic sturgeon, with the consideration of spawning season-specific data collection.
- Determine habitat use by life history stage including adult staging, spawning, and early juvenile residency.
- Expand the understanding of migratory ingress of spawning adults and egress of adults and juveniles along the coast.
- Identify Atlantic sturgeon spawning habit through the collection of eggs or larvae.
- Investigate the influence of warming water temperatures on Atlantic sturgeon, including the effects on movement, spawning, and survival.

Moderate Priority

- Evaluate the effects of predation on Atlantic sturgeon by invasive species (e.g., blue and flathead catfish).

Data Collection

High Priority

- **Establish regional (river or DPS-specific) fishery-independent surveys to monitor Atlantic sturgeon abundance or expand existing regional surveys to include annual Atlantic sturgeon monitoring. Estimates of abundance should be for both spawning adults and early juveniles at age. See Table 8 in the Assessment Report[30] for a list of surveys considered by the SAS.
- **Establish coastwide fishery-independent surveys to monitor Atlantic sturgeon mixed stock abundance or expand existing surveys to include annual Atlantic sturgeon monitoring. See Table 8 in the Assessment Report for a list of surveys considered by the SAS.
- **Continue to collect biological data, PIT tag information, and genetic samples from Atlantic sturgeon encountered on surveys that require it (e.g., NEAMAP). Consider including this level of data collection from surveys that do not require it.
- **Encourage data sharing of acoustic tagged fish, particularly in underrepresented DPSs, and support programs that provide a data sharing platform such as The Atlantic Cooperative

[30] Atlantic States Marine Fisheries Commission. 2017. Atlantic Sturgeon Benchmark Stock Assessment and Peer Review Report. ASMFC, Arlington, VA. 456pp.

Telemetry Network. Data sharing would be accelerated if it was required or encouraged by funding agencies.
- **Maintain and support current networks of acoustic receivers and acoustic tagging programs to improve the estimates of total mortality. Expand these programs in underrepresented DPSs.
- **Collect DPS-specific age, growth, fecundity, and maturity information.
- **Collect more information on regional vessel strike occurrences, including mortality estimates. Identify hot spots for vessel strikes and develop strategies to minimize impacts on Atlantic sturgeon.
- **Monitor bycatch and bycatch mortality at the coastwide level, including international fisheries where appropriate (i.e., the Canadian weir fishery). Include data on fish size, health condition at capture, and number of fish captured.

Assessment Methodology

High Priority

- **Establish recovery goals for Atlantic sturgeon to measure progress of and improvement in the population since the moratorium and ESA listing.
- **Expand the acoustic tagging model to obtain abundance estimates and incorporate movement.

Moderate Priority

- Evaluate methods of imputation to extend time series with missing values. ARIMA models were applied only to the contiguous years of surveys due to the sensitivity of model results to missing years observed during exploratory analyses.

Peer Review Recommendations (Review Panel)

In general, the Review Panel agrees with the research recommendations and priorities developed by the Atlantic sturgeon Technical Committee (see Assessment Report, Section 8, pp. 107-109). Currently there are severe data limitations restricting the type, scope, and usefulness of assessment methodologies that can be applied to Atlantic sturgeon. Most importantly, there is an incomplete accounting for temporal and spatial variability in life-history parameters, an imperfect understanding of the temporal and spatial organization of reproductively discrete spawning populations, and major uncertainties in the scope for direct harm arising from interaction with ongoing human activities (e.g., bycatch, ship strikes) to the recovery of Atlantic sturgeon. To assist in identifying areas with significant data gaps, the Review Panel created a data gaps table (Table 3 in the Peer Review Report) based on the current Atlantic sturgeon assessment report.

The Review Panel provides the following suggested changes to existing research priorities, as well as a set of new research recommendations that are critical to advancing Atlantic sturgeon science, modeling, and future stock assessments.

Future Research

High Priority

- Develop standardized methods that can be used to create reliable indices of abundance for adults and young juveniles (Age 1) to reflect the status of individual DPSs
    - A workshop is recommended to assess the efficacy of existing 'sturgeon surveys' (e.g., those presently conducted in NY, SC) and new approaches
- Expand and improve the genetic stock definitions of Atlantic sturgeon, including the continued development of genetic baselines that can be applied coastwide, within- and among-DPS's, and at the river-specific level. Consideration of spawning season-specific data collection will be required. Particular emphasis should be placed on collecting additional information from the Gulf of Maine and Carolina DPSs (Table 3).

Moderate Priority

- Determine a permitting process to enable authorizations to sample and collect biological materials from any dead Atlantic sturgeon encountered
    - Pectoral fin spines to support age determination are considered to be of high value
    - Additional materials could include gonad tissues to support development of maturation schedules for males and females and fecundity
- Evaluate potential reference point targets and their efficacy for Atlantic sturgeon. Options include (but are not limited too):
    - number of fish in spawning runs
    - number of rivers with sturgeon presence/absence (by DPS and coastwide)
    - frequency of catch in indices and/or observer sampling
    - evaluate rivers where you don't have sturgeon, setting minimum bar
- Determine freshwater, estuarine, and ocean habitat use by life history stage including adult staging, spawning, small and large juvenile residency, and larvae
- Identify spawning units, using appropriate techniques (genetics, tagging, eDNA, collections of eggs or larvae, etc.), along the Atlantic coast that best characterize the meta-population structure of U.S. Atlantic sturgeon
    - Recent search efforts both in previously un-sampled rivers/tributaries and rivers thought to have lost their native populations have revealed evidence of spawning activity that results in the production of young juveniles. Such instances require particular attention to determine whether they are the result of reproduction by self-sustaining populations
- Investigate the influence of warming water temperatures on Atlantic sturgeon, including the effects on movement, spawning, and survival

Low Priority

- Evaluate incidence of and the effects of predation on Atlantic sturgeon

Data Collection

High Priority

- Establish centralized data management and data sharing protocols and policies to promote greater use of all available Atlantic sturgeon data. Priority data sets include (but are not limited to):
    - genetics/tissue samples
    - pectoral fin spines and associated age estimates
    - acoustic tagging and hydrophone metadata
    - external and PIT tag data

  Emphasis should be placed on extracting all available data in underrepresented DPSs. Concurrently, continue to support programs that provide data sharing platforms such as the Atlantic Cooperative Telemetry Network. These initiatives will benefit from the support of federal funding agencies enforcing the requirement to make data collected via federal funds part of the public record within a reasonable period of time. If not a current requirement of funded Atlantic sturgeon research, this should become a requirement.

- Implement directed monitoring of Atlantic sturgeon that is designed to support assessments both coastwide and at the DPS level and/or expand existing regional surveys to include annual Atlantic sturgeon monitoring. Monitoring two or more reproductively discrete populations within each recognized DPS is suggested. Use of emergent technologies such as validated side scan sonar surveys and acoustic tracking may allow for more cost effective monitoring of river runs.
    - Monitoring protocols that enable data gathering for a number of species (e.g., Shortnose sturgeon) is encouraged
    - Development of adult, YOY (or Age 1), and juvenile indices are a high priority, and considerations should be made for the use of appropriate survey gears
        - Associated length and age composition information is needed so that relative abundance-at-age information can be obtained from the adult and juvenile indices
    - See Table 8 in the assessment report for a list of surveys considered by the SAS during the assessment
    - See Table 3 of the review report to see current data gaps identified by the Review Panel
- Continue to collect biological data, PIT tag information, and genetic samples from Atlantic sturgeon encountered on surveys that require it (e.g., NEAMAP). Consider including this level of data collection from surveys that do not require it. Push permitting agencies to allow sampling (to the extent possible) of all encountered Atlantic sturgeon via scientific research activities.
- Maintain and support current networks of acoustic receivers and acoustic tagging programs to improve the estimates of total mortality. Expand these programs in underrepresented DPSs, using a power analysis to define direction and magnitude of expansion, as required to support next assessment.

- Collect sub-population specific (river, tributary, or DPS level) life history information (e.g., age, growth, fecundity, maturity, spawning frequency). Where feasible, emphasis should be on collecting information by sex and for reproductive information by size/age. Particular focus should be on collecting information on Atlantic sturgeon from the South Atlantic DPS given less data and suspected regional life history differences (see Table 3).
- Improve monitoring of bycatch in other fisheries, gears, and locations (notably northern and southern range). When scaling up to unobserved trips, need better data/measures of effective effort that can be reasonably expected to encounter Atlantic sturgeon. This may include collection of more detailed information on type of gear deployed, locations of deployment, etc. To assess the potential for currently missing significant sources of Atlantic sturgeon bycatch, do a simple query of all observed fisheries to see if Atlantic sturgeon are encountered in other gears beyond gillnet and trawl (e.g., scallop dredges)
- Investigate and account for extra-jurisdictional sources of mortality. Include data on fish size, health condition, and number of fish affected.

Moderate Priority

- Collect more information on regional vessel strike occurrences, including mortality estimates. Identify hot spots for vessel strikes and develop strategies to minimize impacts on Atlantic sturgeon.
- Promote greater Canadian-US Atlantic sturgeon data sharing, cooperative research, and monitoring. Exploring interactions between Canadian and US Atlantic sturgeon may more fully explain mortality trends, particularly with regards to the Gulf of Maine DPS.

Assessment Methodology

High Priority

- Establish recovery goals and risk tolerance for Atlantic sturgeon to measure progress of and improvement in the population since the moratorium and ESA listing
- Expand the acoustic tagging model to incorporate movement
- Conduct a power analysis to determine sufficient acoustic tagging sampling sizes by DPS

Moderate Priority

- Evaluate methods of imputation to extend time series with missing values. ARIMA models were applied only to the contiguous years of surveys due to the sensitivity of model results to missing years observed during exploratory analyses.
- Explore feasibility of combining telemetry tagging and sonar/acoustics monitoring to generate abundance estimate

BLACK DRUM

HIGH PRIORITY

- Age otoliths that have been collected and archived.
- Collect information to characterize the size composition of fish discarded in recreational fisheries.
- Collect information on the magnitude and sizes of commercial discards. Obtain better estimates of bycatch of black drum in other fisheries, especially juvenile fish in south Atlantic states.
- Increase biological sampling in commercial fisheries to better characterize the size and age composition of commercial fisheries by state and gear.
- Increase biological sampling in recreational fisheries to better characterize the size and age composition by state and wave.
- Obtain estimates of selectivity-at-age for commercial fisheries by gear, recreational harvest, and recreational discards.
- Continue all current fishery-independent surveys and collect biological samples for black drum on all surveys.
- Develop fishery-independent adult surveys. Consider long line and purse seine surveys. Collect age samples, especially in states where maximum size regulations preclude the collection of adequate adult ages.
- Develop a protocol to alert the SASC to any major changes in harvest and F that could trigger a reassessment of the reference points similar to the 'rumble strips' approach developed by the MAFMC for data-poor stocks.
- Increase age sampling along the coast. Juvenescence of the population is a good indicator of overfishing, and the availability of age data is crucial to being alerted to such changes in age structure.
- Indices, such as the South Carolina trammel net survey, could be used directly in an extended version of DB-SRA. The implementation of xDB-SRA could instead specify stock status at an earlier time period, thus allowing the most recent catches to inform population dynamics and thus stock status.

MODERATE PRIORITY

- Conduct reproductive studies, including: age and size-specific fecundity, spawning frequency, spawning behaviors by region, and movement and site fidelity of spawning adults.
- Conduct a high reward tagging program to obtain improved return rate estimates. Continue and expand current tagging programs to obtain mortality and growth information and movement at size data.
- Improve sampling of night time fisheries.
- Conduct studies to estimate catch and release mortality rates in recreational fisheries.

- Collect genetic material (i.e., create “genetic tags”) over a long time span to obtain information on movement and population structure, and potentially estimate population size.
- Obtain better estimates of harvest from the black drum recreational fishery (especially in states with short seasons).

BLACK SEA BASS

Fishery-Dependent Priorities
High
- Increase sampling of commercial landings.
- Increase sample size of at sea observers and dockside validation for headboats. Increase recreational fisheries sampling.
- Determine depth, temperature, and season specific discard mortality rates. Assess and incorporate the impact of circle hook fishing regulations on discard mortality. Obtain more depth specific information from the private recreational fleet, MRIP At-Sea observer program, and Headboat Survey in the range of the southern stock.

Moderate
- Collect better spatial information in black sea bass fisheries to determine potential localized depletion effects.

Low
- Determine the impact/landings of the historical foreign fleet in the South Atlantic.

Additional Fishery-Dependent Priorities
- Develop hard part sampling coordinated with intercept surveys.
- Expand electronic reporting of headboat logbook for full implementation.

Fishery-Independent Priorities
High
- Conduct a pot survey throughout the range of the northern management unit and consider for an index of abundance.[31]
- Expand fishery-independent surveys to sample all sizes and age classes to develop more reliable catch-at-age and CPUE.
- Expand sampling to cover the entire range of the southern stock over a longer time period.

Additional Fishery-Independent Priorities
- Conduct at sea sex sampling to determine trend of sex change timing and assess the potential influence of population size on sex switching.[32]

Modeling / Quantitative Priorities
High
- Investigate the effect of sex transition rates, sex ratio, and differential M by sex on the calculations of SSB per recruit and eggs per recruit.

Moderate
- Explore alternative assessment models, including non-age based alternatives.

Additional Modeling / Quantitative Priorities
- Continue development of a standardized method for calculating incomplete weight data.

---

[31] A pilot project is ongoing and proposals are being considered for funding to expand the program.
[32] The NEFSC and UMass-Dartmouth are working on trends in sex change timing for the northern stock and UNC-Wilmington is working on the same for the southern stock.

- Further develop the tagging model described by Rudershausen et al. (2010) to address the assumptions of the model.

Life History, Biological, and Habitat Priorities

High

- Analyze size or age specific spawning frequency and seasonality.
- Investigate the movement and migrations of black sea bass using otolith microchemistry, genetic studies, and expanding tagging studies.
- Conduct meta-analysis of patterns of M in protogynous fishes, specifically black sea bass. Determine sex specific mortality rates and growth rates.
- Determine the implications of removing large males on population dynamics through field studies or large scale mesocosm experiments.
- Conduct studies on the efficacy of recompression techniques such as venting to reduce discard mortality.
- Study the movement and mixing of larval and juvenile black sea bass in the southern stock.

Moderate

- Further delineate essential fish habitat (EFH), particularly in nursery areas. Further investigate possible gear impacts on EFH.
- Identify transport mechanisms or behaviors that transport early juvenile black sea bass into estuaries.
- Evaluate overwintering habitat of all black sea bass life stages.
- Evaluate feeding of black sea bass larvae and overwintering adults.
- Develop mariculture techniques.

Low

- Conduct studies determining the value of artificial reefs for increased production of black sea bass to improve potential yield estimates.

Additional Life History, Biological, and Habitat Priorities

- Continue ageing studies to provide a foundation for an age based assessment. Compare scale to otolith age estimates.
- Conduct ageing validation studies to examine the implications of sex change, as well as temperature and salinity changes associated with movement onshore and offshore, on ageing reliability.
- Continue genetics work to determine potential stock delineation in the northern range.

Management, Law Enforcement, and Socioeconomic Priorities

- Evaluate the potential influence of non-compliance on high assumed M.
- Analyze logbook programs to determine current compliance and develop recommendations for improving compliance (i.e., increased education on the effect of not reporting accurately).
- Continue evaluation of methodology for mandatory reporting in the For-hire sector (e.g., Gulf MRIP Pilot).

BLUEFISH

Fishery-Dependent Priorities
High

- Evaluate magnitude and length frequency of discards from the commercial and recreational fisheries.
- Increase sampling of size and age composition of the fisheries by gear type and statistical area.[33]
- Target commercial (especially in the northeast region) and recreational landings for biological data collection and increase intensity of sampling when possible.
- Investigate species associations with recreational angler trips targeting bluefish (on a regional and seasonal basis) to accurately estimate effort for of the MRIP index (reduce risk of hyperstability)
- Determine whether NC scale data from 1985-1995 are available for age determination; if available, re-age based on protocols outlined in ASMFC (2011).

Fishery-Independent Priorities
High

- Develop additional adult bluefish indices of abundance (e.g., broad spatial scale longline survey or gillnet survey) to adequately characterize dynamics of older fish that are currently not well sampled by fishery independent trawl surveys.
- Expand age structure of SEAMAP index; currently, the SEAMAP index used in the assessment indexes age 0 abundance only, but recent age data from SEAMAP suggests collection of age 1 and 2 fish that would help inform the south Atlantic bight age structure

Modeling / Quantitative Priorities
Moderate

- Continue to examine alternative models that take advantage of length-based assessment frameworks.
- Evaluate the source of bimodal length frequency in the catch (e.g., migration, differential growth rates).
- Modify thermal niche model to incorporate water temperature data more appropriate for bluefish in a timelier manner [e.g., sea surface temperature data & temperature data that cover the full range of bluefish habitat (SAB and estuaries)].

Life History, Biological, and Habitat Priorities
Moderate

[33] A biological sampling program has been implemented for states that accounted for >5% of the coast wide bluefish harvest between 1998 and 2008. See Addendum 1 to Amendment 1 of the ASMFC Bluefish FMP.

- Explore age- and time-varying natural mortality from, for example, predator prey relationships; quantify effects of age- and time-varying natural mortality in the assessment model.
- Continue to evaluate the spatial, temporal, and sector-specific trends in bluefish growth and quantify their effects in the assessment model to address the appropriateness of pooling age data spatially (and temporally) and to identify potential changes to improve the efficiency of the biological collection program

Low

- Continue work on catch and release mortality.[34]
- Further evaluate the relationship between environmental factors (temperature, salinity etc.) and coastwide bluefish distribution.

---

[34] Some work completed, see: Fabrizio, et al. 2008. Factors affecting catch-and-release mortality of bluefish. *North American Journal of Fisheries Management* 28:533-546.

COASTAL SHARKS

- More research is necessary on review/improvement/development of shrimp bycatch estimation models for both data-poor and data-rich species
- More research is necessary on integration of various local abundance indices into a global abundance index based on spatio-temporal, physical-biological characteristics and variability.

Previous Research Recommendations for All Coastal Sharks

Fishery-Dependent Priorities

High

- Initiate or expand dockside sampling for sharks to verify landings information and species composition.

Moderate

- The Atlantic menhaden fishery data should be examined to determine shark bycatch estimates, if available.
- Conduct additional length sampling and age composition collection to improve information for developing selectivities.
- Shrimp trawl observer coverage should be expanded to 2 to 5% of total effort, particularly during periods of regulatory or gear changes. The observer coverage program should strive for even spatial coverage (particularly adding more south Atlantic coverage), randomness in vessel selection and full identification of elasmobranch species (continuing on from the 2009 Bycatch Characterization Protocol).
- Increase research on post-release survivorship of all shark species by gear type.
- Continue to acquire better species specific landings information on number of species, by weight, from dealers.[35]

Fishery-Independent Priorities

High

- Investigate the appropriateness of using vertebrae for ageing adult sandbar sharks. If appropriate, implement a systematic sampling program that gathers vertebral samples from entire size range for annual ageing to allow tracking the age distribution of the catch as well as updating of age-length keys.[36]

Moderate

- Develop a fishery-independent porbeagle shark survey to provide additional size composition and catch rate data to calculate an index of abundance.

---

[35] All dealers must report landings by species.

[36] Recent bomb radiocarbon research has indicated that past age estimates based on tagging data for sandbar sharks may be correct and that vertebral ageing may not be the most reliable method for mature individuals. See Andrews et al. 2011.

- Develop a stock wide fishery-independent monitoring program in state coastal waters for dusky sharks that includes annual samples of length and age frequencies.

Modeling / Quantitative Priorities

High

- Explore modeling approaches that do not require an assumption that the population is at virgin level at some point in time.

Moderate

- Develop empirically based estimates of natural mortality.
- Explore alternative approaches to age-length keys for estimating age from length.
- Improve estimates of removals by identifying and incorporating the sources of uncertainty (species misidentification, non-reporting).
- Quantify the uncertainty in time series of catch data.
- Perform exploratory analyses with CPUE indices to identify indices that contribute the most information on stock trends.
- Conduct simulation tests (management strategy evaluation) to assess the performance of alternative assessment methods (including the catch-free model, ASPM, ASPIC, SS, or stock specific models), recruitment parameterizations, harvest control rules, assessment frequency and data collection.
- Develop a two sex model for more direct estimation of the dusky and blacknose shark spawning stocks.
- Explore alternative modeling approaches in the presence of uncertain reproductive information that model reproduction as a function of the number of mature females. Integrate uncertainty in the reproductive frequency, fecundity, and pup-survival into a single parameter (the slope at the origin of the stock-recruit function) and incorporate this uncertainty via priors on the parameter.

Low

- Conduct sensitivity analyses to determine if discard survival estimates have a significant impact on the estimated status of the dusky and blacknose shark stocks in relation to MSY reference points.
- Develop a set of indicators (age-structure, total mortality estimates from catch curves, changes in abundance indices values) to determine whether dusky shark stock status has changed sufficiently to warrant a full assessment.

Life History, Biological, and Habitat Priorities

High

- Re-evaluate finetooth life history in the Atlantic Ocean in order to validate fecundity and reproductive periodicity.[37]
- Develop and conduct tagging studies on dusky and blacknose stock structure with increased international collaboration (e.g., Mexico) to ensure wider distribution and returns of tags.

[37] Work by Frazier, Belcher, and Gelsleichter is underway.

Expand research efforts directed towards tagging of individuals in south Florida and Texas/Mexico border to get better data discerning potential stock mixing.

- Examine female sharks during the spawning periods to determine the proportion of spawning females.[38]

Moderate

- Continue life history studies for all species of the shark complex to allow for additional species specific assessments. Particularly, natural mortality, age, fecundity, and reproductive frequency. Update age, growth, and reproductive studies of blacknose sharks, with emphasis on smaller individuals in the Atlantic and larger individuals in the Gulf of Mexico.
- Coordinate a biological study for Atlantic sharpnose so that samples are made at least monthly, and, within each month, samples would be made consistently at distinct geographic locations. For example, sampling locations would be defined in the northern Gulf, west coast of Florida, the Florida Keys (where temperature is expected to be fairly constant over all seasons), and also several locations in the South Atlantic, including the east coast of Florida, Georgia, South Carolina, and North Carolina. This same sampling design could be applied to all small coastal sharks.
- Population level genetic studies are needed that could lend support to arguments for stock discriminations using new loci and/or methodology that has increased levels of sensitivity.

Low

- Determine what is missing in terms of experimental design and/or data analysis to arrive at incontrovertible (to the extent that it may be scientifically possible) conclusions on the reproductive periodicity of the sandbar shark stock.

Management, Law Enforcement, and Socioeconomic Priorities

High

- Conduct species specific assessments for all shark species, with a priority for smooth dogfish.

[38] Biological information indicates that females of some shark species spawn less often then annually.

COBIA (ATLANTIC MIGRATORY GROUP)

Life History

- The Life History Work Group recommends implementation of a tagging study along the entire east coast of Florida and the evaluation of genetic samples from the same to determine more precise stock boundaries.
- Recommend developing a tagging program for inshore and offshore South Atlantic cobia populations. The goal would be to deploy tags inshore during the spring migration and offshore during the fall and winter to get a clearer picture of fall and spring migrations and to better identify spawning areas and aggregations.
- Explore the feasibility of satellite tags for cobia movement studies.
- Provide genetic sampling kits to interested groups to better understand the stock division line between the Gulf and Atlantic cobia stocks. Possible collectors of genetic samples could include Charter operators, fishing clubs and state fisheries personnel.
- Further research is needed on cobia and Spanish mackerel release mortality.
- To increase the overall amount of data available on Cobia, it is recommended that port samplers do complete workups when sampling, including otolith removal for aging, length, weight, sex, genetic sampling and record a catch location.

Commercial

- Although under the category of research recommendations, this list is not research per se, but rather suggestions to improve data collection. The first three recommendations were modified from the SEDAR17 DW report.
    - Need to expand observer coverage
    - Expand TIP sampling to better cover all statistical strata
    - Trade off with lengths versus ages, need for more ages (i.e., hard parts)
    - Consider the use of VMS to improve spatial resolution of data
    - During discussions at the data workshop it was noted that the logbook categories for discards (all dead, majority dead, majority alive, all alive) are not useful for informing discard mortality. Consider simplified logbook language in regard to discards (e.g., list them as dead or alive)
    - Uniformity between state and federal reporting systems/forms would vastly improve the ease and efficiency of data compilation.
    - Establish online reporting and use logbooks as a backup.
    - Establish a mechanism for identifying age samples that were collected by length or market categories, so as to better address any potential bias in age compositions.
    - Compiling commercial data is surprisingly complex. As this is the 28th SEDAR, one might expect that many of the complications would have been resolved by now through better coordination among NMFS, ACCSP, and the states. Increased attention should be given toward the goal of "one-stop shopping" for commercial data.

Recreational Statistics

- Increase proportion of fish with biological data within MRFSS sampling.
- Continue to develop methods to collect a higher degree of information on released fish (length, condition, etc.) in the recreational fishery.
- Require mandatory reporting for all charter boats state and federal.
- Continue development of electronic mandatory reporting for for-hire sector.
- Continued research efforts to incorporate/require logbook reporting from recreational anglers.
- Establish a review panel to evaluate methods for reconstructing historical landings (SWAS, FWS, etc.).
- Quantify historical fishing photos for use in reconstructing recreational historical landings.
- Narrow down the sampling universe. Identify angler preference and effort. Require a reef fish stamp for anglers targeting reef fish, pelagic stamp for migratory species, and deepwater complex stamp for deep-water species. The program would be similar to the federal duck stamp required of hunters. This would allow the managers to identify what anglers were fishing for.
- 9) Continue and expand fishery dependent at-sea-observer surveys to collect discard information, which would provide for a more accurate index of abundance.

Indices

- Explore SEFIS video data as a potential fishery independent index of abundance for cobia
- Using simulation analysis, evaluate the utility of including interaction terms in the development of a standardized index and identify the potential effects these interaction terms have on stock assessments

HORSESHOE CRAB

Fishery-Dependent Priorities

Moderate

- Characterize the proportion of states' landings that comprise crabs of Delaware Bay origin. This can be done through a directed tag/release study, genetics/microchemistry study, or both.
- Improve measures to characterize landings and bycatch in the commercial fisheries by life stage.
- Estimate fishing discard numbers and associated mortality rates.
- Investigate supplemental bait and alternative trap designs to reduce the commercial fisheries need for horseshoe crabs.

Fishery-Independent Priorities

High

- Expand or implement fishery-independent surveys (e.g., spawning, benthic trawl, tagging) to target horseshoe crabs throughout their full range including estuaries. Highest priority should be given to implementing directed surveys in the New England and New York regions.[39]
- Estimate catchability for gear used in benthic trawl surveys and determine effect of size, sex, substrate, topography, timing, and temperature.
- Investigate factors (habitat, harvest, sampling methods, etc.) that might be causing the large discrepancies between Delaware and New Jersey in egg survey numbers.

Moderate

- Estimate the proportion of the Delaware Bay population that is available in time and space within existing VT benthic trawl survey area. Estimate the selectivity of gear used in the survey. These estimations should take into account age class (i.e., primiparous, multiparous).
- Ground truth sub-sampling method used in Delaware Bay spawning survey for calibration to the "population" scale.

Modeling / Quantitative Priorities

High

- Estimate age/size specific survival of all life stages (e.g., age 0 to adult) and growth rate by instar within Delaware Bay.
- Estimate size specific fecundity of Delaware Bay females.
- Model relationship between egg availability and spawning biomass/abundance.

Moderate

- Further develop catch-survey analysis and apply assessment modeling beyond the Delaware Bay region.

---

[39] Some survey design work done by Landi (2011).

- Continue to conduct additional stock assessments and determine F. Use these data to develop a more reliable sustainable F.
- Estimate mortality from the entire biomedical collection process, from capture to post-return.[40]

Life History, Biological, and Habitat Priorities

High

- Assess horseshoe crab prey availability and determine whether horseshoe crab population growth will be/is limited by prey availability.
- Evaluate the impacts of beach nourishment projects on horseshoe crab populations.

Moderate

- Characterize essential horseshoe crab habitat, other than spawning habitat, in different regions.
- Further evaluate life table information including sex ratio and population age structure.
- Estimate the proportion of sub-tidal spawning and determine if this affects spawning success (i.e., egg survivability).
- Conduct tagging studies and analyze tagging data to identify costal populations, population abundance, mortality rates, migration, and other movements.[41]
- Characterize abundance and size structure of juveniles coastwide as indicators of recruitment to adulthood.
- Evaluate the effect of mosquito control chemicals on horseshoe crab populations.
- Evaluate the importance of horseshoe crabs to other marine resources such as sea turtles.
- Conduct risk assessment for the effect of oil spill (timing, location, and amount) on horseshoe crab and shorebird populations and determine best practices to reduce risk.

Notes:
Several priority research needs are currently being addressed through the following surveys:

<u>Delaware Bay spawning beach survey:</u>

a) Determine sampling frame or list of beaches in the Bay with a nonzero probability of being sampled in a given year.
b) Determine how many beaches need to be surveyed on how many days to meet survey objectives.
c) Determine whether subsampling effort (no. of quadrats per beach) was adequate.
d) Consider a survey design that includes both fixed and random beaches.

<u>Delaware Bay egg count survey:</u>

a) Set primary objective of egg count surveys to be shorebird food availability and focus on density of eggs at the surface (< 5cm).

[40] Tagging work has been done by DeLancey and Floyd (SC DNR) in South Carolina to evaluate mortality from the biomedical bleeding process.
[41] United States Fish and Wildlife Service tagging program in progress.

b) Determine survey frequency (i.e., survey eggs annually, every 3 years, every 5 years, or other?).
c) Determine where, along the beach profile, eggs should be sampled.
d) Determine sample size for sampling eggs on a beach.
e) Determine the relationship between spawning activity and density of eggs at the surface (<5cm). Is there a threshold of spawning activity below which eggs remain buried and unavailable to shorebirds?

<u>Offshore benthic survey:</u>

a) Design comparative surveys or experiments to determine gear efficiencies.

JONAH CRAB

STOCK ASSESSMENT AND POPULATION DYNAMICS

A coastwide stock assessment has yet to be completed for Jonah crab but is considered a high priority need. The assessment will provide much needed data on the status of the Jonah crab resource as well as contribute to recommendations for additional management needs, if any.

RESEARCH AND DATA NEEDS

Biological

- Maturity: The Massachusetts Division of Marine Fisheries recently received a Saltonstall-Kennedy Grant to conduct research to determine male and female gonadal and morphometric maturity for the Gulf of Maine, Georges Bank, and Southern New England areas. Other maturity factors that still need further research include sperm limitations in a male dominated fishery and size ratios of mating crabs.
- Mortality Rates in the Claw Fishery: Research is needed to determine the fishery-mortality rates of crabs with claws removed as well as the spawning success of crabs missing claws. The time needed to regenerate a new claw is also unknown and is a research priority.
- Claw-Carapace Width Ratio: A study is needed to establish a claw length to shell width ratio. This will help inform management in the claw fishery.
- Growth Rates: Research is needed to determine the growth rates of Jonah crabs which are largely unknown. Furthermore, it needs to be determine whether Jonah crabs experience a terminal molt and have a maximum size.
- Seasonality of Growth and Reproduction: Seasonal changes in the molting and mating of Jonah crabs across their range is unknown and needs to be determined.

Economic

- Fishery Description: Information on the fishery is lacking including the proportion of the market for live/claw/processed crab and the proportion of the fishery sold directly to consumers and dealers.

Habitat

- Migration: Studies are needed to determine migrations of the Jonah crab population as well as seasonal habitat preferences.

NORTHERN SHRIMP

Fishery-Dependent Priorities

High

- Continue to quantify the magnitude of bycatch of other species in the shrimp fishery by area and season and take steps necessary to limit negative impacts.[42]
- Improve separator and excluder devices to reduce bycatch and discard of non-targeted species and small shrimp in the shrimp fishery and fisheries targeting other species.[43]
- Evaluate selectivity of shrimp by traps and trawls.

Moderate

- Continue sea sampling efforts.
- Evaluate commercial fishery sampling design. Increase and/or redistribute sampling of commercial catches as necessary, ensuring good allocation of samples among ports and months, to provide better estimates of size composition.

Fishery-Independent Priorities

High

- Continue summer shrimp survey to track abundance and size/stage composition of the population.
- Evaluate effectiveness of summer shrimp survey statistical design, including geographic coverage.

Moderate

- Explore ways to quantify age 1 and younger shrimp.

Low

- Verify that summer shrimp survey tow bottom tending times have been consistent.

Modeling / Quantitative Priorities

High

- Continue refinement of the UME size-structured model for northern shrimp.
- Evaluate adequacy of the current BRPs, possibly through management strategy simulations
- Explore inclusion of the shrimping effort time-series and/or a commercial CPUE time-series standardized for environmental effects in the CSA model.
- Continue research to refine annual estimates of consumption by predators, and include in models as appropriate.

Moderate

- Explore explicit inclusion of temperature effects in stock assessment models.
- Expand the time series of stock and recruitment data using catchability estimates from the production model.
- Continue examination of methods for age determination to develop the possibility of using age based assessment methods.

---

[42] Some work has been done evaluating bycatch (Eayrs 2009) and bycatch in traps (Moffet 2012).

[43] Some work has been done, see He and Balzano (2007) and Pinkham et al. (2006).

- Develop a bioeconomic model to study the interactions between four variables: movements of shrimp, catchability of shrimp, days fished, and market price.

Life History, Biological, and Habitat Priorities

High

- Investigate application of newly developed direct ageing methods to ground truth assumed ages based on size and stage compositions.
- Evaluate larval and adult survival and growth, including frequency of molting and variation in growth rates, as a function of environmental factors and population density.[44]
- Study the effects of oceanographic and climatic variation (i.e., North Atlantic Oscillation) on the cold water refuges for shrimp in the Gulf of Maine.
- Explore the mechanisms behind the stock-recruitment and temperature relationship for Gulf of Maine northern shrimp.[45]

Moderate

- Determine the short and long-term effects of mobile fishing gear on shrimp habitat.[46]
- Study specific habitat requirements and develop habitat maps for early life history stages.
- Evaluate effects of potential habitat loss/degradation on northern shrimp.
- Identify migration routes of immature males offshore and ovigerous females inshore.[47]
- Evaluate maturation, fecundity, and lifetime spawning potential. Estimates of fecundity at length should be updated and the potential for annual variability should be explored. Examine variability of egg quality with female size and stage over time.
- Investigate changes in transition and maturation as a function of stock size and individual size and temperature.[48]
- Investigate diet of northern shrimp for different life history stages.

Management, Law Enforcement, and Socioeconomic Priorities

High

- Characterize demographics of the fishing fleet by area and season. Perform comparative analysis of fishing practices between areas.[49]
- Develop an understanding of product flow and utilization through the marketplace. Identify performance indicators for various sectors of the shrimp industry. Identify significant variables driving market prices and how their dynamic interactions result in the observed intra-annual and inter-annual fluctuations in market price for northern shrimp.
- Explore new markets for Gulf of Maine shrimp, including community supported fisheries.[50]

---

[44] Some work has been done by Stickney and Perkins.
[45] Some work has been done, see Richards et al. (2012).
[46] Short term effects have been studied, see Simpson and Watling (2006).
[47] Some migration work has been done, see Schick et al. (2006) NEC
[48] Some work has been done, see Wieland (2004, 2005).
[49] Dunham and Muller at the University of Maine conducted an economic study characterizing demographics of the fishing fleet by area and season in 1976. This study should be updated.
[50] Maine Fishermen's Forum panel discussions, 2006 and 2007

- Develop a framework to aid evaluation of the impact of limited entry proposals on the Maine fishing industry.[67,51]
- Develop a socioeconomic analysis assessing the importance of the northern shrimp fishery in annual activities of commercial fishing.
- Determine the relative power relationships between the harvesting and processing sector and the larger markets for shrimp and shrimp products.
- Develop an economic-management model to determine the most profitable times to fish, how harvest timing affects markets, and how the market affects the timing of harvesting.

Moderate

- Perform cost-benefit analyses to evaluate management measures.

[51] Maine Coastal Fishery Research Priorities, 2001, online at http://www.maine.gov/dmr/research/table_of_contents.htm

RED DRUM

Short and long-term research recommendations are prioritized, with the highest priorities listed first under each section and the lowest priorities listed last under each section.

Short-term

- Conduct experiments using logbooks to develop estimates of the B2 catch length composition in both the North and South regions.
- Determine if existing and historic recreational data sources (e.g., tagging) can be used to evaluate better B2 selectivities.
- Further study is needed to determine discard mortality estimates for the Atlantic coast, both for recreational and commercial gears. Additionally, discard estimates should examine the impact of slot-size limit management and explore regulatory discard impacts due to high-grading. Investigate covariates affecting discard mortality (e.g., depth, size, seasonality).
- Continued and expand observer coverage for the NC and VA gill net fisheries (5-10% coverage).
- Expand observer coverage to include other gears of concern (i.e. haul seine, pound net, trawls).
- Expand biostatistical sampling (ages and lengths) to better cover all statistical strata (gears/states - principally NC and VA) and collect more ages proportional to lengths, preferably otoliths. Conduct statistical analysis to determine appropriate sample sizes to adequately characterize the age-size composition of removals.
- Conduct a tagging study using emerging technologies (i.e., acoustic tagging, satellite tagging, genetic tags) to evaluate stock mixing and identify movement of sub-adult fish transitioning to maturity.
- Determine batch fecundity estimates of red drum. Need to include age-specific spawning frequency and spawning season length for this indeterminate spawner.
- Update maturity schedules for Atlantic red drum from Florida to Virginia. Preferably, gonad histology samples should be collected from all sizes over time and archived.
- Otolith microchemistry analysis should be considered to look at state level differences between regions to support stock structure differentiation.
- Continue cooperation between state ageing labs, such as the October 2008 red drumageing workshop, to provide consistent age verification between labs.

Long Term

- Investigate iterative re-weighting of data components to identify the appropriate weights given to each data component in the objective function.
- Investigate alternative functions for retention to include recreational harvest and dead releases in the same fleets. Commercial discards should also be considered as a discard component of the landings fleet.

- Allow for time varying reporting rate of tag recaptures in the assessment model. This would allow use of more recent tag-recapture data from NC and estimates of changes over time in both regions.
- Continue genetic analyses (i.e, SC DNR analyses) to evaluate stock structure and mixing and temporal changes in genetic composition of the red drum population.
- Consider a pilot Virginia adult survey and expanding current adult fishery-independent survey coverage in Florida waters.
- Identify impacts of water quality, environmental, and ecosystem changes on red drum stock dynamics. Incorporate in the stock assessment models.
- Quantify habitat changes for future management planning.

SCUP

Modeling / Quantitative Priorities

- Evaluation of indicators of potential changes in stock status that could provide signs to management of potential reductions of stock productivity in the future would be helpful.[52]
- A management strategy evaluation of alternative approaches to setting quotas would be helpful.
- Current research trawl surveys are likely adequate to index the abundance of scup at ages 0 to 2. However, the implementation of new standardized research surveys that focus on accurately indexing the abundance of older scup (ages 3 and older) would likely improve the accuracy of the stock assessment.[53]
- Continuation of at least the current levels of at-sea and port sampling of the commercial and recreational fisheries in which scup are landed and discarded is critical to adequately characterize the quantity, length and age composition of the fishery catches.[54]
- Quantification of the biases in the catch and discards, including non-compliance, would help confirm the weightings used in the model. Additional studies would be required to address this issue.
- The commercial discard mortality rate was assumed to be 100% in this assessment. Experimental work to better characterize the discard mortality rate of scup captured by different commercial gear types should be conducted to more accurately quantify the magnitude of scup discard mortality.
- Refine and update the Manderson et al.[55] availability analysis when/if a new ocean model is available (need additional support). Explore alternative niche model parameterizations including laboratory experiments on thermal preference and tolerance.
- Explore the Study fleet data in general for information that could provide additional context and/or input for the assessment.
- Explore additional sources of length/age data from fisheries and surveys in the early parts of the time series to provide additional context for model results.

---

[52] The WG noted that some progress in SSC work on 'rumble strip' analysis – used in 2013. The 2015 assessment explored the potential use of the Conn (2010) hierarchical method to combine indices across time and space; more developmental work is needed.

[53] The WG noted that the RI Industry Cooperative Trap survey was implemented during 2005-2012. This survey had a higher catch rate for larger and older fish of age 3+ than the bottom trawl surveys. A peer review indicated that some of the design elements should be modified and this advice was followed; however, funding was halted after 2012.

[54] The WG noted that adequate sampling has been maintained (see assessment tables and figures).

[55] Manderson JP, Schmidt A, Palamara L, Richardson D, Kohut J, Bonzek C. MS 2015. TOR 3: Describe the thermal habitat and its influence on the distribution and abundance of scup, and attempt to integrate the results into the stock assessment. 2015 SAW 60 Scup Working Group Working Paper A11. 52 p.

Fishery-Dependent Priorities

- Improve estimates of discards and discard mortality for commercial and recreational fisheries SBRM estimates of commercial fishery discards, which exhibit a less variable time series pattern and improved precision compared to previous estimates, were developed and accepted for this assessment.
- A standardized fishery-dependent CPUE of scup targeted tows, from either NEFOP observer samples or the commercial study fleet, might be considered as an additional index of abundance to complement survey indices in future benchmark assessments.

Fishery-Independent Priorities

- Evaluate indices of stock abundance from new surveys.[56]
- Explore experiments to estimate the catchability of scup in NEFSC and other research trawl surveys (side-by-side, camera, gear mensuration, acoustics, etc.).
- A scientifically designed survey to sample larger and older scup would likely prove useful in improving knowledge of the relative abundance of large fish.

Life History, Biological, and Habitat Priorities

- Quantify the pattern of predation on scup.[57]

Previous Research Recommendations

Fishery-Dependent Priorities

- Continue current level of sea and port sampling of the various fisheries in which scup are landed and discarded to adequately characterize the length composition of both landings and discards. Expanded age sampling of scup from commercial and recreational catches would be beneficial, with special emphasis on the acquisition of large specimens.[58]
- Commercial discard mortality had previously been assumed to be 100% for all gear types. Studies need to be conducted to better characterize the mortality of scup in different gear types to more accurately assess discard mortality.
- Additional information on compliance with regulations (e.g., length limits) and hooking mortality is needed to interpret recreational discard data and confirm weightings used in stock assessment model.

---

[56] The WG noted that the RI Cooperative Trap (ended in 2012), NEAMAP spring and fall surveys, indices at age from the RIDFW spring and fall surveys, and indices at age from the NYDEC survey are now included in the assessment documentation.

[57] The WG noted that the limited NEFSC survey food habits data for scup were reviewed and it is not possible to calculate absolute estimates of consumption of scup by predators due to sample size considerations (~500 identifiable scup in the ~40 year time series).

[58] Improved sampling intensity of landings and increased funding for the observer program since 2004 have improved discard sampling in the directed and bycatch fisheries for scup.

Fishery-Independent Priorities

- Fund, support, and expand the spatial coverage of the ventless trap-based Scup and Black Sea Bass Survey of Hard Bottom Areas.
- Collect total and fork lengths from individual scup in a standardized manner throughout their size and geographic range and across gear types to improve upon the length conversion equation currently cited in the FMP (Hamer, 1979).

Modeling / Quantitative Priorities

- Continue exploration of relative biomass and relative exploitation calculations based on CPUE data from fishery-dependent data (e.g., observer, commercial, P/C VTR, MRIP, etc).
- Evaluate the current biomass reference point and consider alternative proxy reference points such as B_{MAX} (the relative biomass associated with F_{MAX}).
- Explore other approaches for analyzing survey data, including bootstrap resampling methods to generate approximate confidence intervals around the survey index point estimates.[59]
- Evaluate indicators of potential changes in stock status that could provide signs to management of potential reductions of stock productivity in the future.

Life History, Biological, and Habitat Priorities

- Conduct an ageing comparison workshop to (1) compare otoliths and scales and (2) compare state age-length keys.[60]
- Conduct biological studies to investigate factors affecting annual availability of scup to research surveys and maturity schedules.

Management, Law Enforcement, and Socioeconomic Priorities

- A Management Strategy Evaluation of alternative approaches to setting quotas, with attention paid to compliance related to minimum size, would be helpful.

---

[59] Completed for the NEFSC surveys, could be applied to state survey data.
[60] Contact and inform Eric Robillard of NEFSC Population Biology Branch.

SPANISH MACKEREL

Fishery-Dependent Priorities

- Increase proportion of fish with biological data within MRIP sampling.
- Continue to develop methods to collect a higher degree of information on released fish (length, condition, etc.) in the recreational fishery.
- Require mandatory reporting for all charter boats state and federal.
- Continue development of electronic mandatory reporting for for-hire sector.
- Continue research efforts to incorporate/require logbook reporting from recreational anglers.
- Establish a review panel to evaluate methods for reconstructing historical landings (SWAS, FWS, etc.).
- Quantify historical fishing photos for use in reconstructing recreational historical landings.
- Narrow down the sampling universe. Identify angler preference and effort. Require a reef fish stamp for anglers targeting reef fish, pelagic stamp for migratory species, and deepwater complex stamp for deep-water species. The program would be similar to the federal duck stamp required of hunters. This would allow the managers to identify what anglers were fishing for.
- Continue and expand fishery-dependent at-sea-observer surveys to collect discard information, which would provide for a more accurate index of abundance.
- Implement observer coverage for the fisheries for Spanish mackerel (gillnets, castnets (FL), handlines, poundnets, and shrimp trawls for bycatch). Allocate 5-10% observer coverage by strata within states and collect maximum information from fish.
- Expand TIP sampling to better cover all statistical strata, predominantly from FL and by gillnet and castnet gears.
- Determine the tradeoff with length versus ages, need for more ages (i.e., hard parts).
- Consider the use of VMS to improve spatial resolution of data.
- Consider simplified logbook language in regard to discards (e.g., list them as dead or alive).[61]
- Develop uniform state and federal reporting systems/forms to improve the ease and efficiency of data compilation.
- Establish online reporting and use logbooks as a backup.
- Establish a mechanism for identifying age samples that were collected by length or market categories, so as to better address any potential bias in age compositions.
- Continue improving "one-stop shopping" for commercial data from NMFS, ACCSP, and states.

Fishery-Independent Priorities

- Collect and analyze fishery independent data for adult Spanish mackerel.

---

[61] Current logbook categories for discards (all dead, majority dead, majority alive, all alive) are not useful for informing discard mortality.

Modeling / Quantitative Priorities

- Using simulation analysis, evaluate the utility of including interaction terms in the development of a standardized index and identify the potential effects these interaction terms have on stock assessments.
- Establish a fishery-independent survey meant to capture the population trends of coastal pelagic in the south Atlantic.
- Examine how schooling or migratory dynamics may influence the catchability of the species. In particular, research the assumption of the hyperstability of indices that sample the schooling portion of the stock.
- Determine whether it is important to model both sexes in the population for assessment purposes.
- Investigate steepness and alternative models for the stock recruit relationship. In particular, evaluate if there is newer data available on steepness from other analyses of S-R for pelagic stocks with similar reproductive strategies.[62]

.

Life History, Biological, and Habitat Priorities

- Utilize recently developed genetic techniques to investigate the stock structure of Spanish mackerel. Microsatellite information should be explored to consider both stock identity and internal population structure.
- Collect Spanish mackerel maturity data from both regions and both sexes from specimens approximately 275 mm FL and lower to be staged via histological methods.

[62] The Review Panel for the 2012 SEDAR was uncertain as to how much the analysis would further inform the model or management at present

SPINY DOGFISH

Fishery-Dependent Priorities

High

- Determine area, season, and gear specific discard mortality estimates coastwide in the recreational, commercial, and non-directed (bycatch) fisheries.[63]
- Characterize and quantify bycatch of spiny dogfish in other fisheries.

Moderate

- Increase the biological sampling of dogfish in the commercial fishery and on research trawl surveys.

Low

- Further analyses of the commercial fishery is also warranted, especially with respect to the effects of gear types, mesh sizes, and market acceptability on the mean size of landed spiny dogfish.

Fishery-Independent Priorities

Moderate

- Conduct experimental work on NEFSC trawl survey gear performance, with focus on video work to study the fish herding properties of the gear for species like dogfish and other demersal roundfish.
- Investigate the distribution of spiny dogfish beyond the depth range of current NEFSC trawl surveys, possibly using experimental research or supplemental surveys.

Low

- Continue to analyze the effects of environmental conditions on survey catch rates.

Modeling / Quantitative Priorities

High

- Continue work on the change-in-ratio estimators for mortality rates and suggest several options for analyses.

Moderate

- Examine observer data to calculate a weighted average discard mortality rate based on an assumption that the rate increased with catch size.

Life History, Biological, and Habitat Priorities

High

- Conduct a coastwide tagging study to explore stock structure, migration, and mixing rates.
- Standardize age determination along the entire East Coast. Conduct an ageing workshop for spiny dogfish, encouraging participation by NEFSC, NCDMF, Canada DFO, other interested agencies, academia, and other international investigators with an interest in dogfish ageing.

---

[63] A discard mortality study in the North Carolina near-shore trawl and gillnet fisheries conducted by East Carolina University has been considered in previous stock assessments.

Moderate

- Identify how spiny dogfish abundance and movement affect other organisms.

Management, Law Enforcement, and Socioeconomic Priorities

Moderate

- Monitor the changes to the foreign export markets for spiny dogfish, and evaluate the potential to recover lost markets or expand existing ones.

Low

- Update on a regular basis the characterization of fishing communities involved in the spiny dogfish fishery, including the processing and harvesting sectors, based upon Hall-Arber et al. (2001) and McCay and Cieri (2000).
- Characterize the value and demand for spiny dogfish in the biomedical industry on a state by state basis.
- Characterize the spiny dogfish processing sector

SPOT

Short-term:

HIGH PRIORITY

- Expand collection of life history data for examination of lengths and age, especially fishery- dependent data sources.
- Organize an otolith exchange and develop an ageing protocol between ageing labs.
- Increased observer coverage for commercial discards, particularly the shrimp trawl fishery. Develop a standardized, representative sampling protocol and pursue collection of individual lengths and ages of discarded finfish.

MEDIUM PRIORITY

- Develop and implement sampling programs for state-specific commercial scrap and bait fisheries in order to monitor the relative importance of Spot. Incorporate biological data collection into program.
- Conduct studies of discard mortality for commercial fisheries. Ask commercial fishermen about catch processing behavior for Sp/Cr when trawl/gillnets brought over the rail.
- Conduct studies of discard mortality for recreational fisheries.
- Collect data to develop gear-specific fishing effort estimates and investigate methods to develop historical estimates of effort.

Long-term:

HIGH PRIORITY

- Continue state and multi-state fisheries-independent surveys throughout the species range and subsample for individual lengths and ages. Ensure NEFSC trawl survey continues to take lengths and ages. Examine potential factors affecting catchability in long-term fishery independent surveys.
- Continue to develop estimates of length-at-maturity and year-round reproductive dynamics throughout the species range. Assess whether temporal and/or density-dependent shifts in reproductive dynamics have occurred.
- Re-examine historical ichthyoplankton studies for an indication of the magnitude of estuarine and coastal spawning. Pursue specific estuarine data sets from the states (NJ, VA, NC, SC, DE, ME) and coastal data sets (MARMAP, EcoMon).

MEDIUM PRIORITY

- Identify stocks and determine coastal movements and the extent of stock mixing, via genetic and tagging studies.
- Investigate environmental and recruitment/ natural mortality covariates and develop a time series of potential covariates to be used in stock assessment models.
- Investigate environmental covariates in stock assessment models, including climate cycles (e.g., Atlantic Multi-decadal Oscillation, AMO, and El Nino Southern Oscillation, El Nino) and recruitment and/or year class strength, spawning stock biomass, stock distribution, maturity schedules, and habitat degradation.

- Investigate the effects of environmental changes (especially climate change) on maturity schedules for spot, particularly because this is an early-maturing species, and because the sSPR estimates are sensitive to changes in the proportion mature.
- Investigate environmental and oceanic processes in order to develop better understanding of larval migration patterns into nursery grounds.
- Investigate the relationship between estuarine nursery areas and their proportional contribution to adult biomass. I.e., are select nursery areas along Atlantic coast ultimately contributing more to SSB than others, reflecting better quality juvenile habitat?
- Develop estimates of gear-specific selectivity.

SPOTTED SEATROUT

Fishery-Dependent Priorities

High

- Collect data on the size and age of spotted seatrout released alive by anglers and the size and age of commercial discards.
- Increase observer coverage in states that have a commercial fishery for spotted seatrout.
- Expand the MRIP to assure adequate data collection for catch and effort data, increase intercepts, and include state add-ons of social and economic data needs.

Moderate

- Collection of commercial and recreational landings data should be continued and expanded.
- Improve precision of effort reporting through commercial trip ticket programs.

Fishery-Independent Priorities

High

- Develop state-specific juvenile abundance indices.
- Initiate fishery-independent surveys of spotted seatrout.
- Emphasis should be placed on collecting the necessary biological data to be able to conduct stock assessments and to assist in drafting fishery management plans.

Modeling / Quantitative Priorities

High

- Utilize age structure analyses by sex in stock assessments.
- Conduct state specific stock assessments to determine the status of stocks relative to the plan objective of maintaining a spawning potential of at least 20%.
- Provide state specific batch fecundity estimates for use in stock assessments.[64]

Life History, Biological, and Habitat Priorities

High

- Identify essential habitat requirements.
- Evaluate effects of environmental factors, especially cold winters, on spawning frequency and stock density.
- Continue work to examine the stock structure of spotted seatrout on a regional basis, with particular emphasis on advanced tagging and molecular techniques.[65]
- Conduct telemetry tagging surveys to provide precise estimates of mortality attributed to winter kills.[66]

Management, Law Enforcement, and Socioeconomic Priorities

High

- Initiate collection of social and economic aspects of the spotted seatrout fishery.

---

[64] South Carolina fecundity information available in Roumillat and Brouwer (2002).

[65] Masters project in progress examining the genetic structure of spotted seatrout along the Atlantic coast and the effects of winter conditions on genetic diversity of spotted seatrout.

[66] Masters project in progress examining lethal temperature thresholds of spotted seatrout.

SUMMER FLOUNDER

Fishery-Dependent Priorities

- Develop a program to annually sample the length and age frequency of summer flounder discards from the recreational fishery.[67]
- A comprehensive collection of otoliths, for all components of the catch-at-age matrix, needs to be collected on a continuing basis for fish larger than 60 cm (~7 years). The collection of otoliths and the proportion at sex for all of the catch components could provide a better indicator of stock productivity.[68]
- Develop a reference collection of summer flounder scales and otoliths to facilitate future quality control of summer flounder production ageing. In addition, a comparison study between scales and otoliths as ageing structures for summer flounder should be completed.[69]
- Collect and evaluate information on the reporting accuracy of recreational discards estimates in the recreational fishery.[70]
- Evaluate potential changes in fishery selectivity relative to the spawning potential of the stock; analysis should consider the potential influence of the recreational and commercial fisheries.[71]
- Use NEFSC fishery observer age-length keys for 1994 and later years (as they become available) to supplement NEFSC survey data in ageing the commercial fishery discard.

---

[67] The SDWG noted that to date, ongoing programs are in place in the MRFSS/MRIP recreational sampling and the American Littoral Society (ALS). Most states have volunteer angler surveys (NC, VA, MD, NJ, NY, CT, RI, MA) which collects length of fish discarded (and landed) via several different methods (e.g., surveys, e-logbooks, etc.). Some progress has been made, but more synoptic data and potentially less biased data are needed including the length, age, and sex-frequency of discards.

[68] The SDWG noted that through a PMAFS study, 2 years of data collection has occurred to determine sex ratios in the commercial and recreational landings (Working Paper A13). This is not an ongoing study. One year of data collection has occurred to determine the sex of fish in the NJ state survey, and the MA state survey has had ongoing collection of sex data in their survey (2009-present). The Northeast region fishery sampling program now collects otoliths and scales for commercial landings, and is scheduled to start collecting individual weights.

[69] The SDWG noted that an exchange of aging structures between NEFSC and NCDMF was completed and a report was reviewed by the 2007 SDWG, in response to a 2005 SAW 41 high priority Research Recommendation. An additional exchange occurred between the NC-DMF and NEFSC in 2009. The SDWG notes that while the exchanges indicate that the current level of ageing consistency between NC and NEFSC is acceptable, there is a need to conduct and fund exchanges between all production ageing entities (e.g., NC, VIMS, ODU, NEFSC) using scales and otoliths more frequently, on a schedule consistent with benchmark assessments.

[70] The SDWG noted that some research has been conducted on reporting accuracy in the recreational for-hire fishery (Bochenek et al. 2011); however, comprehensive work across all fishing modes has not been completed.

[71] The SDWG noted that some progress has been made on this topic in a report prepared for the MAFMC SSC describing a MSE for the recreational fishery.

- Collect data to determine the sex ratio for all of the catch components.[72]
- Evaluate the size distribution of landed and discarded fish, by sex, in the summer flounder fisheries.
- Develop and ongoing sampling program for the recreational fishery landings and discards (i.e., collect age, length, sex) to develop appropriate age-length keys for ageing the recreational catch.

Fishery-Independent Priorities

- Collect information on overall fecundity for the stock, both egg condition and production, as a better indicator of stock productivity.[73]

Modeling / Quantitative Priorities

- Investigate trends in sex ratios and mean lengths and weights of summer flounder in state agency and federal survey catches.[74]
- Examine the sensitivity of the summer flounder assessment to the various unit stock hypothesis and evaluate spatial aspects of the stock to facilitate sex and spatially explicit modeling of summer flounder.[75]
- Determine the appropriate level for the steepness of the S-R relationship and investigate how that influences the biological reference points.
- Evaluate uncertainties in biomass to determine potential modifications to default OFL CV.
- Evaluate past and possible future changes to size regulations on retention and selectivity in stock assessments and projections.
- Incorporate sex -specific differences in size at age into the stock assessment.
- Apply standardization techniques to all of the state and academic-run surveys, to be evaluated for potential inclusion in the assessment.
- Conduct sensitivity analyses to identify potential causes of the recent retrospective pattern. Efforts should focus on identifying factors in both survey and catch data that could contribute to the decrease in cohort abundance between initial estimates based largely on survey observations and subsequent estimates influenced by fishery dependent data as the cohort recruits to the fishery.

---

[72] The SDWG noted that through a PMAFS study, 2 years of data collection has occurred to determine sex ratios in the commercial and recreational landings (WPA13). This is not an ongoing study.
[73] The SDWG noted that this recommendation has not been fully addressed and remains an ongoing data collection need. An ongoing study conducted by Dr. Chris Chambers (NOAA NMFS NEFSC Sandy Hook Laboratory) is examining summer flounder fecundity and egg condition.
[74] The SDWG noted that these trends were examined in great detail for the federal surveys for this assessment (WPA1). MADMF surveys collect sex data. The VIMS NEAMAP surveys collect sex data.
[75] The SDWG noted that progress has been made on aspects of this recommendation in WPA1, WPA8, WPA11, WPA12, and WPA15.

- Further work examining aspects that create greater realism to the summer flounder assessment (e.g., sexually dimorphic growth, sex-specific F, differences in spatial structure [or distribution by size?] should be conducted. This could include:
  - a) Simulation studies to determine the critical data and model components that are necessary to provide reliable advice, and need to determine how simple a model can be while still providing reliable advice on stock status for management use, and should evaluate both simple and most complex model configurations.
  - b) Development of models incorporating these factors that would create greater realism.
  - c) These first steps (a or b) can be used to prioritize data collection, and determine if additional investment in data streams (e.g., collection of sex at age and sex at length and maturity data from the catch, additional information on spatial structure and movement, etc.) are worthwhile in terms of providing more reliable assessment results.
  - d) The modeling infrastructure should be simultaneously developed to support these types of modeling approaches (flexibility in model framework, MCMC/bootstrap framework, projection framework).
- Develop methods that more fully characterize uncertainty and ensure coherence between assessments, reference point calculation and projections.

Life History, Biological, and Habitat Priorities

- Examine the male to female ratio at age-0 and potential factors (e.g., environmental) that may influence determination of that ratio.[76]
- Conduct further research to examine the predator-prey interactions of summer flounder and other species, including food habitat studies, to better understand the influence of these other factors on the summer flounder population.[77]
- Evaluate range expansion and change in distribution and their implications for stock assessment and management.
- Continued evaluation of natural mortality and the differences between males and females. This should include efforts to estimate natural mortality, such as through mark-recapture programs, telemetry.
- Develop comprehensive study to determine the contribution of summer flounder nursery area to the overall summer flounder population, based off approaches similar to those developed in WPA12.
- Continue efforts to improve understanding of sexually dimorphic mortality and growth patterns. This should include monitoring sex ratios and associated biological information in

---

[76] The SDWG noted that the male female ratio has been updated for the NEFSC surveys. The SDWG reviewed information in Luckenbach et al. 2009 which describes potential environmental factors that may affect sex ratios at age-0.

[77] The SDWG noted that WPA1 reviewed food habits data available on summer flounder predators and prey. The SDWG concludes that the data are not sufficient to estimate predator consumption of summer flounder and has not attempted to estimate summer flounder consumption of prey.

the fisheries and all ongoing surveys to allow development of sex-structured models in the future.

Management, Law Enforcement, and Socioeconomic Priorities

- Consider use of management strategy evaluation techniques to address the implications of harvest policies that incorporate consideration of retrospective patterns (see ICES Journal of Marine Science issue of May 2007). [78]

Previous Research Recommendations

Fishery-Dependent Priorities

High

- Develop a program to annually sample the length and age frequency of summer flounder discards from the recreational fishery.
- Collect and evaluate information on the reporting accuracy of recreational discard estimates in the recreational fishery.
- Conduct more comprehensive collection of otoliths, for all components of the catch-at-age matrix, on a continuing basis for fish larger than 60 cm (~7 years). The collection of otoliths and the proportion at sex for all of the catch components could provide a better indicator of stock productivity.
- Develop a reference collection of summer flounder scales and otoliths to facilitate future quality control of summer flounder production ageing. In addition, a comparison study between scales and otoliths as ageing structures for summer flounder should be completed.[79]
- Examine mesh selectivity patterns for a range of commonly used mesh sizes greater than the currently mandated sizes (5.5 Diamond/6 inch square).[80]
- Continue to collect and analyze age-length samples and CPUE data from the commercial and recreational fisheries throughout the range of summer flounder.

Moderate

---

[78] The SDWG noted that given the retrospective pattern has changed since this recommendation was developed (i.e., smaller and less problematic), this recommendation is no longer considered relevant by the SDWG.

[79] The SDWG reported that an exchange of aging structures between NEFSC and NCDMF was completed and a report was reviewed by the 2007 SDWG, in response to a 2005 SAW 41 high priority Research Recommendation. The SDWG noted that while the Fall 2006 ageing exchange between NC-DMF and the NEFSC indicated that the current level of ageing consistency between NC and NEFSC is acceptable, there is a need to conduct and fund these exchanges more frequently, on a schedule consistent with benchmark assessments.

[80] This research should only be a high priority if managers want to change the commercial minimum size. This research should wait until changes in minimum size are anticipated so outdated research does not have to be updated.

- Research directed at evaluating the mesh exemption program should be continued, with increased sample sizes to allow reliable statistical testing of results.
- Use NEFSC fishery observer age-length keys for 1994 and later years (as they become available) to supplement NEFSC survey data in ageing the commercial fishery discard.
- Undertake research to determine hooking mortality on summer flounder by circle, kahle, and regular "J" hooks and make the results of work already completed available to the Management Board.
- Collect data to determine the sex ratio for all of the catch components.
- Develop fish excluder devices to reduce bycatch of immature flatfish in fisheries that target species other than flounder.

Fishery-Independent Priorities
High
- Collect information on overall fecundity for the stock, both egg condition and production, as a better indicator of stock productivity.[81]
- Continue fishery-independent surveys and expand existing surveys to capture all sizes and age classes in order to develop independent catch-at-age and CPUE should focus on YOY and the southern region.

Modeling / Quantitative Priorities
High
- Investigate trends in sex ratios and mean lengths and weights of summer flounder in state agency and federal survey catches.

Low
- Examine the sensitivity of the summer flounder assessment to the various unit stock hypotheses and evaluate spatial aspects of the stock to facilitate sex and spatially explicit modeling of summer flounder.[82]

Life History, Biological, and Habitat Priorities
Moderate
- Develop or determine stock identification methods via meristics, morphometrics, biochemical research, and tagging (particularly off Virginia and North Carolina).

Low

[81] The SDWG noted that observed change in the sex ratio in NEFSC survey samples may result in the SSB estimates not translating as directly to egg production since there are more males proportionally in those older age categories. While these trends have not been examined in the state survey catches, these trends were examined in the NEFSC spring, autumn, and winter survey data. Additional work to examine and explain these trends in greater detail should be conducted.
[82] Current ASAP model lacks the capability to do sex and spatial modeling, so Stock Synthesis version of this approach (e.g., M. Maunder 2008 SAW 47 work) would be necessary. Above all, there is a lack of sufficient time series data to sex all catch and surveys, and lack of information on spatial movement and/or recruitment patterns.

- Evaluate effects of dissolved oxygen and water current requirements for adult summer flounder and summer flounder eggs.
- Evaluate the relationship between recruitment of summer flounder to nursery areas and Ekman transport or prevailing directions of water flow.
- Examine male female ratio at age 0 and potential factors (e.g., environmental) that may influence determination of that ratio.
- Conduct the basic research necessary to develop land and pen culture techniques.
- Conduct further research to examine the predator-prey interactions of summer flounder and other species, including food habitat studies, to better understand the influence of these other factors on the summer flounder population.

Management, Law Enforcement, and Socioeconomic Priorities
Moderate
- Consider use of MSE techniques to address the implications of harvest policies that incorporate consideration of retrospective patterns (see ICES Journal of Marine Science issue of May 2007).
- Conduct a detailed socioeconomic study of the summer flounder fisheries.

TAUTOG

Fishery-Dependent Priorities

High

- Expand biological sampling of the commercial catch for each gear type over the entire range of the stock (including weight, lengths, age, sex, and discards).
- Continue collecting operculum from the tautog catch as the standard for biological sampling in addition to collecting paired sub-samples of otoliths and operculum.
- Increase catch and discard length sampling from the commercial and recreational fishery for all states from Massachusetts through Virginia.
- Increase collection of effort data for determining commercial and recreational CPUE.
- Increase MRIP sampling levels to improve recreational catch estimates by state and mode. Current sampling levels are high during times of the year when more abundant and popular species are abundant in catches, but much lower in early spring and late fall when tautog catches are more likely.

Fishery-Independent Priorities

High

- Conduct workshop and pilot studies to design a standardized, multi-state fishery independent survey for tautog along the lines of MARMAP and the lobster ventless trap survey.
- Establish standardized state by state long-term fisheries-independent surveys to monitor tautog abundance and length-frequency distributions, and to develop YOY indices.
- Enhance collection of age information for smaller fish (<20 cm) to better fill in age-length keys.
- Address finer-scale spatial issues through techniques like otolith microchemistry analysis and next-generation genetic sequencing.

Modeling / Quantitative Priorities

Moderate

- Develop an alternative flexible selectivity curve to use in the stock assessment model given the characteristics of multiple gear types in the tautog fisheries.
- Consider using alternative catch-at-age modeling frameworks (e.g., Stock Synthesis) in order to overcome some constraints of the ASAP model in the NMFS Toolbox. Simpler methods, such as xDB-SRA, can also be performed in Stock Synthesis, providing a common modeling framework to develop and compare different models and their specifications.

Life History, Biological, and Habitat Priorities

Moderate

- Define local and regional movement patterns and site fidelity in the southern part of the species range. This information may provide insight into questions of aggregation versus recruitment to artificial reef locations, and to clarify the need for local and regional assessment.

- Assemble regional reference collections of paired operculum and otolith samples and schedule regular exchanges to maintain and improve the precision of age readings between states that will be pooled in the regional age-length keys.
- Calibrate age readings every year by re-reading a subset of samples from previous years before ageing new samples. States that do not currently assess the precision of their age readings over time should do so by re-ageing a subset of their historical samples.
- Obtain biological metrics to match the spatial scale of the proposed models, to determine if there is biological justification for such models.

Low

- Evaluate the potential impacts of climate change on tautog range, life history, and productivity.
- Conduct a tag retention study to improve return rates, particularly in the northern region.
- Define the status (condition and extent) of optimum or suitable juvenile habitats and trends in specific areas important to the species. It is critical to protect these habitats or to stimulate restoration or enhancement, if required.
- Define the specific spawning and pre-spawning aggregating areas and wintering areas of juveniles and adults used by all major local populations, as well as the migration routes used by tautog to get to and from spawning and wintering areas and the criteria or times of use. This information is required to protect these areas from damage and overuse or excessive exploitation.
- Define larval diets and prey availability requirements. This information can be used as determinants of recruitment success and habitat function status. Information can also be used to support aquaculture ventures with this species.
- Define the role of prey type and availability in local juvenile/adult population dynamics over the species range. This information can explain differences in local abundance, movements, growth, fecundity, etc. Conduct studies in areas where the availability of primary prey, such as blue mussels or crabs, is dependent on annual recruitment, the effect of prey recruitment variability as a factor in tautog movements (to find better prey fields), mortality (greater predation exposure when leaving shelter to forage open bottom), and relationship between reef prey availability/quality on tautog condition/fecundity.
- Define the susceptibility of juveniles to coastal/anthropogenic contamination and resulting effects. This information can explain differences in local abundance, movements, growth, fecundity, and serve to support continued or increased regulation of the inputs of these contaminants and to assess potential damage. Since oil spills seem to be a too frequent coastal impact problem where juvenile tautog live, it may be helpful to conduct specific studies on effects of various fuel oils and typical exposure concentrations, at various seasonal temperatures and salinities. Studies should also be conducted to evaluate the effect of common piling treatment leachates and common antifouling paints on YOY tautog. The synergistic effects of leaked fuel, bilge water, treated pilings, and antifouling paints on tautog health should also be studied.
- Define the source of offshore eggs and larvae (in situ or washed out coastal spawning).
- Confirm that tautog, like cunner, hibernate in the winter, and in what areas and temperature thresholds, for how long, and if there are special habitat requirements during

these times that should be protected or conserved from damage or disturbance. This information will aid in understanding behavior variability and harvest availability.

Management, Law Enforcement, and Socioeconomic Priorities
Moderate

- Collect data to assess the magnitude of illegal harvest of tautog.

Low

- Collect basic sociocultural data on tautog user groups including demographics, location, and aspects of fishing practices such as seasonality.

WEAKFISH

Fishery-Dependent Priorities

High

- Increase observer coverage to identify the magnitude of discards for all commercial gear types from both directed and non-directed fisheries.[83]

Moderate

- Continue studies on temperature, size, and depth specific recreational hook and release mortality rates, particularly catches from warm, deep waters. Investigate methods to increase survival of released fish.
- Continue studies on mesh size selectivity, particularly trawl fisheries.[84]
- Improve methods to estimate commercial bycatch. Refine estimates of discard mortality based on factors such as distance from shore and other geographical differences for all sizes including below minimum size.

Low

- Determine the onshore versus offshore components of the weakfish fishery.
- Collect catch and effort data including size and age composition of the catch, determine stock mortality throughout the range, and define gear characteristics. In particular, increase length frequency sampling in fisheries from Maryland and further north.
- Develop latitudinal, seasonal, and gear specific age length keys coastwide. Increase sample sizes for gear specific keys.

Modeling / Quantitative Priorities

High

- Evaluate predation of weakfish, by an expanded suite of predators (e.g., marine mammals), including leveraging ongoing ASMFC work on multispecies models by including weakfish as both predator and prey.
- Develop a bioenergetics model that encompasses a broader range of ages than Hartman and Brandt (1995) and use it to evaluate diet and growth data.
- Conduct simulations with the proposed Z based control rules, or thresholds/targets in a time varying environment to explore alternative management options, particularly under a stock recovery scenario.
- Transfer Bayesian model code to more broadly accessible platform. The method likely has broad applicability for other stocks in the region and beyond.

Moderate

- Analyze the recruitment dynamics of weakfish and examine the effects of the relationship between adult stock size and environmental factors on year class strength; explore inconsistencies between YOY and Age 1 results from the assessment model.

---

[83] Some additional Mid-Atlantic trawl fleet observer coverage has been implemented under ACCSP funding.

[84] Gillnet selectivity has been investigated by Swihart et al (2000). Some gear selectivity information in Amendment 3 to the ASMFC Weakfish FMP. Information can also be obtained from the North Carolina Pamlico Sound Independent Gill Net Survey.

- Conduct a simulation-estimation analysis to explore trends in natural mortality.
- Look for consistency and similarity among GLM survey estimation methods and check for sensitivity to collinearity of different drivers with the YEAR effect.
- Currently, spatial asynchrony in the Bayesian model includes a variance parameter for each age and year, but most of the variation seems to be among years. Evaluate whether annual variance is more parsimonious.
- Assessment model input weights-at-age are poorly estimated or at best variable. Conduct sensitivity analyses to evaluate how much of this is real and how it affects model performance.

Low

- Explore alternatives for dealing with uncertainties in age-length keys and catch data through length based or condition-based models, recognizing these come with new issues, like proper representation of growth.
- Catch measurement errors appeared relatively small; explore whether other process or measurement error processes are perhaps overly constraining the fit, possibly through simulation estimation.

Life History, Biological, and Habitat Priorities

High

- Develop a coastwide tagging program to identify stocks and determine migration, stock mixing, and characteristics of stocks in over wintering grounds. Determine the relationship between migratory aspects and the observed trend in weight-at-age.[85]
- Monitor weakfish diets over a broad regional and spatial scale, with emphasis on new studies within estuaries.
- Continue to investigate the geographical extent of weakfish hybridization.
- Estimate weakfish mortality through independent approaches (e.g. alternative models, tagging) to corroborate trends in mortality from the assessment model.
- Conduct a meta-analysis of all factors likely to influence changes in natural mortality to see if the aggregate effect shows stronger statistical likelihood of occurrence than the significance shown by each individual driver effect on its own.

Moderate

- Identify and delineate weakfish spawning habitat locations and environmental preferences to quantify spawning habitat.
- Compile data on larval and juvenile distribution from existing databases to obtain preliminary indications of spawning and nursery habitat location and extant.
- Examine geographical and temporal differences in growth rate (length and weight-at-age).

[85] Tagging work to evaluate mortality, movement, stock mixing, and weakfish predator information was begun in North Carolina in 2013. Otolith samples have been obtained by Old Dominion University, but funding has not been available for processing.

- Determine the impact of power plants and other water intakes on larval, post larval, and juvenile weakfish mortality in spawning and nursery areas. Calculate the resulting impact on adult stock size.[86]
- Monitor predation on weakfish from both fish and marine mammal species.
- Determine the impact of scientific monitoring surveys on juvenile weakfish mortality. Calculate the resulting impact on adult stock size.

Management, Law Enforcement, and Socioeconomic Priorities

High

- Improve implementation of the process for organizing and collecting data from different agencies and sources to assure timely and high quality data input into the model.

Moderate

- Assemble socioeconomic data as it becomes available from ACCSP.

Low

- Define restrictions necessary for implementation of projects in spawning and over wintering areas and develop policies on limiting development projects seasonally or spatially.

---

[86] Data are available for power plants in the Delaware Bay area and North Carolina. Also see Heimbuch et al. 2007. Assessing coastwide effects of power plant entrainment and impingement on fish populations: Atlantic menhaden example. *North American Journal of Fisheries Management*. 27: 569-577.

WINTER FLOUNDER

Coast Wide

Fishery-Dependent Priorities

High

- Increase the intensity of commercial fishery discard length sampling.
- Expand sea sampling to validate commercial discard estimates from VTR.

Fishery-Independent Priorities

Moderate

- Evaluate the maturity-at-age of fish sampled in inshore surveys (i.e., MEDMR, MADMF, NEAMAP, etc.).[87]
- Encourage support for Industry Based Surveys, which can provide valuable information on stock abundance, distribution, and catchability in research surveys that are independent of and supplemental to NMFS effort.

Modeling / Quantitative Priorities

Moderate

- Investigate the skipped spawning percentage for each stock and estimate inter-annual variation when sufficient data have been collected.

Low

- Develop mortality estimates from the American Littoral Society tagging data, if feasible.
- Explore use of a more complex Stock Synthesis model with small rates of migration between stocks.
- Revise the NEFSC assessment software to include the ability to model stock-recruit functions including environmental factors with errors/probabilities.
- Develop time series of winter flounder consumption by the major fish predators of winter flounder.
- Explore development of an index of winter flounder larval abundance based on MARMAP, GLOBEC, and other time series.

Life History, Biological, and Habitat Priorities

High

- Focus research on quantifying mortality associated with habitat loss and alteration, contamination by toxins, and power plant entrainment and impingement. Examine the implications of these anthropogenic mortalities on estimation of YPR, if feasible.

[87] See McBride et al. 2013. Latitudinal and stock-specific variation in size- and age-at-maturity of female winter flounder, *Pseudopleuronectes americanus*, as determined with gonad histology. *Journal of Sea Research*. 75: 41-51.

- Conduct studies to delineate all major sub-stocks in terms of geographic spawning area and seasonal offshore movements (e.g., exposure to fishing pressure).[88,99]

Moderate

- Update and investigate migration rates between stocks and movement patterns. Investigate localized structure/genetics within the stocks.[98,89]

Low

- Conduct studies of flounder populations in impacted areas to quantify physiological adaptation to habitat alteration, and interactive effects, on an individual and population level.

Management, Law Enforcement, and Socioeconomic Priorities

High

- Investigate ways to improve compliance to help VTR. Currently about 300 of the 1,500 permitted vessels consistently under report the number of statistical areas fished.

Southern New England – Mid-Atlantic Stock Complex

Modeling / Quantitative Priorities

Low

- Quantify adult sex ratio to determine the possibility of population decline due to a skewed sex ratio.

Life History, Biological, and Habitat Priorities

Moderate

- Examine egg and larvae distribution and abundance to determine YPR to predict future biomass development for the fishery.
- Assess distribution of winter flounder during each life stage by conducting tagging methods, focusing on juvenile to adult life stages. This information would be useful for estimating YPR and helpful to find answers as to why recruitment is at a vulnerable state.[99]
- Examine winter flounder distribution, abundance, and productivity based on oceanographic and climate warming and how that impacts biomass for the fishery.

Low

- Examine predator-prey relationships due to increased populations of cormorants, seals, and striped bass (examine stomach contents of predators to get a better idea on the quantification of predation on winter flounder by these predators).

Georges Bank Stock

---

[88] The most recent comprehensive tagging study was completed in the 1960's (Howe and Coates). Some telemetry work done in southern Gulf of Maine, see DeCelles and Cadrin 2010. Movement patterns of inter flounder (*Pseudopleuronectes americanus*) in the southern Gulf of Maine: observations with the use of passive acoustic telemetry. *Fisheries Bulletin*. 108: 408-419.

[89] See Fairchild et al. 2009. Using telemetry to monitor movements and habitat use of cultured and wild juvenile winter flounder in a shallow estuary. *Tagging and Tracking of Marine Animals with Electronic Devices.* 9: 5-22.

Fishery-Independent Priorities
High
- Examine maturity data from NEFSC strata on Nantucket Shoals and near Georges Bank separately from more inshore areas.[97]

Life History, Biological, and Habitat Priorities
High
- Investigate use of periodic gonad histology studies to validate maturity estimates, with particular attention to obtaining sufficient samples from the Georges Bank stock.[97]
- Conduct studies to better understand recruitment processes of winter flounder, particularly in the Gulf of Maine and on Georges Bank.

Moderate
- Further explore the relationship between large scale environmental forcing (e.g., temperature, circulation, and climate) for effects on life history, reproduction, and recruitment in the Georges Bank stock.

Gulf of Maine Stock
Fishery-Dependent Priorities
High
- Improve sampling for biological data (particularly hard parts for ageing) of commercial landings for winter flounder.
- Process archived age samples from surveys and commercial landings and develop analytical based assessments.[90]

Low
- Estimate and evaluate the effects of catch and release components of recreational fishery on discard-at-age.

Fishery-Independent Priorities
Moderate
- Evaluate size selectivity performance of survey gear compared to typical commercial gear and implications for estimation of commercial discards from research survey length frequency information.

Modeling / Quantitative Priorities
Low
- Evaluate the effects of smoothed length frequency distributions on the relationship between survey and commercial catches-at-length.

Life History, Biological, and Habitat Priorities
High

[90] Maine DMR has archived winter flounder otoliths since 2002.

- Examine growth variations within the Gulf of Maine, using results from the Gulf of Maine Biological Sampling Survey (1993-94).[91]
- Conduct studies to better understand recruitment processes of winter flounder, particularly in the Gulf of Maine and on Georges Bank.

Moderate

- Further examine the stock boundaries to determine if Bay of Fundy winter flounder should be included in the Gulf of Maine stock complex.[98]

---

[91] Biological data on winter flounder has been collected on the Maine DMR trawl survey from 2000-2008 and should be included.

Common Research Recommendations
for All Commission Managed Diadromous Species

Dams and Other Obstructions

General Fish Passage

- States should work in concert with the USFWS and the NOAA Fisheries Service to identify hydropower dams that pose significant impediment to diadromous fish migration and target them for appropriate recommendations during FERC relicensing.
- States should identify and prioritize barriers in need of fish passage based on clear ecological criteria (e.g., amount and quality of habitat upstream of barrier, size, status of affected populations, etc.). These prioritizations could apply to a single species, but are likely to be more useful when all diadromous species are evaluated together.
- A focused, coordinated, well supported effort among federal, state, and associated interests should be undertaken to address the issue of fish passage development and efficiency. The effort should attempt to develop new technologies and approaches to improve passage efficiency with the premise that existing technology is insufficient to achieve restoration and management goals for several East Coast river systems.
- Where obstruction removal is not feasible, install appropriate passage facilities, including fish lifts, fish locks, fishways, navigation locks, or notches (low-head dams and culverts).
- At sites with passage facilities, evaluate the effectiveness of upstream and downstream passage; when passage is inadequate, facilities should be improved.
- Dams/obstructions where upstream passage structures will be installed should be evaluated for effectiveness of downstream passage. Upstream passage structures should not be installed at these sites, unless downstream passage can be made safe, effective, and timely.
- Facilities for monitoring the effectiveness of the pass should be incorporated into the design where possible.
- Before designing and constructing fish passage systems, determine the behavioral response of each species of interest to major physical factors so that effectiveness can be maximized.
- Protection from predation should be provided at the entrance, exit, and throughout the pass.
- The passage facility should be designed to work under all conditions of head and tail water levels that prevail during periods of migration.
- Passages are vulnerable to damage by high flows and waterborne debris. Techniques for preventing damage include robust construction, siting facilities where they are least exposed to adverse conditions, and removing the facilities in the winter.
- Evaluate performance of conventional fishways, fish lifts, and eel ladders, and determine features common to effective passage structures and those common to ineffective passage structures.
- Conduct basic research into diadromous fish migratory behavior as it relates to depth, current velocity, turbulence, entrained air, light, structures, and other relevant factors.
- Use information from the previous two research recommendations to conduct CFD modeling to develop more effective fishway designs.

- Research technologies (barriers, guidance systems, etc.) for directing emigrating fish to preferred passage routes at dams.
- Identify low-cost alternatives to traditional fishway designs.
- Develop effective downstream passage strategies to reduce mortality.

Upstream Fish Passage

- Diadromous fish must be able to enter the passage facility with little effort and without stress.
- To prevent fish from becoming entrained in intake flow areas of hydropower facilities, construct behavioral barrier devices and re-direct them to safer passage areas.
- Fish ascending the pass should be guided/routed to an appropriate area so that they can continue upstream migration, and avoid being swept back downstream below the obstruction.

Downstream Fish Passage

- To enhance survival at dams during emigration, evaluate survival of fish passed via each route (e.g., turbines, spillage, bypass facilities, or a combination of the three) at any given facility, and pass fish via the route with the best survival rate.

Other Dam Issues

- Where practicable, remove obstructions to upstream and downstream migration.
- Locate facilities along the river where impingement rates are likely to be lowest.
- Alter water intake velocities, if necessary, to reduce mortality to diadromous species.
- To mitigate hydrological changes from dams, consider operational changes such as turbine venting, aerating reservoirs upstream of hydroelectric plants, aerating flows downstream, and adjusting in-stream flows.
- Natural river discharge should be taken into account when alterations are being made to a river because it plays a role in the migration patterns of diadromous fish.
- Document the impact of power plants and other water intakes on larval, post-larval, and juvenile mortality in anadromous fish spawning areas, and calculate the resultant impacts to adult population sizes.
- Evaluate the upstream and downstream impacts of barriers on diadromous species, including population and distribution effects.

Water Quality and Contamination

- Maintain water quality and suitable habitat for all life stages of diadromous species in all rivers with populations of diadromous species.
- Non-point and point source pollution should be reduced in diadromous fish habitat areas.
- Implement BMPs along rivers and streams, restore wetlands, and utilize stream buffers to control non-point source pollution.
- Implement erosion control measures and BMPs in agricultural, suburban, and urban areas to reduce sediment input, toxic materials, and nutrients and organics into streams.
- Upgrade wastewater treatment plants and remove biological and organic nutrients from wastewater.
- Reduce the amount of thermal effluent into rivers. On larger rivers, include a thermal zone of passage.

- Provide management options regarding water withdrawal and land use to minimize the impacts of climate change on temperature and flow regimes.
- Discharge earlier in the year to reduce impacts to migrating fish.
- Conduct studies to determine the effects of dredging on diadromous habitat and migration; appropriate best management practices, including environmental windows, should be considered whenever navigation dredging or dredged material disposal operations would occur in a given waterway occupied by diadromous species.
- Introduction of new categories of contaminants should be prevented.
- Determine effects of change in temperature and pH for all life stages of all diadromous species. Use this information to model impacts of climate change on species.
- Develop studies to document which contaminants have an impact on the various life stages of each diadromous species; also note the life stages that are affected and at what concentrations.
- Determine unknown optima and tolerance ranges for depth, temperature, salinity, dissolved oxygen, pH, substrate, current velocity, and suspended solids.

Habitat Protection and Restoration

- Use multi-scale approaches (including GIS) to assess indicators of suitable habitat, using watershed and stream-reach metrics if possible (it should be noted, that where site specific data is lacking, it may not be appropriate to assess at this scale).
- Use multi-scale approaches for restoring diadromous fish habitat, including vegetated buffer zones along streams and wetlands, and implementing measures to enhance acid-neutralizing capacity.
- Conduct studies on the effects of land use change on diadromous species population size, density, distribution, health, and sustainability.
- Examine how deviation from the natural flow regime impacts all diadromous species. This work should focus on key parameters such as rate of change (increase and decrease), seasonal peak flow, and seasonal base flow, so that the results can be more easily integrated into a year-round flow management recommendation by state officials.
- Investigate consequences to diadromous stocks from wetland alterations.
- When states have identified habitat protection or restoration as a need, state marine fisheries agencies should coordinate with other agencies to ensure that habitat restoration plans are developed, and funding is actively sought for plan implementation and monitoring.
- Any project resulting in elimination of EFH (e.g., dredging, filling) should be avoided.
- Substrate mapping of freshwater tidal portions of rivers should be performed to determine suitable diadromous fish habitat, and that habitat should be protected and restored as needed.
- States should notify in writing the appropriate federal and state regulatory agencies of the locations of habitats used by diadromous species. Regulatory agencies should be advised of the types of threats to diadromous fish populations, and recommended measures that should be employed to avoid, minimize, or eliminate any threat to current habitat quantity or quality.

- Each state encompassing diadromous fish spawning rivers and/or producer areas should develop water use and flow regime guidelines protective of diadromous spawning and nursery areas to ensure the long-term health and sustainability of the stocks.

Permitting

- Develop policies for limiting development projects seasonally or spatially in spawning and nursery areas; define and codify minimum riparian buffers and other restrictions where necessary.
- Projects involving water withdrawal (e.g., power plants, irrigation, water supply projects) should be scrutinized to ensure that adverse impacts resulting from impingement, entrainment, and/or modifications of flow and salinity regimes due to water removal will not adversely impact diadromous fish stocks.
- State fishery regulatory agencies should develop protocols and schedules for providing input on Federal permits and licenses required by the Clean Water Act, Federal Power Act, and other appropriate vehicles, to ensure that diadromous fish habitats are protected.

Other

- Determine survival and mortality rates for all life stages of all diadromous species.
- Investigate predator-prey relationships for all life stages of all diadromous species.
- Determine the effects of channel dredging, shoreline filling, and overboard spoil disposal in the Atlantic coast on diadromous species.
- Define restrictions necessary for implementation of energy projects in diadromous species habitat areas and develop policies on limiting development projects seasonally and/or spatially.
- Promote cooperative interstate research monitoring and law enforcement. Establish criteria, standards, and procedures for plan implementation as well as determination of state compliance with management plan provisions.
- Diadromous fish may be vulnerable to mortality in hydrokinetic power generation facilities, and such projects should be designed and monitored to eliminate, or minimize, fish mortality.
- The use of any fishing gear that is deemed by management agencies to have an unacceptable impact on diadromous fish habitat should be prohibited within appropriate essential habitats (e.g., trawling in spawning areas or primary nursery areas should be prohibited).

Common Socioeconomic Research Recommendations for all Commission Managed Species

- Establish time series of social and economic data for use in management decisions. This is analogous to biological time series data that are currently being used in decision making for monitoring and fisheries management.
- Existing social and economic data sets are deficient and remedial. Develop and collect baseline of sociodemographic data for all Atlantic states by state, species, and community for commercial fishing and by state, species, community, and sector (boat, shore, and for-hire) for recreational and subsistence fisheries. Community profiles should include information on the infrastructure in support of the fisheries (e.g., provision of boat launches, haul-out yards, marine suppliers, recreational fishing docks).
- Update baseline data on a regular basis (e.g., every 3 years).
- Focus on research additional to the baseline for decisions to be made in the next few years.
- Evaluate existence value and non-consumptive use value (cultural and economic) for species that the ASMFC has protected through moratoria.