Northeast Fisheries Science Center Reference Document 18-06

64th Northeast Regional Stock Assessment Workshop (64th SAW) Assessment Report

by the Northeast Fisheries Science Center

April 2018

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NOAA Fisheries, Northeast Fisheries Science Center,
166 Water Street, Woods Hole, MA 02543

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Marine Fisheries Service
Northeast Fisheries Science Center
Woods Hole, Massachusetts

April 2018

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Information Quality Act Compliance: In accordance with section 515 of Public Law 106-554, the Northeast Fisheries Science Center completed both technical and policy reviews for this report. These predissemination reviews are on file at the NEFSC Editorial Office.

This document may be cited as:

Northeast Fisheries Science Center (NEFSC). 2018. 64th Northeast Regional Stock Assessment Workshop (64th SAW) Assessment Report. US Dept Commer, Northeast Fish Sci Cent Ref Doc. 18-04; 529 p. Available from: http://www.nefsc.noaa.gov/publications/

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FOREWORD

The Northeast Regional Stock Assessment Workshop (SAW) process has three parts: preparation of stock assessments by the SAW Working Groups and/or by ASMFC Technical Committees / Assessment Committees; peer review of the assessments by a panel of outside experts who judge the adequacy of the assessment as a basis for providing scientific advice to managers; and a presentation of the results and reports to the Region's fishery management bodies.
Starting with SAW-39 (June 2004), the process was revised in two fundamental ways. First, the Stock Assessment Review Committee (SARC) became smaller panel with panelists provided by the Independent System for Peer Review (Center of Independent Experts, CIE). Second, the SARC provides little management advice. Instead, Council and Commission teams (e.g., Plan Development Teams, Monitoring and Technical Committees, Science and Statistical Committee) formulate management advice, after an assessment has been accepted by the SARC. Starting with SAW-45 (June 2007) the SARC chairs were from external agencies, but not from the CIE. Starting with SAW-48 (June 2009), SARC chairs are from the Fishery Management Council's Science and Statistical Committee (SSC), and not from the CIE. Also at this time, some assessment Terms of Reference were revised to provide additional science support to the SSCs, as the SSC's are required to make annual ABC recommendations to the fishery management councils.

Reports that are produced following SAW/SARC meetings include: An *Assessment Summary Report* - a summary of the assessment results in a format useful to managers; an *Assessment Report* – a detailed account of the assessments for each stock; and the SARC panelist reports – a summary of the reviewer's opinions and recommendations as well as individual reports from each panelist. SAW/SARC assessment reports are available online at

http://www.nefsc.noaa.gov/nefsc/publications/series/crdlist.htm. The CIE review reports and assessment reports can be found at *http://www.nefsc.noaa.gov/nefsc/saw/*".
The 64th SARC was convened in Woods Hole at the Northeast Fisheries Science Center, November 28-30, 2017 to review a benchmark stock assessment of Atlantic mackerel. CIE reviews for SARC64 were based on detailed reports produced by NEFSC Assessment Working Groups. This Introduction contains a brief summary of the SARC comments, a list of SARC panelists, the meeting agenda, and a list of attendees (Tables 1 – 3). Maps of the Atlantic coast of the USA and Canada are also provided (Figures 1 - 5).

Outcome of Stock Assessment Review Meeting:

Text in this section is based on SARC-64 Review Panel reports (available at http://www.nefsc.noaa.gov/nefsc/saw/ under the heading "SARC-64 Panelist Reports").

SARC 64 concluded the stock of Atlantic Mackerel (*Scomber scombrus*) in the Northwest Atlantic is currently overfished and overfishing is occurring. An assessment model (ASAP) containing a northern and a southern contingent of the single stock was

accepted by the SARC as the best scientific information available for determining stock status. $F_{40\%}$, as proposed by the SAW WG, is considered by the SARC to be an acceptable proxy for F_{MSY}, the overfishing threshold.

Table 1. 64th Stock Assessment Review Committee Panel.

SARC Chairman (MAFMC SSC):

Dr. John Boreman
MAFMC SSC Chair
North Carolina State Univ.

SARC Panelists (CIE):

Dr. Robin Cook
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Glasgow, UK
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Dr. Kevin Stokes
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Dr. Joseph Powers
Joseph Powers Consulting
Washington DC, 20002
Email: j.powers.fish@gmail.com

Table 2. Agenda, 64th Stock Assessment Review Committee Meeting.

Nov. 28-30, 2017

Stephen H. Clark Conference Room – Northeast Fisheries Science Center
Woods Hole, Massachusetts

AGENDA* (version: 11/19/2017)

TOPIC	PRESENTER(S)	SARC LEADER	RAPPORTEUR

Tuesday, Nov. 28

10 – 10:30 AM			
Welcome		**James Weinberg**, SAW Chair	
Introduction		**John Boreman,** SARC Chair	
Agenda			
Conduct of Meeting			
10:30 – 12:30 PM	Assessment Presentation (A. Mackerel)		
		Kiersten Curti	**TBD**
12:30 – 1:30 PM	Lunch		
1:30 – 3:30 PM	Assessment Presentation (A. Mackerel)		
		Kiersten Curti	**TBD**
3:30 – 3:45 PM	Break		
3:45 – 5:45 PM	SARC Discussion w/ Presenters (A. Mackerel)		
		John Boreman , SARC Chair	**TBD**
5:45 – 6 PM	Public Comments		
7 PM	**(**Social Gathering**)**		

TOPIC	PRESENTER(S)	SARC LEADER	RAPPORTEUR

Wednesday, Nov. 29

9:00 – 10:45	Revisit with Presenters (A. Mackerel)	**John Boreman,** SARC Chair	**TBD**
10:45 - 11	Break		
11 – 11:45	Revisit with Presenters (A. Mackerel)	**John Boreman ,** SARC Chair	**TBD**
11:45 – Noon	Public Comments		
12 – 1:15 PM	Lunch		
1:15 – 4	Review/Edit Assessment Summary Report (A. Mackerel)	**John Boreman ,** SARC Chair	**TBD**
4 – 4:15 PM	Break		
4:15 – 5:00 PM	SARC Report writing		

Thursday, Nov. 30

9:00 AM – 5:00 PM	SARC Report writing

*All times are approximate, and may be changed at the discretion of the SARC chair. The meeting is open to the public; however, during the Report Writing sessions on Nov 29-30, we ask that the public refrain from engaging in discussion with the SARC.

Table 3. 64th SAW/SARC, List of Attendees, Nov. 28-30, 2017

NAME	AFFILIATION	EMAIL
Russ Brown	NEFSC	russell.brown@noaa.gov
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Robin Cook	Univ. Strathclyde	melford@clara.co.uk
Joe Powers	Joseph Powers Consulting	j.powers.fish@gmail.com

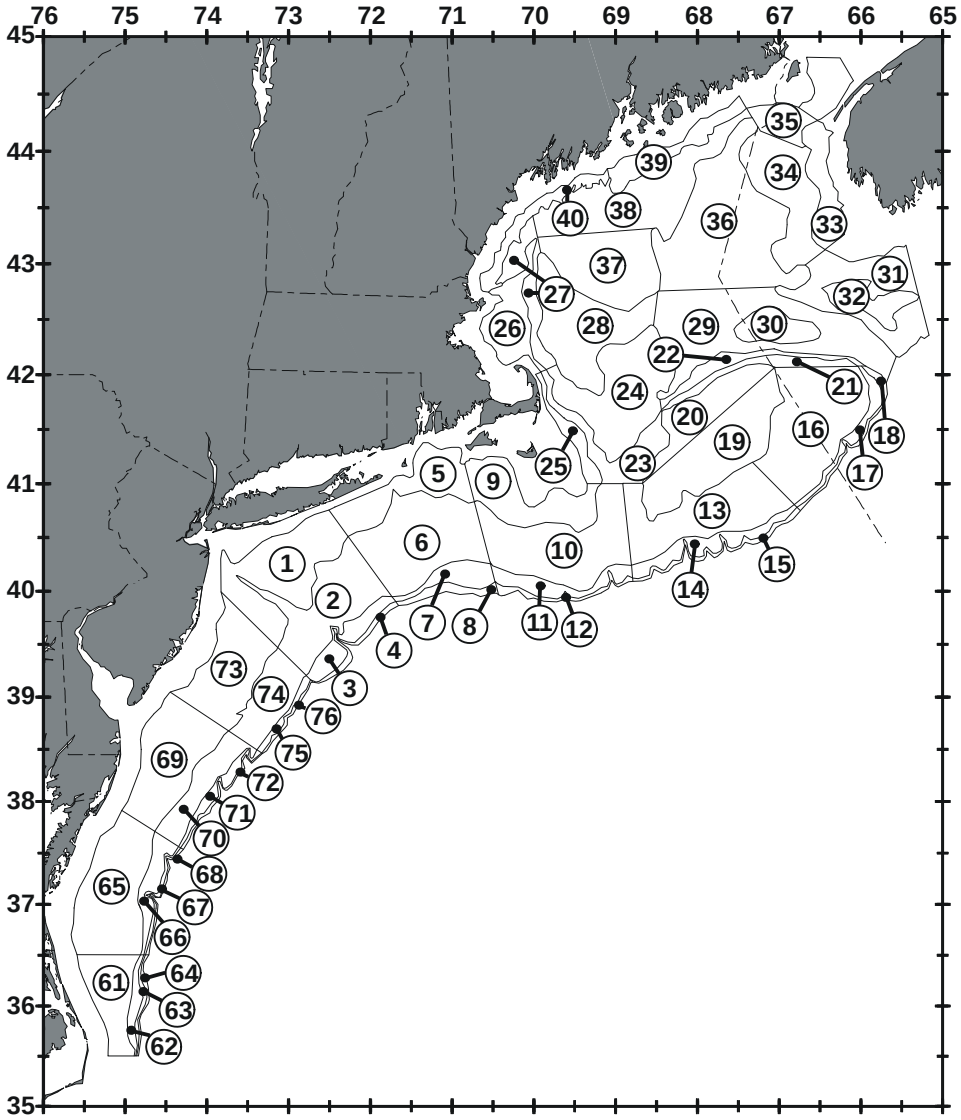


Figure 1. Offshore depth strata that have been sampled during Northeast Fisheries Science Center bottom trawl research surveys. Some of these may not be sampled presently.

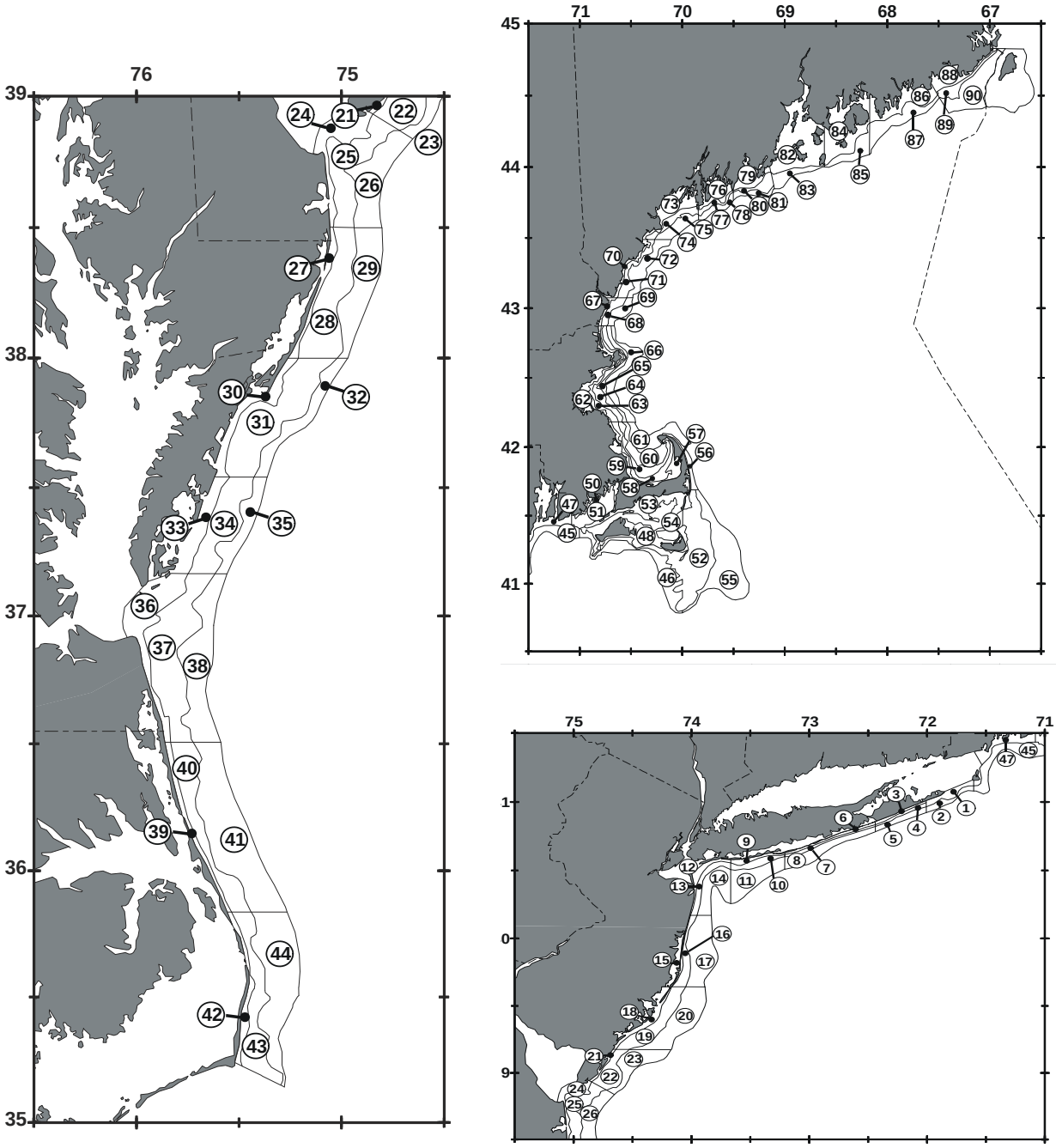


Figure 2. Inshore depth strata that have been sampled during Northeast Fisheries Science Center bottom trawl research surveys. Some of these may not be sampled presently.

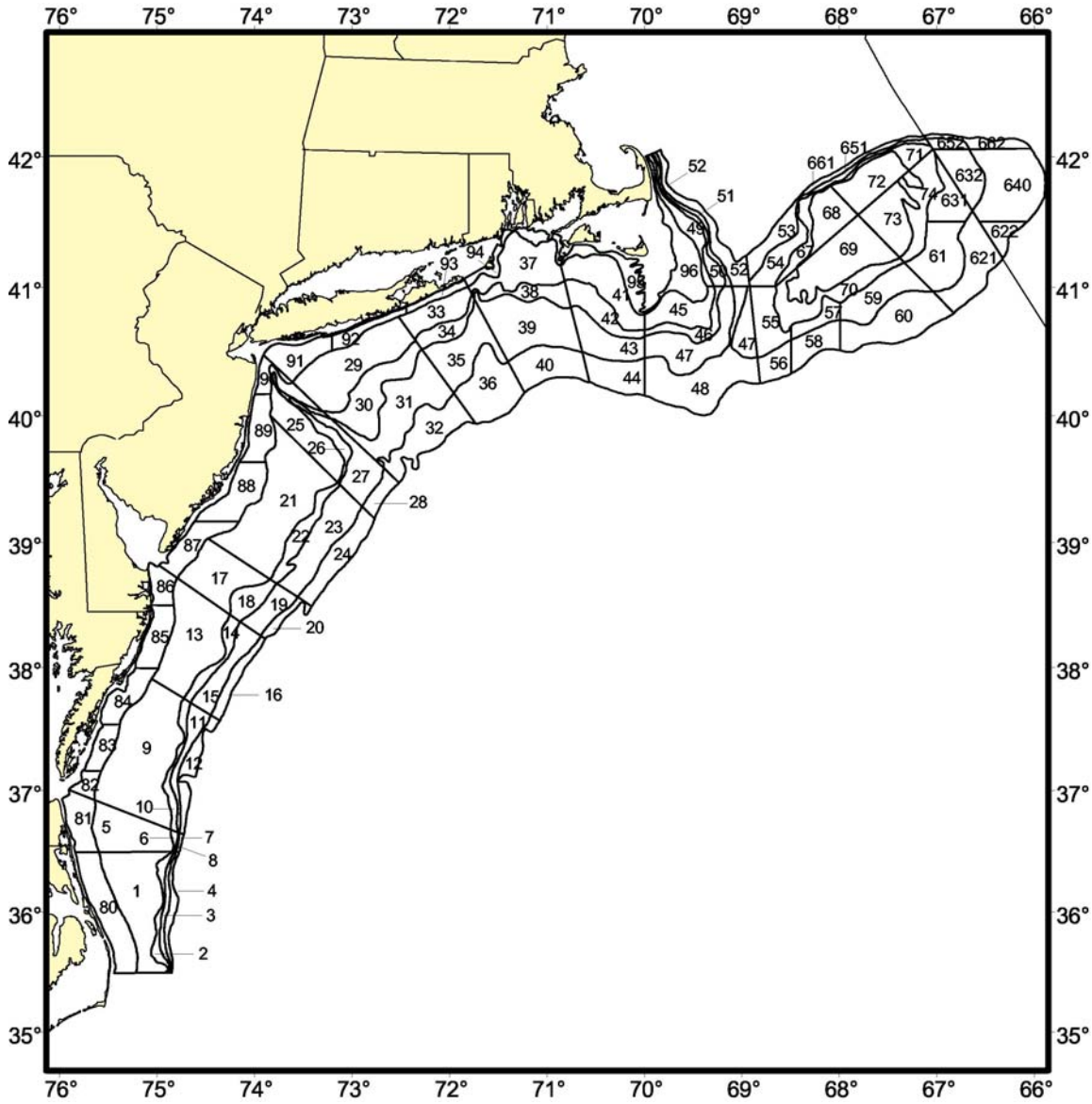
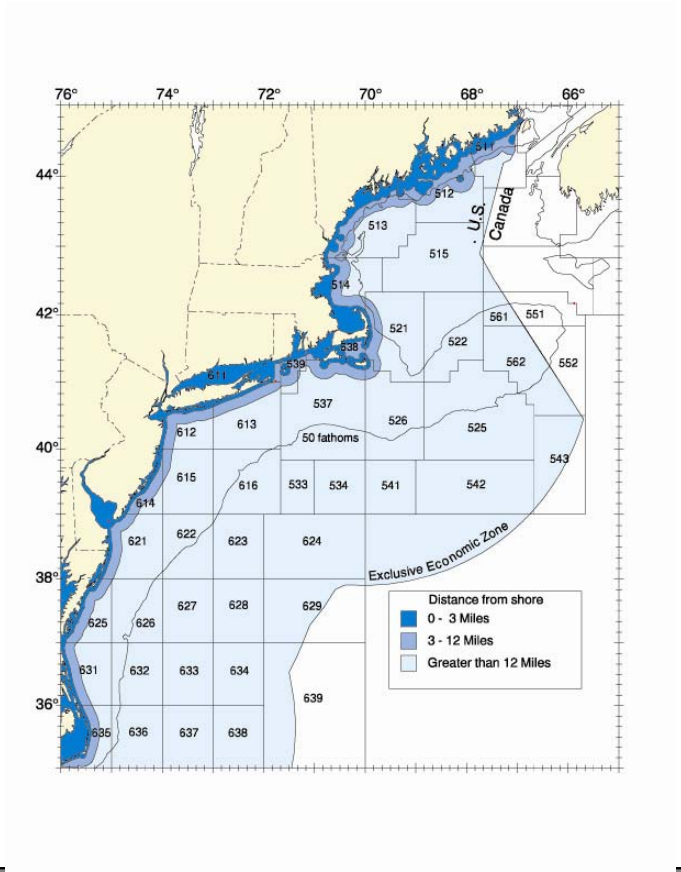


Figure 3. Depth strata sampled during Northeast Fisheries Science Center clam dredge research surveys.



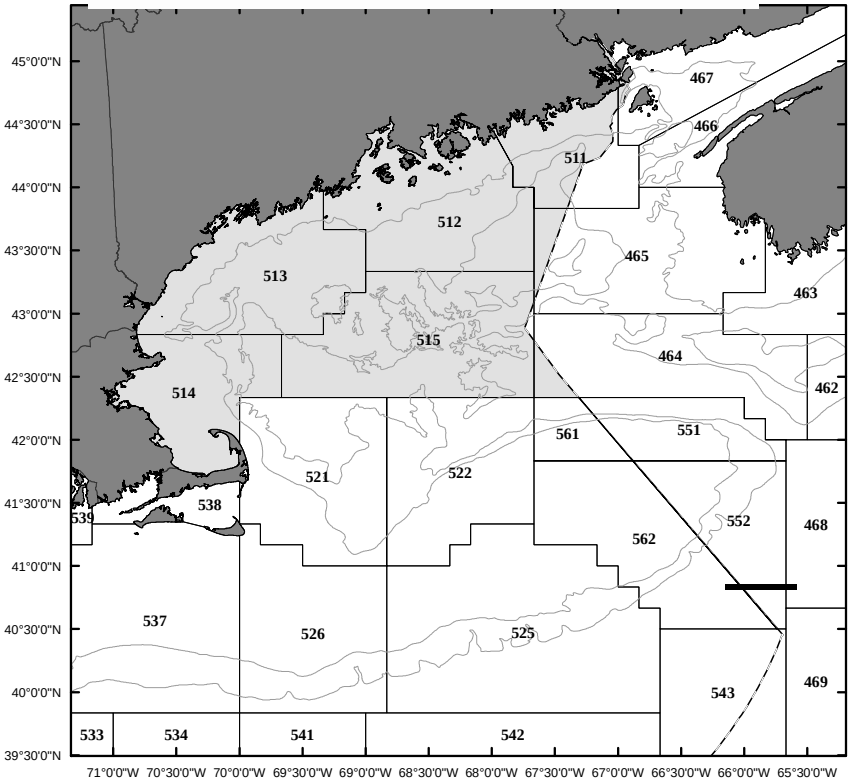


Figure 4. Statistical areas used for reporting commercial catches.

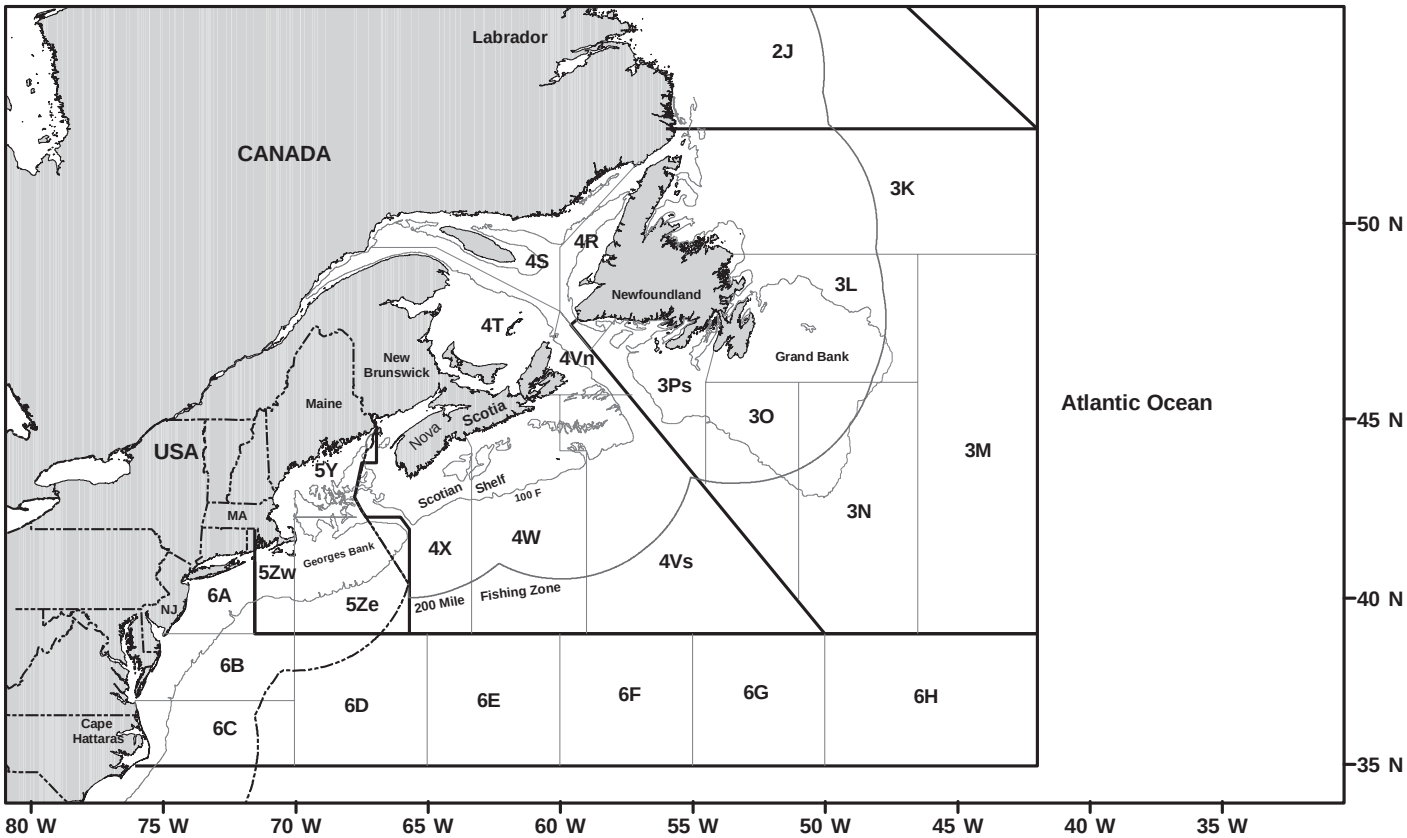


Figure 5. Catch reporting areas of the Northwest Atlantic Fisheries Organization (NAFO) for Subareas 3-6.

EXECUTIVE SUMMARY

TOR 1. Spatial and ecosystem influences on stock dynamics:

a. *Evaluate possible spatial influences on the stock dynamics. Recommend any need to modify the current stock definition for future stock assessments.*

b. *Describe data (e.g., oceanographic, habitat, or species interactions) that might pertain to Atlantic mackerel distribution and availability. If possible, integrate the results into the stock assessment (TOR-4).*

Atlantic mackerel in the northwest Atlantic have two primary spawning contingents: one group in the Gulf of St. Lawrence and a second in the coastal New England/Mid-Atlantic region. Seasonal migrations result in a winter mixture of both contingents in U.S. waters, generally Georges Bank and south. Recent research on otolith microchemistry has shown unique characteristics of fish originating in the U.S. compared to Canada and concluded that juvenile fish remain in their area of origin during the first year. However, by age-2 there is an increasing mixture of both contingents during the winter in U.S. waters. Despite the distinct spawning areas, there is currently no evidence that mackerel spawning is spatially separated to the extent that it results in genetically distinct stocks. Although with additional research it may be possible to distinguish the contingents in the mixed winter fishery, the current assessment was conducted under the assumption of a single stock with two contingents.

Mackerel habitats and species interactions were examined in relation to spatial distribution. Fishermen who have targeted Atlantic mackerel in the U.S. winter fishery since the 1980s describe a seasonal migration along the outer continental shelf of the Mid-Atlantic in early winter, moving as far south as North Carolina. In late winter the migratory schools turned north with some groups moving inshore along the coast and other groups further offshore. In recent years the winter migratory pattern has changed with few fish in the Mid-Atlantic and more remaining in southern New England and Georges Bank. The working group (AMWG) examined changes in thermal habitat, which alone could not explain the change in spatial distribution over time. There have been changes in primary and secondary productivity in the Mid-Atlantic, which the AMWG considered and concluded may contribute to changes in mackerel spatial distributions. Consumption of Atlantic mackerel and predator abundance was also examined but was not informative regarding changes in spatial distributions. The overall pattern of spatial distribution was used to inform decisions regarding recruitment patterns in the stock assessment but was not used explicitly within the model framework.

TOR 2. Estimate catch from all sources including landings and discards. Describe the spatial and temporal distribution of landings, discards, and fishing effort. Characterize the uncertainty in these sources of data.

Commercial fisheries for northwest Atlantic mackerel are prosecuted in U.S. and Canadian waters. Commercial landings in U.S. waters were several metric tons annually until the 1970s with the arrival of foreign fleets. Between 1969 and 1976, foreign landings averaged over 260,000 mt, peaking at 396,759 mt in 1973. Following implementation of the U.S. exclusive economic zone,

some foreign vessels remained and participated in joint-venture operations with U.S. vessels until 1991, at which point it became exclusively U.S. vessels. Atlantic mackerel U.S. commercial landings increased beginning in the late 1980s and reached 56,640 mt in 2006, which also coincided with a peak in Canadian landing of 53,960 mt. Landings in both countries have since declined to a total of 13,687 mt in 2016. In addition to commercial fisheries, recreational fisheries also occur in both countries, although catch estimates are limited to the U.S. fishery. U.S. recreational catch peaked in 1986 at 4,223 mt and has averaged 1,651 mt since 1981. Commercial discards in U.S. fisheries have been a relatively minor component of the catch, ranging from 13 mt in 2015 to 5,409 mt in 1994, and averaging less than 800 mt annually since 1989.

When landings by the U.S. domestic fleet increased, the fishery was prosecuted primarily by trawlers in the Mid-Atlantic/Georges Bank region from January to April. However, since 2011 the timing of the fishery has shifted towards October through December. In addition, fishing effort has shifted north such that the majority of the catch is from southern New England and the Gulf of Maine. The Canadian fishery is primarily a summer fishery in the Gulf of St. Lawrence, although in recent years notable catches have also occurred from the waters around Newfoundland.

Mackerel landings in the U.S. fishery are collected from dealer reports and are considered a census of total landings. The fishery is dominated by commercial landings from one major gear type. Consequently, dockside samples collected from landings are representative of the majority of the fishery. U.S. commercial discard sampling is part of a larger program targeting a variety of gear types. The coefficient of variation (CV) for discard estimates averages 70%, although this is influenced by three years that have CVs greater than 1.0. Recreational sampling is based on dockside intercepts of random trips such that sampling intensity of mackerel is a function of abundance and trip targeted species. The percent standard error for recreational catch estimates has averaged 15.8% since 1981. Canadian fishery landings are collected from annual reports; however commercial discards, bait fishery landings and recreational catch are unreported.

TOR3. Evaluate fishery independent and fishery dependent indices being used in the assessment (e.g., indices of relative or absolute abundance, recruitment, state surveys, age-length data, etc.). Characterize the uncertainty and any bias in these sources of data.

Following evaluation of a variety of fishery independent surveys, the AMWG selected the NEFSC spring bottom trawl survey, the U.S. egg survey and the Canadian egg survey for use in the assessment model. The bottom trawl survey series began in 1968 and involved primarily two vessels, the *Albatross IV* through 2008 and the *Henry. B. Bigelow* since 2009. A change in nets and towing protocol for the *Bigelow* resulted in potential changes in catchability; therefore, survey data were divided into a time series for each vessel. The *Albatross* series showed an increase in relative abundance between 1980 and 2000, followed by indices with large inter-annual variability, with CVs between 0.21 and 0.94. The *Bigelow* indices initially declined but subsequently increased to the series high in 2015. Age composition of the catches included fish to 10^+ until approximately 2000, beyond which the age distribution became increasingly truncated. Since 2000, the indices have been dominated by ages 1 and 2 with occasional 3 year old fish. The maximum age has decreased to age 6 or 7. There remains some uncertainty regarding the suitability of the gear for effectively capturing Atlantic mackerel and whether the indices adequately reflect relative

abundance. The proportion of positive tows rather than abundance-per-tow was also examined; there was a steady increase in the proportion of positive tows from 6.2% in 1969 to 41.6% in 2016.

Canada's Division of Fisheries and Oceans has conducted a dedicated Atlantic mackerel egg survey in the Gulf of St. Lawrence since 1979. Egg densities, in addition to biological data collected during the survey period, are used to develop an estimate of spawning stock biomass. The U.S. also conducts annual ichthyoplankton surveys, although not specifically targeting mackerel. The surveys have occurred from 1977-1987 and 1999 through the present. Recent efforts have been made to identify mackerel eggs in the U.S. samples and develop SSB estimates comparable to those of the Canadians. The estimates from the U.S. and Canadian surveys were combined and used in the assessment model for years when both surveys occurred. The combined SSB index declined over the time series from a peak in 1986 of 1.8 million mt to a low of 29.3 thousand mt in 2010. SSB has increased since 2010, reaching 55 thousand mt in 2016. Although the southern contingent contributed up to 43% of the SSB in 1983, the majority of the SSB has come from the northern contingent since the mid-1980s.

TOR4. Estimate annual fishing mortality, recruitment and stock biomass (both total and spawning stock) for the time series, and estimate their uncertainty. Develop alternative approaches which might also be able to estimate population parameters. Include a comparison of new assessment results with those from previous assessment(s).

A statistical catch-at-age model (ASAP) was developed to estimate fishing mortality, recruitment and biomass beginning with catch from 1968. Catch-at-age data from the previous assessment was used for years prior to 1992. Although the primary model framework was ASAP, a censored catch assessment model (CCAM) and a state-space stock assessment model (SAM) were developed to examine model uncertainty. Spring bottom trawl survey indices for ages-3^+ (evidence suggests ages 1 and 2 may not be representative of the mixed contingents) and the combined egg survey index were used in the ASAP and SAM models. CCAM can only incorporate one index; therefore, the egg index was used. Natural mortality was fixed at 0.2 for all years and ages. The Atlantic mackerel stock in the northwest Atlantic (both contingents combined) exhibited a dramatic drop in spawning stock biomass from a peak in 1972 of 1.1 million mt to 16,837 mt in 2012. Spawning stock biomass in 2016 equaled 43,519 mt with a 90% CI between 23,462 and 77,672 mt. Strong recruitments in 1982 and 1999 resulted in temporary increases in biomass; however, declining recruitment coupled with increases in fishing mortality since 2002 resulted in decreased biomass. Fishing mortality approached or exceeded 1.0 between 2006 and 2014 but declined to 0.47 (90% CI between 0.25 and 0.93) in 2016. Recruitment in 2016 was estimated to be 455 million fish. The results did not show significant retrospective bias and it was concluded that retro-adjustments were unnecessary. The results of the ASAP model were similar to results from both the CCAM and SAM models, implying limited uncertainty in the results due to model selection.

TOR5. State the existing stock status definitions for "overfished" and "overfishing". Then update or redefine biological reference points (BRPs; point estimates or proxies for B_{MSY}, $B_{THRESHOLD}$, F_{MSY} and MSY) and provide estimates of their uncertainty. If analytic model-based estimates are

unavailable, consider recommending alternative measurable proxies for BRPs. Comment on the scientific adequacy of existing BRPs and the "new" (i.e., updated, redefined, or alternative) BRPs.

There are no current biological reference points for this stock of Atlantic mackerel in U.S. waters; therefore, stock status definitions are not available. The assessment working group concluded that Atlantic mackerel results showed no evidence of a stock recruitment relationship and recommended $F_{40\%}$ be used as a proxy for F_{MSY} and total spawning stock biomass at $F_{40\%}$ ($SSB_{40\%}$) be used as the proxy for the stock biomass reference point. The $F_{40\%}$ value produced an $F_{MSY\ proxy}$ of 0.26. Based on a long-term projection at F_{MSY} proxy, the associated $SSB_{MSY\ proxy}$ equaled 196,894 mt, $B_{MSY\ proxy}$ equaled 255,646 mt, and MSY_{proxy} equaled 41,334 mt. The working group recommended that the stock be considered overfished if SSB is below the threshold equal to ½ $SSB_{MSY\ proxy}$, which equals 98,447 mt.

TOR6. Make a recommended stock status determination (overfishing and overfished) based on new results developed for this peer review. Include qualitative written statements about the condition of the stock that will help to inform NOAA Fisheries about stock status.

The Atlantic mackerel assessment working group recommends that the stock be considered overfished and experiencing overfishing. Estimated spawning stock biomass in 2016 is 44% of the biomass threshold for overfished (½ $SSB_{MSY\ proxy}$, 98,447 mt) and 22% of $SSB_{MSY\ proxy}$ (196,894 mt). Additionally, the 2016 estimate of fishing mortality is 0.47, which exceeds the $F_{MSY\ proxy}$ of 0.26. It should be noted that the estimates of F and SSB are the product of fisheries in both the U.S. and Canada. Currently each country independently manages the component of the stock available to that country's fisheries.

TOR7. Develop approaches and apply them to conduct stock projections.

a. *Provide numerical annual projections (3 years) and the statistical distribution (e.g., probability density function) of the catch at F_{MSY} or an F_{MSY} proxy (i.e. the overfishing level, OFL) (see Appendix to the SAW TORs). Each projection should estimate and report annual probabilities of exceeding threshold BRPs for F, and probabilities of falling below threshold BRPs for biomass. Use a sensitivity analysis approach in which a range of assumptions about the most important uncertainties in the assessment are considered (e.g., terminal year abundance, variability in recruitment).*

b. *Comment on which projections seem most realistic. Consider the major uncertainties in the assessment as well as sensitivity of the projections to various assumptions. Identify reasonable projection parameters (recruitment, weight-at-age, retrospective adjustments, etc.) to use when setting specifications.*

c. *Describe this stock's vulnerability (see "Appendix to the SAW TORs") to becoming overfished, and how this could affect the choice of ABC.*

Stochastic short-term projections were conducted to provide forecasts of stock size and catches in 2018-2020 consistent with the new biological reference points proposed in this assessment. Projections at $F_{MSY\ proxy}$ showed an increase in catch to 33,250 mt by 2020. Spawning stock and

January-1 biomass increased to 165,487 and 216,681 mt, respectively, by 2020, and while greater than ½ $SSB_{MSY\ proxy}$ and ½ $B_{MSY\ proxy}$, both biomasses would still be under the biomass estimates associated with $F_{MSY\ proxy}$ (196,894 mt for $SSB_{msy\ proxy}$ and 255,646 mt for $B_{msy\ proxy}$). Accordingly, the stock is vulnerable to being overfished.

Projections at the status quo F (0.47) showed a notable increase in catch to 42,092 - 44,524 mt between 2018-2020, which exceeded MSY_{proxy} (41,334 mt). Both spawning stock and January-1 biomass estimates increased through 2019 and then declined in 2020, with both estimates still below the corresponding reference points associated with $F_{MSY\ proxy}$ in 2020. In the absence of fishing, spawning stock and January-1 biomasses increased substantially across all years and were projected to be 238,976 mt and 281,175 mt, respectively, by 2020, which exceeded $SSB_{msy\ proxy}$ and $B_{msy\ proxy}$.

TOR8. Review, evaluate and report on the status of the SARC and Working Group research recommendations listed in most recent peer reviewed assessment and review panel reports. Identify new research recommendations.

The AMWG reviewed the status of previous research recommendations and proposed new ones to address issued raised during the working group meetings. Of the 16 research recommendations brought forward from the 2009 TRAC, 13 have been either partially or fully addressed. The remaining research recommendations from the 2009 TRAC include the regular exchange of otoliths between the NEFSC and DFO to monitor agreement between age readers, exploration of bottom trawl characteristics for mackerel catchability, and collaboration with industry to investigate alternative sampling gear to survey adult abundance.

The AMWG proposed ten new research recommendations, which include the continuation of the U.S. component of the mackerel egg survey and subsequent sample processing to ensure the range-wide egg index can be used in future assessments, several recommendations regarding mackerel biology (fecundity, maturity, larval survival), and the continuation of stock structure research to distinguish the two spawning contingents.

ATLANTIC MACKEREL WORKING GROUP

The SARC 64 Atlantic Mackerel Working Group conducted a Data meeting (May 8-11, 2017) and a Model meeting (August 15-18, 2017) in the development of this assessment. Prior to the WG meetings, two workshops with stakeholders were conducted in December 2015 and 2016. The SAW/SARC Mackerel Working Group members are:

Gary Shepherd – NEFSC Population Dynamics (WG-Chair)

Kiersten Curti – NEFSC Population Dynamics (Assessment lead)

Martin Castonguay- Department of Fisheries and Oceans Canada

Thomas Doniol-Valcroze – Department of Fisheries and Oceans Canada

Elisabeth Van Beveren – Department of Fisheries and Oceans Canada

Andrew Smith – Department of Fisheries and Oceans Canada

J.J. Maguire – SCeMFIS

Charles Adams – NEFSC Population Dynamics

David Richardson –NEFSC Oceans and Climate

John Manderson – NEFSC Oceans and Climate/Cooperative Research

Jason Didden – Mid-Atlantic Fisheries Management Council

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TERMS OF REFERENCE: Atlantic mackerel (NAFO Subareas 3-6)

1. Spatial and ecosystem influences on stock dynamics:
   a. Evaluate possible spatial influences on the stock dynamics. Recommend any need to modify the current stock definition for future stock assessments.
   b. Describe data (e.g., oceanographic, habitat, or species interactions) that might pertain to Atlantic mackerel distribution and availability. If possible, integrate the results into the stock assessment (TOR-4).
2. Estimate catch from all sources including landings and discards. Describe the spatial and temporal distribution of landings, discards, and fishing effort. Characterize the uncertainty in these sources of data.
3. Evaluate fishery independent and fishery dependent indices being used in the assessment (e.g., indices of relative or absolute abundance, recruitment, state surveys, age-length data, etc.). Characterize the uncertainty and any bias in these sources of data.
4. Estimate annual fishing mortality, recruitment and stock biomass (both total and spawning stock) for the time series, and estimate their uncertainty. Develop alternative approaches which might also be able to estimate population parameters. Include a comparison of new assessment results with those from previous assessment(s).
5. State the existing stock status definitions for "overfished" and "overfishing". Then update or redefine biological reference points (BRPs; point estimates or proxies for B_{MSY}, $B_{THRESHOLD}$, F_{MSY} and MSY) and provide estimates of their uncertainty. If analytic model-based estimates are unavailable, consider recommending alternative measurable proxies for BRPs. Comment

on the scientific adequacy of existing BRPs and the "new" (i.e., updated, redefined, or alternative) BRPs.

6. Make a recommended stock status determination (overfishing and overfished) based on new results developed for this peer review. Include qualitative written statements about the condition of the stock that will help to inform NOAA Fisheries about stock status.
7. Develop approaches and apply them to conduct stock projections.
   a. Provide numerical annual projections (3 years) and the statistical distribution (e.g., probability density function) of the catch at F_{MSY} or an F_{MSY} proxy (i.e. the overfishing level, OFL) (see Appendix to the SAW TORs). Each projection should estimate and report annual probabilities of exceeding threshold BRPs for F, and probabilities of falling below threshold BRPs for biomass. Use a sensitivity analysis approach in which a range of assumptions about the most important uncertainties in the assessment are considered (e.g., terminal year abundance, variability in recruitment).
   b. Comment on which projections seem most realistic. Consider the major uncertainties in the assessment as well as sensitivity of the projections to various assumptions. Identify reasonable projection parameters (recruitment, weight-at-age, retrospective adjustments, etc.) to use when setting specifications.
   c. Describe this stock's vulnerability (see "Appendix to the SAW TORs") to becoming overfished, and how this could affect the choice of ABC.
8. Review, evaluate and report on the status of the SARC and Working Group research recommendations listed in most recent peer reviewed assessment and review panel reports. Identify new research recommendations.

INTRODUCTION

Assessment history

The first assessment of Atlantic mackerel in the northwest Atlantic was conducted in 1973 for NAFO subareas 5-6 (Figure A1, Anderson 1973) and in 1975 for the total stock area incorporating subareas 3-6 (Anderson 1975). The 1975 assessment was based on a virtual population analysis (VPA) and indicated that fishing mortality rates ranging from 0.72-0.82 would be necessary to take the total allowable catches (TACs) set for 1974 and 1975. Fishing mortality generally increased from 1968 through 1972 and reached a maximum of 0.48 in 1972. The stock was reassessed three times in 1976 to provide recommendations for the 1977 TAC, which was upheld when the U.S. extended their fisheries jurisdiction to 200 miles and withdrew from the International Commission for the Northwest Atlantic Fisheries (ICNAF) (Anderson and Paciorkowski 1980).

After the U.S. withdrew from ICNAF, the U.S. National Marine Fisheries Service (NMFS) completed an assessment in 1977 that included international commercial and U.S. recreational catches, U.S. bottom trawl survey indices, fishing mortality and stock size estimated from cohort

analysis, recruitment estimates and stock projections (Anderson 1977). Spawning stock biomass (SSB) generally increased from 1962 through the early 1970s and then decreased through 1977 to the lowest level of the time series. Fishing mortality (F) generally increased from 1962 to a maximum in 1976, and then decreased in 1977; an estimated F of 0.07 would maintain the SSB at the 1978 level and concerns were raised if the SSB decreased below the projected 1978 level. (Anderson 1977).

From 1978-1987, assessments were completed annually (Anderson and Overholtz 1978, Anderson and Overholtz 1979a, Anderson and Overholtz 1979b, Anderson 1980, Anderson 1981, Anderson 1982, Anderson 1983, Anderson 1985, Overholtz and Parry 1985, NEFC 1987). The same basic methodology was maintained, but the assessment was expanded to include NAFO subarea 2 in 1980 (Anderson 1980) and assumed a different natural mortality rate (0.2 instead of 0.3) beginning in 1982 (Anderson 1982). The decrease in the assumed natural mortality was supported by linear regressions between estimates of total mortality derived from catch data and fishing effort that indicated an average natural morality of 0.195 (Anderson 1982). The VPA conducted during the 1987 assessment update indicated that fishing mortality was low, a period of moderate to good recruitment from 1981-1985 caused the stock to increase rapidly, and stock biomass was likely approaching the levels observed in the 1970s (NEFC 1987).

Atlantic mackerel was subsequently assessed in 1990 and 1991, where a transition to the ADAPT model (VPA tuned to survey indices) occurred due to issues tuning the original VPA and a lack of convergence at low stock sizes (NEFC 1990, NEFSC 1991). With an assumed natural mortality of 0.2, the 1991 assessment indicated that stock abundance increased in the 1980s due to strong year classes with the stock reaching an estimated peak SSB in 1990 of 2.4 million mt, though stock size and fishing mortality estimates were deemed imprecise due to low catches in the late 1980s relative to the size of the stock.

An updated analytical assessment was completed in 1995 (NEFSC 1996a, NEFSC 1996b) with the ADAPT VPA model under the assumption of a natural mortality of 0.2, resulting in a fishing mortality estimate of 0.02 and a spawning stock biomass estimate of 2.1 million mt. However, the Stock Assessment Review Committee (SARC) expressed concern over the results, in particular stock size estimates that were imprecisely estimated and exhibited highly correlated residuals. The SARC also noted difficulty in the tuning of the VPA due to low recent fishing mortality rates, noisy survey indices and possibility of a non-linear relationship between indices and stock abundance.

Atlantic mackerel was subsequently assessed in 2000 at the 30th Northeast Regional Stock Assessment Workshop (SAW) (NEFSC 2000). A VPA with an assumed natural mortality of 0.2 was completed for the assessment but was not used to determine stock status due to a lack of convergence, survey variability and a strong retrospective pattern in spawning stock biomass. However due to preliminary VPA results, strong increasing trends in the NEFSC bottom trawl survey indices, and a low relative exploitation index (calculated as landings / survey biomass), it was concluded that stock biomass was likely near carrying capacity, fishing mortality was very low, recruitment was likely well above average during most of the 1990s, and the long-term potential yield of the stock was approximately 150,000 mt.

Atlantic mackerel was assessed in the U.S. in 2005 at the 42nd SAW (NEFSC 2006). A statistical catch-at-age model (Age Structured Assessment Program (ASAP), Legault and Restepo 1998) was chosen rather than the VPA used in previous assessments and natural mortality was assumed to be 0.2. The 2004 fishing mortality was estimated at 0.05 with a corresponding spawning stock biomass of 2.3 million mt. Consequently, the assessment concluded that mackerel were not overfished and overfishing was not occurring. The reviewers also noted the lack of larger, older fish in both the fishery catch-at-age and the NEFSC spring bottom trawl survey. Reviewers again noted the presence of a significant retrospective pattern in SSB, F and recruitment, however there were no adjustments made to account for the retrospective issues.

The most recent assessment of the unit stock of Atlantic mackerel occurred in 2009 within the joint U.S./Canada TRAC (Transboundary Resources Assessment Committee) process (Deroba et al. 2010). Model selection reverted back to the ADAPT VPA as the best available model. The VPA used a variable natural mortality-at-age to account for predation, where age-specific rates represented the natural mortality-at-age estimates from an ASAP predation model averaged among years. The model once again suffered from significant retrospective problems and produced results (unadjusted SSB in 2008 of 96,968 mt and unadjusted F in 2008 of 0.51) which contradicted the previous assessment. However, much of the differences between assessments were reconciled following retrospective adjustments to the 2005 and 2009 assessment results, implying that SSB from the previous assessment was overestimated and F underestimated. Uncertainty in the assessment results and model instability led reviewers to conclude that the assessment was not appropriate for management advice. The reviewers noted that much of the problem stemmed from conflicts among data (CPUE, NEFSC spring bottom trawl survey and fishery catch-at-age time series) which the model could not adequately resolve. In reviewing the results of the U.S.'s 2005 assessment, the TRAC also concluded that due to a significant retrospective pattern, the reference points from this 2005 assessment were now also considered to be inappropriate. Consequently, the TRAC assessment could not determine overfishing and overfished status, and the status of the stock is currently unknown in the U.S. (NMFS 2017).

Atlantic mackerel in Canadian waters (NAFO subareas 3-4) has been regularly assessed by Canada's DFO since approximately 1978. The most recent Canadian assessment occurred in March 2017 (DFO 2017). For this assessment, a censored catch model was developed that explicitly assumed that reported fishery catches for subareas 3-4 were underestimated and therefore biased low because the bait fishery, recreational fishery and discards are not monitored. As such, the assessment model estimated the amount of annual unreported catch based on the spawning stock biomass index developed from their dedicated egg survey, empirical fishery catch-at-age data, and upper limits to annual unreported catches that were informed by available data on bait and an online survey of Canadian mackerel fishery participants. Atlantic mackerel biomass for 2016 was estimated to be 40% of the biomass limit reference point (103,000 mt) and was classified to be in the critical zone of the Precautionary Approach (DFO 2017).

Management history

Atlantic mackerel have been harvested commercially off the U.S. coast since the 17th century, though detailed catch statistics are not available prior to 1804 (Hoy and Clark 1967). Recreational surveys indicate a substantial recreational fishery at least as far back as 1960 (Clark 1962).

Prior to 1973 mackerel fishing was essentially unregulated. From 1973-1976, mackerel was under quota management by the International Commission for the Northwest Atlantic Fisheries (ICNAF), which began to reduce landings from the peak of the early 1970's (caught mostly by foreign fleets and averaging 411,613 mt from 1971-1973). During this period over 100 factory stern trawlers (primarily from the U.S.S.R) fished for mackerel and other species during the winter/early spring (MAFMC 1978).

The Magnuson-Stevens Fishery Conservation and Management Act, first passed in 1976, set the stage for the domestication of the fishery. Direct foreign catches ended by 1978 and the first Atlantic Mackerel Fishery Management Plan (FMP) developed by the Mid-Atlantic Fishery Management Council (MAFMC) was approved in 1979 with a maximum U.S. harvest of 9,200 metric tons (mt) to avoid further depleting an overfished mackerel stock, but a 1979 assessment indicated higher harvests were possible and quotas began increasing. Early Amendments primarily updated quotas (domestic and foreign), implemented monitoring/permitting, and streamlined management by merging the mackerel, squid, and butterfish FMPs (1983). Under the FMP, foreign mackerel catches were permitted beginning in 1981 via joint-venture agreements (U.S. boats supplied foreign processors) and increased gradually to about 15,000 mt in 1984 and then to a peak of about 43,000 mt in 1988 before being phased out again by 1992. Joint venture data, like foreign fishery data, are somewhat uncertain. Since 1992, the fishery has operated solely as a domestic fishery. The fishery has operated under its quotas since 1992, so mackerel availability and world demand have been the primary drivers of recent mackerel catches. Later historical Amendments established/revised overfishing definitions, refined permitting and reporting requirements, and established essential fish habitat (EFH) designations.

Recent Amendments with applicability to Atlantic mackerel include the Omnibus Annual Catch Limit (ACL) Amendment in 2011 that gave the Scientific and Statistical Committee (SSC) the responsibility of setting an upper limit on catches that the Council may not exceed, Amendment 11 in 2012 that established limited access in the Atlantic mackerel fishery and commercial/recreational allocations, and Amendment 14 in 2014, which established a cap on river herring and shad bycatch in the Atlantic mackerel fishery (the cap can close the fishery but has never been triggered). The commercial/recreational allocation instituted in 2012 along with commercial limited access allocated 6.2% to the recreational fishery and 93.8% to the commercial fishery. The allocation was based on historical ratios but modified to recognize the higher recreational set-aside in previous years. There are no restrictions (through 2017) on the mackerel recreational fishery.

Since the 2011 Omnibus ACL Amendment, the upper limit on catches has been set by the Council's SSC. Quotas have decreased substantially in recent years; as recently as 2010 the catch could have been as high as 211,000 mt, while in 2016 the maximum acceptable biological catch (ABC) was set at about 20,000 mt (U.S. + Canada). According to the FMP, expected Canadian catch is deducted from the total catch limit; there is no resource sharing agreement. The reduction

in maximum catch limits was driven by concern that previous catch limits were set too high given the uncertain status of the mackerel stock amidst substantially declining catches.

A system of monitoring, closures, and paybacks currently serves to restrain U.S. catches, but has not been activated (other than monitoring) due to mackerel landings being below quotas. The commercial fishery currently operates under tiered limited access; landings from 1994-2005 were used in Amendment 11 to restrict the fishery to historical/recent participants starting in 2012. Most landings are made by Tier 1 (no trip limit) and Tier 2 (135,000 pound trip limit) vessels. Tier 3 vessels have a trip limit of 100,000 pounds until they catch 7% of the quota, at which point they become restricted to a 20,000 pound trip limit. They have never reached the 7% threshold. In recent years, only a small portion of the limited access vessels have participated substantially in the fishery due to limited mackerel availability; vessels landing over 1,000,000 pounds per year declined from 16-21 in 2004-2006 (peak domestic activity) to 3 in 2016. According to fishermen, much of the recent Atlantic mackerel landings are opportunistic catches on trips focused on Atlantic herring.

A variety of other indirect regulatory influences may also be restricting recent mackerel landings. While the fishery has not closed due to a river herring and shad cap, fishery participants have engaged in voluntary bycatch avoidance measures (Bethoney et al. 2013, Bethoney et al. 2017) to avoid river herring and shad. Fishery participants have also reported that regulations on Atlantic herring, which as mentioned above are co-targeted and/or co-caught at times, have limited fishing opportunities for Atlantic mackerel to varying degrees in recent years (MAFMC 2017).

BIOLOGY

Stock structure

The Atlantic mackerel, *Scomber scombrus* Linnaeus, is considered a schooling, pelagic species ranging in the Northwest Atlantic from the Gulf of St. Lawrence and off the east coast of Newfoundland in the north to North Carolina in the south. Based on size compositions, spawning locations and times, summer distributions and tagging, Oscar Elton Sette's work on the early life history (1943) and on migrations and habits (1950) provides the basis of our current understanding of mackerel stock structure. Mackerel in the Northwest Atlantic is considered to have two main spawning locations. Mackerel spawn in the southern Gulf of St. Lawrence in June-July and then move into Newfoundland, Nova Scotia, Gulf of Maine and more southern waters in fall and winter. Historically, mackerel also spawn during spring (May-June) in U.S. mid-Atlantic and southern New England waters and moves northward to Gulf of Maine and Nova Scotia waters in other seasons. These two biological units are not considered separate stocks as they overlap in overwintering concentrations off the mid-Atlantic Bight and individuals seem to be able to move from one population to the other. The two biological units are called "contingents" to account for the greater fluidity in being in one or the other spawning location. Individuals born in the northern contingent generally overwinter on the Scotian Shelf in their first year, but may join the migration south to off the Mid-Atlantic Bight in various proportion at age-2 and the majority of individuals are expected to migrate south by age-3 onward.

Northwest Atlantic mackerel stock assessments currently assume a single stock, comprised of northern and southern contingents, with natal regions centered in the southern Gulf of St. Lawrence and southern New England/mid-Atlantic Bight, respectively. With support from the NMFS Saltonstall-Kennedy Program and the MAFMC, D. Secor and colleagues (Appendix A2) investigated mixing between the two spawning contingents by discriminating juveniles and adults sampled in the spring NEFSC bottom trawl survey on the basis of otolith stable isotope values. Archived otoliths from the U.S. and Canada were carefully milled to extract carbonates corresponding to the first year of life, which were analyzed by isotope ratio mass spectrometry. Natal δ18O values in milled age-1 juvenile otoliths differed significantly between northern (Canada) and southern (U.S.) contingents based upon differences in the δ18O value of seawater and thermal conditions during otolith carbonate synthesis. Higher natal δ18O values occurred in adults (age>2) than in juveniles for four year-classes (1998-2000, 2011), indicating incursions by the northern contingent and contingent mixing within the region sampled by the NEFSC spring trawl survey.

Length-weight relationship

Length-weight parameters are used to convert commercial and recreational fishery landings and discards sampled lengths (cm) to weight (kg). Since 1992, the NEFSC bottom trawl surveys have used digital scales to record individual fish lengths (fork length is recorded for Atlantic mackerel). Wigley et al. (2003) provided an analysis of length-weight parameters using data from the bottom trawl surveys from 1992-1999 and included individual length and weight information for 5,051 Atlantic mackerel. This analysis yielded significantly different length-weight relationships between winter, autumn and spring seasons. However, a single, time-invariant length-weight equation was used in previous assessments with parameters a=0.0059 and b=3.154 (Shepherd et al. 2009, NEFSC 2006).

For the current assessment, the relationship between individual length and weight was estimated on a $\log_e$ scale as:

$$\ln(Weight) = \ln(a) + b * \ln(Length)$$

where weight was in kg and fork length in cm. Individual length and weight information from 17,096 mackerel were used to update the Wigley et al. (2003) analysis and develop semester-specific length-weight relationships by approximately 9-year intervals (Figure A2, Table A1). It is unclear whether these seasonal relationships differed significantly from the relationship used in previous assessments because the standard errors associated with those parameter estimates were not available.

The commercial mackerel industry collected length-weight data from individual mackerel during January through April 2007-2009. Length-weight relationships that incorporated industry-collected samples were compared to those based on only trawl survey samples. For both 2000-2007 and 2008-2016, length-weight relationships that included industry samples were significantly different than those that only incorporated samples from the spring bottom trawl survey (Figure A3, $p<0.01$). However, the working group decided to use length-weight parameters developed using only trawl survey samples because industry samples were not available for all of the year

intervals and were only available for the first semester. Since catches at length and age from 1992 through the present were re-estimated in this assessment on a semester basis, semester and year-bin specific length-weight relationships developed from the NEFSC trawl survey data were used in catch expansions to convert length samples to weight.

Growth

Atlantic mackerel can reach a maximum size of approximately 56 cm (Collette and Klein-McPhee 2002) with a maximum age of about 20 years. Age determination is made using whole otoliths (Penttila and Dery 1988). Age collections from the NEFSC bottom trawl survey began in 1974 and by 2016 represented 13,080 aged fish. In addition, samples from U.S. commercial fisheries contribute an additional 3,034 ages. A comparison between time series average lengths-at-age from the spring bottom trawl survey and commercial data show very little difference (Table A2, Figure A4).

Mackerel growth is characterized by fast growth within the first year, attaining an average length of 20.5 cm by spring of age 1 (spawning is June-July for the northern contingent and May-June for the southern contingent). Mean length averages 31 cm by age-3 after which growth slows, averaging 0.7 cm per year between ages 3 and 14 (Figure A4). The majority of growth occurs from spring to fall with little growth during the winter months (Figure A5). Among all age classes (age-1 to 14), average growth is 1.5 cm between the spring and fall but drops to 0.004 cm between fall and spring of the following year. Von Bertalanffy growth curve parameters were estimated from NEFSC trawl survey age data as $L_\infty = 39.18$, $t_0 = 0.749$ and $K = 0.387$.

Variation in growth over the NEFSC spring bottom trawl survey time series was most evident for ages 2 to 5 (Figure A6). Mean lengths-at-age were generally higher than the time-series median in the mid-1970s through early 1980s. From the mid-1980s to the present, average lengths-at-age varied without trend. Little or no trend was evident in the average lengths for either age-1 or age-6 and greater, in part due to a lack of data available. Studies have suggested density dependence as a potential cause for the annual variation in mean length-at-age (Overholtz et al. 1988).

Maturity

OBrien et al. (1993) examined the maturity characteristics of Atlantic mackerel based on 1,467 individuals collected during the NEFSC spring bottom trawl survey from 1987-1989. In this analysis, the median length of maturity (L_{50}) was estimated to be 25.7 cm for females and 26.0 cm for males; the median age of maturity was 1.9 years for both sexes.

For the current assessment, 5,438 individuals collected during the 1982-2016 NEFSC winter and spring bottom trawl surveys were used to update maturity ogives and examine temporal trends in maturity. Time-series values of the median age and length of maturity were estimated as 1.7 years and 24.1 cm (Figure A7). Examination of annual empirical maturity ogives showed significant increases in both age-1 ($p<0.01$; $r^2=0.52$) and age-2 ($p<0.01$; $r^2=0.53$) maturity over time, which corresponded to a decline in the maximum age observed in that year ($p<0.01$; $r^2=0.72$) (Figure A8,

Table A3). In contrast, an analysis of annual maturity ogives developed from fishery-dependent Canadian samples did not indicate significant temporal trends in age-1 ($p=0.10$, $r^2=0.06$) and age-2 ($p=0.71$, $r^2=0.003$) maturity (Table A4). Since otolith microchemistry research (see stock structure section) indicated that one and two year-olds largely represent local recruits, these temporal trends indicate a potential increase in the proportion mature-at-age for the southern contingent. Furthermore, since the majority of the spawning stock is comprised of individuals from the northern contingent (TOR3), annual maturity ogives from Canadian samples were used in all population dynamic modeling.

TOR1: Spatial and ecosystem influences on stock dynamics

a. *Evaluate possible spatial influences on the stock dynamics. Recommend any need to modify the current stock definition for future stock assessments.*
b. *Describe data (e.g., oceanographic, habitat, or species interactions) that might pertain to Atlantic mackerel distribution and availability. If possible, integrate the results into the stock assessment (TOR-4).*

Spatial influences on stock dynamics

Based on the work of Sette (1943, 1950), mackerel in the northwest Atlantic are considered to be comprised of two spawning contingents: one in the southern Gulf of St. Lawrence and the other in the Mid-Atlantic Bight, southern New England and the western Gulf of Maine (in particular Cape Cod Bay). The two contingents mix during winter months on the Northeast U.S. shelf; however, the degree of mixing and natal homing is unknown.

For this assessment, Carter and Richardson (Appendix A3) analyzed trends in the distribution of eggs in U.S. waters from 1977-2016 (Figure A9). In the late 70s and 1980s, the majority of spawning in U.S. waters occurred in Southern New England off the coasts of Long Island and Rhode Island, but spawning was also apparent on Georges Bank and the Gulf of Maine (GOM), especially the western portion. From 2000-2006, the range of spawning spread throughout most regions with the exception of the Mid-Atlantic Bight. Spawning was no longer congregated in the Southern New England region and there was more of a grouping in the western GOM and Georges Bank. In the more recent years, spawning became less widespread and eggs were primarily found in the northern regions with aggregations in the western GOM.

No new information was presented during this assessment to suggest that the contingents should be treated as separate stocks. Recent work by Secor et al. (Appendix A2) indicated different natal δ18O values between the two contingents and contingent mixing within the area sampled by the NEFSC spring bottom trawl survey; however, genetic studies to distinguish two stocks are not available. Furthermore, it would be impossible to assign individuals caught in the winter fishery off the U.S. coast back to a specific contingent. Accordingly, the AMWG recommended that northwest Atlantic mackerel continue to be assessed as a unit stock.

Predation

Predator food habits have been systematically sampled during the NEFSC bottom trawl surveys since 1973. These food habits data were evaluated for the top 17 mackerel predators based on the percent occurrence of mackerel in predator diets (Appendix A4). The presence of Atlantic mackerel in fish stomachs was generally low from 1973-2016. A total of 1,284 out of 619,637 stomachs (~0.2%) contained mackerel, including unidentified mackerel Scombridae and *Scomber* spp..

Mackerel predation was examined by estimating per-capita consumption via the evacuation rate method and generating predation indices including a predation pressure index (Richards and Jacobson 2016), as well as percent diet composition by mass, frequency of occurrence, and prey number. These indices indicated an increase in mackerel consumption during the 1990s, followed by a decline from the early 2000s to the present (Figure A10-Figure A11). Spiny dogfish was the most dominant mackerel predator sampled by the trawl surveys, but the frequency of occurrence for mackerel in spiny dogfish diets only average 1.07%.

Additional potentially important predators of mackerel are not sampled in the NEFSC trawl surveys, including highly migratory species, marine mammals, and seabirds. Consumption from these predators is more difficult to estimate due to incomplete information on population levels and annual diet information. Furthermore, predator food habits were not available for the months the northern contingent was outside of the area sampled by the NEFSC trawl survey. Given this incomplete sampling, the low occurrence of mackerel in predator stomachs, and the resulting interannual variability in consumption estimates, the AMWG decided not to incorporate predator diets as an index of abundance. It should be noted though that observed temporal trends in consumption were consistent with trends from the range-wide egg index as well as abundance estimates from the three assessment models (TOR 3 and TOR4).

Distribution and availability

The distribution of Atlantic mackerel in the NEFSC spring bottom trawl survey is detailed in Figure A12. Notable changes in the distribution of mackerel on the Northeast U.S. shelf were apparent, with increased catches along the inner continental shelf beginning in the early 1980s, and increased catches on Georges Bank and in the Gulf of Maine beginning in the early 1990s. During 2011-2016, large catches of mackerel occurred along the northwestern portion of Georges Bank as well as Cape Cod Bay and the western GOM.

Adams (Appendix A5) and Manderson et al. (Appendix A6) examined trends in the proportion of positive tows of the NEFSC spring bottom trawl survey in the Gulf of Maine, which showed a strong increase, especially in the last seven years (Figure A13). More specifically, prior to 1991, there were only four years where mackerel were encountered in the GOM. Beginning in 1991 however, the proportion of positive tows averaged approximately 12%, and with the exception of four years with no mackerel (2002-2005), this level of occupancy was maintained through 2009. From 2010 through 2016, the proportion of positive tows again increased to an average of 38%.

Accordingly, the GOM strata were included in the strata set used to derive Atlantic mackerel relative abundance for the spring survey.

Multiple analyses were completed for this assessment to investigate the impact of both abiotic and biotic factors on the spatial distribution of Atlantic mackerel in the northwest Atlantic. Several spatial indicators, including center of gravity, abundance-weighted average depth and area occupancy were used to investigate patterns in the distribution of mackerel in the NEFSC spring bottom trawl survey (Adams, Appendix A5; Manderson et al., Appendix A6). Trends in the center of distribution indicated a shift to the northeast over the time series from a center located in the Mid-Atlantic Bight in the late 1960s to Southern New England and even the northern edge of Georges Bank in recent years (Figure A14). Over the spring survey time series, a significant shift in the center of gravity was observed to both the north and east for the entire stock as well as immature and mature components. Likewise, significant increases in area occupancy were observed for all components of the stock (Adams, Appendix A5). A weak trend was observed for average depth of the mature component with a decrease in average depth over time. There was also a significant linear relationship between the survey average day-of-year and the center of gravity of mature mackerel such that they were encountered significantly farther to the northeast as the average day-of-year increased. This trend is likely a consequence of seasonal migration patterns.

Manderson et al. (Appendix A7) developed a winter habitat model to provide annual estimates of the availability of northwest Atlantic mackerel to the NEFSC spring bottom trawl survey from 1980-2015. This model integrated mackerel winter temperature preferences with movement constraints associated with habitat connectivity along fall/winter migration pathways to estimate the annual proportion of available mackerel winter habitat that was sampled by the spring trawl survey. From 1980-2015, the spring trawl survey sampled approximately 69% of the available suitable winter habitat. Annual estimates of the proportion of winter habitat sampled did not vary systematically over time (Figure A15) and exhibited 95th percentiles of 0.45 and 0.89. However, observed changes in habitat area and location occurred later in time and at a slower rate than those changes observed in the distribution of mackerel, which indicated that a simple thermal habitat model could not be applied to estimate annual variation in the availability of mackerel to the spring bottom trawl survey. The inability of the thermal habitat model to estimate mackerel availability could arise if the model did not adequately define mackerel habitat or if factors other than overwintering habitat availability controlled the distribution of Atlantic mackerel during the time of the NEFSC spring bottom trawl survey.

Friedland et al. (Appendix A8) constructed a habitat model and in particular a random forest model for Atlantic mackerel on the Northeast U.S. Shelf based on a suite of static and dynamic environmental variables, such as depth, salinity, temperature, chlorophyll, and zooplankton. The time series of estimated habitat scores extended from 1992 to 2016 and provided biomass-informed estimates of habitat within the constraints of a 99% confidence kernel density model of spring occurrence. Model results suggested that over time, the outer continental shelf in the Mid-Atlantic Bight declined as spring mackerel habitat while the inner shelf of the Bight increased in its habitat score. Furthermore, habitat scores increased over much of the Gulf of Maine and Georges Bank.

Trends in selected physical forcing variables and variables related to lower trophic level status were analyzed by Friedland et al. (Appendix A9) between periods of high and low mackerel

abundance in the areas along the U.S. and Canadian coasts where spawning likely occurred: Mid-Atlantic Bight, Gulf of Maine and the Gulf of St. Lawrence. This work demonstrated that there have been dramatic changes in the physical environment of areas supporting mackerel populations in the northwest Atlantic. Increased temperatures, especially during summer into fall, appeared to be associated with lower recruitment and stock abundance. Additionally, there has also been a notable change in the wind regime during spring into summer, with wind speed decreasing on the order of one-third fold. This change in wind speed may have impacted the dynamics of water column stability with associated effects on nutrients and phytoplankton bloom development, and the transport and feeding of early life history stages of mackerel and other species. Changes in secondary production in the GOM and Mid-Atlantic Bight were also apparent. In the GOM, an enhanced spring bloom appeared to be related to a bottom-up effect on the production of the main zooplankton species in the area. However, in the Mid-Atlantic Bight, the change in zooplankton abundance may be related to top-down effects on the levels of chlorophyll concentration. The mechanistic effects of these physical and biological changes on mackerel productivity and abundance are not fully understood; however, it is recognized that notable changes in both abiotic and biotic aspects of the northwest Atlantic were apparent between periods of relatively high and low Atlantic mackerel abundance.

The AMWG also examined an analysis of Atlantic mackerel larval habitat suitability on the Northeast U.S. Shelf that was recently completed by McManus et al (2017) and presented at the working group's data meeting. Species distribution modeling indicated that the presence and abundance of larval mackerel were correlated with temperature and copepod abundances. Furthermore, habitat suitability estimates indicated a decline in the total suitable larval habitat on the Northeast U.S. Shelf as well as a shift in the distribution of suitable habitat along the shelf. In particular, the proportion of suitable habitat located in the Mid-Atlantic Bight decreased while the proportion located in Southern New England and the western GOM increased.

Given these analyses, the working group concluded that the high level of mackerel productivity apparent in the late 1960's and early 1970's may no longer be possible due to the observed changes in physical forcing variables, lower trophic levels and habitat suitability. Accordingly, the working group used this work to inform assumptions about future recruitment in stock projections (TORs 5 and 7).

TOR2: Catch from all sources

Estimate catch from all sources including landings and discards. Describe the spatial and temporal distribution of landings, discards, and fishing effort. Characterize the uncertainty in these sources of data.

Overview

Detailed information of mackerel catches for 1960-1991 from both the U.S. joint-venture (JV) fishery and foreign countries other than Canada was not readily available. Accordingly, updated

Canadian commercial landings estimates were provided by DFO but 1968-1991 aggregate total catch and catch-at-age estimates from all other sources (US and other countries in Table A5) were from the most recent assessment (Deroba et al. 2009). Mackerel catch data from U.S. and Canadian commercial landings, U.S. commercial discards and U.S. recreational landings and discards from 1992 through 2016 were re-estimated as part of the current assessment.

U.S. commercial landings

Until the mid-20th century most of the market demand for mackerel was domestic and limited to New England and Mid-Atlantic states. Distant markets, first in the U.S. and then internationally, subsequently developed with increases in vessel, refrigeration and shipping technology. Mackerel are currently targeted in U.S. waters to meet demand in markets for food and bait. Food-grade mackerel are primarily sold fresh or frozen. The fresh market is largely restricted to the U.S. and Canada while frozen fish are sold world-wide. Markets for lower quality Atlantic mackerel include food for aquarium and zoo animals, bait for commercial and recreational fishing of highly migratory species (HMS), and bait for lobster. Mackerel caught for bait are primarily sold fresh, frozen or salted.

Total U.S. commercial landings are derived from the weighout reports of commercial dealers and are generally considered a census of total landings. Prior to 1994, post-trip interviews were conducted by NMFS port agents to determine fishing effort and area information. Since 1994, fishing vessels are required to submit vessel trip reports (VTRs) containing statistical area and effort information, which are then matched to dealer-reported landings at the fishing trip level using a standardized, multi-tiered allocation procedure (Wigley et al. 2008). Landings are matched to VTRs in a hierarchical manner, with landings matched at the top tier (level A, direct matching) having a higher confidence in the area and fishing effort attribution than those matched at the lower tiers. Paired midwater trawls, however, do not enter the effort and area allocation procedure due to the difficulty in determining effort. Accordingly, area information for many paired midwater trawl trips is unknown.

From 1960 through the early 1980s, total U.S. commercial landings averaged approximately 2,400 mt (Table A5, Figure A16-Figure A17). With the development of the JV fishery, landings increased to a peak of 31,261 mt in 1990 and then declined to an average of approximately 10,000 mt through 2000. Beginning in 2001, landings generally increased to a time-series high of 56,640 mt in 2006, beyond which it exhibited a steep decline to a time-series low of 533 mt in 2011. Since 2012, landings have averaged approximately 5,383 mt.

Trends in U.S. landings were examined for the years updated in this assessment (1992-2016). Prior to the late 1980s, trends in landings were difficult to assess because not all states submitted their landings to the weighout database. Accordingly, reconstruction of landings would be incomplete and resulting estimates would be underestimated.

Since the early 1990s, mackerel have been caught primarily with trawl gear (Table A6, Figure A18). Bottom otter trawls represented at least 50% of the landings through 1999, beyond which midwater trawls have accounted for the majority of landings. Since 2000, 19% of mackerel landings on average were caught with bottom trawls; however, in 2011-2012 as total landings were

near a time-series low, 48% of mackerel were caught using bottom trawls. As landings by midwater trawls increased in the late 1990s, the majority of these landings were initially from single midwater trawls. However, since 2005, paired midwater trawls have accounted for on average 58% of total U.S. mackerel landings.

With the exception of 1993, the majority of mackerel landings were caught in the mid-Atlantic (statistical areas 600) through 2001 (Table A7, Figure A19). Beginning in 2002 and through 2010, however, 38% of total U.S. landings on average could not be attributed to a particular area fished due to the dominance of paired midwater trawls and the associated challenges with the allocation procedure, discussed above. As landings reached a time-series low in 2011, trends in area fished began to change and since 2013, an average of 87% of landings have been caught in New England waters (statistical areas 464-599).

Through 2002, the majority of mackerel (87% average) were landed in Rhode Island and New Jersey (Figure A20). During the mid-2000s, however, the proportion of mackerel landed in Massachusetts steadily increased. With the exception of 2012, the majority of mackerel have been landed in the northern states of Massachusetts and Maine since 2004.

Similar to area fished, mackerel landings exhibited a shift in the dominant time of year after total landings reached a time-series low in 2011 (Figure A21). Over most of the time series, quarters 1 and 2 represented the vast majority of landings (≥85%). Since 2011, however, the proportion of mackerel landed in the third and mainly the fourth quarters, generally increased to reach a maximum of 84% in 2016.

In the 1990s, four primary market categories were used for mackerel: small, medium, large and unclassified (Table A8, Figure A22). In the early 1990s, most mackerel were unclassified, but over the course of the decade the proportion classified into small, medium or large market categories increased, with the proportion of unclassified mackerel correspondingly decreasing. Beginning in 2001, two additional market categories developed: extra-small (XS) and extra-extra-small (XXS). From 2001 through 2016, 43% of landed mackerel on average were categorized as small, XS or XXS. Furthermore, in the late 1990s and early 2000s, the proportion of landed mackerel classified as large decreased from an average of 16% to approximately 3%, though a small increase was apparent in 2015 and 2016. These trends in mackerel landings by market category in the late 1990s and early 2000s corresponded to a pronounced shift in size structure and migration patterns observed by fishermen (Axelson et al., Appendix A10).

Landings-at-length

Collection of length information from commercial landings is conducted by NMFS port agents. Random sampling of landings is completed by market category and quarter. Each sample comprises approximately 100 fish with fish measured to the nearest cm. Size distributions of sampled landings were analyzed by market category, gear, area fished and time (quarter/semester) to determine how catch expansions should be stratified to estimate landings-at-length.

Length distributions were similar between first and second quarters, but varied over subsequent quarters (Figure A23). In the third and fourth quarters, the recruitment and growth of new

individuals were evident. Because the majority of landings occur during the first two quarters and exhibit similar size structures (Figure A21) and samples are more limited during the second half of the year (Table A9), size distributions were grouped by semester (Figure A24). The size distribution of samples collected during the second semester exhibited a greater proportion of fish less than 30 cm and a smaller mode.

Across all years, sampled length distributions also varied by market category (Figure A25). However, substantial overlap was noted for the XXS, XS and small market categories, as well as large and extra-large. Due to this overlap as well as the limited number of samples available, XXS, XS and small were merged into a combined small market category; large, extra-large and jumbo were merged into a combined large category (Figure A26).

For each market category, sample length distributions were examined by gear, area fished and port. Four general gear categories were examined: bottom otter trawls, midwater otter trawls, other active gears and passive gears. Within each market category, bottom trawl and midwater trawl gears exhibited similar size distributions (Figure A27). Length distributions corresponding to passive and other active gears differed from those of bottom and midwater trawl gears, however, these gears represented less than 5% of total annual U.S. landings.

Across unclassified, small and medium market categories, sampled length distributions were similar between the mid-Atlantic and New England regions (Figure A28). For the large market category, however, the mid-Atlantic exhibited a greater mode (36 cm) than New England (30 cm). On average, the combined large market category represented 13% of total U.S. commercial landings from 1992-2016.

While sampled length distributions were similar across areas fished, size distributions for each market category varied considerably between ports (Figure A29). Individual mackerel are classified into market categories by the dealers. These classifications are generally made using weight, not length, and are subjective, potentially driving the observed differences between ports.

Given the differences between ports, catch expansions would ideally be done separately for each port; however, length sampling intensity was not adequate to complete expansions at this level. Accordingly, catch expansions were stratified by semester and market category to account for the differences in size distributions across these factors and take advantage of similar distributions across areas fished and gear.

The number of length samples and total number of measured lengths generally increased from 1992-2016 (Table A9-Table A10). However prior to approximately 2006, mackerel sampling for length information was poor with annual sampling intensity estimates ranging from 269-4,995 mt per 100 lengths (Table A11). Since 2006, annual sampling intensity estimates ranged from approximately 20-461 mt per 100 lengths. For comparison, the unofficial standard is 200 mt per 100 lengths. Though there are exceptions, the unclassified market category was generally the best sampled. In some years (1994, 2014) the only market category with samples was unclassified, though other market categories comprised notable portions of the total landings (Table A12).

Multiple imputations were used to fill holes in the length sampling. Since individual growth between the fall and subsequent spring is minimal (see growth section), the first attempt to fill a hole was to borrow a sample within the same market category from the subsequent spring if the

hole occurred in the fall or from the previous fall if the missing sample occurred in the spring. If samples from these adjacent semesters were not available, a 5-year average over both semesters by market category was used to fill the missing sample. Finally, if there were not sufficient samples to create a 5-year average, a market category time-series average was used. The imputations used to fill each hole are detailed in Table A13.

Landings-at-age

To maintain consistency with length expansions, U.S. commercial landings-at-age were estimated by semester and year. Age sampling of commercial data was not regularly conducted until 1994 and since then has not occurred in every semester (Table A14). Because growth curves constructed using trawl survey age data or commercial landings data showed minimal differences in growth patterns (see growth section), the AMWG concluded that trawl survey and commercial landings age data could be combined to produce semiannual age-length keys. However, even with the combination of commercial and survey age data, holes were still present in age-length keys, especially for the second semester. Consequently, age data from the fall semester were combined with those of the subsequent spring to construct age-length keys for the fall semester and take advantage of the minimal overwinter growth of mackerel. Due to better sampling during the spring semesters, spring age data did not need to be combined with that of the previous fall. Any remaining holes in the semiannual age-length keys were then filled using the multinomial method of Gerritsen et al. (2006).

U.S. commercial landings-at-age for 1992-2016 showed a truncation in age structure beginning in the late 2000s (Table A15, Figure A30). Since 2010, mackerel older than age-6 were only caught in one year (2016). The progression of the 1999 cohort through the fishery was also evident.

U.S. commercial discards

Atlantic mackerel discards were quantified by fishing fleet following the Standardized Bycatch Reporting Methodology (SBRM) (Wigley and Tholke 2017). Fleets included in the analysis were those sampled by the Northeast Fisheries Observer Program (NEFOP) and were stratified by area fished (Mid-Atlantic versus New England), time (year and quarter), gear group and mesh size. The same NAFO statistical areas were used to define Mid-Atlantic and New England areas fished as in landings analyses. Gear groups included in discard estimation were: bottom trawls, midwater trawls (including paired and single), gillnets, dredges, handlines, haul seines, longlines, pots/traps, purse seines, scallop trawl/dredge, seines and shrimp trawls. Bottom trawls and gillnets were further stratified into mesh groups. Definitions for these mesh categories were obtained from the analysis of annual discards for 14 federally managed species groups using the SBRM (Wigley and Tholke 2017). For otter trawls, two mesh groups were formed: small (mesh < 5.5 inches) and large (mesh ≥ 5.5 inches). For gillnets, three mesh groups were formed: small (mesh < 5.5 inches), large (mesh 5.50 - 7.99 inches) and extra-large (mesh ≥ 8.00 inches).

The combined ratio method (Wigley et al. 2007) is the standard discard estimation method implemented in NEFSC stock assessments. This method was used to quantify and estimate the precision (CV) of Atlantic mackerel bycatch for 1992-2016 across all fleets.

The NEFOP data used in this analysis were aggregated at the trip level. The sampling unit for the NEFOP database is a trip (Wigley et al. 2007) and observer sea days are allocated at the trip and fleet level, in contrast to the haul or fishery level. The numbers of trips included in the analyses for the Mid-Atlantic and New England regions are presented in Table A16 and Table A17, respectively.

For each trip, NEFOP data were used to calculate a discard to kept (*d/k*) ratio, where *d* represents the discarded catch of Atlantic mackerel and *k* is the kept weight of all species. Annual estimates of discards were derived by quarter. Imputations by semester were used for quarters with one or less observed trips.

The *d/k* ratios were expanded using a raising factor to quantify total incidental catch. With the exception of the midwater trawl fleets, total landed weight of all species (from the dealer database) was used as the raising factor. Total landings from the dealer database are considered to be more accurate than those of the VTR database because VTR landings represent a captain's hail estimate. However, for the midwater trawl (MWT) fleets, we were unable to use the dealer data to estimate the kept weight of all species when stratifying by fishing area. When the area-allocation (AA) tables were developed, MWT was not included in effort calculations because of difficulties determining effort for paired MWTs. Only those gears with effort information could be assigned to a statistical area. Given these limitations, VTR data were used as the expansion factor for the MWT fleets. When quantifying discards across multiple fleets, total kept weight of all species is an appropriate surrogate for effective fishing power because it is likely that all trips will not exhibit the same attributes (Wigley et al. 2007). The use of effort without standardization makes the implicit assumption that effort is constant across all vessels, thereby resulting in a biased effort metric.

Annual Atlantic mackerel commercial discards from 1992-2016 ranged from a high of approximately 5,409 mt in 1994 to a low of 13 mt in 2015 (Table A18). In 2016, annual discards increased slightly to 17.7 mt. Corresponding estimates of precision ranged from a CV of 2.86 in 1994 to 0.17 in 2016 and have averaged 0.36 since 2010. Annual discards ranged from approximately 0-46% of total commercial catch and generally declined over the years examined. Since 2010, discards averaged 1.4% of total commercial catch.

Analysis of discard estimates by gear indicated that the majority of discards were from bottom trawl fleets, followed by MWT and gillnet fleets (Table A19). Estimates of precision for these fleets indicated high uncertainty in several years (Table A20). Bottom trawl and gillnet estimates by mesh category indicated that most bottom trawl discards occurred in the small-mesh fleet and most gillnet discards occurred in the large-mesh fleet (Table A21).

Discards-at-length

Observers collect length information from the discarded fraction of the catch. The number of mackerel lengths measured by year and semester are detailed in Table A22. While length distributions vary by gear category (Figure A31), length expansions were performed by semester and year but across gears due to limitations in the sample sizes of observer length data.

For all year/semester combinations with less than 20 measured individual mackerel, length data were pulled from other semesters/years. In particular, samples were first pulled from the subsequent spring or previous fall if there were less than 20 measured mackerel in a fall or spring semester, respectively. If length samples from these adjacent semesters did not enhance the number of measured mackerel to greater than 20 individuals, length data were pooled over the previous and subsequent two years to enhance the length sample size. For 1992-2016, a total of 11 imputations were performed.

Discards-at-age

Age information is not regularly collected from the discarded fraction of the catch for Atlantic mackerel. Consequently, the semi-annual age-length keys developed to estimate U.S. landings-at-age were used to convert commercial discards-at-length estimates to discards-at-age. Estimates of U.S. commercial discards-at-age show a truncation in age structure beginning in approximately 2000 (Table A23, Figure A32). In the most recent five years, mackerel greater than age-5 were not apparent in observed discards.

U.S. recreational catch

U.S. recreational fisheries for Atlantic mackerel have traditionally been a winter fishery in the mid-Atlantic and a summer fishery in the Gulf of Maine. Catch information has been collected since 1981 by the NOAA Marine Recreational Information Program (MRIP), previously known as Marine Recreational Fisheries Statistics Survey (MRFSS). The survey conducts dockside interviews of fishermen to determine species composition, size and disposition of their catch (kept=type A, killed but unavailable to sample= type B1 and discarded alive = type B2). Resulting catch-per-angler trip is expanded with total effort information collected via random-digit-dialing (a new MRIP mail survey is pending) to produce total landings and discards. Surveys are conducted for two month periods (waves) and results produced by type of fishery (shore, private boat, party/charter boat) and state.

Mackerel catch (assuming discarded fish do not survive) between 1981 and 1991 averaged 2,957 mt, peaking in 1987 at 4,872 mt (Figure A33). Catch generally declined thereafter, averaging only 1,170 mt between 1992 and 2016. The lowest estimated catch occurred in 1992 with 365 mt.

The spatial distribution of the recreational fishery has shifted north over time. From 1981 to 1991, an average of 48% of the catch occurred between New York and Virginia (mackerel catch has been reported from North Carolina but not included in this analysis due to concerns about incorrect

species identification). However since 1992, only 5% of the catch has occurred in the southern area and since 2000, only 1% (Figure A34). Catches between Connecticut and Maine (primarily Massachusetts to Maine) fluctuated without trend until 2011 when catches increased, reaching a peak catch in 2016 of over 6.6 million fish (Figure A35).

Recreational catch-at-length

Fish sampled during dockside interviews provide length information for the recreational landings. Size compositions of discarded fish were unavailable; therefore, it was assumed that the length distributions of landed fish were representative of total catch. Samples were expanded to total catch by year and semester (waves 1-3 and waves 4-6). Mean weight was calculated as (total number AB1)/(total AB1 weight (kg)). The mean weight was applied to the B2 number to determine total catch weight. Average weight declined steadily between 1986 and 2016. Average weight in 1986 was 0.80 kg per fish compared to the 2016 average of 0.24 kg/fish. The comparable mean length followed a similar pattern, declining from 40 cm in spring 1986 to 26 cm in spring 2016.

Recreational catch-at-age

Age information is not collected from the recreational catch. Consequently, the semi-annual age-length keys developed to estimate U.S. commercial landings-at-age were used to convert recreational catch-at-length estimates to catch-at-age. Similar to U.S. commercial landings and discards, estimates of U.S. recreational catch-at-age show a truncation in age structure beginning in the early 2000s (Table A24, Figure A36). Since 2010, mackerel older than age-6 were only caught in one year in the recreational fishery.

U.S. total catch and catch-at-age

Estimates of total U.S. catch and catch at-age for 1992-2016 were determined by summing total weight and numbers-at-age, respectively, across all U.S. catch components: commercial landings, commercial discards and recreational catch. Trends in total catch largely followed that of commercial landings due to the dominance of commercial landings compared to other catch components (Table A5, Figure A17). From 1992-2016, commercial landings averaged 83% of total catch with commercial discards and recreational catch averaging 5.4% and 11.6%, respectively. Following the trends of all individual components, a strong truncation in the age structure was evident beginning in the mid to late 2000s (Table A25, Figure A37). Since 2010, mackerel older than age-6 were only caught in one year. Similar to trends in commercial landings, the progression of the 1999 cohort is evident due to the high proportion of landings to total catch.

Spatial and temporal distribution of U.S. mackerel catches

VTR and observer data were used to investigate the spatial and temporal distribution of U.S. Atlantic mackerel catches. Trends in VTR catch by season supported knowledge of the seasonal migration patterns of Atlantic mackerel. During the winter/spring (January-June) semester, most mackerel catches occur in the mid-Atlantic and southern New England, often on the outer portion of the shelf (Figure A38). In contrast, catches during the summer/fall (July-December) semester generally occur in inshore waters of the mid-Atlantic, southern New England and the Gulf of Maine (Figure A39). Furthermore, trends show increased catches off of Cape Cod and the northern edge of Georges Bank during the spring semesters of the last five years and increased catches in the Gulf of Maine during the corresponding fall semesters. Together these trends support the northeast shift in mackerel's center of distribution observed in the NEFSC trawl survey data (see TOR1). Atlantic mackerel catches, including kept and discarded catch, from the observer database showed similar patterns across years as VTR catch with increased occurrences in the Gulf of Maine and on the edges of Georges Bank during recent years (Figure A40).

Canadian aggregate catch and catch-at-age

Canadian aggregate catch and catch-at-age were obtained from Canada's DFO and detailed in their most recent stock assessment for NAFO subareas 3-4 (DFO 2017). These catches represent a subset of total Canadian catch because the bait fishery, recreational fishery and commercial discards are not monitored. Undeclared catches estimated with a censored catch model represented an average of 6,000 mt over the past 10 years (DFO 2017). However due to the seasonal migration patterns of the northern contingent (see stock structure section) and the geographic scope of the Canadian assessment (NAFO subareas 3-4), it is possible that a portion of the undeclared catch estimated by the censored model represented catches that were declared in the U.S. fishery.

A summary of DFO's sampling intensity of Atlantic mackerel is detailed in Table A26. Data collected from biological samples were used to estimate weight-at-age, fecundity and age-length keys; length samples were used in catch expansions. Length sampling intensity averaged 217 mt per 100 lengths over the time series and 129 mt per 100 lengths since 2010.

The Canadian assessment indicated that the age structure of the catch was influenced by periodic, strong year classes such as 1967, 1974, 1982 and 1999 (Table A27, Figure A41). The assessment further noted that the 1999 year class did not persist as long as previous dominant year classes, with medium-sized year classes since 1999 caught quickly by the fishery, and age truncation since the 2000s with fish greater than 7 years old no longer present in catches. Similar to U.S. catches, a slight improvement in Canadian catches was observed since 2013.

Total catch, catch-at-age and average weight-at-age

Aggregate total catch across all countries increased from 7,353 mt in 1960 to a high of 432,608 mt in 1973 during the peak of the distant water fleets (Table A5, Figure A16). With the development of 200-mile exclusive economic zones, total catch declined to an average of approximately 30,000

mt from 1978-1983 before increasing to a peak of approximately 86,000 mt in 1990, likely due to the 1982 year class as well as the operation of the U.S. joint-venture fishery. From 1992-2001, total catch averaged approximately 35,000 mt and then increased to a peak of 112,000 mt in 2006, presumably due to the 1999 year class. Total catch then declined after 2006 and has averaged 13,500 mt since 2011.

Total catch-at-age from all sources, including foreign catches, showed the high catches of the distant water fleets during the 1970s that caught individuals from several year-classes (Table A28, Figure A42). In some years, fish as old as 5-7 years made up as much as 40% of the total annual catch. Over the 1968-2016 time series, the progression of multiple year classes through the fishery, including the 1967, 1982, and 1999 cohorts, was evident. In recent years, a truncation in age structure was apparent with fish older than 6 years not regularly caught.

Average annual weights-at-age of the total U.S. catch are detailed in Table A29. January-1 weights-at-age were calculated from these catch weights using the Rivard approach (Rivard 1980, Rivard 1982) (Table A30). For the U.S. component of the stock, average spawning stock biomass weights-at-age were assumed to be equivalent to catch weights-at-age because the dominant months for the fishery are in the beginning and end of the year (Nov-Dec, Jan-March) while the spawning season is in the middle (May/June). Average Canadian spawning stock biomass (Table A31) and January-1 weights-at-age (Table A32) were provided by Canada's DFO. For the Canadian component of the stock, average catch weights-at-age were assumed to be equal to spawning stock biomass weights-at-age due to the proximity in time of the Canadian fishery (summer/fall) and the spawning season (June/July) of the northern contingent.

Average catch / SSB (Table A33) and January-1 (Table A34) weights-at-age for the combined stock (U.S. plus Canada) were estimated using a weighted average of the region-specific weights-at-age, weighted by the catches of each region. Missing values (ages where annual catch was zero) were imputed using the average from 1992-2016. Since SSB weights-at-age were only available for Canada beginning in 1979, U.S. catch weights-at-age were assumed to be representative of the entire stock for 1968-1978.

TOR 3: Fishery independent and dependent indices

Evaluate fishery independent and fishery dependent indices being used in the assessment (e.g., indices of relative or absolute abundance, recruitment, state surveys, age-length data, etc.). Characterize the uncertainty and any bias in these sources of data.

Overview

Several fishery-independent trawl surveys were considered for use in the assessment model, including the NEFSC bottom trawl surveys, Massachusetts Division of Marine Fisheries (MADMF) bottom trawl survey, VIMS Northeast Area Monitoring and Assessment Program (NEAMAP) bottom trawl survey, Maine-New Hampshire (ME-NH) bottom trawl survey and New Jersey (NJ) ocean trawl survey. Due to the infrequent occurrence of mackerel or the limited

geographic range of the surveys compared to the range of the mackerel stock during that season, trawl surveys other than the NEFSC spring bottom trawl survey were removed from further consideration. However, these trawl surveys should be re-evaluated in future assessments if an assessment model with separate contingents is considered because they may adequately represent a particular contingent.

Other fishery-independent indices evaluated for inclusion in the assessment model included egg and larval indices. A range-wide egg index was developed through the combination of DFO's dedicated mackerel egg survey and the NEFSC's ichthyoplankton surveys, the Marine Resources Monitoring, Assessment and Prediction (MARMAP) and Ecosystem Monitoring (ECOMON) surveys. A larval index was developed using available data from the NEFSC surveys and therefore included data from historical spawning grounds within the Mid-Atlantic Bight, Gulf of Maine and southern New England. As such, this larval index presumably represented the dynamics of only the southern spawning contingent and since a comparable Canadian survey was unavailable, it was not considered for use in the model.

NEFSC spring bottom trawl survey

The NEFSC spring bottom trawl survey began in 1968 and originally sampled offshore waters from Cape Hatteras, North Carolina, through the Gulf of Maine (GOM). Inshore strata (depths less than 27m) south of Massachusetts were sampled beginning in fall 1972/spring 1973 and inshore GOM strata were added beginning in 1979. Several gear changes have occurred over the course of the survey, including the use of multiple vessels (*RVs Albatross IV* and *Delaware II*) through 1968, use of a #41 Yankee trawl from 1973-1981 (instead of a #36 Yankee trawl), a switch in the trawl doors in 1985, and a change in the primary research vessel in 2009 from the *Albatross IV* to the *Henry B. Bigelow*. Conversion coefficients between the *RVs Albatross IV* and *Delaware II* as well as for the door change were not significant for mackerel (Byrne and Forrester 1991). However, the change to the *Bigelow* in 2009 resulted in not only changes to the vessel but also to the trawl gear and survey protocols, resulting in different fishing power and therefore also survey catchability (Table A35).

Due to the large changes in the survey design with the change to the *Bigelow* in 2009, the working group decided to derive relative abundance indices as two separate time series: 1968-2008 and 2009-2016. This decision eliminated the need for conversion coefficients and also permitted the use of different strata sets for each time series. For the *Albatross* years of 1968-2008, all offshore strata that encountered mackerel were used to estimate relative abundance. Inshore strata were not included because they were not sampled in all years. Furthermore, for years where both inshore and offshore strata were sampled (1980-2008), a comparison of indices derived using just offshore strata with those derived using both inshore and offshore strata showed minimal differences in relative abundance and biomass (Figure A43). Accordingly, strata incorporated for 1968-2008 included the following offshore strata: 01010-01310, 01330-01410, 01490, and 01610-01760 (Figure A44). Due to the inclusion of GOM strata, this strata set represents a change from that previously used to develop relative abundance indices.

For the *Bigelow* years (2009 onward), all offshore and inshore strata that encountered mackerel during these years were used to derive relative abundance, which included offshore strata 01010-01300, 01340, 01351, 01360-01400, 01610-01630, 01650-01760 and inshore strata 03020, 03050, 03080, 03110, 03140, 03170, 03200, 03230, 03260, 03290, 03320, 03350, 03380, 03410, 03440, 03450, 03460, 03560, 03590-03610, 03640-03660 (Figure A45).

The AMWG also investigated potential diel differences in spring survey mackerel catches. The working group concluded that only minimal differences were apparent between relative abundance indices derived using all tows and those derived using just daytime tows (Figure A46-Figure A47). Furthermore, indices derived using only daytime tows exhibited higher variance estimates due to the smaller number of sampled stations. Consequently, the AMWG decided that spring survey indices should be developed using all (both day and night) tows.

NEFSC spring survey indices suggested a general increase in both relative abundance and biomass from approximately 1980 through 2000, beyond which indices exhibited high interannual variability and varied without trend (Figure A48). Annual CVs for 1968-2008 ranged from approximately 0.21 to 0.94 (Table A36). During the first six *Bigelow* years, relative abundance and biomass declined, but then increased to a time-series high in 2015 (Figure A49). Annual CVs during *Bigelow* years were smaller than those of the *Albatross*, ranging from 0.22-0.48 for relative abundance and 0.23-0.63 for relative biomass (Table A37). Across both time series, the proportion of stations that captured mackerel generally increased from a low of 6.2% in 1969 to a time-series high of 41.6% in 2016 (Figure A50).

Age information for Atlantic mackerel has been collected during the spring survey since 1974. Annual age-length keys (ALKs) were developed using age data collected during each spring survey. Missing age-at-length information within the bounds of empirical data in each age-length key was filled using the multinomial method of Gerritsen et al. (2006). Age composition data indicated a limited age structure at the start of the time series, with individuals older than five years rarely caught, and an expansion in age structure beginning in the late 1970s (Figure A51, Table A38). These age composition data also showed an increase in the relative abundance of age-1 and age-2 fish, and to a lesser extent age-3, indicating that the increase in aggregate abundance observed during the *Albatross* years was predominantly composed of young individuals. However, the stock began to again show a truncation in age structure around 2000 and since 2009, no individuals older than age-7 have been captured (Figure A52, Table A39). Accordingly, abundance of individuals age-5 and older peaked during the 1980s and 1990s (Figure A53).

Recent stock structure work (see stock structure section) has indicated that age-1 and age-2 individuals caught in the spring survey reflect local recruits, but age-3 onward represent a mix of individuals from both the northern and southern contingents. Consequently, concerns were raised by the AMWG that a spring survey index incorporating all age classes would not be representative of the unit stock. To address this issue, relative abundance indices from the spring survey were also derived using just ages-3^+. For the *Albatross* years 1974-2008, aggregate indices for ages-3^+ showed strong interannual variability but indicated a slight increase in relative abundance and biomass (Figure A54). Aggregate indices were not available prior to 1974 because age composition data were not available. For the *Bigelow* years of 2009-2016, relative abundance and biomass varied without trend, though the relative abundance estimates for 2015 were almost an order of magnitude larger than the other seven years (Figure A55).

Range-wide egg index

Canada's DFO has conducted an annual dedicated egg survey for Atlantic mackerel in the southern Gulf of St. Lawrence since 1979. Egg densities at each station are converted to daily egg production based on incubation time as a function of mean temperature of the upper 10 meters of water. The stratified mean daily egg production of all stations is then used to calculate total annual egg production and ultimately spawning stock biomass using the proportion of eggs spawned at the median survey date, and the mean weight of fish, sex ratio, and fecundity estimates obtained from biological samples of the commercial fixed-gear fishery (Grégoire et al. 2013b, DFO 2017). The proportion of eggs spawned at the median survey date is estimated annually from empirical gonadosomatic indices (GSI), and fecundity is calculated following the model of Pelletier 1986, as cited in Grégoire et al. (2013a). Spawning stock biomass estimates from this egg survey have been used in VPA and state-space models to assess the stock status of Atlantic mackerel in Canadian waters (NAFO subareas 3-4) (Grégoire et al. 2014, DFO 2017).

Until this assessment, a comparable time series of egg production and spawning stock biomass estimates were not available for the southern contingent. The U.S. does not conduct a dedicated egg survey but has two ichthyoplankton surveys (MARMAP, 1977-1987 and ECOMON, 1999-present) that in most years have comprehensively sampled the southern contingent's spawning area during the peak spawning season of May/June, the early spawning period of March/April and after most spawning is complete in August. A comparison of egg production and spawning stock biomass estimates between U.S. and Canadian waters in 1987 indicated that Canadian estimates were approximately nine times higher than those for the U.S. (Berrien 1987); however, data were only available for one year. For this assessment, a backlog of samples were processed to quantify egg abundances, which were then used to estimate daily egg production, annual egg production and spawning stock biomass (Carter and Richardson, Appendix A3). GSI estimates are not available for the southern contingent because the U.S. fishery does not catch many mackerel during the spawning season and the seasonal bottom trawl surveys occur before and after the spawning season. Consequently, an average spawning seasonality function was used to calculate annual egg production. Similarly, due to a lack of fecundity estimates for the southern contingent, annual fecundity estimates from the Gulf of St. Lawrence were used to calculate spawning stock biomass from annual egg production.

To create a range-wide index of abundance that was representative of both the northern and southern contingents, annual egg production (AEP) and spawning stock biomass estimates were summed across contingents in years where both Canadian and U.S. estimates were available. Two estimates were available for the U.S. in 1977; therefore, these estimates were averaged to obtain one annual value. Due to gaps between the U.S.'s MARMAP and ECOMON surveys and therefore the absence of AEP and SSB estimates for the southern contingent, combined AEP and SSB estimates could not be developed for 1988-1999. The working group discussed using the average proportion of the total spawning stock biomass represented by the southern contingent to estimate AEP and SSB for the southern contingent during these years. However, the working group ultimately concluded to treat these years as missing in order to avoid the assumption of a constant proportion.

The AMWG also discussed whether the range-wide egg index should be inputted into assessment models in units of spawning stock biomass or annual egg production. Because the modeling approaches explored in this assessment (TOR4) incorporated this index by tuning to biomass, the working group decided to use SSB estimates as the range-wide index because it represented a closer link to biomass, directly accounted for annual variation in fecundity, and provided a simpler interpretation of resulting catchability estimates from the assessment models.

The combined SSB index showed a general decline over the time series from a maximum of 1,846,983 mt in 1986 to 29,256 mt in 2010, beyond which SSB increased slightly to 55,805 mt in 2016 (Table A40, Figure A56). This general trend was also observed in the time series of both individual spawning contingents. The proportion of the total spawning biomass represented by the southern contingent varied over time from a maximum of 43% in 1983 to a minimum of 1% in 2005 and averaged 6.6% since 2010. Accordingly, trends in the combined SSB index closely followed those of the northern contingent. The strong increases in the combined SSB index around 1986 and 2002 were thought to be due to the arrival of the 1982 and 1999 dominant year-classes, respectively (DFO 2017). Trends in annual egg production generally followed those of spawning stock biomass, though annual egg production did not exhibit the same increase as SSB at the end of the time series (Table A40). This increase in SSB was due to comparatively higher fecundity estimates for 2013-2016 that exceeded the time-series median.

TOR4: Annual fishing mortality, recruitment and stock biomass estimates

Estimate annual fishing mortality, recruitment and stock biomass (both total and spawning stock) for the time series, and estimate their uncertainty. Develop alternative approaches which might also be able to estimate population parameters. Include a comparison of new assessment results with those from previous assessment(s).

Overview

For this assessment, an Age Structured Assessment Program (ASAP) statistical catch-at-age model (Legault and Restrepo 1998) was developed as the primary analytical model. In addition, a censored catch assessment (CCAM) model (Cadigan 2016, Van Beveren 2017b) and a state-space stock assessment (SAM) model (Nielsen and Berg 2014; Berg and Nielsen 2016) were developed to explore model uncertainty. Due to the lack of a previously accepted assessment, a bridge from the previous assessment was not warranted.

Ages and years

All models incorporated ages 1-10^+ with age-10 considered a plus group, began in 1968 corresponding to the first year where abundance indices were available, and incorporated data through 2016. This configuration was also consistent with the censored catch model developed in the recent DFO assessment (DFO 2017, Van Beveren 2017b).

The AMWG discussed beginning the model in 1981 or 1989, corresponding to the first years when recreational catches and commercial discards, respectively, were available. However, the working group ultimately decided to begin the model in 1968 to permit inclusion of the high foreign catches of the late 1960s-1970s, and recommended modifying the first year to 1981 or 1989 if diagnostic issues arose. Initial ASAP model runs that began in 1981 and 1989 yielded similar results, indicating a robustness to the choice of the first modeled year.

Spatial considerations

Due to the paucity of available contingent-specific time series, an inability to assign fishery catches back to a specific contingent, and the absence of a known covariate related to interannual variation in seasonal migrations and the extent of contingent mixing, the AMWG decided to model northwest Atlantic mackerel as a single stock. Consequently, all models incorporated combined U.S. and Canadian fishery catches.

Fishery catches

The most recent DFO assessment (DFO 2017) assessed Atlantic mackerel in NAFO subareas 3-4 and explicitly assumed that reported fishery catches for these subareas were underestimated and therefore biased low. As such, the assessment model estimated the amount of annual unreported catch based on the spawning stock biomass index developed from their dedicated egg survey, empirical fishery catch-at-age data, and upper limits to annual unreported catches that were informed by available data on bait and recreational fisheries and an online survey of Canadian mackerel fishery participants (Van Beveren et al. 2017a). For this assessment, the AMWG considered including DFO's unreported catch estimates in the total catch time series of removals. However, due to contingent mixing during winter/spring months on the northeast U.S. shelf (see stock structure section), there were concerns that some of the unreported catches estimated in the Canadian assessment could represent catches of the northern contingent that occurred in U.S. waters and therefore were accounted for in reported U.S. catches. Accordingly, the AMWG decided to only include the empirical estimates of total catch to eliminate any possibility of double counting. Sensitivity runs were conducted to evaluate the potential impact of unreported catches.

Indices

Indices explored in the assessment models included the range-wide SSB index and the NEFSC spring trawl survey indices with separate time series for the *Albatross* (1968-2008) and *Bigelow* (2009-2016) years. Due to new information on age-specific seasonal migration patterns from recent research (see stock structure section), the AMWG concluded that spring survey indices derived using just ages 3^+ were most representative of the unit stock and should be used in modeling efforts. Accordingly, ages $3\text{-}10^+$ were included in the *Albatross* time series, but only ages 3-7 were included in the *Bigelow* time series because no mackerel older than age-7 were caught during the spring survey from 2009 onward. The working group further recommended a sensitivity analysis with trawl survey indices derived using ages 2^+. Because age information was not collected during the spring survey until 1974, aggregate spring survey indices and corresponding age compositions for the *Albatross* time series incorporated data from 1974-2008; 1968-1973 were treated as missing.

ASAP and SAM models are capable of incorporating multiple index time series. Accordingly, both the range-wide SSB index and the two NEFSC spring survey time series were incorporated into these models. The censored model can only include one index; therefore, the range-wide SSB index was used.

Biological assumptions

Previous assessments of Atlantic mackerel that have modeled natural mortality as a time-invariant constant have assumed natural mortality equaled 0.2 or 0.3 (see assessment history section). For this assessment, Atlantic mackerel natural mortality was estimated as a function of longevity and an assumed maximum age of 19, which corresponded to the maximum age observed in the NEFSC bottom trawl surveys. Atlantic mackerel natural mortality estimated using Hoenig's linear regression model for fish (1983) resulted in a natural mortality estimate of 0.22. Natural mortality was also estimated using the rule of thumb approach (Hewitt and Hoenig 2005)

$$M = \frac{-\ln(P)}{maximum\ age}$$

where P represents the proportion of individuals surviving to the maximum age. Using this rule of thumb approach, natural mortality was estimated to be 0.16 if 5% of individuls survived to the maximum age and 0.23 if 1% of individuals survived.

For all models, natural mortality was assumed to be both time- and age-invariant. While the AMWG acknowledged that natural mortality likely varied over time, the percent occurrence of mackerel in the diets of those predators well sampled by the NEFSC's bottom trawl surveys (TOR1, Appendix A4) was not sufficient to inform time-varying natural mortality rates. In addition, estimates of predation mortality were not available for the months the northern contingent was outside of the NEFSC trawl survey area. The working group also discussed the possibility of modeling natural mortality as age-varying, though time-invariant. However, recent work on the performance of assessment models across varying assumed natural mortality rates indicated that an assumed age-invariant natural mortality that approximates the average natural mortality across ages performed similarly to age-varying natural mortality values (Deroba and Schueller 2013). Accordingly, the working group moved forward with the assumption that natural mortality was constant across all ages and years. Natural mortality was assumed to be 0.2 for this assessment, though a likelihood profile across varying assumed constant natural mortality rates was completed for the final ASAP model.

Annual maturity ogives developed from Canadian samples representing the northern spawning contingent were used in all model runs. This assumption is consistent with the results of the egg index (TOR3), which indicated that the majority of the spawning stock is composed of individuals from the northern contingent. The AMWG recommended a sensitivity analysis using the annual maturity ogives derived from the NEFSC winter and spring trawl surveys. Since maturity data from the NEFSC bottom trawl surveys began in 1982, an average maturity ogive derived from the first three years of the time series (1982-1985) was used for 1968-1981 in the sensitivity runs.

Use of a range-wide SSB index required the incorporation of maturity estimates into the assessment models to link predicted stock abundance to survey spawning stock biomass. The CCAM and SAM models directly incorporated maturity estimates. However, for the ASAP model,

a modified weight-at-age matrix, defined as SSB weights-at-age multiplied by annual maturity ogives, was used to link SSB from the range-wide egg index to predicted stock abundance. For sensitivity runs that used annual egg production estimates, scaled annual fecundity estimates were also incorporated into the modified weight-at-age matrix.

All sensitivity analyses were completed using the final ASAP model.

Age Structured Assessment Program (ASAP)

ASAP is an age-structured model that uses forward computations, assuming separability of fishing mortality into year and age components, to estimate population sizes given observed catches, catch-at-age, and indices of abundance. Various components of the catch may be treated as separate fleets. The separability assumption is partially relaxed by allowing for fleet-specific computations and by allowing selectivity-at-age to change in blocks of years. Weights are inputted for different components of the objective function, which allows for configurations ranging from relatively simple age-structured production models to fully parameterized statistical catch-at-age models. The objective function is the sum of the negative log-likelihood of the fit to various model components. Fishery and survey age compositions are modeled assuming a multinomial distribution, while most other model components are assumed to have lognormal error distributions. Specifically, lognormal error is assumed for: total catch in weight by fleet, survey indices, stock recruit relationship, and annual deviations in fishing mortality. Recruitment deviations are also assumed to follow a lognormal distribution, with annual deviations estimated as a bounded vector to force them to sum to zero (this centers the predictions on the expected stock recruit relationship). Additional technical details can be found in the technical manual (Legault 2012).

Examined model configurations

To develop the final ASAP model, over 150 different model runs were explored. The configurations examined fell into two general categories: 1) investigation of alternative configurations to evaluate whether model diagnostics and fits to input data improved, and 2) sensitivity analyses to evaluate robustness of model outputs to varying assumptions. For each configuration, the annual CVs associated with each index were iteratively adjusted to match the specified uncertainty of the index with the level of precision estimated by the model. In particular, the annual CVs were iteratively adjusted until the resulting root mean square error (RMSE) approached the confidence bounds associated with a N(0,1) distribution for the index's sample size. These CVs were adjusted by adding a constant to each year to preserve interannual variation in the CVs. Likewise, effective samples sizes (ESS) for age composition datasets were iteratively adjusted using the RMSEs and comparisons between pre-specified and estimated ESSs (Francis 2011, McAllister and Ianelli 1997). Across all configurations, the use of likelihood penalties for fishery or survey selectivity, deviation in first year abundance or recruitment deviation parameters were minimized.

Alternative configurations explored to improve diagnostics/fits included:

- One versus two fishing fleets (split as U.S. and Canadian fisheries)

- One versus multiple time blocks for fishery selectivity. Explored time blocks included:
  - Three blocks of approximately equal size (1968-1983, 1984-1999 and 2000-2016)
  - Two blocks (1968-1998, 1999-2016) with the split corresponding to the approximate timing of the shift in size structure and migration patterns observed by fishermen
  - Four time blocks (1968-1977, 1978-1991, 1992-1999, 2000-2016) that separated the periods of the distant water fleet fishery, JV fishery and the recent shift in size structure.
- Fishery and NEFSC trawl survey selectivity: flat-topped or one age fixed with variation in the age-specific selectivity parameter fixed at one to anchor the selectivity ogive
- Variation in included indices: Egg and NEFSC trawl survey indices versus egg index only or trawl survey indices only
- NEFSC trawl survey units as number/tow or weight/tow
- One *Albatross* time series versus two, split between #41 Yankee trawl and #36 Yankee trawl years
- Model start year of 1968 versus 1981 or 1989

Alternative configurations explored to examine model sensitivity included:

- Egg index units as annual egg production instead of spawning stock biomass
- Ages-2^+ included in NEFSC trawl survey indices instead of ages-3^+
- Annual maturity ogives derived from NEFSC trawl survey samples instead of those derived from Canadian samples
- Likelihood profile across varying assumed time- and age-invariant natural mortality rates
- Variation in Canada's fishery catch estimates: Reported landings versus censored catches from DFO's most recent assessment (DFO 2017)

The sequence of alternative model configurations is further detailed in Appendix A11.

Final ASAP model

Following evaluation of alternative model configurations, the base ASAP model adopted by the AMWG was structured as follows:

- One fishing fleet with constant fishery selectivity over time
- Flat-topped fishery selectivity with age-specific selectivity parameters fixed at 1.0 for ages 6-10^+; It should be noted that by age-6, mackerel have generally reached the asymptotic portion of their growth curve (see growth section), which supports the selection of a constant selectivity for fish older than age-6.
- Indices included the range-wide SSB index, one time series for the *Albatross* years of the NEFSC spring trawl survey (number/tow for ages 3^+) and one time series for the *Bigelow* years of the spring trawl survey (number/tow for ages 3^+).

- NEFSC trawl survey selectivity fixed at 1.0 for age-3 with ages-4^+ estimated parameters (ages 4-10 for the *Albatross* years and ages 4-6 for the *Bigelow* years); In initial ASAP runs where survey selectivity parameters for ages 1-3 were free to vary, these parameters often hit the upper bounds of 1.0. Furthermore, fishermen have also suggested that due to the NEFSC trawl survey's tow speed and length, the trawl survey is likely better able to catch smaller fish than larger individuals (Axelson et al., Appendix A10).

The contribution of each objective function component to the total likelihood of the final ASAP model is detailed in Table A41. With the exception of the *Albatross* index, the RMSEs for all indices fell close to or inside the confidence bounds associated with a N(0,1) distribution for the corresponding sample size of the index (Figure A57). While the final RMSE of the *Albatross* time series was high, this RMSE was achieved by inputting the index CVs as the annual empirical CVs plus a constant of 0.6 in each year; in contrast, the CVs for the range-wide SSB index and *Bigelow* trawl survey were inputted as the annual empirical CVs plus 0.15 and 0.3, respectively. Accordingly, the index values predicted by the model generally followed the observed temporal trends of the SSB and *Bigelow* indices (Figure A58-Figure A59), but not those of the *Albatross* time series (Figure A60). The aggregate fishery catches predicted by the model closely followed the observed catches (Figure A61). Diagnostics for the fishery, *Albatross*, and *Bigelow* age composition data are detailed in Figure A62-Figure A64. While large residuals were apparent for some age/year combinations, strong patterns in the residuals were not evident. Furthermore, these residual patterns were largely robust to assumptions regarding the number of time blocks for fishery selectivity, number of fleets for fishery catches, and the assumed effective sample size values for the age composition data.

The final ASAP model indicated that SSB has ranged from a high of 1,134,034 mt in 1972 to a low of 16,837 mt in 2012 (Table A42, Figure A65). After 1972, spawning stock biomass generally declined to the historic low in 2012, with the exception of two periods of increasing SSB trends during the mid-1980s and early-2000s as the 1982 and 1999 cohorts moved through the stock. Since 2012, spawning stock slightly increased to 43,519 mt in 2016. Recruitment estimates indicated strong year classes from 1968-1975, and with the exception of strong year classes in 1982, 1999 and to a lesser extent 2003, recruitment has been comparatively low since (Table A43, Figure A66-Figure A67).

Total January 1 biomass in 2016 was estimated to be 101,687 mt (Table A42, Figure A68). With the exception of the early portion of the time series, total stock biomass was very similar to spawning stock and exploitable biomass estimates. During the initial part of the time series however, total biomass was much greater than spawning stock and exploitable biomasses due to strong recruitment events and the resulting abundance of young mackerel that were not mature or exploitable to the fishery.

Estimated fishery selectivity was flat-topped with mackerel fully selected from age-6 through age-10^+ (Table A44, Figure A69). Fishing mortality estimates during the early portion of the time series exhibited a peak of 0.74 in 1976 as stock estimates declined and then sharply declined as foreign catches decreased (Table A42 and Table A45, Figure A70). Fishing mortality then slowly increased during the 1980s and 1990s before spiking to a high of 2.1 in 2010. Since 2010, fishing mortality generally decreased and was estimated to be 0.47 in 2016. The spike in fishing mortality

during 2009-2010 was likely a result of comparatively high catches (50-65 000s mt) relative to very low estimated spawning stock biomass (24,001 mt) and recruitment (18,036,000 fish).

As expected, age-specific selectivity of the NEFSC trawl survey during both the *Albatross* and *Bigelow* years generally declined beyond full selectivity at age-3 (Figure A71). *Albatross* selectivity slightly increased for ages 9-10; however, this increase was likely an artifact of the low number of observations for these age classes. Selectivity for the range-wide SSB index was fixed at one because annual maturity information was incorporated into the weight-at-age matrix used to link spawning stock biomass to predicted stock abundance. Estimates of survey catchability indicated a higher catchability of the *Bigelow* (7.7e-5) compared to the *Albatross* (1.0e-5), which is consistent with the higher head rope height of the *Bigelow's* net.

A retrospective analysis was conducted to examine the stability of model estimates as years of data were removed from the end of the time series. Retrospective runs were made for 5 years in total, the 2011-2015 terminal years. Retrospective runs for 7 years were investigated; however, some models failed to converge due to the resulting short time series of the NEFSC trawl survey for the *Bigelow* years. The 5-year Mohn's rho values for spawning stock biomass, average fishing mortality and recruitment were 0.16, 0.11 and -0.07, respectively. Persistent retrospective patterns were not evident, with terminal year estimates exhibiting both positive and negative relative differences from the estimates of the final run (Figure A72-Figure A74). Accordingly, the working group concluded that no retrospective adjustments were needed for terminal year estimates.

MCMC simulations were completed to estimate the posterior distributions of total biomass, spawning stock biomass and fishing mortality; simulations were conducted using a chain of an initial length of 2,000,000 with every thousandth value saved to result in a final chain length of 2,000. The trace of the 2,000 saved values suggested adequate mixing (Figure A75-Figure A76). From the MCMC distributions, 90% posterior probability intervals (PIs) were calculated to provide a measure of uncertainty associated with the point estimates. Trends in SSB and fishing mortality estimates with their associated 90% PIs and terminal year (2016) posterior distributions for SSB and F are shown in Figure A77-Figure A82.

Sensitivity analyses

ASAP sensitivity runs for the alternative model assumptions discussed above indicated a strong consistency in model estimates across sensitivity runs. Spawning stock biomass (Figure A83), January 1 biomass (Figure A84) and fishing mortality (Figure A85) estimates across sensitivity runs generally fell within the corresponding 90% probability intervals from the final ASAP run. Some runs fell slightly outside the 90% PIs during intermediate years of the time series (ex: SSB estimates in the early 2000s from the U.S. maturity run and 2010 fishing mortality estimates from the runs with 2 fishing fleets, 4 fishery selectivity time blocks and a 1989 start year), but temporal trends were largely the same across all runs. The only difference in trend was the fishing mortality estimates at the end of the time series for the sensitivity run using annual egg production for the egg index. In this sensitivity run, fishing mortality increased during the last three years, but this difference was likely due to the lack of an increasing trend in AEP (in contrast to SSB) at the end of the time series (Table A40). Accordingly, ASAP model results were robust to a wide range of varying model assumptions and configurations.

The final ASAP model was also rerun with a range of alternative, constant natural mortality values ranging from 0.05 to 0.50 to assess the consequences of assuming a natural mortality rate of 0.2. Based on the total objective function value (minimum log-likelihood), this analysis indicated similar model fits across assumed natural mortality rates ranging from 0.2 to 0.35 (Figure A86), with the minimum value from the likelihood profile corresponding to a natural mortality rate of 0.28.

State-space stock assessment model (SAM)

A state-space stock assessment model (SAM) was also applied to the northwest Atlantic mackerel stock (Nielsen and Berg 2014, Berg and Nielsen 2016). Traditional statistical catch-at-age models assume observation errors in the data time series but not process errors in the model. However, state-space models can separate observation and process errors using relatively few parameters (Nielsen and Berg 2014). This efficiency is achieved by estimating the variances of the assumed distributions for the observation and process errors, where fishing mortality and abundance states are predictions from the assumed distributions, as opposed to free parameters as in statistical catch-at-age models.

Observations

Catch and index observations are assumed to have lognormal errors, with separate variance parameters applied to different user-selected age groups:

$$\log\left(C_{a,y}\right) = \log\left(\frac{F_{a,y}}{Z_{a,y}}\left(1 - e^{-Z_{a,y}}\right)N_{a,y}\right) + e_{a,y}^{(o)} \; ;$$

$$e_{a,y}^{(o)} \sim N\left(0, \hat{\sigma}_{o,a}^2\right) \; ;$$

$$\log\left(I_{a,y}\right) = \log\left(\hat{q}N_{a,y}\right) + e_{a,y}^{(s)} \; ;$$

$$e_{a,y}^{(s)} \sim N\left(0, \hat{\sigma}_{s,a}^2\right) \; .$$

Age groups were defined to share variance parameters based on AIC and residual patterns.

Processes

SAM allows for process errors in recruitment, survival between sequential ages, and age-specific fishing mortality rates. The recruitment and survival processes are assumed to follow lognormal distributions:

$$\log\left(R_{a=1,y}\right) = \log\left(f\left(SSB_{y-1} \; or \; R_{a=1,y-1}\right)\right) + \gamma_{a=1,y} \; ;$$

$$\gamma_{a=1,y} \sim N\left(0, \hat{\sigma}_R^2\right) \; ;$$

$$\log\left(N_{a,y}\right) = \log\left(N_{a-1,y-1}\right) - F_{a-1,y-1} - M_{a-1,y-1} + \gamma_{a>1,y} \; ;$$

$$\gamma_{a>1,y} \sim N\left(0, \hat{\sigma}_{a>1}^2\right) \; .$$

Recruitment in all model runs was assumed to follow a random walk. As with the observation variances, age groups were defined to share survival process variance parameters based on AIC and residual patterns.

Fishing mortality rates can be age-specific or groups of ages can be coupled to share fishing mortality rates, and these rates follow a random walk between years. The random walk fishing mortality rates can be correlated among the age couplings, for example, with a correlation of 0.0 producing independent random walks among age couplings and a correlation of 1.0 producing parallel time trajectories in fishing mortality rates among age couplings (i.e., time invariant selectivity). This results in age- and year-specific random walk increments following a multivariate normal distribution:

$$\log\left(F_{a,y}\right) = \log\left(F_{a,y-1}\right) + \delta_y \ ;$$

$$\delta_y \sim \boldsymbol{N}\left(0, \widehat{\boldsymbol{E}}\right) .$$

The degree of correlation in the random walks can be fixed at 0.0 (i.e., independent) or estimated, and both were attempted. Age groups were defined to share fishing mortality states and process variances based on AIC and residual patterns.

Estimating Misreported Catch

SAM has the ability to estimate misreported catch as year- and age-specific multipliers of the observed catches. The misreported catches are distinct from the observation errors because they allow for bias in the observations and not just unbiased imprecision. Missing catches were suspected for Atlantic mackerel and misreported catch was estimated in some years, with the specific years chosen based on the models ability to converge, results from the censored population assessment model, and a priori knowledge about missing catches. A comparison of time series estimates between models with and without estimates of misreported catch was also conducted.

Final SAM model

The structure of the final SAM model was as follows:

- One fishery catch observation variance common to all ages (1 parameter).
- One observation variance for each survey, common to all ages within each survey (3 parameters).
- One catchability for the egg index, a separate catchability for age-3 and ages 4-10 in the *Albatross* survey years, and a separate catchability for age-3 and ages 4-7 in the *Bigelow* survey years (5 parameters).
- Separate fishing mortality rates for age-1, age-2, age-3, and ages 4-10$^+$, with a shared process variance (1 parameter).
- Process variance for recruitment and a survival process variance for ages 2-10$^+$ (2 parameters).
- Misreported catch in 1969-1972, 1977-1978, 1992-1996, 1998-2003, and 2008-2016 (5 parameters).

Diagnostics of the final SAM model are detailed in Appendix A12.

Censored catch assessment model (CCAM)

For the 2017 Canadian mackerel assessment of NAFO subareas 3-4 (DFO 2017), a censored catch assessment model was developed using Template Model Builder and accepted to resolve the issue of missing catches. This state-space age-structured model assumes catches are "censored", i.e., falling in between a predetermined upper and lower bound, which can vary annually. The idea of censored catches was first proposed by Hammond and Trenkel (2005) and further explored by Bousquet et al. (2010) and Cadigan (2016). In the Canadian model, catches were modelled exactly as in Cadigan (2016).

Model Framework

A full description of model equations and choices can be found in Van Beveren et al. (2017b). For convenience, key equations are provided below and parameters are detailed in Table A46. Note that since its use in the Canadian mackerel assessment (DFO 2017) and its description in Van Beveren et al. (2017b), two modifications were made to CCAM. Process error was here assumed to follow a multivariate normal distribution, exactly as in the SAM model from Nielsen and Berg (2014), and fishing mortality-at-age (F_a) was replaced by selectivity-at-age (Sel_a).

Abundance (N) was modelled as:

$$logN_{a,y} = \begin{cases} logN_{y-1} + \delta_{a,y}, & \text{a = 1,} \\ logN_{a-1,y-1} - Z_{a-1,y-1} + \delta_{a,y}, & \text{a = 2, …, A-1,} \\ \log(\exp(logN_{a-1,y-1} - Z_{a-1,y-1}) + \exp(logN_{a,y-1} - Z_{a,y-1})) + \delta_{a,y}, & \text{a = A} \end{cases}$$

where $\delta_{a,y}$ is the process error and $Z_{a,y}$ total mortality ($Z_{a,y} = F_{a,y} + M_{a,y}$). Fishing mortality was assumed separable ($F_{a,y} = Sel_a F_y$, F_y being a random walk and Sel_a flat-topped from age-4 onwards) and spawning stock biomass was calculated following $SSB_y = \sum_{y=1}^{Y} N_{a,y} Weight_{a,y} PropMature_{a,y}$.

Concerning the observation equations, only the use of one index is possible ($I_y = \sum_{y=1}^{Y} qN_{a,y} exp(-Z_{a,y} t_s) Weight_{a,y} PropMature_{a,y}$) and catches were calculated according to the Baranov Catch equation ($C_{a,y}$=$N_{a,y} \frac{F_{a,y}}{Z_{a,y}} [1 - \exp(-Z_{a,y})]$).

Estimated total catch and catch composition were linked to the observed data independently (as in Cadigan 2016). The estimated catch-at-age proportions matrix was transformed with the continuation-ratio logit approach and matched to the observed data using a lognormal distribution with 3 different variances (σ^2_{crl-A} for a=1, σ^2_{crl-B} for a=2 and 9, σ^2_{crl-C} for 1<a<9). Total catches had a lognormal measurement error given by:

$$l(C_{o1}, \dots, C_{oY}; \theta) = \sum_{y=1}^{Y} log \left\{ \phi_N \left[\frac{log(U_y/C_y)}{\sigma_C} \right] - \phi_N \left[\frac{log(L_y/C_y)}{\sigma_C} \right] \right\}$$

where L_y is the annual observed catch in mass (i.e. the lower limit), U_y the annual upper catch limit in mass and ϕ_N the cumulative distribution function for a N(0,1) random variable. The

likelihood equation and the effect of measurement error σ_C (here 0.01) are visualized in Figure A87.

Both CCAM and SAM are state-space models which make use of the same R package. Key differences are provided in Table A47.

Final CCAM model

The final CCAM model incorporated the range-wide egg index (in units of SSB) as well as combined (U.S. + Canada) catch and weight-at-age matrices. Annual maturity ogives from Canadian samples were used for the maturity time series and natural mortality was set to 0.2 for all ages and years. The lower catch limit was set as the total declared catch (Canada + USA), to which the range of possible undeclared catches defined during the Canadian assessment (DFO 2017) was added to obtain an upper catch limit. On average, this allowed catches to increase by 30% (range; 3-100%). Diagnostics of the final CCAM model are detailed in Appendix A13.

Comparison of ASAP, SAM and CCAM estimates

Atlantic mackerel stock size and fishing mortality estimates were compared among the ASAP, SAM and CCAM models. For this model comparison, fishing mortality estimates from the SAM model represented annual averages across ages. Since SAM does not assume separable fishing mortality, fishing mortality time series estimates from each model were rescaled as $x/mean(x)$ to enhance comparability in fishing mortality trends among models.

While differences were apparent in some years, the three models exhibited the same temporal trends in spawning stock biomass, fishing mortality and recruitment (Figure A88). The ASAP model predicted a stronger increase in recruitment in the last two years compared to SAM and CCAM, which drove an increase in the terminal year SSB and a decrease in terminal year F, however all three models exhibited similar estimates at the end of the time series. Accordingly, biomass, recruitment and fishing mortality trends were robust to the underlying model structure.

Historical retrospective

The time series of Atlantic mackerel stock size and fishing mortality estimates from the final ASAP model were compared to those of the previous two assessments (NEFSC 2006, Deroba et al. 2010). The estimates used from previous assessments for this comparison were the rho-adjusted values that accounted for observed retrospective patterns. The 2005 assessment passed peer review at the time but exhibited a retrospective pattern that was not taken into account; the results were later deemed inappropriate during the 2009 assessment. The 2009 assessment split the NEFSC spring trawl survey into three segments, which helped but did not fully resolve an apparent retrospective pattern, and so the model was deemed inappropriate for use in management. A comparison of the estimates from these three models, however, indicated similar trends between the currently proposed model (SAW64) and the rho-adjusted values from the 2005 and 2009 assessments, especially with respect to recruitment estimates across all three models and SSB estimates between the SAW64 and TRAC 2009 models (Figure A89).

SARC-64 peer review

Several additional analyses were requested during the review by the Stock Assessment Review Committee (SARC). These analyses are presented in Appendix A1.

TOR5: Stock status definitions

State the existing stock status definitions for "overfished" and "overfishing". Then update or redefine biological reference points (BRPs; point estimates or proxies for B_{MSY}, $B_{THRESHOLD}$, F_{MSY} and MSY) and provide estimates of their uncertainty. If analytic model-based estimates are unavailable, consider recommending alternative measurable proxies for BRPs. Comment on the scientific adequacy of existing BRPs and the "new" (i.e., updated, redefined, or alternative) BRPs.

Existing stock status definitions

Atlantic mackerel are currently managed as a unit stock in the Northwest Atlantic. Due to the lack of an accepted previous assessment, stock status definitions for 'overfished' and 'overfishing' do not exist and the status of the stock is currently listed as unknown (NMFS 2017).

New stock status definitions

The AMWG examined resulting stock size estimates from the final ASAP model for a relationship between spawning stock biomass and subsequent recruitment. The AMWG concluded, however, that there was no evidence of any stock-recruitment relationship over the range of stock sizes estimated in the ASAP model (Figure A90). Consequently, there was no direct calculation of MSY, F_{MSY} or B_{MSY} and the non-parametric spawner-per-recruit (SPR) reference point of $F_{40\%}$ was instead chosen as a proxy for F_{MSY}. $F_{40\%}$ was estimated to be 0.26 using the final ASAP model (Table A48).

Long-term projections were completed to estimate the spawning stock biomass and catch levels associated with $F_{40\%}$. These long-term projections were made from the 2000 estimates of numbers-at-age resulting from the MCMC analysis completed using the final ASAP model (TOR4). For each of the 2000 iterations, 100 population simulations were completed, each of 100 years.

Recent 5-year averages (2012-2016) and corresponding CVs for January 1 and spawning stock biomass/catch weight-at-age estimates as well as proportion mature-at-age (from Canadian samples) were used for projection inputs. Since the final ASAP model was parameterized with only one time block for fishery selectivity, the point estimates and corresponding CVs from the final ASAP model were used in projections.

Total fishery catch for the first projection year was set to 21,898 mt, which represented the 2017 stock-wide Allowable Biological Catch (ABC) set by the MAFMC's Science and Statistical Committee in May 2016 plus an additional 2,000 mt due to a subsequent increase (August) in the

2017 Canadian TAC. In all other years, the harvest scenario was set to the $F_{40\%}$ of 0.26. Natural mortality was set to M=0.2 for all ages.

Recruitment was modeled by sampling from an empirical cumulative density function derived from the 1975-2016 recruitment estimates of the final ASAP model. The AMWG felt that recruitment over 1975-2016 was most reflective of current productivity and observed ecosystem changes (TOR1) likely prevented the recruitments seen in the early 1970s. The average spawning date was specified as June 1st.

An average of the final 10 years of predicted catch and stock biomass estimates from the long-term projections was used to define the biological reference points ($SSB_{MSY\ proxy}$, $B_{MSY\ proxy}$, MSY_{proxy}) associated with the $F_{MSY\ proxy}$ ($F_{40\%}$) of 0.26. Final reference point estimates (with 90% confidence intervals) equaled 196,894 mt (108,161 - 429,550 mt) for $SSB_{MSY\ proxy}$, 255,646 mt (140,103 - 534,278 mt) for $B_{MSY\ proxy}$, and 41,334 mt (22,878 – 87,281 mt) for MSY (Table A48). The AMWG considered these biological reference points to be scientifically adequate.

The working group recommended that the northwest Atlantic mackerel stock be considered overfished if spawning stock biomass was less than half of $SSB_{MSY\ PROXY}$, which for this assessment equaled 98,447 mt. Overfishing was considered to be occurring if the fishing mortality rate was greater than $F_{MSY\ PROXY}$, which equaled 0.26 for this assessment.

TOR6: Stock status

Make a recommended stock status determination (overfishing and overfished) based on new results developed for this peer review. Include qualitative written statements about the condition of the stock that will help to inform NOAA Fisheries about stock status.

Spawning stock biomass and fishing mortality estimates from the final ASAP model were used for stock status determination (Table A49). Spawning stock biomass in 2016 was estimated to be 43,519 mt, which was 22.1% of the $SSB_{MSY\ proxy}$ of 196,894 mt (Table A48). Corresponding 90% confidence intervals for this terminal-year SSB estimate were both below the overfished threshold of one-half of the $SSB_{MSY\ PROXY}$ (98,447 mt). The fully recruited fishing mortality in 2016 was estimated to be 0.47, which was 80% greater than the $F_{MSY\ proxy}$ of 0.26 (Table A48). Corresponding 90% confidence intervals for the terminal-year fishing mortality estimate overlapped with $F_{MSY\ proxy}$ but was largely greater than this overfishing threshold. Furthermore, fishery and survey age-composition data showed a truncation in age structure and the range-wide egg index indicated a 2016 SSB estimate below the time series median. Accordingly, it is recommended that Atlantic mackerel be considered overfished and that overfishing is occurring (Figure A91).

TOR7: Stock projections

a. *Provide numerical annual projections (3 years) and the statistical distribution (e.g., probability density function) of the catch at F_{MSY} or an F_{MSY} proxy (i.e. the overfishing level, OFL) (see Appendix to the SAW TORs). Each projection should estimate and report annual probabilities of exceeding threshold BRPs for F, and probabilities of falling below threshold BRPs for biomass. Use a sensitivity analysis approach in which a range of assumptions about the most important uncertainties in the assessment are considered (e.g., terminal year abundance, variability in recruitment).*

b. *Comment on which projections seem most realistic. Consider the major uncertainties in the assessment as well as sensitivity of the projections to various assumptions. Identify reasonable projection parameters (recruitment, weight-at-age, retrospective adjustments, etc.) to use when setting specifications.*

c. *Describe this stock's vulnerability (see "Appendix to the SAW TORs") to becoming overfished, and how this could affect the choice of ABC.*

Stochastic short-term projections were conducted to provide forecasts of stock size and catches in 2018-2020 consistent with the new biological reference points proposed in this assessment (Table A48). All biological inputs, including fishery selectivity, maturity-at-age, natural mortality, and weights-at-age, were identical to those used for reference point determination. One hundred projections were made for each of the 2000 MCMC realizations of 2016 stock size (TOR5). Following the method used for reference point determination, recruitment was modeled by sampling from an empirical cumulative density function derived from the 1975-2016 recruitment estimates of the final ASAP model. Additionally, since 2017 catch estimates were not available, 2017 catch was assumed to equal the 2017 stock-wide ABC set by the MAFMC's SSC plus an additional 2,000 mt due to a subsequent increase in the 2017 TAC for Canada. Accordingly, 2017 catch was assumed to equal 21,898 mt in total. Projections were conducted under the assumptions of $F_{MSY\ proxy}$, status quo F and F = 0.

Projections at $F_{MSY\ proxy}$ showed an increase in catch to 33,250 mt by 2020 (Table A50, Figure A92). Spawning stock and January-1 biomass increased to 165,487 and 216,681 mt, respectively, by 2020, but would still be under the biomass estimates associated with $F_{MSY\ proxy}$ (Table A50, Figure A93-Figure A94). The large increase (134%) in SSB in 2017 was due to strong incoming 2014 and 2015 year classes (Table A43) that were projected to be 88 and 100 percent mature, respectively, in 2017. This increase in SSB was common to all projection scenarios because the same value was assumed for the 2017 catch in all scenarios.

Projections at the status quo F (0.47) showed a notable increase in catch to 42,092 - 44,524 mt between 2018-2020, which exceeded MSY_{proxy} (Table A51, Figure A92). Spawning stock biomass increased substantially to 101,825 mt in 2017 and subsequently ranged between 124,616-127,506 mt (Table A51, Figure A93). January-1 biomass showed similar trends, increasing to 135,714 mt in 2017 and subsequently ranging between 172,598-180,145 mt (Table A51, Figure A94). For all three metrics, estimates increased through 2019 and then declined in 2020, with spawning stock

and January-1 biomass estimates still below the corresponding reference points associated with $F_{MSY\ proxy}$ in 2020.

In the absence of fishing, both spawning stock and January-1 biomasses increased substantially across all years and were projected to be 238,976 mt and 281,175 mt, respectively, by 2020 (Table A52). For this scenario, the stock would be considered rebuilt in 2020, as both biomass estimates would exceed those associated with $F_{MSY\ proxy}$ (Figure A93-Figure A94).

TOR8: Research recommendations

Review, evaluate and report on the status of the SARC and Working Group research recommendations listed in most recent peer reviewed assessment and review panel reports. Identify new research recommendations.

Recommendations from the 2009 TRAC assessment

- Exchange otoliths every other year to monitor agreement between NEFSC and DFO age readers. Initiate development of a reference collection.

  This recommendation was not completed but remains a relevant research task.

- Investigate the need for a conversion factor for the length-weight relationship for frozen mackerel samples.

  This research task is no longer relevant because the working group concluded that industry samples should not be included in the development of length-weight relationships because of their limited temporal scope.

- Explore opportunities for the development of alternative indices of abundance. Attempt to develop total stock abundance estimates.

  This research recommendation was completed though the development of a range-wide egg index.

- Initiate broad scale international egg surveys covering potential spawning habitat that is consistently representative of the total stock area, including the shelf break. Investigate potential to conduct work in cooperation with commercial fishing industry.

  This research task has largely been completed. While one combined, international egg survey was not completed, eggs surveys were conducted for each of the spawning contingents and indices from each of the surveys were combined to develop a range-wide egg index. Furthermore, the two independent surveys showed consistent trends in annual egg production and spawning stock biomass over the time series. In response to industry requests, Canada's DFO completed mackerel egg sampling outside of the southern Gulf of St. Lawrence between 2005 and 2016. This additional sampling culminated in 2009, when the entire Scotian Shelf as well as Newfoundland's west and south coasts were sampled in June with bongo nets, and

indicated that only about 2% of mackerel egg production came from outside the main southern Gulf of St. Lawrence spawning area.

- Explore spatial distribution of stock relative to the mixing of the northern and southern 'contingents' of mackerel (i.e. tagging, genetics, chemical assay, microchemistry of otoliths).

  This research task is ongoing and the AMWG indicated that this work remains a high priority and should be continued. The U.S.'s NEFSC has begun to preserve larvae in ethanol for future genetic studies. Secor et al. completed an otolith microchemistry project (Appendix A2), which demonstrated that age-1 and 2 individuals caught in the NEFSC spring bottom trawl survey reflected local recruits where ages-3 onward represented a mix of individuals from both spawning contingents. Furthermore, both the U.S.'s NEFSC and Canada's DFO have sent tissue samples to researchers in the eastern Atlantic that are currently conducting a genetics study that incorporates samples from both the NW (southern New England, Gulf of Maine, Gulf of St. Lawrence and Newfoundland) and NE Atlantic (Mediterranean, spawning grounds, including the southern, western and northern components, as well as feeding grounds that include northern Norway, Faroe Islands and Greenland).

- Explore influence of environmental factors on spatial distribution of the stock e.g. rate of mixing and distribution of stock relative to the survey area (high priority, short term).

  Multiple working papers (Adams, Appendix A5; Manderson et al., Appendix A6, Friedland et al., Appendix A8) were completed for this assessment that investigated the impact of environmental factors on the spatial distribution of Atlantic mackerel in the northwest Atlantic. While these analyses examined the distribution of the stock relative to the survey area, they did not address the rate of mixing. Furthermore, a larval distribution study recently completed by McManus et al. (2017) and presented during the working group's data meeting, developed species distribution models to investigate the impact of temperature and zooplankton on larval abundance and larval habitat suitability of the Northeast U.S. Shelf.

- Extend predation estimates to include DFO data and entire predator spectrum (marine mammals, highly migratory species).

  DFO completed a modeling effort that included the development of ecosystem models and provided an estimate of predation mortality in Canadian waters. Savenkoff et al. (2005) used results of mass-balance inverse models to compare changes in the Gulf of St. Lawrence ecosystem between the mid-1980s, mid-1990s and the early 2000s as they relate to mackerel. Predation was the main cause of mackerel mortality in all periods. Demersal fish predators were progressively replaced by seals and cetaceans as the main predators.

  Mackerel predators, and in particular marine mammals and highly migratory species, are not adequately sampled in either U.S. or Canadian waters. However, a project was recently funded though NOAA MAPP to quantify the overlap of marine mammals and forage fish on the northeast U.S. shelf (Thorne et al.).

- Examine methodology for incorporating consumption estimates in the assessment.

  This research recommendation was not explicitly addressed because a preliminary analysis of the NEFSC's food habits database indicated that the percent occurrence of mackerel in the

diets of those predators well sampled by the NEFSC's bottom trawl surveys was not sufficient to inform time-varying natural mortality rates.

- Quantify the magnitude of additional sources of mortality in Canada including the bait fishery, recreational catch and discards.

  This research recommendation is ongoing. For the last Canadian assessment (2017), a censored catch assessment model was developed and accepted to address the issue of unmonitored catches from the bait and recreational fisheries. This state-space age-structured model estimated the amount of unreported catch in each year based on the spawning stock biomass index developed from their dedicated egg survey, fishery catch-at-age data, and upper limits to annual unreported catches that were informed by available data on bait and recreational fisheries and an online survey of Canadian mackerel fishery participants. Rough estimates of Canadian recreational catch are also available from a survey of recreational fishing conducted every 5 years.

- Explorations of bottom trawl characteristics for catchability of mackerel.

  This research recommendation has not been completed.

- Participate with industry in investigating the contemporary overlap of survey stock area, commercial fishery, and mackerel distribution and explore historical databases for the same purpose to better understand interpretation of abundance indices (survey, CPUE).

  This research recommendation has been completed. Two population ecology workshops were held in December 2015 and 2016, and included participants from industry, academia, NOAA's NEFSC, Canada's DFO and a non-governmental organization. During these workshops, changes in the distribution and migration patterns of mackerel in the northwest Atlantic were discussed. Several follow-up interviews of fishermen were conducted by the NEFSC's cooperative research branch and a working paper (Axelson et al., Appendix A10) was prepared for this assessment. U.S. observer and vessel trip report databases were also analyzed to examine changes in the distribution of mackerel over the available time series.

- Collaborate with industry to investigate alternative sampling gear (i.e. jigging) to survey adult abundance.

  This research recommendation has not been completed.

- Explore MARMAP database relative to spatial distribution of survey indices.

  A larval distribution study recently completed by McManus et al. (2017) and presented during the working group's data meeting used zooplankton and Atlantic mackerel larval data from both the MARMAP and ECOMON databases to develop species distribution models. These models investigated the impact of temperature and zooplankton on mackerel larval abundance and larval habitat suitability of the Northeast U.S. Shelf. Furthermore, Friedland et al. (Appendix A8) completed an analysis for this assessment that used both static and dynamic variables (including zooplankton data from the MARMAP/ECOMON databases) to develop random forest models for Atlantic mackerel on the Northeast U.S. shelf. This work indicated notable changes in the spring habitat for Atlantic mackerel that potentially reflected a change in the availability of mackerel to the spring bottom trawl survey. These changes included a

decline in habitat on the outer continental shelf of the mid-Atlantic bight (MAB) but increases on the MAB's inner shelf as well as much of the Gulf of Maine and Georges Bank.

- Investigate alternative assessment models that incorporate spatial structure (i.e. northern and southern contingents, different age groups).

  This research recommendation is ongoing. A spatially-explicit assessment model distinguishing the two spawning contingents was considered; however, additional research is needed to pursue this recommendation further with available data.

- Explore alternative assessment models that incorporate covariates.

  This research recommendation is ongoing. For this assessment, Manderson et al. (Appendix A7) developed a thermal habitat model that could potentially be used to estimate the proportion of available mackerel habitat that is sampled by the NEFSC spring bottom trawl survey each year. However, observed changes in habitat area and location occurred later in time and at a slower rate than those changes observed in the distribution of mackerel, which indicated that a simple thermal habitat model could not be applied to estimate annual variation in the availability of mackerel to the spring bottom trawl survey.

- Initiate a technical TRAC WG in order to advance and monitor progress of research recommendations.

  Scientists from the U.S.'s NEFSC and Canada's DFO have regularly collaborated over the last few years. U.S. scientists visited DFO in September 2015 and 2016 to collaborate on the analysis of the U.S. egg data used to develop the range-wide egg index. DFO participated in the U.S.'s population ecology meeting of December 2016, where they presented both their egg index and censored catch assessment model. U.S. scientists participated in both the model framework and final meetings for DFO's 2017 assessment, and three DFO scientists are working group members for this current U.S. assessment (SAW64). DFO also provided samples for the otolith microchemistry work conducted by Secor et al. for this assessment.

New research recommendations developed during the 2017 SAW64 assessment

- Continue the U.S. component of the mackerel egg survey so that the range-wide egg index can be updated and used in future assessments. This recommendation requires a continuation of the work done to identify and quantify mackerel eggs collected in the survey.
- Initiate a reproductive study in the U.S. to obtain fecundity estimates and spawning seasonality. Update Canadian fecundity estimates (which are currently based on a 1986 publication) and compare estimates between countries.
- Investigate possible growth and maturity differences between spawning contingents.
- Expand otolith microchemistry work to address stock structure, and explore the importance of the time-varying components. Research to-date has been critical for the interpretation of bottom trawl survey indices.
- Continue engagement with fishing industry through working group meetings, etc..

- Investigate the socio-economic impacts of the mackerel fishery on other fisheries such as Atlantic herring and lobster.
- Pursue, in a more formalized fashion, genetic work to distinguish the two spawning components.
- Continue to pursue modeling approaches that explicitly account for the spatial structure of the stock (i.e. two spawning contingents).
- Obtain biological samples from the recreational fisheries of both spawning contingents.
- Explore potential changes in environmental conditions (habitat changes, larval diets, cannibalism, etc.) that impact larval survival and recruitment.

REFERENCES

Anderson, E.D. 1973. Assessment of Atlantic mackerel in ICNAF Subarea 5 and Statistical Area 6. Int. Comm. Northw. Atlant. Fish., Res. Doc. 73/14, Ser. No. 2916.

Anderson, E.D. 1975. The effect of a combined assessment for mackerel in ICNAF Subareas 3, 4, and 5, and Statistical Area 6. Int. Comm. Northw. Atlant. Fish., Res. Doc. 75/14, Ser. No. 3458.

Anderson, E.D. 1977. Assessment of the northwest Atlantic mackerel stock. NMFS, NEFC, Woods Hole Lab. Ref. Doc. No. 77-10. 35 p.

Anderson, E.D. 1980. Status of the northwest Atlantic mackerel stock - 1980. NMFS, NEFC, Woods Hole Lab. Ref. Doc. No. 80-29. 43 p.

Anderson, E.D. 1981. Status of the northwest Atlantic mackerel stock - 1981. NMFS, NEFC, Woods Hole Lab. Ref. Doc. No. 81-38. 43 p.

Anderson, E.D. 1982. Status of the northwest Atlantic mackerel stock - 1982. NMFS, NEFC, Woods Hole Lab. Ref. Doc. No. 82-44. 49 p.

Anderson, E.D. 1983. Status of the northwest Atlantic mackerel stock - 1983. NMFS, NEFC, Woods Hole Lab. Ref. Doc. No. 83-40. 48 p.

Anderson, E.D. 1985. Status of the northwest Atlantic mackerel stock - 1984. NMFS, NEFC, Woods Hole Lab. Ref. Doc. No. 85-03. 49 p.

Anderson, E.D. and W.J. Overholtz. 1978. Status of the northwest Atlantic mackerel stock - 1978. NMFS, NEFC, Woods Hole Lab. Ref. Doc. No. 78-49. 30 p.

Anderson, E.D. and W.J. Overholtz. 1979a. Status of the northwest Atlantic mackerel stock – 1978. Int. Comm. Northw. Atlant. Fish., Res. Doc.79/VI/90, Ser. No. 5452.

Anderson, E.D. and W.J. Overholtz. 1979b. Status of the northwest Atlantic mackerel stock - 1979. NMFS, NEFC, Woods Hole Lab. Ref. Doc. No. 79-35. 35 p.

Anderson, E.D. and A.J. Paciorkowski. 1980. A review of the northwest Atlantic mackerel fishery. Rapp. P.-v. Réun. Cons. Int. Explor. Mer 177:175-211.

Berg, C.W., A. and Nielsen. 2016. Accounting for correlated observations in an age-based state-space stock assessment model. ICES J. Mar. Sci. 73: 1788-1797.

Berrien, P. 1987. Atlantic mackerel, *Scomber scombrus*, total annual egg production and spawner biomass estimates for the Gulf of St. Lawrence and northeastern United States waters, 1987. NMFS, NEFC, Sandy Hook Lab. Rep. No. 88-02. 18 p.

Bethoney, N.D., B.P. Schondelmeier, K.D.E. Stokesbury, W.S. Hoffman. 2013. Developing a fine scale system to address river herring (*Alosa pseudoharengus, A. aestivalis*) and American shad (*A. sapidissima*) bycatch in the U.S. Northwest Atlantic mid-water trawl fishery. Fisheries Research 141:79-87.

Bethoney, N.D., B.P. Schondelmeier, J. Kneebone, W.S. Hoffman. 2017. Bridges to best management: Effects of a voluntary bycatch avoidance program in a mid-water trawl fishery. Marine Policy 83:172-178.

Bousquet, N., N. Cadigan, T. Duchesne, L.-P. Rivest, 2010. Detecting and correcting underreported catches in fish stock assessment: trial of a new method. Can. J. Fish. Aquat. Sci. 67: 1247–1261.

Byrne C.J., J.R.S. Forrester. 1991. Relative Fishing Power of NOAA R/V's Albatross IV and Delaware II. In: Report of the Twelfth Northeast Regional Stock Assessment Workshop. NMFS, NEFSC Ref. Doc. 91-03. 187 p.

Cadigan, N., 2016. A state-space stock assessment model for northern cod, including under-reported catches and variable natural mortality rates. Can. J. Fish. Aquat. Sci. 73: 296–308.

Clark, J.R. 1962. The 1960 salt-water angling survey. U.S. Fish & Wildlife Service Circ. 153: 36p.

Collette, B.B. and G. Klein-MacPhee, eds. 2002. Bigelow and Schroeder's Fishes of the Gulf of Maine, 3rd ed. Smithsonian Institution Press, Washington, DC. 748 p.

Deroba, J.J. and A.M. Schueller. 2013. Performance of stock assessments with misspecified age- and time-varying natural mortality. Fisheries Research 46: 27-40.

Deroba, J.J., G. Shepherd, F. Gregoire, J. Nieland, J. Link. 2010. Stock Assessment of Atlantic Mackerel in the Northwest Atlantic - 2009. TRAC Reference Document 2010/01.

DFO. 2017. Assessment of the Atlantic Mackerel Stock for the Northwest Atlantic (Subareas 3 and 4) in 2016. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2017/034.

Francis R.I.C.C. 2011. Data weighting in statistical fisheries stock assessment models. Can. J. Fish. Aquat. Sci. 68:1124-1138.

Gerritsen, H.D., D. McGrath, C. Lordan. 2006. A simple method for comparing age-length keys reveals significant regional differences within a single stock of haddock (*Melanogrammus aeglefinus*). ICES J. Mar. Sci. 63: 1096-1100.

Grégoire, F., J.-L. Beaulieu, M.-H. Gendron, D. LeBlanc. 2013a. Results of the Atlantic mackerel (*Scomber scombrus* L.) egg survey conducted on the Scotian Shelf and Newfoundland's South Coast in 2009. DFO Can. Sci. Advis. Sec. Res. Doc. 2012/127. iii + 25 p.

Grégoire, F., M.-F. Gendron, J.-L. Beaulieu, I. Lévesque. 2013b. Results of the Atlantic mackerel (*Scomber scombrus* L.) egg surveys conducted in the southern Gulf of St. Lawrence from 2008 to 2011. DFO Can. Sci. Advis. Sec. Res. Doc. 2013/035. v + 57 p.

Grégoire, F., L. Girard, and J.-L. Beaulieu. 2014. Analytical assessment of the Atlantic Mackerel (*Scomber scombrus* L.) in NAFO Subareas 3 and 4 in 2011. DFO Can. Sci. Advis. Sec. Res. Doc. 2013/137. v + 31 p.

Hammond, T.R., and V.M. Trenkel. 2005. Censored catch data in fisheries stock assessment. ICES J. Mar. Sci. 62: 1118–1130.

Hewitt, D.A., and J.M. Hoenig. 2005. Comparison of two approaches for estimating natural mortality based on longevity. Fishery Bulletin 103: 433-437.

Hoenig, J. M. 1983. Empirical use of longevity data to estimate mortality rates. Fish. Bull. 81(4): 898–903.

Hoy, D.W., and G.M. Clark. 1967. Atlantic Mackerel Fishery, 1804-1965. U.S. Fish & Wildlife Service, Fish. Leaflet 603: 9p.

Legault, C.M. 2012. Technical Documentation for ASAP Version 3.0 NOAA Fisheries Toolbox (http://nft.nefsc.noaa.gov/).

Legault C.M., Restrepo V.R. 1998. A flexible forward age-structured assessment program. ICCAT Col Vol Sci Pap. 49: 246-253.

MAFMC (Mid-Atlantic Fisheries Management Council) 1978. Final Environmental Impact Statement/Fishery Management Plan for the Atlantic Mackerel Fishery of the Northwest Atlantic Ocean, available at: http://www.mafmc.org/s/SMB__Mackerel__Original_Plan.pdf.

MAFMC (Mid-Atlantic Fisheries Management Council) 2017. Advisory Panel Fishery Performance Report, available at: http://www.mafmc.org/ s/2017-MSB_FPR.pdf.

McAllister, M.K., and Ianelli, J.N. 1997. Bayesian stock assessment using catch-age data and the sampling-importance resampling algorithm. Can. J. Fish. Aquat. Sci. 54(2): 284-300.

McManus, M.C., J.A. Hare and D.E. Richardson. 2017. Tracking shifts in Atlantic mackerel (*Scomber scombrus*) larval habitat suitability on the Northeast U.S. Continental Shelf. Fisheries Oceanography: 1-14. DOI: 10.1111/fog.12233.

NEFC (Northeast Fisheries Center). 1987. Report of the Fourth NEFC Stock Assessment Workshop (Fourth SAW). NMFS, NEFC, Woods Hole Lab. Ref. Doc. No. 87-07. 103 p.

NEFC (Northeast Fisheries Center). 1990. Report of the Spring 1990 NEFC Stock Assessment Workshop (Tenth SAW). NMFS, NEFC, Woods Hole Lab. Ref. Doc. No. 90-07. 99 p.

NEFSC (Northeast Fisheries Science Center). 1991. Report of the Twelfth Northeast Regional Stock Assessment Workshop (12th SAW). NMFS NEFSC Ref. Doc. No. 91-03. 192 p.

NEFSC (Northeast Fisheries Science Center). 1996a. Report of the 20th Northeast Regional Stock Assessment Workshop (20th SAW): Stock Assessment Review Committee (SARC) Consensus Summary of Assessments. NMFS NEFSC Ref. Doc. No. 95-18. 219 p.

NEFSC (Northeast Fisheries Science Center). 1996b. Report of the 20th Northeast Regional Stock Assessment Workshop (20th SAW): SAW Public Review Workshop. NMFS NEFSC Ref. Doc. No. 95-19. 52 p.

NEFSC (Northeast Fisheries Science Center). 2000. 30th Northeast Regional Stock Assessment Workshop (30th SAW): Public Review Workshop. NMFS NEFSC Ref. Doc. No. 00-04. 58 p.

NEFSC (Northeast Fisheries Science Center). 2006. 42nd Northeast Regional Stock Assessment Workshop (42nd SAW) Stock Assessment Report Part A: Silver Hake, Atlantic Mackerel, and Northern Shortfin Squid. NMFS NEFSC Ref. Doc. No. 06-09a. 290 p.

NEFSC (Northeast Fisheries Science Center). 2013. 55th Northeast Regional Stock Assessment Workshop (55th SAW) Assessment Report. NMFS NEFSC Ref. Doc. No. 13-11. 849 p.

Nielsen, A., and C.W. Berg. 2014. Estimation of time-varying selectivity in stock assessments using state-space models. Fisheries Research 158: 96-101.

NMFS (National Marine Fisheries Service). 2017. National Marine Fisheries Service - 3rd Quarter 2017 Update, Table A: Summary of Stock Status for FSSI Stocks. Retrieved from: http://www.nmfs.noaa.gov/sfa/fisheries_eco/status_of_fisheries/archive/2017/third/q3-2017-stock-status-table.pdf.

O'Brien, L., J. Burnett, R.K. Mayo. 1993. Maturation of nineteen species of finfish off the northeast coast of the United States, 1985-1990. NOAA Technical Report NMFS 113. 72 p.

Overholtz, W.J. and B.L. Parry. 1985. Update of the status of the northwest Atlantic mackerel stock for 1985. NMFS, NEFC, Woods Hole Lab. Ref. Doc. No. 85-13. 16 p.

Overholtz, W.J., S.A. Murawski, W.L. Michaels, L.M. Dery. 1988. The effects of density dependent population mechanisms on assessment advice for the Northwest Atlantic mackerel stock. NOAA Technical Memorandum NMFS-F/NEC-62.

Penttila, J. and L.M. Dery, eds. 1988. *Age determination methods for northwest Atlantic species.* NOAA Technical Report NMFS 72. 135 p.

Richards, R.A., L.D. Jacobson. 2016. A simple predation pressure index for modeling changes in natural mortality: Application to Gulf of Maine northern shrimp stock assessment. Fish. Res. 179:224-236.

Rivard, D. 1980. APL programs for stock assessment. Can. Tech. Rep. Fish. Aquat. Sci. 953. 103 p.

Rivard, D. 1982. APL programs for stock assessment (revised). Can. Tech. Rep. Fish. Aquat. Sci. 1091. 146 p.

Savenkoff, C., F. Grégoire, M. Castonguay, D.P. Swain, D. Chabot, J.M. Hanson. 2005. Main prey and predators of Atlantic mackerel (*Scomber scombrus* L.) in the northern and southern Gulf of St. Lawrence during the mid-1980s, mid-1990s, and early 2000s. Can. Tech. Rep. Fish. Aquat. Sci. No. 2619. 29 pp.

Sette, O.E. 1943. Biology of the Atlantic Mackerel (*Scomber scombrus*) of North America, Part I: Early Life History, Including the Growth, Drift, and Mortality of the Egg and Larval Populations. Fishery Bulletin 38, Volume 50: 149-237.

Sette, O.E. 1950. Biology of the Atlantic Mackerel (*Scomber scombrus*) of North America, Part II: Migrations and Habits. Fishery Bulletin 49, Volume 51: 251-358.

Shepherd, G., J. Deroba, S. Sutherland, M. Jones, J. Blaylock, E. Holmes, J. Nieland. 2009. U.S.A. Data Summary. TRAC Working Paper 2009/20.

Van Beveren, E., M. Castonguay, T. Doniol-Valcroze, D. Duplisea. 2017a. Results of an informal survey of Canadian Atlantic mackerel commercial, recreational and bait fishers. DFO Can. Sci. Advis. Sec. Res. Doc. 2017/029. v + 26 p.

Van Beveren, E., D. Duplisea, M. Castonguay, T. Doniol-Valcroze, S. Plourde, N. Cadigan. 2017b. How catch underreporting can bias stock assessment and advice in northwest Atlantic mackerel and a possible resolution using censored catch. Fisheries Research 194: 146-154.

Wigley S.E., P. Hersey, J.E. Palmer. 2008. A description of the allocation procedure applied to the 1994 to 2007 commercial landings data. NMFS NEFSC Ref. Doc. No. 08-18. 61 p.

Wigley, S.E., H.M. McBride, N.J. McHugh. 2003. Length-weight relationships for 74 fish species collected during NEFSC research vessel bottom trawl surveys, 1992-99. NOAA Tech. Memo. NMFS-NE-171.

Wigley, S.E., P.J. Rago, K.A. Sosebee, D.L. Palka. 2007. The analytic component to the Standardized Bycatch Reporting Methodology Omnibus Amendment: sampling design, and estimation of precision and accuracy (2nd edition). NMFS NEFSC Ref. Doc. 07-09. 156 p.

Wigley, S.E. and C. Tholke. 2017. 2017 discard estimation, precision, and sample size analyses for 14 federally managed species groups in the waters off the northeastern United States. NMFS NEFSC Ref. Doc. 17-07. 170 p.

TABLES

Biology

Table A1: Atlantic mackerel length-weight parameters corresponding to semester-specific relationships developed for approximately 9-year intervals and derived from the NEFSC bottom trawl survey data.

		ln(a)		b	
Semester	**Year interval**	**Estimate**	**Standard error**	**Estimate**	**Standard error**
Summer/Fall (July-Dec.)	1991-1999	-12.473	0.054	3.291	0.017
	2000-2007	-12.457	0.073	3.273	0.023
	2008-2016	-12.601	0.049	3.322	0.015
Winter/Spring (Jan.-June)	1991-1999	-12.673	0.026	3.313	0.008
	2000-2007	-12.878	0.022	3.368	0.007
	2008-2016	-12.748	0.026	3.335	0.008

Table A2: Atlantic mackerel average length-at-age (cm) derived from either commercial age data or NEFSC spring bottom trawl survey data.

Age	Commercial	Survey
1	20.4	20.3
2	27.2	27.2
3	30.8	31.0
4	33.1	33.4
5	34.9	34.4
6	36.1	35.7
7	37.4	37.0
8	37.9	37.7
9	38.5	39.0
10	39.4	38.9
11	40.3	39.8
12	40.0	39.9
13	40.0	39.6
14	39.0	39.9
15		42.0
16		44.0

Table A3: Atlantic mackerel annual maturity ogives and observed maximum age derived from the NEFSC winter and spring bottom trawl survey for 1982-2016.

	1	2	3	4	5	6	7	8	9	10	Maximum age
1982	0.00	0.42	1.00	0.95	1.00	1.00	1.00	1.00	1.00	1.00	13
1983	0.01	0.46	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	12
1984	0.00	0.45	0.76	1.00	1.00	1.00	1.00	1.00	1.00	1.00	19
1985	0.00	0.17	0.83	0.99	0.93	1.00	1.00	1.00	1.00	1.00	19
1986	0.00	0.09	1.00	0.99	0.92	1.00	1.00	1.00	1.00	1.00	15
1987	0.00	0.50	0.95	1.00	1.00	1.00	1.00	1.00	1.00	1.00	14
1988	0.00	0.88	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	16
1989	0.08	0.65	0.89	1.00	1.00	1.00	1.00	1.00	1.00	1.00	16
1990	0.01	0.86	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	9
1991	0.05	0.54	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	9
1992	0.02	0.51	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	10
1993	0.02	0.43	0.97	1.00	1.00	1.00	1.00	1.00	1.00	1.00	12
1994	0.00	0.37	0.92	1.00	1.00	1.00	1.00	1.00	1.00	1.00	12
1995	0.06	0.67	0.97	0.99	1.00	1.00	0.98	1.00	1.00	1.00	12
1996	0.12	0.51	0.94	1.00	1.00	1.00	1.00	1.00	1.00	1.00	11
1997	0.09	0.64	0.97	0.98	1.00	1.00	1.00	1.00	1.00	1.00	12
1998	0.09	0.67	0.98	1.00	1.00	1.00	1.00	1.00	1.00	1.00	11
1999	0.10	0.67	0.98	1.00	1.00	1.00	1.00	1.00	1.00	1.00	10
2000	0.08	0.86	0.97	1.00	1.00	1.00	1.00	1.00	1.00	1.00	12
2001	0.06	0.54	0.92	1.00	1.00	1.00	1.00	1.00	1.00	1.00	9
2002	0.27	0.67	0.95	1.00	1.00	1.00	1.00	1.00	1.00	1.00	9
2003	0.10	0.75	0.98	1.00	1.00	1.00	1.00	1.00	1.00	1.00	7
2004	0.22	0.69	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	6
2005	0.14	0.69	0.97	1.00	1.00	1.00	1.00	1.00	1.00	1.00	8
2006	0.10	0.77	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	8
2007	0.17	0.68	0.97	1.00	1.00	1.00	1.00	1.00	1.00	1.00	9
2008	0.16	0.94	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	9
2009	0.06	0.85	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	6
2010	0.04	0.74	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	7
2011	0.22	0.78	0.97	1.00	1.00	1.00	1.00	1.00	1.00	1.00	6
2012	0.09	0.84	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	6
2013	0.30	0.78	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	6
2014	0.23	0.94	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	4
2015	0.12	0.91	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	6
2016	0.13	0.95	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	7

Table A4: Atlantic mackerel annual maturity ogives from 1968-2016 derived from Canadian samples.

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1968	0.288	0.495	0.705	0.853	0.934	0.972	0.988	0.995	0.998	0.999
1969	0.288	0.495	0.705	0.853	0.934	0.972	0.988	0.995	0.998	0.999
1970	0.288	0.495	0.705	0.853	0.934	0.972	0.988	0.995	0.998	0.999
1971	0.288	0.495	0.705	0.853	0.934	0.972	0.988	0.995	0.998	0.999
1972	0.288	0.495	0.705	0.853	0.934	0.972	0.988	0.995	0.998	0.999
1973	0.288	0.495	0.705	0.853	0.934	0.972	0.988	0.995	0.998	0.999
1974	0.288	0.495	0.705	0.853	0.934	0.972	0.988	0.995	0.998	0.999
1975	0.163	0.857	0.995	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1976	0.204	0.785	0.981	0.999	1.000	1.000	1.000	1.000	1.000	1.000
1977	0.049	0.841	0.998	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1978	0.429	0.907	0.992	0.999	1.000	1.000	1.000	1.000	1.000	1.000
1979	0.368	0.593	0.785	0.902	0.958	0.983	0.993	0.997	0.999	1.000
1980	0.231	0.972	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1981	0.123	0.984	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1982	0.015	0.995	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1983	0.378	0.654	0.854	0.948	0.983	0.994	0.998	0.999	1.000	1.000
1984	0.010	0.503	0.990	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1985	0.402	0.879	0.988	0.999	1.000	1.000	1.000	1.000	1.000	1.000
1986	0.422	0.847	0.974	0.996	0.999	1.000	1.000	1.000	1.000	1.000
1987	0.442	0.815	0.961	0.993	0.999	1.000	1.000	1.000	1.000	1.000
1988	0.395	0.904	0.980	0.996	0.999	1.000	1.000	1.000	1.000	1.000
1989	0.349	0.992	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1990	0.283	0.937	0.998	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1991	0.216	0.881	0.995	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1992	0.229	0.807	0.977	0.997	1.000	1.000	1.000	1.000	1.000	1.000
1993	0.229	0.807	0.977	0.997	1.000	1.000	1.000	1.000	1.000	1.000
1994	0.229	0.807	0.977	0.997	1.000	1.000	1.000	1.000	1.000	1.000
1995	0.242	0.733	0.959	0.995	0.999	1.000	1.000	1.000	1.000	1.000
1996	0.195	0.736	0.970	0.997	1.000	1.000	1.000	1.000	1.000	1.000
1997	0.132	0.830	0.985	0.999	1.000	1.000	1.000	1.000	1.000	1.000
1998	0.068	0.925	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1999	0.117	0.766	0.988	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2000	0.459	0.908	0.991	0.999	1.000	1.000	1.000	1.000	1.000	1.000
2001	0.430	0.929	0.996	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2002	0.306	0.949	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2003	0.241	0.953	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2004	0.138	0.855	0.995	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2005	0.088	0.624	0.966	0.998	1.000	1.000	1.000	1.000	1.000	1.000

Table A4, contd.: Atlantic mackerel annual maturity ogives derived from Canadian samples.

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
2006	0.253	0.847	0.989	0.999	1.000	1.000	1.000	1.000	1.000	1.000
2007	0.081	0.922	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2008	0.210	0.793	0.982	0.999	1.000	1.000	1.000	1.000	1.000	1.000
2009	0.029	0.854	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2010	0.025	0.615	0.990	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2011	0.255	0.860	0.991	0.999	1.000	1.000	1.000	1.000	1.000	1.000
2012	0.210	0.873	0.994	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2013	0.165	0.886	0.997	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2014	0.168	0.909	0.998	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2015	0.172	0.933	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2016	0.115	0.815	0.993	1.000	1.000	1.000	1.000	1.000	1.000	1.000

TOR2: Catch from all sources

Table A5: Total catch (mt) of Atlantic mackerel for the U.S., Canada and other countries during 1960-2016.

Year	US commercial landings	US recreational catch	US commercial discards	US total catch	Canadian catch	Foreign landings	Total catch
1960	1,396			1,396	5,957	0	7,353
1961	1,361			1,361	5,459	11	6,831
1962	938			938	6,865	175	7,978
1963	1,320			1,320	6,473	1,299	9,092
1964	1,644			1,644	10,960	801	13,405
1965	1,998			1,998	11,590	2,945	16,533
1966	2,724			2,724	12,821	7,951	23,496
1967	3,891			3,891	11,243	19,047	34,181
1968	3,929			3,929	26,097	65,747	95,773
1969	4,364			4,364	21,247	114,189	139,800
1970	4,049			4,049	19,613	210,864	234,526
1971	2,406			2,406	24,280	355,892	382,578
1972	2,006			2,006	26,183	391,464	419,653
1973	1,336			1,336	34,513	396,759	432,608
1974	1,042			1,042	42,300	321,837	365,179
1975	1,974			1,974	24,773	271,719	298,466
1976	2,712			2,712	25,425	223,275	251,412
1977	1,377			1,377	22,511	56,067	79,955
1978	1,605			1,605	25,432	841	27,878
1979	1,990			1,990	30,245	440	32,675
1980	2,683			2,683	22,136	566	25,385
1981	2,941	3,210		6,151	19,296	5,361	30,808
1982	3,330	1,191		4,521	16,378	6,647	27,546
1983	3,805	3,002		6,807	19,792	5,955	32,554
1984	5,954	2,319		8,273	17,331	15,045	40,649
1985	6,632	2,713		9,345	29,862	32,409	71,616
1986	9,637	4,223		13,860	28,469	26,507	68,837
1987	12,310	4,032		16,342	27,492	36,564	80,398
1988	12,309	3,265		15,574	24,051	42,858	82,483
1989	14,556	1,787	160	16,503	20,854	36,823	74,180
1990	31,261	1,867	827	33,955	21,790	30,678	86,423

Table A5, contd.: Total catch (mt) of Atlantic mackerel for the U.S., Canada and other countries during 1960-2016.

Year	US commercial landings	US recreational catch	US commercial discards	US total catch	Canadian catch	Foreign landings	Total catch
1991	26,961	2,566	1,098	30,625	25,899	15,714	72,238
1992	11,761	365	2,072	14,198	26,382	0	40,580
1993	4,662	652	3,902	9,216	26,712	0	35,928
1994	8,917	1,815	5,409	16,141	20,830	0	36,971
1995	8,468	1,587	54	10,109	18,309	0	28,418
1996	15,728	1,517	2,053	19,297	21,025	0	40,322
1997	15,403	1,982	229	17,614	21,306	0	38,920
1998	14,525	814	98	15,436	18,940	0	34,376
1999	12,031	1,501	771	14,303	17,695	0	31,998
2000	5,649	1,680	153	7,482	17,856	0	25,338
2001	12,340	1,832	718	14,890	24,474	0	39,364
2002	26,530	1,430	155	28,115	34,847	0	62,962
2003	34,298	837	264	35,399	44,912	0	80,311
2004	54,990	516	2,141	57,647	53,730	0	111,377
2005	42,209	1,029	1,083	44,321	55,282	0	99,603
2006	56,640	1,690	135	58,465	53,960	0	112,425
2007	25,546	633	159	26,339	53,394	0	79,733
2008	21,734	857	747	23,338	29,671	0	53,008
2009	22,635	684	125	23,443	42,232	0	65,676
2010	9,877	938	97	10,912	38,736	0	49,648
2011	533	1,042	38	1,613	11,534	0	13,147
2012	5,333	767	33	6,133	6,468	0	12,601
2013	4,372	951	20	5,343	9,017	0	14,360
2014	5,905	1,142	52	7,099	6,872	0	13,971
2015	5,616	1,384	13	7,013	4,937	0	11,950
2016	5,687	1,611	18	7,316	8,000	0	15,316

Table A6: U.S. commercial landings (mt) of Atlantic mackerel by gear during 1992-2016.

		Midwater trawl						Gillnet		
	Bottom trawl	Single	Paired	Purse Seine	Pound net	Floating trap	Weir	Fixed	Drift	Other
1992	11,305.5	0.0	1.2	11.2	17.7	152.0	0.0	151.7	6.4	114.9
1993	3,798.3	479.4	0.0	0.0	52.6	155.5	0.0	83.3	23.6	69.1
1994	8,238.4	129.7	0.0	3.6	179.5	262.8	0.0	54.7	1.0	47.7
1995	7,381.5	595.8	0.0	0.0	70.4	234.3	0.0	111.1	1.6	73.8
1996	12,621.9	2,298.0	0.0	154.2	68.0	386.5	0.0	178.6	11.8	8.5
1997	10,095.9	4,473.2	0.0	0.0	244.3	378.5	0.0	154.8	32.0	23.9
1998	8,444.2	4,266.7	1,363.1	0.0	106.5	104.4	51.2	115.5	32.3	40.9
1999	7,103.0	4,222.1	0.0	0.0	136.2	183.6	126.7	204.6	19.7	35.4
2000	2,671.3	2,616.0	0.0	0.0	136.5	66.6	0.9	120.9	6.3	30.3
2001	2,036.0	9,944.0	0.0	0.2	83.9	82.3	5.4	153.6	10.0	25.0
2002	2,924.7	12,751.1	10,476.5	0.0	112.1	110.9	29.1	67.6	3.9	54.0
2003	5,041.1	17,461.5	11,572.3	0.4	12.7	79.1	10.0	72.7	9.9	38.2
2004	4,249.9	23,791.2	21,660.3	0.0	86.5	23.9	2.2	5,063.0	0.1	113.1
2005	4,284.1	9,769.9	26,825.6	0.0	25.0	14.9	13.6	147.6	0.7	1,127.7
2006	11,799.0	23,740.0	20,971.6	0.0	7.5	1.7	4.3	6.8	0.1	109.4
2007	1,913.2	7,475.8	15,339.2	0.0	6.4	8.1	0.0	38.5	0.0	765.0
2008	2,202.2	3,131.8	16,299.5	16.1	10.0	0.0	1.6	4.9	0.0	67.7
2009	2,502.4	3,403.7	16,608.3	0.0	20.7	3.0	0.7	3.5	0.0	92.1
2010	1,901.1	862.1	6,976.3	0.0	19.4	25.0	10.1	2.7	0.0	80.1
2011	253.6	41.9	195.0	0.0	0.4	8.1	4.2	5.0	0.0	24.9
2012	2,555.2	810.5	1,855.6	0.0	6.7	0.5	2.6	4.6	0.1	96.8
2013	597.2	549.3	3,133.1	0.0	3.8	1.8	1.3	6.9	0.0	79.1
2014	328.7	1,310.3	3,986.1	0.7	0.1	0.0	14.1	11.0	0.0	254.0
2015	1,038.3	876.2	2,931.6	0.0	0.0	0.0	2.8	8.7	0.0	758.8
2016	528.0	1,321.1	2,839.4	0.0	0.2	0.0	0.8	16.6	0.0	981.4

Table A7: U.S. commercial landings (mt) of Atlantic mackerel by NEFSC statistical division during 1992-2016. Division 00 represents unknown division.

	00	46	50	51	52	53	54	56	60	61	62	63	64	70	71
1992	0.0	0.0	0.0	154.6	1,637.2	3,291.5	256.3	55.4	0.0	4,638.6	1,726.9	0.2	0.0	0.0	0.0
1993	0.0	0.0	0.0	145.8	477.8	1,759.5	0.0	133.3	0.0	1,161.0	953.6	31.0	0.0	0.0	0.0
1994	164.8	0.0	0.0	202.5	149.2	1,778.7	0.0	1.3	0.0	6,015.7	605.1	0.0	0.0	0.0	0.0
1995	76.9	0.2	0.0	231.5	381.9	2,764.4	0.8	0.1	0.0	4,681.1	323.2	8.2	0.2	0.0	0.0
1996	2.6	0.0	0.0	198.9	429.3	3,609.2	0.0	2.2	0.1	7,430.6	4,051.7	0.7	0.0	2.4	0.0
1997	21.7	0.0	0.0	133.4	328.7	2,667.7	24.1	0.4	0.3	9,536.2	1,630.5	1,058.1	1.7	0.0	0.0
1998	1,423.3	0.1	0.0	970.4	59.9	1,192.7	0.4	0.4	0.0	2,280.4	7,374.9	1,222.2	0.0	0.0	0.0
1999	66.7	0.0	0.0	127.3	57.4	1,446.0	0.0	24.5	0.0	2,605.4	7,680.1	16.5	0.0	7.3	0.0
2000	29.2	0.1	0.0	51.5	21.3	804.7	2.3	0.0	0.0	3,326.5	1,304.8	108.3	0.0	0.0	0.0
2001	54.3	0.0	0.0	39.2	25.7	248.3	0.0	0.2	0.0	11,265.2	679.7	24.1	0.0	3.5	0.0
2002	15,612.3	0.0	0.0	138.7	332.2	3,562.3	3.0	325.8	0.0	6,543.3	9.4	2.9	0.0	0.0	0.0
2003	15,324.8	0.0	0.0	79.7	455.0	652.3	0.0	1.0	0.0	16,139.5	1,643.5	1.8	0.0	0.1	0.0
2004	21,840.5	0.0	0.0	600.2	3,528.8	3,198.3	0.0	166.8	0.0	16,561.8	9,087.0	6.8	0.0	0.0	0.0
2005	19,990.9	0.0	0.0	417.2	460.8	1,445.3	0.0	0.0	0.0	6,639.8	13,185.2	69.8	0.0	0.0	0.0
2006	17,046.8	0.0	0.0	622.0	709.8	7,557.2	0.0	279.2	0.0	25,041.7	5,383.7	0.0	0.0	0.0	0.0
2007	8,420.7	0.0	0.0	288.1	4,420.5	5,548.5	0.0	0.6	0.0	6,646.4	118.5	102.7	0.0	0.0	0.0
2008	6,247.0	0.0	0.0	1,094.2	3,661.7	1,002.7	0.0	177.1	0.0	9,449.8	100.7	0.4	0.0	0.0	0.0
2009	4,872.6	0.0	0.0	44.3	444.2	3,136.9	0.0	12.7	0.0	13,170.1	780.2	13.6	0.0	0.1	159.7
2010	3,674.0	0.0	0.0	80.5	124.8	41.9	0.0	43.8	0.0	4,069.7	1,815.5	26.4	0.0	0.1	0.0
2011	10.7	0.0	0.0	35.5	145.4	60.2	0.1	22.7	0.0	139.3	118.7	0.4	0.0	0.0	0.0
2012	85.1	0.0	0.0	23.3	209.2	166.5	0.0	3.1	0.0	4,837.4	7.5	0.5	0.0	0.0	0.0
2013	36.8	0.0	0.0	42.8	3,515.4	87.6	0.0	11.1	0.0	657.2	2.2	19.5	0.0	0.1	0.0
2014	26.3	0.0	0.0	2,076.8	3,667.4	72.6	0.0	4.3	0.0	32.6	10.3	14.6	0.0	0.1	0.0
2015	60.0	0.0	0.0	2,182.8	1,351.8	489.6	0.3	119.3	0.0	1,310.2	81.1	21.0	0.0	0.4	0.0
2016	78.1	0.3	0.0	3,523.7	1,405.4	255.0	0.0	40.8	0.0	378.7	5.1	0.4	0.0	0.0	0.0

Table A8: U.S. commercial landings (mt) of Atlantic mackerel by market category during 1992-2016.

	Unclassified	Extra extra small	Extra small	Small	Medium	Large	Extra large
1992	9,195	0	0	1,451	14	1,101	0
1993	3,761	0	0	471	0	430	0
1994	6,913	0	0	1,515	375	115	0
1995	5,212	0	0	401	2,630	226	0
1996	6,611	0	0	3,714	3,283	2,120	0
1997	3,238	0	0	3,196	5,873	3,096	0
1998	6,020	0	0	2,185	2,934	3,387	0
1999	2,018	0	0	4,294	3,228	2,456	35
2000	1,269	0	0	2,041	1,063	1,164	113
2001	645	505	6,036	2,585	1,041	1,440	88
2002	13,680	0	1,001	10,676	698	474	3
2003	18,801	0	443	12,228	1,445	1,171	210
2004	35,554	0	652	6,015	11,492	1,276	2
2005	11,249	3,002	4,662	6,883	12,908	3,504	1
2006	5,638	433	15,740	11,197	22,319	854	461
2007	2,719	3,201	3,765	4,267	11,232	358	5
2008	1,972	565	2,275	6,025	10,529	349	19
2009	2,352	1,016	3,329	6,684	8,937	313	4
2010	1,467	1,602	2,289	1,958	2,531	30	1
2011	236	6	35	127	123	6	0
2012	690	502	2,712	666	752	10	1
2013	950	654	96	535	2,124	14	0
2014	1,023	298	165	2,057	2,206	157	0
2015	1,039	3	1,072	1,730	1,278	445	50
2016	1,192	201	462	269	3,048	337	178

Table A9: Total number of Atlantic mackerel length samples taken from commercial landings by combined market category, year and semester during 1992-2016.

	Unclassified		Small combined		Medium		Large combined		
	Semester 1	Semester 2	Semester 1	Semester 2	Semester 1	Semester 2	Semester 1	Semester 2	Total
1992	23	0	2	0	0	0	1	0	26
1993	1	1	0	0	0	0	0	0	2
1994	4	0	0	0	0	0	0	0	4
1995	4	2	2	0	0	0	1	0	9
1996	3	5	5	1	1	2	2	2	21
1997	11	0	6	0	3	0	3	0	23
1998	7	0	5	0	1	0	5	0	18
1999	24	0	7	0	5	0	5	0	41
2000	5	0	2	0	1	0	2	0	10
2001	7	1	14	0	1	0	7	0	30
2002	3	0	15	2	1	0	3	0	24
2003	15	1	7	1	0	0	2	1	27
2004	2	2	2	0	3	0	2	0	11
2005	16	2	3	1	1	0	2	2	27
2006	28	3	8	0	4	1	10	0	54
2007	22	3	41	2	14	1	9	1	93
2008	24	7	50	0	26	1	9	1	118
2009	23	5	7	0	7	0	8	0	50
2010	9	4	7	0	4	0	5	0	29
2011	20	2	4	0	2	0	0	0	28
2012	11	4	6	0	5	0	1	0	27
2013	21	3	8	0	1	0	1	0	34
2014	27	10	0	0	0	0	0	0	37
2015	27	11	10	0	1	0	8	0	57
2016	29	12	4	4	4	1	1	6	61

Table A10: Total number of Atlantic mackerel lengths sampled from commercial landings by combined market category, year and semester during 1992-2016. Lengths per sample represents the average number of lengths measured per sample.

	Unclassified		Small combined		Medium		Large combined			
	Semester 1	Semester 2	Semester 1	Semester 2	Semester 1	Semester 2	Semester 1	Semester 2	Total	Lengths per sample
1992	2,232	0	202	0	0	0	100	0	2,534	97
1993	101	110	0	0	0	0	0	0	211	106
1994	395	0	0	0	0	0	0	0	395	99
1995	401	270	200	0	0	0	100	0	971	108
1996	359	580	500	100	143	200	200	200	2,282	109
1997	1,112	0	631	0	308	0	298	0	2,349	102
1998	740	0	606	0	105	0	505	0	1,956	109
1999	2,551	0	732	0	500	0	514	0	4,297	105
2000	407	0	203	0	99	0	198	0	907	91
2001	710	116	1,400	0	100	0	700	0	3,026	101
2002	348	0	1,516	197	100	0	300	0	2,461	103
2003	1,546	100	712	104	0	0	207	118	2,787	103
2004	238	163	200	0	300	0	200	0	1,101	100
2005	1,815	200	354	200	109	0	233	206	3,117	115
2006	2,733	163	855	0	401	110	988	0	5,250	97
2007	2,164	315	4,280	207	1,405	99	900	104	9,474	102
2008	2,396	1,231	4,935	0	2,329	9	901	110	11,911	101
2009	2,158	545	702	0	694	0	812	0	4,911	98
2010	981	431	700	0	400	0	513	0	3,025	104
2011	1,897	200	400	0	200	0	0	0	2,697	96
2012	797	388	601	0	500	0	100	0	2,386	88
2013	1,646	295	802	0	100	0	78	0	2,921	86
2014	2,021	1,011	0	0	0	0	0	0	3,032	82
2015	2,458	1,095	904	0	104	0	805	0	5,366	94
2016	2,584	1,196	400	401	307	100	100	601	5,689	93

Table A11: Sampling intensity, expressed as metric tons of landings per 100 lengths measured, by combined market category, year and semester during 1992-2016.

	Unclassified		Small combined		Medium		Large combined		
	Semester 1	Semester 2	Semester 1	Semester 2	Semester 1	Semester 2	Semester 1	Semester 2	Total
1992	402.4	No samples	716.0	No samples	No samples	No landings	1,098.8	No samples	462.6
1993	3,031.4	155.3	No samples	No samples	No landings	No landings	No samples	No samples	1,959.2
1994	1,720.5	No samples	No samples	No samples	No samples	No samples	No samples	No samples	2,247.8
1995	1,253.2	68.8	169.1	No samples	No samples	No samples	222.8	No samples	872.1
1996	1,785.6	34.0	717.8	124.7	2,247.5	34.4	1,037.3	22.6	689.0
1997	276.8	No samples	502.7	No samples	1,902.2	No samples	1,031.5	No samples	655.7
1998	720.9	No samples	343.7	No samples	2,633.5	No samples	643.1	No samples	742.6
1999	74.2	No samples	585.2	No samples	644.6	No samples	483.2	No samples	280.0
2000	295.7	No samples	772.3	No samples	813.2	No samples	635.3	No samples	622.8
2001	76.4	88.6	651.7	No samples	1,036.8	No samples	218.3	No samples	407.8
2002	3,792.9	No samples	742.0	216.9	493.6	No samples	146.8	No samples	1,065.3
2003	1,192.3	368.2	1,774.7	33.2	No samples	No samples	666.6	1.3	1,230.6
2004	14,887.7	74.6	3,309.7	No samples	3,704.7	No samples	637.5	No samples	4,994.6
2005	613.3	58.4	4,016.0	165.2	11,812.1	No samples	1,501.2	3.5	1,354.2
2006	205.7	9.5	3,170.0	No samples	5,543.1	83.1	131.2	No samples	1,078.9
2007	124.7	6.2	261.2	26.0	796.9	36.1	40.3	0.6	269.6
2008	80.2	4.2	172.0	No samples	436.5	4,029.9	40.1	6.0	182.5
2009	105.0	15.6	1,565.4	No samples	1,286.2	No samples	39.0	No samples	460.9
2010	143.2	14.4	833.9	No samples	630.4	No samples	5.5	No samples	326.5
2011	7.7	45.2	33.9	No samples	59.9	No samples	No samples	No samples	19.8
2012	82.5	8.4	645.1	No samples	143.7	No samples	10.6	No samples	223.5
2013	45.9	66.1	103.4	No samples	1,930.3	No samples	0.3	No samples	149.7
2014	42.1	16.9	No samples	No samples	No samples	No samples	No samples	No samples	194.8
2015	16.7	57.3	212.8	No samples	566.6	No samples	8.9	No samples	104.7
2016	7.4	83.7	62.6	169.9	96.9	2,750.8	150.7	60.7	100.0

Table A12: Proportion of each market category to total annual landings by year and semester during 1992-2016.

	Unclassified		Small combined		Medium		Large combined		
	Semester 1	Semester 2	Semester 1	Semester 2	Semester 1	Semester 2	Semester 1	Semester 2	Total
1992	0.76	0.01	0.12	0.00	0.00	0.00	0.09	0.00	11,722
1993	0.66	0.04	0.10	0.00	0.00	0.00	0.09	0.00	4,134
1994	0.76	0.01	0.17	0.00	0.04	0.00	0.01	0.00	8,879
1995	0.59	0.02	0.04	0.01	0.31	0.00	0.03	0.00	8,468
1996	0.41	0.01	0.23	0.01	0.20	0.00	0.13	0.00	15,724
1997	0.20	0.01	0.21	0.00	0.38	0.00	0.20	0.00	15,403
1998	0.37	0.05	0.14	0.01	0.19	0.01	0.22	0.01	14,525
1999	0.16	0.01	0.36	0.00	0.27	0.00	0.21	0.00	12,031
2000	0.21	0.01	0.28	0.08	0.14	0.05	0.22	0.00	5,649
2001	0.04	0.01	0.74	0.00	0.08	0.00	0.12	0.00	12,340
2002	0.50	0.01	0.42	0.02	0.02	0.01	0.02	0.00	26,218
2003	0.54	0.01	0.37	0.00	0.04	0.00	0.04	0.00	34,298
2004	0.64	0.00	0.12	0.00	0.20	0.01	0.02	0.00	54,990
2005	0.26	0.00	0.34	0.01	0.31	0.00	0.08	0.00	42,209
2006	0.10	0.00	0.48	0.00	0.39	0.00	0.02	0.00	56,640
2007	0.11	0.00	0.44	0.00	0.44	0.00	0.01	0.00	25,546
2008	0.09	0.00	0.39	0.02	0.47	0.02	0.02	0.00	21,734
2009	0.10	0.00	0.49	0.00	0.39	0.00	0.01	0.00	22,634
2010	0.14	0.01	0.59	0.00	0.26	0.00	0.00	0.00	9,877
2011	0.27	0.17	0.25	0.06	0.22	0.01	0.01	0.00	533
2012	0.12	0.01	0.73	0.00	0.13	0.01	0.00	0.00	5,333
2013	0.17	0.04	0.19	0.10	0.44	0.04	0.00	0.00	4,372
2014	0.14	0.03	0.24	0.19	0.24	0.13	0.00	0.02	5,905
2015	0.07	0.11	0.34	0.16	0.10	0.12	0.01	0.08	5,616
2016	0.03	0.18	0.04	0.12	0.05	0.48	0.03	0.06	5,687

Table A13: Summary of imputations required to fill holes in the length sampling of Atlantic mackerel commercial landings for 1992-2016.

	Unclassified		Small combined		Medium		Large combined	
	Semester 1	Semester 2	Semester 1	Semester 2	Semester 1	Semester 2	Semester 1	Semester 2
1992	None	Subsequent spring	None	5yr average	Time series average	No landings	None	5yr average
1993	None	None	5yr average	5yr average	No landings	No landings	5yr average	5yr average
1994	None	Subsequent spring	5yr average	Subsequent spring	5yr average	5yr average	5yr average	Subsequent spring
1995	None	None	None	Subsequent spring	5yr average	Subsequent spring	None	Subsequent spring
1996	None	None	None	None	None	None	None	None
1997	None	Subsequent spring	None	Subsequent spring	None	Subsequent spring	None	Subsequent spring
1998	None	Subsequent spring	None	Subsequent spring	None	Subsequent spring	None	Subsequent spring
1999	None	Subsequent spring	None	Subsequent spring	None	Subsequent spring	None	Subsequent spring
2000	None	Subsequent spring	None	Subsequent spring	None	Subsequent spring	None	Subsequent spring
2001	None	None	None	Subsequent spring	None	Subsequent spring	None	Subsequent spring
2002	None	Subsequent spring	None	None	None	5yr average	None	Subsequent spring
2003	None	None	None	None	5yr average	Subsequent spring	None	None
2004	None	None	None	Subsequent spring	None	Subsequent spring	None	Subsequent spring
2005	None	None	None	None	None	Subsequent spring	None	None
2006	None	None	None	Subsequent spring	None	None	None	Subsequent spring
2007	None	None	None	None	None	None	None	None
2008	None	None	None	Subsequent spring	None	None	None	None
2009	None	None	None	Subsequent spring	None	Subsequent spring	None	Subsequent spring
2010	None	None	None	Subsequent spring	None	Subsequent spring	None	5yr average
2011	None	None	None	Subsequent spring	None	Subsequent spring	5yr average	Subsequent spring
2012	None	None	None	Subsequent spring	None	Subsequent spring	None	Subsequent spring
2013	None	None	None	5yr average	None	5yr average	None	5yr average
2014	None	None	5yr average	Subsequent spring	5yr average	Subsequent spring	5yr average	Subsequent spring
2015	None	None	None	Subsequent spring	None	Subsequent spring	None	Subsequent spring
2016	None	None	None	None	None	None	None	None

Table A14: Total number of Atlantic mackerel age samples from U.S. commercial landings by semester and year between 1992 and 2016.

	Semester 1	Semester 2	Total
1992			
1993			
1994	33	62	95
1995	107	24	131
1996	107	109	216
1997	238		238
1998	22		22
1999	56		56
2000	86		86
2001	228		228
2002	234	11	245
2003	178		178
2004	72		72
2005	217	60	277
2006	250	15	265
2007	306	55	361
2008	229	16	245
2009	184	25	209
2010	97	12	109
2011	42	11	53
2012	131		131
2013	64		64
2014	26	132	158
2015	228	142	370
2016	283	181	464

Table A15: U.S. commercial landings-at-age (thousands of fish) of Atlantic mackerel during 1992-2016.

	1	2	3	4	5	6	7	8	9	10
1992	193	3,517	2,141	12,023	7,126	794	813	23	246	4,481
1993	914	3,608	2,293	1,499	3,453	967	247	239	658	740
1994	888	3,678	9,068	7,686	1,851	4,557	830	127	13	373
1995	1,589	6,936	1,868	5,825	3,426	1,007	3,676	1,054	144	352
1996	854	15,472	18,050	815	7,195	3,624	908	2,181	728	114
1997	2,507	9,802	15,386	7,680	511	3,571	2,628	1,234	2,173	704
1998	247	9,941	9,588	8,345	3,452	797	3,018	3,278	430	701
1999	259	2,547	12,552	8,590	4,693	1,517	99	1,436	1,040	665
2000	2,297	7,275	3,760	3,835	1,675	733	180	2	59	29
2001	579	22,004	15,224	5,490	3,933	574	255	132	51	0
2002	6,980	14,349	73,641	5,059	1,877	3,586	1,001	91	12	4
2003	5,120	23,010	22,370	55,095	4,682	3,242	3,617	505	0	0
2004	19,600	60,320	15,412	16,868	68,403	5,863	1,711	2,214	2,240	0
2005	1,175	60,184	40,547	11,173	7,182	31,642	1,782	712	0	350
2006	1,269	19,137	125,219	28,739	6,290	4,879	20,605	638	93	42
2007	2,289	34,423	22,207	29,375	5,221	851	763	2,499	120	0
2008	5,672	17,808	35,857	8,972	9,985	1,673	174	237	658	15
2009	2,310	58,198	12,773	18,173	2,179	2,015	171	52	25	32
2010	4,975	31,400	11,645	912	727	21	40	0	0	0
2011	2,207	528	665	58	13	2	0	0	0	0
2012	2,860	27,222	1,657	1,098	290	29	0	0	0	0
2013	2,791	9,821	7,779	127	123	32	0	0	0	0
2014	9,255	8,366	6,738	1,412	2	0	0	0	0	0
2015	8,237	12,222	1,921	887	131	8	0	0	0	0
2016	14,323	10,389	1,392	88	25	11	3	0	0	0

Table A16: Total number of trips recorded for each fleet in the observer (Obs.), dealer and VTR databases for the Mid-Atlantic. Landings from the VTR database were used as the raising factor to estimate discards in the midwater trawl fleets. For all other fleets, the dealer database was used.

	Bottom trawl				Midwater trawl		Gillnet						Other	
	Small mesh		Large mesh				Small mesh		Large mesh		X-large mesh			
Year	Obs.	Dealer	Obs.	Dealer	Obs.	VTR	Obs.	Dealer	Obs.	Dealer	Obs.	Dealer	Obs.	Dealer
1989	34	4,592	4	2,627			0	67	0	1,646			0	12,592
1990	47	4,131	0	2,864	0	0	0	137	0	2,494	0	3	1	13,787
1991	78	4,355	4	3,699	5	0	0	121	0	3,364			7	15,166
1992	47	3,363	14	4,719	9	0	0	100	0	2,627			8	14,519
1993	16	3,068	12	5,904	14	0	0	80	0	2,856			29	14,972
1994	15	4,013	21	4,865	31	108	83	85	58	2,844	20	24	19	11,764
1995	63	5,061	55	6,745	33	170	137	185	207	4,028	73	294	20	9,634
1996	80	5,351	18	6,500	0	265	146	343	174	5,073	65	638	0	10,101
1997	48	5,866	9	6,554	0	211	106	422	136	10,134	111	1,021	4	12,617
1998	32	6,053	13	6,866	0	272	104	699	132	5,750	73	1,403	20	11,316
1999	35	5,432	8	6,712	0	233	44	848	23	5,402	19	1,443	48	10,765
2000	39	5,380	26	5,938	6	267	49	1,110	18	4,972	18	1,954	44	9,692
2001	55	4,661	50	6,493	0	227	54	1,280	17	3,834	17	2,193	3	9,593
2002	32	4,472	39	6,958	1	178	34	1,267	10	3,701	11	2,139	8	9,916
2003	74	2,964	16	7,107	5	311	25	750	4	3,838	13	2,104	5	9,683
2004	257	3,100	109	6,796	10	348	12	1,303	6	3,292	38	1,409	51	9,839
2005	172	1,888	93	8,441	15	299	19	1,270	4	4,122	82	1,739	50	10,694
2006	151	3,086	71	6,938	14	258	20	1,160	7	3,512	32	1,470	20	11,265
2007	218	2,910	160	5,976	3	170	19	1,231	13	5,760	32	2,045	32	11,445
2008	152	2,954	132	6,159	16	163	7	905	2	4,558	44	2,029	50	12,280
2009	286	3,165	167	6,945	25	193	9	1,252	8	7,132	43	1,693	16	11,394
2010	361	2,725	276	5,555	17	99	12	851	52	3,851	91	1,455	13	7,906
2011	365	2,868	254	6,297	26	47	11	1,529	24	5,901	62	2,275	0	12,203
2012	226	3,157	169	5,115	11	75	0	1,142	3	4,719	68	2,035	3	12,242
2013	396	3,179	251	4,749	3	78	8	890	9	7,392	29	1,789	0	14,649
2014	436	3,008	269	4,177	1	65	29	1,181	44	5,914	85	1,623	36	11,473
2015	360	2,528	231	4,367	3	57	162	1,118	141	5,100	126	1,427	60	10,726
2016	668	3,406	286	4,184	3	40	246	1,182	249	5,624	162	1,304	110	11,137

Table A17: Total number of trips recorded for each fleet in the observer (Obs.), dealer and VTR databases for New England. Landings from the VTR database were used as the raising factor to estimate discards in the midwater trawl fleets. For all other fleets, the dealer database was used.

	Bottom trawl				Midwater trawl		Gillnet						Other	
	Small mesh		Large mesh				Small mesh		Large mesh		X-large mesh			
Year	Obs.	Dealer	Obs.	Dealer	Obs.	VTR	Obs.	Dealer	Obs.	Dealer	Obs.	Dealer	Obs.	Dealer
1989	86	5,588	57	21,439	0	0	0	10	0	12,688	0	1	0	8,554
1990	37	5,205	54	21,518	0	0	0	10	0	13,303	0	26	1	10,270
1991	96	4,528	78	22,429	2	0	0	50	0	13,336	0	2	25	13,935
1992	57	4,277	68	22,518	0	0	0	5	0	13,367	0	47	46	13,088
1993	31	5,207	44	21,468	7	0	0	2	0	13,184	0	81	22	13,559
1994	18	5,761	36	21,084	4	359	0	3	61	13,510	40	934	22	14,660
1995	40	4,372	68	20,376	6	796	0	8	105	12,798	46	2,030	18	15,201
1996	50	3,945	44	19,750	0	915	0	21	55	10,957	23	1,533	8	14,197
1997	22	3,888	29	17,417	0	794	0	12	51	9,487	19	1,214	4	12,945
1998	6	4,292	13	18,156	0	682	3	14	115	9,579	15	1,061	5	14,031
1999	19	4,129	41	16,345	3	685	1	7	98	7,122	21	1,352	9	12,589
2000	17	3,462	103	17,473	7	830	0	17	107	7,547	50	1,881	3	11,694
2001	19	3,007	157	17,372	1	965	1	17	69	7,086	33	2,530	7	11,433
2002	65	2,404	220	17,480	0	1,026	0	14	91	7,095	41	2,827	15	14,783
2003	73	2,410	387	16,813	20	868	0	20	326	7,857	190	2,990	37	11,150
2004	173	1,974	531	13,384	83	838	1	16	699	5,922	536	2,973	157	10,898
2005	253	1,639	1,350	11,902	134	730	0	39	587	5,833	459	2,958	345	30,887
2006	85	2,237	619	10,612	31	684	0	67	142	6,683	79	2,421	102	37,925
2007	76	2,358	621	10,760	21	322	2	78	132	7,905	164	2,102	116	33,840
2008	61	2,556	753	11,013	47	218	3	27	170	9,453	112	2,274	127	47,605
2009	219	2,566	879	10,936	77	272	2	12	313	10,014	76	1,989	135	59,183
2010	246	2,852	1,054	9,423	135	272	0	22	1,267	7,837	771	2,653	203	140,214
2011	192	2,100	1,597	8,351	113	311	0	9	1,589	6,515	715	2,847	166	149,281
2012	160	2,536	1,551	8,357	161	368	0	6	1,379	5,844	454	2,502	269	159,640
2013	241	2,366	1,095	7,343	96	416	0	4	620	3,432	323	2,272	98	158,515
2014	326	2,512	1,198	6,404	102	378	0	9	919	3,338	588	2,339	120	158,875
2015	289	2,629	897	6,106	16	347	0	4	471	1,951	450	2,451	327	161,111
2016	329	3,807	632	5,091	49	294	1	6	278	2,021	218	2,525	128	173,738

Table A18: Estimates of total annual U.S. commercial discards (mt), corresponding coefficients of variation (CV), U.S. commercial landings (mt) and the proportion of total commercial catch that is discarded (proportion discarded) during 1992-2016.

Year	Discards (mt)	CV	Landings (mt)	Proportion discarded
1992	2,072.3	0.65	11,760.7	0.15
1993	3,902.3	0.43	4,661.9	0.46
1994	5,409.0	2.86	8,917.4	0.38
1995	53.9	0.35	8,468.4	0.01
1996	2,052.5	0.42	15,727.6	0.12
1997	228.8	0.56	15,402.6	0.01
1998	97.5	2.17	14,524.8	0.01
1999	770.5	0.68	12,031.4	0.06
2000	152.9	0.81	5,648.8	0.03
2001	718.2	0.70	12,340.2	0.05
2002	155.3	0.84	26,530.0	0.01
2003	264.3	0.61	34,297.8	0.01
2004	2,140.8	0.54	54,990.3	0.04
2005	1,082.6	0.61	42,208.9	0.03
2006	134.9	0.35	56,640.4	0.00
2007	159.4	0.45	25,546.1	0.01
2008	746.7	0.45	21,733.8	0.03
2009	124.9	1.18	22,634.5	0.01
2010	96.9	0.42	9,876.7	0.01
2011	37.8	0.37	533.1	0.07
2012	33.2	0.51	5,332.6	0.01
2013	19.8	0.43	4,372.4	0.00
2014	52.0	0.35	5,905.1	0.01
2015	13.0	0.30	5,616.4	0.00
2016	17.7	0.17	5,687.4	0.00

Table A19: Annual U.S. commercial discard estimates (mt) of Atlantic mackerel by gear between 1992 and 2016.

	Bottom trawl	Dredge	Gillnet	Handline	Haul Seine	Longline	Midwater trawl	Pots/Traps	Purse Seine	Scallop	Seine	Shrimp
1992	2070.7	0	0	0	0	0		0	0	0	0	1.6
1993	3897.1	0	0	0	0	0		0	0	1.9	0	3.3
1994	5390.7	0	16.4	0	0	0	1.4	0	0	0.2	0	0.4
1995	38.4	0	12.7	0	0	0	1	0	0	0.3	0	1.4
1996	1834.9	0	214.5	0	0	0	0	0.4	0	1.7	0	1.1
1997	131.1	0	90.8	0	0	0	0	0	0	0.9	0	6
1998	51.2	0	46.1	0	0	0	0	0	0	0.2	0	0
1999	745.1	0	22.1	0	0	0	2.7	0.4	0	0.1	0	0
2000	122.4	0	30	0	0	0	0	0	0	0.5	0	0
2001	685.5	0	16.6	0	0	0	0	0	0	0.1	0	15.9
2002	146.2	0	9.1	0	0	0	0	0	0	0	0	0
2003	206.8	0	18.4	38.5	0	0	0.2	0	0	0.4	0	0
2004	698.4	0	9.6	0	0	0	1431.8	0	0	1	0	0
2005	758.4	0	14.6	0	0	0	307.2	0	0.1	1	0	1.2
2006	119.6	0	5	0	0	0	10	0	0	0	0	0.2
2007	129.1	0	1.9	0	0	0	28.4	0	0	0	0	0
2008	745.6	0	0.6	0	0	0	0.2	0	0.1	0.1	0	0
2009	79.7	0	1.3	0	0	0	43.8	0	0	0.1	0	0
2010	91.3	0	3	0	0	0	2.2	0	0	0	0	0.4
2011	28.4	0	1.6	0.1	0	0	7.1	0	0	0.1	0	0.6
2012	25	0	1.5	0	0	0	0	0	0	0.4	0	6.3
2013	10.6	0	1.3	0.3	0	0	0	0	0	0	0	7.7
2014	35.3	0	1.2	15.4	0	0	0	0	0	0	0	0
2015	10.5	0	2.3	0	0	0	0.1	0	0	0.1	0	0
2016	17.2	0	0.3	0	0	0	0.1	0	0	0.1	0	0

Table A20: Coefficients of variation (CVs) corresponding to annual U.S. Atlantic mackerel commercial discard estimates by gear between 1992 and 2016.

	Bottom trawl	Dredge	Gillnet	Handline	Haul Seine	Longline	Midwater trawl	Pots/Traps	Purse Seine	Scallop	Seine	Shrimp
1992	0.65											0.43
1993	0.43									0.67		0.53
1994	2.87		0.43			1.46	0.21			0.77		0.77
1995	0.48		0.21				0.7			0.59		0.6
1996	0.43		1.58					1.33		0.78		0.76
1997	0.92		0.51							0.43		0.88
1998	4.11		0.55							1		
1999	0.7		0.57				1.01	1.32		0.36		
2000	0.82		2.36							0.36		
2001	0.73		0.49							0.76	0.73	0.46
2002	0.89		1.38									
2003	0.72		0.74	1.54			1.03			0.48		
2004	1.11		0.35				0.59		1.31	0.45		
2005	0.8		0.37				0.83		0.96	0.71		0.58
2006	0.38		0.82				0.84					0.72
2007	0.48		0.77				1.29			0.96		1.05
2008	0.45		0.3		2.39		0.85	5.79	1.03	0.44		
2009	1.83		0.25				0.59		1.56	0.36		
2010	0.45		0.24				0.46			0.63		1.1
2011	0.35		0.14	2.56			1.4		0.79	0.58		0
2012	0.67		0.15				0.15		0.37	0.37		0.27
2013	0.33		0.26	2.32			0.29		0.53	0.41		1.01
2014	0.36		0.17	0.86			0.2		0.98	0.69		
2015	0.37		0.21				0.23	1.09	0.64	0.53		
2016	0.18		0.23				0.64		2.7	0.4		

Table A21: Annual U.S. commercial discard estimates (mt) of Atlantic mackerel for bottom trawl and gillnet gears by mesh category during 1992-2016.

	Bottom trawl		Gillnet		
	Small	Large	Small	Large	Extra large
1992	1,953.90	116.90	0.00	0.00	0.00
1993	903.50	2,993.60	0.00	0.00	0.00
1994	4,492.60	898.10	0.00	16.20	0.10
1995	20.10	18.40	0.00	11.00	1.70
1996	1,760.30	74.50	0.90	209.00	4.60
1997	130.90	0.30	0.10	70.50	20.10
1998	21.00	30.20	0.90	30.40	14.70
1999	137.10	608.00	0.00	14.90	7.20
2000	72.70	49.70	0.00	10.60	19.40
2001	352.30	333.20	0.00	7.80	8.90
2002	36.00	110.20	0.00	2.20	6.90
2003	203.90	3.00	0.00	17.60	0.80
2004	648.50	50.00	0.80	6.30	2.50
2005	753.90	4.50	0.00	1.00	13.60
2006	111.60	8.00	0.00	0.30	4.70
2007	128.20	0.90	0.00	1.80	0.10
2008	743.60	2.00	0.00	0.50	0.10
2009	77.20	2.50	0.00	1.30	0.00
2010	87.50	3.80	0.00	2.10	0.90
2011	26.80	1.60	0.00	1.40	0.20
2012	23.90	1.20	0.00	1.50	0.00
2013	7.60	3.00	0.00	1.20	0.00
2014	31.40	3.90	0.00	1.10	0.10
2015	6.70	3.80	0.10	2.10	0.20
2016	15.40	1.70	0.00	0.30	0.10

Table A22: Total number of Atlantic mackerel lengths sampled from U.S. commercial discards by semester and year between 1992 and 2016.

	Semester 1	Semester 2
1992	520	6
1993	403	133
1994	92	11
1995	2	1,204
1996	791	346
1997	1,055	2
1998	185	0
1999	930	374
2000	341	1
2001	287	16
2002	13	22
2003	247	636
2004	850	998
2005	926	434
2006	214	16
2007	1,527	19
2008	273	205
2009	523	95
2010	434	363
2011	484	172
2012	420	34
2013	22	100
2014	53	51
2015	97	44
2016	113	20

Table A23: U.S. commercial discards-at-age (thousands of fish) of Atlantic mackerel during 1992-2016.

	1	2	3	4	5	6	7	8	9	10
1992	555	623	346	1,099	582	177	178	261	61	915
1993	3,623	2,634	636	191	784	353	166	123	449	689
1994	8,441	654	2,301	1,962	530	1,396	333	96	45	352
1995	3	22	4	10	6	3	10	4	1	3
1996	4,271	2,859	687	19	171	98	43	155	55	22
1997	23	99	108	61	10	54	56	21	39	11
1998	85	101	51	31	10	2	8	10	3	6
1999	722	1,091	673	173	75	27	0	20	13	3
2000	326	216	109	41	8	2	1	1	0	0
2001	412	1,489	317	120	230	55	10	3	3	0
2002	209	51	128	26	16	28	66	1	0	0
2003	365	101	109	222	28	13	18	9	0	0
2004	5,713	1,669	353	348	1,277	106	42	15	15	0
2005	583	1,929	564	92	91	599	32	55	0	0
2006	402	133	115	22	4	2	9	0	5	0
2007	100	341	64	54	6	1	1	2	0	0
2008	3,684	248	414	59	51	7	0	1	0	0
2009	343	216	19	49	6	4	0	0	0	0
2010	190	219	37	3	4	0	6	0	0	0
2011	93	28	38	7	1	1	0	0	0	0
2012	278	34	0	0	0	0	0	0	0	0
2013	13	45	12	0	1	0	0	0	0	0
2014	155	45	35	16	0	0	0	0	0	0
2015	14	20	5	4	3	0	0	0	0	0
2016	22	48	7	0	1	0	0	0	0	0

Table A24: U.S. recreational catch-at-age (thousands of fish) of Atlantic mackerel during 1992-2016.

	1	2	3	4	5	6	7	8	9	10
1992	95	110	54	237	127	23	27	4	5	175
1993	272	279	171	94	235	98	29	36	111	130
1994	917	97	482	664	220	727	285	79	15	522
1995	760	826	156	578	382	135	507	167	75	77
1996	487	346	641	69	664	422	106	228	76	32
1997	904	1,123	749	606	65	405	295	133	267	147
1998	490	296	357	309	132	20	105	169	14	72
1999	590	484	831	528	391	142	9	144	93	77
2000	1,008	989	459	741	319	89	45	2	70	60
2001	691	1,097	481	316	868	383	281	490	13	3
2002	446	996	1,737	359	164	240	84	15	0	0
2003	673	519	344	731	83	69	60	8	0	0
2004	597	364	88	96	393	33	11	12	12	0
2005	280	892	821	141	91	651	28	14	0	0
2006	610	836	1,996	471	104	83	562	17	1	1
2007	494	372	346	611	62	4	2	26	2	0
2008	1,162	908	902	128	155	23	1	33	34	0
2009	975	1,290	196	165	18	54	6	1	0	7
2010	956	1,603	703	120	16	1	0	0	0	0
2011	3,370	734	401	98	10	1	0	0	0	0
2012	1,468	1,223	147	85	56	1	0	0	0	0
2013	1,784	1,323	402	5	6	0	0	0	0	0
2014	2,771	502	225	74	0	0	0	0	0	0
2015	2,594	1,900	383	213	37	1	0	0	0	0
2016	2,526	2,832	450	26	11	5	1	0	0	0

Table A25: U.S. catch-at-age (thousands of fish) of Atlantic mackerel from 1968-2016.

	1	2	3	4	5	6	7	8	9	10
1968	118,409	57,679	53,778	34,153	12,795	5,880	315	115	534	48
1969	3,051	243,349	147,855	64,358	5,039	2,392	1,218	2,787	1,871	1,431
1970	178,335	51,767	496,983	156,882	25,733	6,663	4,982	8,720	8,770	3,358
1971	70,235	289,693	126,362	536,983	198,852	33,531	7,556	2,669	3,154	11,935
1972	22,100	85,601	253,001	178,572	372,354	83,684	20,185	4,144	7,803	4,433
1973	156,661	271,650	279,696	228,373	184,575	184,715	26,542	9,448	3,631	4,502
1974	92,677	233,097	254,413	96,039	109,590	107,156	102,549	24,184	5,759	2,646
1975	368,394	422,098	108,826	96,454	55,966	64,989	49,862	49,037	12,192	3,083
1976	11,697	343,418	259,590	80,470	48,714	25,458	38,156	32,706	21,113	14,245
1977	1,353	20,757	81,258	44,098	8,778	7,652	4,892	5,038	3,015	2,694
1978	98	18	869	2,667	1,725	2,042	1,543	551	3,098	4,803
1979	196	120	111	485	1,398	779	610	318	498	4,043
1980	1,194	9,445	1,156	463	1,813	3,967	1,448	692	604	3,202
1981	9,955	4,264	4,057	217	344	1,431	3,957	1,591	905	1,608
1982	1,555	5,901	1,091	4,096	485	291	777	3,572	1,351	2,596
1983	1,956	13,678	4,041	985	2,988	222	254	2,381	2,430	2,899
1984	440	20,626	13,140	1,787	419	3,049	261	221	1,378	8,360
1985	2,748	1,047	99,205	19,695	1,648	299	1,755	131	186	7,266
1986	926	8,433	3,449	60,057	13,872	1,171	211	2,549	98	4,173
1987	2,877	11,470	11,264	5,417	82,985	12,102	2,279	180	2,024	2,815
1988	888	12,306	9,246	8,023	9,199	82,006	18,546	2,401	1,058	4,980
1989	1,533	8,301	9,757	6,384	5,536	1,777	67,672	2,284	556	1,471
1990	3,731	23,183	37,408	6,945	5,730	3,506	161	38,427	1,711	923
1991	767	8,504	38,582	15,066	5,248	3,138	2,248	151	16,336	643
1992	842	4,251	2,541	13,359	7,835	993	1,019	288	312	5,571
1993	4,809	6,521	3,100	1,785	4,472	1,418	443	398	1,218	1,559
1994	10,245	4,430	11,850	10,312	2,600	6,680	1,447	302	73	1,247
1995	2,352	7,784	2,028	6,413	3,814	1,144	4,193	1,225	220	432
1996	5,613	18,678	19,378	902	8,030	4,144	1,056	2,565	859	168
1997	3,433	11,024	16,243	8,348	586	4,030	2,979	1,388	2,479	861
1998	821	10,338	9,996	8,685	3,594	818	3,131	3,458	447	779
1999	1,571	4,122	14,057	9,291	5,159	1,686	109	1,600	1,146	745
2000	3,630	8,480	4,329	4,618	2,001	825	227	5	128	89
2001	1,682	24,589	16,021	5,926	5,031	1,012	546	625	67	3
2002	7,636	15,397	75,505	5,444	2,056	3,854	1,150	107	12	4
2003	6,157	23,630	22,822	56,047	4,793	3,325	3,695	523	0	0
2004	25,910	62,353	15,854	17,312	70,073	6,002	1,764	2,241	2,268	0
2005	2,038	63,004	41,932	11,407	7,364	32,893	1,841	781	1	350
2006	2,281	20,106	127,331	29,232	6,397	4,964	21,176	655	100	44
2007	2,883	35,136	22,617	30,040	5,289	856	766	2,526	122	0
2008	10,518	18,964	37,173	9,159	10,191	1,703	176	270	693	15
2009	3,628	59,703	12,988	18,387	2,203	2,074	178	52	25	38
2010	6,121	33,222	12,385	1,034	747	21	46	0	0	0

Continued

Table A25, contd.: U.S. catch-at-age (thousands of fish) of Atlantic mackerel from 1968-2016.

	1	2	3	4	5	6	7	8	9	10
2011	5,670	1,290	1,104	163	24	4	0	0	0	0
2012	4,605	28,479	1,804	1,183	346	30	0	0	0	0
2013	4,588	11,190	8,194	133	130	32	0	0	0	0
2014	12,181	8,913	6,998	1,501	2	0	0	0	0	0
2015	10,845	14,142	2,310	1,104	171	9	0	0	0	0
2016	16,871	13,269	1,848	114	36	16	4	0	0	0

Table A26: Canadian DFO's sampling intensity of Atlantic mackerel from 1973-2016. Biological samples were used in estimation of weight-at-age, fecundity and age-length keys; length samples were used in catch expansions.

	Biological samples			Length samples	
Year	**Samples**	**Number of fish**	**Fish / sample**	**Number of lengths**	**Length sampling intensity**
1973	102	3,945	39	NA	NA
1974	47	2,000	43	NA	NA
1975	59	2,319	39	NA	NA
1976	103	3,082	30	14,286	178
1977	104	3,422	33	12,458	181
1978	106	2,125	20	11,330	225
1979	123	3,225	26	13,555	223
1980	103	1,927	19	12,002	184
1981	82	1,751	21	10,006	193
1982	87	1,522	18	9,621	170
1983	123	4,190	34	1,608	1,231
1984	151	4,774	32	19,933	87
1985	110	4,003	36	14,001	213
1986	91	3,568	39	10,903	261
1987	123	3,118	25	17,961	153
1988	140	2,344	17	23,780	101
1989	127	3,375	27	20,908	100
1990	63	2,333	37	10,295	212
1991	67	2,131	32	12,549	206
1992	57	2,457	43	11,256	234
1993	71	2,856	40	11,305	236
1994	55	1,903	35	11,750	177
1995	72	2,503	35	16,970	108
1996	55	1,940	35	12,808	164
1997	51	2,035	40	12,188	175
1998	55	1,997	36	13,213	143
1999	65	2,272	35	13,875	128
2000	66	2,595	39	12,779	140
2001	79	2,600	33	19,219	127
2002	78	2,798	36	15,694	222
2003	82	2,593	32	18,947	237
2004	96	3,994	42	19,175	280
2005	121	4,259	35	15,003	369
2006	131	5,076	39	15,505	348
2007	132	4,151	31	14,053	380
2008	82	2,812	34	9,948	298
2009	96	3,412	36	12,970	326
2010	139	4,899	35	13,429	289
2011	69	2,573	37	8,504	136
2012	45	2,137	48	7,401	87
2013	36	1,117	31	5,954	151
2014	46	1,418	31	7,495	92
2015	43	1,337	31	7,144	69
2016	63	1,933	31	10,561	76

Table A27: Canadian catch-at-age (thousands of fish) of Atlantic mackerel from 1968-2016.

	1	2	3	4	5	6	7	8	9	10
1968	43,062	7,157	10,343	7,393	2,819	1,349	721	1,658	10,425	97
1969	5,692	26,359	18,057	2,027	929	855	1,099	440	462	9,656
1970	20,277	3,654	33,584	8,047	2,496	451	425	1,578	1,645	4,335
1971	7,156	7,389	1,702	35,931	7,620	1,753	2,203	1,526	1,879	5,517
1972	1	136	4,401	5,541	24,826	4,975	5,248	77	546	6,833
1973	9,176	20,624	9,649	9,333	13,972	22,293	8,317	2,771	837	1,603
1974	8,618	24,340	26,703	14,602	12,594	12,417	15,377	4,053	1,714	1,749
1975	14,206	24,905	13,049	11,636	7,052	7,526	5,456	3,917	825	581
1976	1,686	21,171	27,110	10,982	7,740	3,868	4,922	3,977	3,123	1,165
1977	740	7,136	22,566	11,319	3,683	2,570	809	1,443	897	1,721
1978	2	182	3,831	14,733	11,575	6,358	3,157	1,649	1,402	2,497
1979	204	480	1,189	6,615	17,202	12,321	5,590	2,282	1,702	2,457
1980	6	1,455	2,156	1,463	5,087	9,833	6,148	2,692	1,604	1,998
1981	6,145	2,836	5,143	1,183	1,656	4,669	7,743	3,309	1,595	1,892
1982	2,145	5,899	1,609	5,004	715	1,609	2,623	4,828	1,549	2,504
1983	244	1,622	2,459	915	4,012	478	946	3,119	7,770	3,601
1984	60	19,774	14,060	1,413	781	1,551	339	479	2,022	5,640
1985	357	511	23,790	12,844	1,252	656	2,197	289	551	7,605
1986	363	4,282	3,259	40,844	11,522	933	485	635	117	1,915
1987	1,291	3,118	3,358	2,288	27,133	5,692	232	183	83	716
1988	117	703	1,028	1,932	2,481	24,769	4,493	227	131	572
1989	2,399	8,862	1,276	937	1,541	575	20,957	2,693	369	781
1990	390	6,222	9,737	1,457	888	966	639	16,765	923	277
1991	646	6,106	17,808	9,560	1,212	762	1,052	849	10,964	557
1992	628	2,627	3,014	14,148	8,630	1,411	733	1,048	884	11,142
1993	117	4,900	8,493	4,497	13,011	7,686	1,660	651	699	6,882
1994	672	231	3,896	5,905	2,856	13,672	5,977	929	244	2,925
1995	10,603	14,206	698	4,674	4,093	1,768	5,757	2,281	203	590
1996	2,505	8,050	7,052	1,013	5,380	6,519	1,622	7,094	1,806	893
1997	5,083	11,823	10,923	4,604	638	3,709	3,081	545	4,212	785
1998	1,927	18,525	9,977	9,560	4,291	505	2,432	2,024	412	1,472
1999	1,348	4,463	14,625	7,509	4,698	2,049	478	681	663	354
2000	28,460	2,689	1,800	5,465	2,869	2,941	458	65	195	371
2001	8,215	60,111	11,234	2,482	4,184	842	870	144	33	371
2002	6,088	3,832	70,334	6,047	2,275	2,136	538	407	48	73
2003	3,763	4,381	5,832	73,840	8,480	1,123	1,199	32	5	0
2004	27,524	24,574	6,017	4,753	56,010	2,457	1,322	606	9	0
2005	17,391	42,971	24,381	4,007	3,807	40,391	1,680	746	81	45
2006	31,651	14,756	41,630	21,769	3,765	1,917	17,117	448	36	0
2007	2,968	31,233	22,784	43,885	11,105	2,471	1,328	4,819	39	7
2008	23,622	8,120	25,964	8,655	12,703	1,631	633	218	1,033	9
2009	38,026	24,443	6,613	28,416	6,363	9,425	358	127	5	482

Continued

Table A27, contd.: Canadian catch-at-age (thousands of fish) of Atlantic mackerel from 1968-2016.

	1	2	3	4	5	6	7	8	9	10
2010	5,402	31,923	28,384	3,829	13,988	2,033	3,286	83	1	132
2011	2,288	1,230	11,611	6,091	639	3,100	336	474	25	40
2012	193	10,775	1,969	3,142	332	34	113	7	1	0
2013	574	5,685	13,651	776	1,593	101	0	0	0	0
2014	1,134	3,475	6,902	4,397	119	80	0	1	0	0
2015	2,883	3,919	2,450	3,142	852	221	29	2	0	0
2016	2,111	3,030	3,501	2,028	1,788	723	77	0	0	0

Table A28: Total (U.S. and Canada combined) catch-at-age (thousands of fish) of Atlantic mackerel from 1968 -2016.

	1	2	3	4	5	6	7	8	9	10
1968	161,471	64,836	64,121	41,546	15,614	7,229	1,036	1,773	10,959	145
1969	8,743	269,708	165,912	66,385	5,968	3,247	2,317	3,227	2,333	11,087
1970	198,612	55,421	530,567	164,929	28,229	7,114	5,407	10,298	10,415	7,693
1971	77,391	297,082	128,064	572,914	206,472	35,284	9,759	4,195	5,033	17,452
1972	22,101	85,737	257,402	184,113	397,180	88,659	25,433	4,221	8,349	11,266
1973	165,837	292,274	289,345	237,706	198,547	207,008	34,859	12,219	4,468	6,105
1974	101,295	257,437	281,116	110,641	122,184	119,573	117,926	28,237	7,473	4,395
1975	382,600	447,003	121,875	108,090	63,018	72,515	55,318	52,954	13,017	3,664
1976	13,383	364,589	286,700	91,452	56,454	29,326	43,078	36,683	24,236	15,410
1977	2,093	27,893	103,824	55,417	12,461	10,222	5,701	6,481	3,912	4,415
1978	100	200	4,700	17,400	13,300	8,400	4,700	2,200	4,500	7,300
1979	400	600	1,300	7,100	18,600	13,100	6,200	2,600	2,200	6,500
1980	1,200	10,900	3,312	1,926	6,900	13,800	7,596	3,384	2,208	5,200
1981	16,100	7,100	9,200	1,400	2,000	6,100	11,700	4,900	2,500	3,500
1982	3,700	11,800	2,700	9,100	1,200	1,900	3,400	8,400	2,900	5,100
1983	2,200	15,300	6,500	1,900	7,000	700	1,200	5,500	10,200	6,500
1984	500	40,400	27,200	3,200	1,200	4,600	600	700	3,400	14,000
1985	3,105	1,558	122,995	32,539	2,900	955	3,952	420	737	14,871
1986	1,289	12,715	6,708	100,901	25,394	2,104	696	3,184	215	6,088
1987	4,168	14,588	14,622	7,705	110,118	17,794	2,511	363	2,107	3,531
1988	1,005	13,009	10,274	9,955	11,680	106,775	23,039	2,628	1,189	5,552
1989	3,932	17,163	11,033	7,321	7,077	2,352	88,629	4,977	925	2,252
1990	4,121	29,405	47,145	8,402	6,618	4,472	800	55,192	2,634	1,200
1991	1,413	14,610	56,390	24,626	6,460	3,900	3,300	1,000	27,300	1,200
1992	1,470	6,878	5,555	27,507	16,465	2,404	1,752	1,336	1,196	16,713
1993	4,926	11,421	11,593	6,282	17,483	9,104	2,103	1,049	1,917	8,441
1994	10,917	4,661	15,746	16,217	5,456	20,352	7,424	1,231	317	4,172
1995	12,955	21,990	2,726	11,087	7,907	2,912	9,950	3,506	423	1,022
1996	8,118	26,728	26,430	1,915	13,410	10,663	2,678	9,659	2,665	1,061
1997	8,516	22,847	27,166	12,952	1,224	7,739	6,060	1,933	6,691	1,646
1998	2,748	28,863	19,973	18,245	7,885	1,323	5,563	5,482	859	2,251
1999	2,919	8,585	28,682	16,800	9,857	3,735	587	2,281	1,809	1,099
2000	32,090	11,169	6,129	10,083	4,870	3,766	685	70	323	460
2001	9,897	84,700	27,255	8,408	9,215	1,854	1,416	769	100	374
2002	13,724	19,229	145,839	11,491	4,331	5,990	1,688	514	60	77
2003	9,920	28,011	28,654	129,887	13,273	4,448	4,894	555	5	0
2004	53,434	86,927	21,871	22,065	126,083	8,459	3,086	2,847	2,277	0
2005	19,429	105,975	66,313	15,414	11,171	73,284	3,521	1,527	82	395
2006	33,932	34,862	168,961	51,001	10,162	6,881	38,293	1,103	136	44
2007	5,851	66,369	45,401	73,925	16,394	3,327	2,094	7,345	161	7
2008	34,140	27,084	63,137	17,814	22,894	3,334	809	488	1,726	24
2009	41,654	84,146	19,601	46,803	8,566	11,499	536	179	30	520

Continued

Table A28, contd.: Total (U.S. and Canada combined) catch-at-age (thousands of fish) of Atlantic mackerel from 1968 -2016.

	1	2	3	4	5	6	7	8	9	10
2010	11,523	65,145	40,769	4,863	14,735	2,054	3,332	83	1	132
2011	7,958	2,520	12,715	6,254	663	3,104	336	474	25	40
2012	4,798	39,254	3,773	4,325	678	64	113	7	1	0
2013	5,162	16,875	21,845	909	1,723	133	0	0	0	0
2014	13,315	12,388	13,900	5,898	121	80	0	1	0	0
2015	13,728	18,061	4,760	4,246	1,023	230	29	2	0	0
2016	18,982	16,299	5,349	2,142	1,824	739	81	0	0	0

Table A29: Average weight-at-age of the U.S. total catch of Atlantic mackerel from 1968-2016. Cells shaded in grey were imputed using age-specific averages from 1992-2016.

	1	2	3	4	5	6	7	8	9	10
1968	0.148	0.241	0.335	0.425	0.506	0.576	0.634	0.683	0.722	0.753
1969	0.131	0.214	0.300	0.382	0.456	0.520	0.574	0.618	0.654	0.683
1970	0.107	0.179	0.253	0.324	0.389	0.444	0.491	0.530	0.562	0.605
1971	0.110	0.181	0.256	0.327	0.391	0.446	0.494	0.532	0.564	0.602
1972	0.123	0.210	0.300	0.386	0.464	0.533	0.590	0.638	0.677	0.712
1973	0.113	0.189	0.269	0.345	0.414	0.473	0.524	0.565	0.600	0.636
1974	0.111	0.190	0.273	0.352	0.425	0.487	0.541	0.585	0.621	0.656
1975	0.104	0.176	0.252	0.326	0.393	0.451	0.500	0.540	0.573	0.606
1976	0.097	0.168	0.244	0.316	0.382	0.440	0.489	0.530	0.563	0.592
1977	0.114	0.198	0.288	0.375	0.454	0.524	0.582	0.631	0.671	0.709
1978	0.192	0.285	0.425	0.463	0.509	0.582	0.625	0.659	0.673	0.721
1979	0.190	0.272	0.531	0.567	0.579	0.603	0.652	0.714	0.752	0.824
1980	0.146	0.376	0.527	0.572	0.617	0.635	0.663	0.711	0.738	0.798
1981	0.114	0.315	0.523	0.577	0.643	0.660	0.674	0.707	0.723	0.782
1982	0.152	0.340	0.541	0.606	0.666	0.743	0.737	0.722	0.719	0.809
1983	0.098	0.257	0.479	0.593	0.628	0.659	0.712	0.709	0.705	0.734
1984	0.098	0.162	0.338	0.525	0.625	0.657	0.696	0.715	0.705	0.721
1985	0.111	0.260	0.277	0.416	0.558	0.644	0.677	0.665	0.737	0.714
1986	0.079	0.234	0.349	0.366	0.452	0.581	0.640	0.729	0.777	0.737
1987	0.107	0.210	0.316	0.404	0.411	0.505	0.502	0.706	0.747	0.766
1988	0.100	0.222	0.343	0.408	0.453	0.484	0.584	0.694	0.755	0.763
1989	0.100	0.231	0.375	0.414	0.474	0.509	0.529	0.631	0.753	0.815
1990	0.096	0.175	0.298	0.430	0.466	0.498	0.343	0.522	0.600	0.747
1991	0.132	0.253	0.382	0.451	0.538	0.588	0.603	0.486	0.669	0.773
1992	0.165	0.191	0.292	0.356	0.382	0.449	0.457	0.579	0.593	0.590
1993	0.159	0.190	0.267	0.348	0.384	0.439	0.564	0.527	0.574	0.614
1994	0.154	0.189	0.263	0.325	0.390	0.426	0.477	0.551	0.652	0.615
1995	0.152	0.196	0.308	0.343	0.388	0.456	0.470	0.501	0.593	0.625
1996	0.159	0.201	0.300	0.386	0.403	0.440	0.487	0.536	0.575	0.626
1997	0.105	0.211	0.313	0.376	0.438	0.460	0.494	0.551	0.579	0.620
1998	0.142	0.204	0.318	0.419	0.445	0.467	0.487	0.524	0.624	0.675
1999	0.188	0.197	0.296	0.365	0.449	0.495	0.589	0.550	0.530	0.667
2000	0.142	0.208	0.265	0.392	0.466	0.490	0.545	0.528	0.675	0.720
2001	0.114	0.178	0.293	0.337	0.417	0.535	0.607	0.785	0.594	0.758
2002	0.085	0.178	0.248	0.375	0.423	0.510	0.566	0.567	0.713	0.694
2003	0.084	0.186	0.258	0.322	0.427	0.517	0.587	0.651	0.583	0.639
2004	0.069	0.187	0.285	0.332	0.392	0.465	0.476	0.576	0.579	0.639
2005	0.117	0.159	0.279	0.334	0.359	0.423	0.535	0.569	0.514	0.698
2006	0.132	0.168	0.243	0.311	0.367	0.407	0.452	0.482	0.600	0.489
2007	0.105	0.165	0.265	0.325	0.400	0.487	0.459	0.519	0.524	0.639
2008	0.115	0.194	0.262	0.345	0.385	0.418	0.542	0.499	0.548	0.600
2009	0.138	0.186	0.281	0.333	0.407	0.424	0.436	0.473	0.451	0.589
2010	0.085	0.182	0.276	0.351	0.397	0.410	0.538	0.554	0.583	0.639

Table A29, contd.: Average weight-at-age of the U.S. total catch of Atlantic mackerel from 1968-2016. Cells shaded in grey were imputed using age-specific averages from 1992-2016.

	1	2	3	4	5	6	7	8	9	10
2011	0.110	0.191	0.287	0.362	0.335	0.457	0.504	0.554	0.583	0.639
2012	0.105	0.155	0.251	0.330	0.365	0.395	0.504	0.554	0.583	0.639
2013	0.152	0.186	0.247	0.314	0.392	0.433	0.504	0.554	0.583	0.639
2014	0.191	0.202	0.249	0.330	0.337	0.448	0.504	0.554	0.583	0.639
2015	0.168	0.244	0.285	0.311	0.390	0.322	0.504	0.554	0.583	0.639
2016	0.149	0.237	0.311	0.372	0.386	0.416	0.304	0.554	0.583	0.639

Table A30: Average U.S. January-1 weight-at-age of Atlantic mackerel from 1968-2016. January-1 weights were estimated from catch weights using the Rivard approach.

	1	2	3	4	5	6	7	8	9	10
1968	0.123	0.216	0.314	0.410	0.499	0.577	0.642	0.698	0.702	0.753
1969	0.112	0.178	0.269	0.358	0.440	0.513	0.575	0.626	0.668	0.683
1970	0.082	0.153	0.233	0.312	0.385	0.450	0.505	0.552	0.589	0.605
1971	0.080	0.139	0.214	0.288	0.356	0.417	0.468	0.511	0.547	0.602
1972	0.099	0.152	0.233	0.314	0.390	0.457	0.513	0.561	0.600	0.712
1973	0.087	0.152	0.238	0.322	0.400	0.468	0.528	0.577	0.619	0.636
1974	0.088	0.147	0.227	0.308	0.383	0.449	0.506	0.554	0.592	0.656
1975	0.082	0.140	0.219	0.298	0.372	0.438	0.493	0.540	0.579	0.606
1976	0.068	0.132	0.207	0.282	0.353	0.416	0.470	0.515	0.551	0.592
1977	0.072	0.139	0.220	0.302	0.379	0.447	0.506	0.555	0.596	0.709
1978	0.161	0.180	0.290	0.365	0.437	0.514	0.572	0.619	0.652	0.721
1979	0.135	0.229	0.389	0.491	0.518	0.554	0.616	0.668	0.704	0.824
1980	0.099	0.267	0.379	0.551	0.591	0.606	0.632	0.681	0.726	0.798
1981	0.066	0.214	0.443	0.551	0.606	0.638	0.654	0.685	0.717	0.782
1982	0.117	0.197	0.413	0.563	0.620	0.691	0.697	0.698	0.713	0.809
1983	0.076	0.198	0.404	0.566	0.617	0.662	0.727	0.723	0.713	0.734
1984	0.060	0.126	0.295	0.501	0.609	0.642	0.677	0.713	0.707	0.721
1985	0.076	0.160	0.212	0.375	0.541	0.634	0.667	0.680	0.726	0.714
1986	0.048	0.161	0.301	0.318	0.434	0.569	0.642	0.703	0.719	0.737
1987	0.074	0.129	0.272	0.375	0.388	0.478	0.540	0.672	0.738	0.766
1988	0.066	0.154	0.268	0.359	0.428	0.446	0.543	0.590	0.730	0.763
1989	0.076	0.152	0.289	0.377	0.440	0.480	0.506	0.607	0.723	0.815
1990	0.059	0.132	0.262	0.402	0.439	0.486	0.418	0.525	0.615	0.747
1991	0.110	0.156	0.259	0.367	0.481	0.523	0.548	0.408	0.591	0.773
1992	0.154	0.159	0.272	0.369	0.415	0.492	0.518	0.591	0.537	0.590
1993	0.145	0.177	0.226	0.319	0.370	0.410	0.503	0.491	0.576	0.614
1994	0.137	0.173	0.223	0.295	0.368	0.405	0.458	0.557	0.586	0.615
1995	0.132	0.174	0.241	0.300	0.355	0.422	0.448	0.489	0.571	0.625
1996	0.138	0.175	0.243	0.345	0.372	0.413	0.471	0.502	0.537	0.626
1997	0.075	0.183	0.251	0.336	0.411	0.431	0.466	0.518	0.557	0.620
1998	0.120	0.146	0.259	0.362	0.409	0.452	0.473	0.509	0.586	0.675
1999	0.179	0.167	0.246	0.341	0.434	0.469	0.525	0.518	0.527	0.667
2000	0.127	0.198	0.229	0.341	0.412	0.469	0.519	0.557	0.610	0.720
2001	0.091	0.159	0.247	0.299	0.404	0.499	0.546	0.654	0.560	0.758
2002	0.058	0.142	0.210	0.332	0.377	0.461	0.550	0.587	0.748	0.694
2003	0.056	0.126	0.214	0.283	0.400	0.467	0.547	0.607	0.575	0.639
2004	0.045	0.125	0.230	0.293	0.355	0.445	0.496	0.581	0.614	0.639
2005	0.098	0.105	0.228	0.309	0.345	0.407	0.499	0.520	0.544	0.698
2006	0.118	0.141	0.197	0.294	0.350	0.382	0.437	0.508	0.584	0.489
2007	0.078	0.148	0.211	0.281	0.353	0.423	0.432	0.484	0.503	0.639
2008	0.090	0.143	0.208	0.302	0.354	0.409	0.514	0.479	0.533	0.600
2009	0.120	0.146	0.234	0.296	0.374	0.404	0.427	0.506	0.474	0.589
2010	0.057	0.158	0.227	0.314	0.363	0.408	0.478	0.492	0.525	0.639

Table A30, contd.: Average U.S. January-1 weight-at-age of Atlantic mackerel from 1968-2016. January-1 weights were estimated from catch weights using the Rivard approach.

	1	2	3	4	5	6	7	8	9	10
2011	0.092	0.128	0.228	0.316	0.343	0.426	0.455	0.546	0.568	0.639
2012	0.079	0.131	0.219	0.308	0.364	0.364	0.480	0.528	0.568	0.639
2013	0.131	0.140	0.196	0.281	0.359	0.398	0.446	0.528	0.568	0.639
2014	0.168	0.175	0.216	0.286	0.326	0.419	0.467	0.528	0.568	0.639
2015	0.141	0.216	0.240	0.278	0.359	0.329	0.475	0.528	0.568	0.639
2016	0.111	0.199	0.276	0.326	0.346	0.403	0.313	0.528	0.568	0.639

Table A31: Average Canadian spawning stock biomass/catch weight-at-age of Atlantic mackerel from 1979-2016 provided by Canada's DFO. Average weight-at-age of the total catch was assumed to be equal to spawning stock biomass average weight-at-age due to the proximity in time of the Canadian fishery and the spawning season of the northern contingent.

	1	2	3	4	5	6	7	8	9	10
1979	0.190	0.272	0.531	0.567	0.579	0.603	0.652	0.714	0.752	0.769
1980	0.146	0.376	0.548	0.609	0.617	0.635	0.672	0.705	0.781	0.743
1981	0.114	0.315	0.523	0.577	0.643	0.660	0.674	0.707	0.723	0.756
1982	0.152	0.340	0.541	0.606	0.666	0.743	0.737	0.722	0.719	0.740
1983	0.098	0.257	0.479	0.593	0.628	0.659	0.712	0.709	0.705	0.727
1984	0.098	0.162	0.338	0.525	0.625	0.657	0.696	0.715	0.705	0.709
1985	0.203	0.393	0.399	0.505	0.601	0.742	0.767	0.779	0.840	0.866
1986	0.163	0.306	0.435	0.436	0.520	0.671	0.784	0.800	0.856	0.844
1987	0.214	0.309	0.405	0.483	0.506	0.599	0.701	0.785	0.888	0.892
1988	0.203	0.398	0.467	0.502	0.549	0.579	0.670	0.732	0.795	0.876
1989	0.169	0.329	0.450	0.545	0.619	0.618	0.660	0.753	0.810	0.884
1990	0.280	0.331	0.416	0.534	0.620	0.628	0.676	0.678	0.724	0.863
1991	0.251	0.336	0.435	0.478	0.564	0.627	0.644	0.724	0.712	0.816
1992	0.184	0.297	0.408	0.449	0.508	0.552	0.616	0.672	0.678	0.694
1993	0.180	0.280	0.361	0.446	0.489	0.547	0.607	0.664	0.699	0.724
1994	0.232	0.371	0.384	0.461	0.554	0.549	0.594	0.643	0.714	0.714
1995	0.197	0.300	0.435	0.488	0.532	0.607	0.616	0.661	0.738	0.799
1996	0.224	0.333	0.433	0.535	0.543	0.595	0.647	0.684	0.729	0.845
1997	0.240	0.375	0.448	0.524	0.594	0.601	0.635	0.757	0.700	0.751
1998	0.157	0.273	0.412	0.517	0.577	0.603	0.665	0.666	0.721	0.716
1999	0.186	0.298	0.439	0.509	0.569	0.649	0.703	0.719	0.730	0.769
2000	0.208	0.328	0.409	0.488	0.564	0.610	0.658	0.674	0.697	0.704
2001	0.139	0.280	0.401	0.475	0.562	0.625	0.668	0.693	0.758	0.775
2002	0.161	0.294	0.389	0.464	0.498	0.607	0.637	0.666	0.671	0.696
2003	0.207	0.314	0.387	0.490	0.554	0.667	0.726	0.828	0.839	0.680
2004	0.212	0.281	0.394	0.480	0.554	0.593	0.661	0.754	0.682	0.680
2005	0.110	0.306	0.385	0.466	0.520	0.618	0.654	0.698	0.708	0.665
2006	0.204	0.316	0.429	0.482	0.544	0.569	0.655	0.679	0.667	0.679
2007	0.206	0.308	0.427	0.503	0.582	0.629	0.665	0.711	0.767	0.692
2008	0.175	0.293	0.416	0.497	0.536	0.612	0.644	0.587	0.724	0.733
2009	0.208	0.316	0.416	0.495	0.580	0.605	0.675	0.612	0.707	0.775
2010	0.148	0.348	0.431	0.527	0.575	0.661	0.652	0.602	0.716	0.667
2011	0.188	0.293	0.428	0.491	0.565	0.574	0.704	0.649	0.650	0.710
2012	0.169	0.339	0.414	0.503	0.563	0.680	0.713	0.696	0.645	0.689
2013	0.174	0.289	0.433	0.470	0.589	0.620	0.640	0.700	0.647	0.689
2014	0.200	0.348	0.433	0.527	0.602	0.620	0.640	0.700	0.647	0.689
2015	0.191	0.299	0.413	0.492	0.585	0.620	0.640	0.700	0.647	0.689
2016	0.164	0.315	0.442	0.524	0.556	0.620	0.640	0.700	0.647	0.689

Table A32: Average Canadian January-1 weight-at-age of Atlantic mackerel from 1968-2016 provided by Canada's DFO.

	1	2	3	4	5	6	7	8	9	10
1968	0.123	0.216	0.314	0.410	0.499	0.577	0.642	0.698	0.702	0.753
1969	0.112	0.178	0.269	0.358	0.440	0.513	0.575	0.626	0.668	0.683
1970	0.082	0.153	0.233	0.312	0.386	0.450	0.505	0.552	0.589	0.587
1971	0.080	0.139	0.214	0.288	0.356	0.417	0.468	0.511	0.547	0.589
1972	0.099	0.152	0.233	0.314	0.390	0.457	0.513	0.561	0.600	0.733
1973	0.087	0.153	0.238	0.322	0.400	0.469	0.529	0.577	0.619	0.628
1974	0.088	0.147	0.227	0.308	0.383	0.449	0.506	0.554	0.592	0.649
1975	0.082	0.140	0.219	0.298	0.372	0.438	0.494	0.541	0.579	0.600
1976	0.068	0.132	0.207	0.282	0.353	0.416	0.470	0.515	0.551	0.590
1977	0.072	0.139	0.220	0.303	0.379	0.447	0.506	0.556	0.596	0.703
1978	0.161	0.180	0.290	0.365	0.437	0.514	0.572	0.619	0.652	0.697
1979	0.135	0.229	0.389	0.491	0.518	0.554	0.616	0.668	0.704	0.769
1980	0.099	0.267	0.386	0.569	0.592	0.606	0.637	0.678	0.747	0.743
1981	0.066	0.215	0.444	0.562	0.626	0.638	0.654	0.689	0.714	0.756
1982	0.117	0.197	0.413	0.563	0.620	0.691	0.697	0.698	0.713	0.740
1983	0.076	0.198	0.404	0.566	0.617	0.663	0.727	0.723	0.713	0.727
1984	0.049	0.126	0.295	0.502	0.609	0.642	0.677	0.714	0.707	0.709
1985	0.165	0.196	0.254	0.413	0.562	0.681	0.710	0.736	0.775	0.866
1986	0.118	0.249	0.414	0.417	0.512	0.635	0.763	0.783	0.817	0.844
1987	0.157	0.224	0.352	0.458	0.470	0.558	0.686	0.785	0.843	0.892
1988	0.160	0.292	0.380	0.451	0.515	0.541	0.634	0.716	0.790	0.876
1989	0.121	0.258	0.423	0.505	0.557	0.583	0.618	0.710	0.770	0.884
1990	0.256	0.237	0.370	0.490	0.581	0.624	0.646	0.669	0.738	0.863
1991	0.231	0.307	0.380	0.446	0.549	0.624	0.636	0.700	0.695	0.816
1992	0.149	0.273	0.370	0.442	0.493	0.558	0.622	0.658	0.701	0.694
1993	0.125	0.227	0.327	0.427	0.469	0.527	0.579	0.640	0.685	0.724
1994	0.204	0.258	0.328	0.408	0.497	0.518	0.570	0.625	0.689	0.714
1995	0.152	0.264	0.402	0.433	0.495	0.580	0.582	0.627	0.689	0.799
1996	0.173	0.256	0.360	0.482	0.515	0.563	0.627	0.649	0.694	0.845
1997	0.225	0.290	0.386	0.476	0.564	0.571	0.615	0.700	0.692	0.751
1998	0.114	0.256	0.393	0.481	0.550	0.599	0.632	0.650	0.739	0.716
1999	0.140	0.216	0.346	0.458	0.542	0.612	0.651	0.692	0.697	0.769
2000	0.179	0.247	0.349	0.463	0.536	0.589	0.654	0.688	0.708	0.704
2001	0.096	0.241	0.363	0.441	0.524	0.594	0.638	0.675	0.715	0.775
2002	0.115	0.202	0.330	0.431	0.486	0.584	0.631	0.667	0.682	0.696
2003	0.178	0.225	0.337	0.437	0.507	0.576	0.664	0.726	0.748	0.680
2004	0.177	0.241	0.352	0.431	0.521	0.573	0.664	0.740	0.752	0.680
2005	0.065	0.255	0.329	0.429	0.500	0.585	0.623	0.679	0.731	0.665
2006	0.166	0.186	0.362	0.431	0.504	0.544	0.636	0.666	0.682	0.679
2007	0.173	0.251	0.367	0.465	0.530	0.585	0.615	0.682	0.722	0.692
2008	0.130	0.246	0.358	0.461	0.519	0.597	0.637	0.625	0.718	0.733
2009	0.161	0.235	0.349	0.454	0.537	0.570	0.643	0.628	0.644	0.775
2010	0.105	0.269	0.369	0.468	0.534	0.619	0.628	0.638	0.662	0.667

Table A32, contd.: Average Canadian January-1 weight-at-age of Atlantic mackerel from 1968-2016 provided by Canada's DFO.

	1	2	3	4	5	6	7	8	9	10
2011	0.140	0.208	0.386	0.460	0.546	0.575	0.682	0.651	0.626	0.710
2012	0.126	0.253	0.348	0.464	0.526	0.620	0.640	0.651	0.647	0.689
2013	0.174	0.289	0.433	0.470	0.589	0.620	0.640	0.651	0.647	0.689
2014	0.200	0.348	0.433	0.527	0.602	0.620	0.640	0.651	0.647	0.689
2015	0.191	0.299	0.413	0.492	0.585	0.620	0.640	0.651	0.647	0.689
2016	0.164	0.315	0.442	0.524	0.556	0.620	0.640	0.651	0.647	0.689

Table A33: Average combined (U.S. + Canada) catch / spawning stock biomass weight-at-age of Atlantic mackerel from 1968-2016. Averages for the combined stock were estimated using a weighted average of region-specific weights-at-age, weighted by the catches of each region. For 1968-1978, U.S. catch weights-at-age were assumed to be representative of the entire stock. Missing values (ages where annual catch was zero) were imputed using the average from 1992-2016.

	1	2	3	4	5	6	7	8	9	10
1968	0.148	0.241	0.335	0.425	0.506	0.576	0.634	0.683	0.722	0.753
1969	0.131	0.214	0.300	0.382	0.456	0.520	0.574	0.618	0.654	0.683
1970	0.107	0.179	0.253	0.324	0.389	0.444	0.491	0.530	0.562	0.605
1971	0.110	0.181	0.256	0.327	0.391	0.446	0.494	0.532	0.564	0.602
1972	0.123	0.210	0.300	0.386	0.464	0.533	0.590	0.638	0.677	0.712
1973	0.113	0.189	0.269	0.345	0.414	0.473	0.524	0.565	0.600	0.636
1974	0.111	0.190	0.273	0.352	0.425	0.487	0.541	0.585	0.621	0.656
1975	0.104	0.176	0.252	0.326	0.393	0.451	0.500	0.540	0.573	0.606
1976	0.097	0.168	0.244	0.316	0.382	0.440	0.489	0.530	0.563	0.592
1977	0.114	0.198	0.288	0.375	0.454	0.524	0.582	0.631	0.671	0.709
1978	0.192	0.285	0.425	0.463	0.509	0.582	0.625	0.659	0.673	0.721
1979	0.190	0.272	0.531	0.567	0.579	0.603	0.652	0.714	0.752	0.803
1980	0.146	0.376	0.541	0.600	0.617	0.635	0.670	0.706	0.769	0.777
1981	0.114	0.315	0.523	0.577	0.643	0.660	0.674	0.707	0.723	0.768
1982	0.152	0.340	0.541	0.606	0.666	0.743	0.737	0.722	0.719	0.775
1983	0.098	0.257	0.479	0.593	0.628	0.659	0.712	0.709	0.705	0.730
1984	0.098	0.162	0.338	0.525	0.625	0.657	0.696	0.715	0.705	0.716
1985	0.122	0.304	0.301	0.451	0.577	0.711	0.727	0.743	0.814	0.792
1986	0.103	0.258	0.391	0.394	0.483	0.621	0.740	0.743	0.820	0.771
1987	0.140	0.231	0.336	0.427	0.434	0.535	0.520	0.746	0.753	0.792
1988	0.112	0.232	0.355	0.426	0.473	0.506	0.601	0.697	0.759	0.775
1989	0.142	0.282	0.384	0.431	0.506	0.536	0.560	0.697	0.776	0.839
1990	0.113	0.208	0.322	0.448	0.487	0.526	0.609	0.569	0.643	0.774
1991	0.186	0.288	0.399	0.461	0.543	0.596	0.616	0.688	0.686	0.793
1992	0.173	0.232	0.355	0.404	0.448	0.510	0.524	0.652	0.656	0.659
1993	0.159	0.228	0.336	0.418	0.462	0.530	0.598	0.612	0.620	0.704
1994	0.159	0.198	0.293	0.375	0.476	0.509	0.571	0.620	0.700	0.684
1995	0.189	0.263	0.340	0.404	0.462	0.548	0.554	0.605	0.662	0.726
1996	0.179	0.241	0.335	0.465	0.459	0.535	0.584	0.645	0.679	0.810
1997	0.186	0.296	0.367	0.429	0.519	0.528	0.565	0.609	0.655	0.683
1998	0.152	0.248	0.365	0.471	0.517	0.519	0.565	0.577	0.671	0.702
1999	0.187	0.250	0.369	0.429	0.506	0.579	0.682	0.601	0.603	0.700
2000	0.201	0.237	0.308	0.444	0.524	0.584	0.621	0.664	0.688	0.707
2001	0.135	0.250	0.338	0.377	0.483	0.576	0.645	0.768	0.648	0.775
2002	0.119	0.201	0.316	0.422	0.462	0.545	0.588	0.646	0.680	0.696
2003	0.131	0.206	0.284	0.418	0.508	0.555	0.621	0.662	0.839	0.695
2004	0.143	0.214	0.315	0.364	0.464	0.502	0.555	0.614	0.579	0.695
2005	0.111	0.219	0.318	0.369	0.414	0.530	0.592	0.632	0.707	0.694

Table A33, contd.: Average combined (U.S. + Canada) catch / spawning stock biomass weight-at-age of Atlantic mackerel from 1968-2016. Averages for the combined stock were estimated using a weighted average of region-specific weights-at-age, weighted by the catches of each region. For 1968-1978, U.S. catch weights-at-age were assumed to be representative of the entire stock. Missing values (ages where annual catch was zero) were imputed using the average from 1992-2016.

	1	2	3	4	5	6	7	8	9	10
2006	0.199	0.231	0.289	0.384	0.433	0.452	0.543	0.562	0.617	0.489
2007	0.156	0.232	0.346	0.431	0.523	0.592	0.590	0.645	0.583	0.692
2008	0.157	0.224	0.325	0.419	0.469	0.513	0.622	0.538	0.653	0.650
2009	0.202	0.224	0.327	0.431	0.535	0.572	0.596	0.571	0.493	0.761
2010	0.115	0.263	0.384	0.489	0.566	0.658	0.650	0.602	0.716	0.667
2011	0.132	0.241	0.416	0.488	0.557	0.574	0.704	0.649	0.650	0.710
2012	0.108	0.206	0.336	0.456	0.462	0.547	0.713	0.696	0.645	0.695
2013	0.154	0.221	0.363	0.447	0.574	0.575	0.606	0.633	0.654	0.695
2014	0.191	0.243	0.340	0.477	0.597	0.620	0.606	0.700	0.654	0.695
2015	0.172	0.256	0.351	0.445	0.552	0.608	0.640	0.700	0.654	0.695
2016	0.150	0.251	0.397	0.516	0.553	0.615	0.625	0.633	0.654	0.695

Table A34: Average combined (U.S. + Canada) January-1 weight-at-age of Atlantic mackerel from 1968-2016. Averages for the combined stock were estimated using a weighted average of region-specific weights-at-age, weighted by the catches of each region. Missing values (ages where annual catch was zero) were imputed using the average from 1992-2016.

	1	2	3	4	5	6	7	8	9	10
1968	0.123	0.216	0.314	0.410	0.499	0.577	0.642	0.698	0.702	0.753
1969	0.112	0.178	0.269	0.358	0.440	0.513	0.575	0.626	0.668	0.683
1970	0.082	0.153	0.233	0.312	0.386	0.450	0.505	0.552	0.589	0.595
1971	0.080	0.139	0.214	0.288	0.356	0.417	0.468	0.511	0.547	0.598
1972	0.099	0.152	0.233	0.314	0.390	0.457	0.513	0.561	0.600	0.725
1973	0.087	0.153	0.238	0.322	0.400	0.469	0.529	0.577	0.619	0.634
1974	0.088	0.147	0.227	0.308	0.383	0.449	0.506	0.554	0.592	0.653
1975	0.082	0.140	0.219	0.298	0.372	0.438	0.494	0.541	0.579	0.605
1976	0.068	0.132	0.207	0.282	0.353	0.416	0.470	0.515	0.551	0.592
1977	0.072	0.139	0.220	0.303	0.379	0.447	0.506	0.556	0.596	0.707
1978	0.161	0.180	0.290	0.365	0.437	0.514	0.572	0.619	0.652	0.713
1979	0.135	0.229	0.389	0.491	0.518	0.554	0.616	0.668	0.704	0.803
1980	0.099	0.267	0.383	0.565	0.592	0.606	0.636	0.679	0.741	0.777
1981	0.066	0.215	0.444	0.560	0.623	0.638	0.654	0.688	0.715	0.768
1982	0.117	0.197	0.413	0.563	0.620	0.691	0.697	0.698	0.713	0.775
1983	0.076	0.198	0.404	0.566	0.617	0.663	0.727	0.723	0.713	0.730
1984	0.059	0.126	0.295	0.502	0.609	0.642	0.677	0.714	0.707	0.716
1985	0.087	0.172	0.220	0.390	0.550	0.666	0.691	0.719	0.763	0.792
1986	0.068	0.191	0.356	0.358	0.469	0.598	0.726	0.719	0.772	0.771
1987	0.100	0.149	0.290	0.400	0.408	0.503	0.554	0.729	0.742	0.792
1988	0.077	0.162	0.280	0.377	0.446	0.468	0.561	0.601	0.737	0.775
1989	0.103	0.207	0.304	0.393	0.465	0.505	0.532	0.663	0.742	0.839
1990	0.078	0.154	0.285	0.417	0.458	0.516	0.600	0.569	0.658	0.774
1991	0.165	0.219	0.297	0.397	0.494	0.543	0.576	0.656	0.633	0.793
1992	0.152	0.202	0.325	0.407	0.456	0.531	0.562	0.643	0.658	0.659
1993	0.145	0.198	0.300	0.396	0.444	0.509	0.563	0.583	0.616	0.704
1994	0.141	0.177	0.249	0.336	0.436	0.481	0.548	0.608	0.665	0.684
1995	0.148	0.232	0.282	0.356	0.428	0.518	0.525	0.579	0.628	0.726
1996	0.149	0.199	0.274	0.417	0.429	0.505	0.566	0.610	0.643	0.810
1997	0.165	0.239	0.305	0.386	0.491	0.498	0.542	0.569	0.642	0.683
1998	0.116	0.217	0.326	0.424	0.486	0.508	0.543	0.561	0.660	0.702
1999	0.161	0.193	0.297	0.393	0.485	0.547	0.628	0.570	0.589	0.700
2000	0.173	0.210	0.264	0.407	0.485	0.563	0.609	0.679	0.669	0.707
2001	0.095	0.217	0.295	0.341	0.459	0.542	0.602	0.658	0.611	0.775
2002	0.083	0.154	0.268	0.384	0.434	0.505	0.576	0.650	0.695	0.696
2003	0.103	0.141	0.239	0.370	0.468	0.495	0.576	0.614	0.748	0.695
2004	0.113	0.158	0.264	0.322	0.429	0.482	0.568	0.615	0.615	0.695
2005	0.068	0.166	0.265	0.340	0.398	0.505	0.558	0.598	0.730	0.694

Table A34, contd.: Average combined (U.S. + Canada) January-1 weight-at-age of Atlantic mackerel from 1968-2016. Averages for the combined stock were estimated using a weighted average of region-specific weights-at-age, weighted by the catches of each region. Missing values (ages where annual catch was zero) were imputed using the average from 1992-2016.

	1	2	3	4	5	6	7	8	9	10
2006	0.163	0.160	0.237	0.353	0.407	0.427	0.526	0.572	0.610	0.489
2007	0.126	0.196	0.289	0.390	0.473	0.543	0.548	0.614	0.556	0.692
2008	0.118	0.174	0.270	0.379	0.445	0.501	0.610	0.544	0.644	0.650
2009	0.157	0.172	0.272	0.392	0.495	0.540	0.571	0.592	0.502	0.761
2010	0.080	0.213	0.326	0.435	0.525	0.617	0.626	0.638	0.662	0.667
2011	0.106	0.167	0.372	0.456	0.539	0.575	0.682	0.651	0.626	0.710
2012	0.081	0.164	0.286	0.421	0.443	0.500	0.640	0.651	0.647	0.695
2013	0.136	0.190	0.344	0.442	0.572	0.567	0.584	0.613	0.639	0.695
2014	0.171	0.223	0.324	0.466	0.597	0.620	0.584	0.651	0.639	0.695
2015	0.151	0.234	0.329	0.436	0.547	0.608	0.640	0.651	0.639	0.695
2016	0.117	0.221	0.385	0.513	0.552	0.615	0.625	0.613	0.639	0.695

TOR3: Fishery independent and dependent indices

Table A35: Summary of the differences in survey protocol from the SV *Albatross IV* (2008 and earlier) and SV *Henry B. Bigelow* (2009 - present). Reproduced from NEFSC (2013).

Measure	FSV *Henry B Bigelow*	FSV *Albatross IV*
Ground gear (cookies, rock hoppers, etc)	Rockhopper Sweep Total Length-25.5m Center- 8.9m length, 16" rockhoppers Wings- 8.2m each 14" rockhoppers	Roller Sweep Total Length-24.5m Center-5m length, 16" rollers Wings- 9.75m each, 4" cookies
Mesh	Poly webbing Forward Portion of trawl 12cm, 4cm Square aft to codend: 6cm, 2.5mm Codend: 12cm, 4mm dbl. Codend Liner: 2.54cm, knotless	Nylon webbing Body of trawl = 12.7cm Codend- 11.5cm Liner (codend and aft portion of top belly) - 1.27cm knotless
Net design	4 seam, 3 bridle	Yankee 36 (recent years)
Door type	550 kg PolyIce oval	450 kg polyvalent
Other comments	Wing end to door distance = 36.5m	Wing end to door distance = 9m

Table A36: NEFSC spring bottom trawl survey indices of relative abundance (number-per-tow) and biomass (kg-per-tow) for Atlantic mackerel from 1968-2008.

Year	Number/tow	CV	Kg/tow	CV	Age 3^+ number/tow	Age 3^+ kg/tow
1968	43.36	0.37	3.43	0.47		
1969	0.30	0.51	0.04	0.55		
1970	5.76	0.31	1.36	0.31		
1971	7.71	0.42	1.95	0.46		
1972	5.21	0.40	0.96	0.48		
1973	41.74	0.91	13.44	0.93		
1974	4.45	0.37	1.32	0.49	2.78	1.19
1975	4.52	0.70	0.29	0.48	0.26	0.09
1976	3.58	0.46	0.51	0.45	0.00	0.00
1977	0.61	0.38	0.17	0.31	0.61	0.18
1978	1.92	0.23	0.69	0.21	1.56	0.61
1979	0.36	0.34	0.19	0.36	0.33	0.18
1980	1.18	0.35	0.42	0.33	0.39	0.22
1981	12.33	0.48	5.19	0.55	8.98	4.97
1982	3.36	0.68	0.55	0.51	0.55	0.35
1983	0.58	0.34	0.09	0.43	0.00	0.00
1984	10.51	0.49	1.69	0.46	0.79	0.29
1985	5.34	0.31	1.45	0.33	4.96	1.41
1986	2.71	0.62	0.82	0.64	1.83	0.66
1987	23.19	0.39	4.93	0.31	8.81	3.44
1988	11.37	0.36	2.80	0.27	5.15	2.33
1989	8.43	0.36	0.76	0.37	0.19	0.08
1990	7.27	0.44	1.05	0.44	0.84	0.23
1991	15.84	0.45	3.80	0.50	8.09	2.50
1992	16.65	0.35	3.23	0.43	5.48	2.01
1993	17.75	0.42	3.84	0.29	6.15	2.45
1994	26.25	0.28	4.10	0.27	7.54	2.29
1995	16.55	0.31	3.46	0.32	4.75	1.91
1996	28.20	0.43	7.79	0.66	13.11	5.79
1997	15.10	0.38	1.73	0.31	1.08	0.42
1998	17.08	0.37	2.30	0.42	2.03	0.69
1999	34.78	0.32	4.88	0.25	6.75	2.19
2000	49.55	0.26	4.82	0.26	3.13	1.05
2001	79.00	0.38	10.66	0.38	1.36	0.43
2002	23.86	0.35	5.18	0.37	16.18	4.02
2003	41.00	0.27	7.51	0.35	15.67	4.75
2004	75.02	0.30	5.48	0.30	0.25	0.09
2005	21.91	0.47	2.90	0.43	2.09	0.62
2006	47.10	0.35	6.89	0.30	13.48	3.23
2007	20.85	0.41	3.85	0.42	5.15	1.55
2008	49.02	0.49	7.88	0.59	17.01	4.54

Table A37: NEFSC spring bottom trawl survey indices of relative abundance (number-per-tow) and biomass (kg-per-tow) for Atlantic mackerel from 2009-2016.

Year	Number/tow	CV	Kg/tow	CV	Age 3^+ number/tow	Age 3^+ kg/tow
2009	86.76	0.30	8.63	0.37	2.34	0.67
2010	26.00	0.31	3.83	0.32	1.81	0.48
2011	73.55	0.25	5.52	0.23	1.82	0.51
2012	40.48	0.33	3.40	0.31	1.30	0.41
2013	21.79	0.22	3.01	0.23	3.12	0.73
2014	3.46	0.27	0.60	0.28	1.00	0.24
2015	101.84	0.48	13.79	0.63	16.85	4.84
2016	20.32	0.30	2.73	0.23	1.34	0.39

Table A38: Stratified mean number-per-tow-at-age derived from the NEFSC spring bottom trawl survey for 1974-2008.

	1	2	3	4	5	6	7	8	9	10
1974	1.29	0.38	1.09	0.00	1.69	0.00	0.00	0.00	0.00	0.00
1975	3.96	0.31	0.11	0.08	0.01	0.03	0.02	0.01	0.00	0.00
1976	0.34	3.24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1977	0.00	0.00	0.44	0.11	0.00	0.00	0.00	0.00	0.00	0.06
1978	0.12	0.24	0.40	0.65	0.32	0.10	0.02	0.01	0.02	0.05
1979	0.02	0.01	0.01	0.03	0.10	0.05	0.02	0.03	0.01	0.08
1980	0.05	0.73	0.02	0.01	0.07	0.18	0.02	0.02	0.06	0.02
1981	3.07	0.27	2.32	0.18	0.00	0.53	3.02	1.06	0.27	1.61
1982	2.56	0.25	0.00	0.19	0.02	0.04	0.02	0.10	0.16	0.03
1983	0.26	0.32	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1984	0.18	9.54	0.47	0.21	0.01	0.00	0.01	0.01	0.00	0.08
1985	0.38	0.00	4.43	0.21	0.00	0.00	0.00	0.32	0.00	0.00
1986	0.12	0.76	0.09	1.55	0.15	0.00	0.00	0.00	0.00	0.05
1987	11.45	2.94	1.00	0.48	6.23	0.63	0.15	0.00	0.25	0.06
1988	5.39	0.83	0.34	0.33	0.36	3.41	0.48	0.00	0.03	0.20
1989	5.19	3.05	0.08	0.00	0.01	0.00	0.06	0.01	0.00	0.02
1990	2.40	4.04	0.73	0.00	0.02	0.03	0.00	0.05	0.01	0.00
1991	2.06	5.68	6.36	1.23	0.03	0.09	0.00	0.00	0.39	0.00
1992	6.60	4.56	0.94	2.59	1.29	0.09	0.16	0.00	0.04	0.38
1993	5.83	5.77	1.64	0.80	1.79	0.57	0.17	0.12	0.30	0.76
1994	14.16	4.55	4.73	0.96	0.40	1.00	0.21	0.05	0.01	0.18
1995	4.80	7.01	0.64	1.42	1.06	0.20	1.19	0.15	0.00	0.08
1996	8.41	6.68	3.11	0.47	3.79	3.36	0.99	0.72	0.60	0.07
1997	10.97	3.05	0.46	0.36	0.03	0.04	0.10	0.00	0.06	0.03
1998	10.26	4.80	1.37	0.36	0.06	0.03	0.15	0.04	0.01	0.02
1999	20.05	7.98	4.65	1.27	0.49	0.08	0.00	0.17	0.09	0.00
2000	40.98	5.44	1.82	0.85	0.28	0.11	0.03	0.00	0.02	0.01
2001	22.21	55.42	1.01	0.20	0.13	0.02	0.00	0.00	0.00	0.00
2002	1.70	5.98	15.84	0.15	0.14	0.03	0.02	0.00	0.00	0.00
2003	14.29	11.03	4.68	10.24	0.66	0.04	0.06	0.00	0.00	0.00
2004	66.07	8.70	0.07	0.04	0.13	0.00	0.00	0.00	0.00	0.00
2005	7.91	11.91	1.41	0.19	0.08	0.38	0.02	0.00	0.00	0.00
2006	15.74	17.88	12.42	0.86	0.08	0.03	0.10	0.00	0.00	0.00
2007	3.36	12.34	2.41	2.54	0.15	0.01	0.01	0.03	0.00	0.00
2008	22.88	9.12	16.16	0.43	0.39	0.00	0.00	0.00	0.03	0.00

Table A39: Stratified mean number-per-tow-at-age derived from the NEFSC spring bottom trawl survey for 2009-2016.

	1	2	3	4	5	6	7	8	9	10
2009	63.09	21.33	1.63	0.70	0.00	0.01	0.00	0.00	0.00	0.00
2010	8.06	16.13	1.66	0.06	0.07	0.00	0.01	0.00	0.00	0.00
2011	69.71	2.02	1.62	0.16	0.03	0.00	0.00	0.00	0.00	0.00
2012	31.83	7.35	0.57	0.61	0.12	0.01	0.00	0.00	0.00	0.00
2013	8.06	10.61	3.03	0.03	0.04	0.01	0.00	0.00	0.00	0.00
2014	1.31	1.15	0.93	0.07	0.00	0.00	0.00	0.00	0.00	0.00
2015	63.99	20.99	9.41	6.63	0.74	0.08	0.00	0.00	0.00	0.00
2016	11.39	7.59	1.25	0.06	0.01	0.02	0.00	0.00	0.00	0.00

Table A40: U.S., Canadian and combined (U.S. plus Canadian) annual egg production (AEP) and spawning stock biomass (SSB) estimates from egg (Canada) and ichthyoplankton (U.S.) surveys from 1977-2016.

	Combined Index			U.S. Index			Canadian Index			
Year	AEP	CV	SSB (mt)	AEP	CV	SSB (mt)	AEP	CV	SSB (mt)	U.S. SSB proportion
1977				2.29E+14	0.24	389,975				
1978										
1979	6.72E+14	0.15	1,131,094	1.91E+14	0.22	310,540	4.81E+14	0.2	820,554	0.27
1980				1.88E+14	0.62	363,192				
1981				8.25E+13	0.45	185,736				
1982				5.95E+13	0.35	130,673				
1983	2.84E+14	0.21	597,553	1.11E+14	0.55	254,962	1.73E+14	0.22	342,591	0.43
1984	3.90E+14	0.12	798,037	3.44E+13	0.33	71,854	3.56E+14	0.13	726,183	0.09
1985	6.56E+14	0.1	1,237,678	1.16E+13	0.33	20,500	6.44E+14	0.1	1,217,178	0.02
1986	1.29E+15	0.1	1,846,983	6.30E+13	0.37	92,931	1.23E+15	0.1	1,754,052	0.05
1987	5.32E+14	0.18	952,925	4.17E+13	0.3	80,222	4.90E+14	0.19	872,703	0.08
1988							4.10E+14	0.15	739,208	
1989							4.94E+14	0.2	757,877	
1990							4.24E+14	0.16	725,415	
1991							6.64E+14	0.16	1,284,928	
1992							5.12E+14	0.17	796,459	
1993							5.73E+14	0.21	935,545	
1994							2.18E+14	0.26	467,261	
1995										
1996							7.08E+13	0.21	123,464	
1997										
1998							5.58E+13	0.18	105,801	
1999										
2000	1.14E+14	0.44	184,827	1.31E+13	0.59	23,254	1.01E+14	0.48	161,573	0.13
2001				5.68E+12	0.37	10,334				

Continued

Table A40, contd.: U.S., Canadian and combined (U.S. plus Canadian) annual egg production (AEP) and spawning stock biomass (SSB) estimates from egg (Canada) and ichthyoplankton (U.S.) surveys from 1977-2016.

	Combined Index			U.S. Index			Canadian Index			
Year	AEP	CV	SSB (mt)	AEP	CV	SSB (mt)	AEP	CV	SSB (mt)	U.S. SSB proportion
2002	2.66E+14	0.24	449,102	3.25E+13	0.67	60,095	2.33E+14	0.25	389,007	0.13
2003							2.08E+14	0.23	307,091	
2004	1.37E+14	0.25	173,186	7.44E+12	0.5	10,384	1.30E+14	0.25	162,802	0.06
2005	7.28E+13	0.29	88,986	7.56E+11	0.21	1,027	7.20E+13	0.29	87,959	0.01
2006	4.87E+13	0.31		1.40E+12	0.47	1,840	4.73E+13	0.33		
2007	6.56E+13	0.24	78,689	1.65E+12	0.26	2,157	6.40E+13	0.24	76,532	0.03
2008							7.70E+13	0.17	99,631	
2009	5.35E+13	0.27	74,911	7.39E+11	0.39	1,168	5.28E+13	0.27	73,743	0.02
2010	2.25E+13	0.26	29,257	2.28E+12	0.4	3,297	2.02E+13	0.27	25,960	0.11
2011	2.89E+13	0.42	36,538	5.52E+11	0.43	824	2.83E+13	0.43	35,714	0.02
2012							8.67E+12	0.24	14,568	
2013	6.05E+11	0.51	34,108	6.05E+11	0.51	746	3.23E+13		33,362	0.02
2014							4.42E+13		49,796	
2015	5.41E+12	0.29	47,342	5.41E+12	0.29	5,559	4.28E+13		41,783	0.12
2016	2.39E+12	0.43	55,805	2.39E+12	0.43	3,138	4.53E+13		52,667	0.06

TOR4: Annual fishing mortality, recruitment and stock biomass estimates

Table A41: Contribution of objective function components to the total likelihood for the final ASAP run.

Run118	Value
total	5685.8
catch.total	-91.3
discard.total	0
index.fit.total	56.0
index.fit.ind01	-0.5
index.fit.ind02	6.1
index.fit.ind03	50.3
catch.age.comp	4543.5
discards.age.comp	0
index.age.comp	1178.7
sel.param.total	0
index.sel.param.t	-1.1
q.year1	0
q.devs	0
Fmult.year1.total	0
Fmult.devs.total	0
N.year1	0
Recruit.devs	0
SR.steepness	0
SR.scaler	0
Fmult.Max.penalty	0
F.penalty	0

Table A42: Annual January-1 biomass (January-1 B, mt), spawning stock biomass (SSB, mt), exploitable biomass (Exploitable B, mt) and fully recruited fishing mortality (F) estimates from the final ASAP model.

	January-1 B	SSB	Exploitable B	F
1968	1,330,598	621,759	599,392	0.186
1969	1,490,085	854,505	949,934	0.171
1970	1,606,842	967,918	1,155,152	0.244
1971	1,531,212	1,042,578	1,293,566	0.371
1972	1,521,799	1,134,034	1,435,015	0.378
1973	1,301,412	814,768	1,111,667	0.526
1974	978,359	620,472	846,915	0.571
1975	760,288	509,803	601,148	0.630
1976	530,772	377,976	456,040	0.739
1977	365,995	359,134	372,910	0.259
1978	363,602	379,297	379,817	0.084
1979	399,577	352,118	383,747	0.099
1980	369,037	346,861	358,019	0.081
1981	341,985	300,168	325,027	0.109
1982	366,914	305,313	310,570	0.101
1983	506,171	360,459	333,740	0.114
1984	516,880	393,831	409,916	0.117
1985	566,401	583,088	563,437	0.150
1986	581,679	525,549	534,490	0.155
1987	481,482	411,664	451,024	0.227
1988	402,102	338,213	394,780	0.276
1989	393,556	326,577	335,816	0.290
1990	316,956	258,213	276,268	0.425
1991	289,298	245,469	265,101	0.348
1992	242,694	177,878	186,729	0.273
1993	194,746	158,500	168,772	0.267
1994	163,047	122,523	140,980	0.336
1995	157,003	113,974	121,685	0.290
1996	151,923	104,193	118,234	0.466
1997	153,541	100,988	109,277	0.498
1998	129,393	97,210	98,455	0.481
1999	122,726	82,218	91,505	0.493
2000	305,472	181,497	110,751	0.282
2001	303,849	268,593	186,865	0.255
2002	283,480	255,991	244,107	0.322
2003	286,614	226,488	240,812	0.445

Table A42, contd.: Annual January-1 biomass (January-1 B, mt), spawning stock biomass (SSB, mt), exploitable biomass (Exploitable B, mt) and fully recruited fishing mortality (F) estimates from the final ASAP model.

	January-1 B	SSB	Exploitable B	F
2004	300,142	172,130	206,778	0.771
2005	231,655	149,476	183,060	0.725
2006	224,272	129,322	157,851	1.047
2007	157,846	103,390	118,570	1.016
2008	112,584	66,969	81,692	0.926
2009	100,048	43,732	66,599	1.616
2010	56,766	24,001	43,776	2.086
2011	32,710	16,899	19,592	1.059
2012	28,855	16,837	16,971	1.211
2013	32,850	18,849	20,529	1.120
2014	38,105	17,007	19,157	1.014
2015	51,906	24,328	21,747	0.746
2016	101,687	43,519	40,998	0.468

Table A43: Age-specific abundance estimates (millions of fish) from the final ASAP model.

	1	2	3	4	5	6	7	8	9	10
1968	5,254.05	1,412.08	494.72	178.25	77.94	46.86	27.16	14.70	80.47	1.07
1969	1,561.86	4,195.69	1,061.07	351.25	124.94	54.14	31.86	18.46	9.99	55.43
1970	2,892.42	1,249.72	3,174.30	761.93	249.24	87.93	37.35	21.98	12.74	45.13
1971	976.92	2,291.78	914.14	2,155.24	508.63	164.44	56.38	23.95	14.09	37.10
1972	1,252.33	761.05	1,581.54	563.43	1,294.65	300.14	92.93	31.86	13.53	28.93
1973	916.07	974.66	523.43	969.34	336.40	759.06	168.39	52.14	17.88	23.82
1974	1,280.38	698.93	626.08	286.41	511.39	173.04	367.22	81.46	25.22	20.17
1975	1,202.85	971.02	439.74	330.96	145.52	252.79	80.03	169.83	37.67	21.00
1976	219.60	905.04	594.56	222.20	160.08	68.29	110.23	34.89	74.05	25.58
1977	39.66	162.83	526.99	276.36	98.12	68.22	26.70	43.10	13.64	38.96
1978	34.11	31.36	118.30	353.79	182.23	63.90	43.11	16.87	27.23	33.23
1979	188.97	27.62	24.70	90.85	270.12	138.57	48.12	32.46	12.70	45.53
1980	50.38	152.69	21.61	18.75	68.50	202.70	102.80	35.70	24.08	43.20
1981	250.41	40.80	120.40	16.62	14.35	52.19	152.98	77.58	26.94	50.78
1982	495.18	202.04	31.76	90.68	12.42	10.67	38.32	112.31	56.96	57.06
1983	2,030.20	399.95	157.86	24.06	68.21	9.30	7.89	28.34	83.08	84.35
1984	89.24	1,636.97	310.68	118.44	17.91	50.50	6.79	5.76	20.71	122.31
1985	137.46	71.93	1,270.12	232.64	87.97	13.23	36.79	4.95	4.20	104.21
1986	85.72	110.29	54.94	926.71	167.98	63.06	9.32	25.92	3.49	76.36
1987	114.57	68.74	84.08	39.95	666.65	119.94	44.22	6.53	18.17	55.99
1988	369.21	90.99	50.69	57.84	27.06	446.57	78.25	28.85	4.26	48.39
1989	517.58	291.30	65.59	33.59	37.60	17.36	277.42	48.61	17.92	32.71
1990	102.81	407.57	208.60	42.99	21.58	23.82	10.63	169.88	29.77	31.00
1991	171.63	79.51	274.25	123.29	24.67	12.13	12.74	5.69	90.89	32.51
1992	180.57	134.11	55.44	171.98	75.47	14.85	7.01	7.37	3.29	71.33
1993	35.21	142.53	96.81	36.83	112.09	48.55	9.25	4.37	4.59	46.49
1994	152.07	27.81	103.16	64.59	24.12	72.47	30.43	5.80	2.74	32.02
1995	179.06	119.02	19.50	65.29	39.94	14.67	42.40	17.80	3.39	20.33
1996	165.48	141.02	85.26	12.79	41.96	25.31	8.99	25.98	10.91	14.54
1997	205.28	127.28	93.13	48.85	7.09	22.76	13.00	4.62	13.35	13.07
1998	94.23	157.22	82.84	52.08	26.39	3.74	11.33	6.47	2.30	13.15
1999	163.23	72.33	103.11	46.92	28.53	14.13	1.89	5.73	3.28	7.82
2000	1,222.76	125.10	47.19	57.89	25.45	15.12	7.07	0.95	2.87	5.55
2001	196.64	963.92	89.92	31.12	37.44	16.24	9.33	4.36	0.58	5.20
2002	152.43	155.59	701.69	60.57	20.59	24.47	10.30	5.92	2.77	3.67
2003	349.94	119.53	109.79	448.84	37.88	12.68	14.52	6.11	3.51	3.82
2004	743.56	269.90	79.69	63.91	253.30	20.93	6.65	7.61	3.21	3.84
2005	196.99	548.98	154.85	36.14	27.47	104.93	7.92	2.52	2.88	2.67

Table A43, contd.: Age-specific abundance estimates (millions of fish) from the final ASAP model.

	1	2	3	4	5	6	7	8	9	10
2006	380.03	146.34	321.70	72.74	16.14	11.85	41.60	3.14	1.00	2.20
2007	99.13	270.39	73.93	118.10	24.83	5.24	3.41	11.95	0.90	0.92
2008	216.94	70.83	138.59	27.80	41.39	8.29	1.55	1.01	3.54	0.54
2009	156.78	156.88	37.83	55.82	10.50	14.95	2.69	0.50	0.33	1.32
2010	18.04	103.36	60.96	8.98	11.85	2.06	2.43	0.44	0.08	0.27
2011	115.78	11.16	32.34	10.10	1.29	1.54	0.21	0.25	0.04	0.04
2012	82.85	82.25	5.61	11.77	3.41	0.41	0.44	0.06	0.07	0.02
2013	37.79	57.67	38.53	1.82	3.50	0.96	0.10	0.11	0.01	0.02
2014	91.24	26.63	28.17	13.38	0.58	1.07	0.26	0.03	0.03	0.01
2015	162.72	65.21	13.66	10.61	4.70	0.20	0.32	0.08	0.01	0.01
2016	455.43	120.55	37.86	6.32	4.66	1.99	0.08	0.12	0.03	0.01

Table A44: Estimates of fishery selectivity-at-age from the final ASAP model.

Age	Fishery selectivity
1	0.13
2	0.46
3	0.77
4	0.84
5	0.88
6	1.00
7	1.00
8	1.00
9	1.00
10	1.00

Table A45: Age-specific fishing mortality estimates from the final ASAP model.

	1	2	3	4	5	6	7	8	9	10
1968	0.025	0.086	0.142	0.155	0.164	0.186	0.186	0.186	0.186	0.186
1969	0.023	0.079	0.131	0.143	0.151	0.171	0.171	0.171	0.171	0.171
1970	0.033	0.113	0.187	0.204	0.216	0.244	0.244	0.244	0.244	0.244
1971	0.050	0.171	0.284	0.310	0.327	0.371	0.371	0.371	0.371	0.371
1972	0.051	0.174	0.290	0.316	0.334	0.378	0.378	0.378	0.378	0.378
1973	0.071	0.243	0.403	0.439	0.465	0.526	0.526	0.526	0.526	0.526
1974	0.077	0.263	0.437	0.477	0.505	0.571	0.571	0.571	0.571	0.571
1975	0.084	0.291	0.483	0.526	0.557	0.630	0.630	0.630	0.630	0.630
1976	0.099	0.341	0.566	0.617	0.653	0.739	0.739	0.739	0.739	0.739
1977	0.035	0.119	0.198	0.216	0.229	0.259	0.259	0.259	0.259	0.259
1978	0.011	0.039	0.064	0.070	0.074	0.084	0.084	0.084	0.084	0.084
1979	0.013	0.045	0.076	0.082	0.087	0.099	0.099	0.099	0.099	0.099
1980	0.011	0.038	0.062	0.068	0.072	0.081	0.081	0.081	0.081	0.081
1981	0.015	0.050	0.084	0.091	0.096	0.109	0.109	0.109	0.109	0.109
1982	0.014	0.047	0.078	0.085	0.090	0.101	0.101	0.101	0.101	0.101
1983	0.015	0.053	0.087	0.095	0.101	0.114	0.114	0.114	0.114	0.114
1984	0.016	0.054	0.089	0.097	0.103	0.117	0.117	0.117	0.117	0.117
1985	0.020	0.069	0.115	0.126	0.133	0.150	0.150	0.150	0.150	0.150
1986	0.021	0.071	0.119	0.129	0.137	0.155	0.155	0.155	0.155	0.155
1987	0.030	0.105	0.174	0.190	0.201	0.227	0.227	0.227	0.227	0.227
1988	0.037	0.127	0.211	0.231	0.244	0.276	0.276	0.276	0.276	0.276
1989	0.039	0.134	0.222	0.243	0.257	0.290	0.290	0.290	0.290	0.290
1990	0.057	0.196	0.326	0.355	0.376	0.425	0.425	0.425	0.425	0.425
1991	0.047	0.161	0.267	0.291	0.308	0.348	0.348	0.348	0.348	0.348
1992	0.037	0.126	0.209	0.228	0.241	0.273	0.273	0.273	0.273	0.273
1993	0.036	0.123	0.205	0.223	0.236	0.267	0.267	0.267	0.267	0.267
1994	0.045	0.155	0.257	0.281	0.297	0.336	0.336	0.336	0.336	0.336
1995	0.039	0.134	0.222	0.242	0.256	0.290	0.290	0.290	0.290	0.290
1996	0.062	0.215	0.357	0.389	0.412	0.466	0.466	0.466	0.466	0.466
1997	0.067	0.229	0.381	0.416	0.440	0.498	0.498	0.498	0.498	0.498
1998	0.064	0.222	0.368	0.402	0.425	0.481	0.481	0.481	0.481	0.481
1999	0.066	0.227	0.377	0.411	0.435	0.493	0.493	0.493	0.493	0.493
2000	0.038	0.130	0.216	0.236	0.249	0.282	0.282	0.282	0.282	0.282
2001	0.034	0.118	0.195	0.213	0.225	0.255	0.255	0.255	0.255	0.255
2002	0.043	0.149	0.247	0.269	0.285	0.322	0.322	0.322	0.322	0.322
2003	0.060	0.205	0.341	0.372	0.393	0.445	0.445	0.445	0.445	0.445
2004	0.103	0.356	0.591	0.644	0.681	0.771	0.771	0.771	0.771	0.771
2005	0.097	0.334	0.556	0.606	0.641	0.725	0.725	0.725	0.725	0.725

Table A45 contd.: Age-specific fishing mortality estimates from the final ASAP model.

	1	2	3	4	5	6	7	8	9	10
2006	0.140	0.483	0.802	0.875	0.925	1.047	1.047	1.047	1.047	1.047
2007	0.136	0.468	0.778	0.848	0.897	1.016	1.016	1.016	1.016	1.016
2008	0.124	0.427	0.709	0.774	0.818	0.926	0.926	0.926	0.926	0.926
2009	0.217	0.745	1.238	1.350	1.428	1.616	1.616	1.616	1.616	1.616
2010	0.280	0.962	1.598	1.742	1.843	2.086	2.086	2.086	2.086	2.086
2011	0.142	0.488	0.811	0.885	0.936	1.059	1.059	1.059	1.059	1.059
2012	0.162	0.558	0.927	1.011	1.070	1.211	1.211	1.211	1.211	1.211
2013	0.150	0.516	0.858	0.935	0.989	1.120	1.120	1.120	1.120	1.120
2014	0.136	0.467	0.776	0.847	0.895	1.014	1.014	1.014	1.014	1.014
2015	0.100	0.344	0.571	0.623	0.659	0.746	0.746	0.746	0.746	0.746
2016	0.063	0.216	0.358	0.391	0.413	0.468	0.468	0.468	0.468	0.468

Table A46: Censored catch assessment model (CCAM) parameters.

Parameter	Definition
$N_{a,y}$	Total stock abundance
Sel_a	Fishing selectivity
F_y	Fishing mortality rate
σ_s^2	Survey measurement error
$\sigma_{F_y}^2$	Annual fishing mortality variance
σ_R^2	Recruitment variance
σ_{crl}^2	Catch-at-age measurement error
σ_ε^2	Process error measurement error
q	Survey index catchability coefficient

Table A47: Key differences between the CCAM (Censored Catch Assessment Model, Van Beveren et al. 2017) and SAM (Stock Assessment Model, Nielsen and Berg 2014) state-space models.

	CCAM	**SAM**
Random effects	N, Fy	N, F
selectivity	Flat-topped and constant over time	Time-varying as an outcome of random walk in F (no functional form)
F	Separable	Random walk in F with possible correlation among ages
Index	Limited to 1	Multiple indices possible
Catches	Total catch and catch proportions separately linked	Estimated catch-at-age directly linked to observations
Total catch	Censored	Lognormal error distribution; possible use of a catch multiplier

TOR5: Stock status definitions

Table A48: MSY proxy biological reference point and corresponding overfished threshold (½ $SSB_{MSY\ proxy}$) estimates for Atlantic mackerel resulting from the final ASAP model.

	Estimate	5th percentile	95th percentile
$F_{MSY\ proxy}$	0.26	0.26	0.26
$SSB_{MSY\ proxy}$	196,894	108,161	429,550
$B_{MSY\ proxy}$	255,646	140,103	534,278
MSY_{proxy}	41,334	22,878	87,281
½ $SSB_{MSY\ proxy}$	98,447		

TOR6: Stock status

Table A49: Atlantic mackerel 2016 biomass, recruitment and fishing mortality estimates from the final ASAP model.

	Estimate	5th percentile	95th percentile
Spawning stock biomass (mt)	43,519	23,462	77,672
January 1 biomass (mt)	101,687	56,692	185,921
Recruitment (000s)	455,428		
Average F (ages 6-9)	0.468	0.247	0.931

TOR7: Projections

Table A50: Short-term Atlantic mackerel projections at $F_{MSY\ proxy}$ for the final ASAP model.

		2017	2018	2019	2020
SSB (mt)	Median	101,825	132,532	153,198	165,487
	5th Percentile	44,017	62,299	81,410	92,754
	95th Percentile	207,193	260,273	305,940	359,842
Recruitment (000s)	Median	164,337	164,359	164,453	164,332
	5th Percentile	35,335	35,381	35,344	35,315
	95th Percentile	1,169,815	1,179,224	1,201,696	1,178,003
January 1 biomass (mt)	Median	135,714	172,598	200,558	216,681
	5th Percentile	71,745	84,355	107,435	121,498
	95th Percentile	252,303	344,668	401,743	455,147
Catch (mt)	Median	21,898	24,948	30,023	33,250
	5th Percentile	21,898	11,069	15,549	18,428
	95th Percentile	21,898	50,317	56,857	68,034

Table A51: Short-term Atlantic mackerel projections at the status quo fishing mortality for the final ASAP model.

		2017	2018	2019	2020
SSB (mt)	Median	101,825	124,616	127,506	125,625
	5th Percentile	44,017	58,878	68,636	70,705
	95th Percentile	207,193	244,025	261,505	292,193
Recruitment (000s)	Median	164,337	164,359	164,453	164,332
	5th Percentile	35,335	35,381	35,344	35,315
	95th Percentile	1,169,815	1,179,224	1,201,696	1,178,003
January 1 biomass (mt)	Median	135,714	172,598	180,145	178,916
	5th Percentile	71,745	84,355	97,339	100,463
	95th Percentile	252,303	344,668	371,077	398,889
Catch (mt)	Median	21,898	42,092	44,524	44,446
	5th Percentile	21,898	18,778	23,456	24,929
	95th Percentile	21,898	84,601	84,849	95,613

Table A52: Short-term Atlantic mackerel projections at F = 0 for the final ASAP model.

		2017	2018	2019	2020
SSB (mt)	Median	101,825	143,064	193,484	238,976
	5th Percentile	44,017	66,787	100,992	132,134
	95th Percentile	207,193	281,975	377,879	483,250
Recruitment (000s)	Median	164,337	164,359	164,453	164,332
	5th Percentile	35,335	35,381	35,344	35,315
	95th Percentile	1,169,815	1,179,224	1,201,696	1,178,003
January 1 biomass (mt)	Median	135,714	172,598	230,280	281,175
	5th Percentile	71,745	84,355	121,763	155,949
	95th Percentile	252,303	344,668	449,227	554,494
Catch (mt)	Median	21,898	0	0	0
	5th Percentile	21,898	0	0	0
	95th Percentile	21,898	0	0	0

FIGURES

Introduction

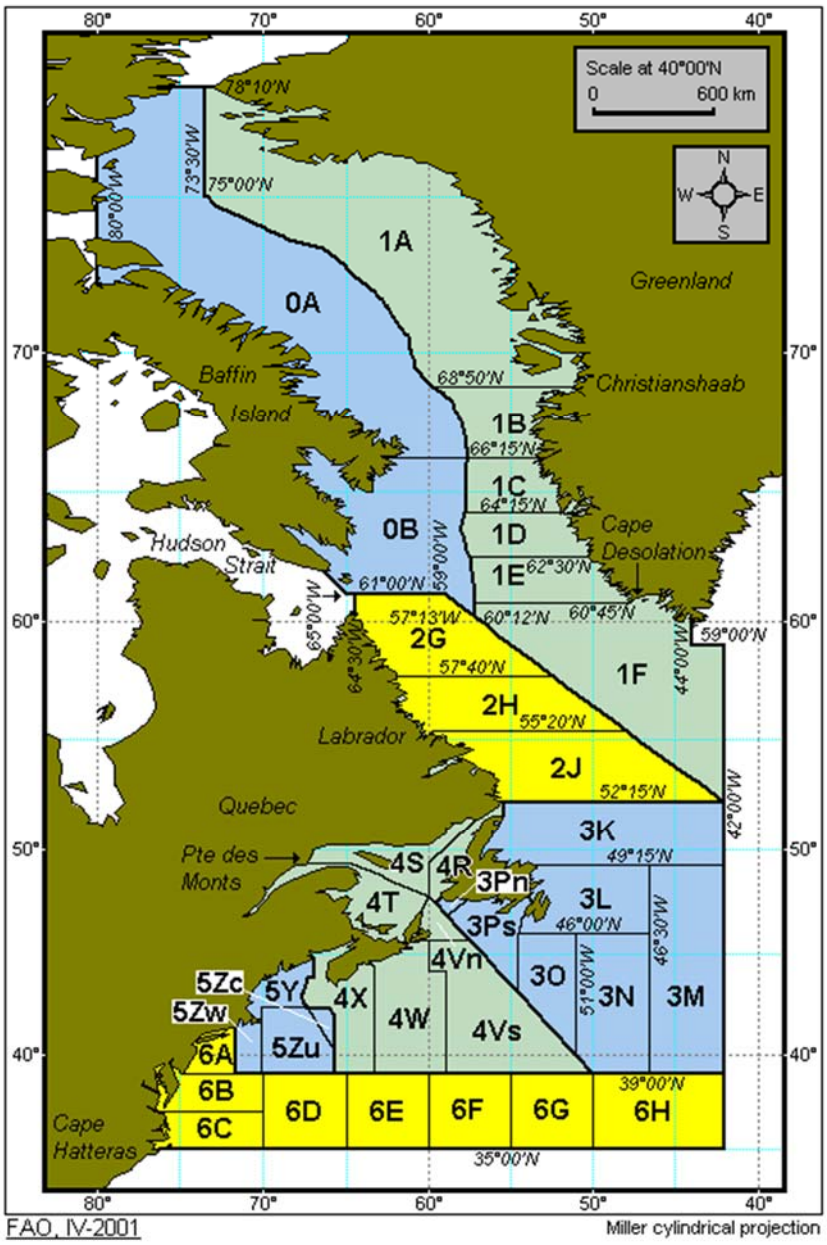


Figure A1: Catch reporting areas of the Northwest Atlantic Fisheries Organization (NAFO) for Subareas 2-6.

Biology

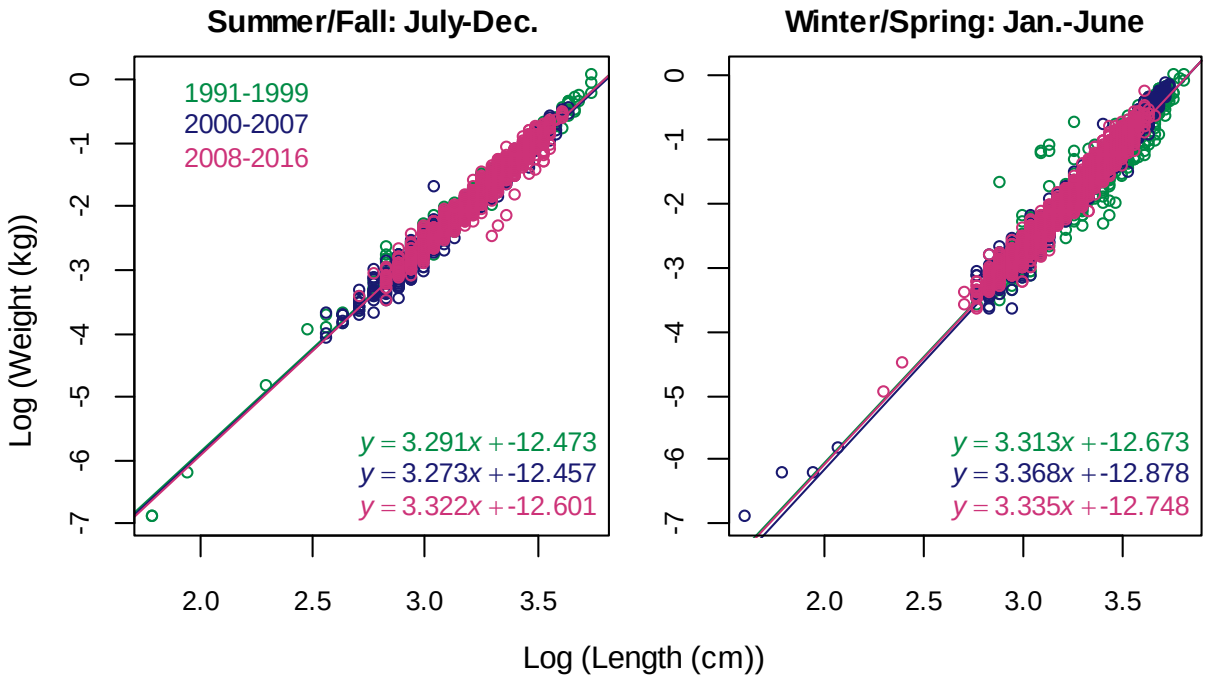


Figure A2: Semester-specific Atlantic mackerel length-weight relationships by approximately 9-year intervals derived from the NEFSC bottom trawl survey data.

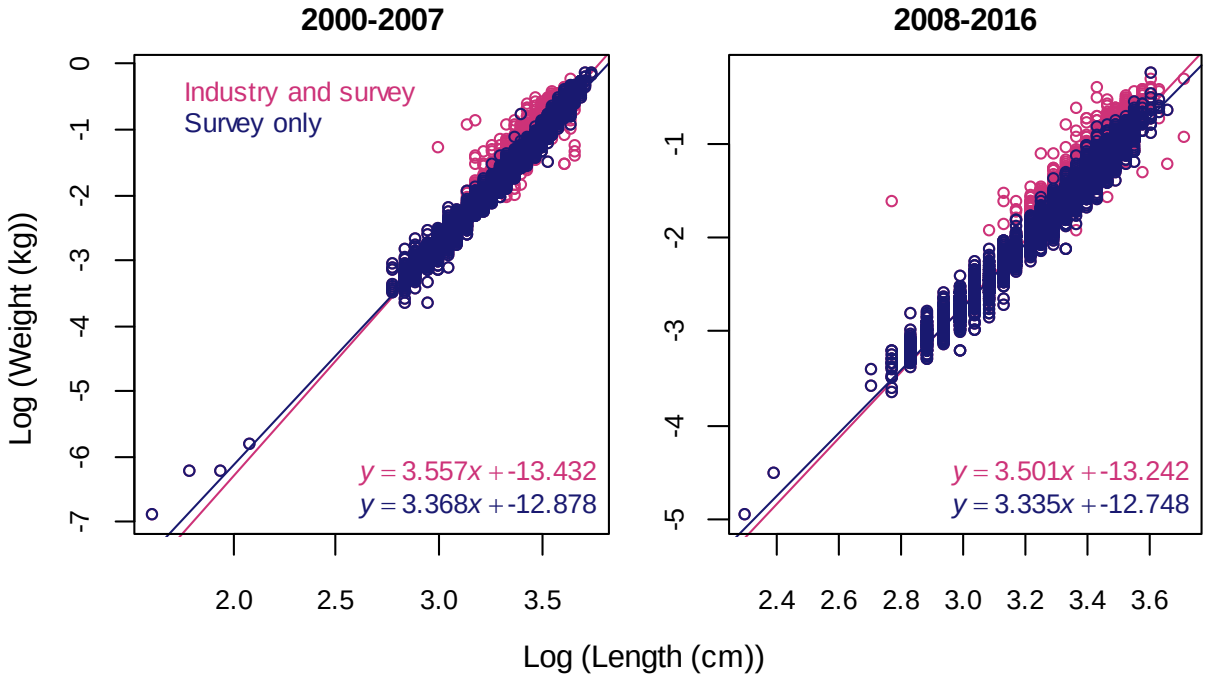


Figure A3: Comparison of semester-specific Atlantic mackerel length-weight relationships by approximately 9-year intervals derived from either both industry and NEFSC bottom trawl survey data or just NEFSC trawl survey data.

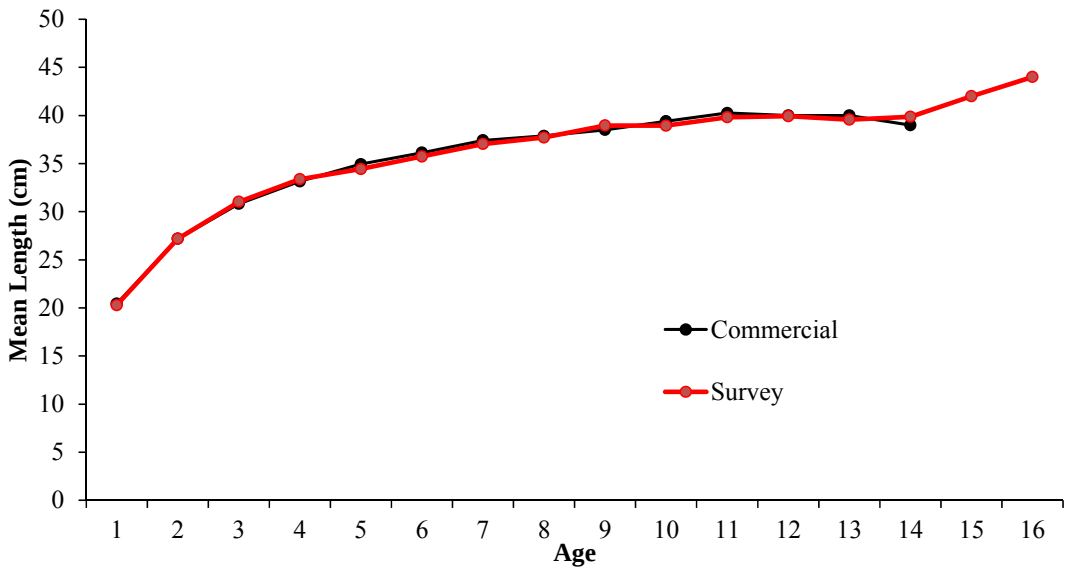


Figure A4: Atlantic mackerel mean length-at-age derived from U.S. commercial age samples and NEFSC spring bottom trawl survey age data.

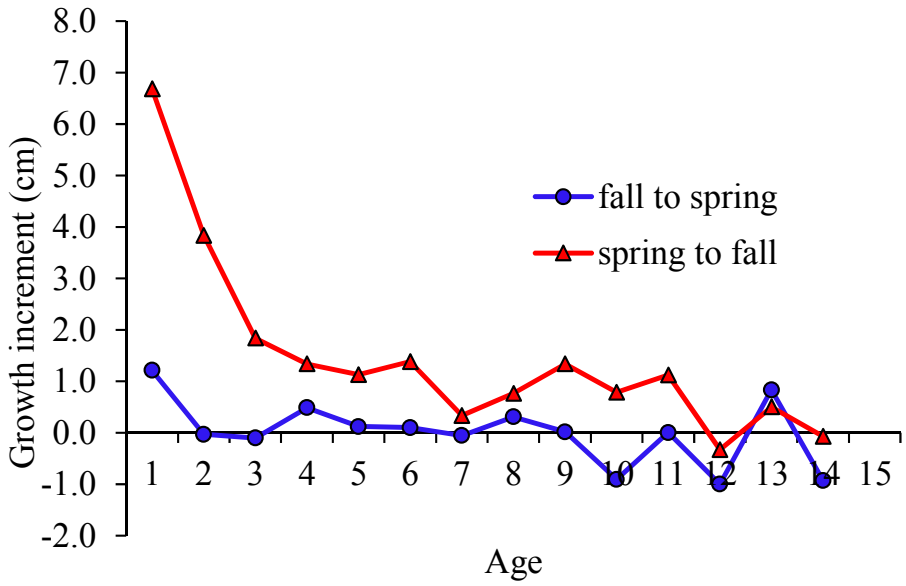


Figure A5: Growth increments (cm) of Atlantic mackerel by season derived from NEFSC spring and fall bottom trawl survey data.

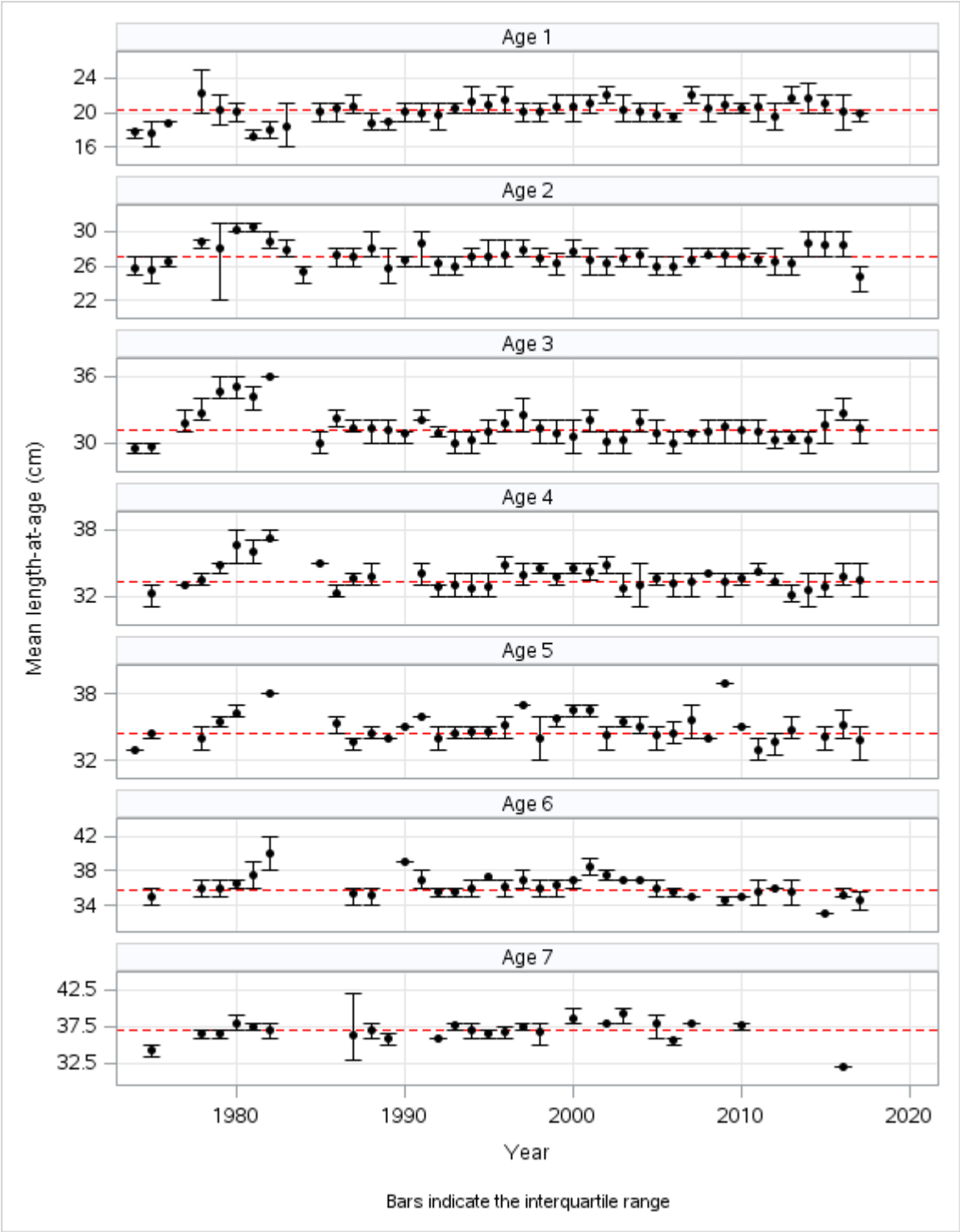


Figure A6: Atlantic mackerel mean length-at-age (cm) derived from NEFSC spring bottom trawl survey age data.

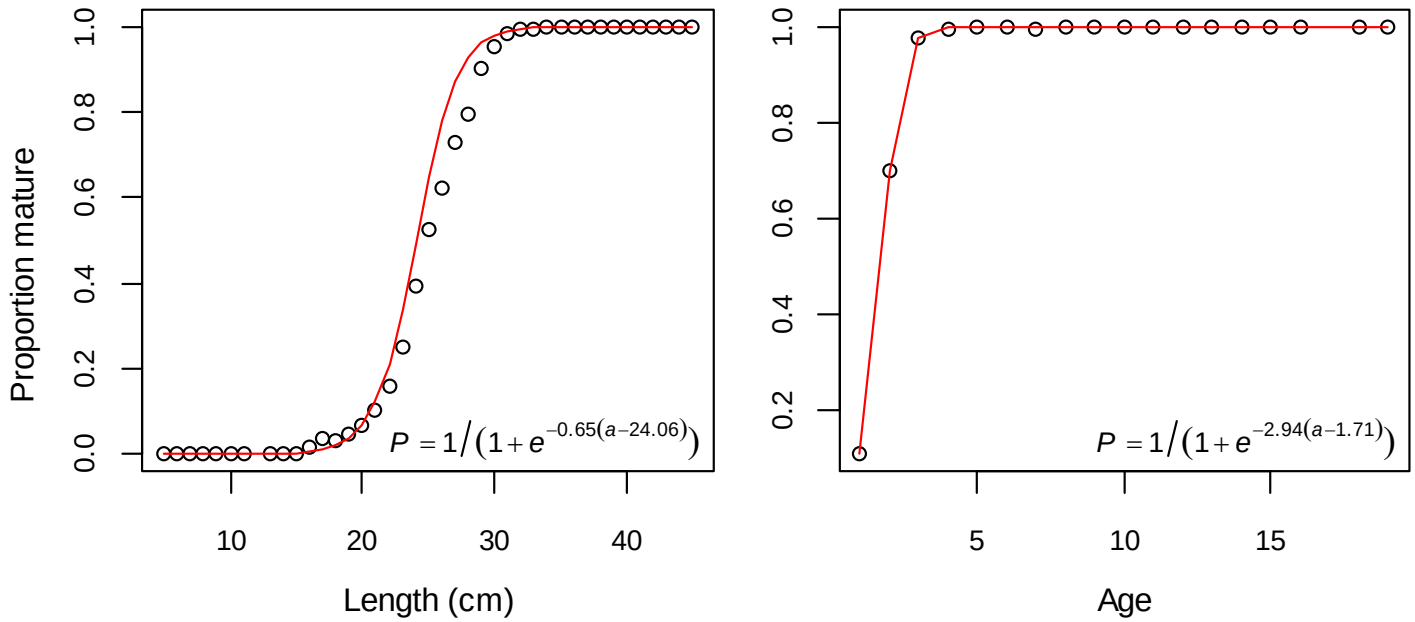


Figure A7: Time-invariant maturity ogives for Atlantic mackerel derived from NEFSC winter and spring bottom trawl survey data.

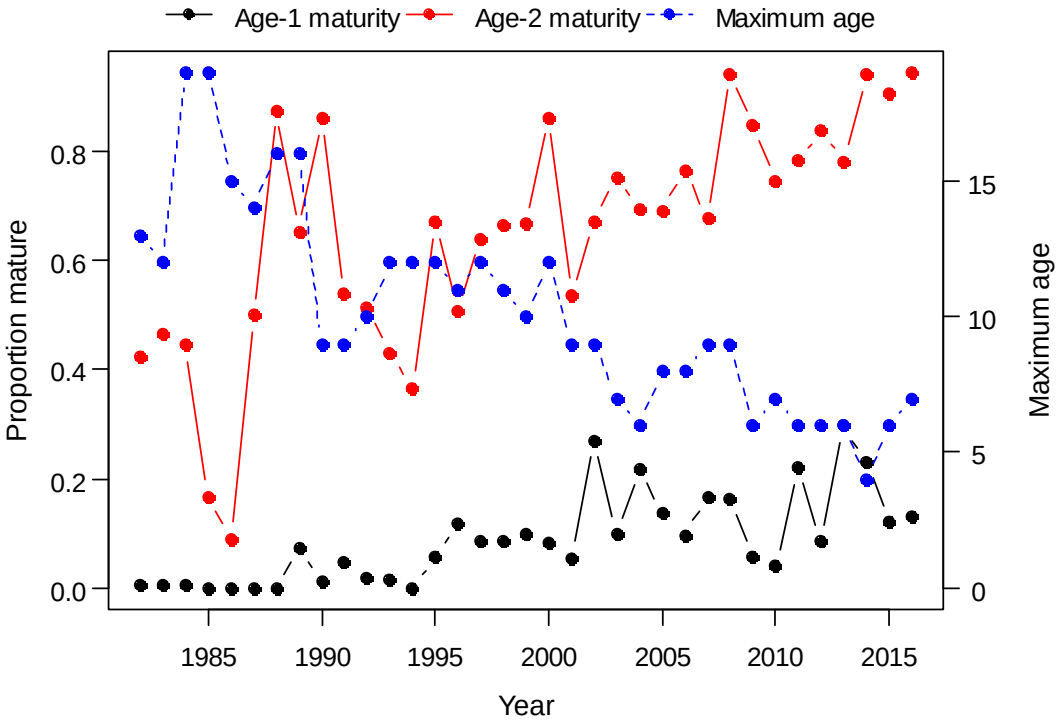


Figure A8: Atlantic mackerel age-1 and age-2 maturity derived from NEFSC winter and spring bottom trawl survey data and the maximum age observed in the surveys each year.

TOR1: Spatial and ecosystem influences on stock dynamics

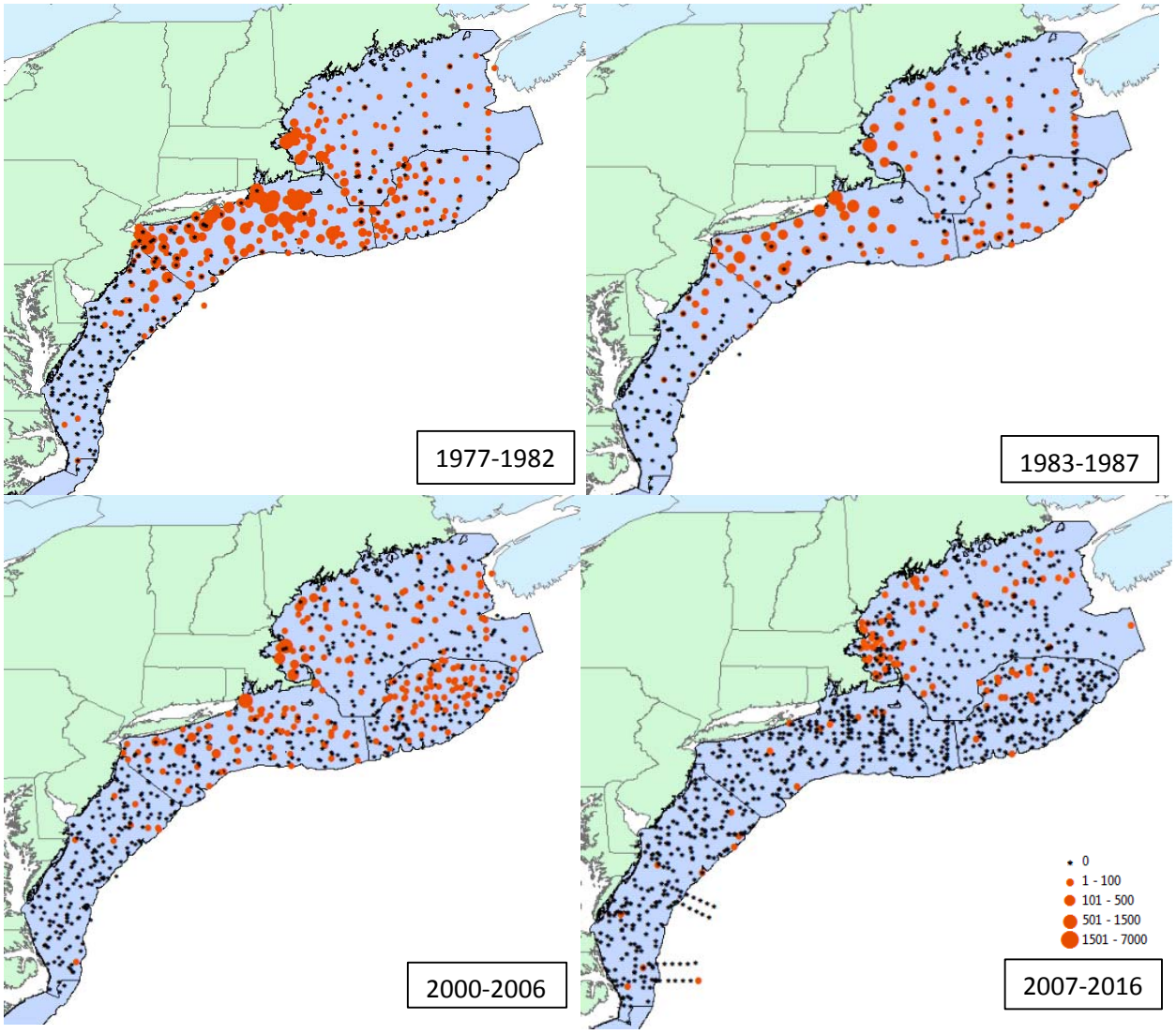


Figure A9: Distribution of Atlantic mackerel eggs from U.S. ecosystem surveys during 1977 to 2016.

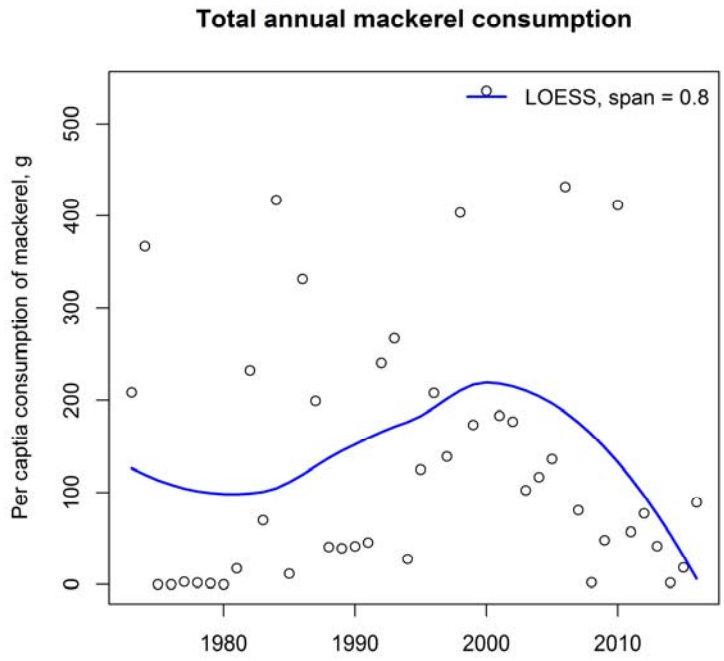


Figure A10: Total annual per-capita consumption of mackerel for 17 predators sampled during the NEFSC bottom trawl surveys.

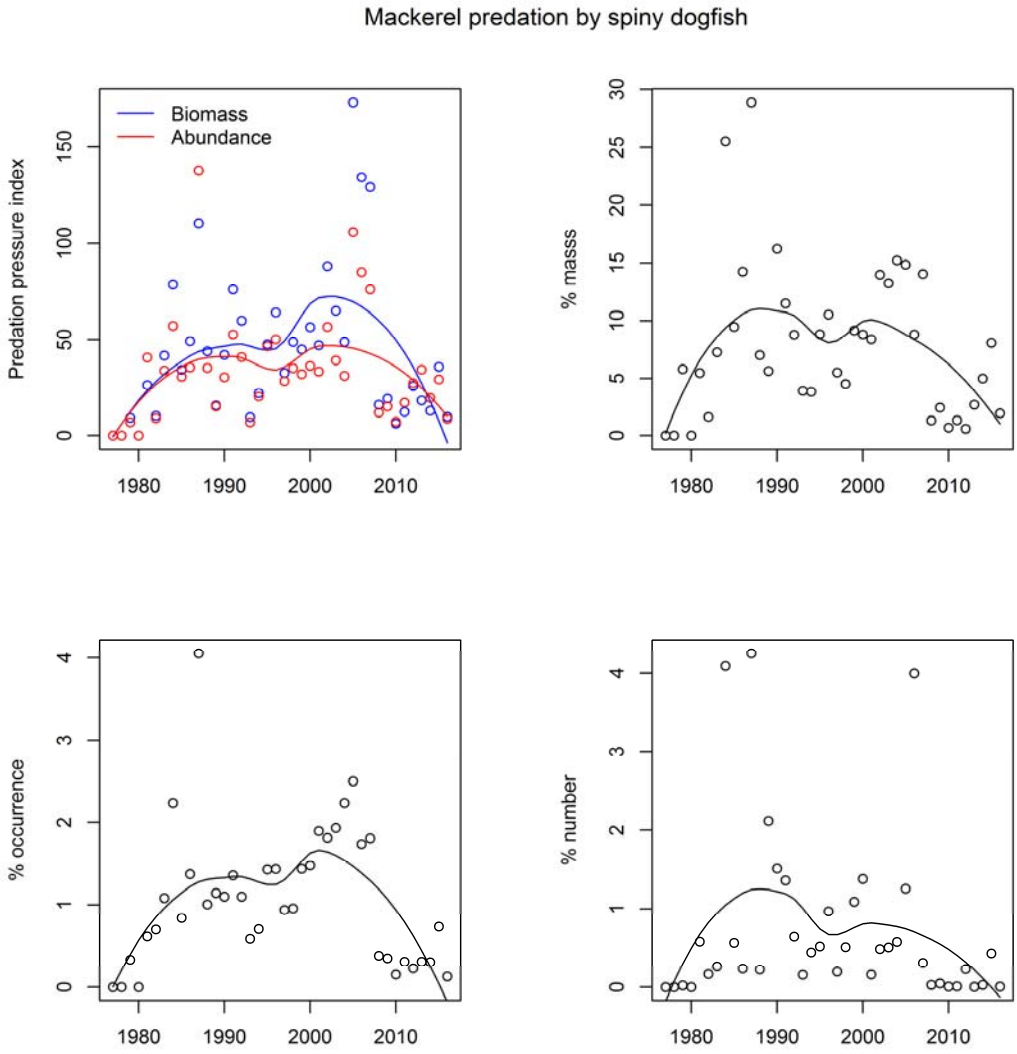


Figure A11: Mackerel predation indices for spiny dogfish: predation pressure index, and percent diet composition by mass, frequency of occurrence, and prey number. Smoother is LOESS, span = 0.8.

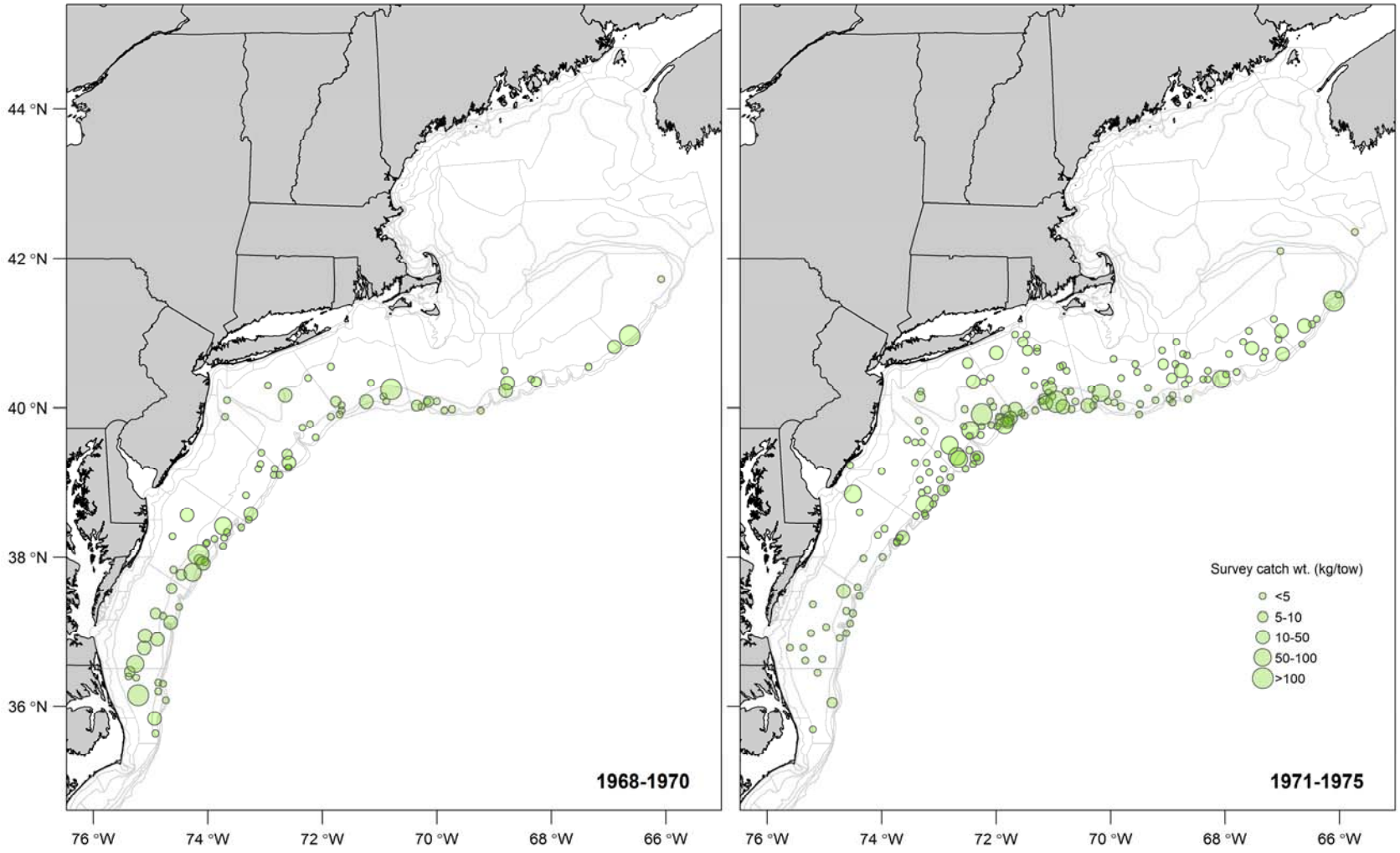


Figure A12: NEFSC spring bottom trawl survey catches (kg/tow) of Atlantic mackerel from 1968-2016 by approximately 5-year intervals.

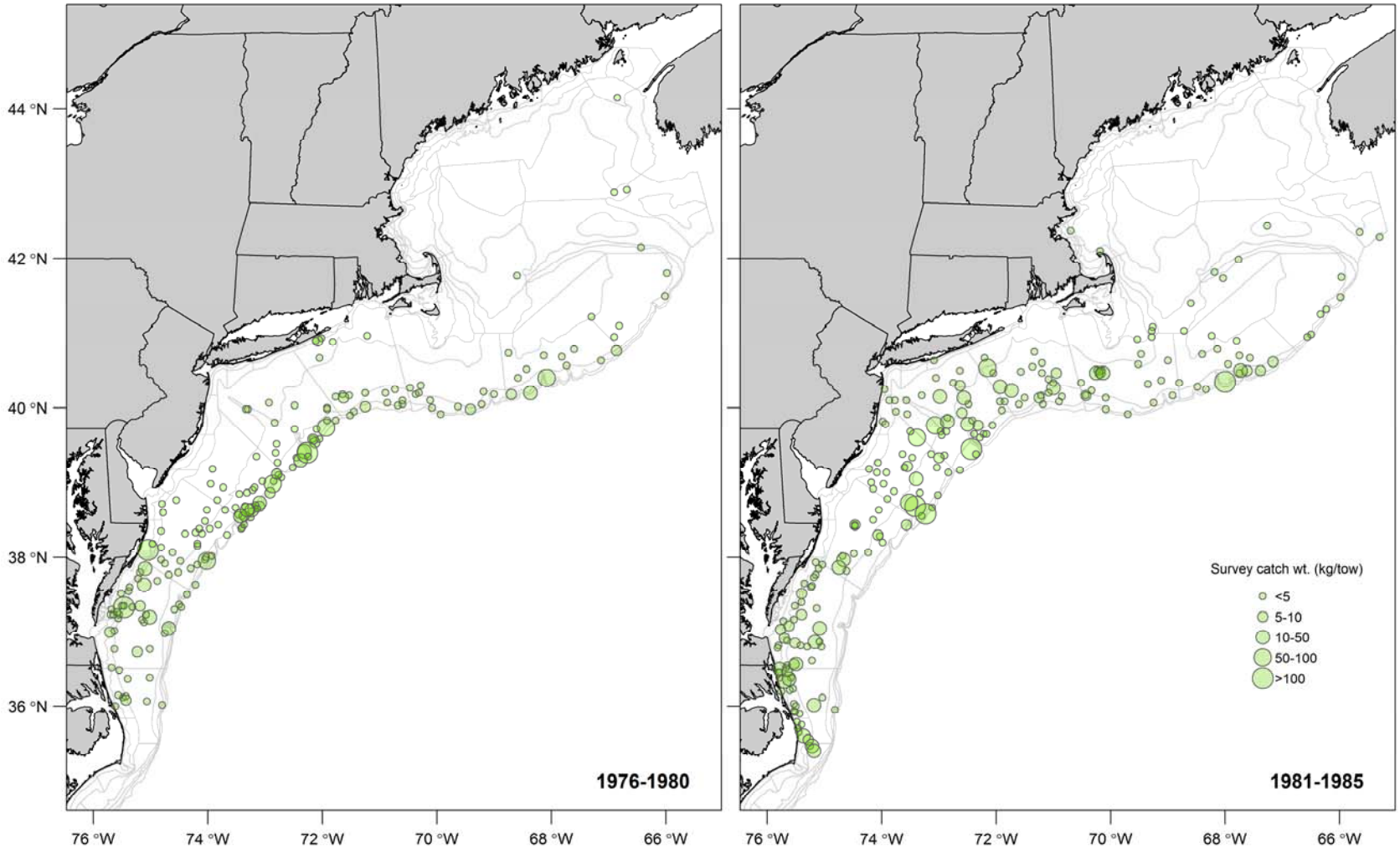


Figure A12, contd.: NEFSC spring bottom trawl survey catches (kg/tow) of Atlantic mackerel from 1968-2016 by approximately 5-year intervals.

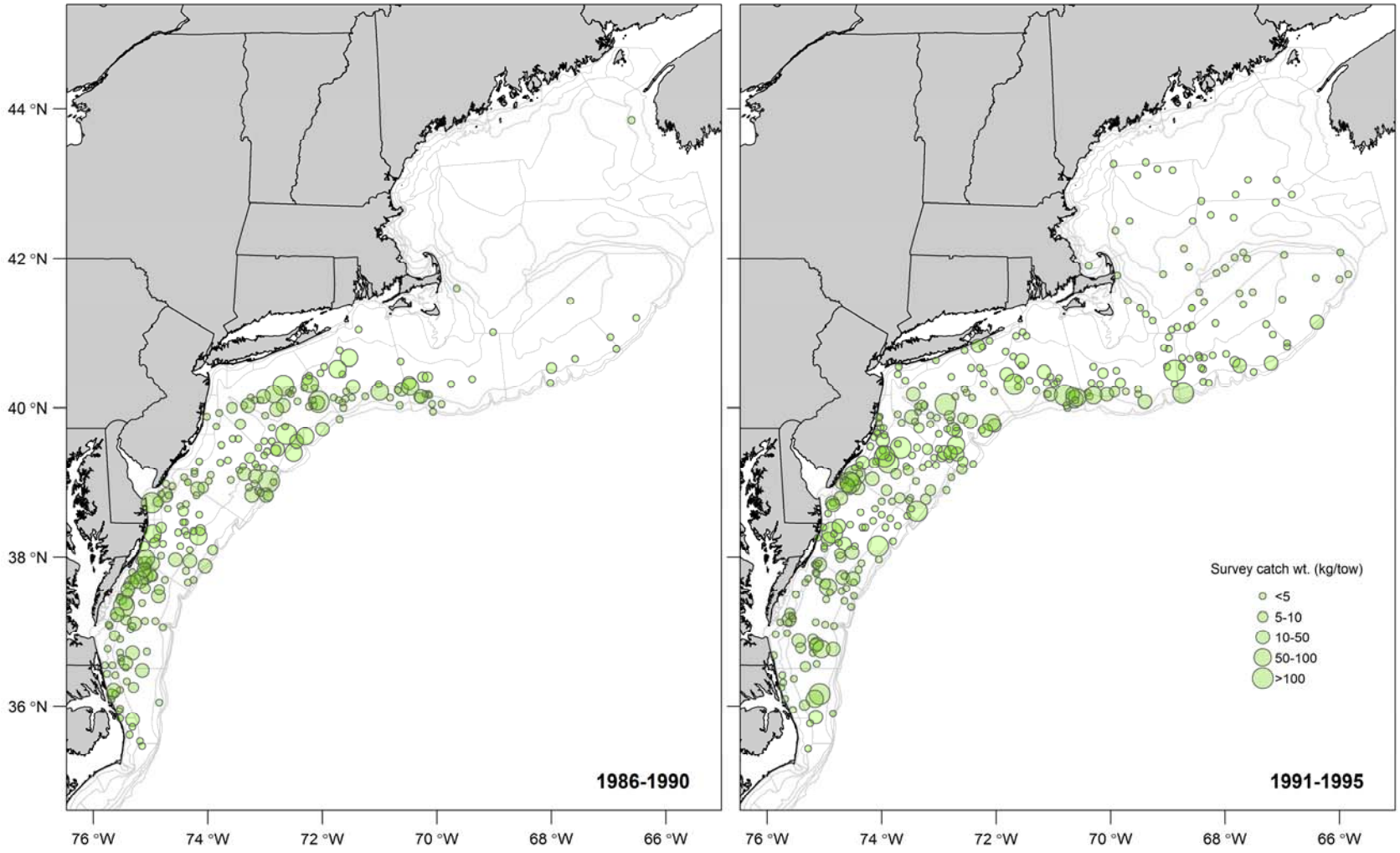


Figure A12, contd.: NEFSC spring bottom trawl survey catches (kg/tow) of Atlantic mackerel from 1968-2016 by approximately 5-year intervals.

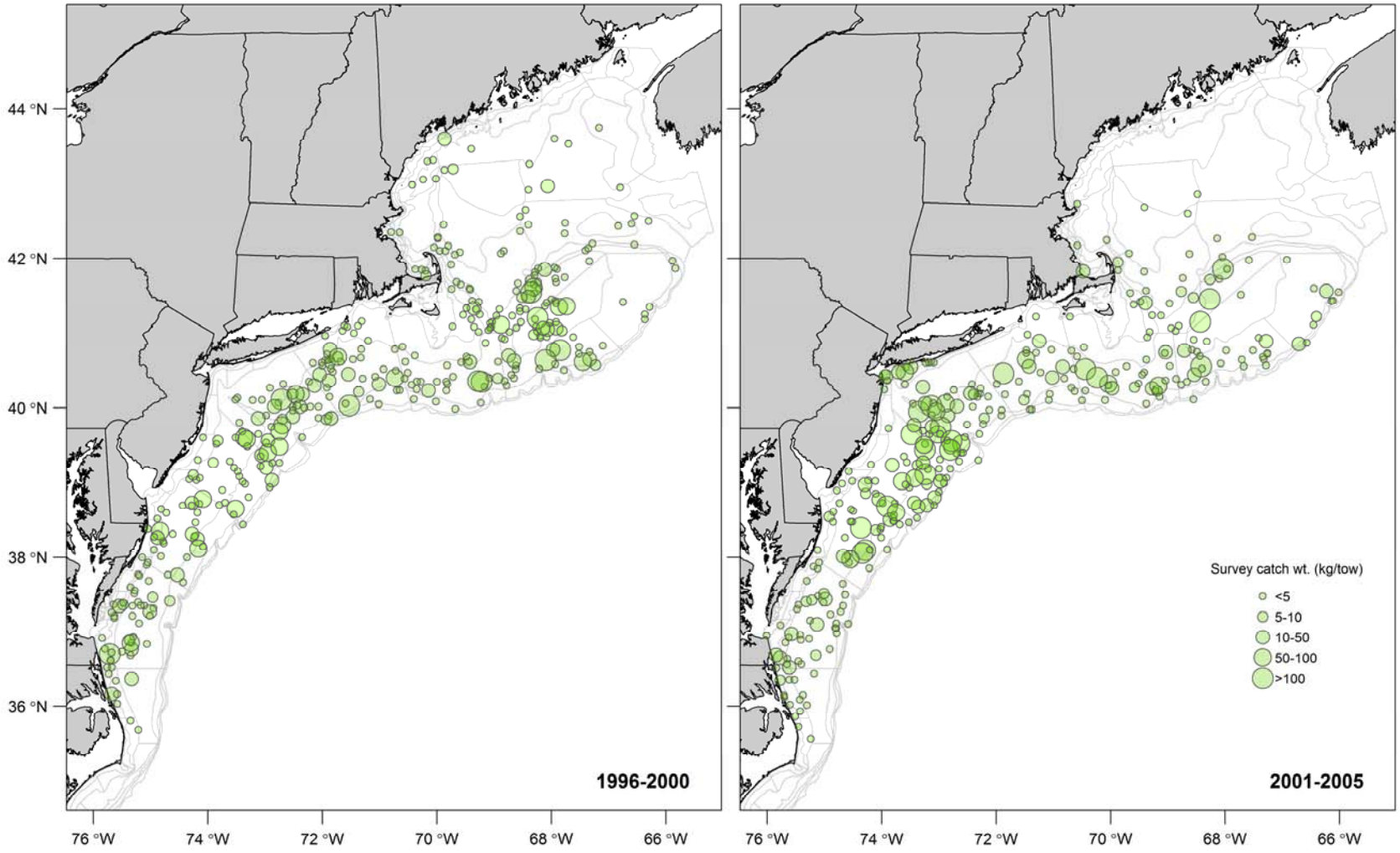


Figure A12, contd.: NEFSC spring bottom trawl survey catches (kg/tow) of Atlantic mackerel from 1968-2016 by approximately 5-year intervals.

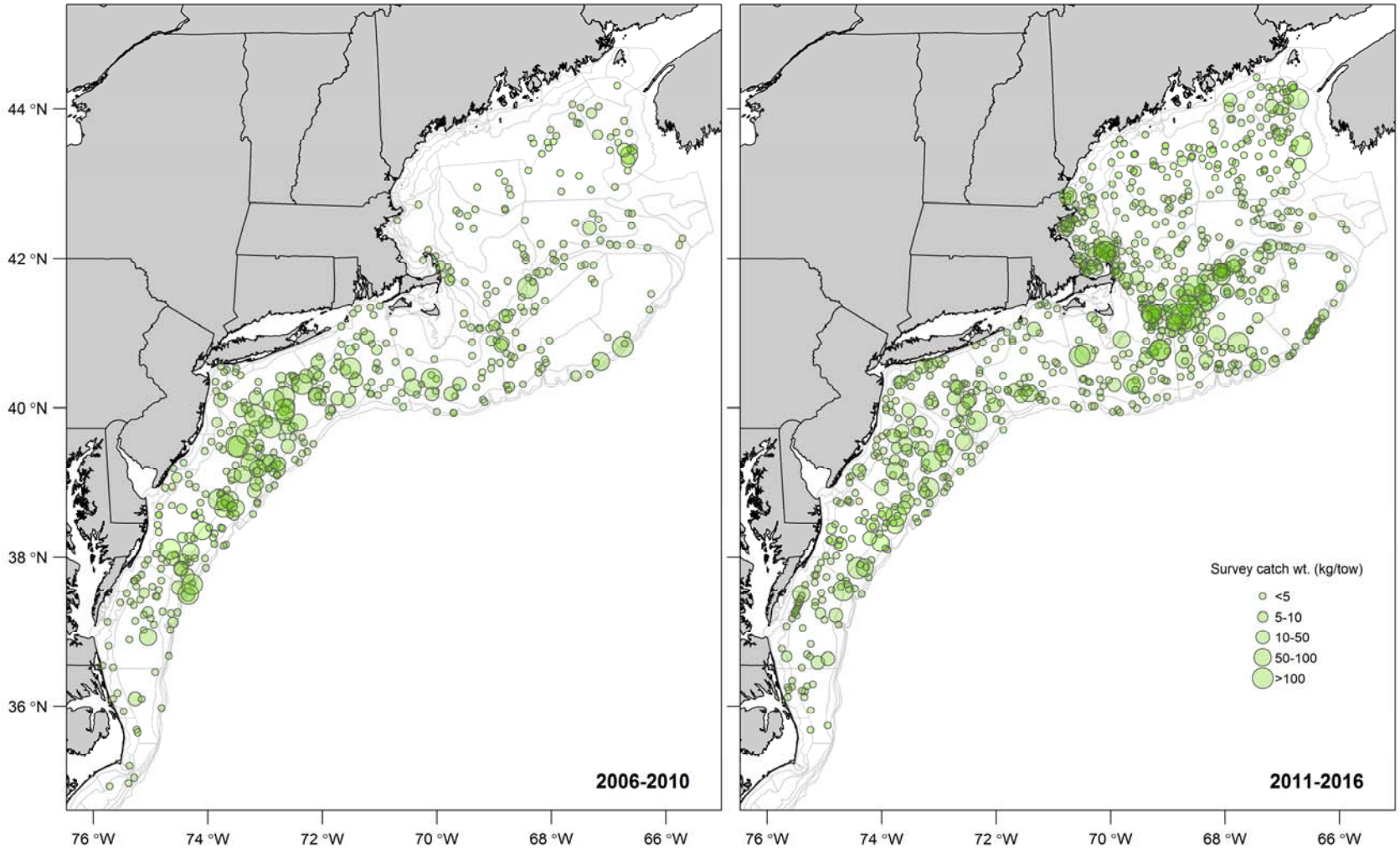


Figure A12, contd.: NEFSC spring bottom trawl survey catches (kg/tow) of Atlantic mackerel from 1968-2016 by approximately 5-year intervals.

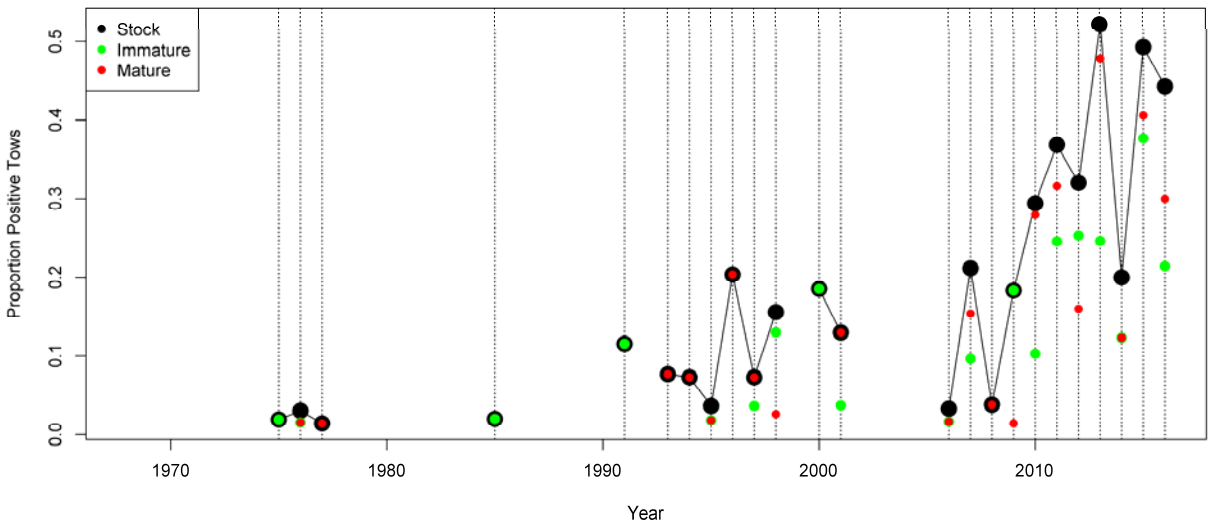


Figure A13: The proportion of tows conducted in the Gulf of Maine during the NEFSC spring bottom trawl survey that encountered Atlantic mackerel from 1968-2016.

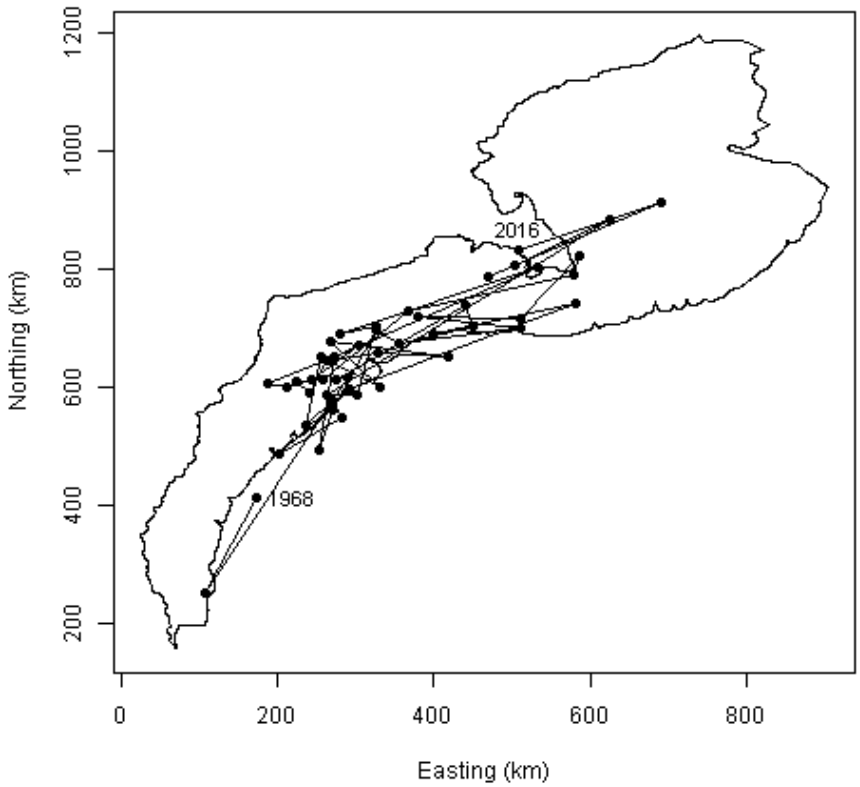


Figure A14: Annual centers of gravity for Atlantic mackerel from the NEFSC spring bottom trawl survey for 1968-2016.

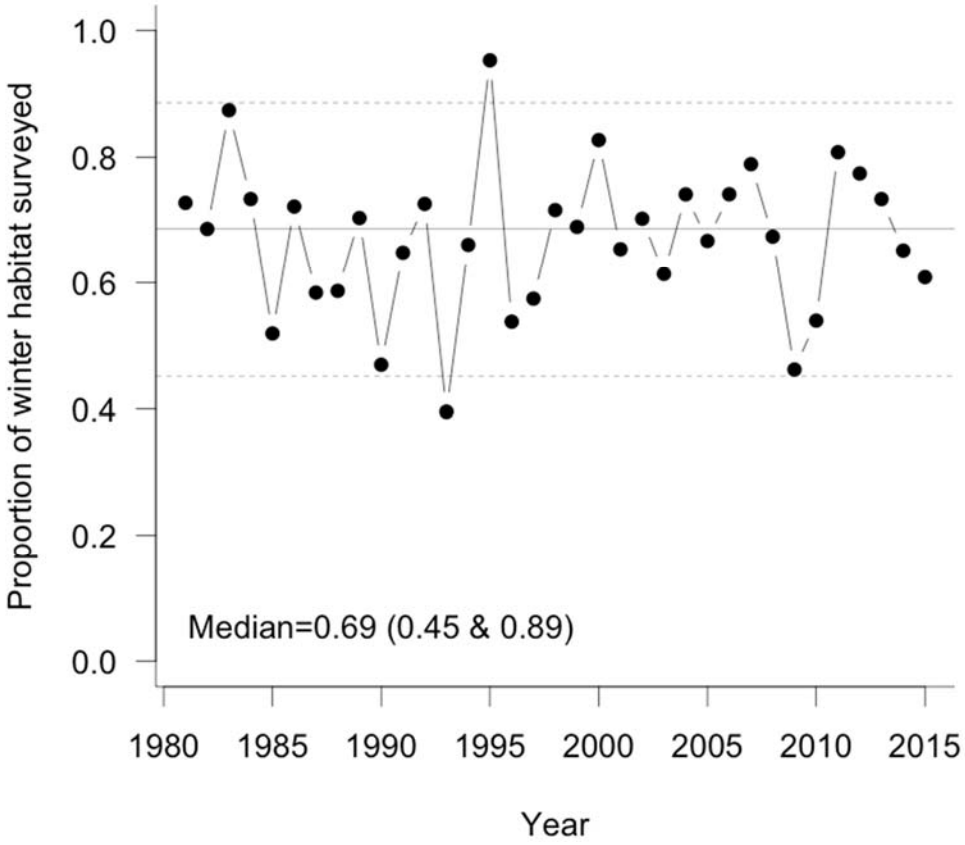


Figure A15: Model-based estimates of the proportion of winter habitat surveyed in the spring NEFSC bottom trawl survey from 1980-2015.

TOR2: Catch from all sources

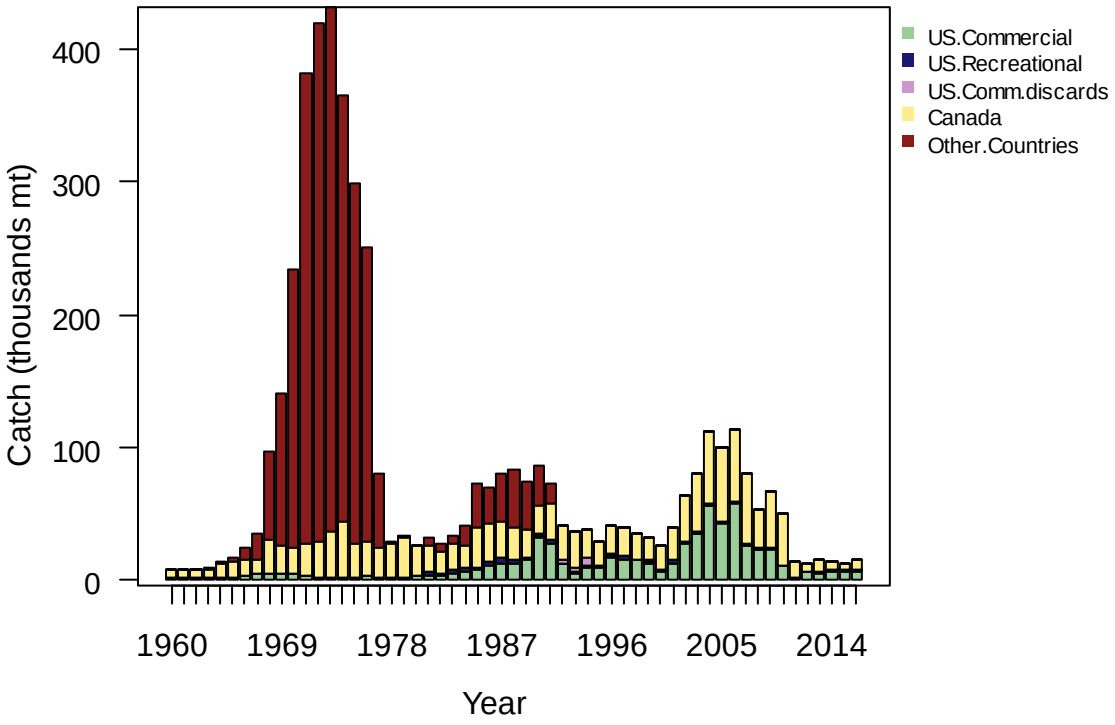


Figure A16: Total catch of Atlantic mackerel by all sources from 1960 through 2016. US.Commercial represents U.S. commercial landings, US.Recreational represents U.S. recreational catch (landings plus discards), US.Comm.discards, represents discards by the U.S. commercial fishery, Canada represents Canadian landings (discards are not available), and Other.Countries represents landings by all other countries.

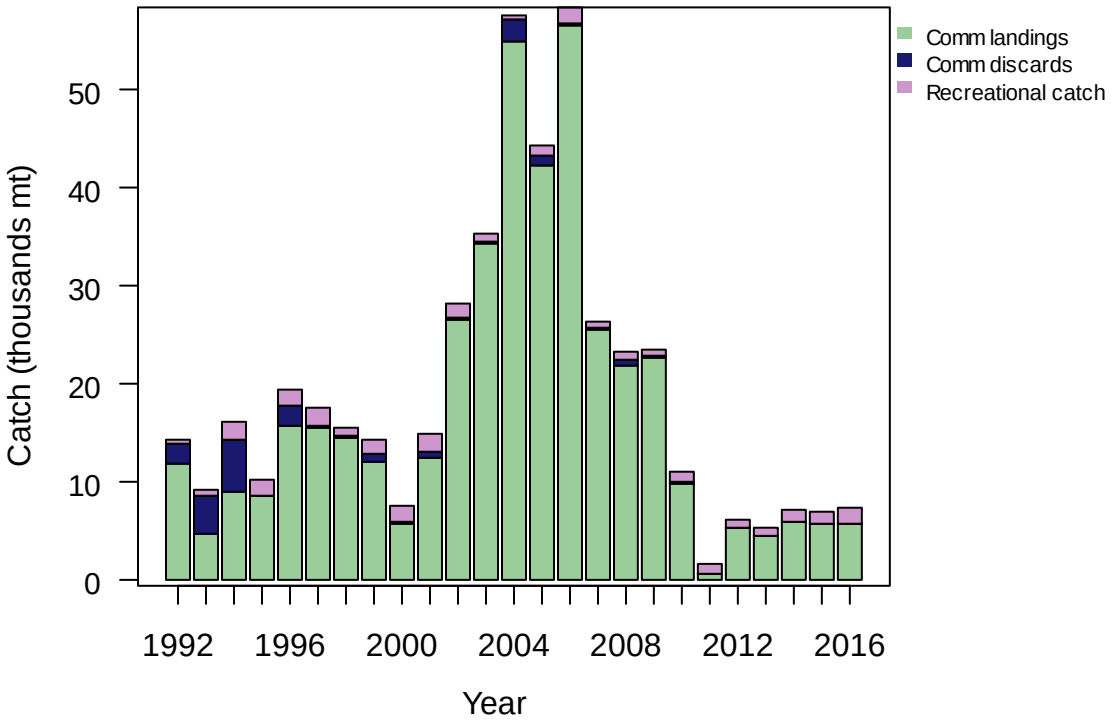


Figure A17: Total U.S. aggregate catch of Atlantic mackerel during 1992-2016.

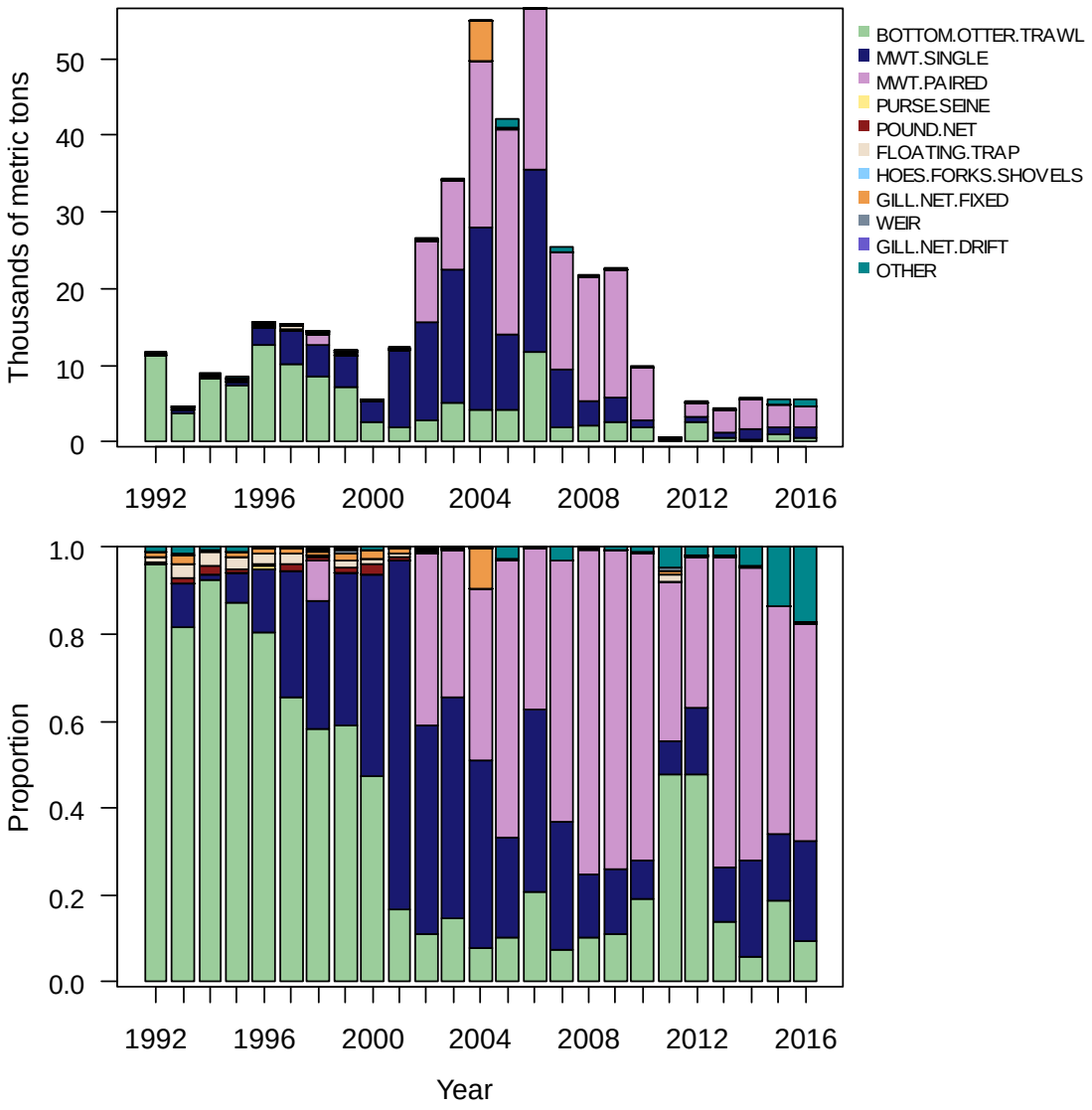


Figure A18: U.S. commercial landings by gear from 1992 through 2016.

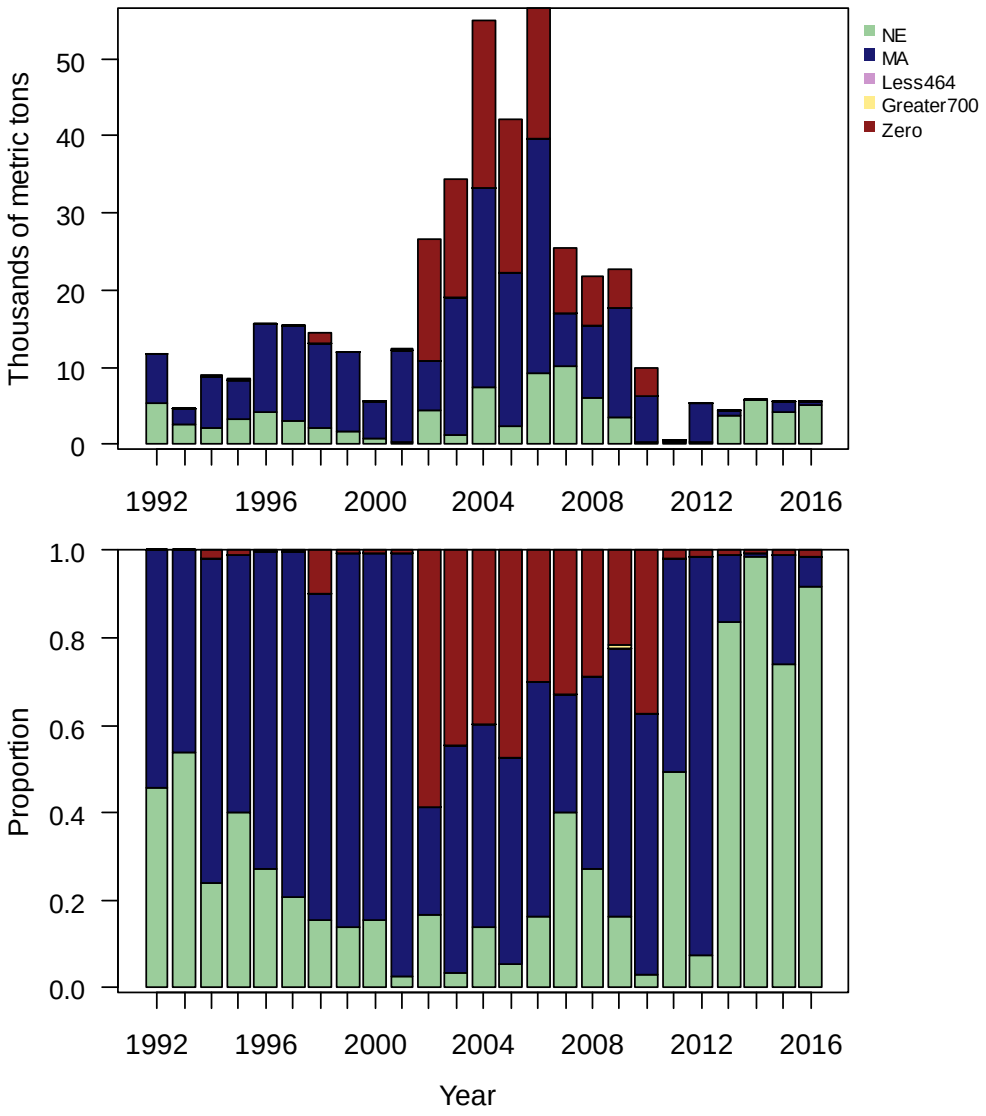


Figure A19: U.S. commercial landings by area fished from 1992 through 2016. Less464 and Greater700 represent NAFO statistical areas less than 464 and greater than 700, respectively, which did not fall into the New England and Mid-Atlantic area fished definitions.

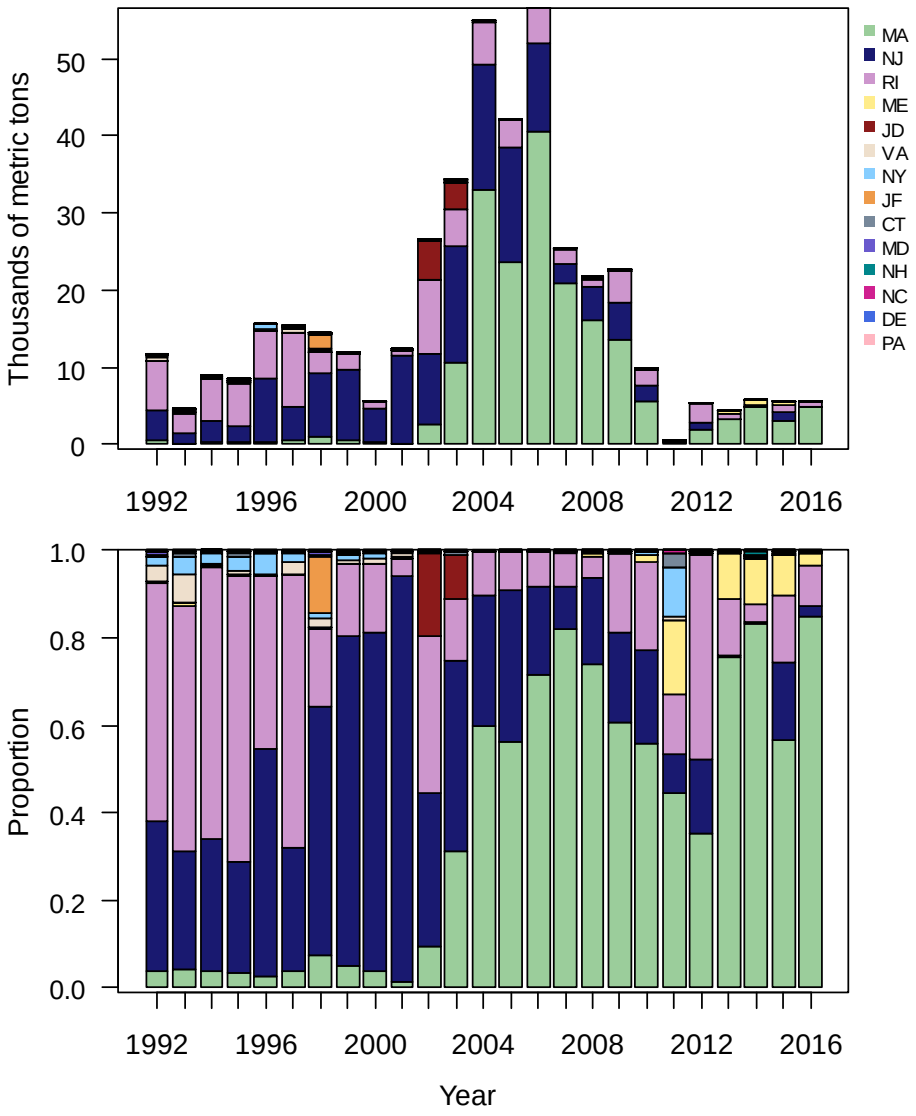


Figure A20: U.S. commercial landings by state from 1992 through 2016. JD and JF represent joint venture domestic and foreign fisheries, respectively.

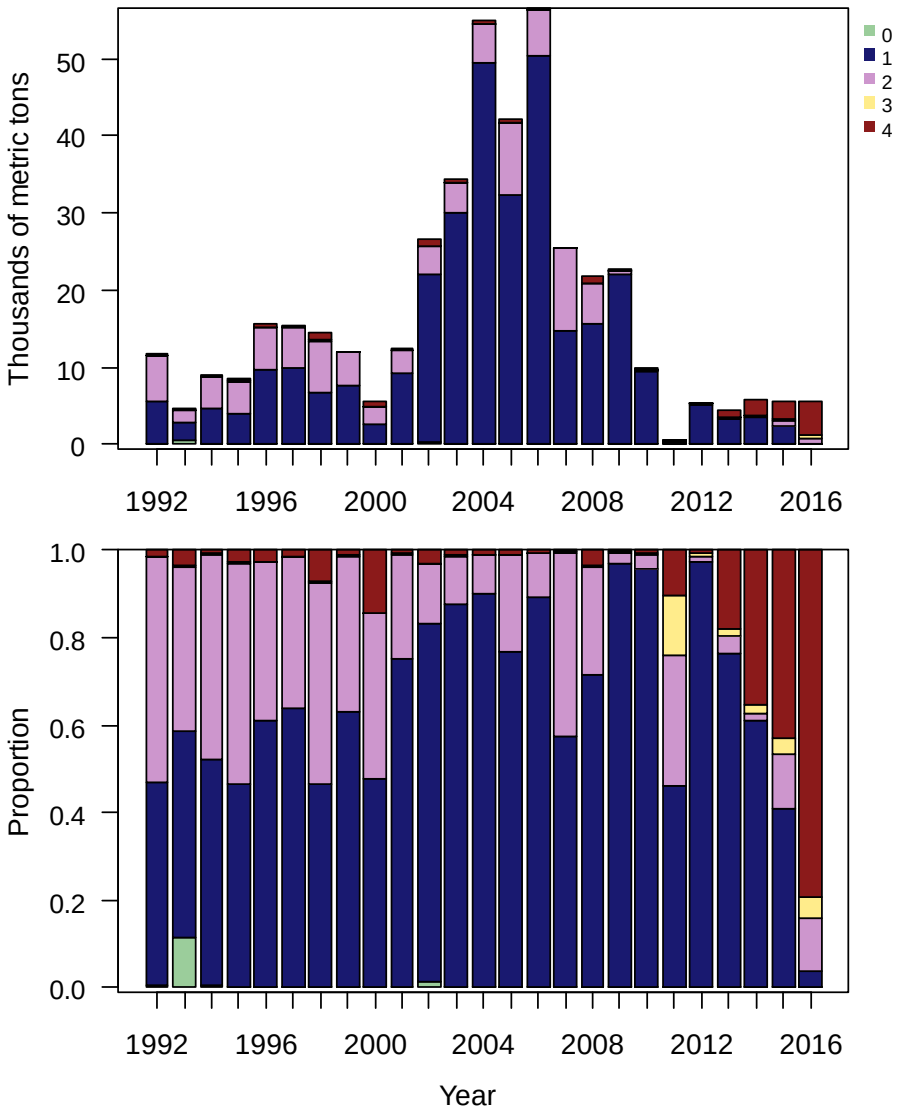


Figure A21: U.S. commercial landings by quarter from 1992 through 2016. Quarters equal to zero represent unknown quarters.

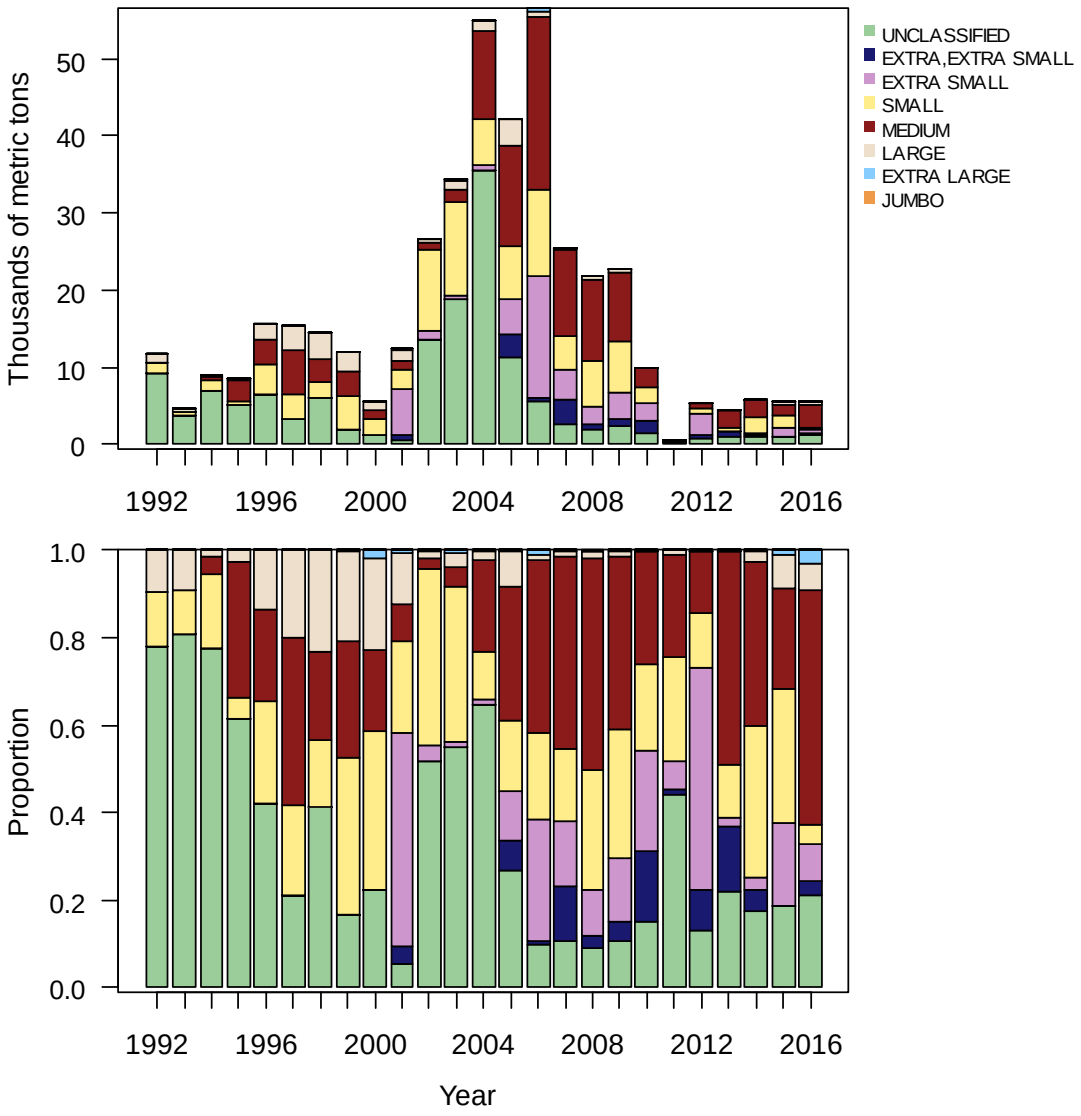


Figure A22: U.S. commercial landings by market category from 1992 through 2016.

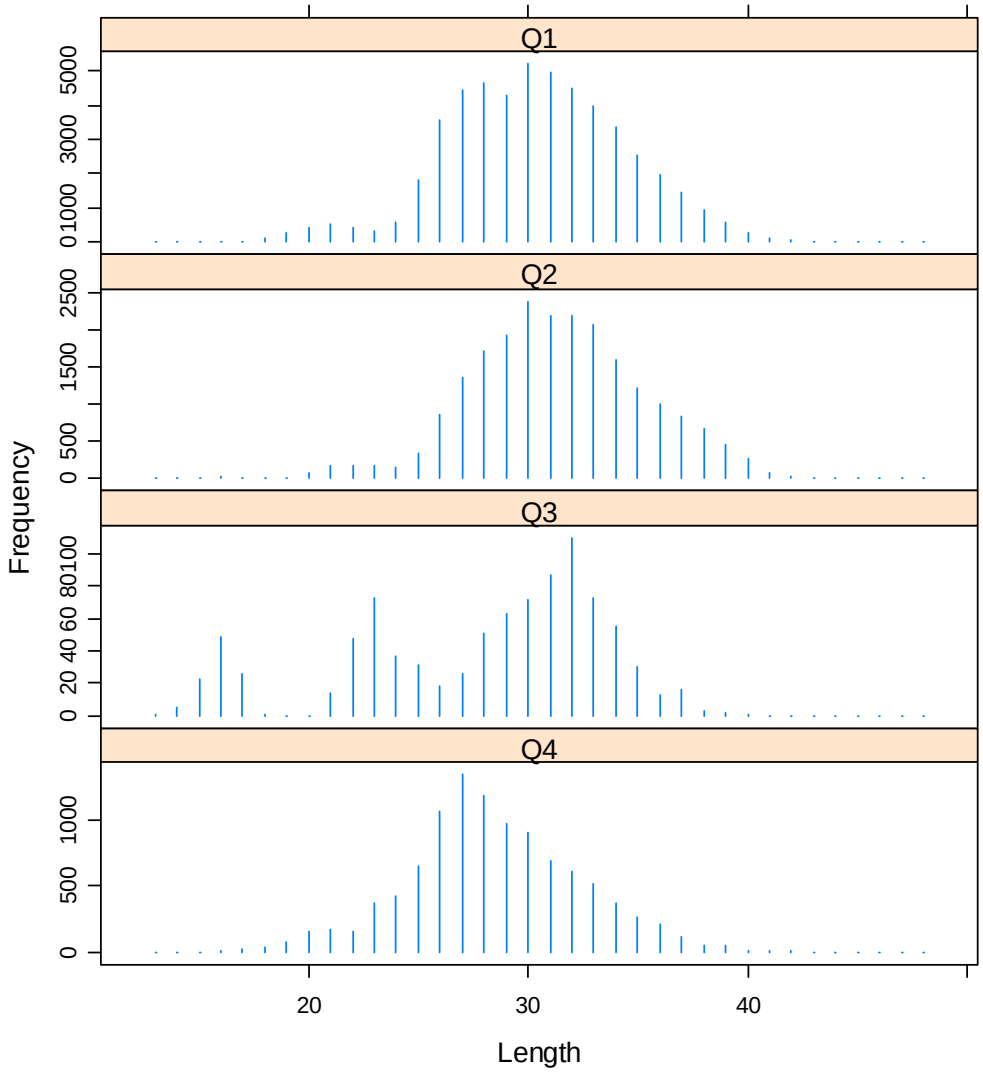


Figure A23: Length frequency distributions of U.S. commercial landings samples by quarter.

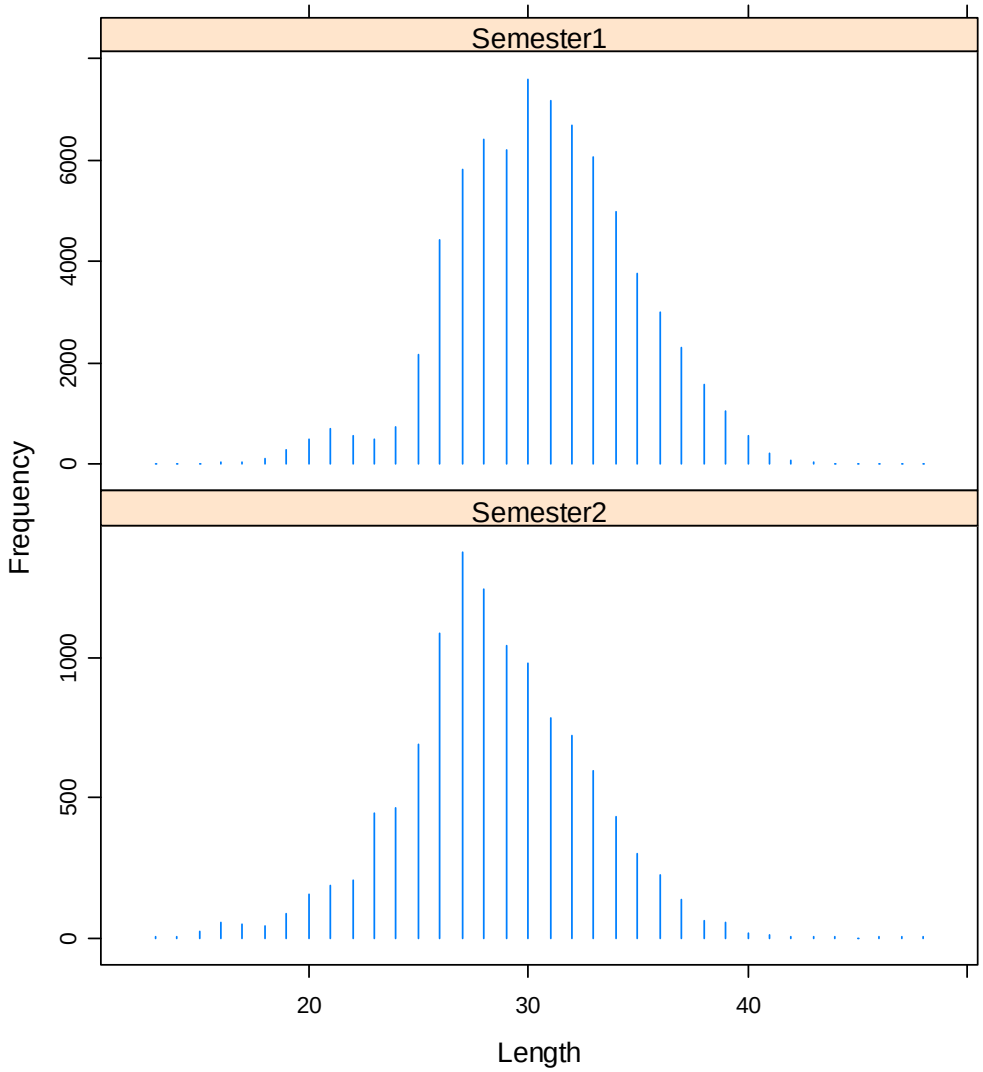


Figure A24: Length frequency distributions of U.S. commercial landings samples by semester.

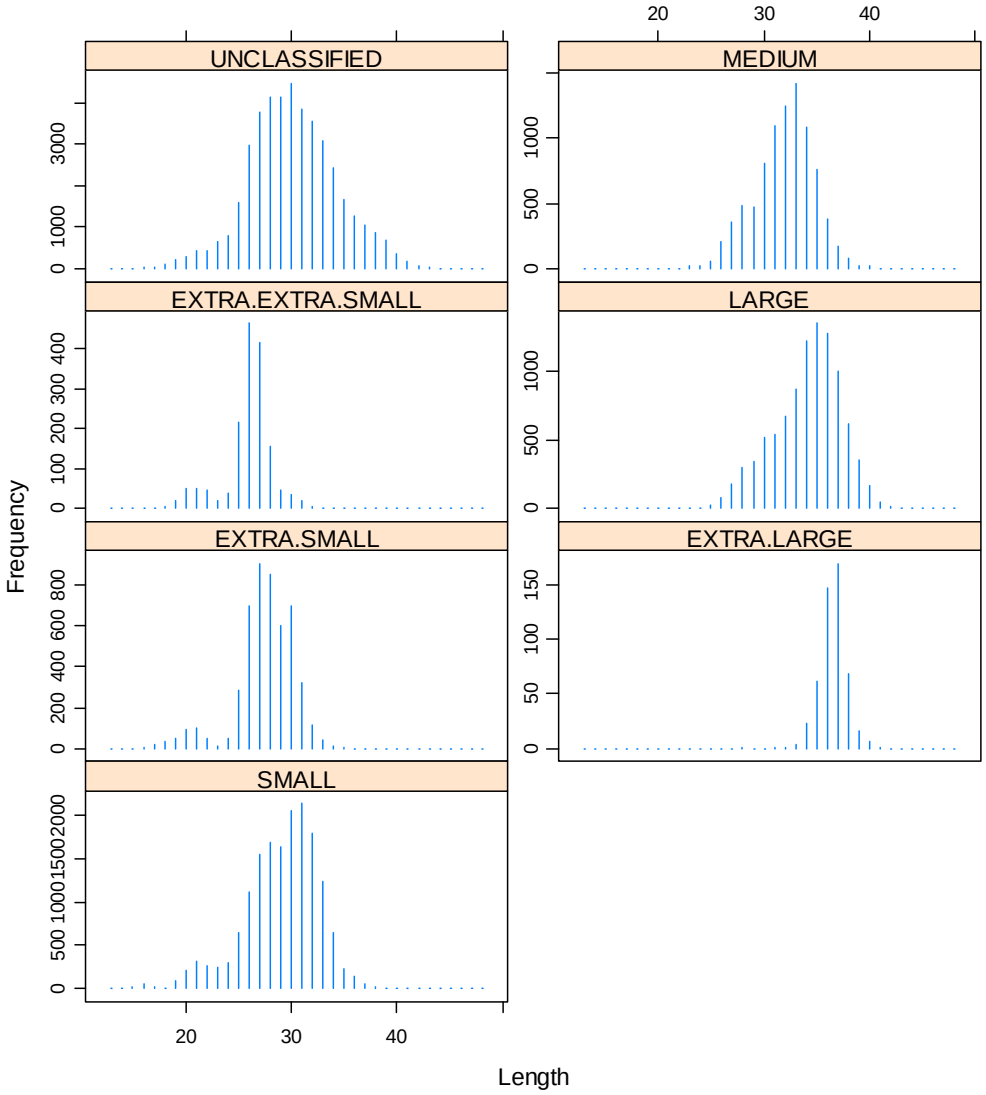


Figure A25: Length frequency distributions of U.S. commercial landings samples by market category.

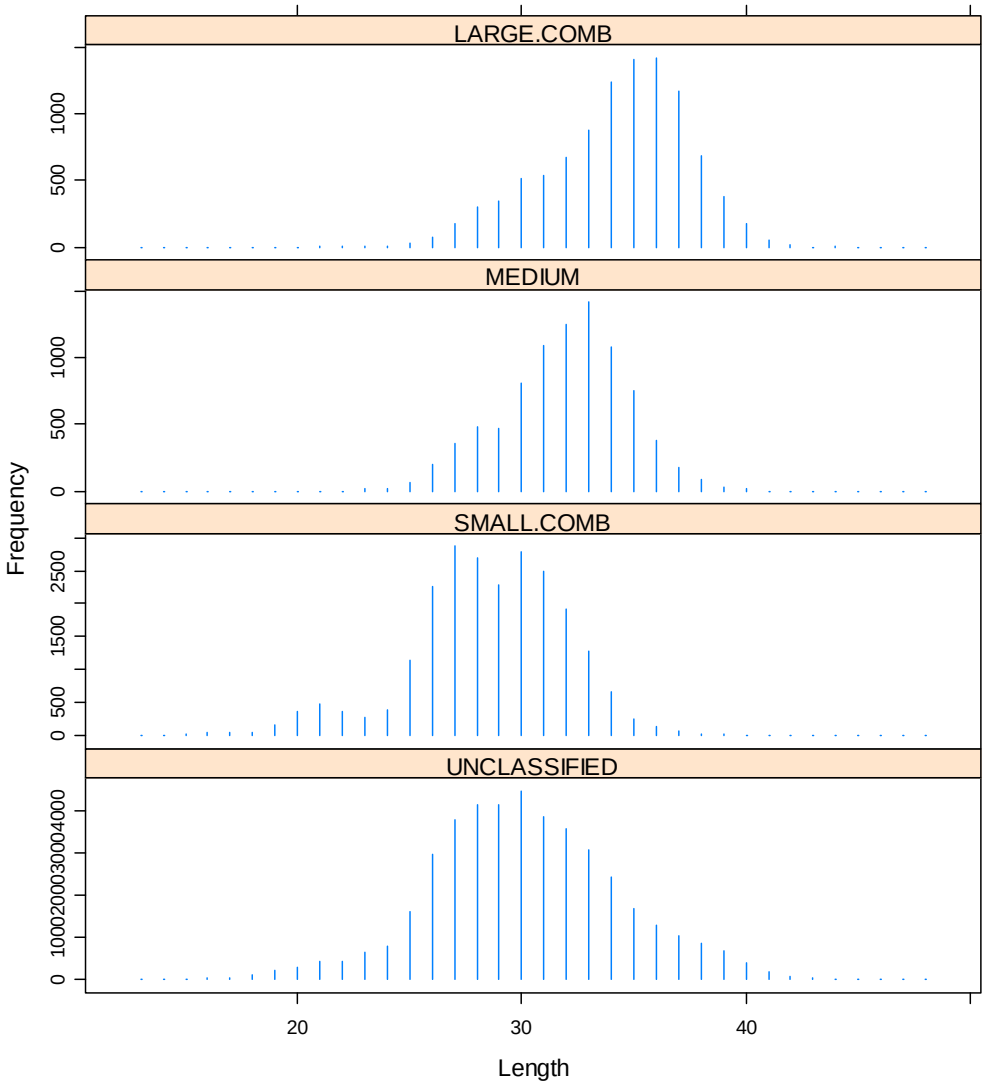


Figure A26: Length frequency distributions of U.S. commercial landings samples by combined market categories. Small.comb represents the combined small category that includes small, extra-small and extra-extra-small. Large.comb represents the combined large category that includes large, extra-large and jumbo.

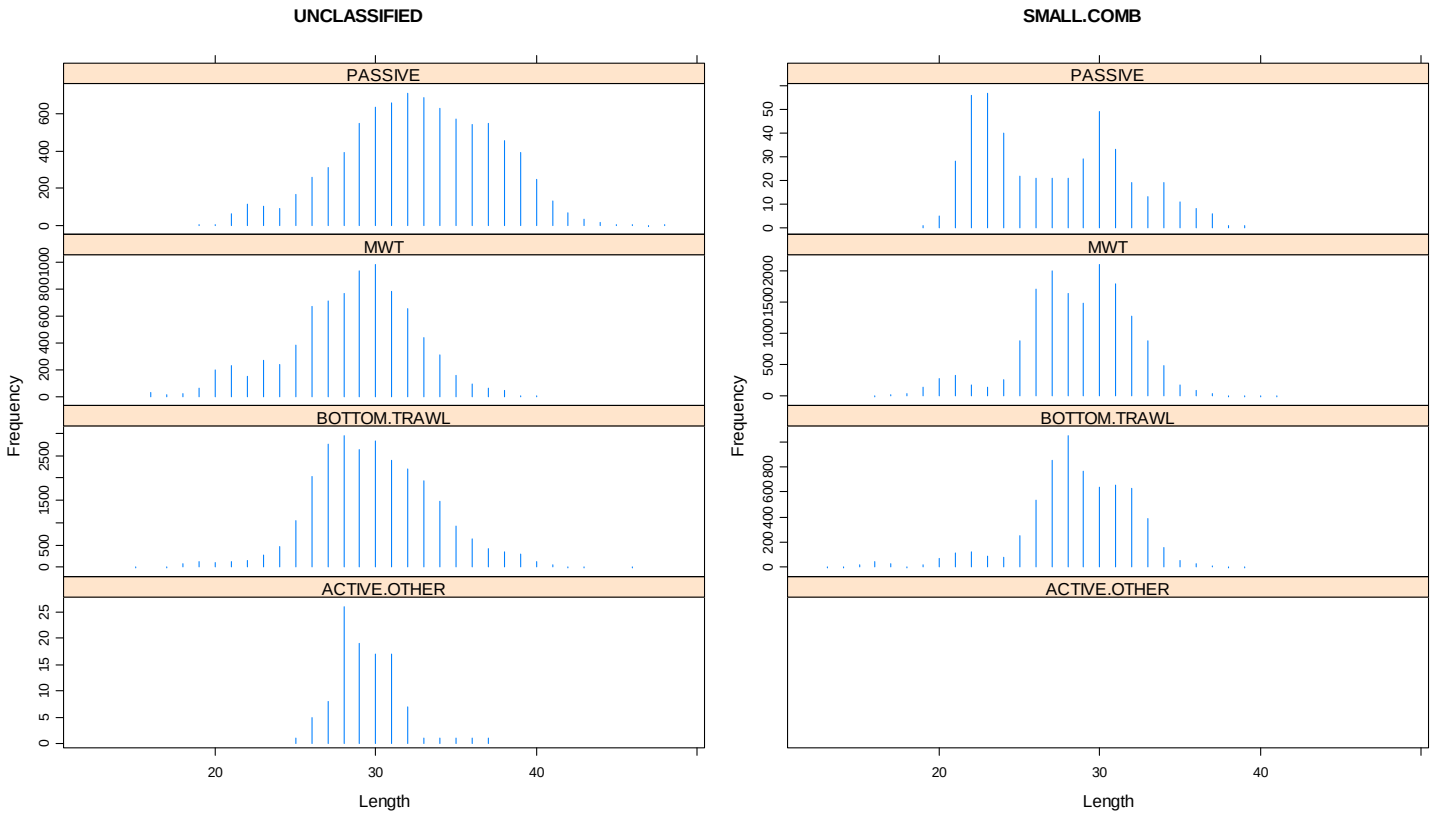


Figure A27: Length frequency distributions of U.S. commercial landings samples by gear for each market category.

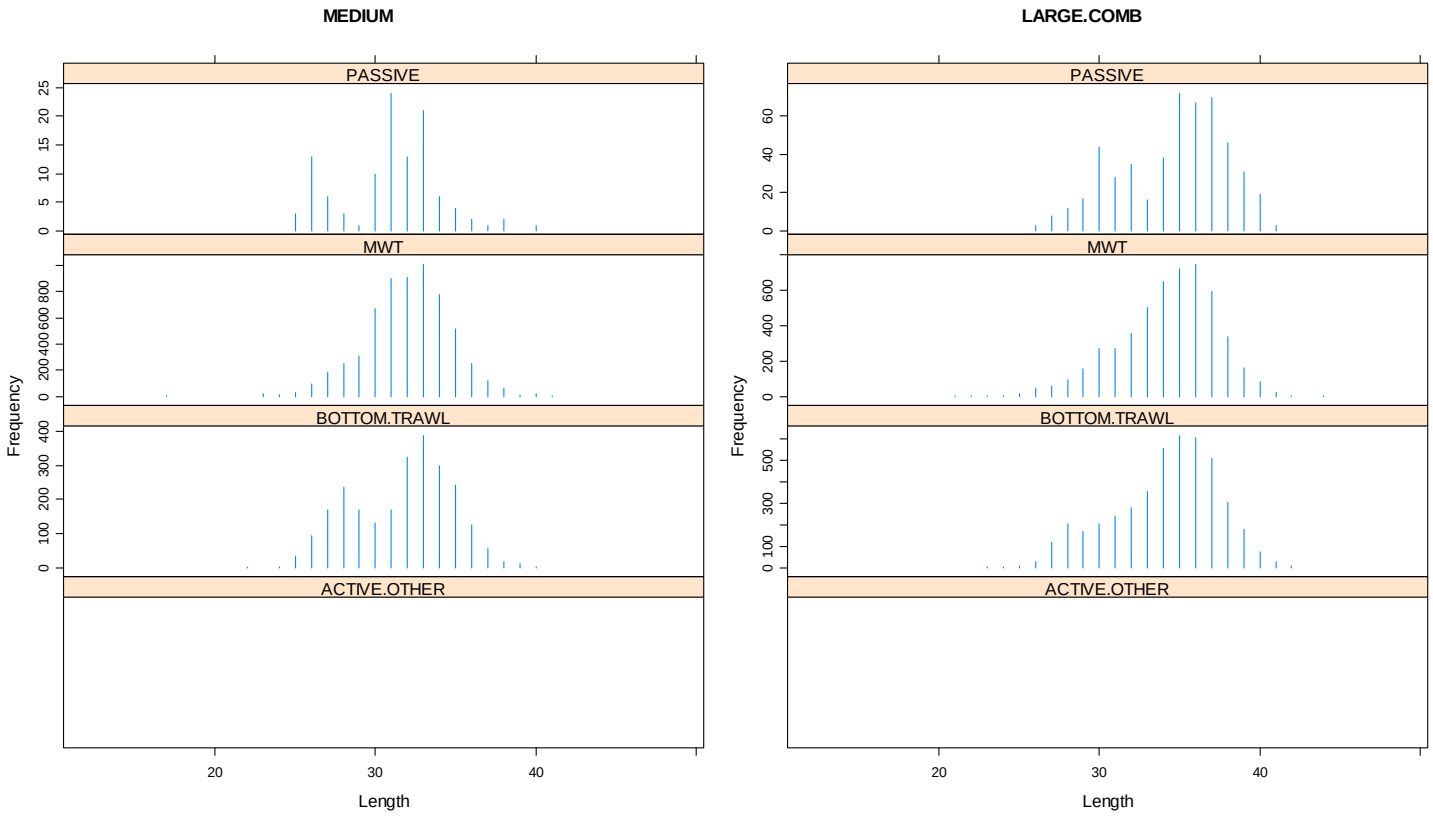


Figure A27, contd.: Length frequency distributions of U.S. commercial landings samples by gear for each market category

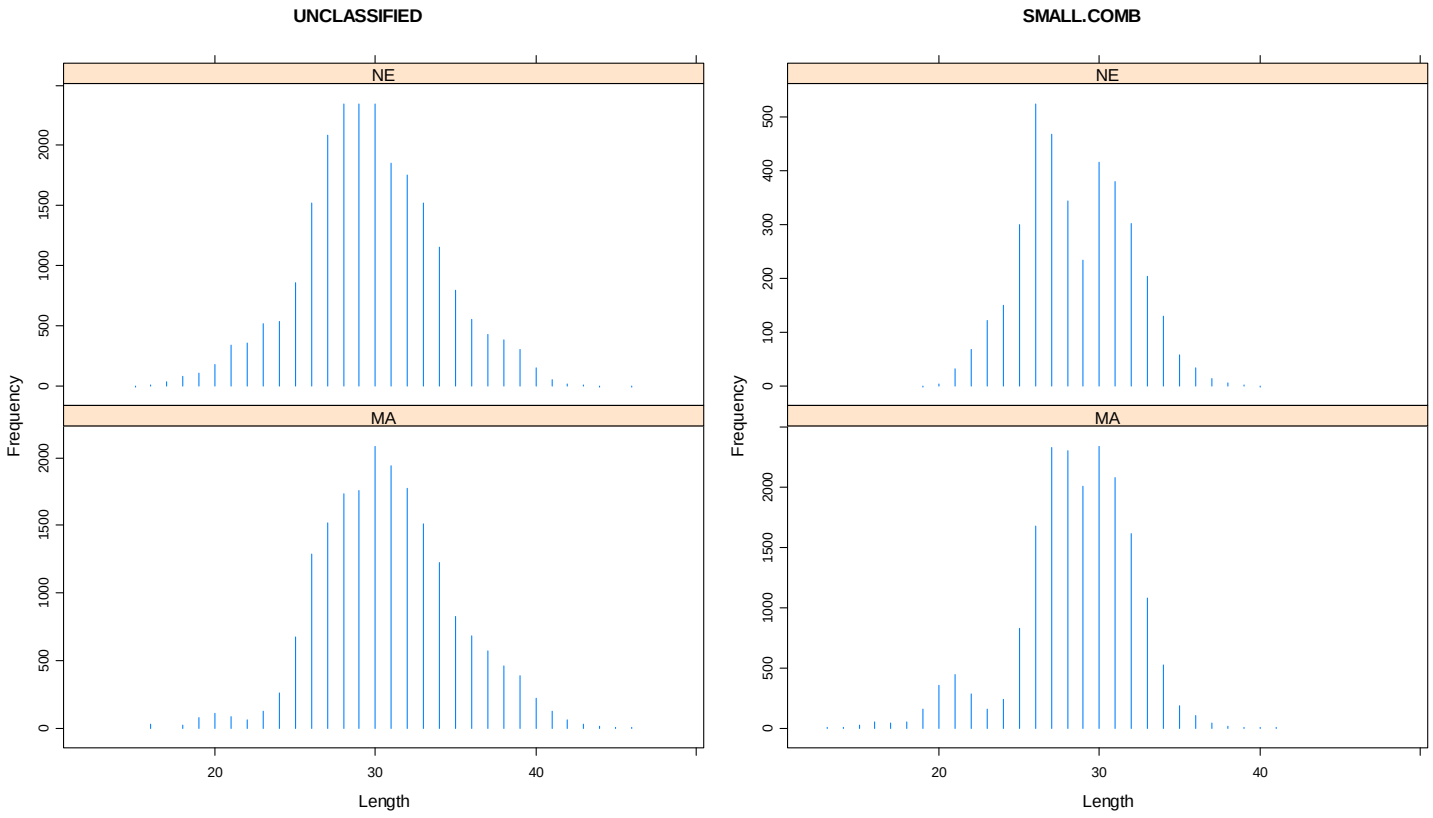


Figure A28: Length frequency distributions of U.S. commercial landings samples by area fished for each market category.

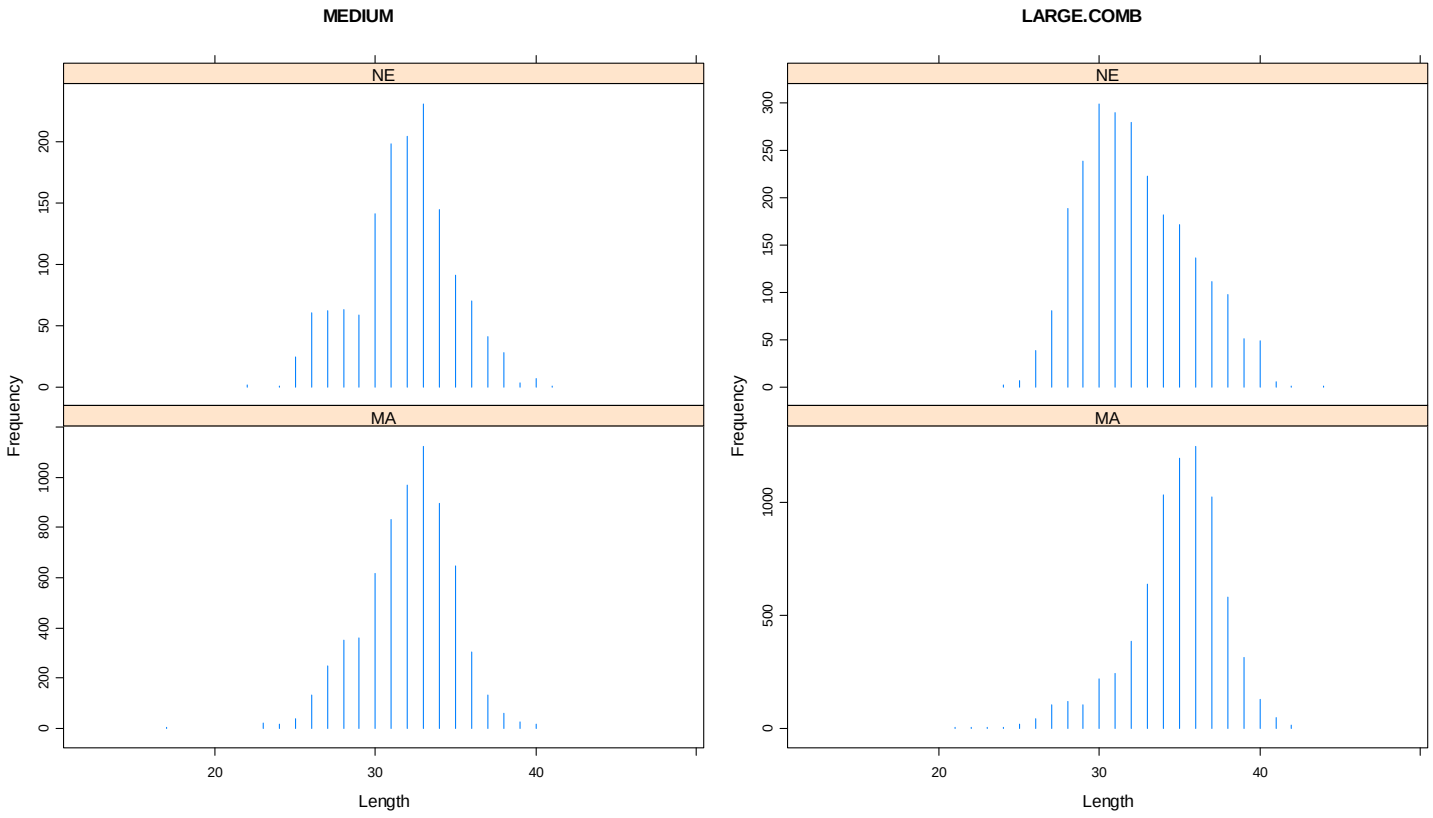


Figure A28, contd.: Length frequency distributions of U.S. commercial landings samples by area fished for each market category.

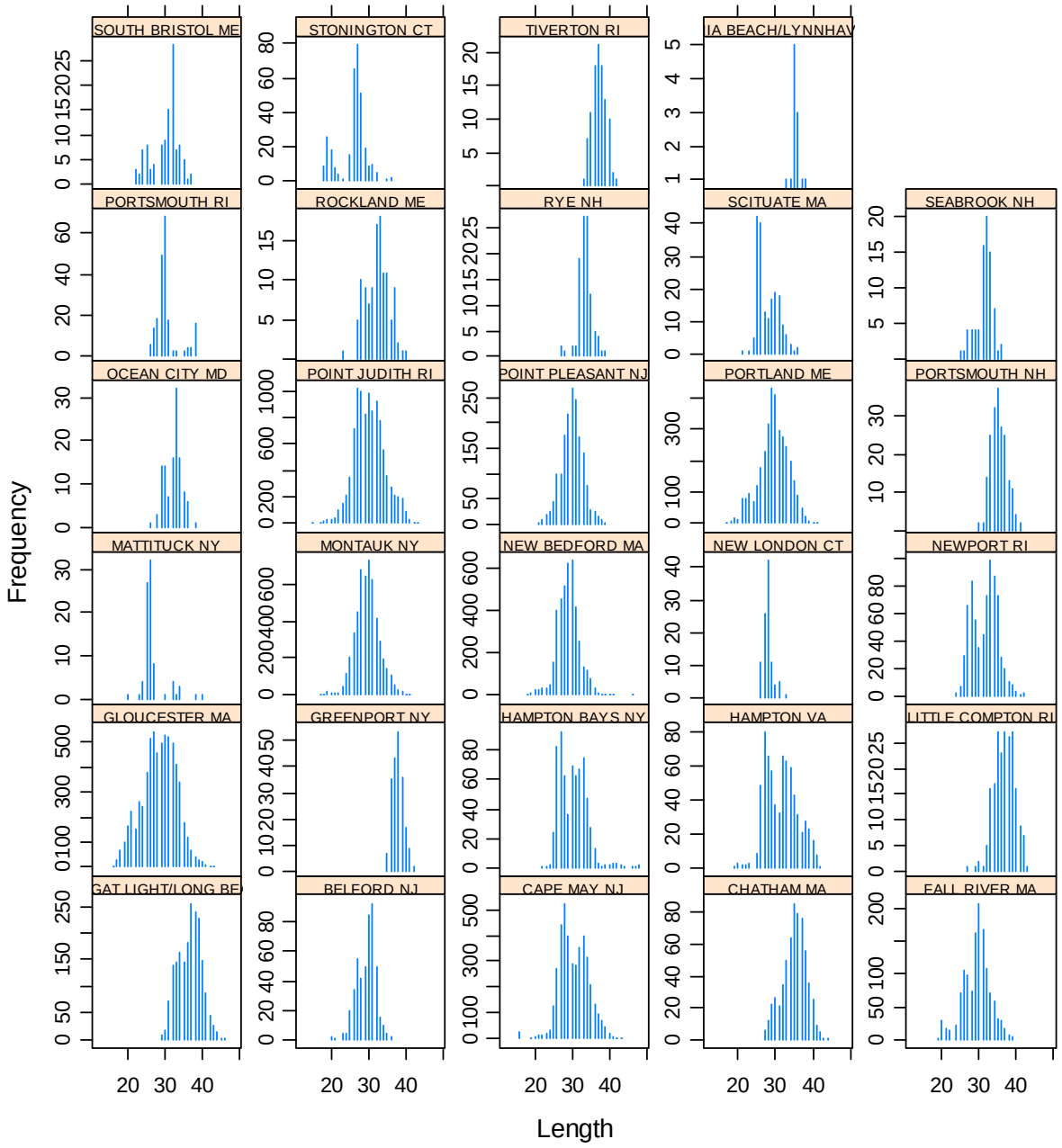


Figure A29: Length frequency distributions of U.S. commercial landings samples by port for each market category.

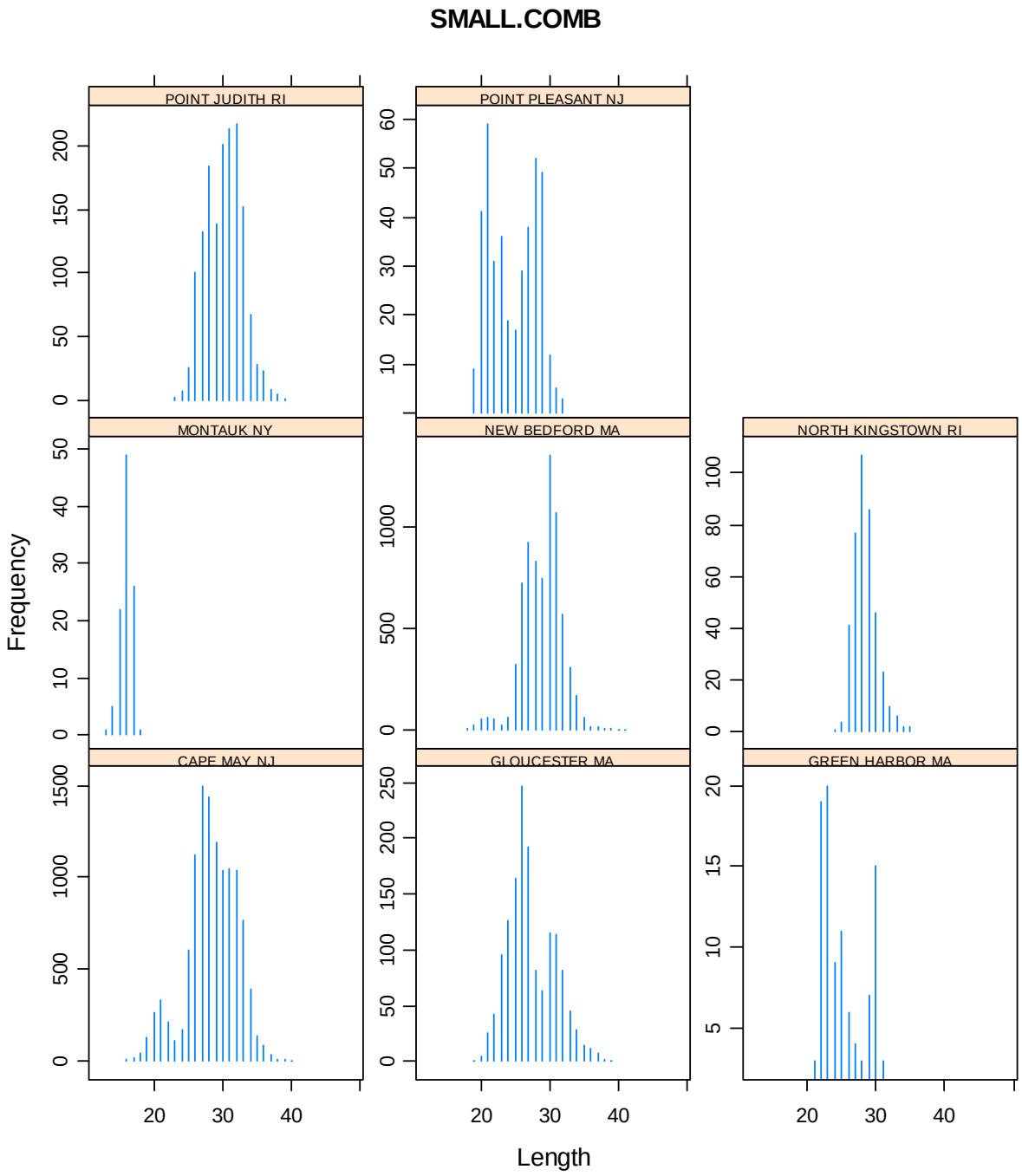


Figure A29, contd.: Length frequency distributions of U.S. commercial landings samples by port for each market category.

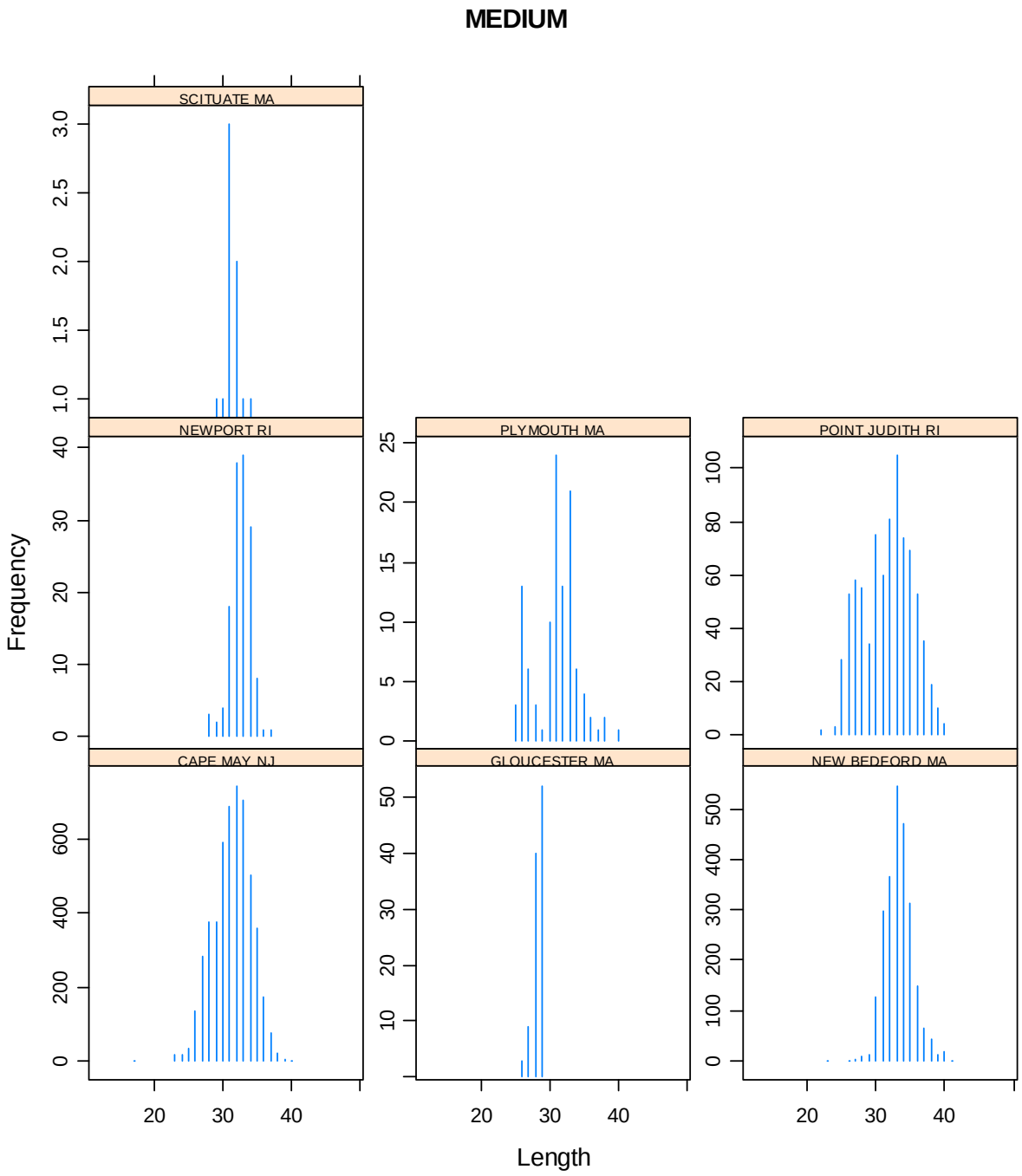


Figure A29, contd.: Length frequency distributions of U.S. commercial landings samples by port for each market category.

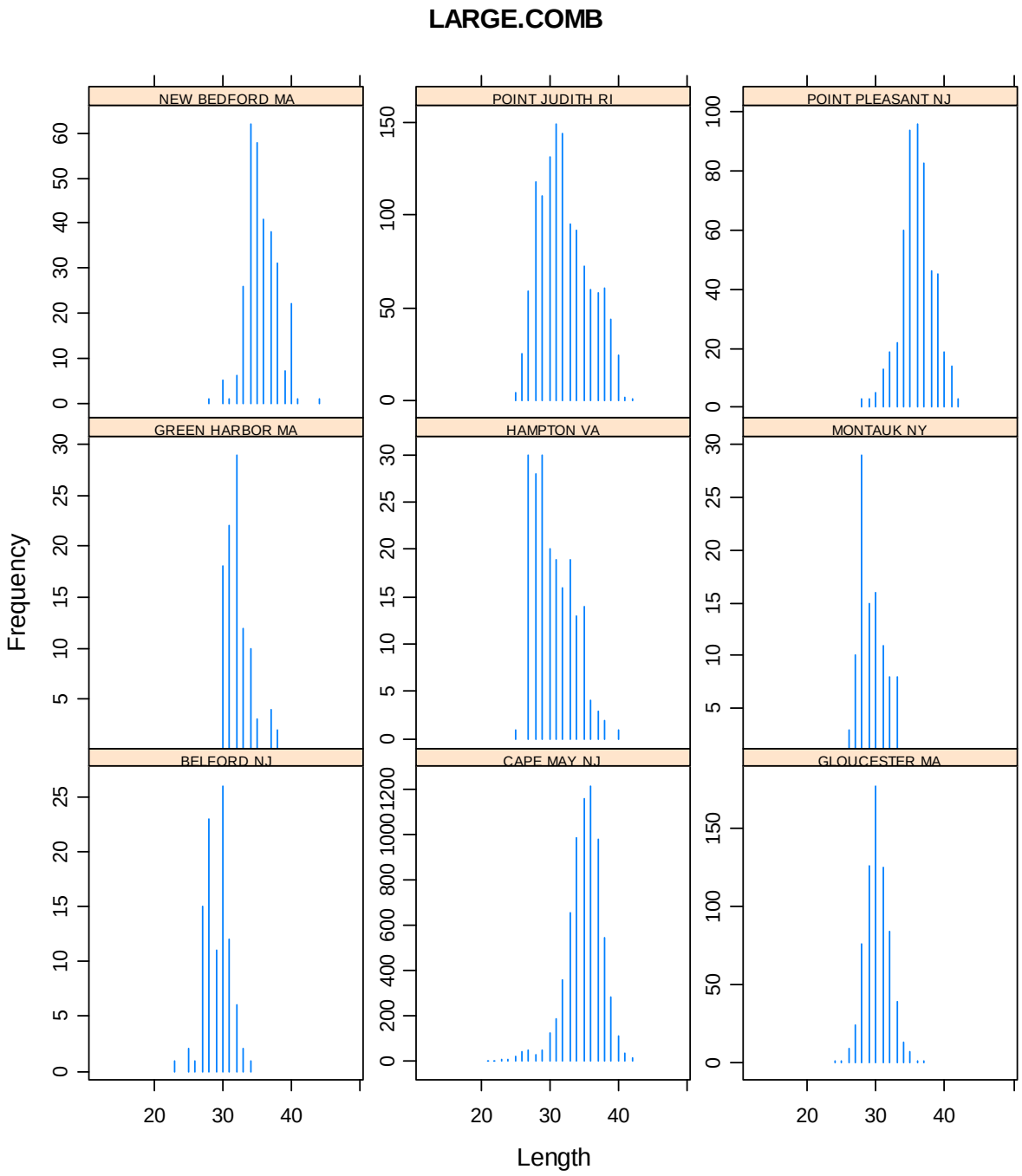


Figure A29, contd.: Length frequency distributions of U.S. commercial landings samples by port for each market category.

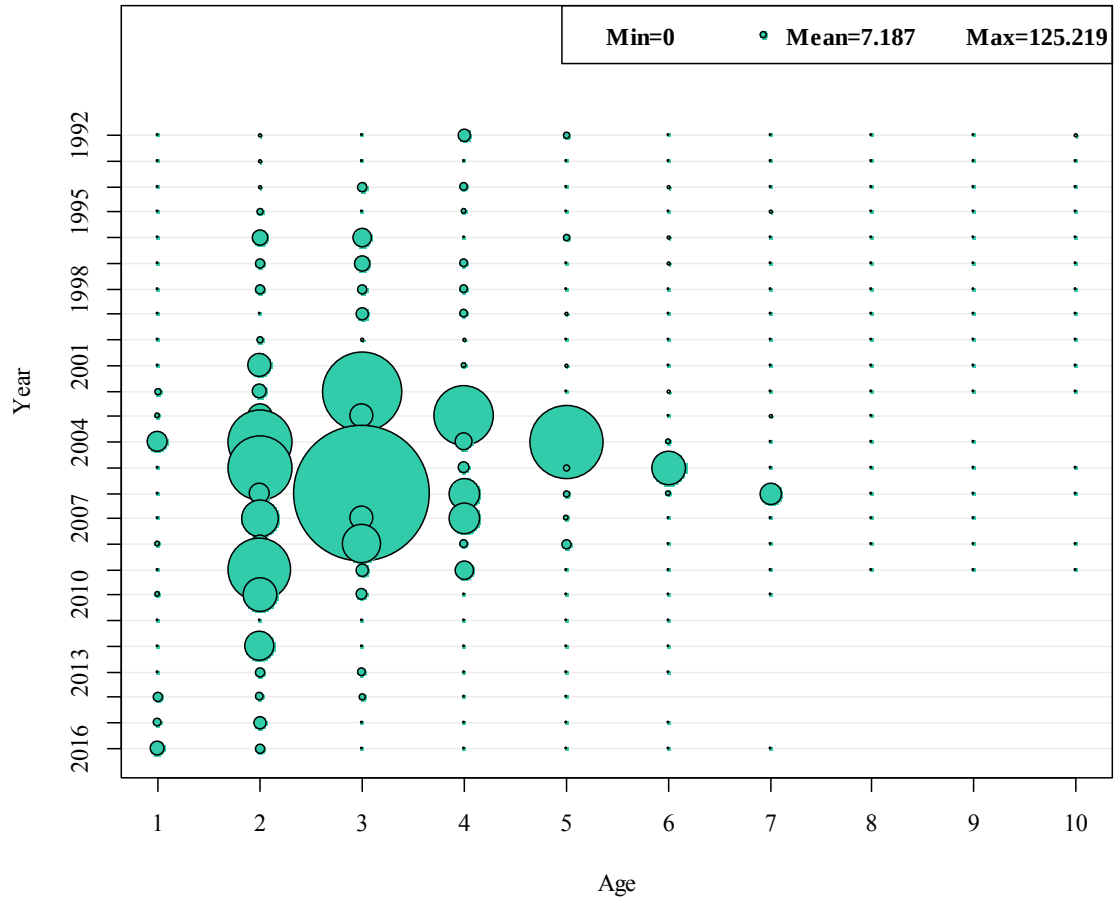


Figure A30: Atlantic mackerel U.S. commercial landings-at-age during 1992-2016.

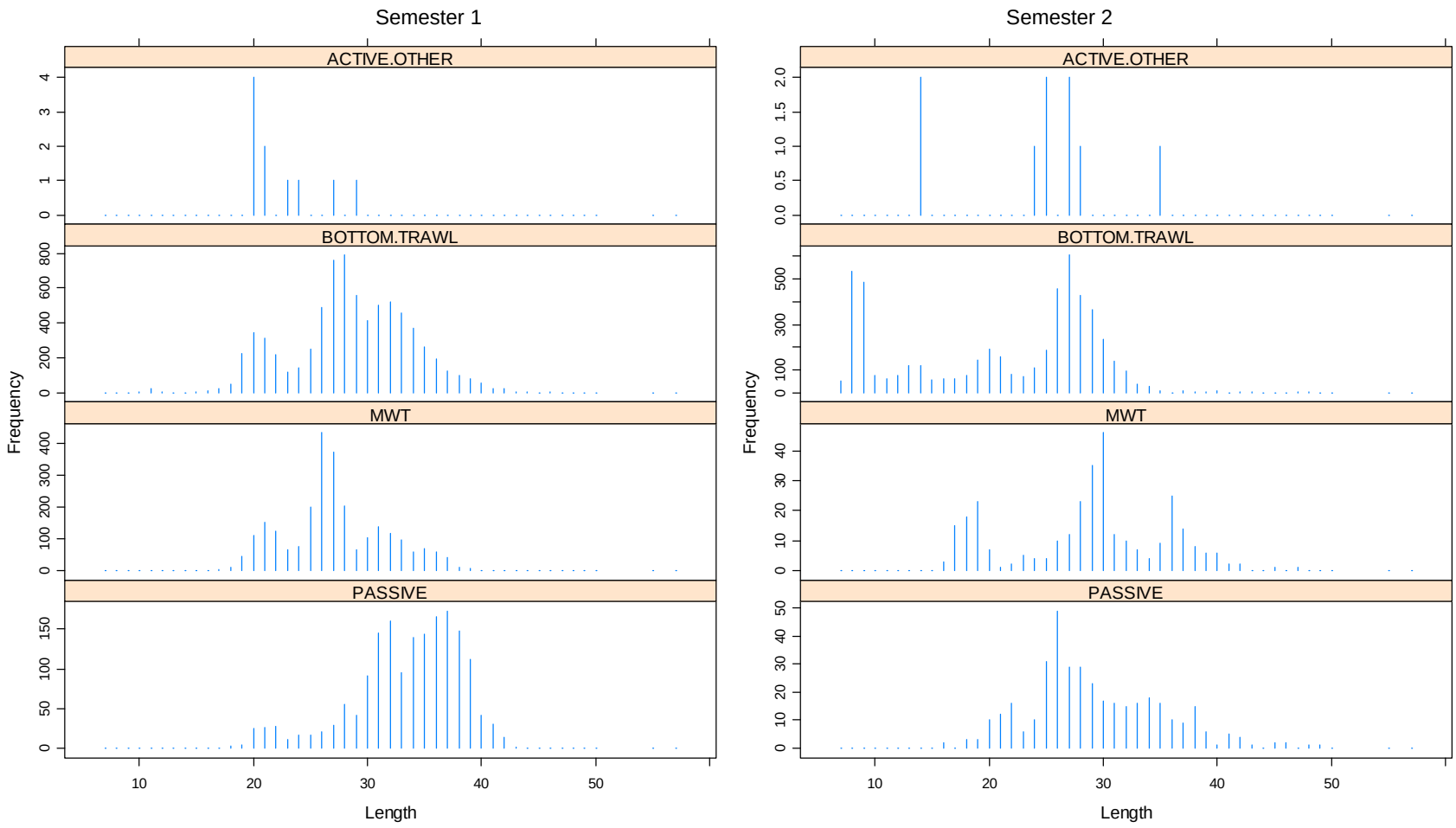


Figure A31: Length frequency distributions of U.S. commercial discards samples by gear and semester.

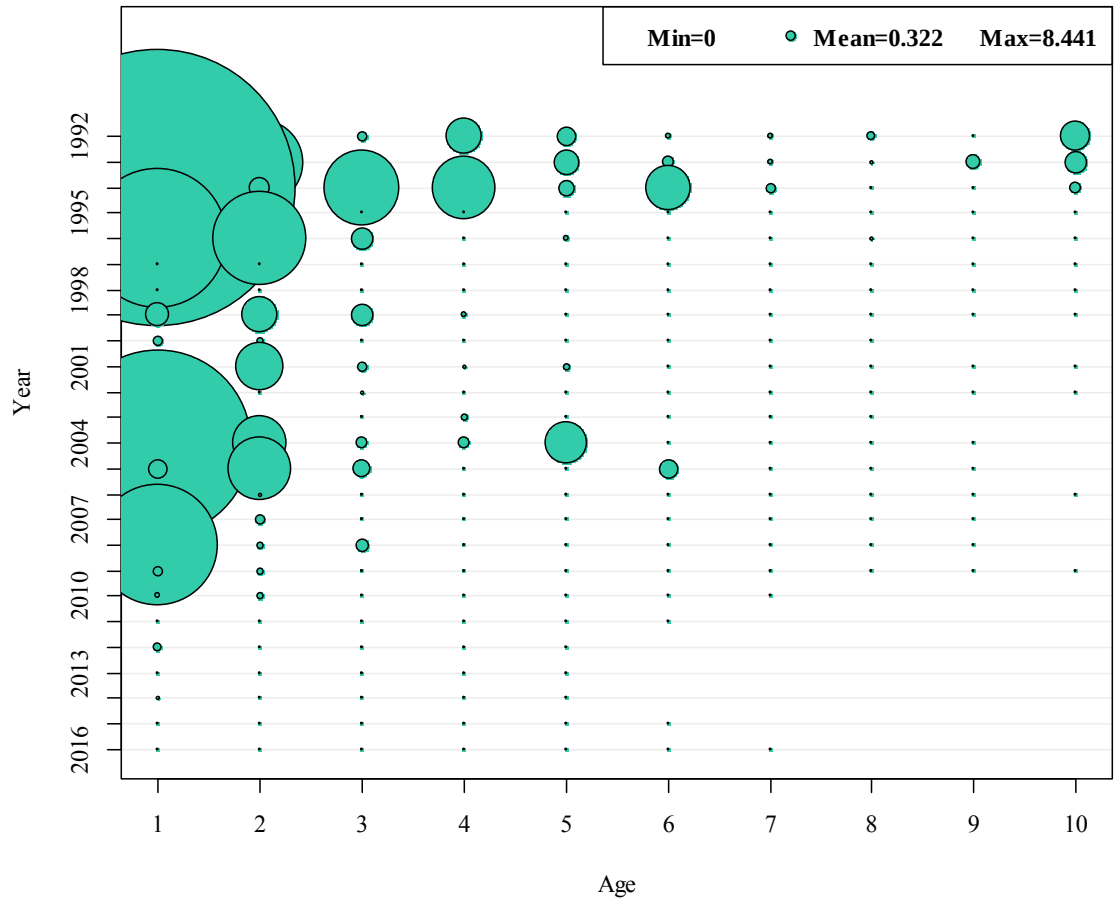


Figure A32: Atlantic mackerel U.S. commercial discards-at-age during 1992-2016.

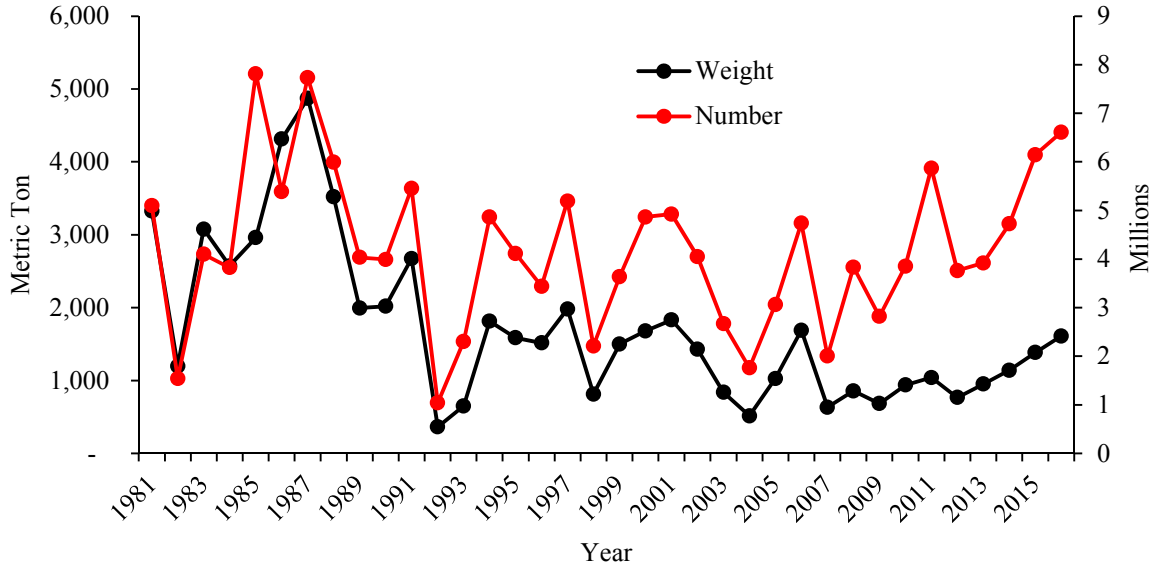


Figure A33: Total U.S. recreational catch of Atlantic mackerel in weight (mt) and number (millions of fish), 1981-2016.

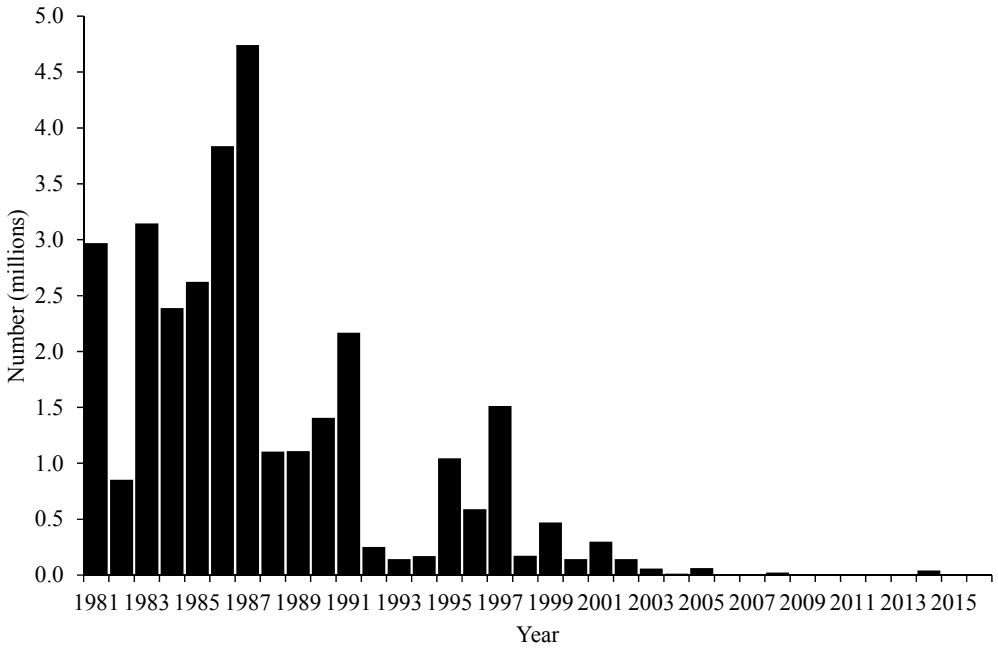


Figure A34: U.S. recreational catch (number in millions) of Atlantic mackerel from New York to Virginia, 1981-2016.

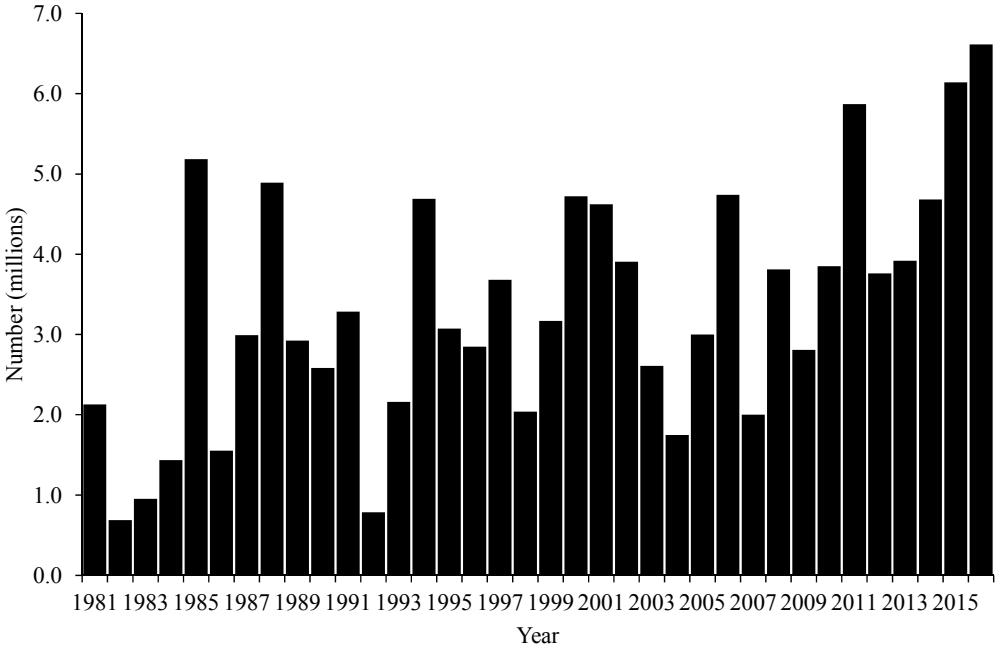


Figure A35: U.S. recreational catch (number in millions) of Atlantic mackerel from Connecticut to Maine, 1981-2016.

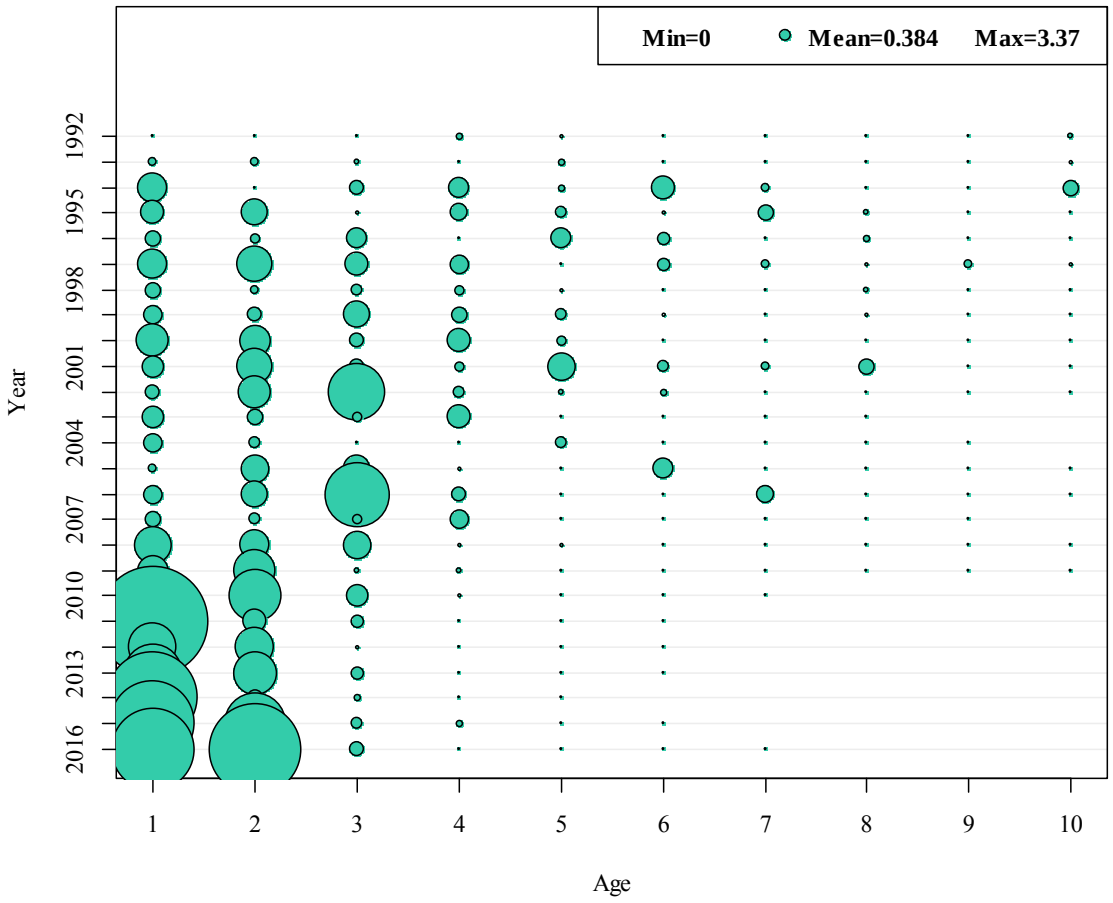


Figure A36: Atlantic mackerel U.S. recreational catch-at-age during 1992-2016.

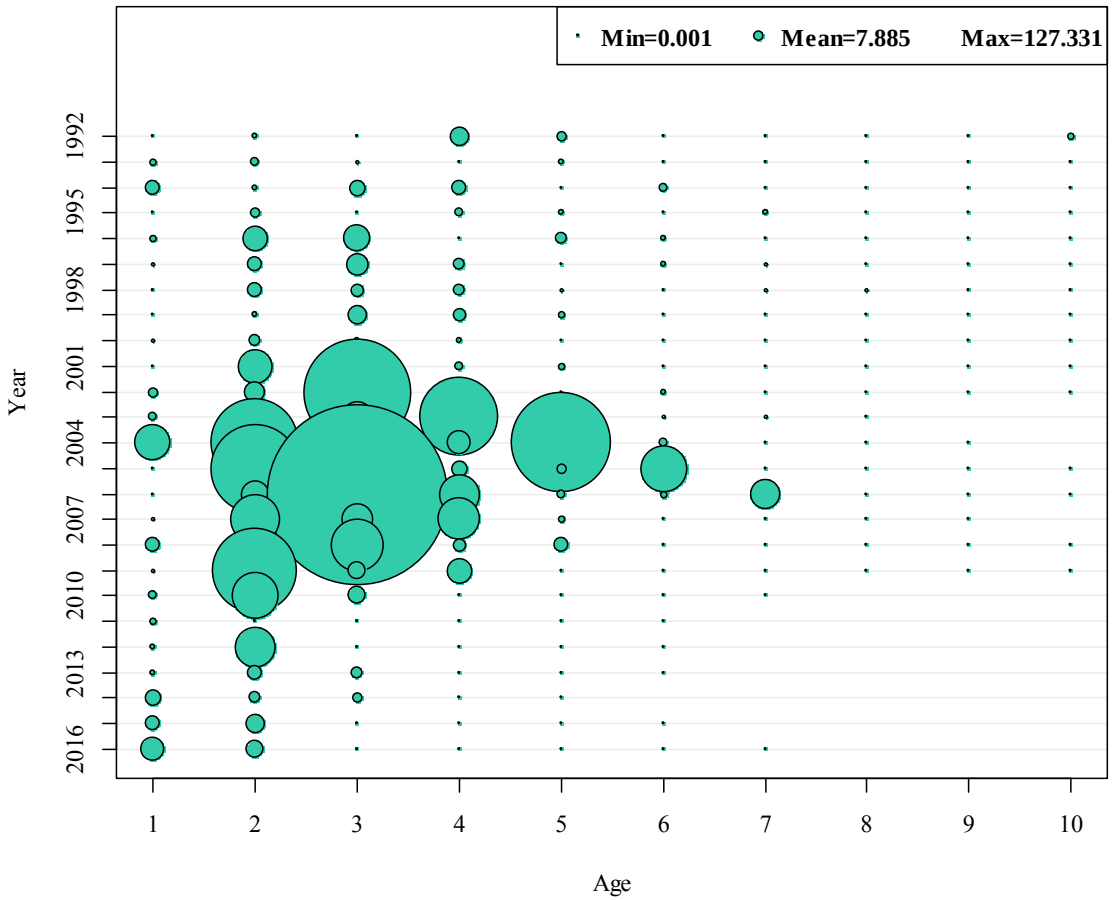


Figure A37: Total U.S. catch-at-age of Atlantic mackerel during 1992-2016.

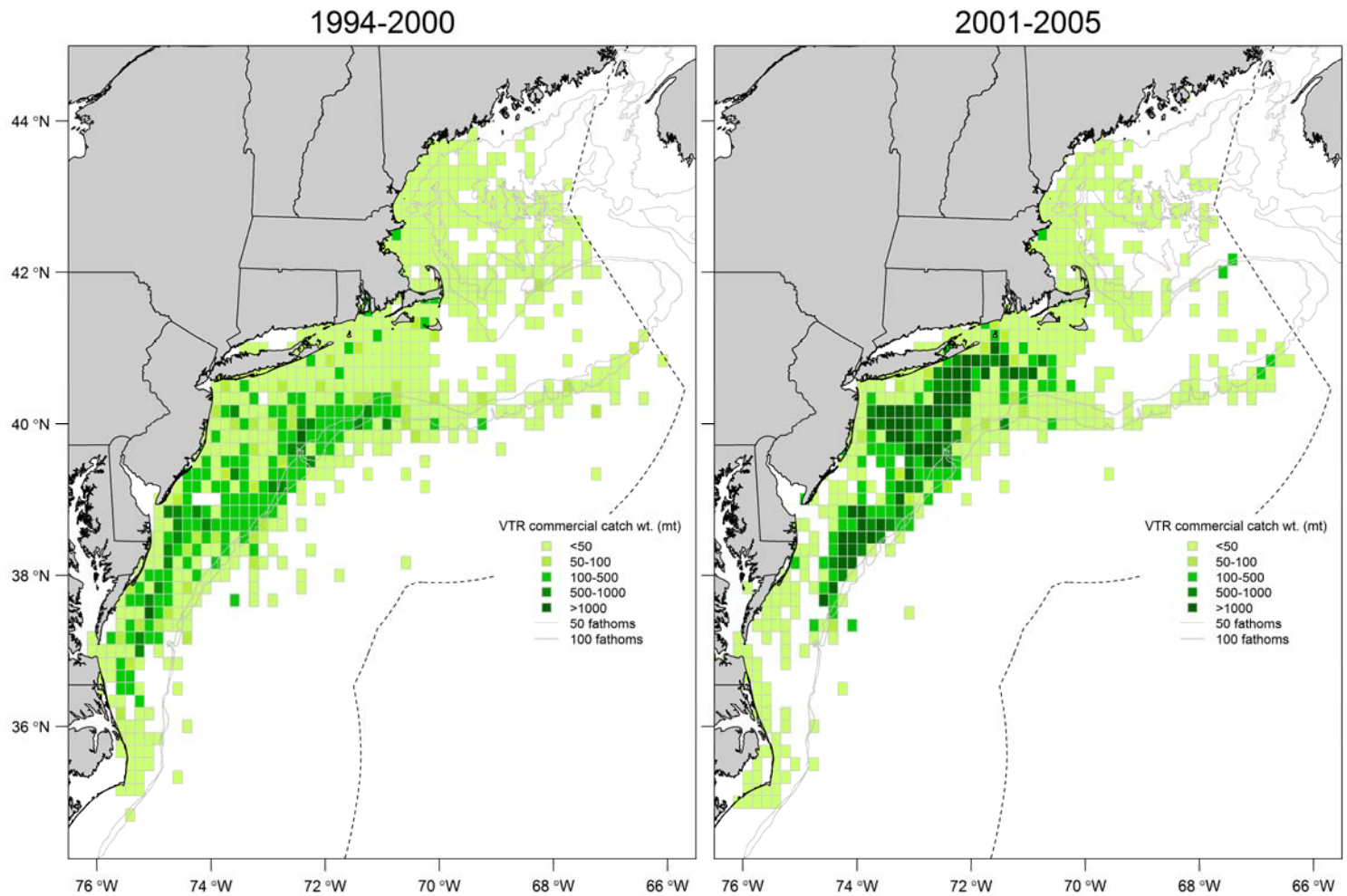


Figure A38: Atlantic mackerel catch (mt) from the VTR database during the winter/spring (January-June) semester by approximately 5-year intervals.

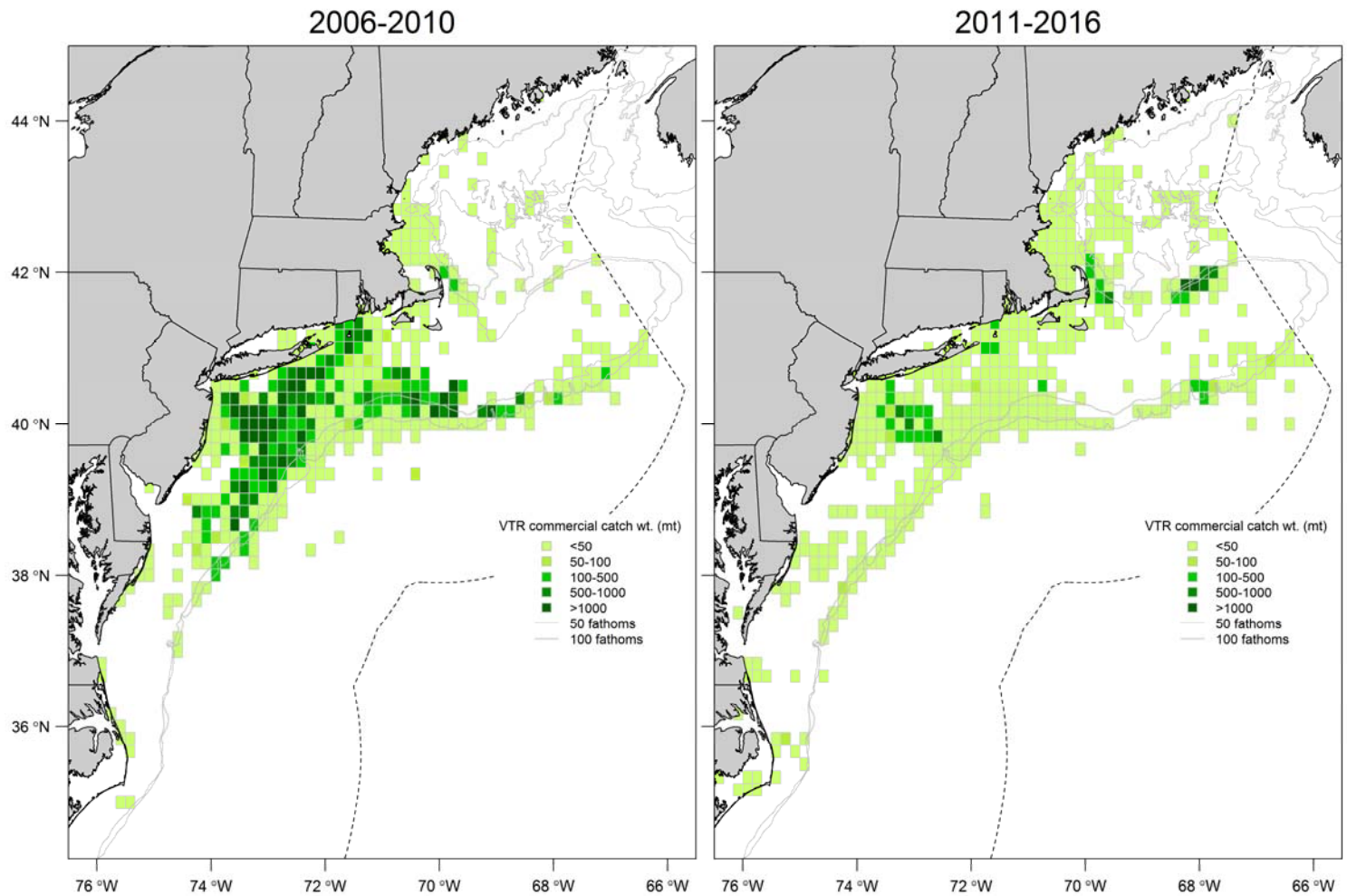


Figure A38, contd.: Atlantic mackerel catch (mt) from the VTR database during the winter/spring (January-June) semester by approximately 5-year intervals.

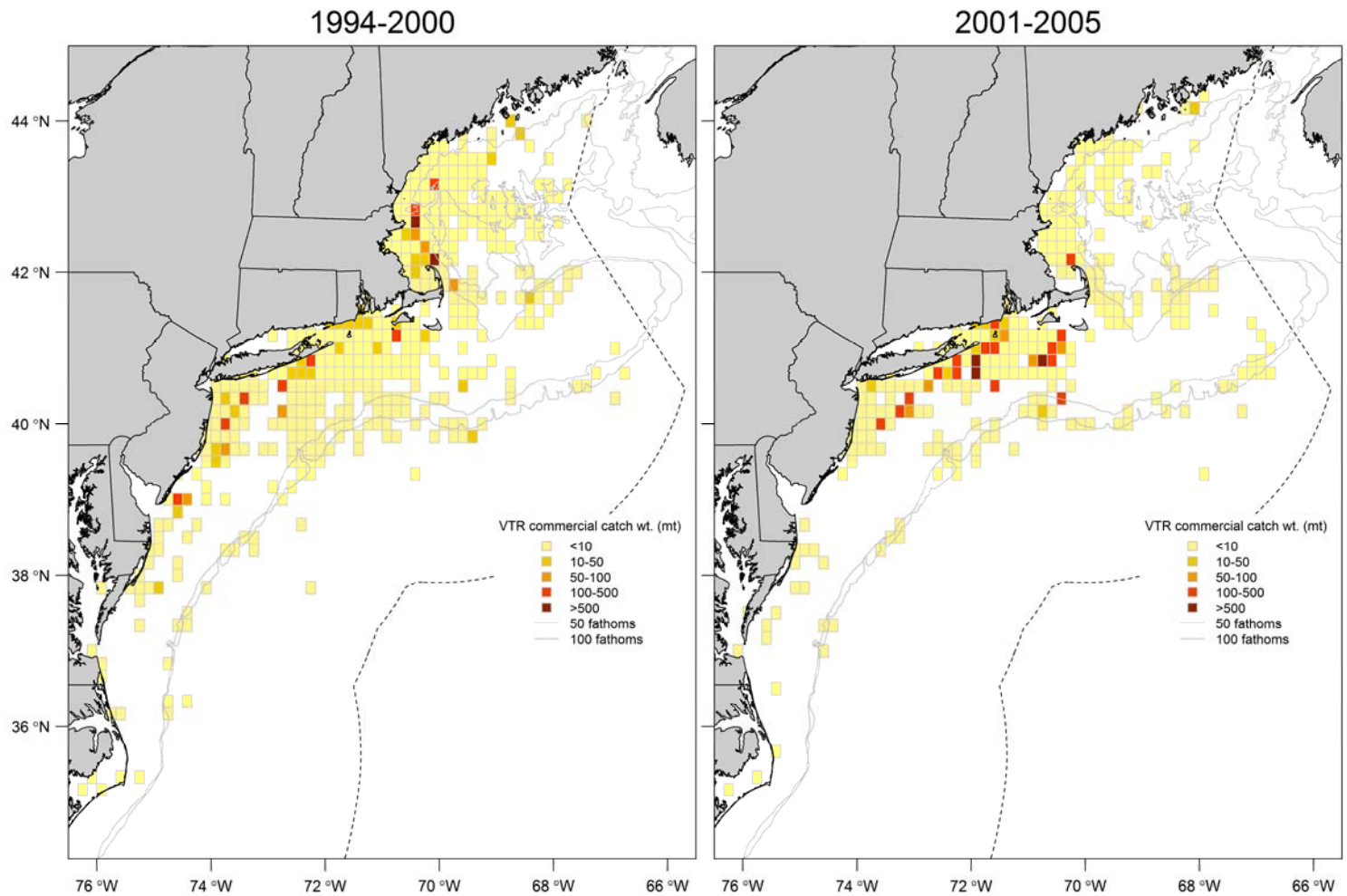


Figure A39: Atlantic mackerel catch (mt) from the VTR database during the summer/fall (July-December) semester by approximately 5-year intervals.

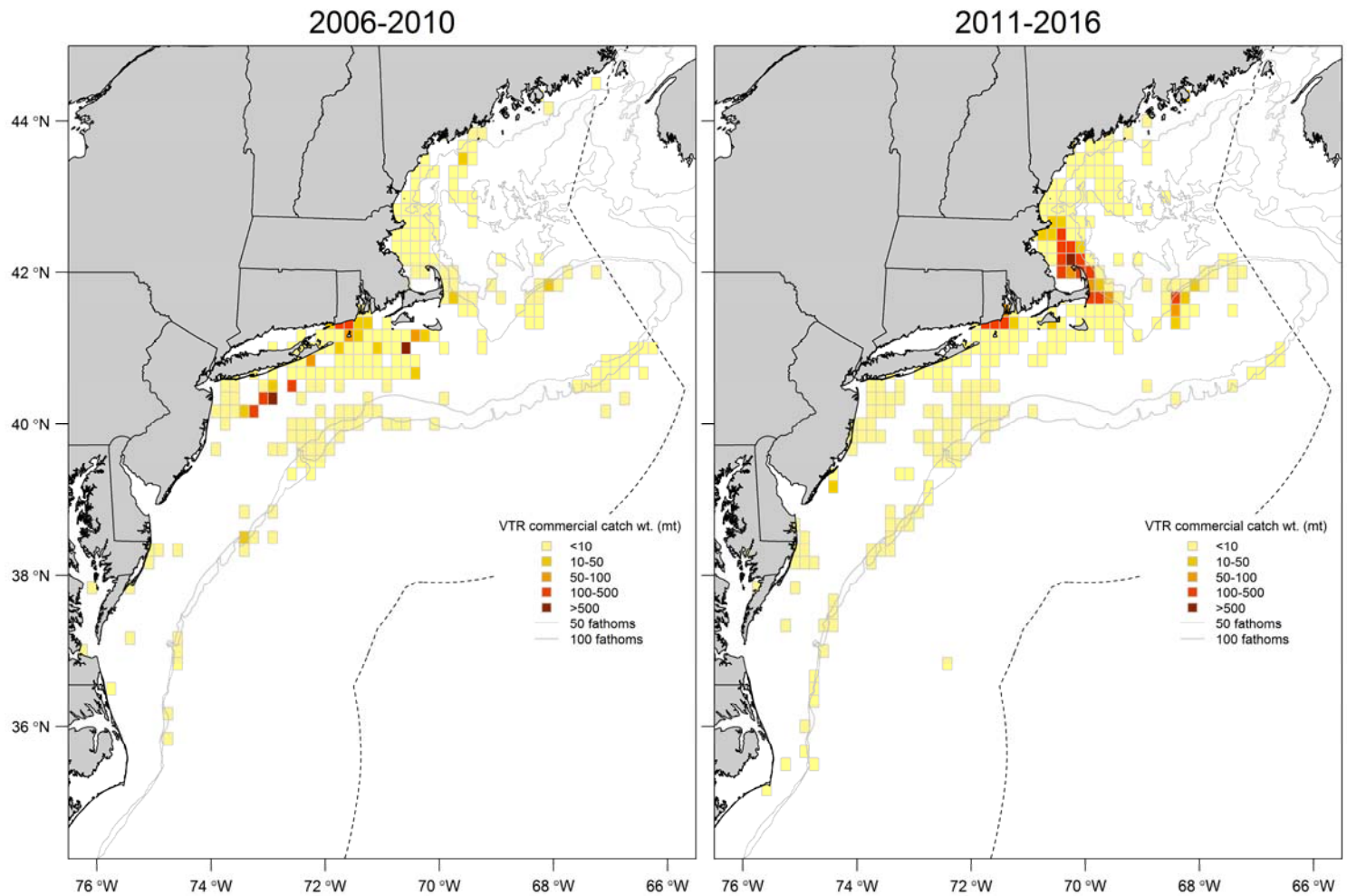


Figure A39 contd.: Atlantic mackerel catch (mt) from the VTR database during the summer/fall (July-December) semester by approximately 5-year intervals.

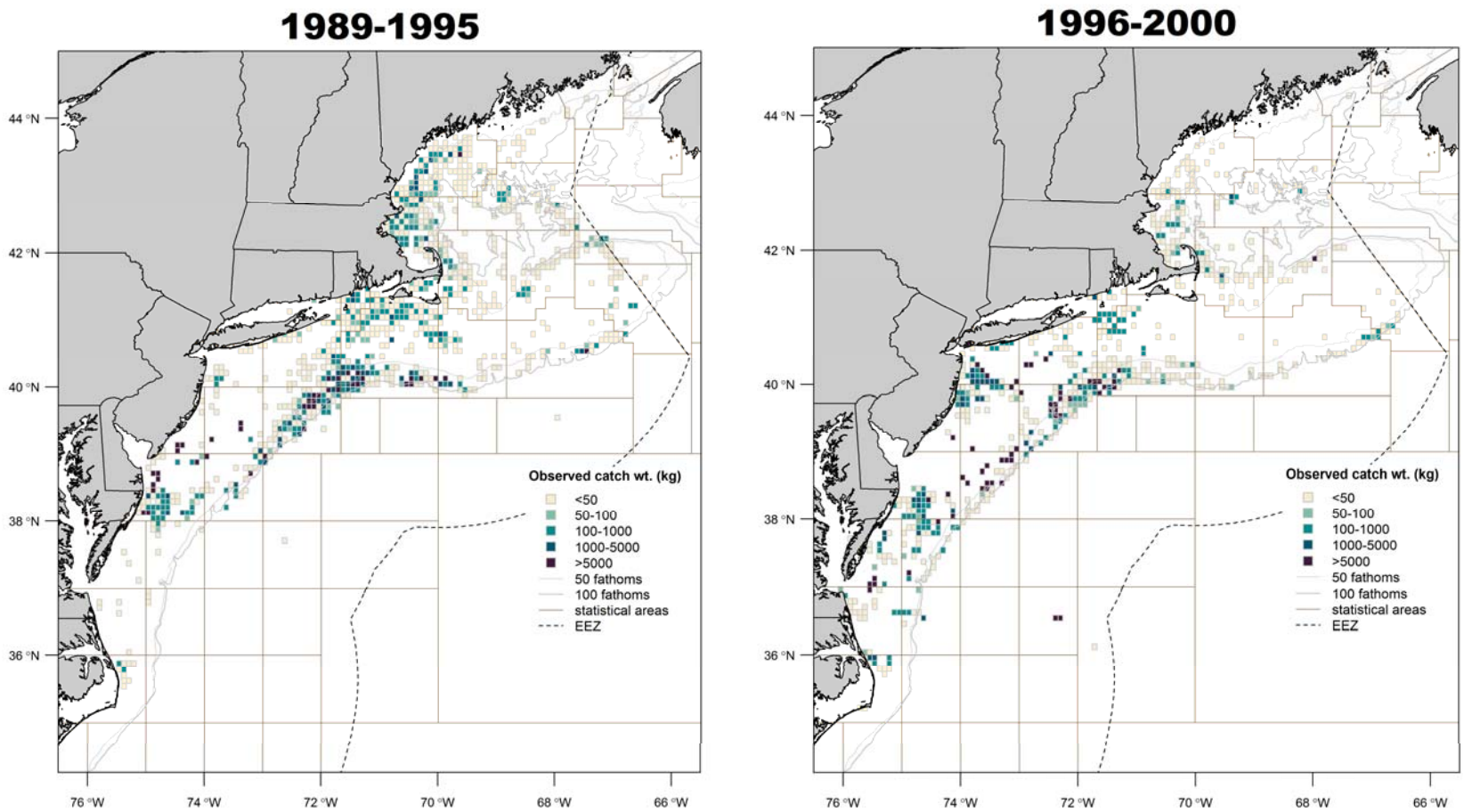


Figure A40: Total (kept and discarded) catch of Atlantic mackerel from observed trips by approximately 5-year intervals.

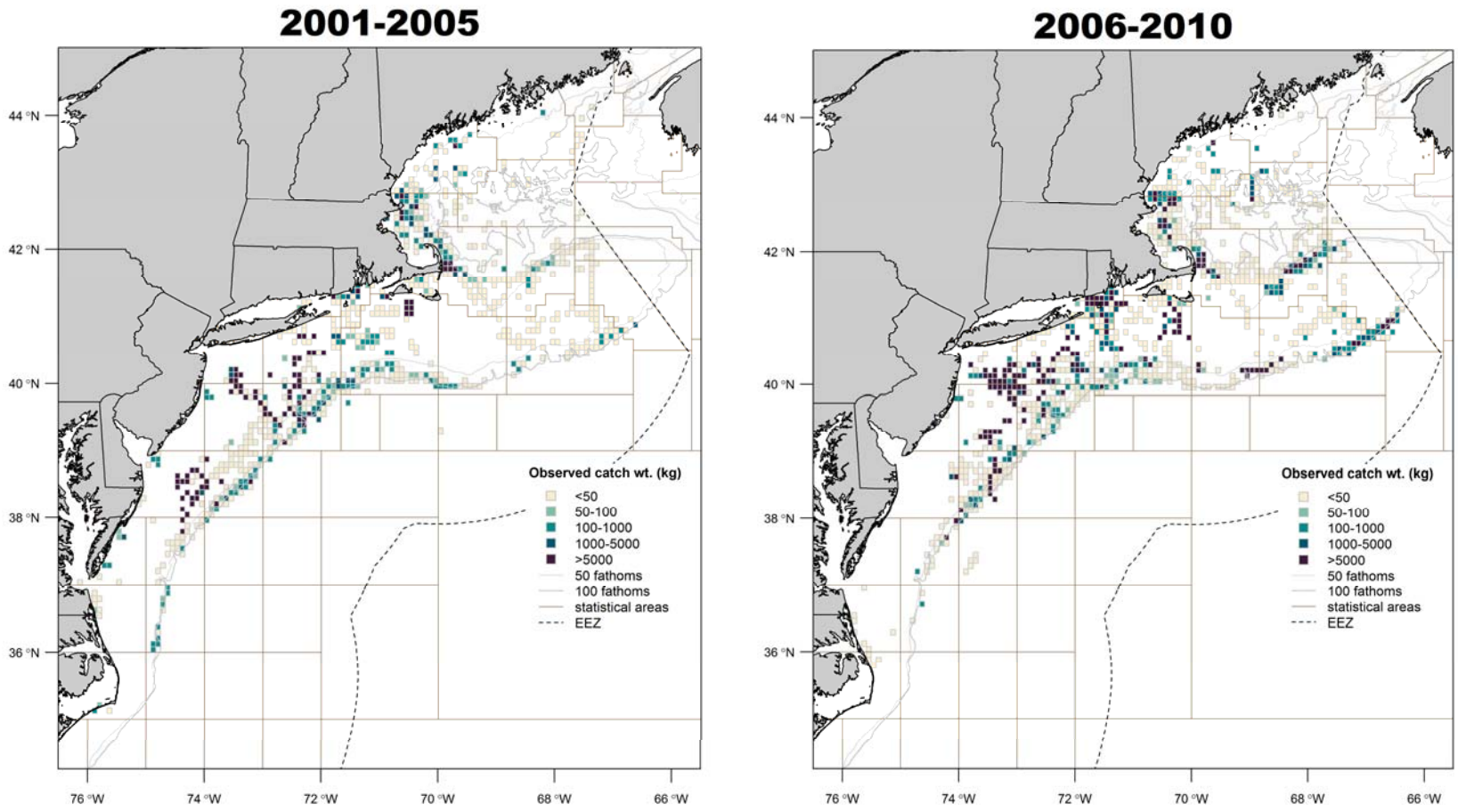


Figure A40, contd.: Total (kept and discarded) catch of Atlantic mackerel from observed trips by approximately 5-year intervals.

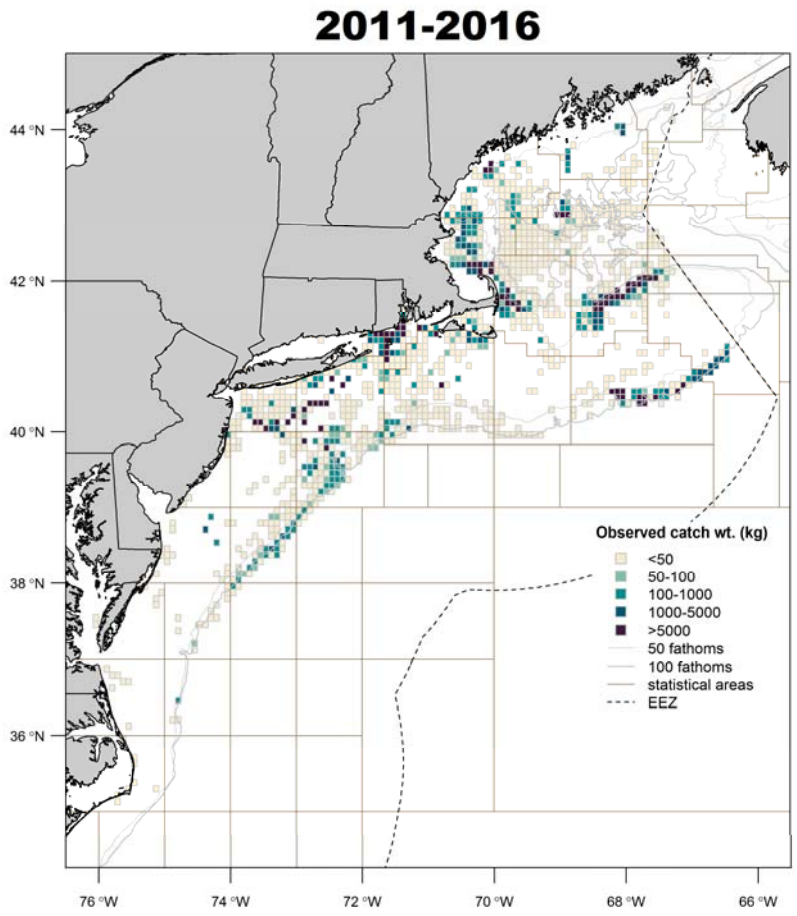


Figure A40, contd.: Total (kept and discarded) catch of Atlantic mackerel from observed trips by approximately 5-year intervals.

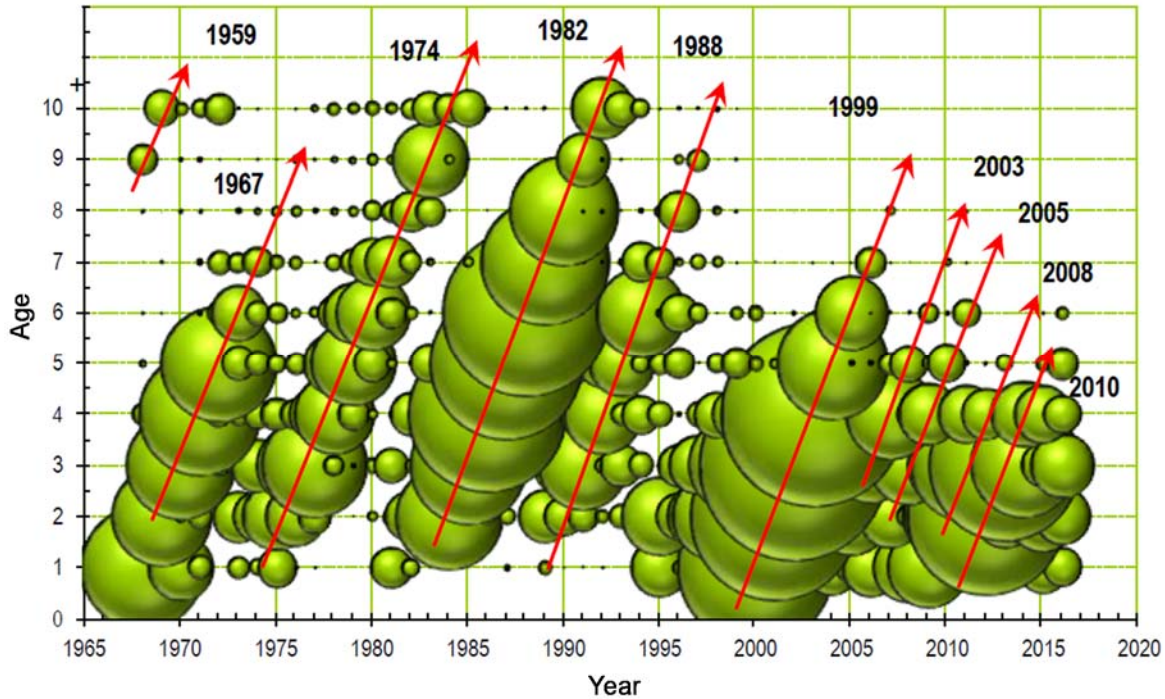


Figure A41: Total catch-at-age of Atlantic mackerel in the Canadian commercial fishery. The red arrows indicate dominant year classes and circle size is proportional to abundance. Obtained from DFO (2017).

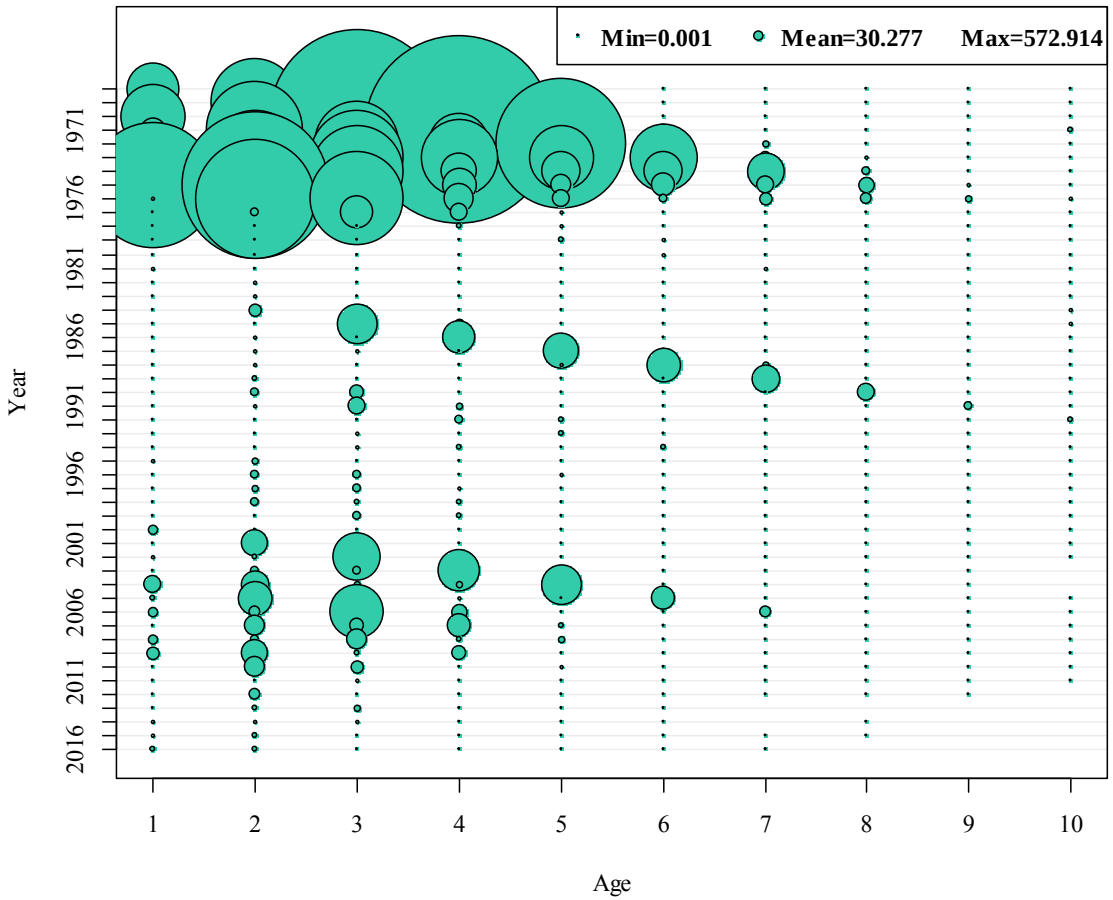


Figure A42: Total catch-at-age of Atlantic mackerel from all sources (U.S., Canadian and foreign catches) during 1968-2016.

TOR3: Fishery independent and dependent indices

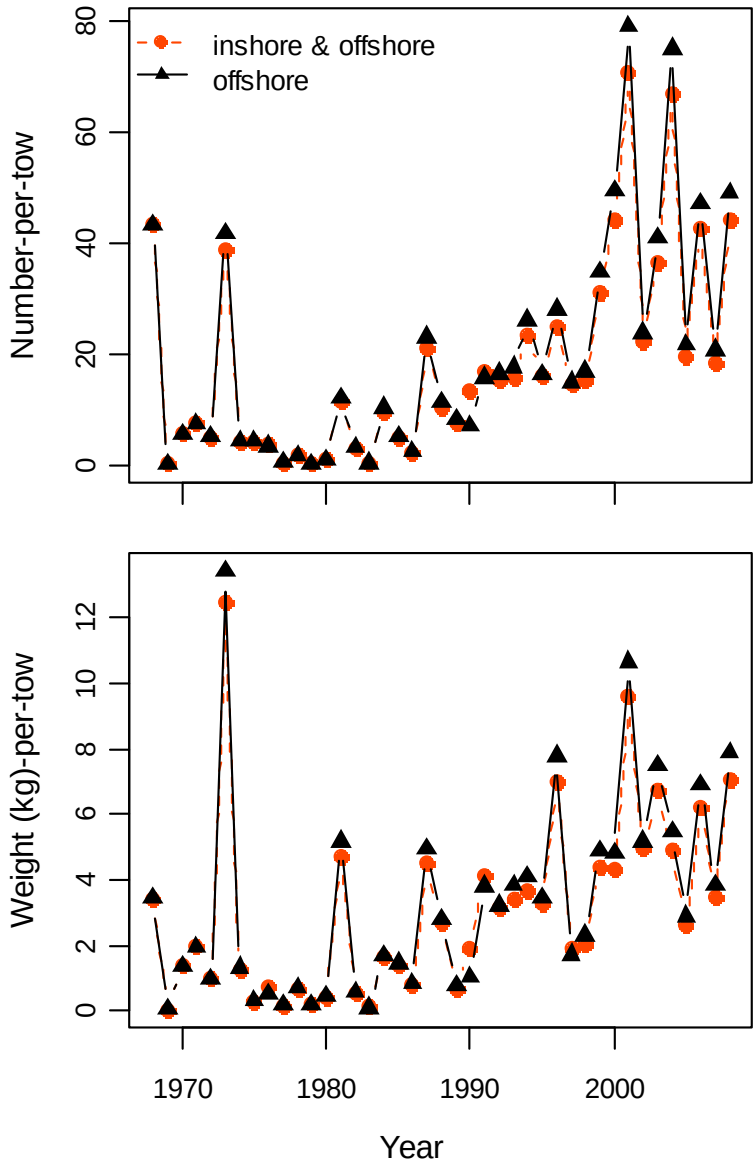


Figure A43: Atlantic mackerel stratified mean number and weight (kg) per-tow derived from the NEFSC spring bottom trawl survey for the *Albatross* years of 1968-2008 using either both inshore and offshore strata or only offshore strata.

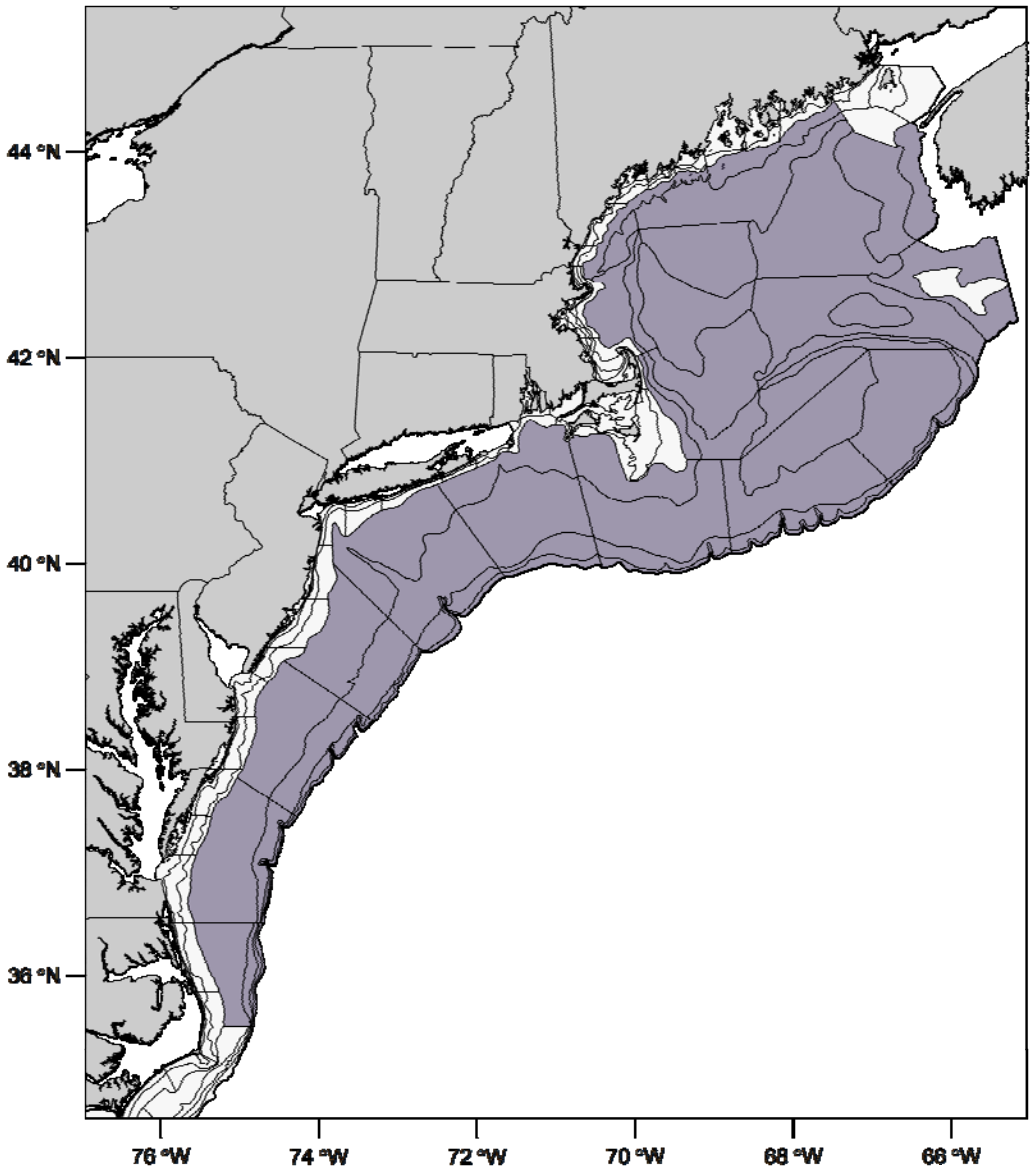


Figure A44: NEFSC bottom trawl survey offshore strata used to develop an Atlantic mackerel index of relative abundance for the *Albatross* years of 1968-2008.

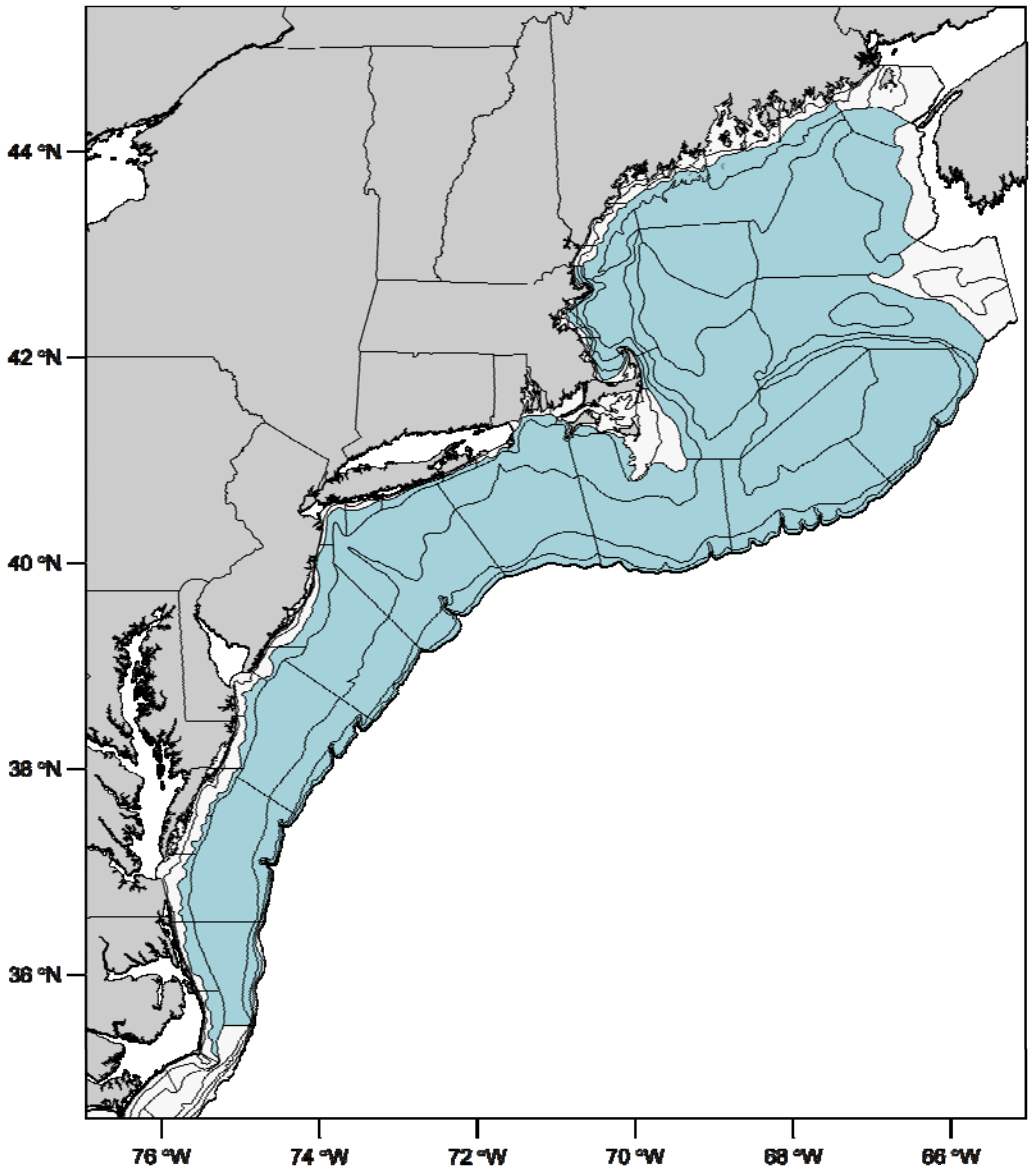


Figure A45: NEFSC bottom trawl survey strata used to develop an Atlantic mackerel index of relative abundance for the *Bigelow* years of 2009-2016.

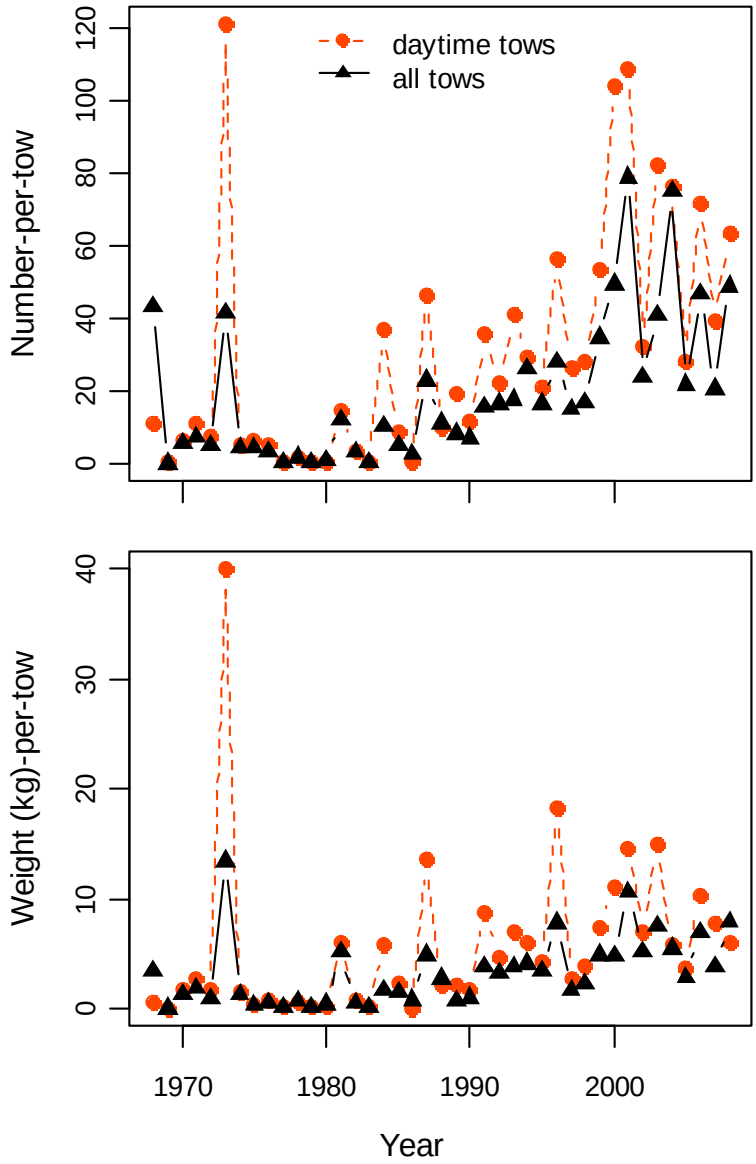


Figure A46: Atlantic mackerel stratified mean number and weight (kg) per-tow derived from the offshore strata of the NEFSC spring bottom trawl survey for the *Albatross* years of 1968-2008 using all tows or daytime only tows.

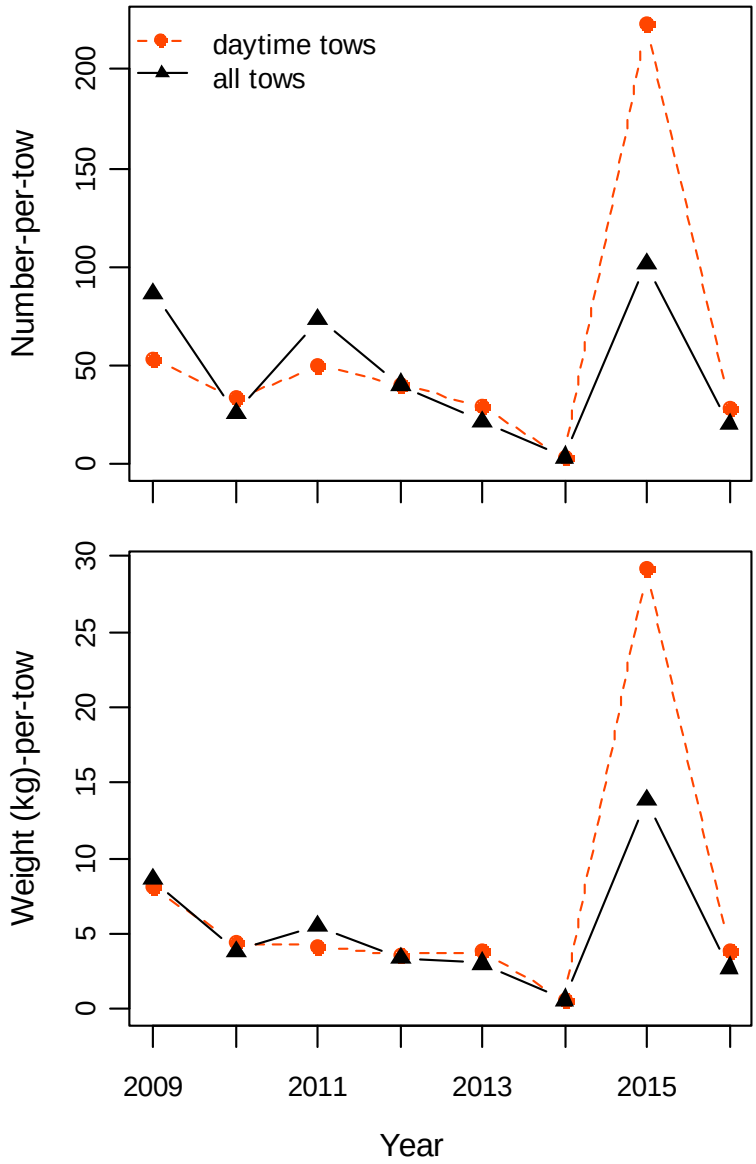


Figure A47: Atlantic mackerel stratified mean number and weight (kg) per-tow derived from the NEFSC spring bottom trawl survey for the *Bigelow* years of 2009-2016 using either both inshore and offshore strata or only offshore strata.

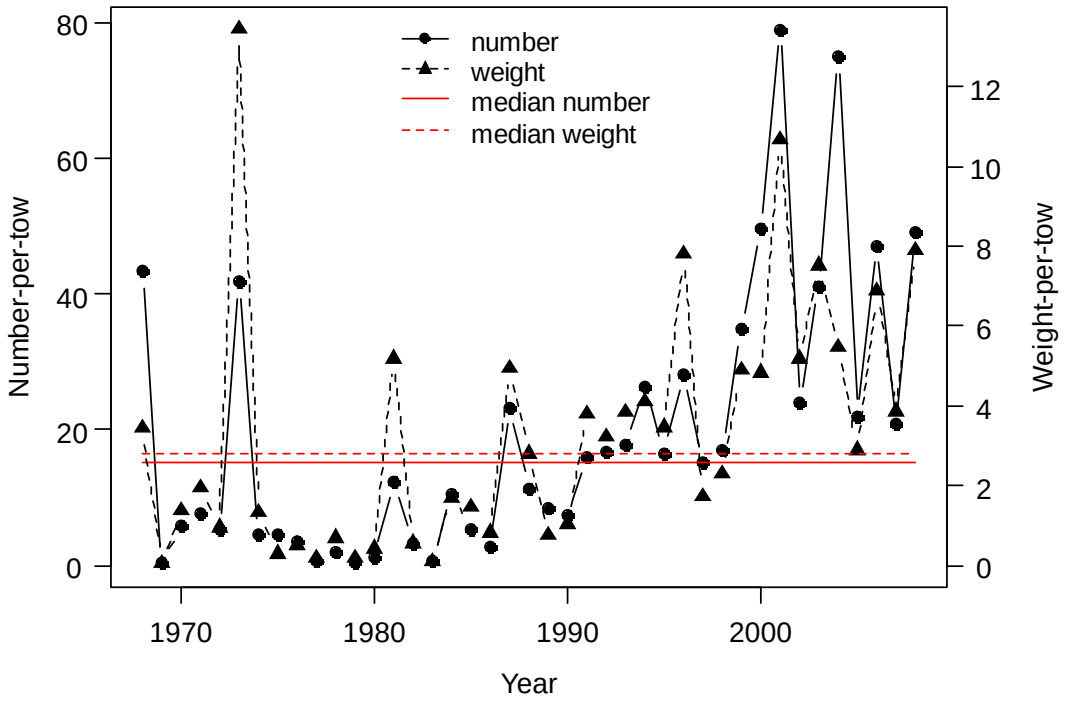


Figure A48: Atlantic mackerel relative abundance (stratified mean number-per-tow) and biomass (stratified mean kg-per-tow) indices derived from the NEFSC spring bottom trawl survey for the *Albatross* years of 1968-2008. The median number- and weight-per-tow values represent the median indices over 1968-2008.

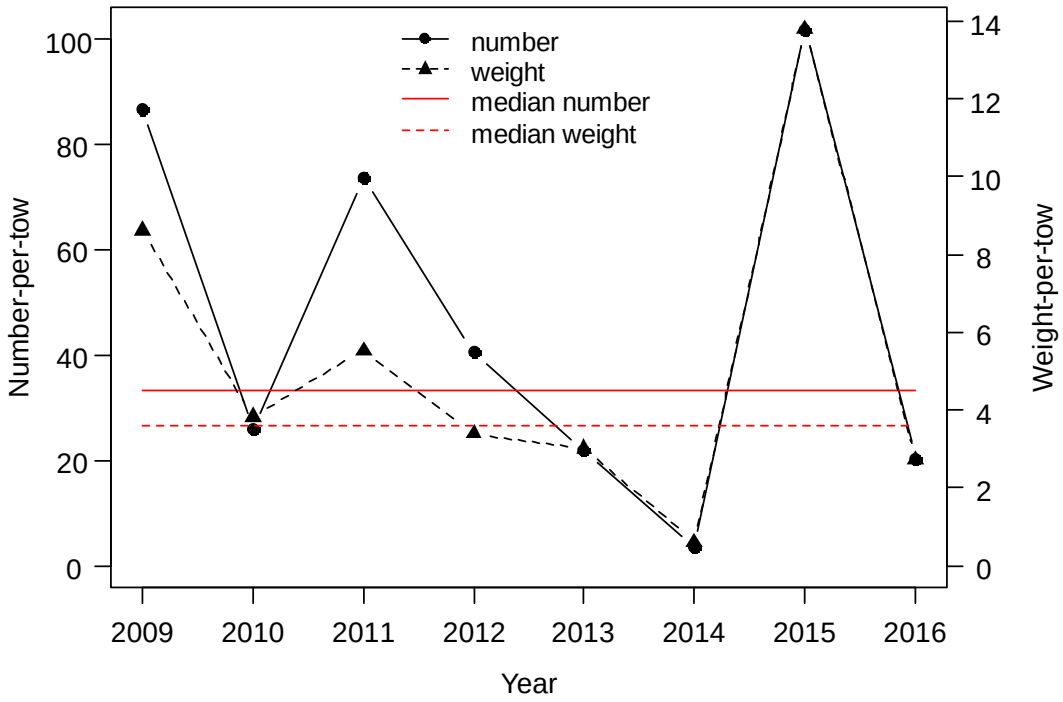


Figure A49: Atlantic mackerel relative abundance (stratified mean number-per-tow) and biomass (stratified mean kg-per-tow) indices derived from the NEFSC spring bottom trawl survey for the *Bigelow* years of 2009-2016. The median number- and weight-per-tow values represent the median indices over 2009-2016.

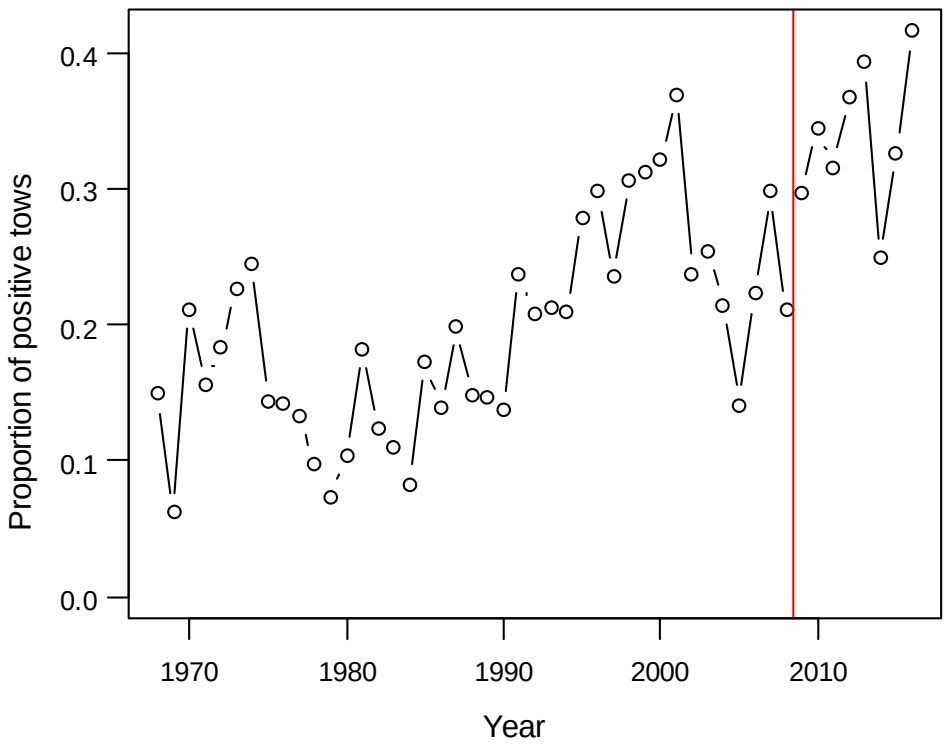


Figure A50: The proportion of tows that captured mackerel in each spring survey cruise from 1968-2016. The vertical red line marks the transition from the *RV Albatross IV* to the *RV H.B. Bigelow*.

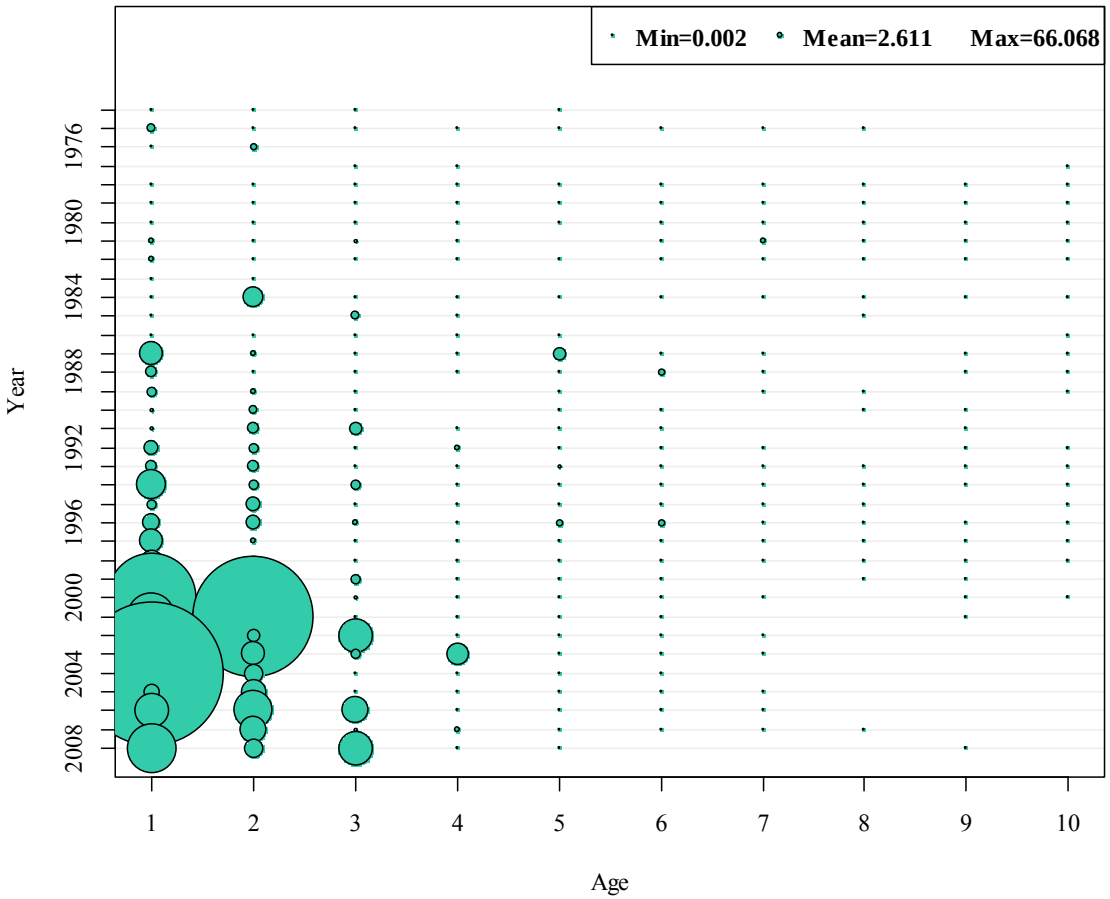


Figure A51: Atlantic mackerel catch-at-age in the NEFSC spring survey for the *Albatross* years of 1968-2008.

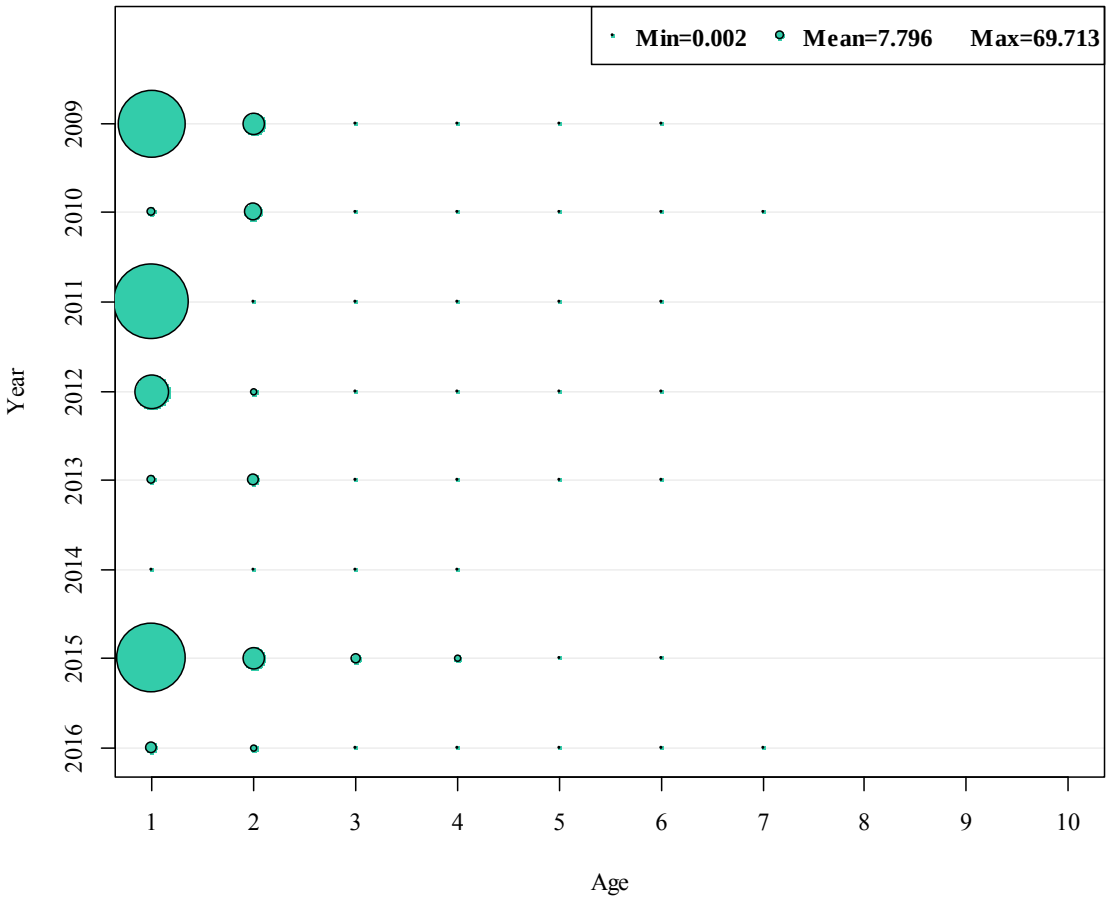


Figure A52: Atlantic mackerel catch-at-age in the NEFSC spring survey for the *Bigelow* years of 2009-2016.

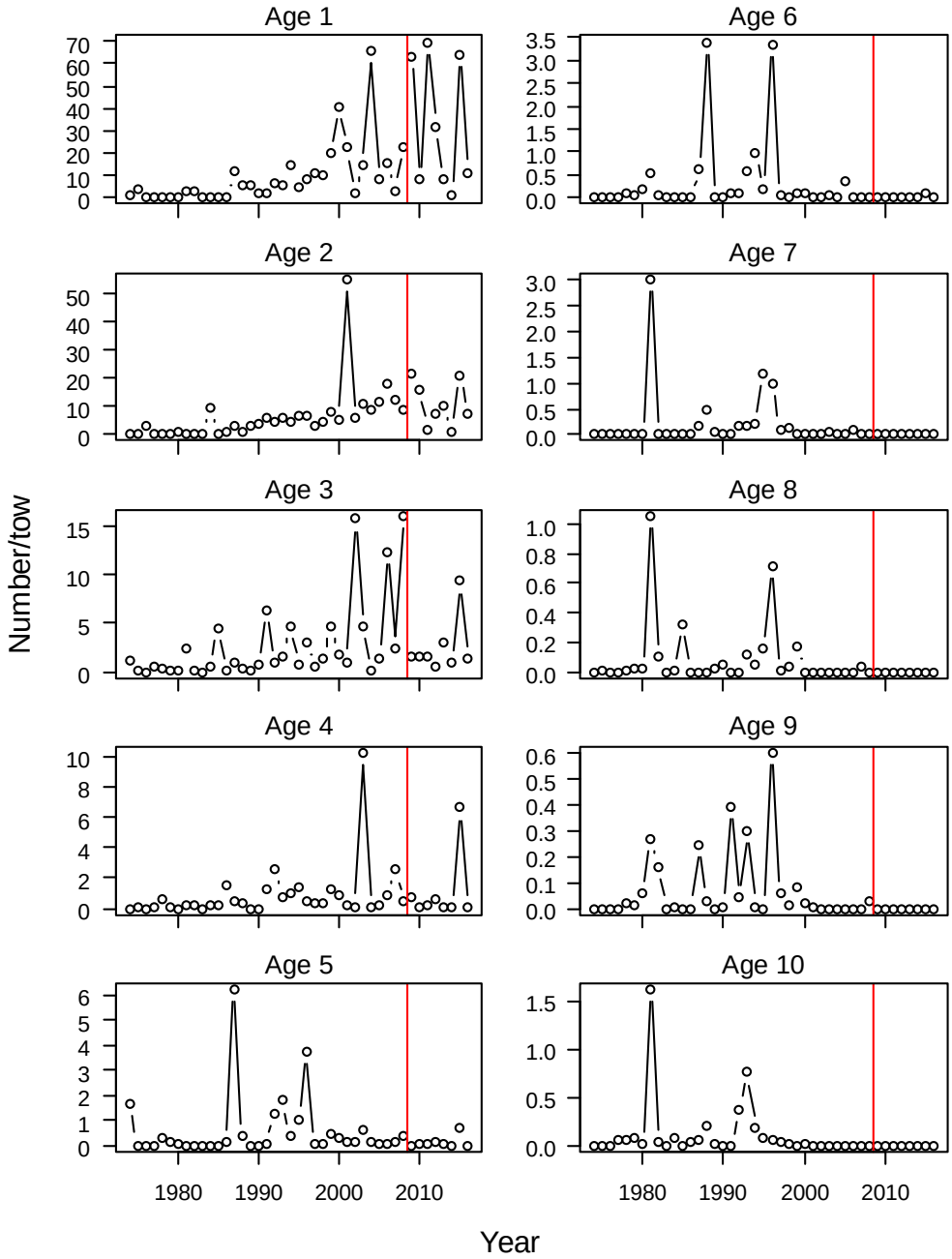


Figure A53: Age-specific relative abundance (number-per-tow) of Atlantic mackerel in the NEFSC spring survey from 1974-2016. The vertical red line marks the transition from the *Albatross IV* to the *H.B. Bigelow*.

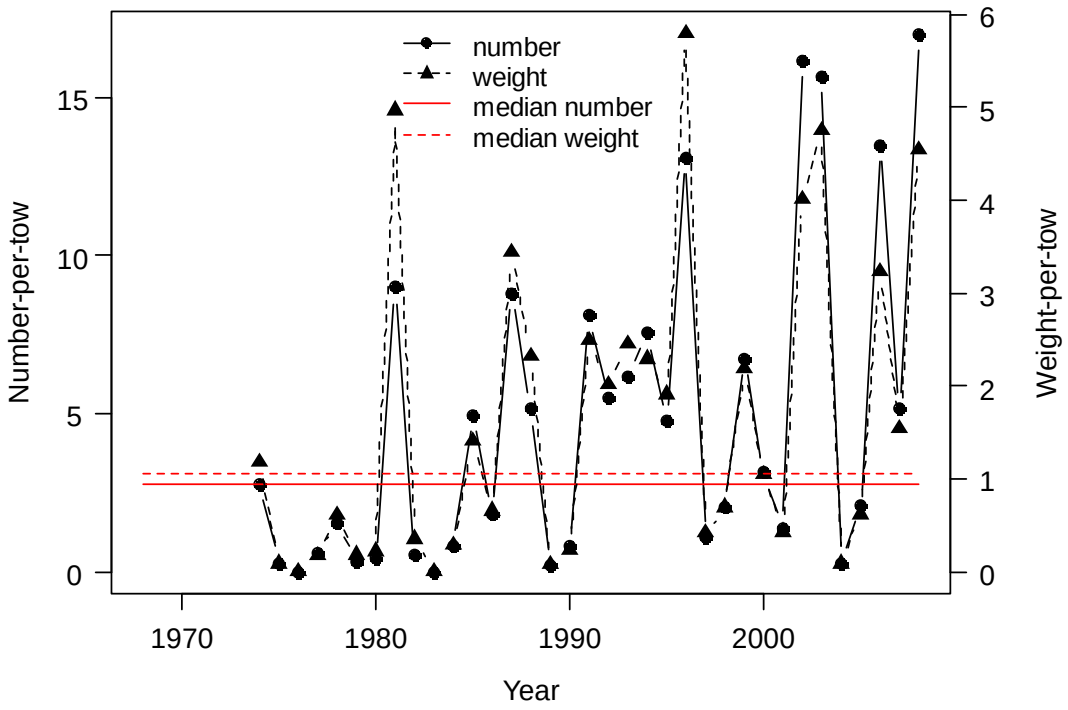


Figure A54: Atlantic mackerel relative abundance (stratified mean number-per-tow) and biomass (stratified mean kg-per-tow) indices for ages 3^+ derived from the NEFSC spring bottom trawl survey for the *Albatross* years of 1974-2008. Aggregate indices were not available for 1968-1974 because age composition data were not available. The median number- and weight-per-tow values represent the median indices over 1974-2008.

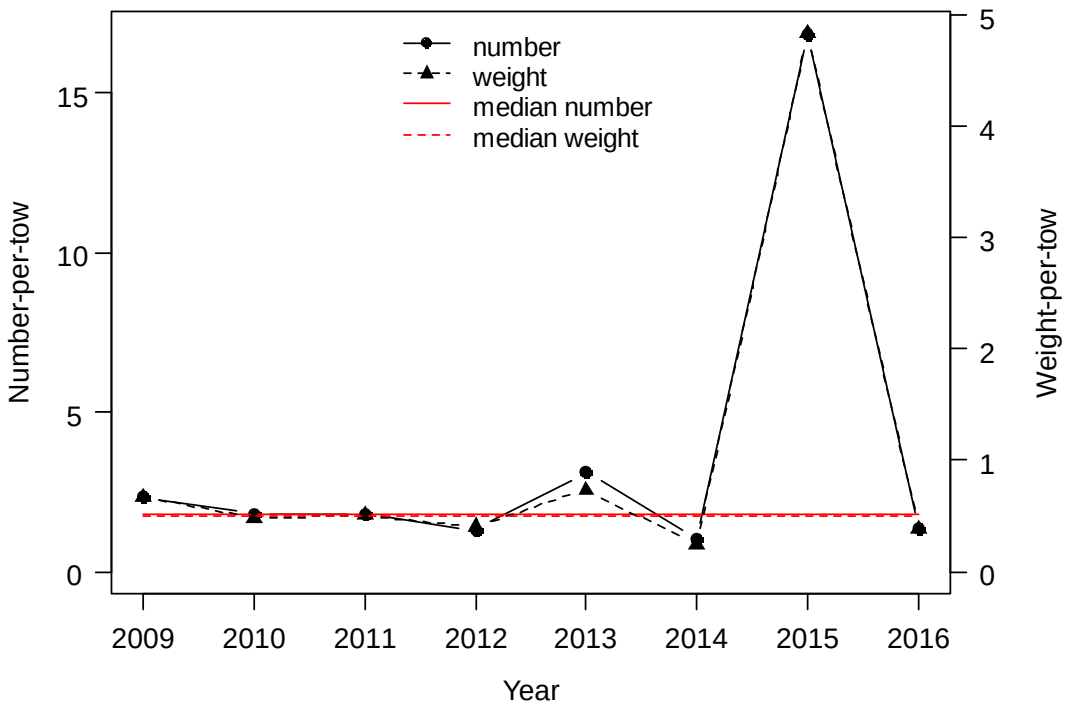


Figure A55: Atlantic mackerel relative abundance (stratified mean number-per-tow) and biomass (stratified mean kg-per-tow) indices for ages 3^+ derived from the NEFSC spring bottom trawl survey for the *Bigelow* years of 2009-2016. The median number- and weight-per-tow values represent the median indices over 2009-2016.

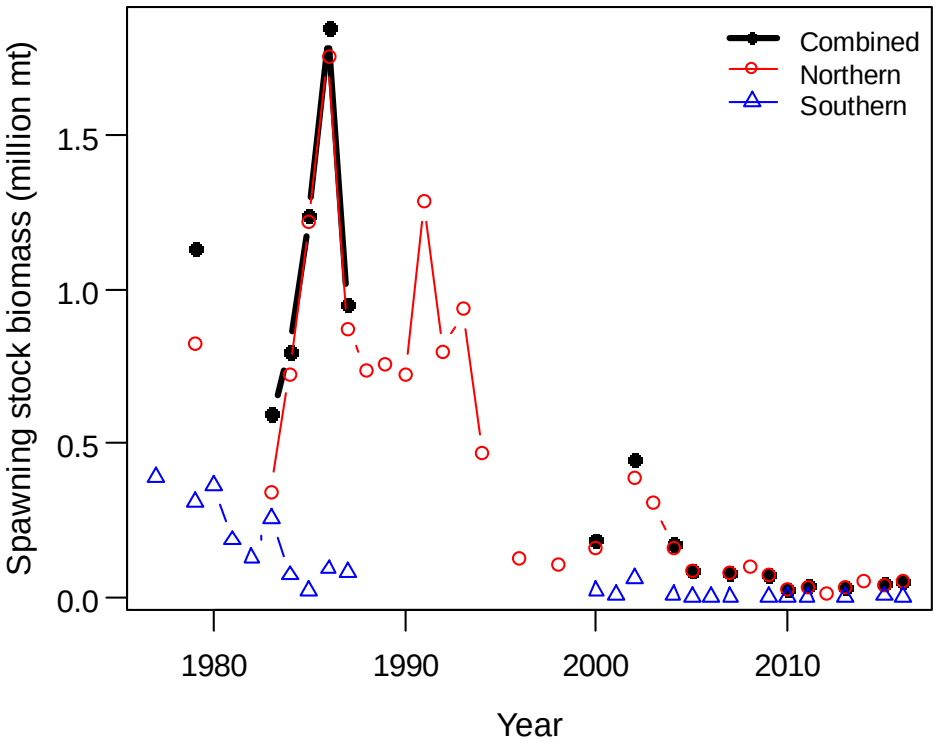


Figure A56: Atlantic mackerel spawning stock biomass index (millions metric tons) calculated using the total egg production method, based on egg densities observed in the southern Gulf of St. Lawrence (northern contingent) and the Northeast U.S. Continental Shelf (southern contingent). The combined SSB index represents the sum of northern and southern contingents and was only calculated in years where indices from both contingents were available.

TOR4: Annual fishing mortality, recruitment and stock biomass estimates

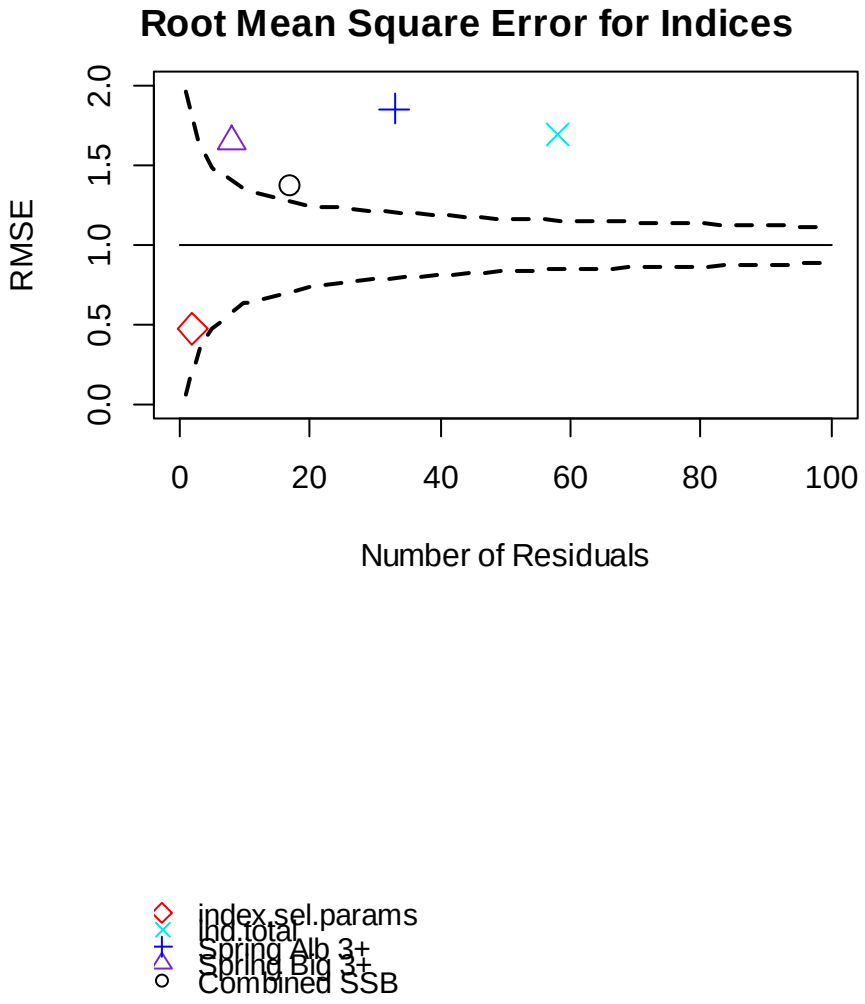


Figure A57: Final root mean square errors (RMSE) for each index included in the final ASAP model.

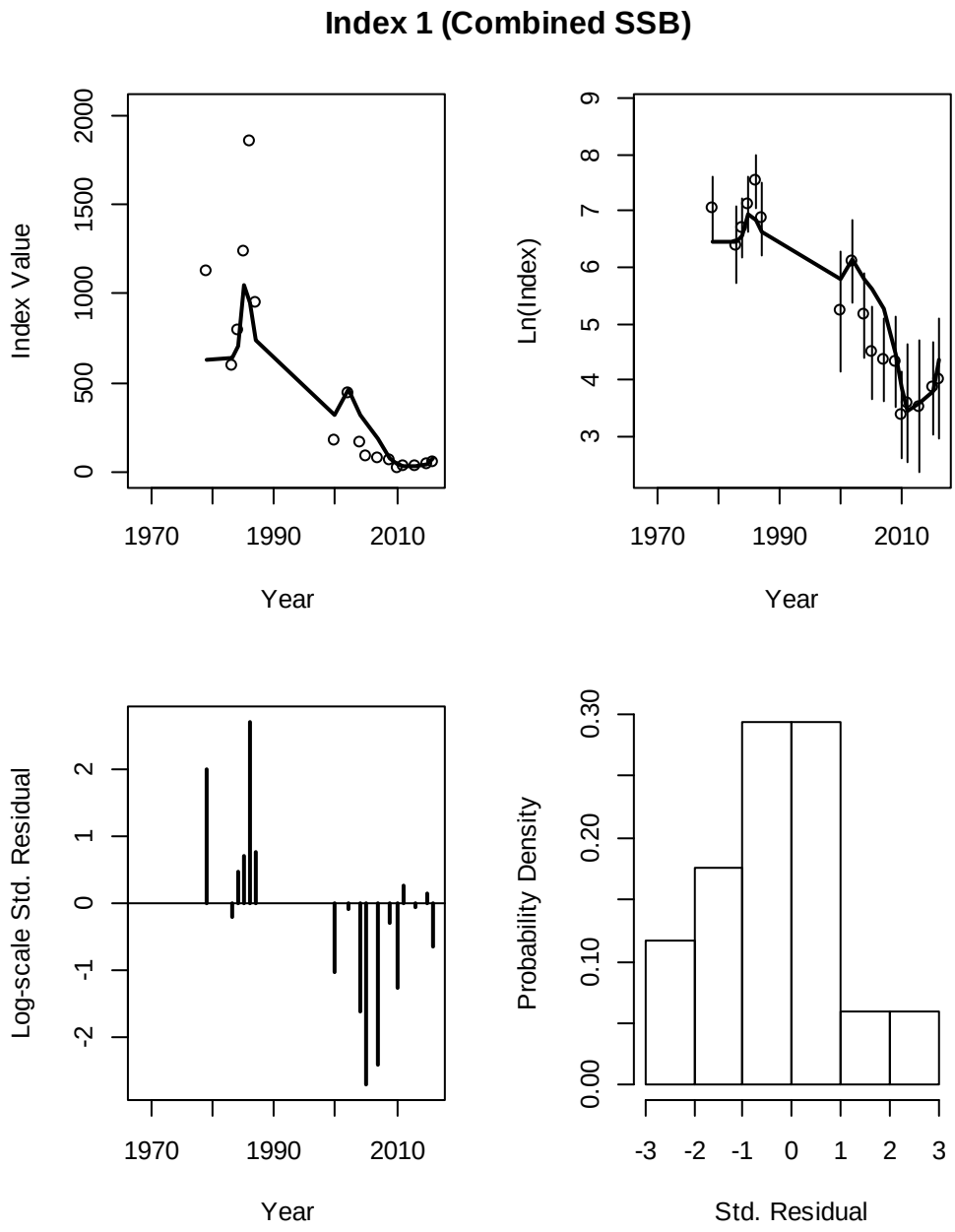


Figure A58: Fit diagnostics for the range-wide SSB index in the final ASAP model.

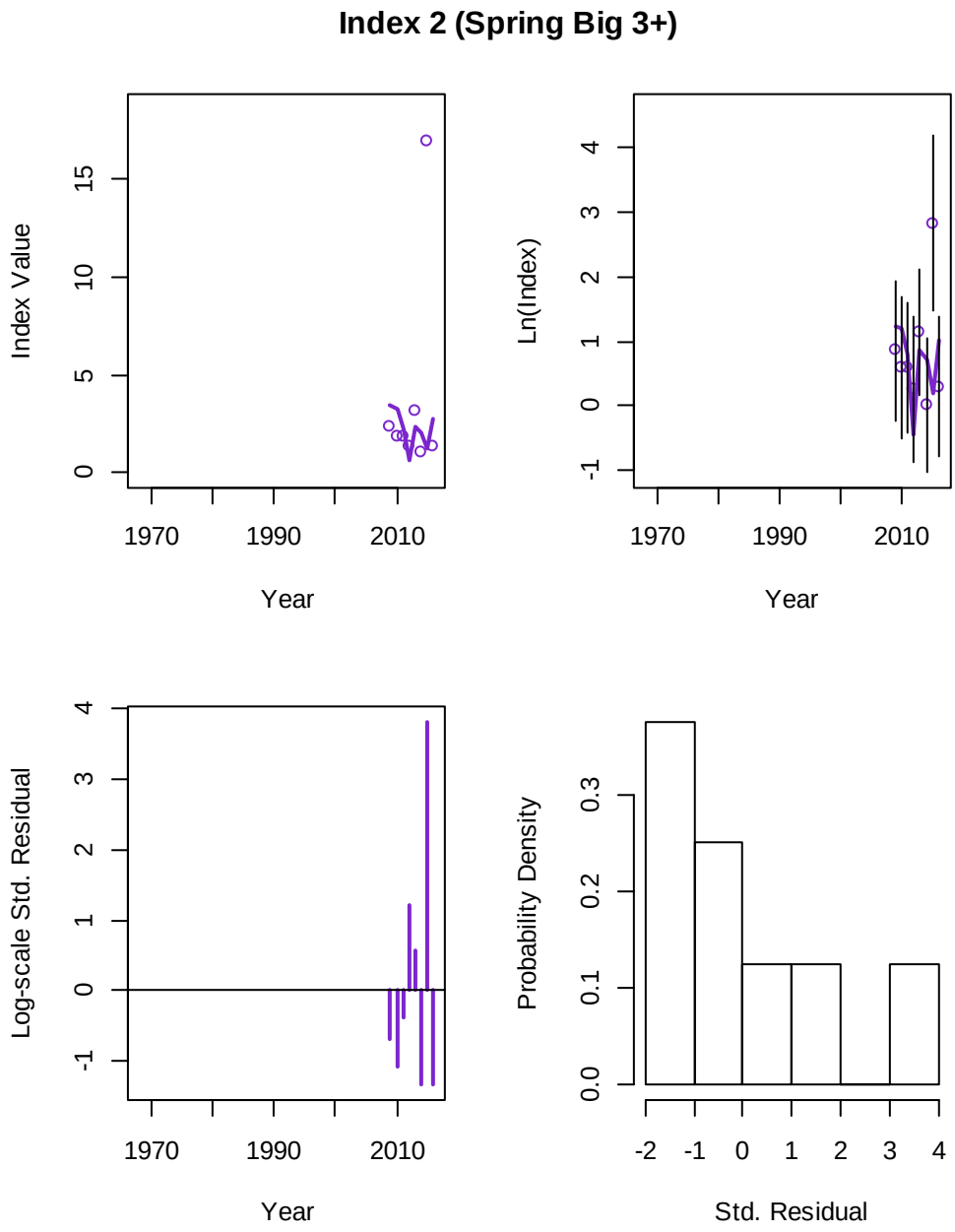


Figure A59: Fit diagnostics for the *Bigelow* years of the NEFSC spring bottom trawl survey (number/tow for ages-3^+) in the final ASAP model.

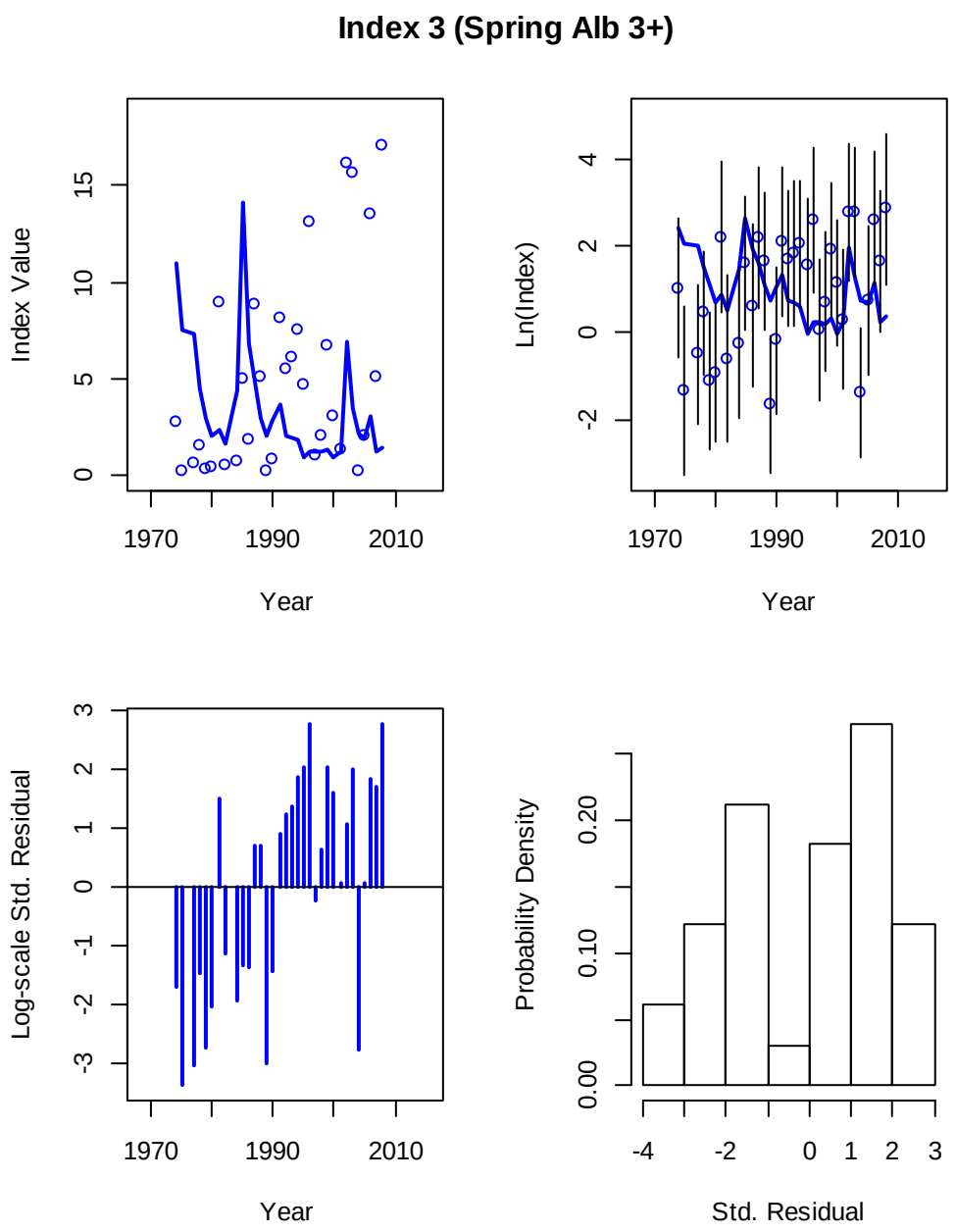


Figure A60: Fit diagnostics for the *Albatross* years of the NEFSC spring bottom trawl survey (number/tow for ages-3^{+}) in the final ASAP model.

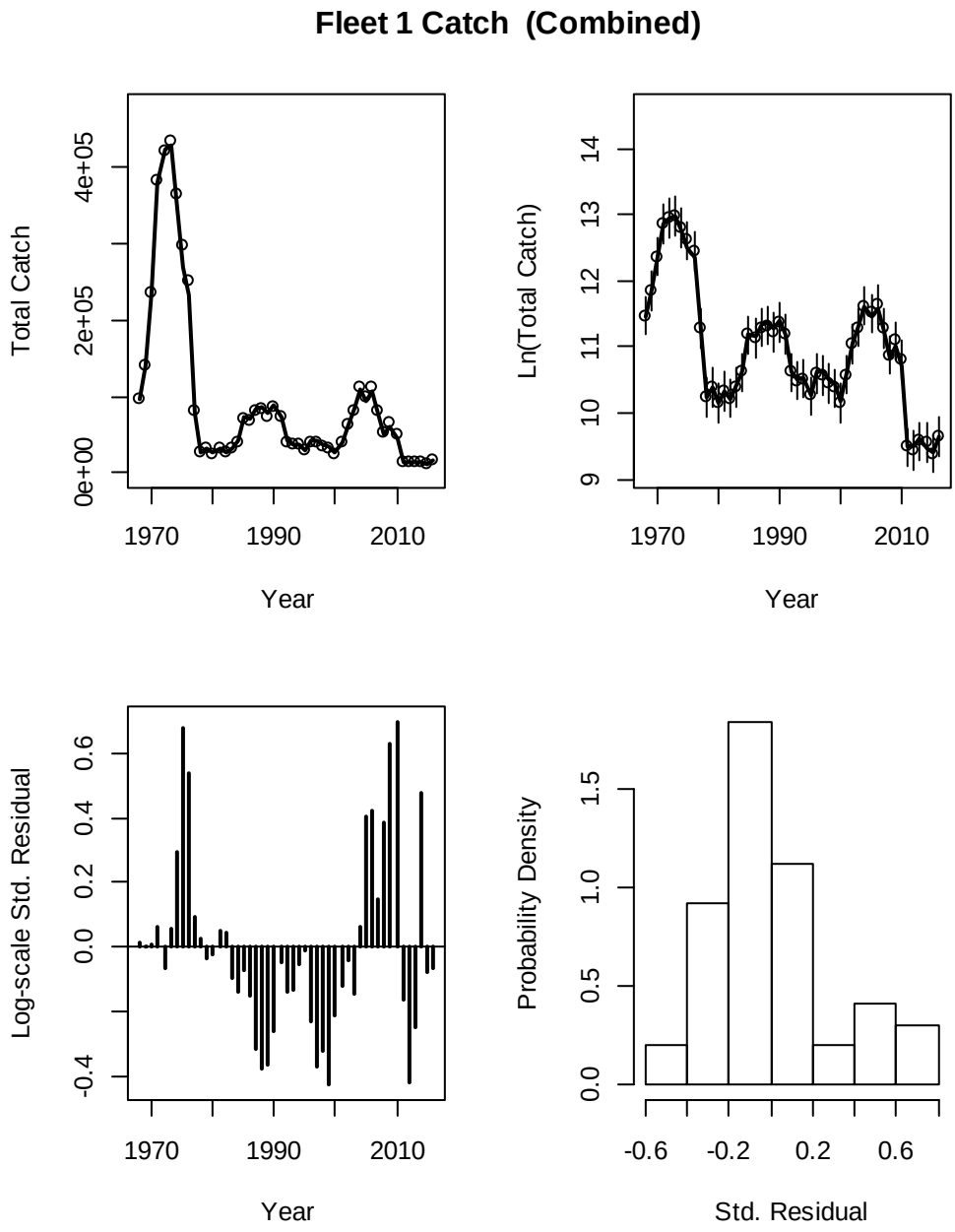


Figure A61: Fit diagnostics for total aggregate catch (modeled as one fleet) in the final ASAP model.

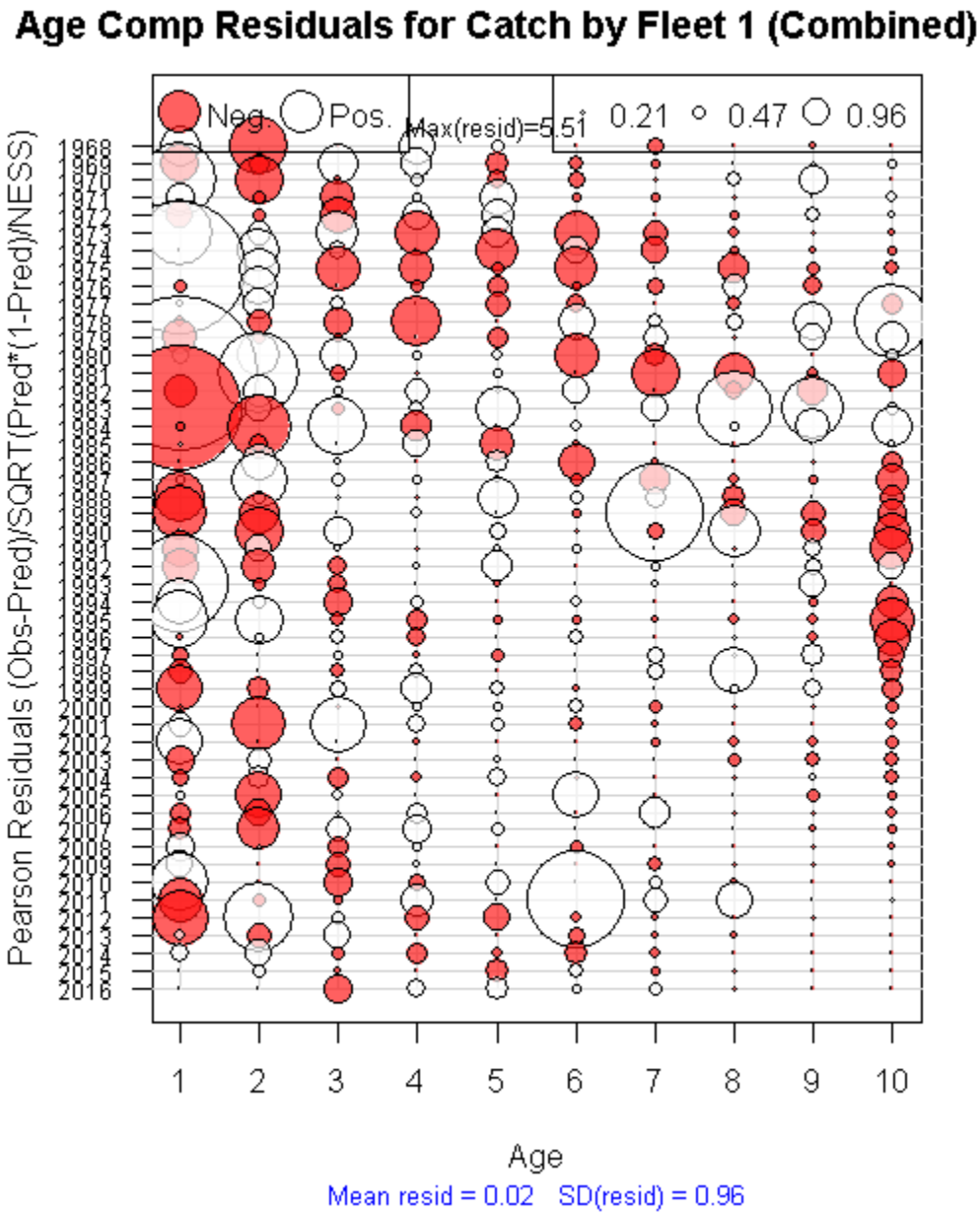


Figure A62: Pearson residuals for fishery age composition data from the final ASAP model.

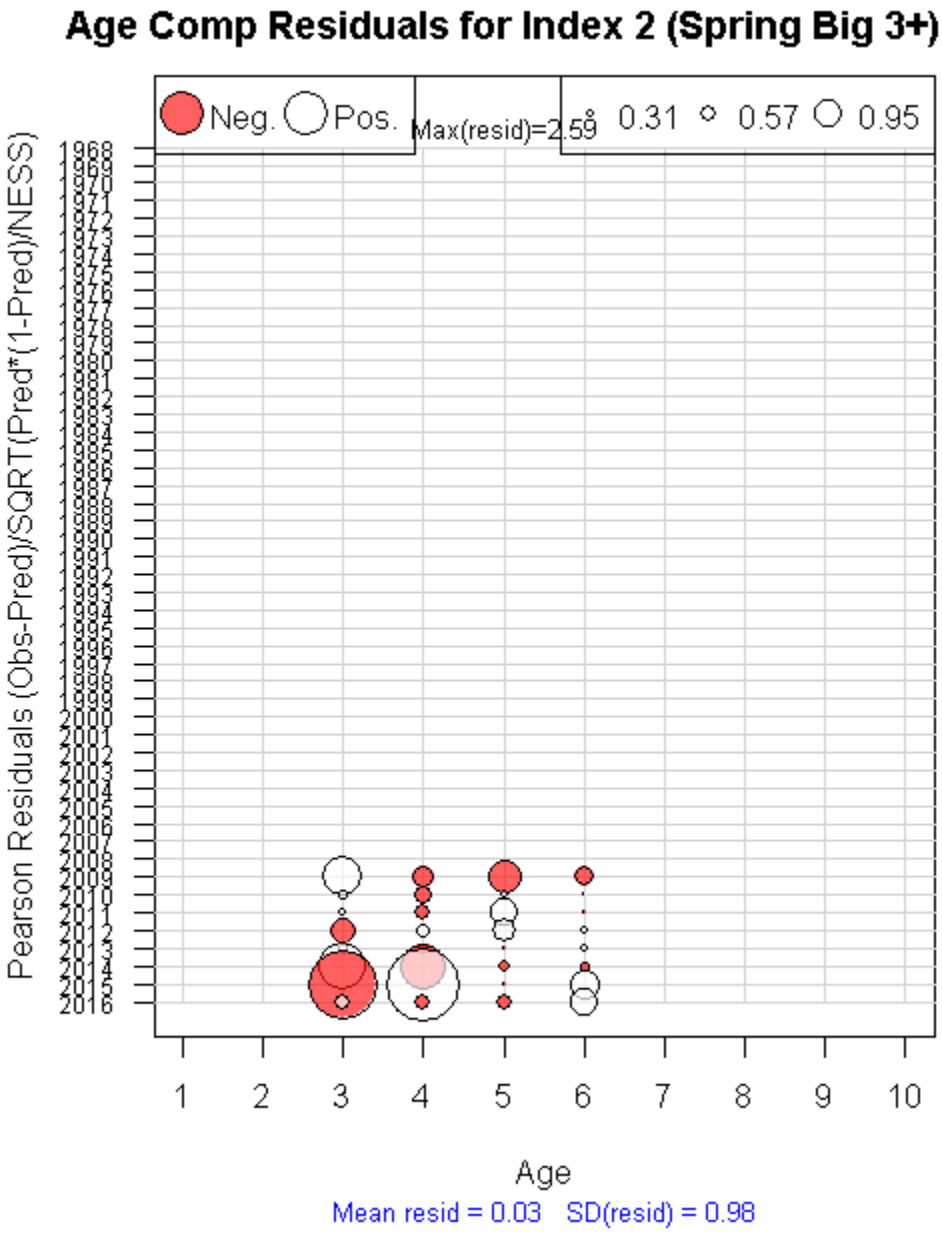


Figure A63: Pearson residuals for age composition data of the *Bigelow* years of the NEFSC spring bottom trawl survey for the final ASAP model.

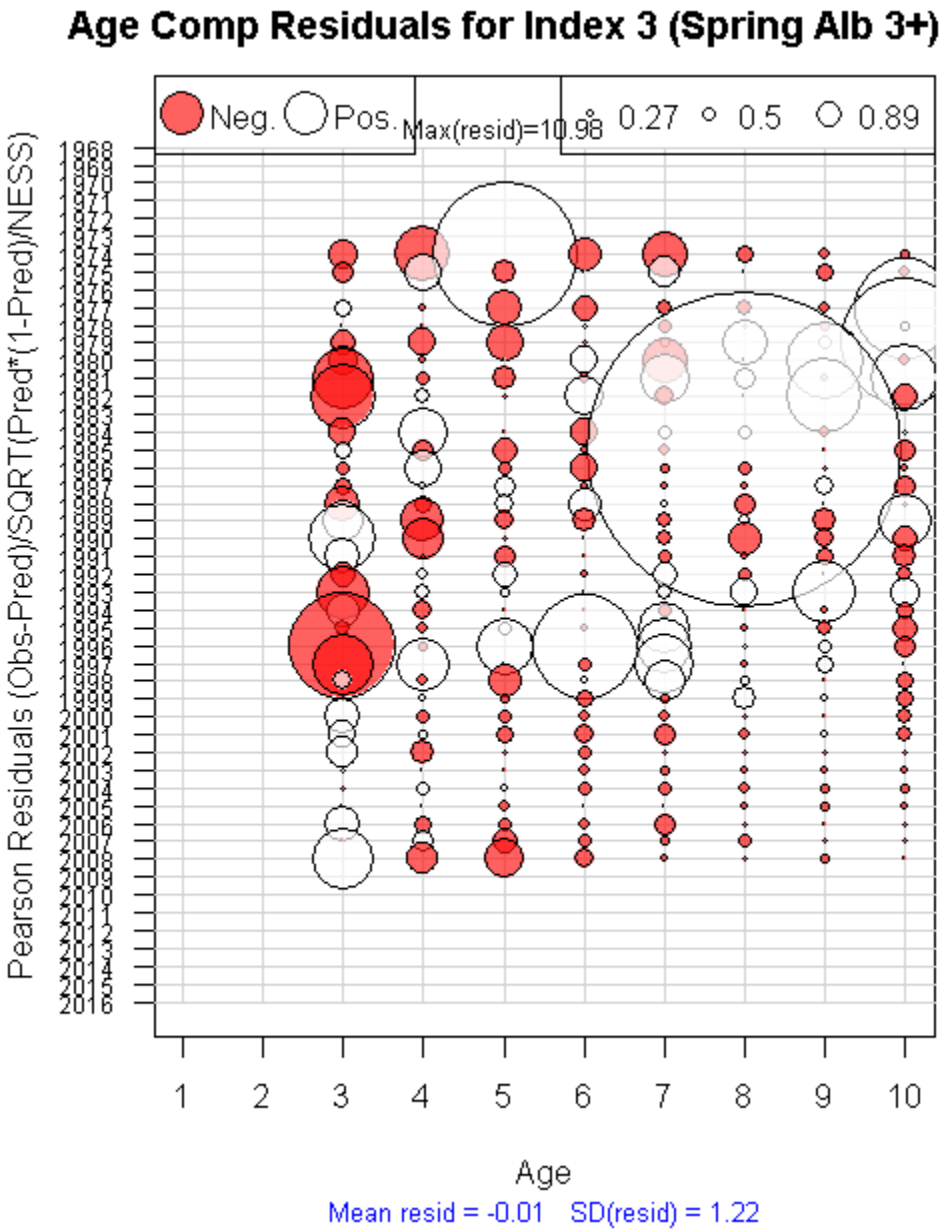


Figure A64: Pearson residuals for age composition data of the *Albatross* years of the NEFSC spring bottom trawl survey for the final ASAP model.

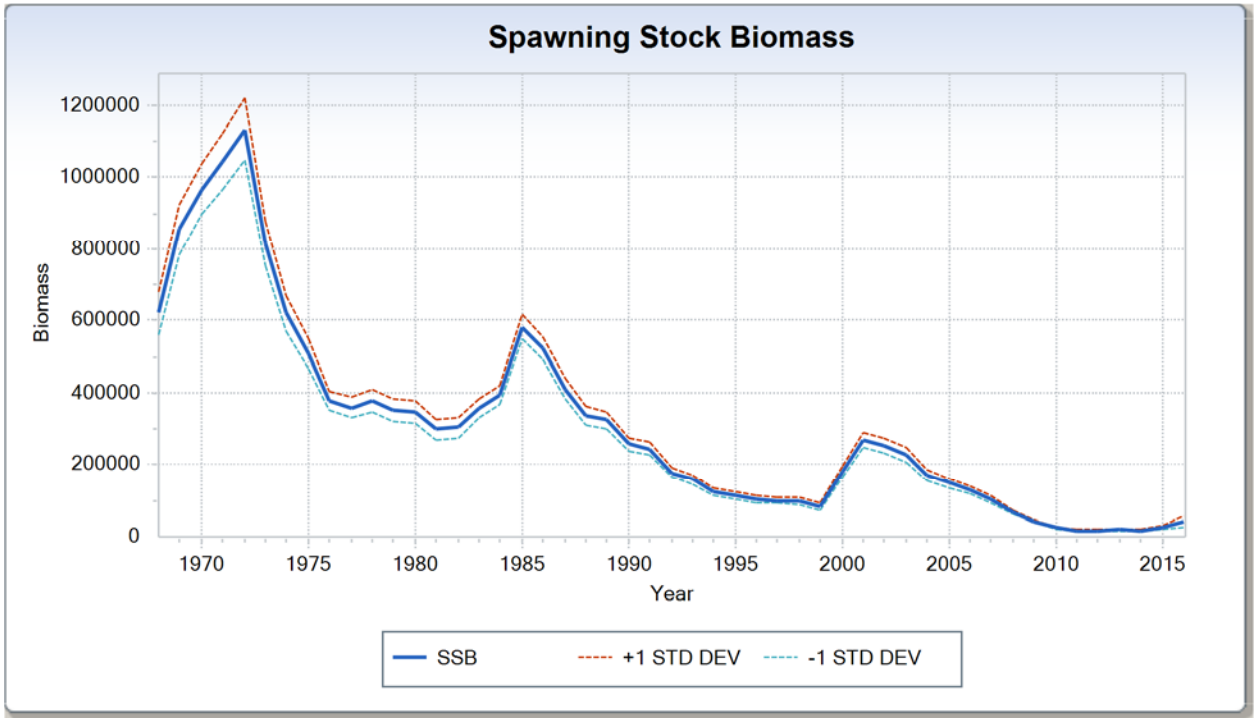


Figure A65: Temporal trends in Atlantic mackerel spawning stock biomass (mt) estimated in the final ASAP model.

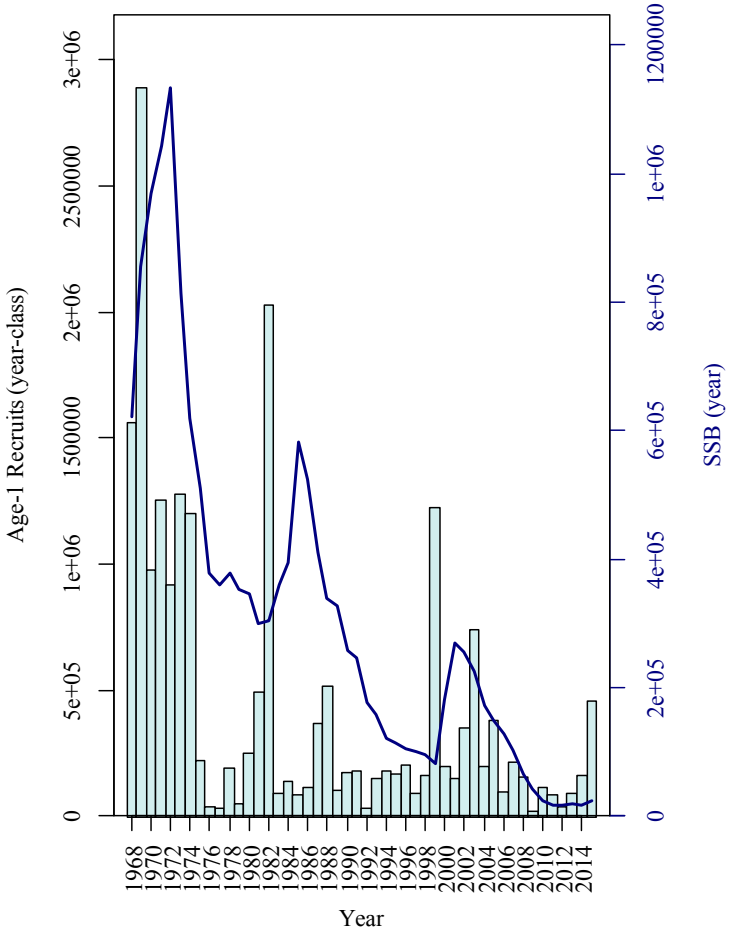


Figure A66: Estimates of Atlantic mackerel spawning stock biomass (solid blue line) and lagged age-1 recruitment labeled as year class (light blue bars) from the final ASAP model.

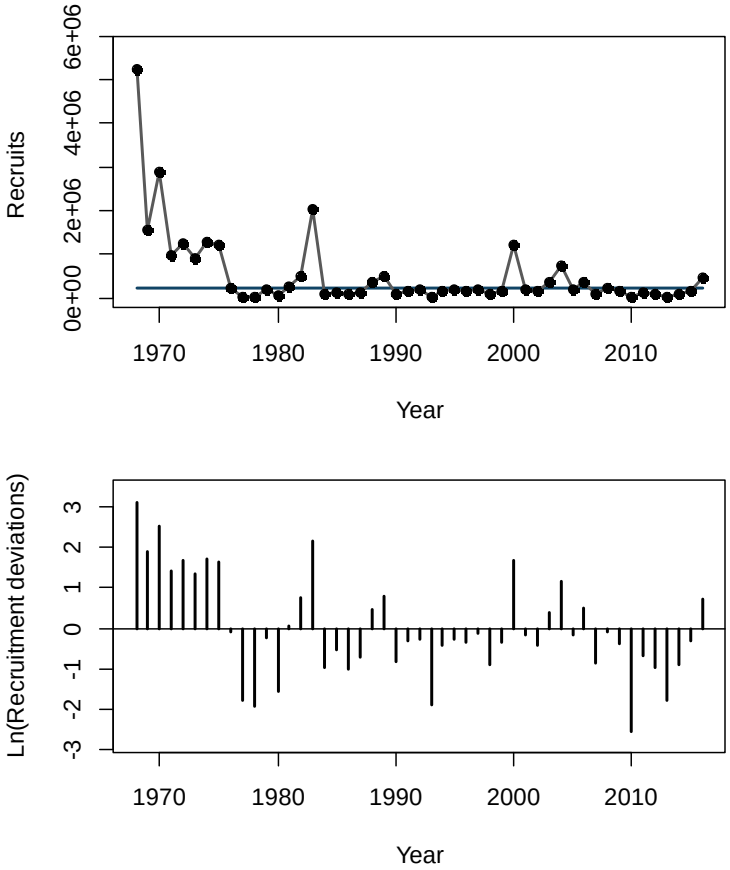


Figure A67: Estimated Atlantic mackerel recruitment and recruitment residuals from the geometric mean for the final ASAP model.

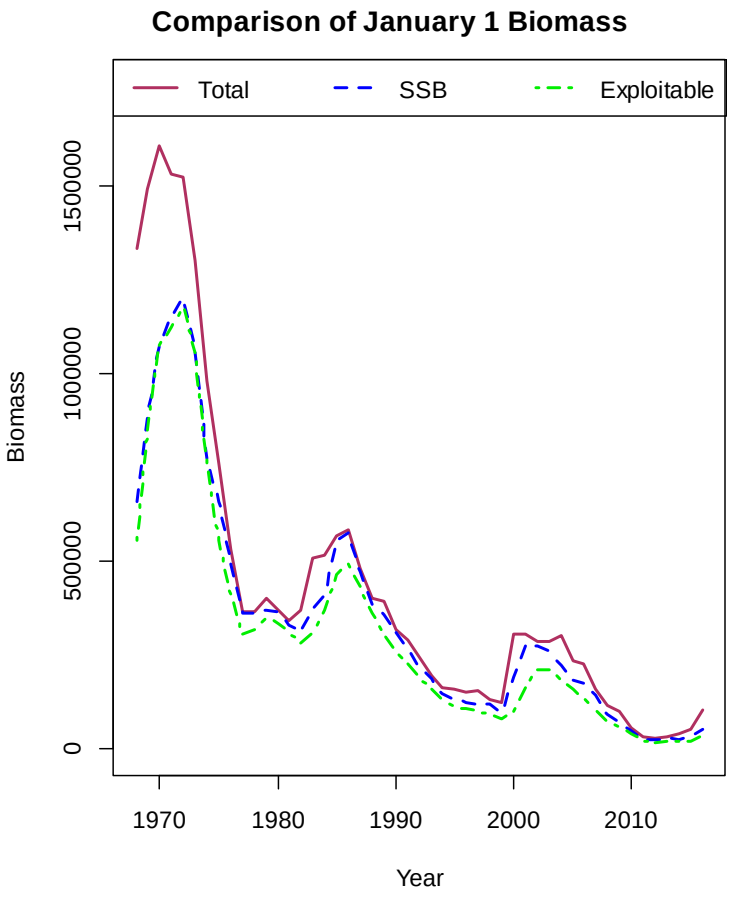


Figure A68: Temporal trends in Atlantic mackerel total, spawning stock and exploitable biomass estimates from the final ASAP model.

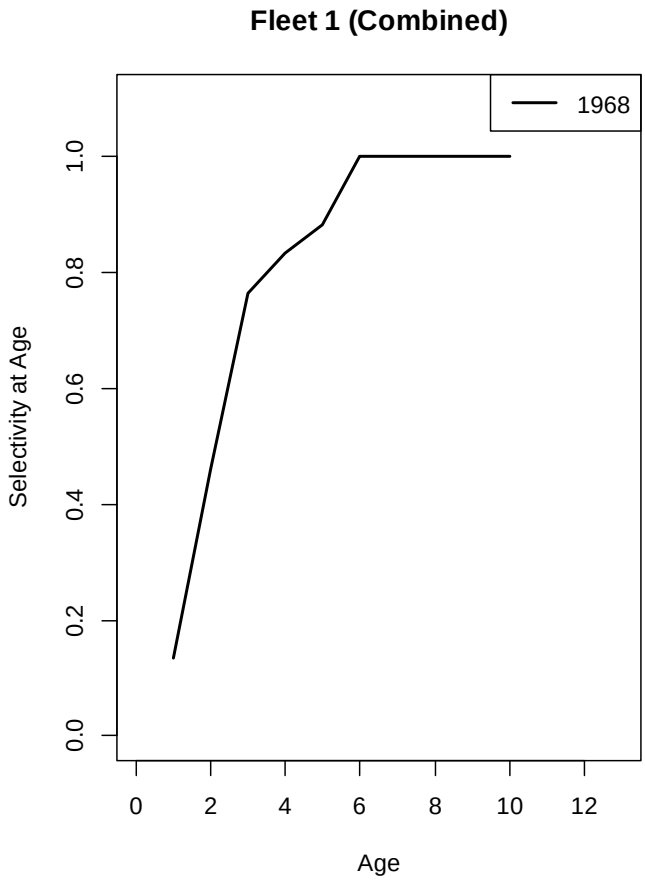


Figure A69: Atlantic mackerel age-specific fishery selectivity estimates from the final ASAP model.

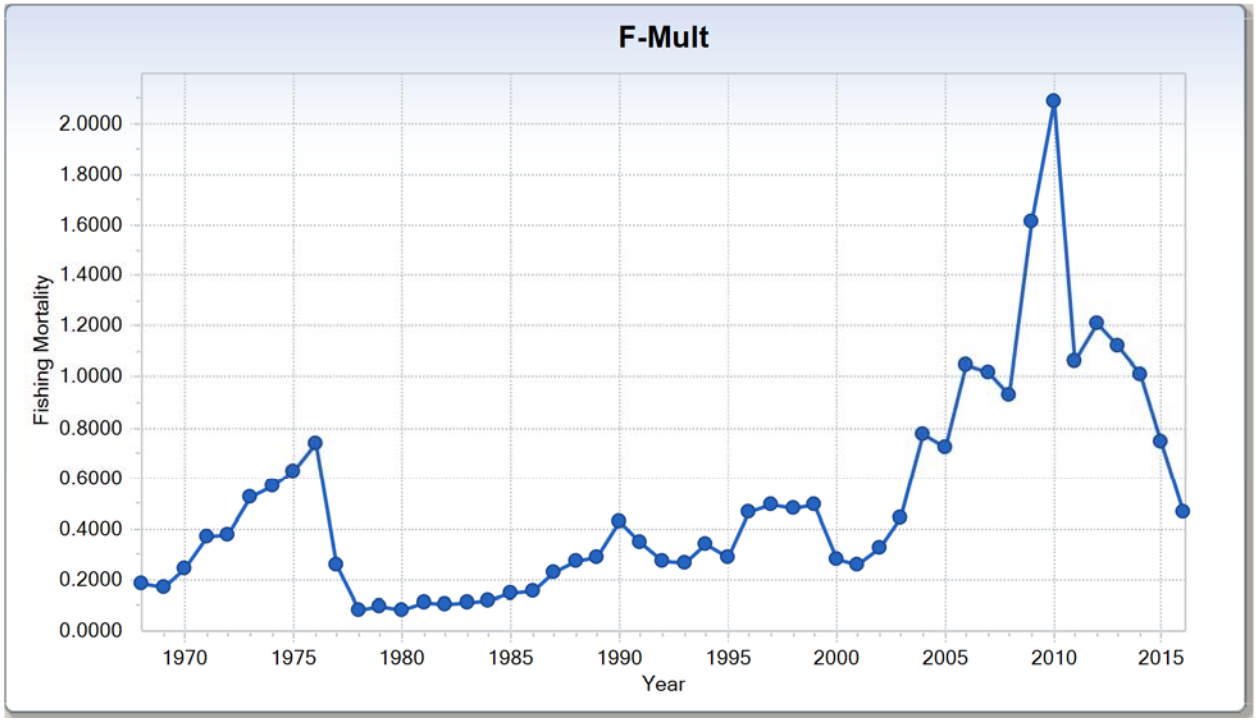


Figure A70: Temporal trends in fishing mortality estimated in the final ASAP model.

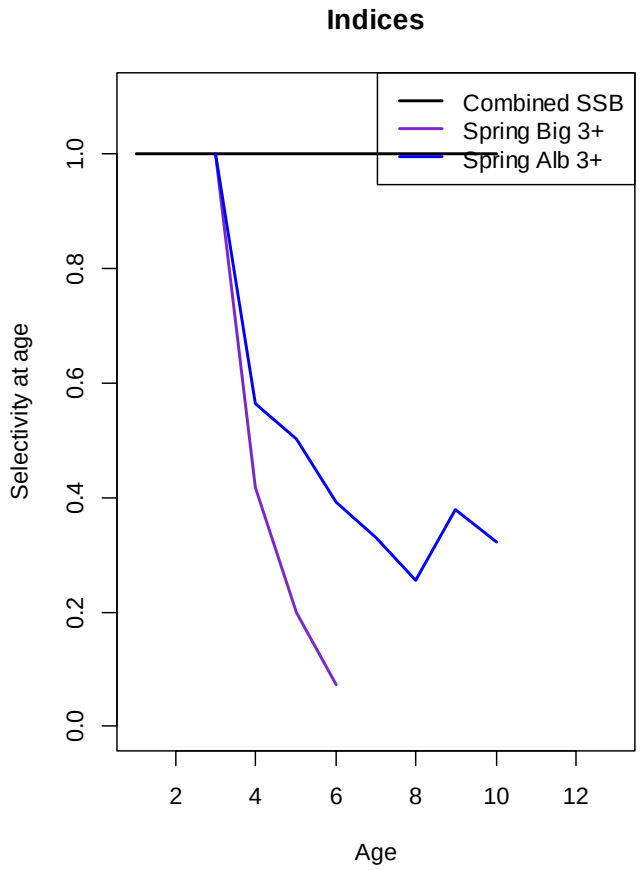


Figure A71: Age-specific selectivity estimates of the three indices included in the final ASAP model: range-wide egg index in units of SSB (Combined SSB), NEFSC spring survey during the *Bigelow* years of 2009-2016, and NEFSC spring survey during the *Albatross* years of 1968-2008.

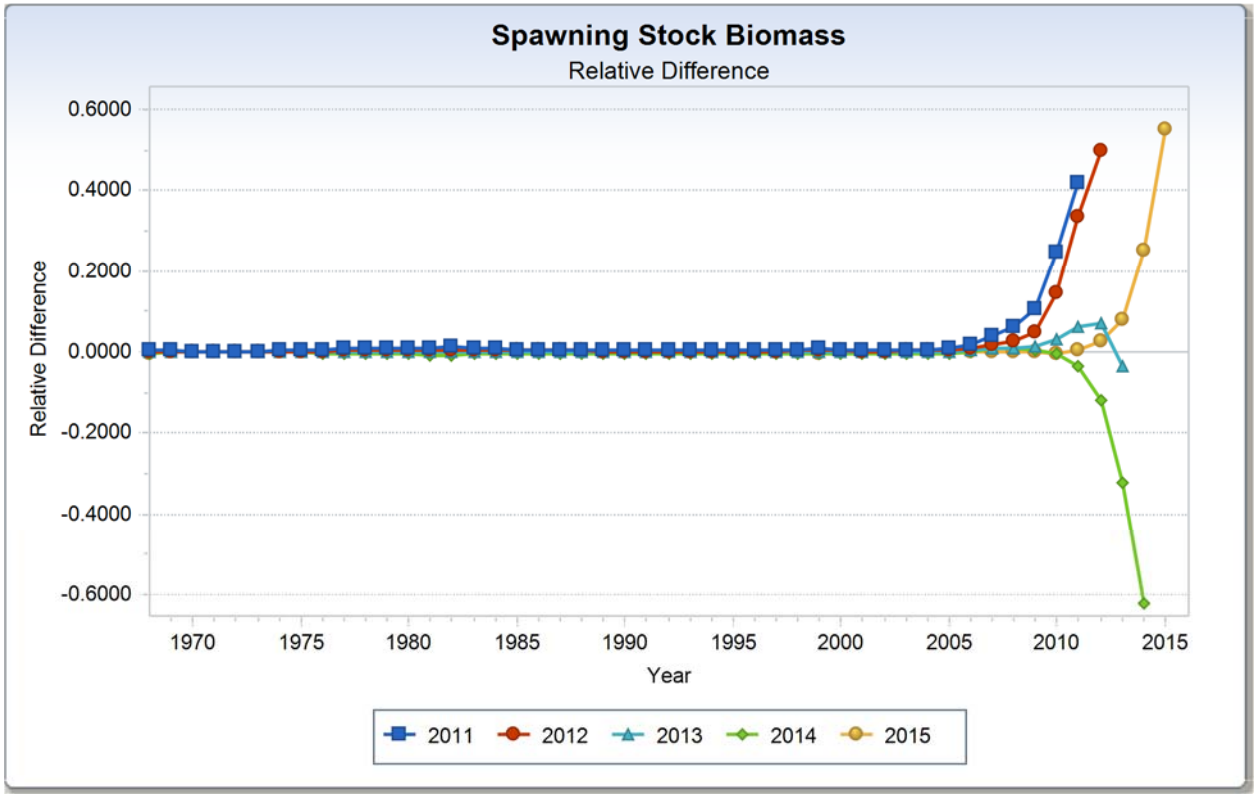


Figure A72: Retrospective analysis, expressed as the relative difference from the final model, for Atlantic mackerel spawning stock biomass. Mohn's rho based on a five-year retrospective peel was 0.162.

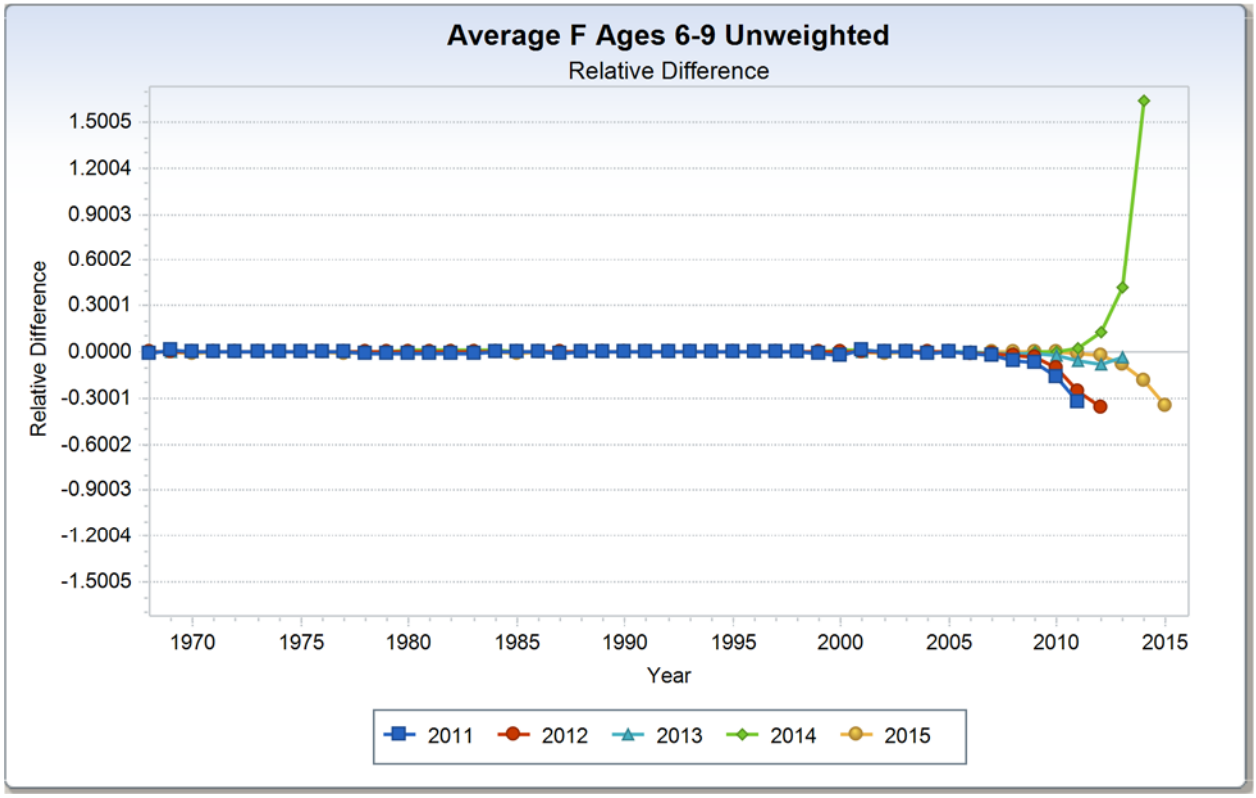


Figure A73: Retrospective analysis, expressed as the relative difference from the final model, for Atlantic mackerel average fishing mortality for ages 6-9. Mohn's rho based on a five-year retrospective peel was 0.112.

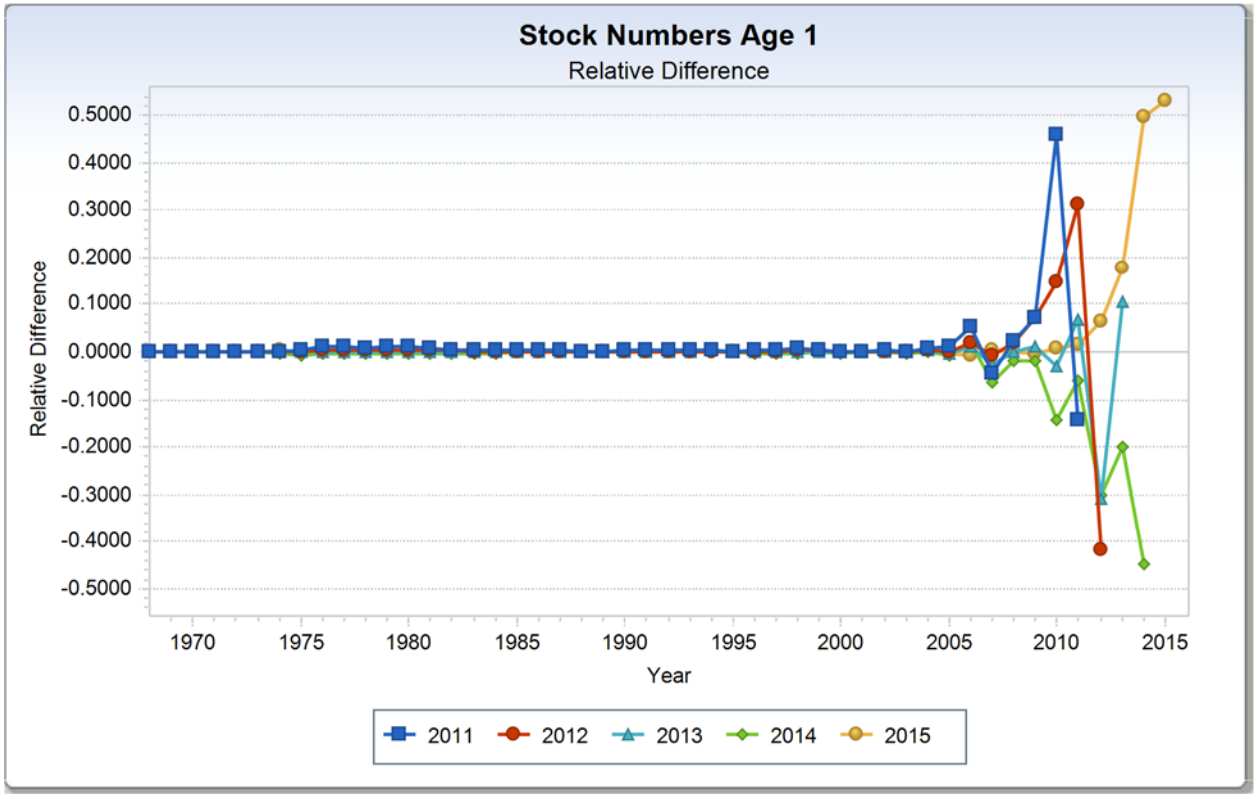


Figure A74: Retrospective analysis, expressed as the relative difference from the final model, for Atlantic mackerel recruitment. Mohn's rho based on a five-year retrospective peel was -0.074.

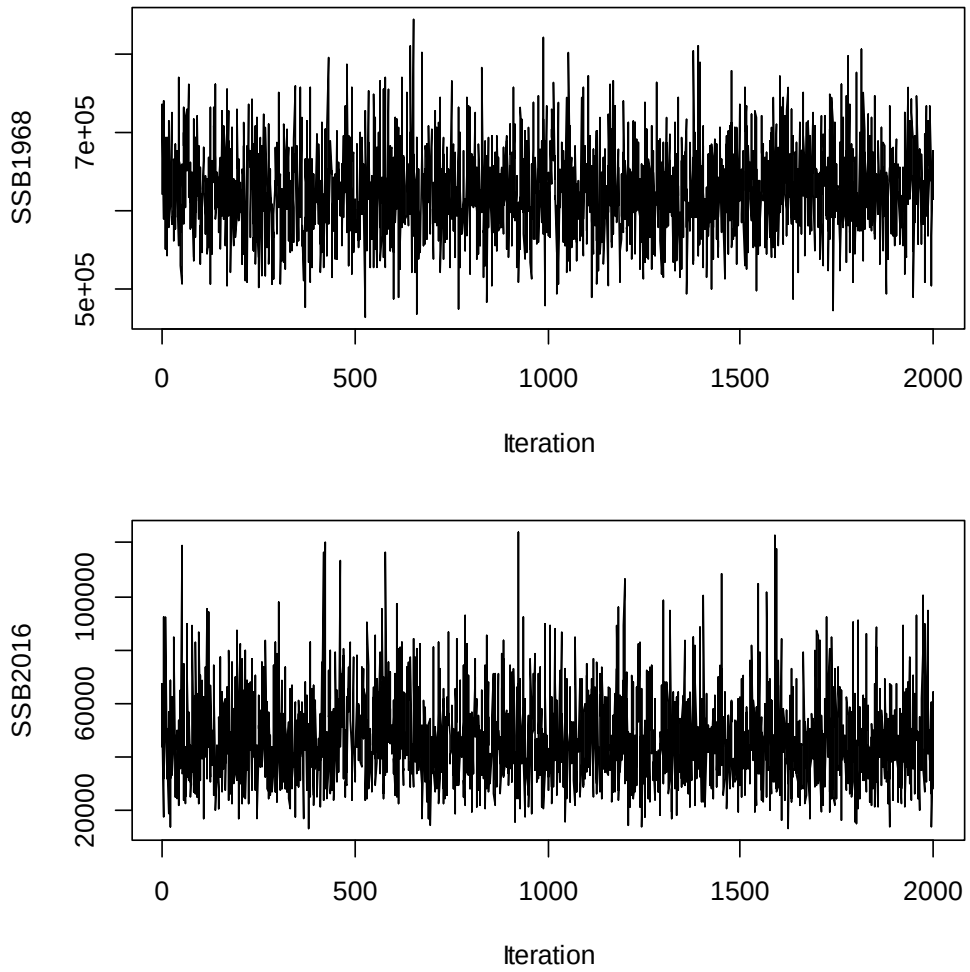


Figure A75: Traces of the MCMC chain for Atlantic mackerel 1968 and 2016 spawning stock biomass estimates.

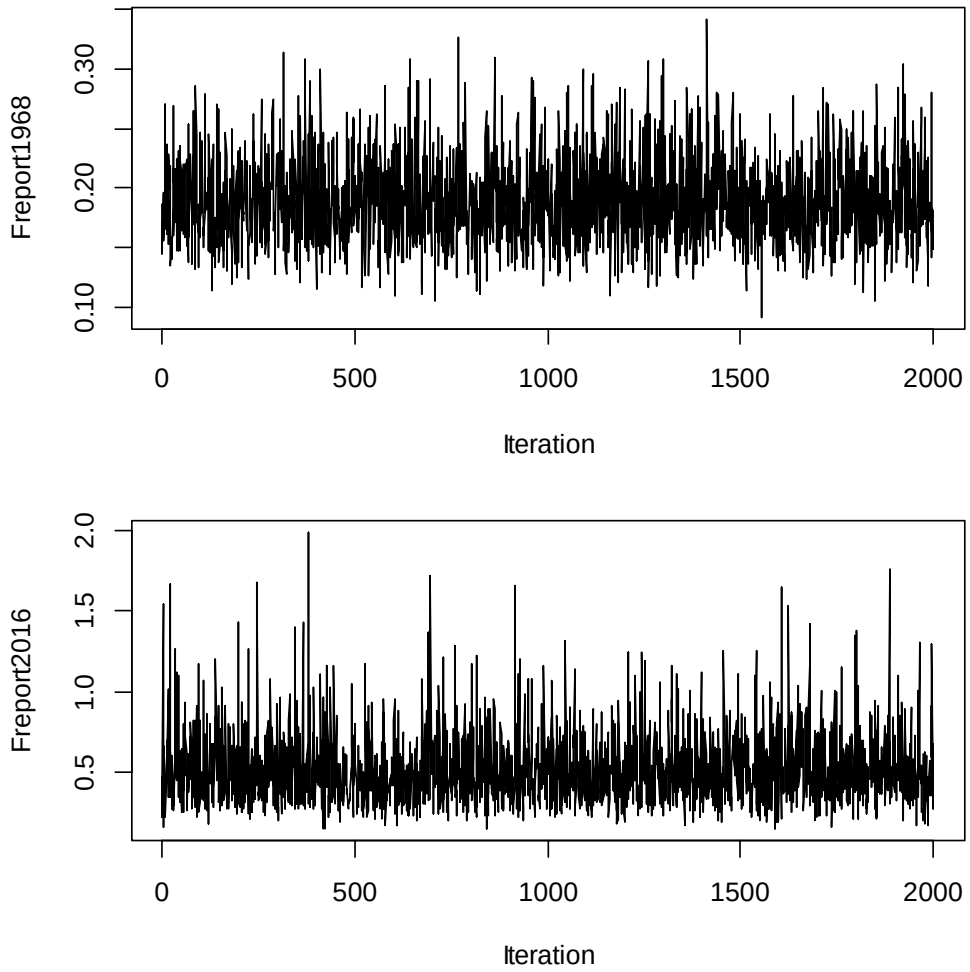


Figure A76: Traces of the MCMC chain for Atlantic mackerel 1968 and 2016 average fishing morality estimates for ages 6-9 (F_{report}).

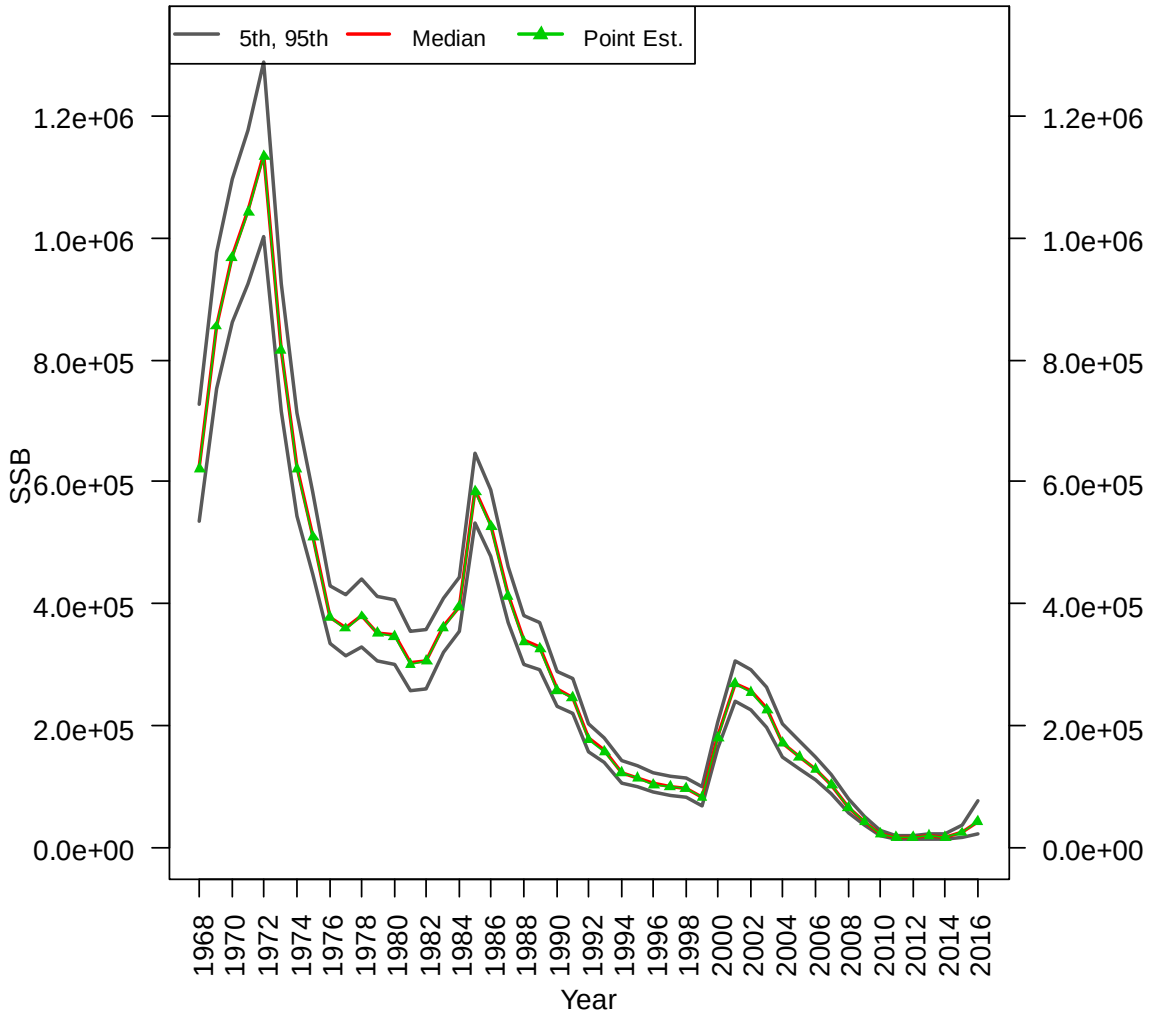


Figure A77: 90% probability interval associated with Atlantic mackerel spawning stock biomass estimates from the final ASAP model. The dark grey lines represent the 5th and 95th percentiles and the green triangles represent the model point estimates.

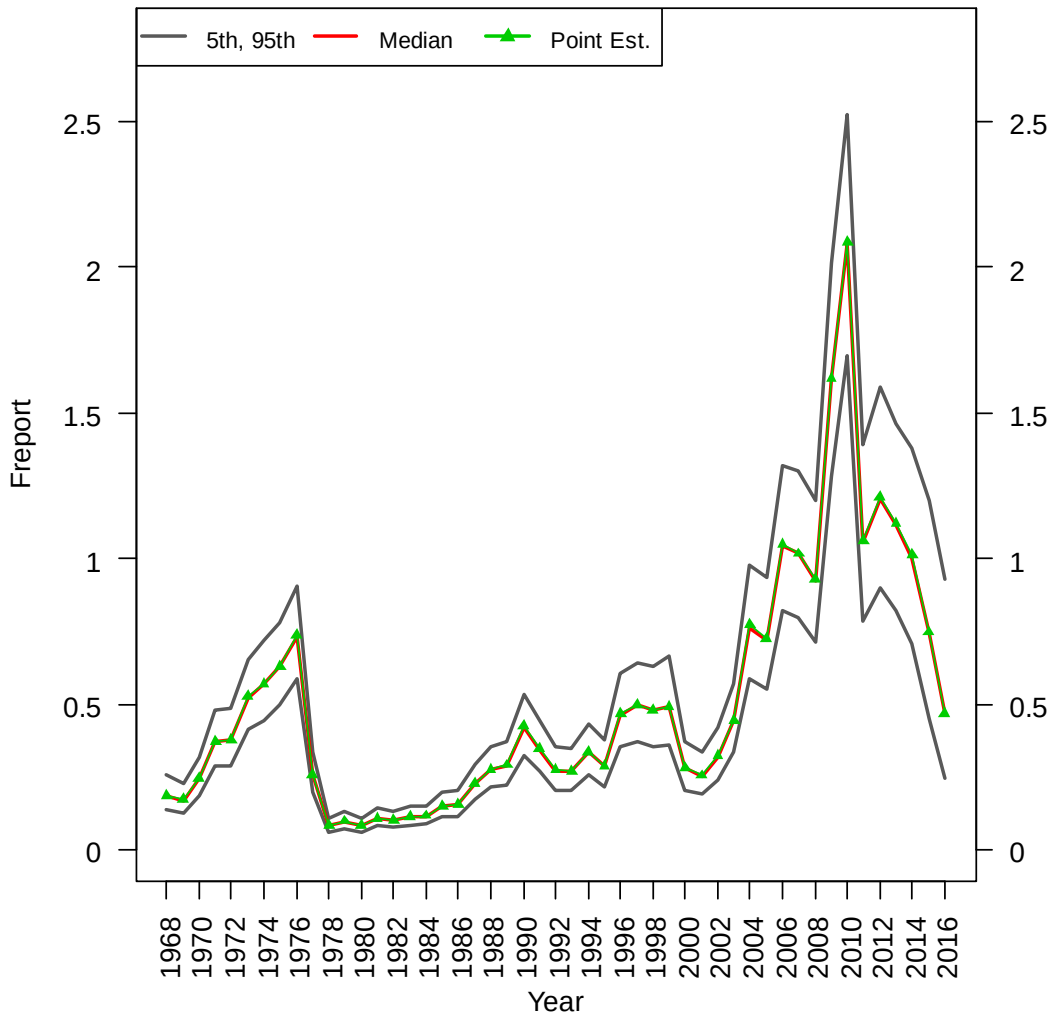


Figure A78: 90% probability interval associated with Atlantic mackerel average fishing morality estimates for ages 6-9 (F_{report}) from the final ASAP model. The dark grey lines represent the 5th and 95th percentiles and the green triangles represent the model point estimates.

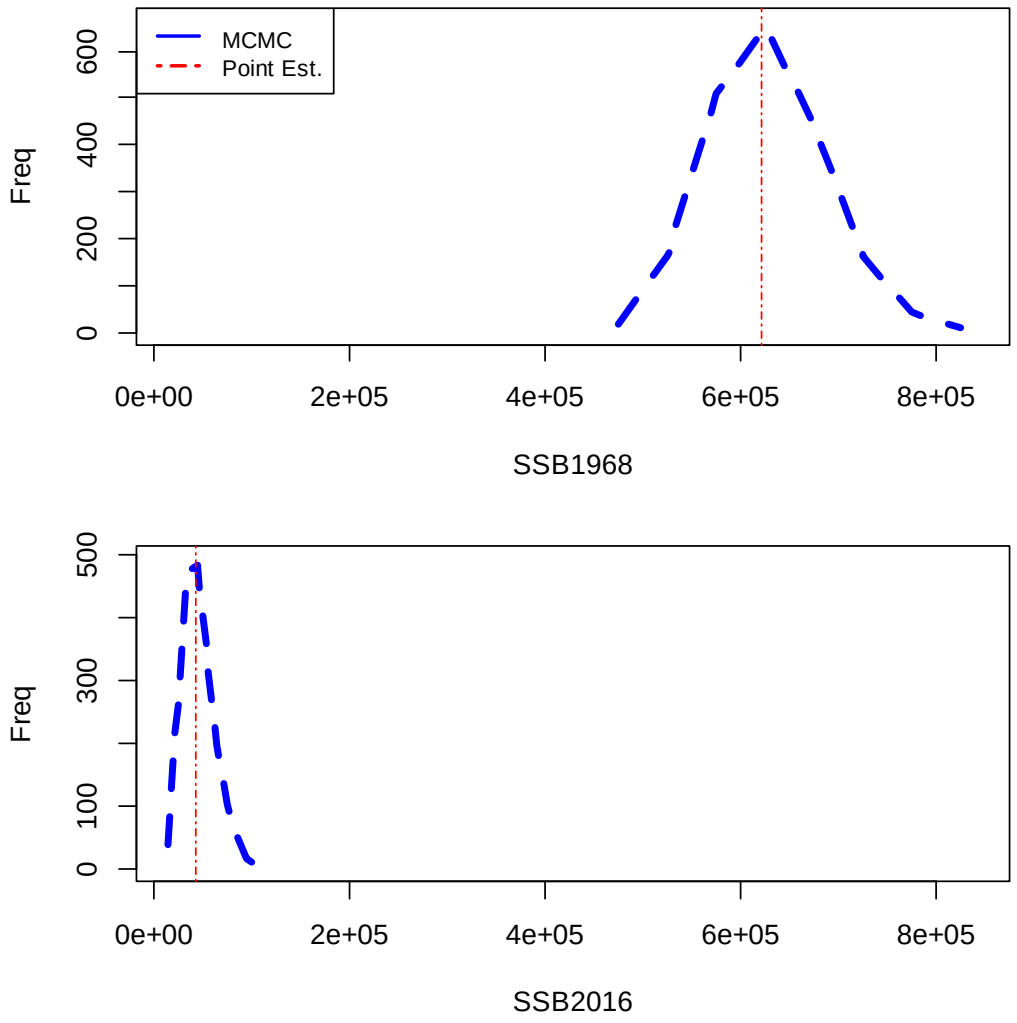


Figure A79: MCMC posterior probability distributions of Atlantic mackerel spawning stock biomass estimates in the first (1968) and terminal (2016) years of the final ASAP model. The dashed red line represents the model point estimate.

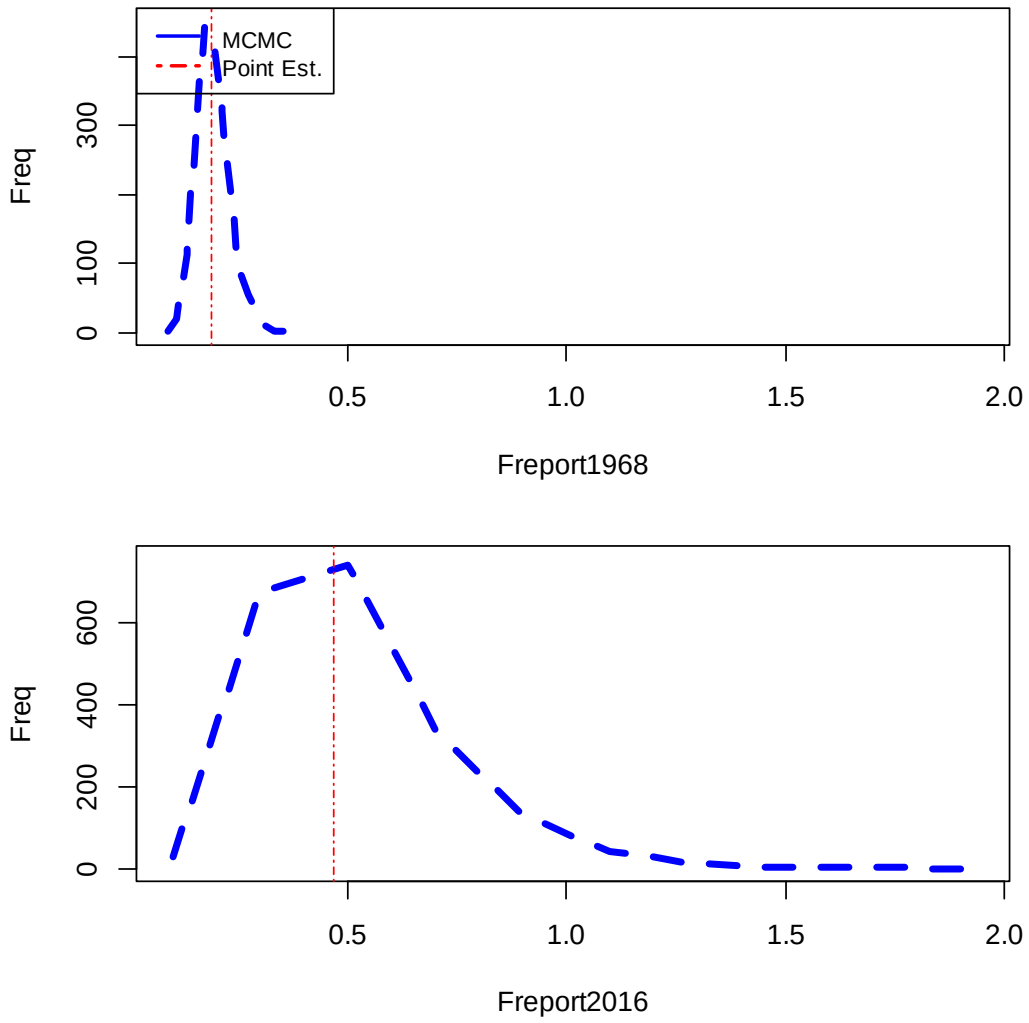


Figure A80: MCMC posterior probability distributions of Atlantic mackerel average age 6-9 fishing mortality estimates in the first (1968) and terminal (2016) years of the final ASAP model. The dashed red line represents the model point estimate.

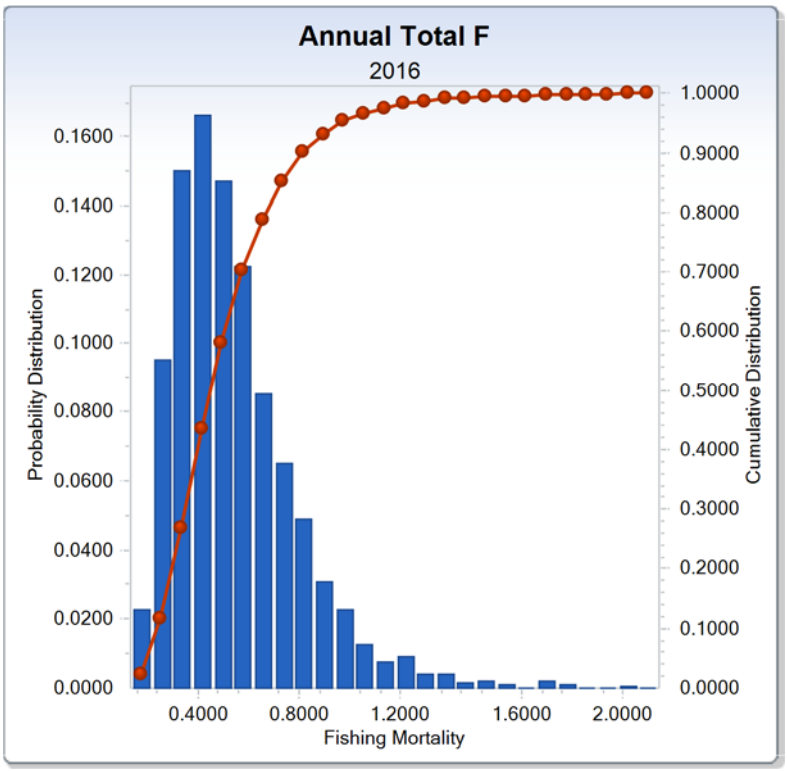


Figure A81: MCMC posterior probability and cumulative distributions of estimated Atlantic mackerel average age 6-9 fishing mortality in the terminal year (2016) of the final ASAP model.

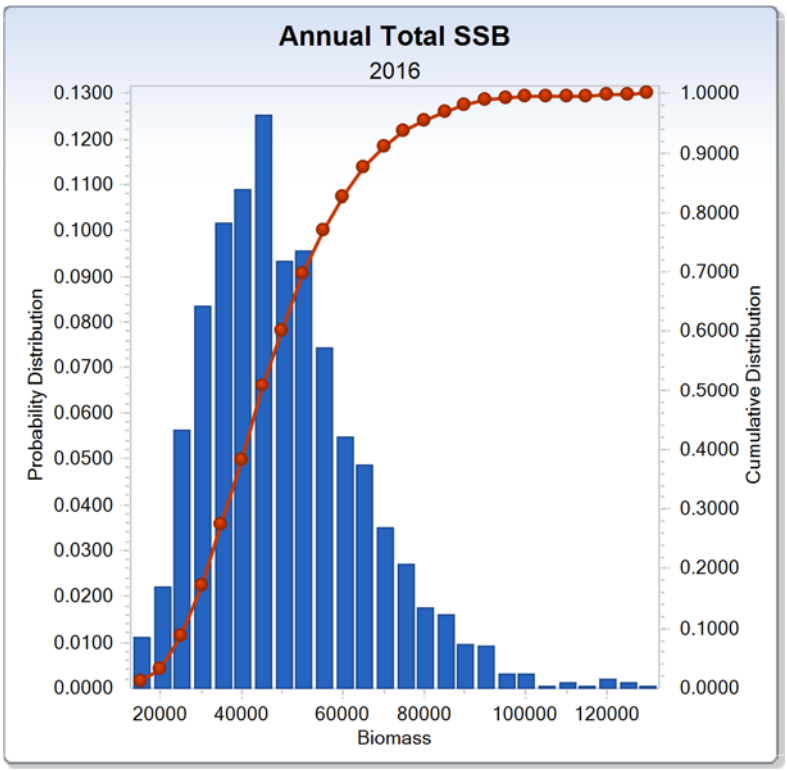


Figure A82: MCMC posterior probability and cumulative distributions of estimated Atlantic mackerel spawning stock biomass in the terminal year (2016) of the final ASAP model.

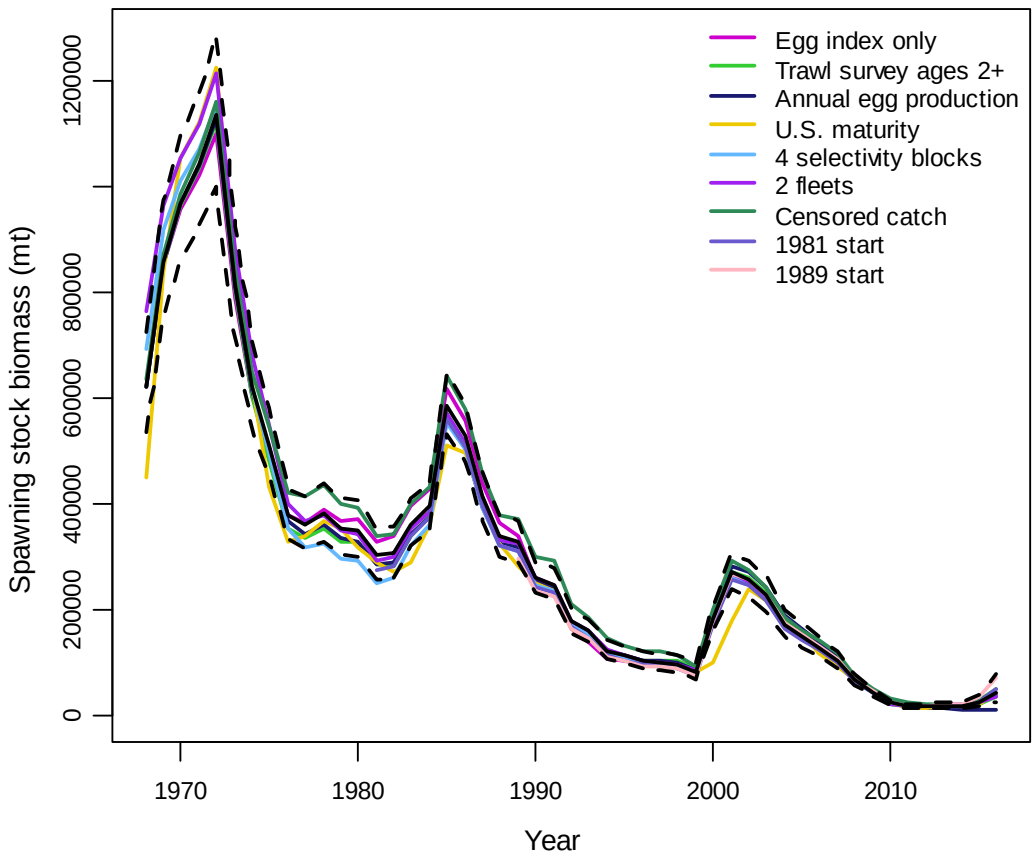


Figure A83: Comparison of Atlantic mackerel spawning stock biomass estimates across ASAP sensitivity runs. The solid black line represents the median of the 90th probability interval from the final ASAP model and the black dashed lines represent the 5th and 95th percentiles.

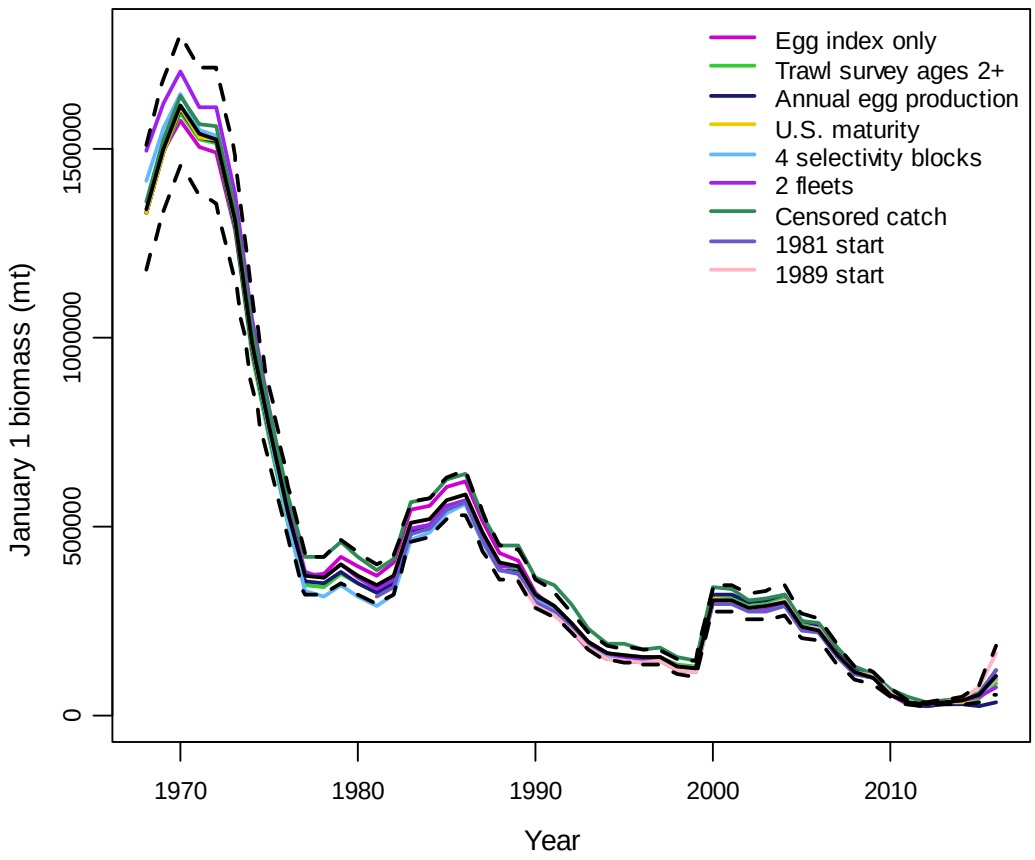


Figure A84: Comparison of Atlantic mackerel January-1 biomass estimates across ASAP sensitivity runs. The solid black line represents the median of the 90th probability interval from the final ASAP model and the black dashed lines represent the 5th and 95th percentiles.

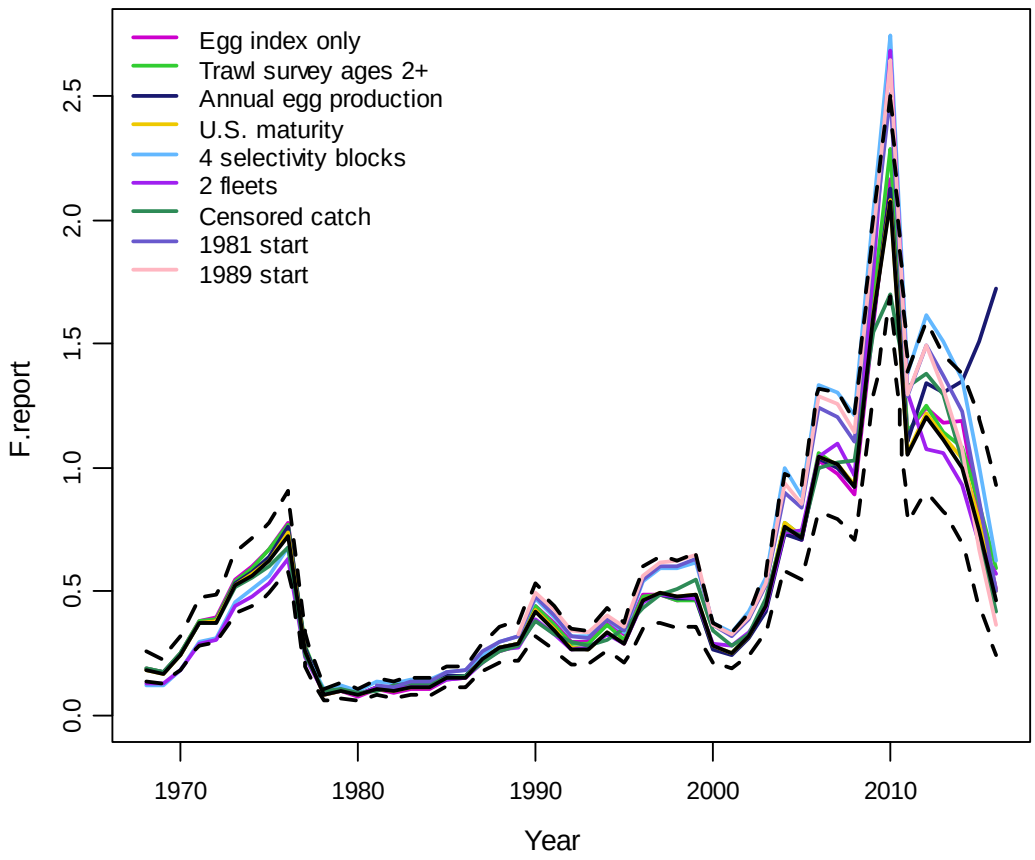


Figure A85: Comparison of Atlantic mackerel average age 6-9 fishing mortality estimates across ASAP sensitivity runs. The solid black line represents the median of the 90th probability interval from the final ASAP model and the black dashed lines represent the 5th and 95th percentiles.

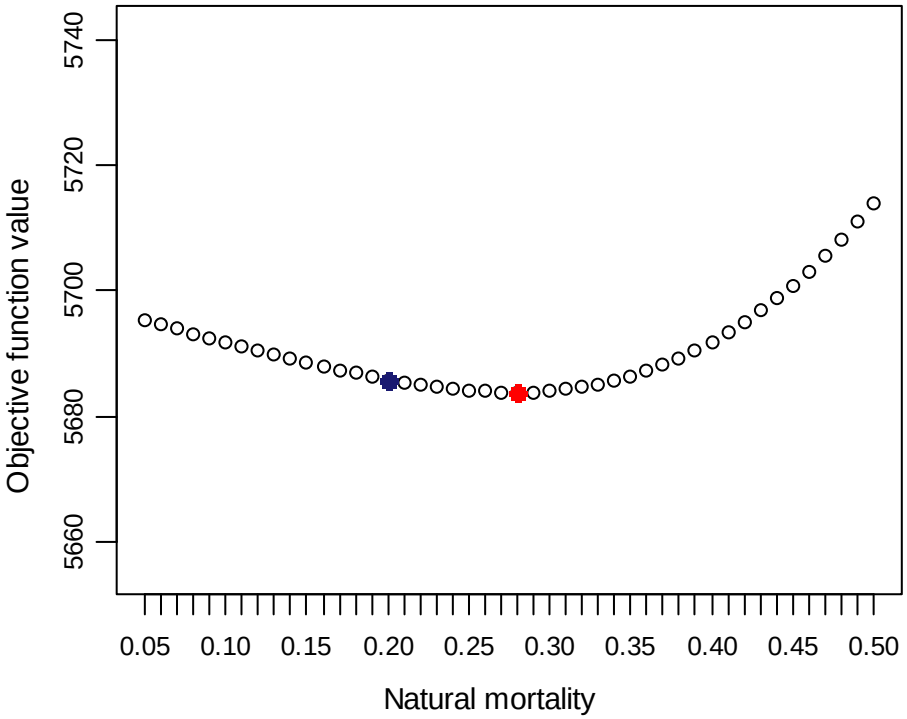


Figure A86: Likelihood profile of natural mortality for the final ASAP model. A constant natural mortality of 0.2 (blue circle) was used in the final ASAP model and the minimum value from the profile corresponded to a natural mortality of 0.28 (orange circle).

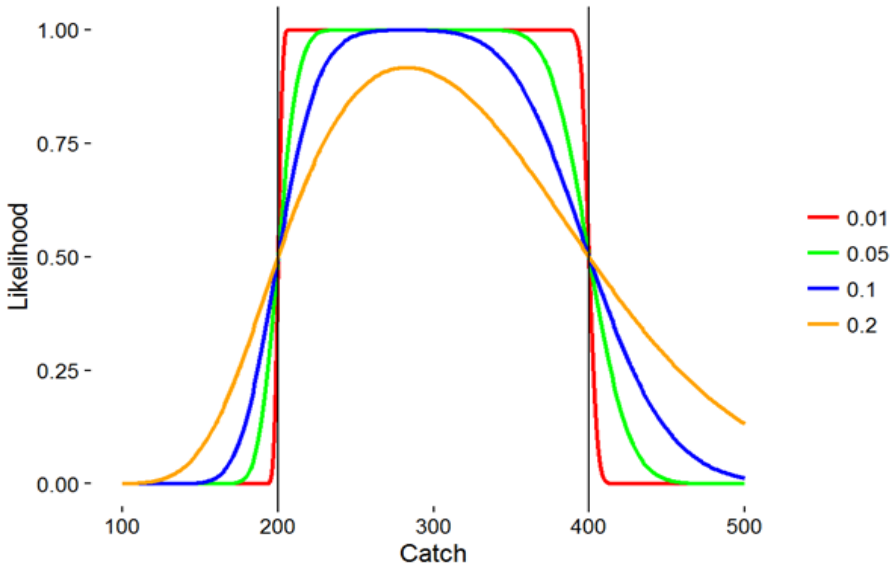


Figure A87: Schematic representation of the censored catch likelihood as used in the Censored Catch Assessment Model.

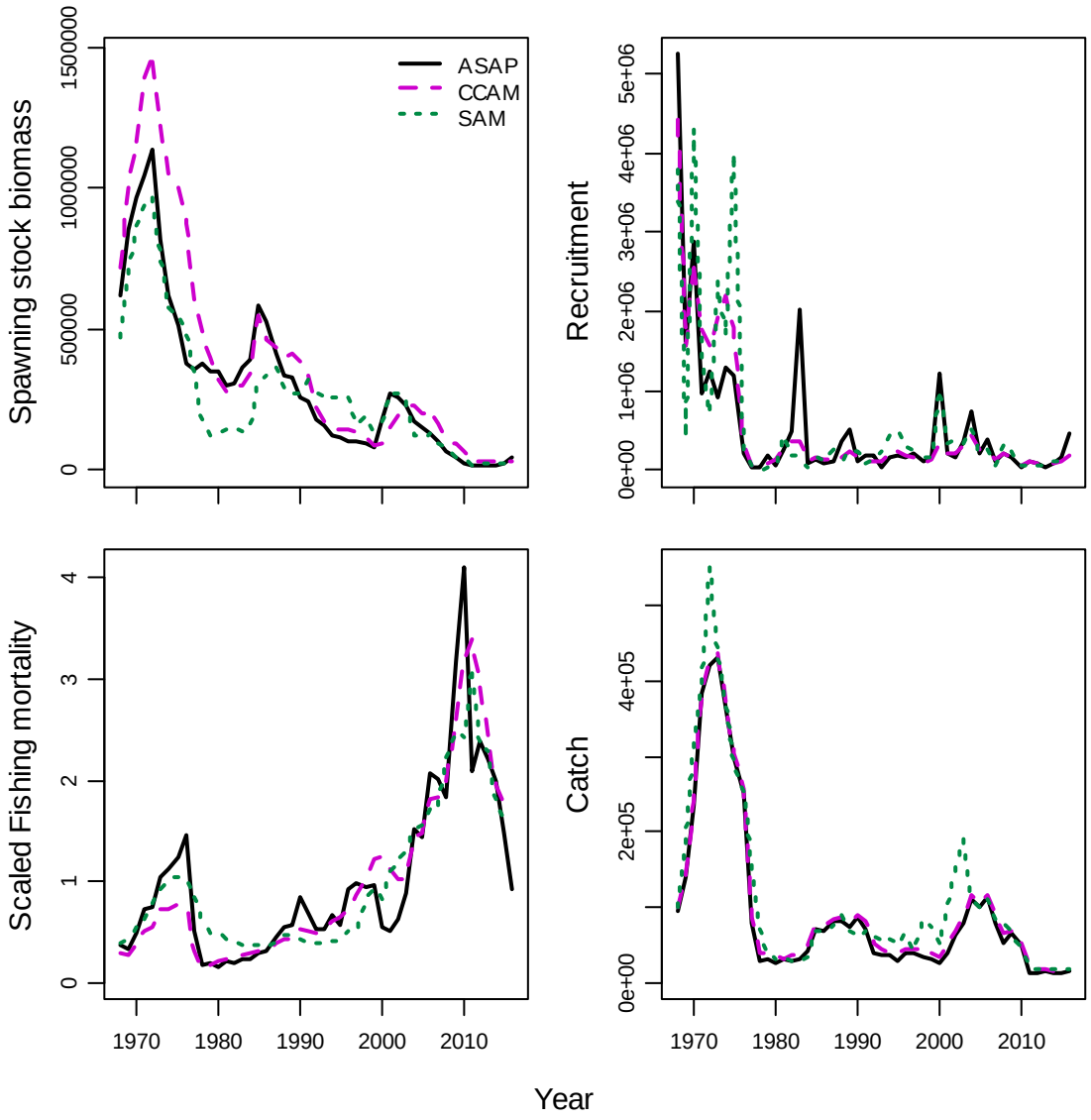


Figure A88: Comparison of spawning stock biomass, recruitment, fishing mortality and fishery catch estimates from the final ASAP, SAM and censored catch (CCAM) models.

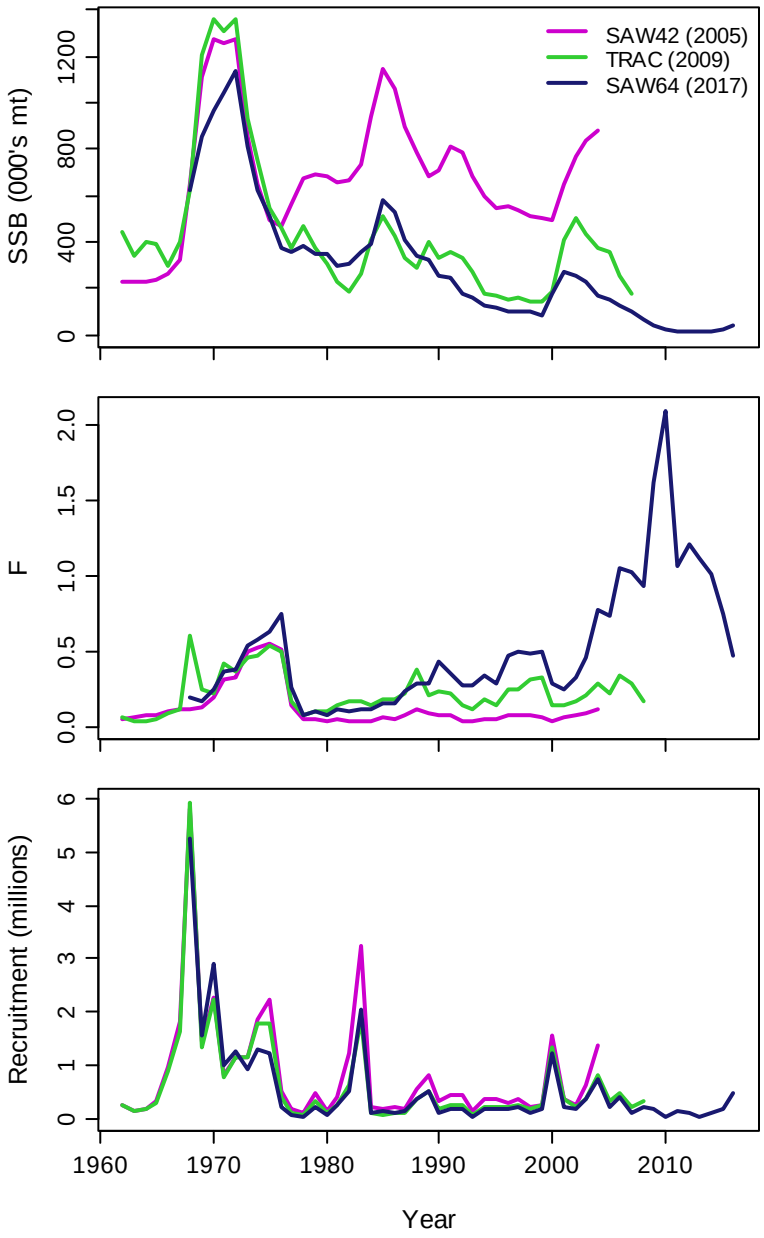


Figure A89: Historical retrospective comparison of spawning stock biomass (SSB), fishing mortality (F) and recruitment estimates from the final ASAP model (SAW64, black line) with those of the previous two Atlantic mackerel assessments. Previous assessment estimates represent rho-adjusted values to account for observed retrospective patterns. The model from the 2009 assessment (green line) was deemed inappropriate for management use. The 2005 assessment (pink line) passed peer review at the time but results were later also deemed inappropriate.

TOR5: Stock status definitions

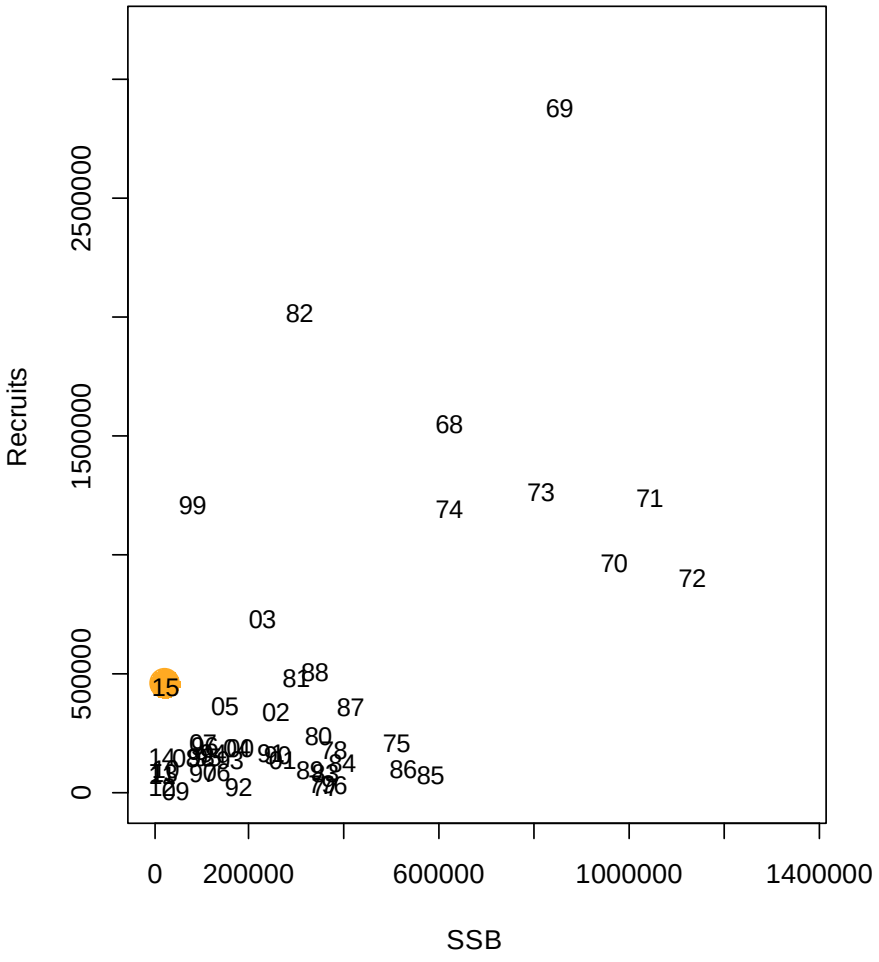


Figure A90: Spawning stock biomass (SSB, mt) and recruitment (Recruits, number of fish) estimates for the 1968-2015 year classes.

TOR6: Stock status

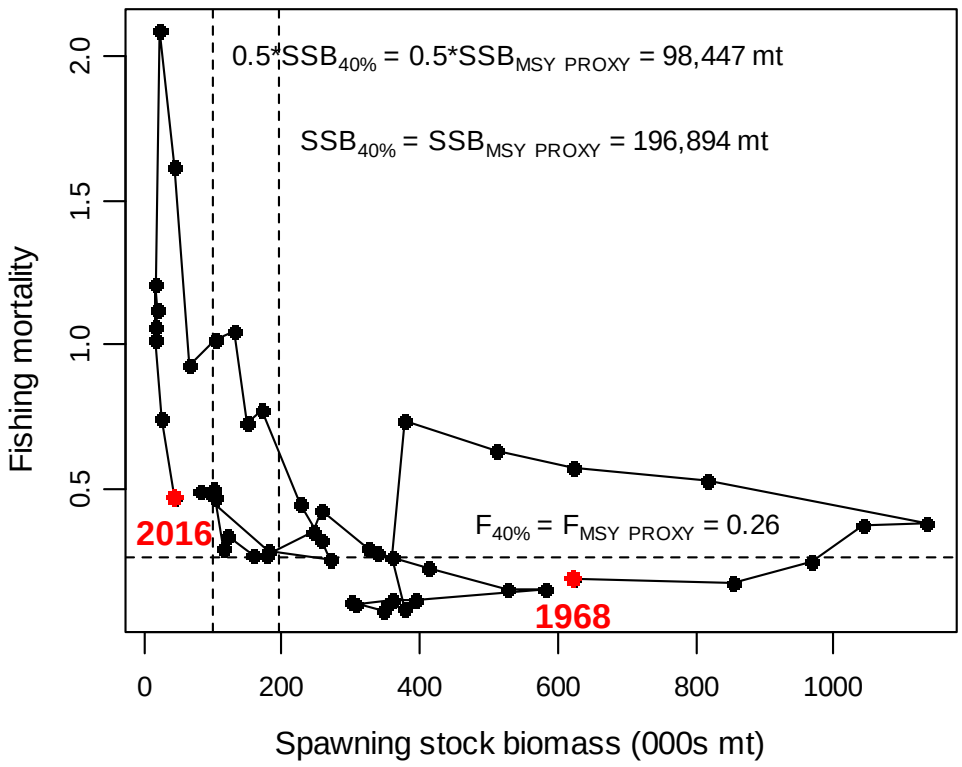


Figure A91: Time series trajectory of Atlantic mackerel fully selected fishing mortality and spawning stock biomass estimates from 1968 to 2016 relative to the corresponding biological reference points.

TOR7: Projections

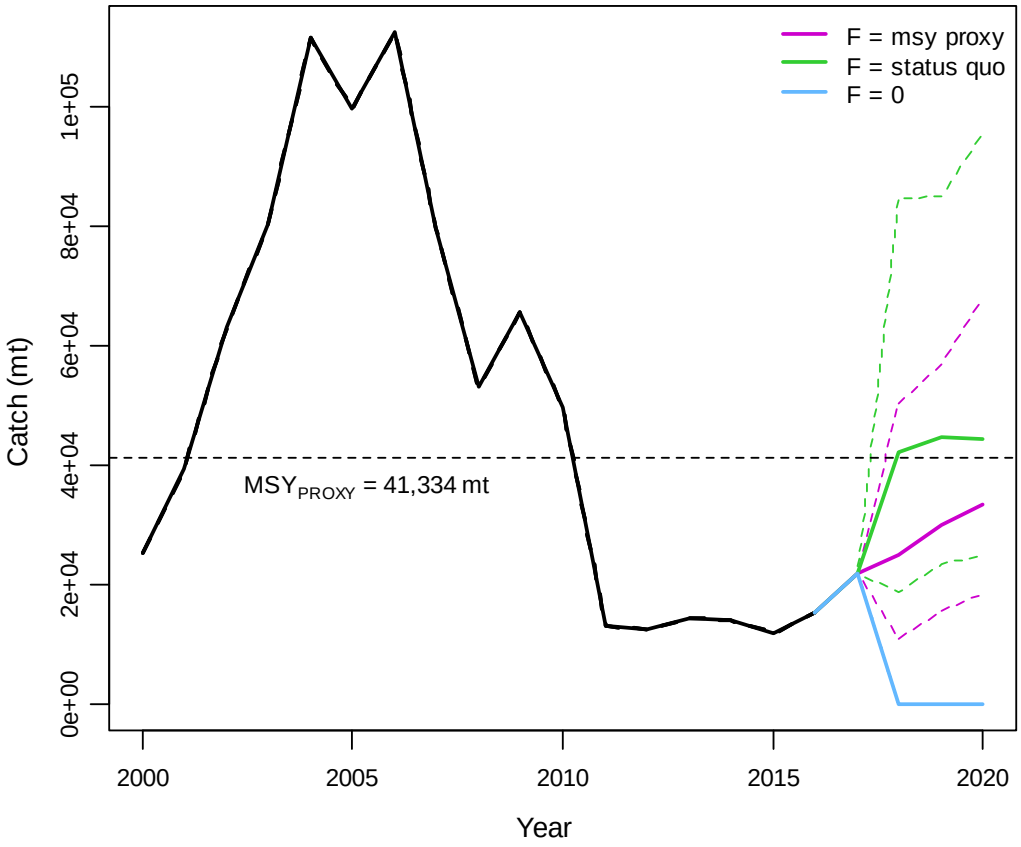


Figure A92: Time series of Atlantic mackerel catch (mt) with three-year projections at $F_{msy\ proxy}$, $F_{status\ quo}$ and F = 0. The solid lines represent the reported catches and the median of the catch for each fishing scenario. The dotted lines represent the 90% confidence intervals.

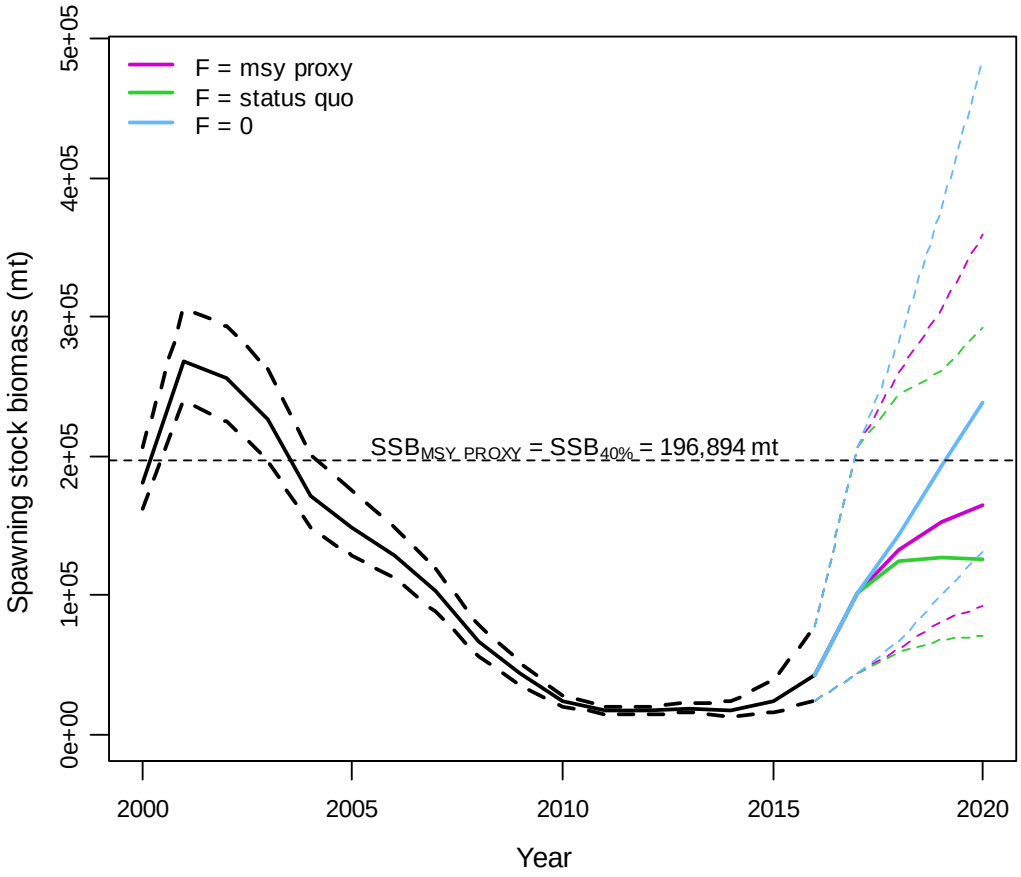


Figure A93: Time series of Atlantic mackerel spawning stock biomass (mt) with three-year projections at $F_{msy\ proxy}$, $F_{status\ quo}$ and F = 0. The solid lines represent the point estimates from the final ASAP model and the median of the projected spawning stock biomass for each fishing scenario. The dotted lines represent the 90% confidence intervals.

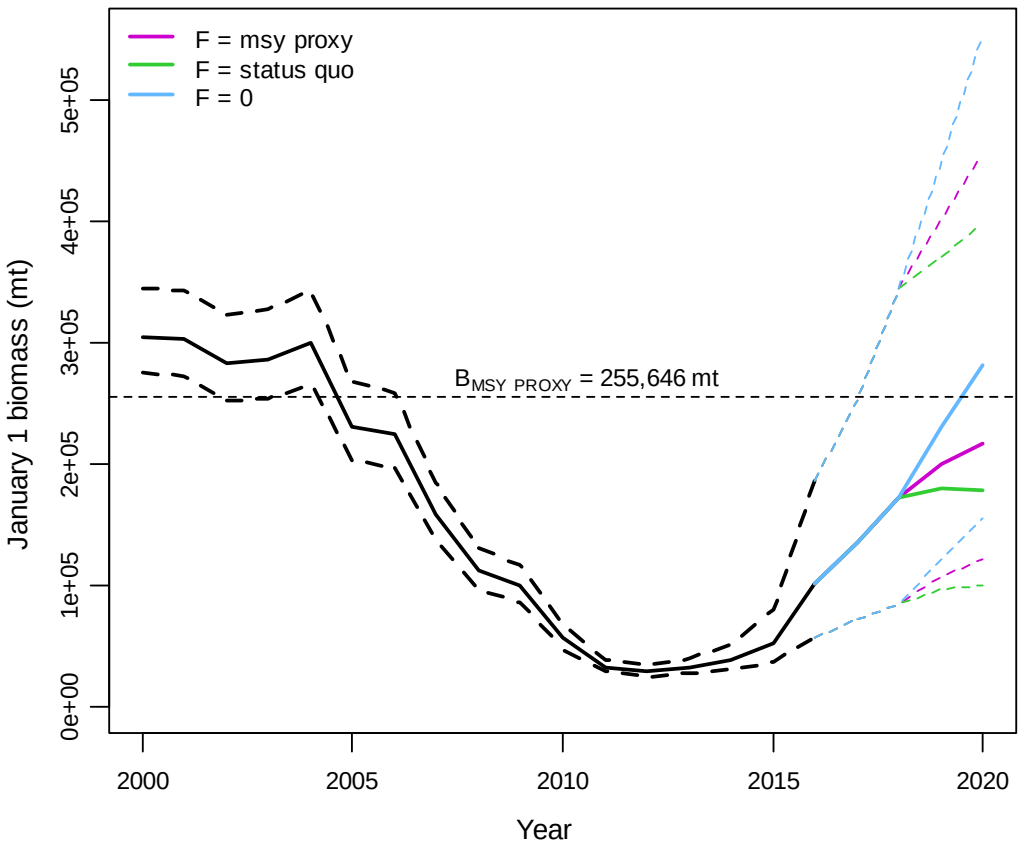


Figure A94: Time series of Atlantic mackerel January-1 biomass (mt) with three-year projections at $F_{msy\ proxy}$, $F_{status\ quo}$ and F = 0. The solid lines represent the point estimates from the final ASAP model and the median of the projected January-1 biomass for each fishing scenario. The dotted lines represent the 90% confidence intervals.

APPENDICES

Appendix A1: Additional analyses provided during the SARC-64 peer review

Appendix A2: Secor, D., G. Redding, M. Castonguay. Contingent Mixing by Atlantic mackerel sampled in the Spring NEFSC Trawl survey: Inferences from otolith stable isotope analysis

Appendix A3: Carter, L. and D. Richardson. Development of an egg index for Atlantic Mackerel (*Scomber scombrus*) on the northeast U.S. Continental Shelf

Appendix A4: Smith, B. and S. Gaichas. Mackerel predation estimates from predators sampled in the NEFSC bottom trawl surveys

Appendix A5: Adams, C.F.. Spatial patterns in the spring NEFSC survey for Atlantic mackerel

Appendix A6: Manderson, J., J. Kohut, J. Pessutti, D. Politikos, W.K. Bright, P. Moore, M. Roffer, L. Nazarro, E. Curchister, G. Didomenico. Changes in the spatial structure of Atlantic Mackerel and thermal habitat during the spring NEFSC bottom trawl survey and a winter habitat model accounting for movement constraints. Part I. changes in spatial structure

Appendix A7: Manderson, J.P., J. Pessutti, L. Nazarro, W.K. Bright, J. Kohut, D. Politikos, P. Moore, M. Roffer, E. Curchister, G. Didomenico. Winter habitat for juvenile and adult North West Atlantic Mackerel and its value for for estimating availability to the spring NEFSC bottom trawl survey

Appendix A8: K. Friedland, J. Manning, J. Manderson, and R. Morse. Change in the spatial distribution of mackerel habitat during spring

Appendix A9: K. Friedland, M.C. McManus, R. Morse, M. Castonguay. Physical conditions and lower trophic level ecology in the Atlantic mackerel spawning areas in US and Canadian waters

Appendix A10: Axelson, L., W.K. Bright, G. DiDomenico, G. Goodwin, J. Hoey, J. Knight, M. Lapp, J.P. Manderson, G. McCallig, B.P. Mitchell, P. Moore, R. Mullen, G. O'Neill, P. Quinn, W. Reichle, J. Rhule, C. Sarro. Fishing industry perspectives on the socioecological factors driving catchability and landings of Atlantic Mackerel in US waters

Appendix A11: Sequence of ASAP model configurations

Appendix A12: Deroba, J.. A State-Space Stock Assessment Model (SAM) for Northwest Atlantic Mackerel

Appendix A13: Censored Catch Assessment Model (CCAM) figures

APPENDIX A1: Additional analyses provided during the SARC-64 peer review

Several additional analyses were requested during the review by the Stock Assessment Review Committee (SARC).

The SARC requested an investigation of the impact of assuming flat-topped fishery selectivity in the ASAP sensitivity run that incorporated four time blocks for fishery selectivity. Accordingly, an additional sensitivity run was completed that still assumed four selectivity time blocks but only fixed age-6 selectivity at 1 and estimated age-specific selectivity parameters for all other ages (1-5 and 7-10^+). Resulting age-specific fishing selectivity estimates and Pearson residuals for fishery age-composition data are detailed in Figures 1 and 2, respectively. Furthermore, comparisons of predicted fishing mortality and spawning stock biomass (SSB) estimates between the two runs are detailed in Figures 3 and 4 and Table 1.

The SARC also requested an analysis investigating the impact of assuming multiple fishing fleets (defined as U.S. and Canada) and multiple selectivity time blocks. Consequently, an analysis was completed that summarized the impacts of assuming one versus two fishing fleets and one versus four fishing selectivity time blocks for either the combined or U.S fleet (depending on fleet configuration). Trends in fishing mortality and SSB across these ASAP sensitivity runs are detailed in Figures 5 and 6, respectively. Likewise, estimates of $F_{40\%}$, 2016 fishing mortality and 2016 SSB are detailed in Table 2.

The SARC inquired about the impact of the assumed number of fishing fleets and selectivity time blocks on estimated biological reference points and terminal-year SSB. The biological reference points from the final ASAP run and the sensitivity run with two fishing fleets (U.S. and Canada) and four fishery selectivity time blocks for the U.S. fishing fleet are compared in Table 3. A comparison across ASAP runs of the probability distributions for estimated 2016 SSB from the MCMC analysis is detailed in Figure 7. Furthermore, a comparison of 2016 fishing mortality and SSB estimates across SAM, CCAM and ASAP sensitivity runs is detailed in Table 4 and Figure 8.

Tables

Table 1: Comparison of $F_{40\%}$ and 2016 fishing mortality and spawning stock biomass (mt) estimates from ASAP sensitivity runs with four selectivity time blocks that either assumed flat-topped selectivity at age-6 or fixed only age-6 selectivity at 1 and estimated age-specific parameters for all other ages (1-5 and 7-10^+).

	$F_{40\%}$	F_{2016}	SSB_{2016} (mt)
Flat-topped selectivity	0.32	0.63	42,713
Age-6 selectivity fixed at 1	0.33	0.61	44,108

Table 2: Comparison of $F_{40\%}$ and 2016 fishing mortality and spawning stock biomass (mt) estimates from ASAP sensitivity runs that assumed either one or two fishing fleets (defined as U.S. and Canada) and either one or four time blocks of fishery selectivity for the combined or U.S. fishing fleet (depending on fishing fleet configuration).

	$F_{40\%}$	F_{2016}	SSB_{2016} (mt)
Final ASAP run	0.26	0.47	43,519
1 fleet, 4 selectivity blocks	0.32	0.63	42,713
2 fleets, 1 selectivity block	0.27	0.58	36,660
2 fleets, 4 selectivity blocks	0.31	0.70	35,096

Table 3: Comparison of MSY proxy biological reference point estimates from the final ASAP model and the ASAP sensitivity run with two fishing fleets (U.S. and Canada) and four time blocks of fishery selectivity for the U.S. fishing fleet.

		Estimate	**5th percentile**	**95th percentile**
Final ASAP run	$F_{MSY\ proxy}$	0.26	NA	NA
	$SSB_{MSY\ proxy}$	196,894	108,161	429,550
	$B_{MSY\ proxy}$	255,646	140,103	534,278
	MSY proxy	41,334	22,878	87,281
2 fishing fleets, 4 selectivity blocks for the U.S. fleet	$F_{MSY\ proxy}$	0.3	NA	NA
	$SSB_{MSY\ proxy}$	192,968	105,556	431,704
	$B_{MSY\ proxy}$	251,425	136,997	535,909
	MSY proxy	38,546	21,364	80,863

Table 4: Comparison of $F_{40\%}$ and 2016 fishing mortality estimates across SAM, CCAM and ASAP sensitivity runs.

Model	**Description**	F_{40}	F_{2016}
Base	Base ASAP model	0.26	0.47
119	ASAP: Egg index only	0.26	0.51
121	ASAP: Trawl survey ages 2^+	0.27	0.60
124	ASAP: Annual egg production	0.26	1.73
126	ASAP: U.S. maturity	0.27	0.50
127	ASAP: 4 selectivity blocks	0.32	0.63
129	ASAP: 2 fleets	0.27	0.58
131	ASAP: Censored catch	0.26	0.42
132	ASAP: 1981 start year	0.30	0.50
133	ASAP: 1989 start year	0.31	0.37
135	ASAP: Fix only age-6 selectivity at 1	0.33	0.61
136	ASAP: 2 fleets, 4 sel. blocks for U.S. fleet	0.30	0.70
SAM	Stock Assessment Model		0.59
CCAM	Censored Catch Assessment Model		1.19

Figures

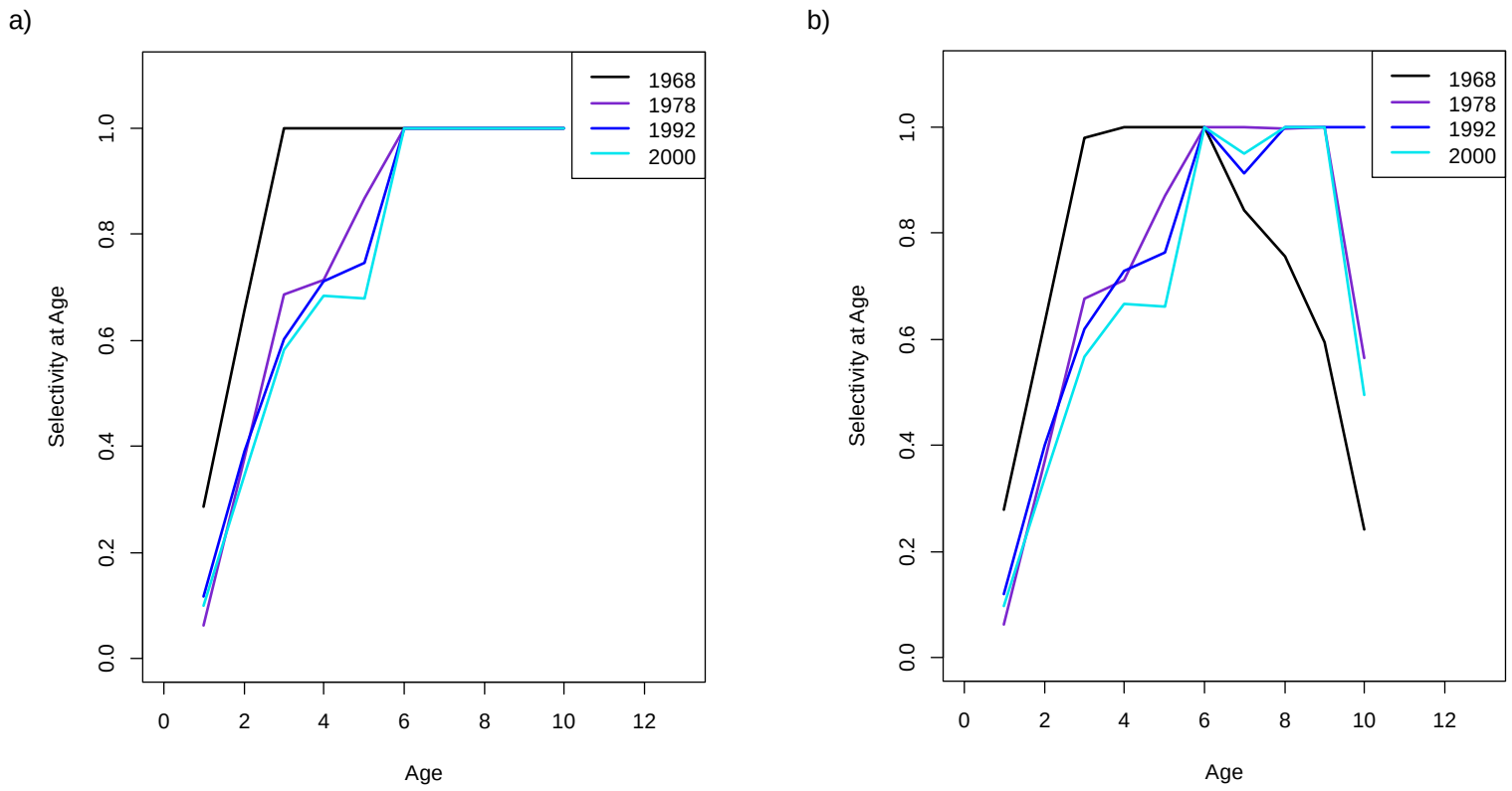


Figure 1: Atlantic mackerel age-specific fishery selectivity estimates for ASAP sensitivity runs with four selectivity time blocks that either (a) assumed flat-topped selectivity at age-6 or (b) fixed only age-6 selectivity at 1 and estimated age-specific parameters for all other ages (1-5 and 7-10^{+}).

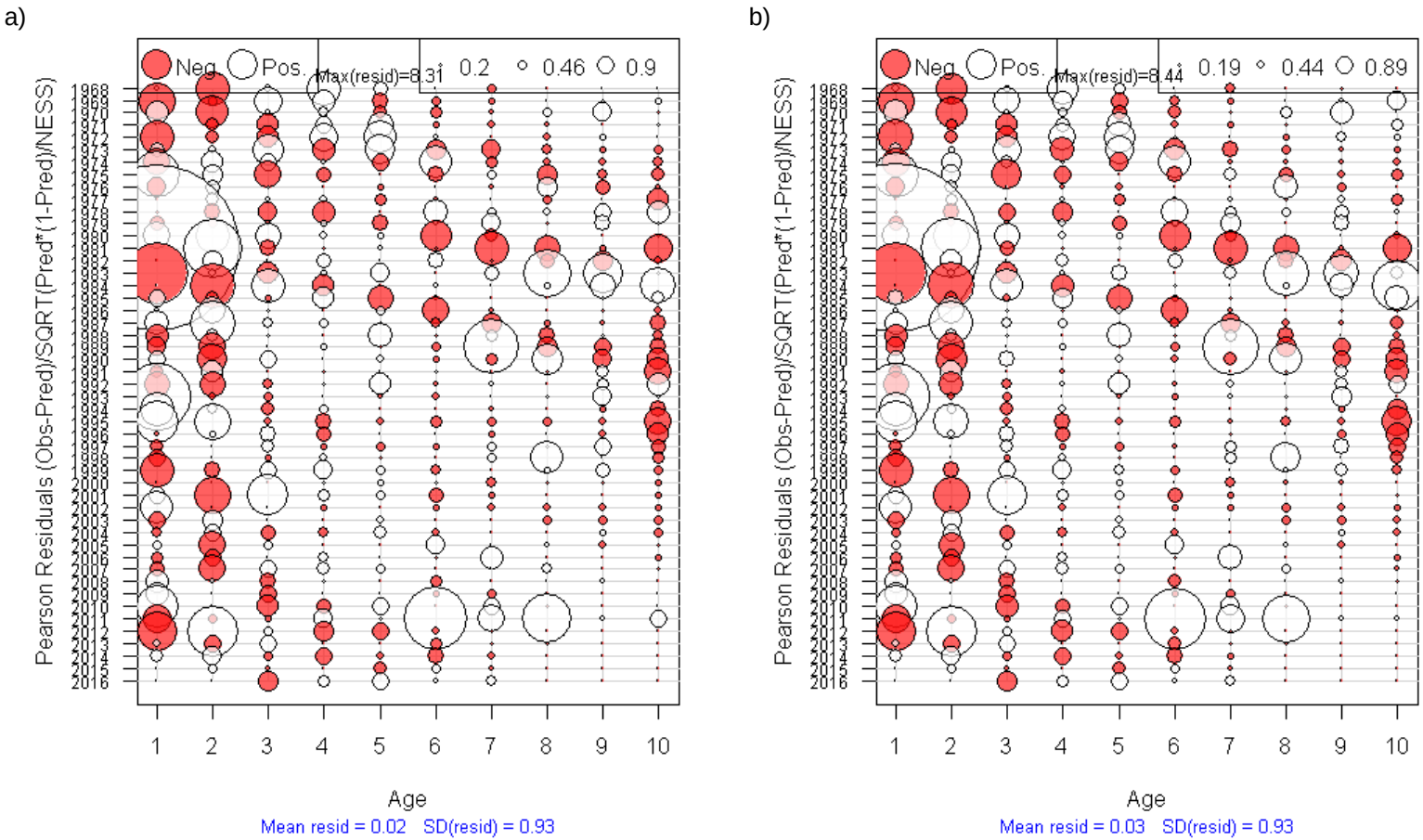


Figure 2: Pearson residuals for fishery age composition data from ASAP sensitivity runs with four selectivity time blocks that either (a) assumed flat-topped selectivity at age-6 or (b) fixed only age-6 selectivity at 1 and estimated age-specific parameters for all other ages (1-5 and 7-10^{+}).

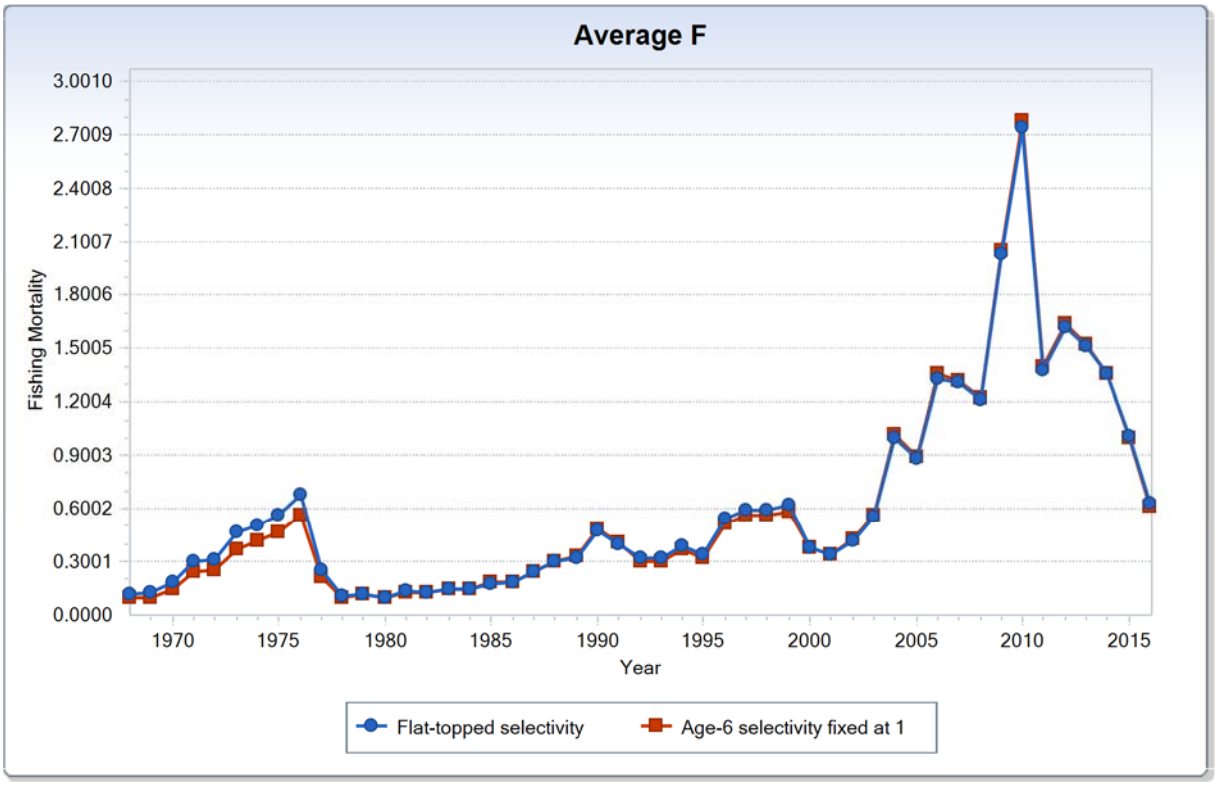


Figure 3: Estimates of Atlantic mackerel fishing mortality from 1968-2016 from ASAP sensitivity runs with four selectivity time blocks that either assumed flat-topped selectivity at age-6 or fixed only age-6 selectivity at 1 and estimated age-specific parameters for all other ages (1-5 and 7-10^{+}).

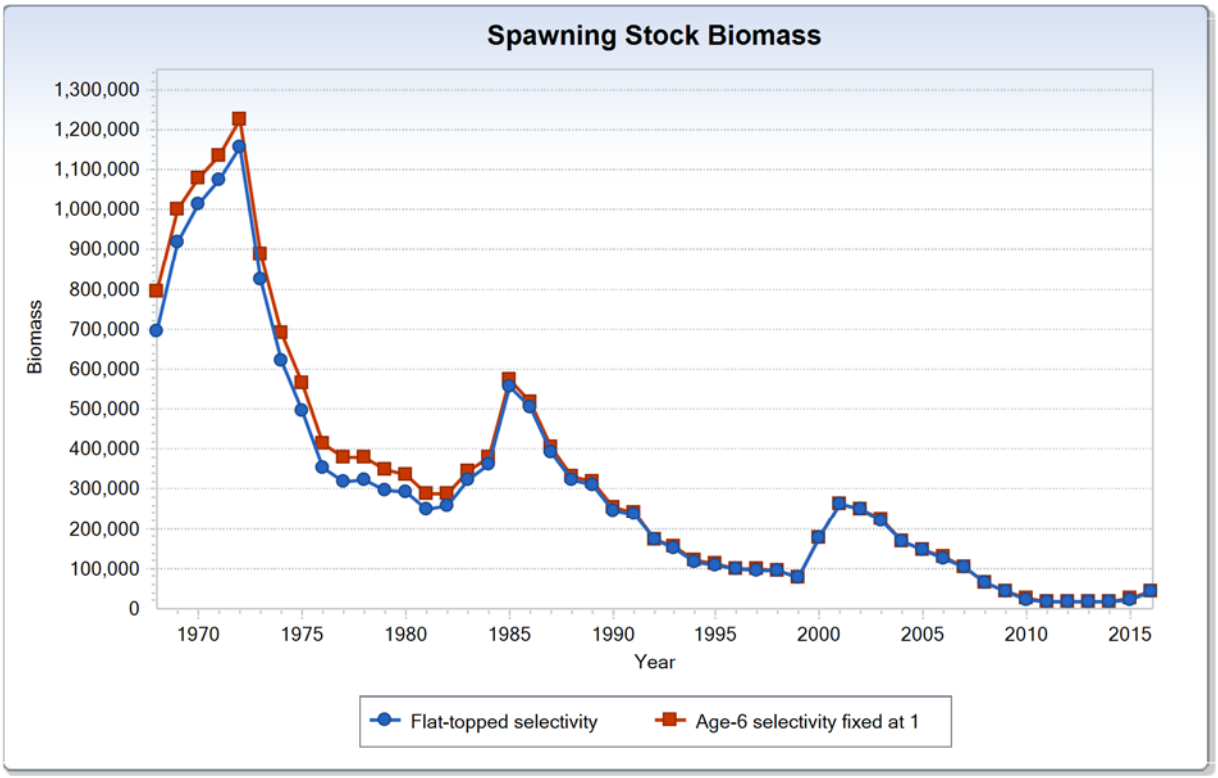


Figure 4: Estimates of Atlantic mackerel spawning stock biomass (mt) from 1968-2016 from ASAP sensitivity runs with four selectivity time blocks that either assumed flat-topped selectivity at age-6 or fixed only age-6 selectivity at 1 and estimated age-specific parameters for all other ages (1-5 and 7-10^{+}).

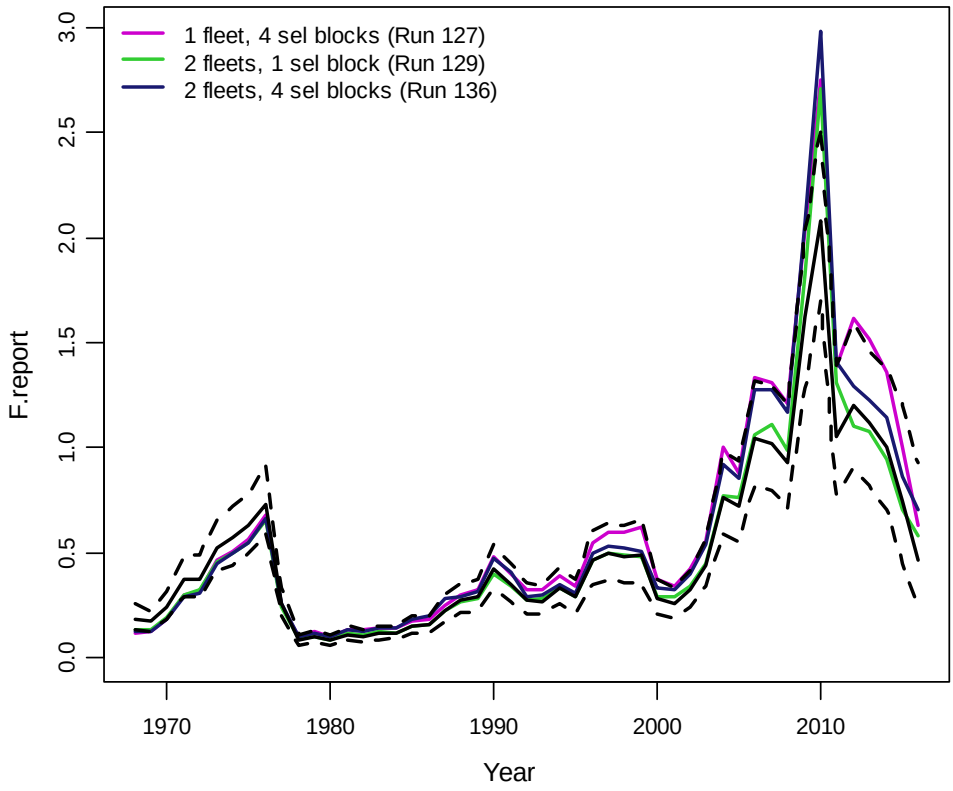


Figure 5: Comparison of Atlantic mackerel average age 6-9 fishing mortality estimates across ASAP sensitivity runs that assumed either one or two fishing fleets (defined as U.S. and Canada) and either one or four time blocks of fishery selectivity for the combined or U.S. fishing fleet (depending on fishing fleet configuration). The solid black line represents the median of the 90th probability interval from the final ASAP model and the black dashed lines represent the 5th and 95th percentiles.

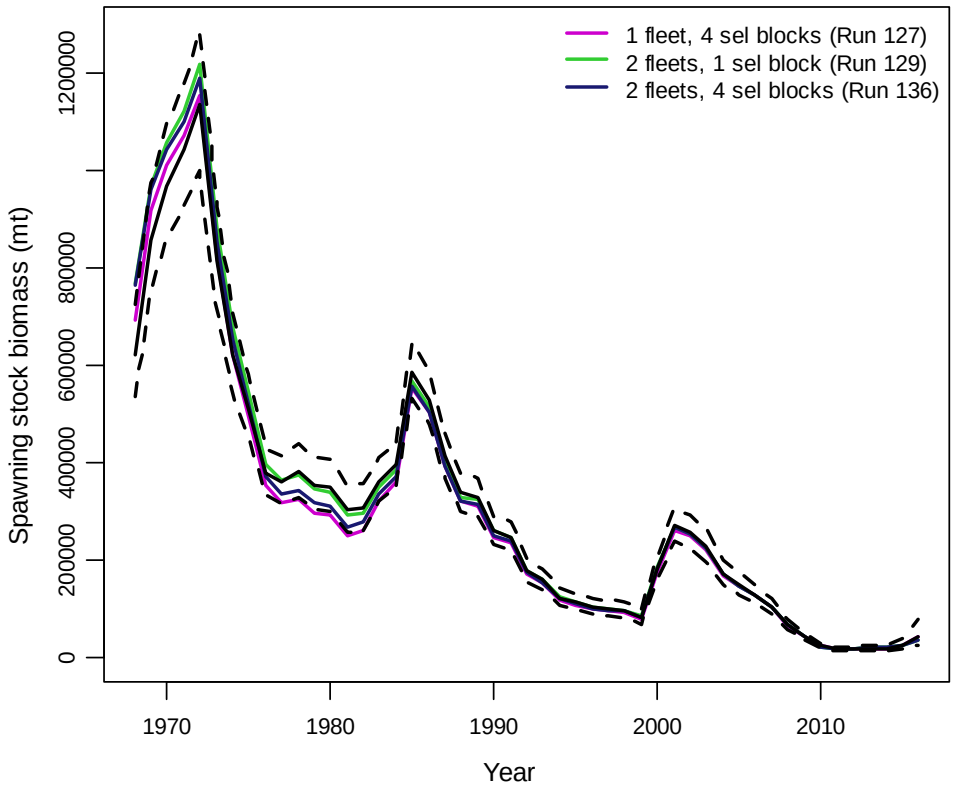


Figure 6: Comparison of Atlantic mackerel spawning stock biomass estimates across ASAP sensitivity runs that assumed either one or two fishing fleets (defined as U.S. and Canada) and either one or four time blocks of fishery selectivity for the combined or U.S. fishing fleet (depending on fishing fleet configuration). The solid black line represents the median of the 90th probability interval from the final ASAP model and the black dashed lines represent the 5th and 95th percentiles.

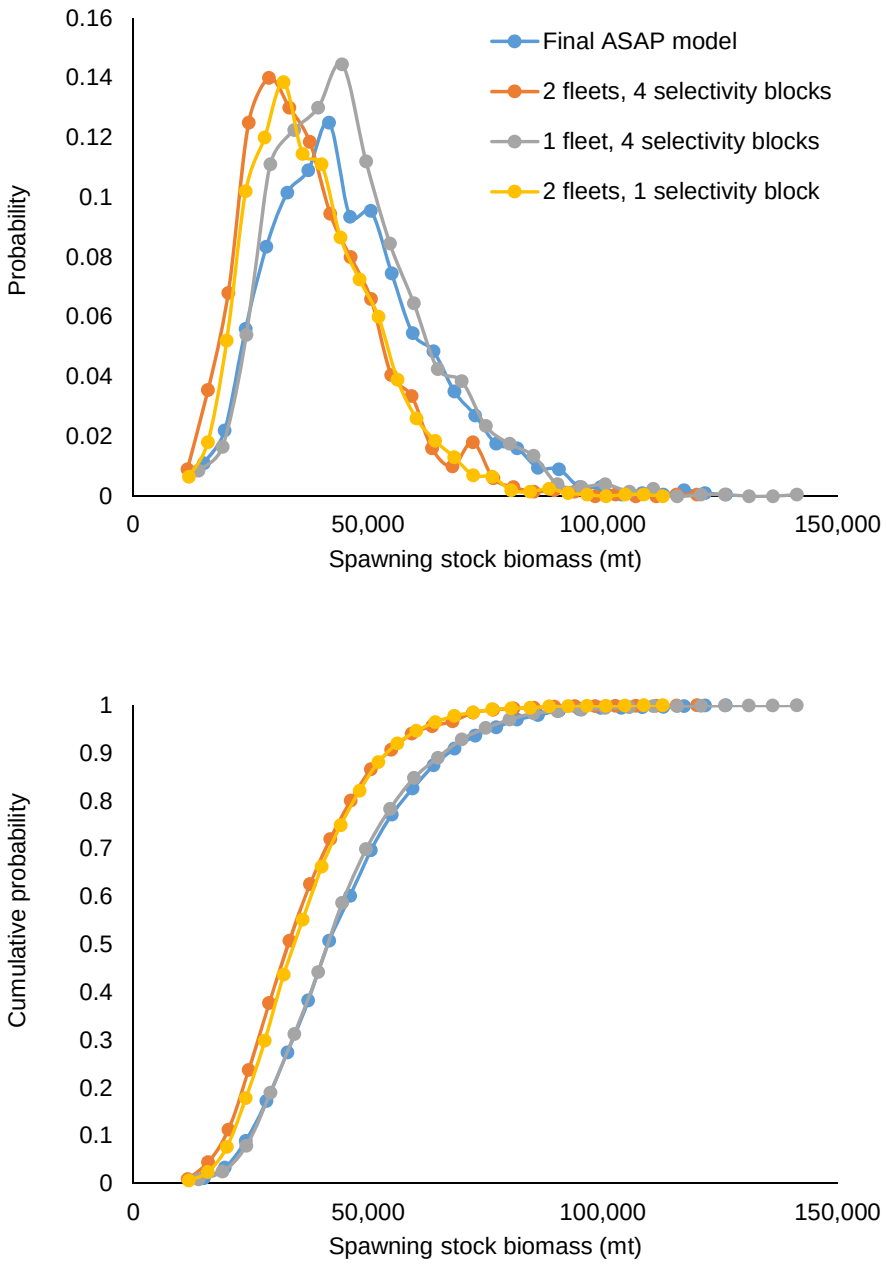


Figure 7: MCMC probability and cumulative probability distributions of estimated spawning stock biomass (mt) in 2016 across ASAP sensitivity runs that assumed either one or two fishing fleets (defined as U.S. and Canada) and either one or four time blocks of fishery selectivity for the combined or U.S. fishing fleet (depending on fishing fleet configuration) .

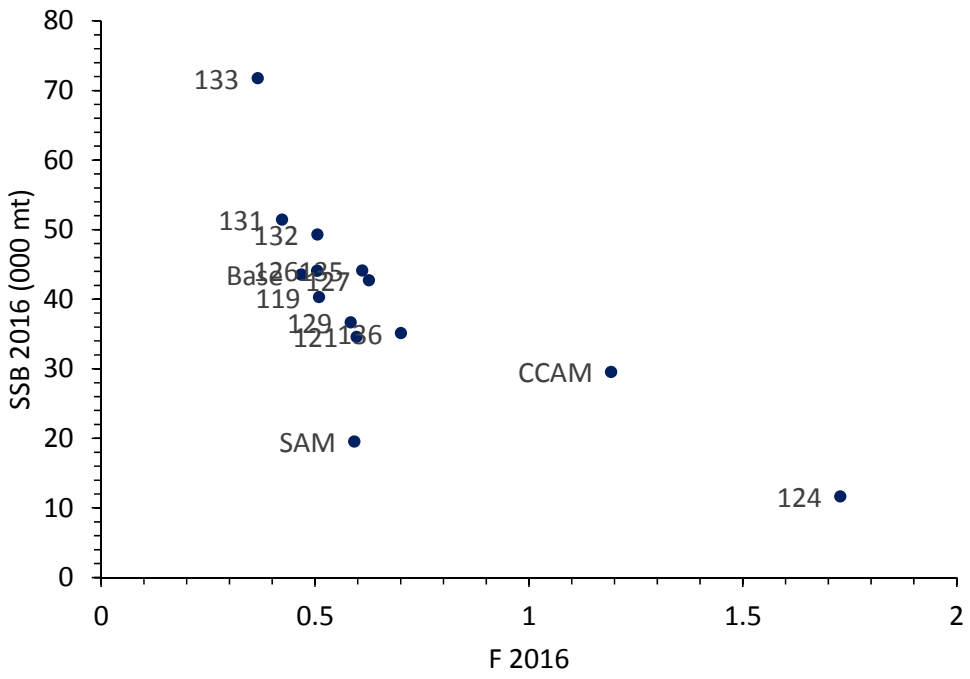


Figure 8: Comparison of 2016 fishing mortality (F) and spawning stock biomass (SSB) estimates across SAM, CCAM and ASAP sensitivity runs. A description of each model run is included in Table 4.

Appendix A2: Contingent Mixing by Atlantic mackerel sampled in the Spring NEFSC Trawl survey: Inferences from otolith stable isotope analysis

Secor, David[1]
Redding, Gray[1]
Castonguay, Martin[2]

[1]University of Maryland Center for Environmental Science
[2]Fisheries and Oceans, Mont Joli, Quebec, Canada

Summary: Stock mixing between the two contingents of NW Atlantic mackerel was evaluated by discriminating juveniles and adults sampled in the Spring NEFSC trawl survey on the basis of otolith stable isotope composition. Natal $\delta^{18}O$ values in milled age-1 juveniles differed significantly between northern (Canada) and southern (US) contingents in accordance with predictions on the effects of $\delta^{18}O$ in seawater and thermal conditions on otolith $\delta^{18}O$ uptake. Higher otolith $\delta^{18}O$ values in adults (age>2) than juveniles for four year-classes (1998-2000, 2011) were consistent with incursions by the northern contingent and stock mixing within the region sampled by the NEFSC trawl survey. Random Forest classifications for year-classes 1998-2000 supported inferences that (1) southern contingent juveniles tended to range within their natal (US) region; and (2) adult (age>2) samples were dominated by northern contingent individuals. An implication of this study is that age-structured assessments of the southern (US) contingent will be biased should they exclusively rely upon the Spring NEFSC trawl survey, owing to substantial contingent mixing within adult age-classes.

Background

The seasonal migrations and spatial ranges of Atlantic mackerel are influenced by population structuring: that is, the propensity of individuals to adopt stock-specific behaviors such as natal homing and seasonal migrations. Stock structure remains highly uncertain for Atlantic mackerel. Nursery regions are very broad and genetic markers have not uncovered strong evidence for reproductive isolation. Past evidence indicates that Atlantic mackerel, like other pelagic stocks, may be structured as contingents: intra-population groups that exhibit similar seasonal migration behaviors (Hjort 1914; Sette 1950; Secor 1999). The two-contingent premise for NW Atlantic mackerel postulates (1) a northern contingent centered in Canada that spawns during summer in the southern Gulf of St. Lawrence in June and July and then moves into Newfoundland, Nova Scotia, Gulf of Maine and perhaps more southern waters in fall and winter; and (2) a southern contingent that spawns (historically) during spring in US mid-Atlantic and Southern New England waters and moves northward to Gulf of Maine and Nova Scotia waters in other seasons (Sette 1950; NEFSC 2016). This two-contingent premise is supported by discrete spawning and nursery areas centered in the Gulf of St. Lawrence and Southern New England waters. Diverse approaches

have been used to test for stock structure including genetic analysis, otolith morphometrics and tagging, but none have demonstrated strong differentiation between the northern and southern contingents (Castonguay *et al.* 1991; Simard et al. 1992; Lambrey de Souza *et al.* 2006).

Patterns of stock (contingent) mixing, if neglected, can create biased and false trends in perceived abundance and stock health. In his classic 1950 review, O. Sette set out to understand the widely fluctuating catches of Atlantic mackerel. By tracking seasonal changes in regional length distributions of commercial catches, Sette inferred abrupt appearance of novel cohorts in fisheries (those with unique size distributions) and tracked the seasonal migrations by the northern contingent into southern US fisheries. This pattern was corroborated by a subsequent analysis of size distributions and tag-recapture data (Moores et al. 1975), in which the authors concluded that US fisheries received substantial seasonal subsidies from a dominant northern contingent, but that the southern contingent did not contribute in a substantive way to Canadian fisheries. At a recent workshop, commercial fishers from Southern New England remarked that historically - prior to 1999 - they too witnessed pulses of larger fish in winter, which they assumed originated from Canadian waters (Manderson et al. 2017a). This was an important segment of the regional fishery that apparently is no longer available to them.

Here we evaluate the hypothesis that Spring NEFSC trawl samples of Atlantic mackerel may represent recruitments and abundances of older individuals, comprised of both southern and northern contingents. This question bears on the upcoming benchmark stock assessment (SARC 64) planned for late summer 2017. Currently NMFS NEFSC assesses both northern ("Canadian) and southern ("US") contingents as part of the same unit stock, whereas Fisheries and Oceans Canada assesses the northern contingent separately. By deploying newly developed otolith stable isotope composition analysis (Redding 2017), we investigated the contingent-source of certain year-classes and ages of Atlantic mackerel captured in the Spring NEFSC trawl survey.

Assessing contingent mixing through stable isotope analysis of otoliths

We have developed an approach to classify contingents in mixed Atlantic mackerel samples (Redding 2017). Atlantic mackerel contingents are identified by where their members occurred during their first growth season (nursery habitat). Increasingly, oxygen and carbon isotopic composition of otoliths has been used to distinguish nursery habitats and evaluate natal homing (Secor 2015). Atlantic mackerel are exposed to NW Atlantic shelf waters of differing salinity and temperature, which results in consistent regional differences in the otolith stable isotope composition of mackerel collected from US and Canada (Redding 2017). Coastal mixing of waters from the Gulf Stream and Labrador currents result in salinity gradients across Southern New England, Gulf of Maine and Gulf of St. Lawrence shelf surface waters, which are reflected in the ratio between two oxygen isotopes, ^{18}O and ^{16}O (Fairbanks 1982). By convention this ratio is described relative to a standard carbonate, and expressed as a $\delta^{18}O$ value. In marine fish otoliths,

the $\delta^{18}O$ value typically ranges between -3 and 3‰ relative to the standard, which is set by convention to be 0. Surface salinity generally decreases with latitude, depending in part on the northward position of the Gulf Stream (NEFSC 2009). Sea surface $\delta^{18}O$ values similarly decline at higher latitudes (McMahon et al. 2013). However, the influence of temperature is a more dominant influence on otolith $\delta^{18}O$ values than the oxygen isotope composition of ambient seawater. As temperature declines, incorporation of the heavier ^{18}O isotope into carbonate is favored by isotopic equilibrium, and this isotopic fractionation is responsible for a positive latitudinal gradient in otolith $\delta^{18}O$ composition on the NW Atlantic Shelf in response to cooler temperatures. Based on laboratory-derived otolith fractionation estimates (Høie et al. 2004) and available surface seawater $\delta^{18}O$ data from throughout the North Atlantic (LeGrande and Schmidt 2006), Trueman et al. (2012) developed an "isoscape" of predicted isotopic composition for cod (*Gadus morhua*) otoliths in surface waters (Figure 1). Note the strong positive gradients between US (negative $\delta^{18}O$ values) and Canadian and Icelandic (positive $\delta^{18}O$ values) shelf waters.

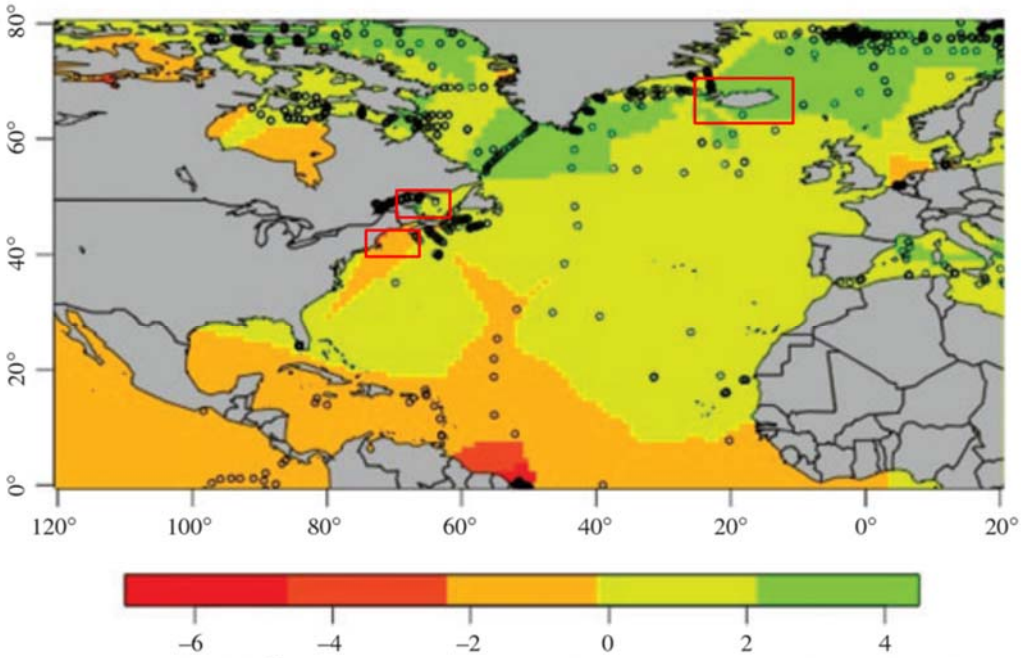


Figure 1. Interpolated otolith $\delta^{18}O$ composition across the North Atlantic Ocean. Note the general latitudinal trend for increasing otolith $\delta^{18}O$ values owing to increased fractionation, which occurs at colder temperatures. Open circles indicate sites where sea surface $\delta^{18}O$ data were used to support this "isoscape." Figure extracted from Figure 1 in Trueman et al. (2012). Regions associated with mackerel collected in US, Canada, and Iceland are shown in red rectangular boxes.

Regional differences observed in Atlantic mackerel otolith $\delta^{18}O$ values conform remarkably well to predicted differences owing to source water composition and temperature fractionation (Figures 1, 2), but also suggest regional differences that are influenced by annual variations related to weather and ocean circulation (Redding 2017). Material isolated for the juvenile period from otoliths of age-1 Atlantic mackerel showed significant separation for pooled samples

between the Northeast Atlantic (Iceland-Norway) and Northwest Atlantic (US-Canada) in accordance with predictions of elevated $\delta^{18}O$ in the otoliths of the former group. US and Canada samples overlapped broadly, but as shown below, on a year-class specific basis, US age-1 and age-2 otolith samples had consistently lower $\delta^{18}O$ values than Canadian samples (Table 1), again in accordance with predictions based on temperature fractionation. The overall range of mackerel otolith $\delta^{18}O$ values over the available data from the North Atlantic is lower than the range predicted in Trueman et al.'s isoscape analysis (Figure 1) perhaps owing to species-specific fractionation or differences between projections used in the Trueman et al. (2012) predictions and actual seawater conditions.

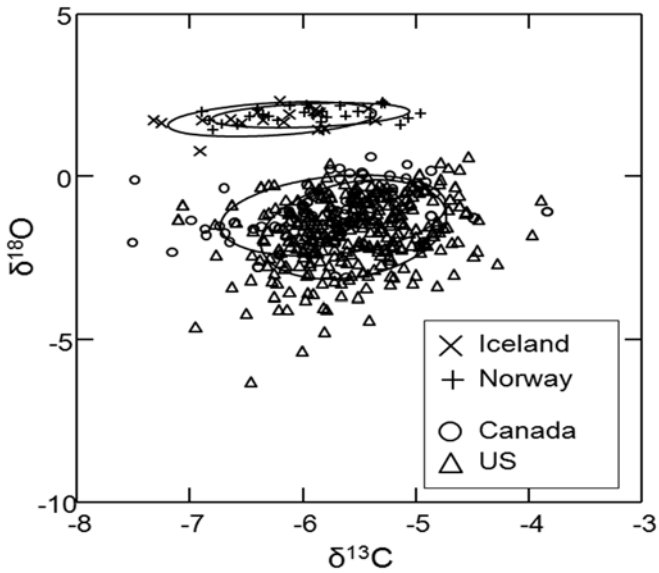


Figure 2. Scatterplot of otolith $\delta^{18}O$ and $\delta^{13}C$ for Atlantic mackerel samples collected in Iceland, Norway, Canada and US. Data and analysis are reported in Redding (2017).

Objective

Classify contingent-origin for age 2-5 Atlantic mackerel collected for four year-classes (1998, 1999, 2000, 2011) from the Spring NEFSC trawl survey.

Approach

Atlantic mackerel otolith samples (Table 1) were obtained from archives held at the Fisheries Biology Program at the NEFSC in Woods Hole, Massachusetts, United States; and Fisheries and Oceans, Maurice Lamontagne Institute, Mont-Joli, Quebec, Canada. US otolith samples were collected from the Spring NEFSC trawl survey. Canadian otoliths were collected from fishery-dependent sampling of mackerel principally captured in the Gulf of St. Lawrence and on the

Scotian Shelf. To the extent possible, principal sub-regions were represented for each survey (Figure 3). Otoliths had been previously aged through visual interpretations of their annuli by NEFSC and DFO experts.

Table 1. Samples of Northwest Atlantic mackerel otoliths obtained from US and Canadian Sources. Mean $\delta^{18}O$ values and SD correspond to milled material deposited during the first year of life.

Country	Age	N	$\delta^{18}O$ Mean	$\delta^{18}O$ SD
1998 Year-Class				
Canada	1	15	-1.40	0.84
Canada	2	13	-0.60	0.44
US	1	32	-3.27	0.96
US	2	21	-2.18	0.69
US	3	19	-0.58	0.56
US	5	2	-0.57	0.51
1999 Year-Class				
Canada	1	12	-1.18	0.33
Canada	2	15	-1.29	0.38
US	1	27	-2.66	0.87
US	2	30	-2.13	0.51
US	4	23	-1.05	0.50
2000 Year-Class				
Canada	1	12	0.00	0.34
US	1	39	-2.09	0.76
US	3	15	-0.35	0.50
2010 Year-class				
Canada	2	19	-1.66	0.76
2011 Year-class				
US	1	20	-1.32	0.49
US	2	20	-1.53	0.45
US	3	20	-1.07	0.56
US	4	20	-0.89	0.48

According to developed and tested protocols (Redding 2017), the otolith region corresponding to the first year of growth was isolated and powdered using a New Wave Research Micro-Mill (Figure 4). Otolith powders were analyzed for $\delta^{18}O$ and $\delta^{13}C$ values using a ThermoFisher Delta Plus stable isotope mass spectrometer operated in a continuous flow mode following flushing with high-purity helium and reaction with purified and dried phosphoric acid. Analytical precision of this mass spectrometer for carbonates is better than ±0.1% for $\delta^{18}O$ (±1 standard deviation,

SD). Isotope ratios are calibrated based on repeated measurements of internal otolith standards calibrated to the NBS-19 and NBS-18 carbonate standards and data are reported relative to the international Vienna PeeDee Belemnite (V-PDB) standard.

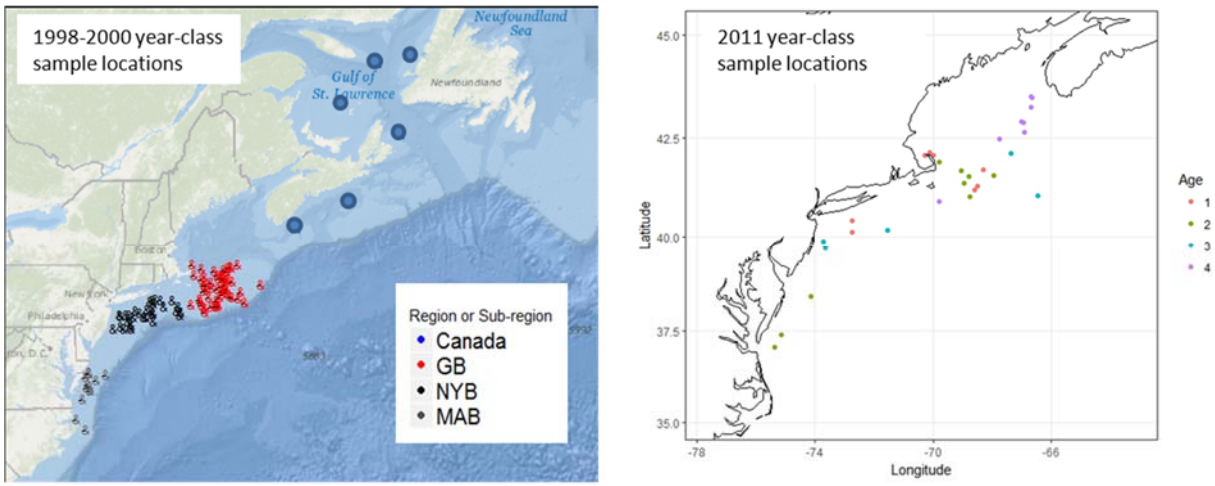


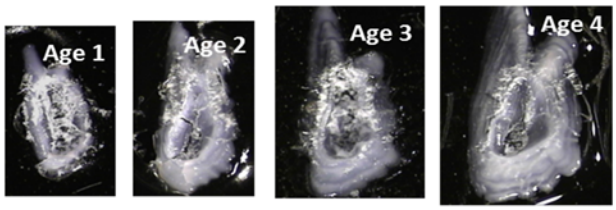
Figure 3. Map depicting sample locations for Atlantic mackerel otoliths from the Northwest Atlantic, including Canadian and US samples for year-classes 1998-2000 (left panel; from Redding 2017) and year-class 2011. For US samples, the points indicate the Spring NEFSC trawl survey tows in which the fish was captured. For Canadian samples, the point indicates the approximate center of the statistical areas from which samples were collected. GB=Georges Bank, NYB=New York Bight, MAB=Mid-Atlantic Bight. For the 2011 year-class, sample locations are given by age-class.

We assigned individuals to contingents based upon a Random Forest classification approach. Random Forest classification assumes no underlying distribution and is a resampling methodology, which recursively assigns data subsets into binary groups, maximizing homogeneity within each group. Hundreds of resampled trees are combined through "majority rules" (Cutler et al. 2007). Mixed unknown samples were classified according to year-class. Each classification procedure yielded a probability that an individual is correctly classified as one or the other contingent. Our assignment convention was >0.5 classification probability to one or the other contingent. Given this stringent threshold we also evaluated mixing through mean estimates of individual assignment probabilities to the Canadian contingent.

Results

Age-specific differences in $\delta^{18}O$ values

For Spring NEFSC trawl samples, all year-classes showed a general pattern of increasing $\delta^{18}O$ values with age (Figure 4). For all year-classes except 2011, $\delta^{18}O$ values were higher at ages >2 than for age 1 (Tukey posthoc test; $p<0.05$). Year-classes 1999 and 2011 showed similar $\delta^{18}O$ levels between ages 1 and 2. Recall that $\delta^{18}O$ data represent otolith material formed during the first year of life across all age-classes. Thus the null hypothesis is that $\delta^{18}O$ values should not change between ages. As $\delta^{18}O$ values departs from the age-1 baseline, the inference is that there is a second natal source at older ages.



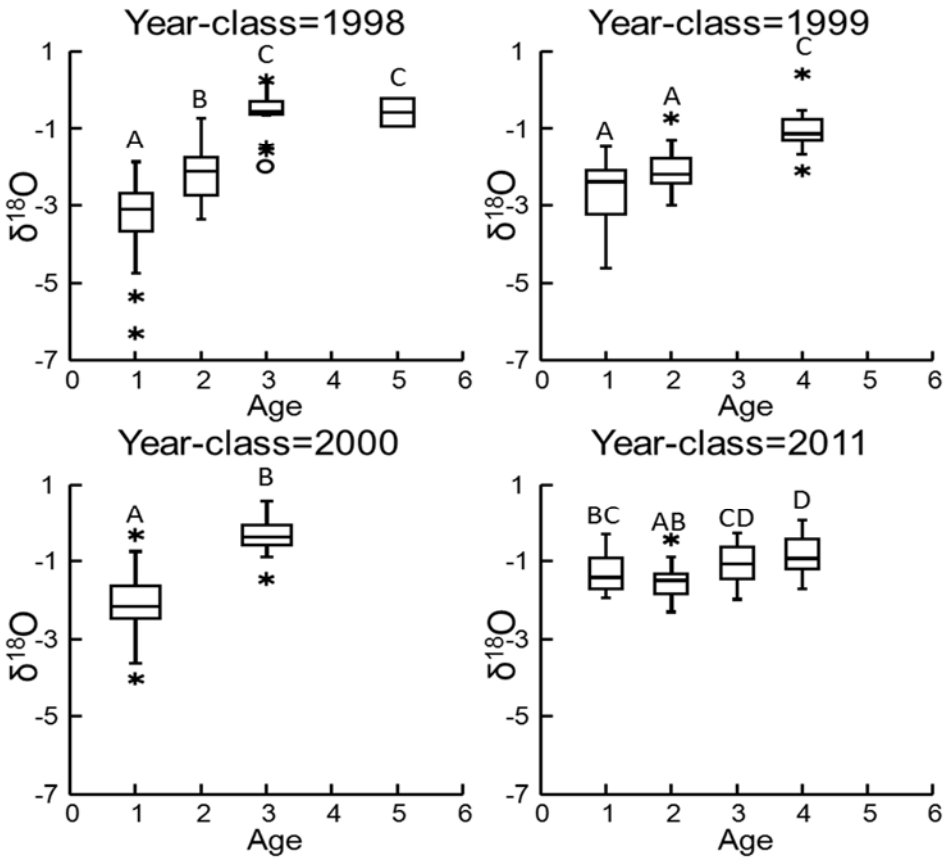


Figure 4. Top panel: Series of micrographs showing portion of milled natal otolith material for juvenile and adult otoliths; Bottom panels: Box whisker plots of age-specific natal otolith $\delta^{18}O$ levels by year-class. Ages with different letters correspond to statistically differing groups (ANOVA; Tukey posthoc test).

Classification of contingents by year-class

For year-classes 1998-2000, US age-1 juvenile otoliths exhibited significantly lower $\delta^{18}O$ values than Canadian samples in accordance with predictions of expected stable isotope incorporation into carbonate between these regions (Figure 5; ANOVA: $\delta^{18}O$ = Country + Year + error; significance for both factors: p=0.01). Note that there is also a strong effect of year on the overall levels of $\delta^{18}O$ values, with both countries showing increasing trends from the 1998 to 2000 year-classes. The US juvenile $\delta^{18}O$ values for the 2011 year-class were substantially higher than other year-classes (Figure 4; Table 1). Regrettably Canadian age-1 juveniles for the 2011 year-class were unavailable for analysis.

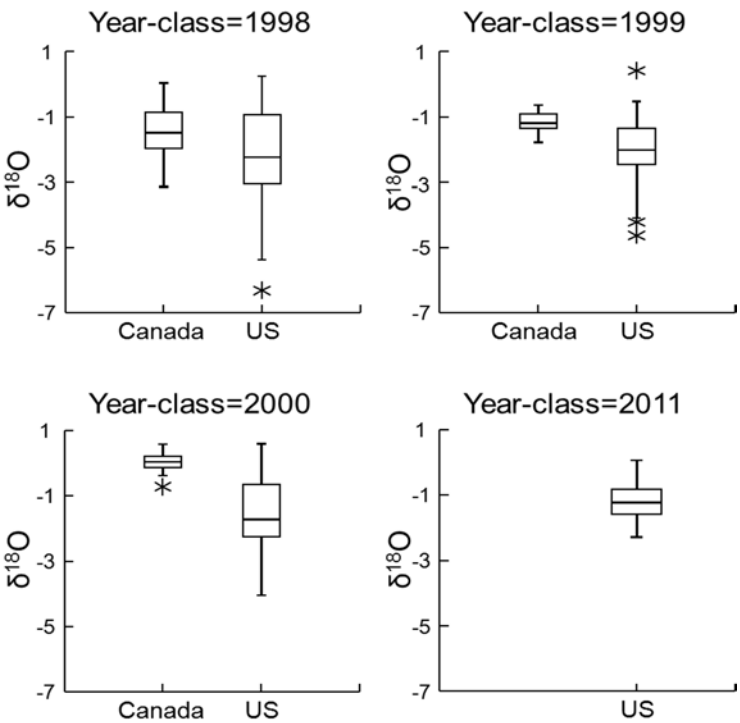


Figure 5. Box-whisker plots of natal otolith $\delta^{18}O$ values between contingents (Canada v. US) and year-classes.

Differences in the natal $\delta^{18}O$ values between US and Canada juveniles supported Random Forest classifications separating the two associated contingents. Assignment probabilities to the

Canadian (northern) contingent showed a threshold of rapidly changing probabilities over a narrow intermediate range of $\delta^{18}O$ values for the 1998-2000 year-classes (Figure 6).

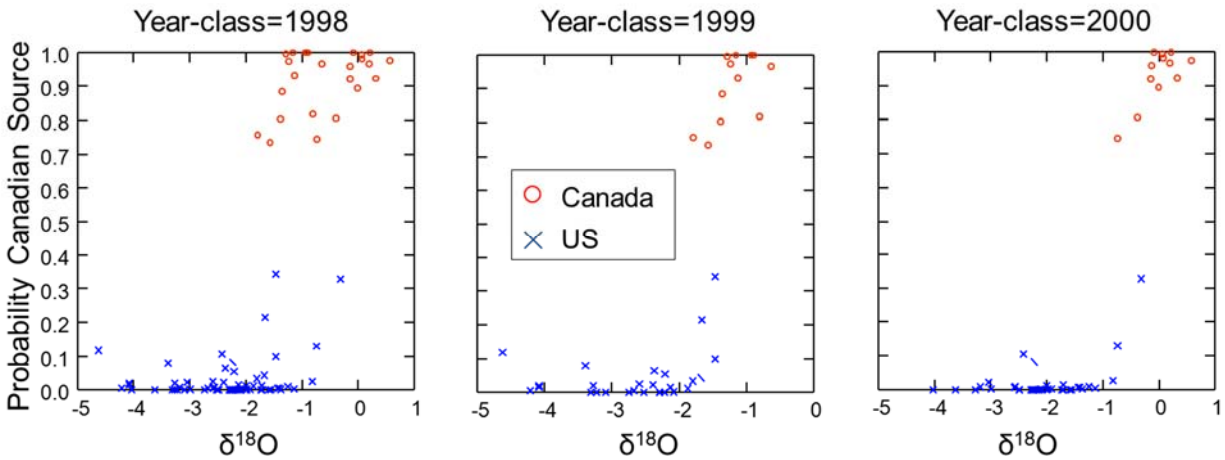


Figure 6. Random Forest assignment probabilities for age-1 juveniles versus otolith natal $\delta^{18}O$ values for 1998 (top), 1999 (middle), and 2000 (bottom) year-classes. Probabilities represent the probability of northern (Canada) contingent membership.

Contingent classification by age-class

Classifications of age year 2-5 fish to the Canadian contingent showed a similar trend across 1999-2000 year-classes with a low level of mixing at age 2 and increased probability of Canadian assignment at older age-classes (Figure 7). Two measures of contingent assignment were employed: (1) Mean individual assignment probability and (2) classification of individuals based on the probability of assignment >0.5. Both measures showed similar trends (Figure 7). The 1998 year-class exhibited the strongest shift towards Canadian contingent membership at older ages; other year-classes showed greater mixing between the two contingents at ages > 2. Still, across year-classes both measures indicated that the Canadian contingent contributed the majority of adults sampled in this study.

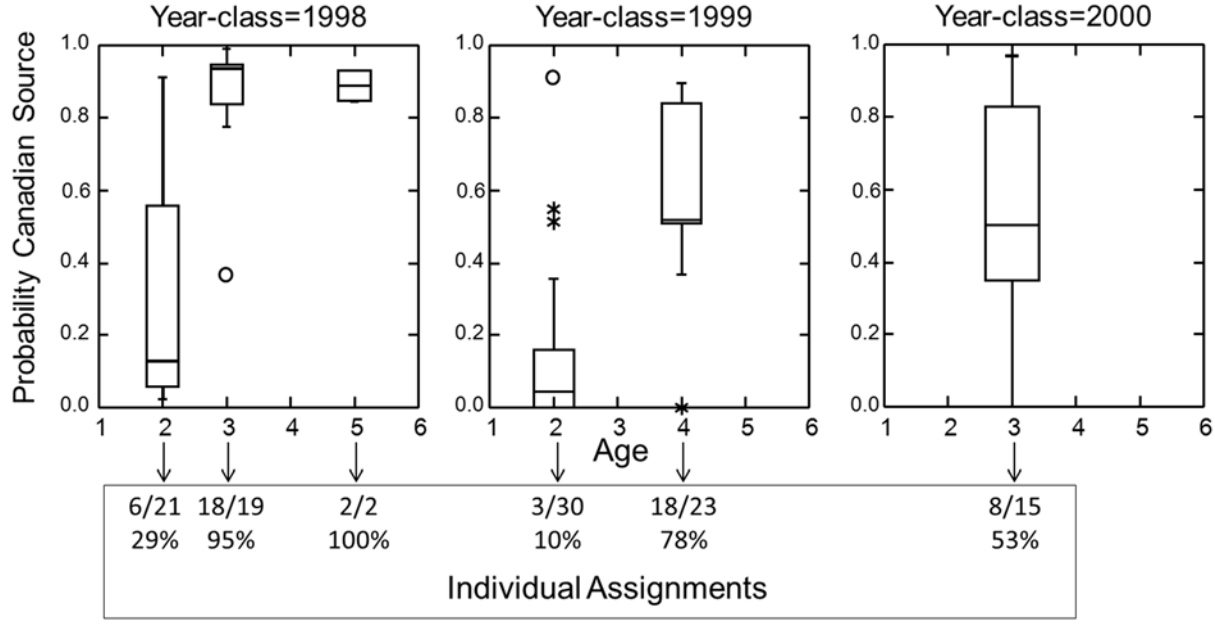


Figure 7. Random Forest classification of age-classes for three year-classes of Atlantic mackerel sampled in the Spring NEFSC trawl survey. Box whisker plots represent the distribution of all probabilities of classification to the northern contingent. Below the box plots, individuals are classified based on a probability of assignment>0.5.

Discussion

Contingent mixing through lens of otolith stable isotope analysis

Otolith $\delta^{18}O$ analysis supported separation of Atlantic mackerel populations and contingents, owing to the influence of regional thermal regimes between (1) the Northeast and Northwest Atlantic; and (2) Canadian and US regions of the Northwest Atlantic (Figures 1-3; Redding 2017). Within the Northwest Atlantic, thermal conditions and seawater levels of $\delta^{18}O$ will vary seasonally and annually owing to oceanographic conditions. These in turn will influence contingent classification on an annual basis, requiring careful consideration towards developing year-class specific baselines that are representative of each contingent's juvenile distribution. Redding (2017) examined analytical precision in $\delta^{18}O$ measurement (milling and instrumental precision) and classification error associated with differing statistical approaches (e.g. Random Forest, Logistic Regression, Quadratic Discrimination Function analysis). He observed that these

sources of error did not influence inferences related to age-specific contingent membership reported here.

Operationally, we defined contingents based on where an age-0 fish grew during their first year of life: either in US or Canadian portions of the NW Atlantic. We milled otolith material associated with this juvenile phase from age-1 juveniles collected from the Spring NEFSC trawl survey or summer Canadian fisheries. We are thus assuming that prior to their capture, age-1 fish remained in their respective nurseries. The strong separation in age-1 $\delta^{18}O$ levels between US and Canadian samples support this assumption. In 1998 and 1999, age-2 natal $\delta^{18}O$ levels were similar to age-1 levels, supporting continued regional fidelity, albeit with some level of mixing apparent (Figure 4). Higher rates of emigration by the Canadian contingent into US water at older ages was supported by higher natal $\delta^{18}O$ values in adult samples. This was supported by Random Forest classifications for year-classes 1998-2000. For the 2011 year-class, this inference was solely supported by age-specific trends in $\delta^{18}O$ levels for US samples (Figure 4).

Contingent mixing through the lens of migration behavior

Results presented here support traditional concepts of contingent structure for NW Atlantic mackerel and their respective seasonal migrations. Landings data and surveys of commercial fishers (Sette 1950; Manderson et al. 2017a) indicated that contingent migrations are rapid and far ranging during spring (March-April) months, but that juveniles and adults show different distribution patterns across shelf waters and migrate at different rates. Sette inferred from length frequency analyses that juveniles tended to range closer to their natal regions than did adults. Historically, adults of the southern contingent were hypothesized to make early northward coastal migrations from southern regions in nearshore shelf waters off Cape Hatteras and the southern Mid-Atlantic Bight to spring spawning areas centered in southern New England waters. Since 1999, Manderson et al. (2017a, b) suggest that these inshore migration runs have become rare and that the overall distribution has shifted to regions northeast of the Hudson Canyon. Under the premise that southern adult distributions during early spring historically comprised the southern contingent, this could explain the dominance of northern contingent adults in more recent years' spring samples.

As the southern contingent migrates northeastward in the spring, Sette (1950) hypothesized that it was joined by some members of the northern contingent north of the Hudson Canyon. Thus fisheries in southern New England during spring and early summer were supported by both contingents. The northeastward shift in Atlantic mackerel distributions observed in landings and the Spring NEFSC trawl survey (Overholtz et al. 2011; Manderson et al. 2017 a,b) would be consistent with a high level of contingent mixing in samples of adults drawn from the trawl survey during the last decade. Currently available otolith stable isotope data are insufficient to draw inferences on how contingents may segregate across sub-regions of the US EEZ (Redding 2017),

but such a study is feasible using NEFSC archived samples and would improve our understanding of contingent-specific migration patterns.

Contingent mixing through the lens of the NEFSC trawl survey

The NEFSC trawl survey intercepts Atlantic mackerel during a period in which their migrations are highly dynamic. These migrations can results in a biased representation of abundance, which depends on thermal conditions at the time of sampling, the inclusion of inshore sampling strata (lacking since 2008), and complex schooling behaviors (Manderson et al. 2017b). Another important bias is how the southern (US) contingent is represented in the survey. Results reported here suggest that the trawl survey predominantly samples the southern contingent during the juvenile period (ages 1 and 2), but that adult samples (ages>2) represent a mixture of northern and southern contingent fish. For the year-classes that we sampled (1998-2000, 2011), adults received dominant contributions from the northern contingent. Age-structured assessments of the southern (US) contingent that exclusively rely upon the Spring NEFSC trawl survey will be biased, particularly if contingents vary in underlying recruitments; or growth, reproduction or exploitation rates.

Acknowledgments

Support for this research came from the Saltonstall Kennedy Program and the Mid-Atlantic Fishery Management Council. Lee Cooper is a principal collaborator and will serve as a co-author on published findings. Mike O'Brien assisted in modifying G. Redding's Random Forest R script (Redding 2017). Caroline Wiernicki assisted with otolith and data analysis associated with 2011 year-class samples. Sandy Sutherland, Richard McBride, and Mélanie Broudreau assisted in securing archived otoliths.

References

Castonguay, M., P. Simard, and P. Gagnon. 1991. Usefulness of Fourier-analysis of otolith shape for Atlantic mackerel (*Scomber scombrus*) stock discrimination. Canadian Journal of Fisheries and Aquatic Sciences 48(2):296-302.

Cutler, D. R., T. C. Edwards, K. H. Beard, A. Cutler, and K. T. Hess. 2007. Random forests for classification in ecology. Ecology 88(11):2783-2792.

Fairbanks, R. G. 1982. The origin of continental-shelf and slope water in the New York Bight and Gulf of Maine - evidence from $H_2^{18}O/H_2^{16}O$ ratio measurements. Journal of Geophysical Research-Oceans and Atmospheres 87(NC8):5796-5808.

Hjort, J. (1914). Fluctuations in the great fisheries of Northern Europe. Conseil Permanent International Pour L'exploration de la Mer. 20: 1-228.

Høie, H., C. Andersson, A. Folkvord, and O. Karlsen. 2004. Precision and accuracy of stable isotope signals in otoliths of pen-reared cod (*Gadus morhua*) when sampled with a high-resolution micromill. Marine Biology 144(6):1039-1049.

Lambrey de Souza, J., Sévigny, J., Chanut, J., Barry, W. F., and Grégoire, F. 2006. High genetic variability in the mtDNA control region of a Northwestern Atlantic teleost, *Scomber scombrus* L. Canadian Technical Report of Fisheries and Aquatic Sciences: 33 p.

LeGrande, A.N., Schmidt, G.A., 2006. Global gridded data set of the oxygen isotopic composition in seawater. Geophysical Research Letters 33.

MAFMC (Mid Atlantic Fishery Management Council) Scientific and Statistical Committee. 2015. Memorandum, Report of May 2015 Meeting on squids, butterfish and Atlantic mackerel. https://static1.squarespace.com/static/511cdc7fe4b00307a2628ac6/t/555e328de4b0e15bc3f35256/1432236685060/May+2015+SSC+Report.pdf

Manderson, J.P. and 16 co-authors. 2017a. Fishing industry perspectives on the socioecological factors driving catchability and landings of Atlantic Mackerel in US waters. SARC-64 Atlantic Mackerel Data working paper. 33 p.

Manderson, J.P., J. Kohut, J. Pessutti, D. Politikos, W.K. Bright, P. Moore, M. Roffer, L. Nazarro, E. Curchister, and G. Didomenico. 2017b. Changes in the spatial structure of Atlantic Mackerel and thermal habitat during the spring NEFSC bottom trawl survey and a winter habitat model

accounting for movement constraints. Part I. changes in spatial structure. SARC-64 Atlantic Mackerel Data working paper. 13 p +.

McMahon, K. W., L. L. Hamady, and S. R. Thorrold. 2013. Ocean ecogeochemistry: a review. Oceanography and Marine Biology: Annual Review, Vol 51: 327-373

Mercier, L., and 8 coauthors. 2011. Selecting statistical models and variable combinations for optimal classification using otolith microchemistry. Ecological Applications 21(4):1352-1364.

Moores, J. A., G. H. Winters, and L. S. Parsons. 1975. Migrations and biological characteristics of Atlantic mackerel *(Scomber scombrus*) occurring in Newfoundland waters. Journal of the Fisheries Research Board of Canada 32(8):1347-1357.

NEFSC (Northeast Fisheries Science Center). 2016. Summary report for Atlantic Mackerel Population Ecology and Fishery Workshop Industry & Science Perspectives, December 2-3, 2015 55 State Street, Narragansett, Rhode Island, 27 p.

NEFSC (Northeast Fisheries Science Center). 2015. Atlantic Mackerel Update for 2016 Specifications. Report to Mid Atlantic Fishery Management Council. 16 p.

NEFSC (Northeast Fisheries Science Center). 2009. Ecosystem Status Report for the Northeast US Continental Shelf Large Marine Ecosystem. NEFSC Ref. Doc. 09-11. 38 p.

NEFSC (Northeast Fisheries Science Center). 2006. 42nd Northeast Regional Stock Assessment Workshop (42nd SAW) stock assessment report, part A: silver hake, Atlantic mackerel, and northern shortfin squid (CRD 06-09a). U.S. Department of Commerce Northeast Fisheries Science Center Reference Document 06-09a; 284 p.

Overholtz, W. J., J. A. Hare, and C. M. Keith. 2011. Impacts of interannual environmental forcing and climate change on the distribution of Atlantic Mackerel on the US Northeast Continental Shelf. Marine and Coastal Fisheries 3(1):219-232.

Redding, S.G., 2017. Northwest Atlantic mackerel (*Scomber scombrus*) population structure evaluated using otolith stable isotopes. MSc thesis. University of Maryland Center for Environmental Science

Secor, D.H. 2015. Migration Ecology of Marine Fishes. Johns Hopkins University Press. 304 p.

Secor, D.H. 2014. The Unit Stock Concept: Bounded Fish and Fisheries. In S. Cadrin, L. Kerr, and S. Mariani (ed.s) Stock Identification Methods. Elsevier Press.

Secor, D.H. 1999. Specifying divergent migrations in the concept of stock: the contingent hypothesis. Fisheries Research 43: 13-34.

Sette, O.E. 1950. Biology of the Atlantic Mackerel of North America, Part II: Migrations and Habits. Fishery Bulletin 49. http://www.nefsc.noaa.gov/nefsc/publications/classics/index.htm

Simard, P., M. Castonguay, D. D'Amours and P. Magnan. 1992. Growth comparison between juvenile Atlantic mackerel (*Scomber scombrus*) from the two spawning groups of the Northwest Atlantic. Can. J. Fish. Aquat. Sci. 49: 2242-2248.

Siskey, M.R., W.J. Wilberg, R.J. Allman, B.K. Barnett, and D.H. Secor. 2016. Forty years of fishing: Changes in age structure and stock mixing in Northwestern Atlantic bluefin tuna (*Thunnus thynnus*) associated with size-selective and long-term exploitation. ICES Journal of Marine Science.

TRAC (Transboundary Resources Assessment Committee). 2010. Stock Assessment of Atlantic Mackerel in the Northwest Atlantic-2009. Reference Document 2010/01. 59 p. http://www2.mar.dfo-mpo.gc.ca/science/TRAC/documents/TRD_2010_01_E.pdf

Trueman, C. N., K. M. MacKenzie, and M. R. Palmer. 2012. Identifying migrations in marine fishes through stable-isotope analysis. Journal of Fish Biology 81(2):826-847.

Appendix A3: Development of an egg index for Atlantic Mackerel (*Scomber scombrus*) on the northeast U.S. Continental Shelf

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Working Paper for the 2017 Atlantic Mackerel Stock Assessment Data meeting

ABSTRACT

Atlantic mackerel (*Scomber scombrus*) in the western North Atlantic are thought to have two primary spawning grounds, one on the northeast U.S. continental shelf and the second in the Gulf of St. Lawrence. In the U.S. these two spawning contingents are assessed as a single stock. In the Gulf of St. Lawrence, the Daily Egg Production Method has been used to develop an index of abundance for the northern spawning contingent. However, in recent assessments a similar egg index has not been available from U.S. waters. Here we describe the methodology for developing a U.S. egg index, with the goal of providing a stock wide measure of population trends and abundance. In U.S. waters, the mackerel spawning season and spawning ground were well sampled most years from 1977-1987 and 2000-present. Over these two time periods there has been a major decline in egg abundance, with historic lows reached in 2011 and 2013. Comparisons to the Gulf of St. Lawrence egg index suggest that spawning by the northern contingent is approximately 10 fold the spawning by the southern contingent.

INTRODUCTION

A stock wide index of Atlantic mackerel eggs is an important fisheries independent measure to evaluate the status of this population. The egg production method was originally developed by the Southwest Fisheries Science Center in order to assess the Northern anchovy stock off the west coast of North America (Parker, 1980). It provides a practical option for evaluating the population trends of small pelagic species due to the nature of their spawning activities (spawn multiple batches of pelagic eggs over a single spawning season). This survey method has been used on other small pelagic species including sardine, sprat, mackerel and horse mackerel in at least 16 different locations around the world including Peru, South Africa, Europe, Canada, Australia and others (Stratoudakis et al. 2006). Mackerel specific egg production surveys have been done in the NW Atlantic (Berrien et al. 1981), a separate survey within the Gulf of St. Lawrence (Gregoire et al., 2013), and within the shelf waters of the NE Atlantic including the Bay of Biscay, Celtic Sea, and west of Ireland (Lockwood et al. 1981; Priede and Watson, 1993).

The egg production method has many advantages and disadvantages as a means of estimating population trends and the scale of population biomass. Prominent among the advantages, from a sampling standpoint, are that 1) eggs do not display a behavioral response in response to sampling gear and thus there is not a concern about net evasion, 2) eggs diameters typically far exceed standard sample gear mesh sizes and thus there is not a concern about net extrusion, 3) standard plankton nets are simple to deploy and tow, allowing for ready standardization of sampling and 4) eggs are collected very shortly after spawning minimizing the impact of changes in mortality that may have a more prominent effect on larval indices.

Disadvantages include that after sampling notable laboratory processing time is required by trained personnel, requiring a continuous commitment of resources to properly implement the technique and a delay from sample collection to index provisioning.

This working paper describes the approach for calculating annual egg production of Atlantic mackerel on the northeast U.S. continental shelf. The process of calculating spawning stock biomass from the egg production method is also presented, though notably the lack of reproductive studies of mackerel on the northeast U.S. continental shelf, requires borrowing data on annual fecundity, sex ratios, and fish size from studies on the Gulf of St. Lawrence spawning ground.

METHODS

Field collections

Atlantic mackerel eggs were collected in two multi-year sampling programs. Details of each sampling program are available in Richardson et al. 2010 and Walsh et al. 2015. The first sampling program, MARMAP, occurred from 1977-1987. The second sampling program, ECOMON, has been ongoing from 1999-present. Sampling followed a random stratified design, with strata modified based on those used on the bottom trawl survey (Figure 1). Specifically, narrow inshore and offshore trawl survey strata were often merged into single stratum.

All plankton tows used a 61-cm bongo net that was fished from the surface to within 5 m of the bottom or to a maximum depth of 200 m. A CTD attached above the net measured temperatures through the water column. During MARMAP, the bongo net included both a 333-µm and 505-µm mesh net, with samples from the wider mesh net processed for ichthyoplankton. During ECOMON, a paired 333-µm mesh bongo net has been used, with ichthyoplankton processed from a single net. Atlantic mackerel eggs are >1 mm in diameter and are not extruded through either mesh size. All samples were fixed at sea in 3% seawater buffered with formalin.

Initial processing of most samples occurred at the Morski Instytut Rybacki in Szczecin, Poland. All eggs were removed from samples and quantified. During MARMAP, two individuals, Peter Berrien and John Sibunka identified eggs from all taxa. Upon their retirement egg identification at the NEFSC stopped, but the eggs continued to be sorted from the samples. The current project focused on processing this backlog of eggs, with an exclusive focus on Atlantic mackerel rather than the full suite of species.

Laboratory Processing

Eggs were collected aboard the May/June ECOMON survey from 2000-present. Samples in 2003, 2008, 2012, and 2014 were not analyzed due to lack of a cruise during that time period or lack of full coverage in the primary mackerel spawning area on a given cruise. Complete coverage is considered the entire NE Atlantic continental shelf of the Mid-Atlantic Bight, Southern New England and western Gulf of Maine (Figure 1). For the ECOMON samples, vials were available that included all eggs collected at each station. These vials are further sorted for Atlantic mackerel and developmentally staged (see Figure 2 for staging and egg pictures).

Atlantic mackerel have eggs that can be distinguished from all other species at all stages of development. The diameter of the egg ranges from 1.07 to 1.35mm and they have an oil globule present which measures 0.27 to 0.35mm. The pigmentation pattern (especially in stage 3 eggs), is easily distinguishable (Colton and Marak, 1969; Berrien, 1975). There is some overlap with Cusk (*Brosme brosme)* in morphological characteristics, however, Cusk eggs are slightly

larger and have a textured outer chorion, whereas Atlantic mackerel eggs do not. The stage descriptions were matched with and verified in Canada with their egg identification expert (Girard, 2000) during a visit in 2015 by NEFSC scientists to the Maurice Lamontagne Institute, Mont Joli.

Atlantic mackerel egg incubation times

Stage specific egg incubation times, an important parameter in calculating daily egg production, are temperature dependent in fishes. Experimental work has been used to establish the duration of Stage 1 Atlantic mackerel eggs as a function of temperature (Figure 3):

$$I = (e^{[-1.61 * Ln(T) + 7.76]})$$

Where T= average temperature of the first 10m of water column
For each station, the associated CTD data (ftp://ftp.nefsc.noaa.gov/pub/hydro/matlab_files/) was used to calculate the average temperature of the first 10 meters of the water column.

Calculation of Daily Egg production:

Daily egg production is calculated using the following equation:

DEP = (abundance (stage 1+5)(n/m^2)/incubation time (hr)) * 24 hr

Focusing on only Stage 1 and 5 eggs ensures that they were very recently spawned, and minimizes the effect that egg mortality may have on the index. We calculated a stratified mean of the daily egg production per 10 m^2 across the sampling area, and then scaled that up to the entire sample area to obtain a cumulative average daily egg production for the cruise. Calculation of the Coefficient of Variation of the Daily Egg Production estimates followed Smith (1997).

Annual egg production:

To calculate annual egg production from a measure of daily egg production the seasonality of spawning must be accounted for. For the Canadian egg survey there is a fishery that is operational throughout the spawning season, providing frequent samples of adults that are suitable for calculating a spawning seasonality function. Specifically, a logistic function is fit to the Gonosomadic Index by day of year to establish the spawning seasonality for that year. In contrast the U.S. fishery is neither targeting nor catching many mackerel during the spawning season (the average percentage of annual landing for 2000-2015 in May and June is 1.46% and 0.09% respectively; source: https://www.st.nmfs.noaa.gov/commercial-fisheries/commercial-landings/). Instead we used an average spawning seasonality function derived using a larval index methodology (Figure 4; Richardson et al. 2010). This spawning seasonality represents the average for the MARMAP and ECOMON time-series rather than any year specific spawning seasonality.

Annual egg production is calculated by dividing the daily egg production by the proportion of eggs spawned on the mean day of the survey. We use the cumulative daily egg production and divide that by the spawning seasonality derived from larval index.

AEP = Cumulative DEP / proportion spawned on that day

The average day of the cruise was used in the spawning seasonality function. Sensitivity analyses were performed to evaluate the impact on the Annual Egg Production value of a

shift in spawning seasonality away from the time series mean. A shift of 10 days earlier and later was evaluated. For the Canadian spawning seasonality estimates peak spawning has ranged from day 166 to day 179 from 1979-2011.

Spawning Stock Biomass

Spawning stock biomass (t) can be calculated based on an estimate of the annual egg production from the plankton surveys and the annual egg production per unit weight of mature fish from a fecundity study. More specifically, spawning stock biomass is estimated using the following equation:

$$SSB = (P*W)/(F*R*10^6)$$

P= Annual Egg Production
W= mean weight
F = fecundity of females
R = sex ratio
(10^6 converts grams into tons)

Fecundity sampling has not occurred on the northeast U.S. continental shelf. We thus borrowed annual fecundity values that were obtained in the Gulf of St. Lawrence sampling.

RESULTS AND DISCUSSION

Spatial distribution of egg production

Figure 5 shows the intensity of Atlantic mackerel in the western North Atlantic in the 1930s according to Sette, 1943. The majority of spawning was thought to occur in Southern New England and the Gulf of St. Lawrence and it was thought that there was considerably more spawning occurring in Southern New England than in the Gulf of St. Lawrence. Importantly, the conclusion of Sette 1943 that Southern New England was the dominant spawning ground reversed the conclusion of Bigelow and Welsh 1923 that much more egg production occurs east and north of Cape Cod than south and west of Cape Cod. Furthermore, Sette provides a number of caveats to his conclusion, including 1) differences in the sampling approaches in the two regions (Gulf of St Lawrence and U.S. waters) and 2) the fact that egg numbers for the Gulf of St. Lawrence were from 1915, over a decade earlier than egg numbers for U.S. waters.

Figure 6 shows the progression of egg distribution in U.S. waters from 1977 to 2016. In the late 70s and early 80s, the majority of spawning occurring in U.S. waters was in the Southern New England region off the coasts of Long Island and Rhode Island. Moving into the mid and late 80s, the majority of spawning remained in Southern New England, however, it also spread throughout the northern regions. From 2000-2006, the range of spawning spread throughout most regions with the exception of the Mid Atlantic Bight. Spawning was no longer congregated in the Southern New England region and there is more of a grouping in the Western Gulf of Maine and Georges Bank. In the more recent years, spawning become less widespread and eggs were primarily found in the northern regions with aggregations in the Western Gulf of Maine.

Egg Production

Daily egg production is presented in Figure 6 and Table 1. Values ranged from 5.36 x 10^9 to 5,600 x 10^9 across the northeast United States Continental Shelf. The average CV on daily egg production was 0.40.

Annual Egg production is presented in Figures 8 and 9 and Table 1 with values ranging from 0.653 x 10^{12} to 230 x 10^{12}. For comparison, annual egg production values in the Gulf of St. Lawrence ranged from 20 x 10^{12} to 1,230 x 10^{12} roughly an order of magnitude higher than those in U.S waters. Specifically, these comparisons indicated that only from 1% (in the mid-2000s) to 43% (in the mid-1980s) of the egg production was occurring on the northeast U.S. Continental Shelf. Another comparison to make is U.S annual egg production numbers are currently lower than the U.S daily egg production numbers in the late 1970s.

The sensitivity analysis of spawning seasonality shifts revealed year specific patterns based on the timing of sampling relative to peak spawning. That is an earlier or later spawning season could result in both a positive and negative bias to the index. Typically the bias for 10 day shifts was constrained to 0.5-2 fold the index values.

Spawning stock biomass

The biomass of spawners on the northeast U.S. continental shelf was estimated to have declined from a high of 390,000 mt in the late 1970s to a low of 746 mt in 2013 (Table 2). This trend matches the annual egg production trend. The majority of the biomass is estimated to spawn in the northern spawning ground. Recently, the southern spawning contingent make up a little less than 10% of the total biomass.

The 2015 data showed an increase in the spawning stock biomass, however, the 2016 data showed numbers about half of what they were in 2015 (Table 2).

References

Berrien, P.L. 1975. A description of Atlantic mackerel, *Scomber scombrus*, eggs and early larvae. Fish. Bull., 73(1): 186-192.

Berrien, P. L., N. A. Naplin and M. R. Pennington. 1981. Atlantic mackerel, *Scomber scombrus*, egg production and spawning population estimates for 1977 in the Gulf of Maine, Georges Bank and middle Atlantic Bight. Rapp. Reun. Cons. Int. Explor. Mer 178: 279-288.

Colton, J.B., and Marak, R.R. 1969. Guide for identifying the common planktonic fish eggs and larvae of continental shelf waters, Cape Sable to Block Island. Bur. Comm. Fish. Lab. Ref. 69-9.

Girard, L. 2000. The Atlantic mackerel (*Scomber scombrus* L.) of NAFO Subareas 2 to 6. Chapter 4. Identification of mackerel (*Scomber scombrus* L.) eggs sampled during abundance surveys in the southern Gulf of St. Lawrence. DFO Can. Sci. Advis. Sec. Res. Doc. 2000/021. pp. 119-137.

Gregoire, F., Gendron, M.-H., Beaulieu, J.-L., and Levesque, I. 2013. Results of the Atlantic mackerel (*Scomber scombrus L.*) egg surveys conducted in the southern Gulf of St. Lawrence from 2008-2011. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2013/035. 62 pp.

Lasker, R. 1985. An Egg Production Method for estimating Spawning Biomass of Pelagic Fish: Application to the Northern Anchovy, *Engraulis mordax*. Introduction: An egg production method for anchovy biomass assessment. NOAA Tech. Rep. NMFS 36. pp. 1-4

Lockwood, S.J., Nichols, J.H., and Dawson, W.A. 1981. The mackerel (*Scomber scombrus*) spawning in the Bay of Biscay, Celtic Sea and west of Ireland. Rapp. P.-v. Reun. Cons. Int. Explor. Mer, 178: 171–173.

Parker, K. 1980. A direct method for estimating northern anchovy, Engraulis mordax, spawning biomass. Fish. Bull., U.S. 78:541-544.

Priede, I.G., and Watson, J.J. 1993. An evaluation of the daily egg production method for estimating biomass of Atlantic mackerel (*Scomber scombrus*). Bull. Mar. Sci. 53: 891–911.

Richardson, D. E., Hare, J. A., Overholtz, W. J., and Johnson, D. L. 2010. Development of long-term larval indices for Atlantic herring (*Clupea harengus*) on the northeast US continental shelf. ICES J. Mar. Sci. **67**:617-627

Sette,O.E. 1943. Biology of the Atlantic mackerel (*Scomber scombrus*) of North America. Part I: Early life history, including the growth, drift, and mortality of the egg and larval population. U.S. Fish Hildl. Serv., Fish. Bull., 50(38):149-237.

Smith, S. J. 1997. Boostrap confidence limits for groundfish trawl survey estimates of mean abundance. Can. J. Fish. Aquat. Sci. **54**:616-630.

Stratoudakis, Y., Bernal, M., Ganias, K., and Uriarte, A. 2006. The daily egg production methods: recent advances, current applications and future challenges. Fish and Fisheries, 7: 35–57.

Walsh, H.J., Richardson, D.E., Marancik, K.E., and Hare, J.A. 2015. Long-Term Changes in the Distributions of Larval and Adult Fish in the Northeast U.S Shelf Ecosystem. PLoS ONE 10(9): e0137382

Table 1. U.S Daily Egg Production (with CV), Annual Egg Production, and Spawning Stock Biomass for the years 1977-1987 and 2000-2016.

Year	DEP	CV (DEP)	AEP	SSB
1977	5.59E+12	0.24	2.29E+14	389,975
1979	4.44E+12	0.22	1.82E+14	310,540
1980	3.53E+12	0.62	2.13E+14	363,192
1981	1.49E+12	0.45	9.40E+13	185,736
1982	1.24E+12	0.35	6.61E+13	130,673
1983	1.68E+12	0.55	1.29E+14	254,962
1984	8.44E+11	0.33	3.52E+13	71,854
1985	2.62E+11	0.33	1.08E+13	20,500
1986	1.54E+12	0.37	6.52E+13	92,931
1987	1.12E+12	0.24	4.55E+13	80,957
1987	2.93E+11	0.54	4.46E+13	79,488
2000	2.82E+11	0.59	1.45E+13	23,254
2001	1.29E+11	0.37	6.18E+12	10,334
2002	7.00E+11	0.67	3.59E+13	60,095
2004	1.50E+11	0.50	8.32E+12	10,384
2005	1.58E+10	0.21	8.40E+11	1,027
2006	2.21E+10	0.47	1.61E+12	1,840
2007	3.64E+10	0.26	1.80E+12	2,157
2009	1.39E+10	0.39	8.37E+11	1,168
2010	4.44E+10	0.40	2.56E+12	3,297
2011	6.13E+9	0.43	6.53E+11	824
2013	5.36E+9	0.51	7.23E+11	746
2015	1.28E+11	0.29	5.77E+12	5,559
2016	4.14E+10	0.43	2.74E+12	3,138

Table 2. Spawning Stock Biomass of both contingents and the unit stock from 1977 to 2016 with a gap from 1988 to 2000 due to lack of cruise coverage on the US side.

SPAWNING STOCK BIOMASS				
YEAR	**US**	**Canada**	**Total Biomass**	**U.S Proportion**
1977	389,975			
1979	310,540	820,554	1,131,094	0.274
1980	363,192			
1981	185,736			
1982	130,673			
1983	254,962	342,591	597,553	0.427
1984	71,854	726,183	798,037	0.090
1985	20,500	1,217,178	1,237,678	0.017
1986	92,931	1,754,052	1,846,983	0.050
1987	80,957	872,703	953,660	0.085
1987	79,488	872,703	952,191	0.083
2000	23,253	165,017	188,270	0.124
2001	10,334			
2002	60,095	379,070	439,165	0.137
2003		314,752		
2004	10,384	162,714	173,098	0.060
2005	1,027	86,487	87,514	0.012
2006	1,840	54,133	55,973	0.033
2007	2,158	76,532	78,690	0.027
2008		99,631		
2009	1,168	73,743	74,911	0.016
2010	3,297	25,960	29,257	0.113
2011	824	35,714	36,538	0.023
2013	746	33,362	34,108	0.022
2015	5,559	41,783	47,342	0.117
2016	3,138	52,667	55,805	0.056

(Note: U.S Spawning Stock Biomass (SSB) in 1980 was calculated using Canadian data from 1979. U.S SSB in 1981 and 1982 used Canadian data from 1983, and in 2001 used Canadian data from 2002. This is due the lack of a cruise on the Canadian side during those years.)

Figure 1. Strata sampled during the ECOMON surveys on the northeast U.S. continental shelf.

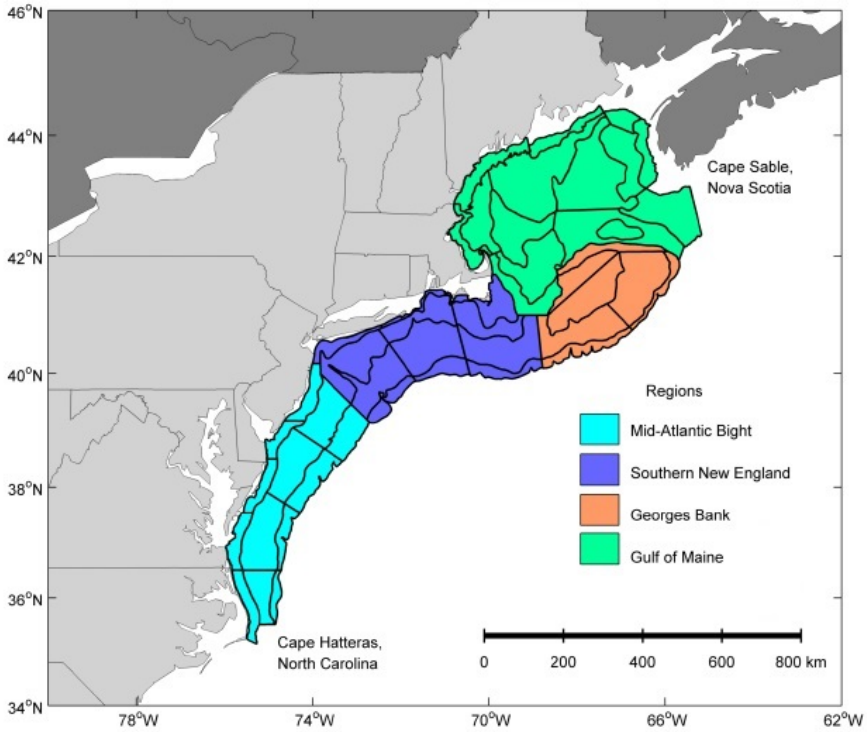


Figure 2. Developmental stages of the Atlantic mackerel egg: (a) Stage 1: absence of an embryo, but presence of a mass of cells at the animal pole; (b) Stage 2: appearance of the embryo, pigmentation becomes apparent; (c) Stage 3: embryo grows to a length equal to more than ½ the circumference of yolk; (d) Stage 4: abnormal development, not assignable to a normal stage; (e) Stage 5: dead/unfertilized

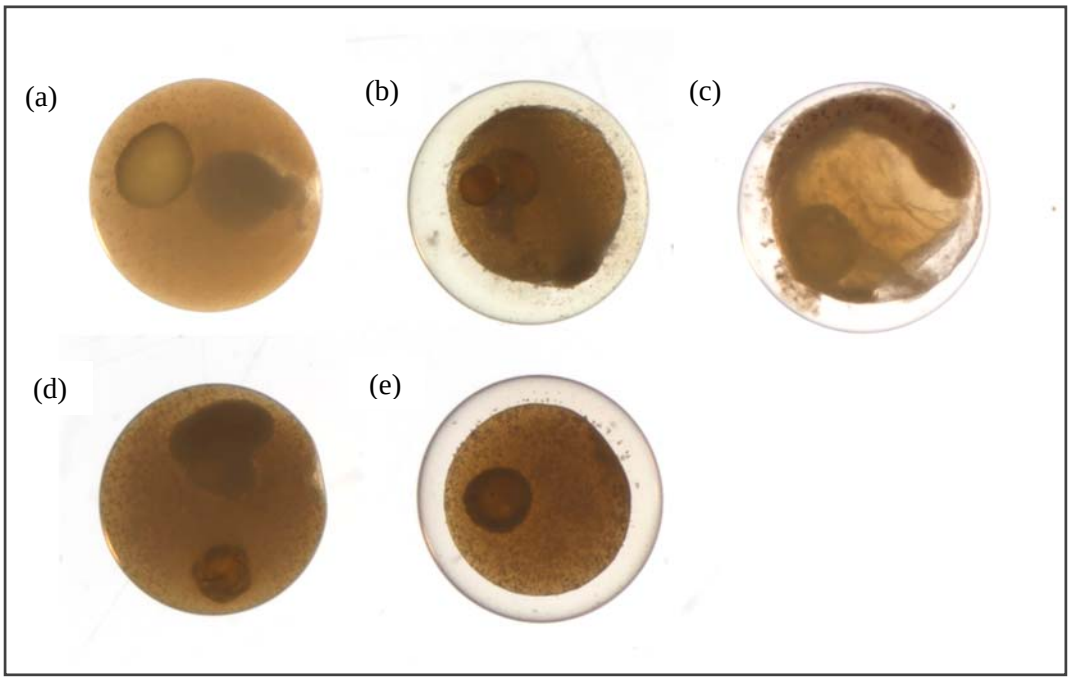


Figure 3. The above graph shows that as the temperature of the water gets colder, the development time of stage 1 eggs gets longer. Warmer temperatures = shorter development times.

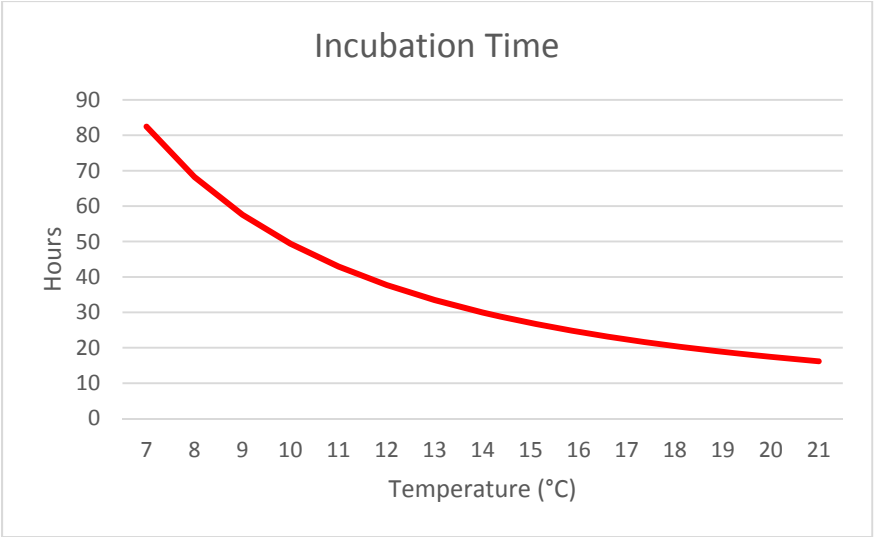


Figure 4. Spawning seasonality by day of year. The highest proportion of spawning occurs on day 139 (May 19th) at 2.5%.

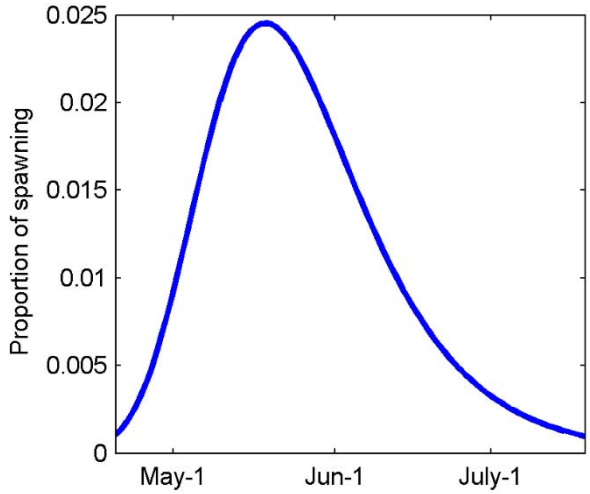


Figure 5. Relative intensity of Atlantic mackerel spawning in various regions along the NW Atlantic coast (as indicated by average number of eggs caught in plankton nets) (Sette, 1943).

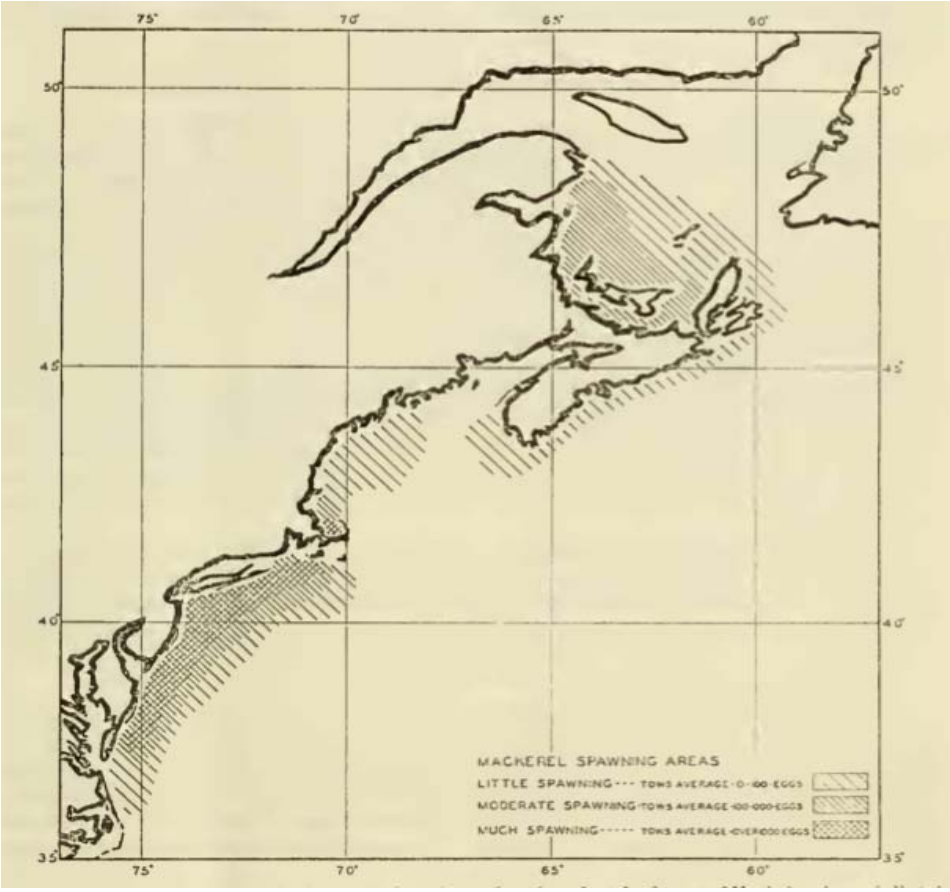


Figure 6. Progression of egg distribution in U.S. waters from 1977 to 2016.

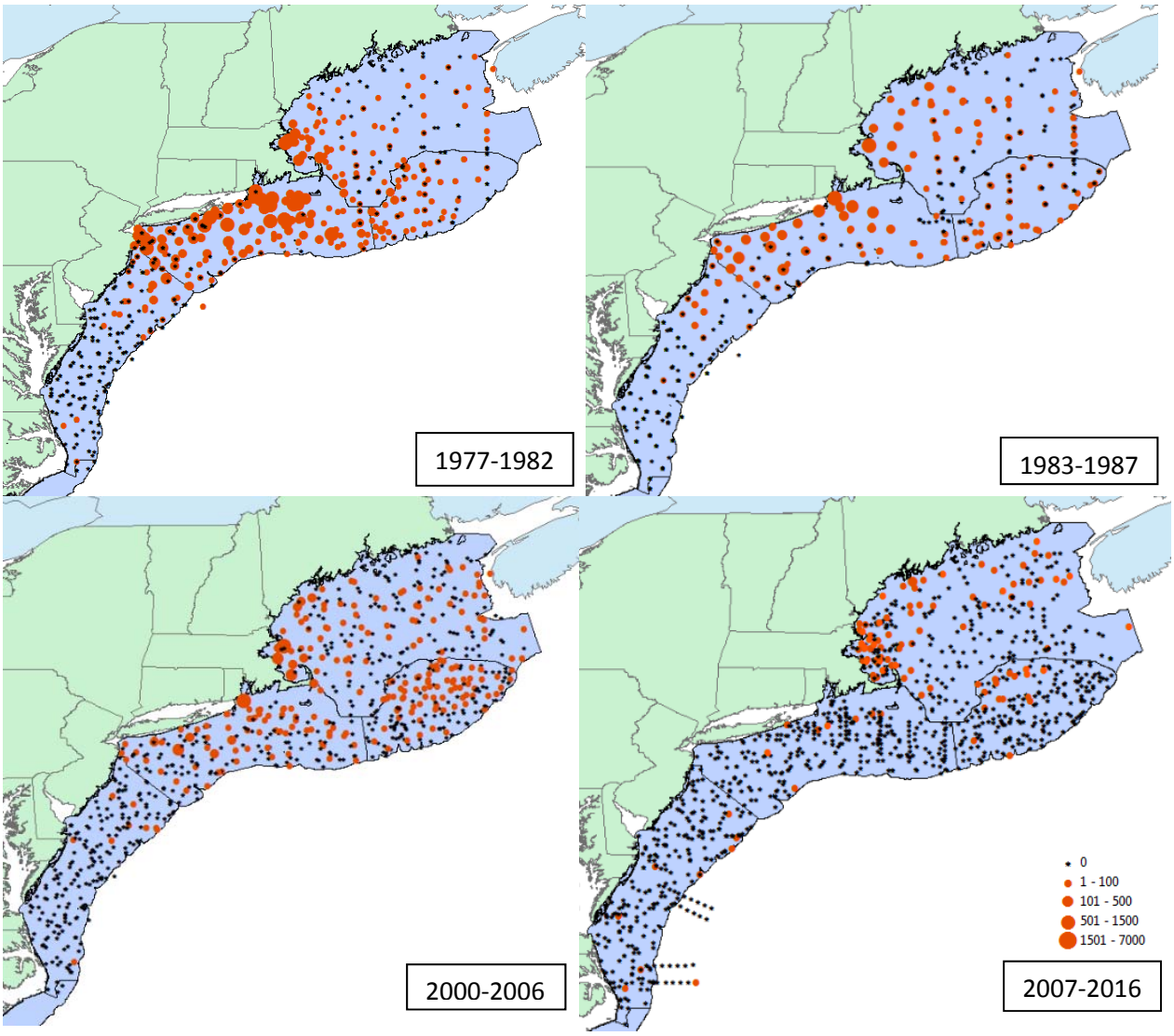


Figure 7. U.S. Daily Egg Production. (a) Daily Egg Production from 1977-2016; (b) Daily Egg Production during the MARMAP time period (1977-1987); (c) Daily Egg Production during the current ECOMON time period (2000-present).

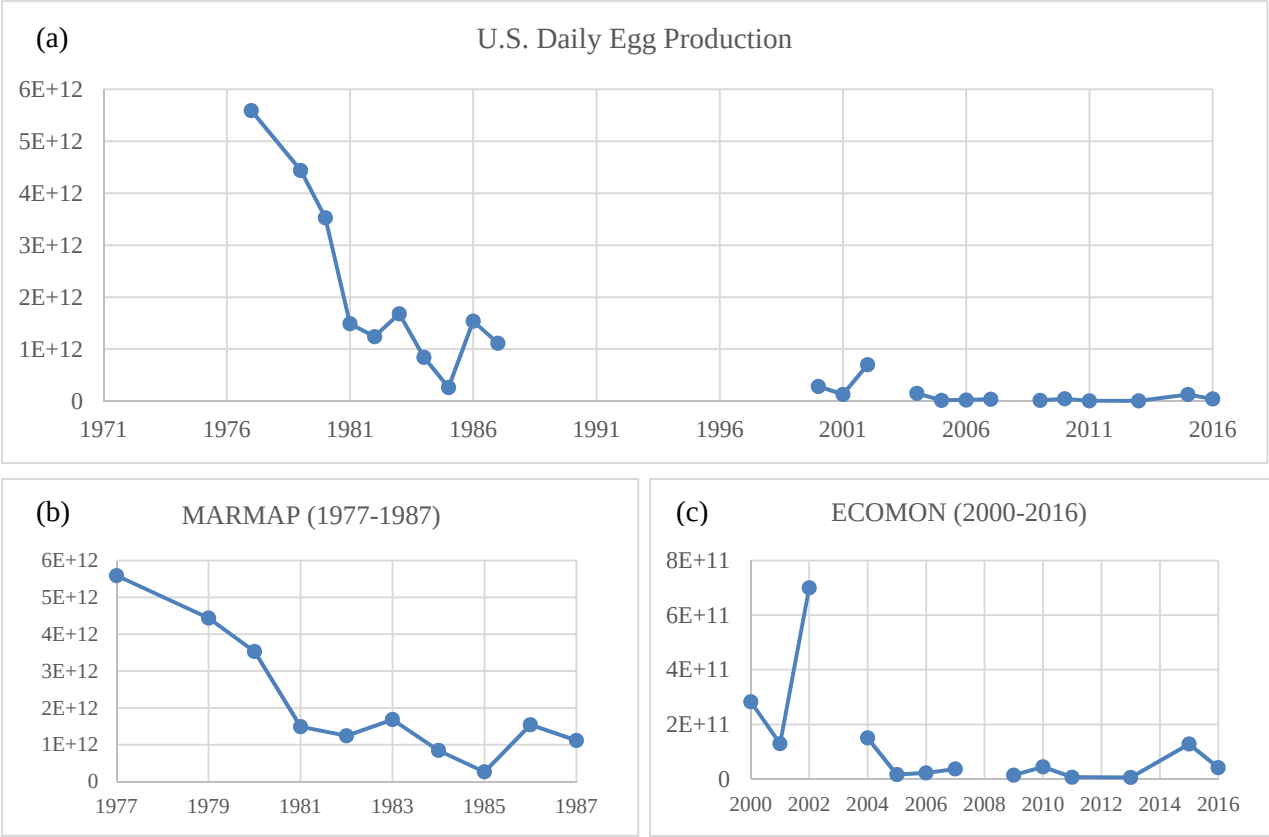


Figure 8. U.S Annual Egg Production. (a) Annual Egg Production from 1977-2016. The 2nd dot in 1987 represents a 2nd full coverage cruise beginning 3 weeks after the first; (b) Annual Egg Production during the MARMAP time period (1977-1987); (c) Annual Egg Production during the current ECOMON time period (2000-present).

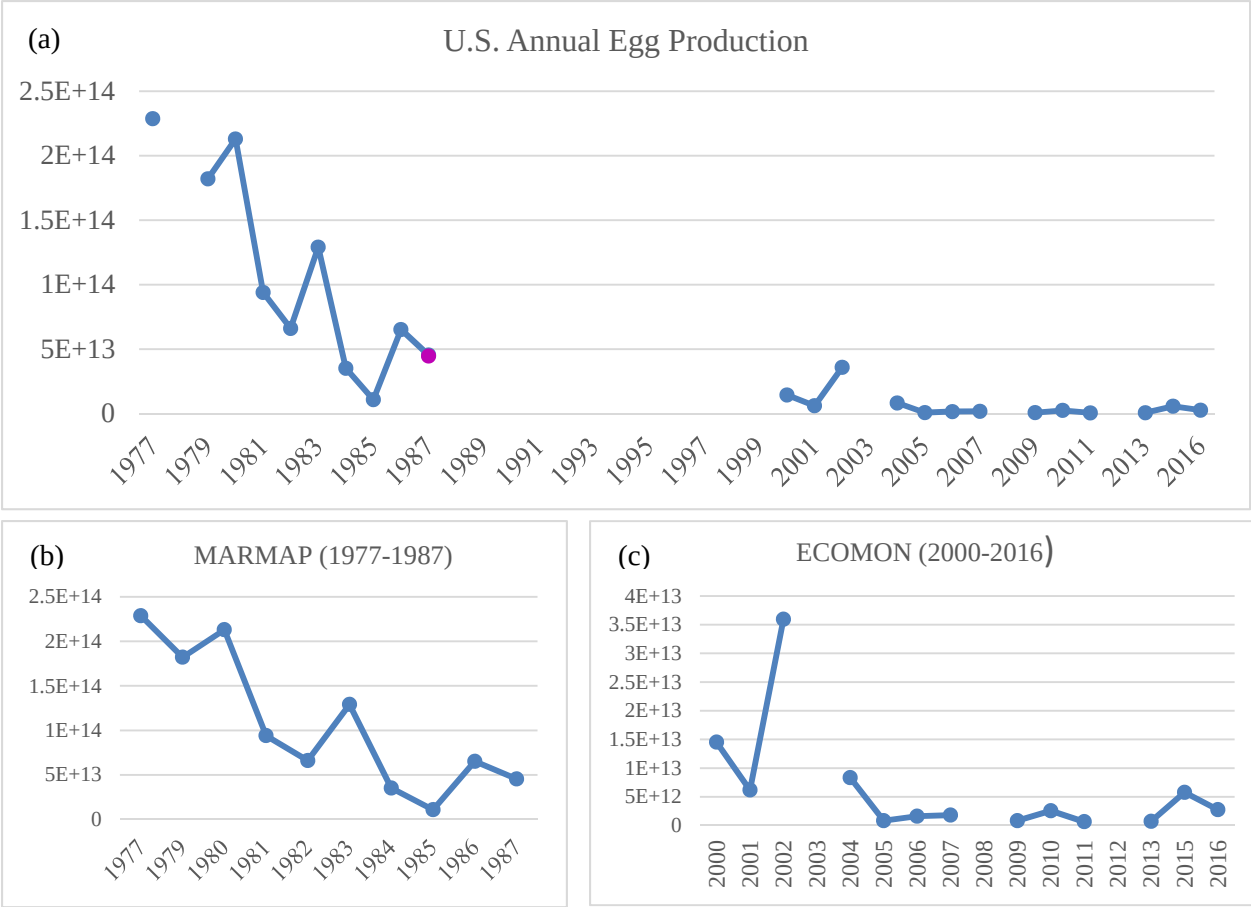


Figure 9. U.S and Canadian Annual Egg Production 1977-2016.

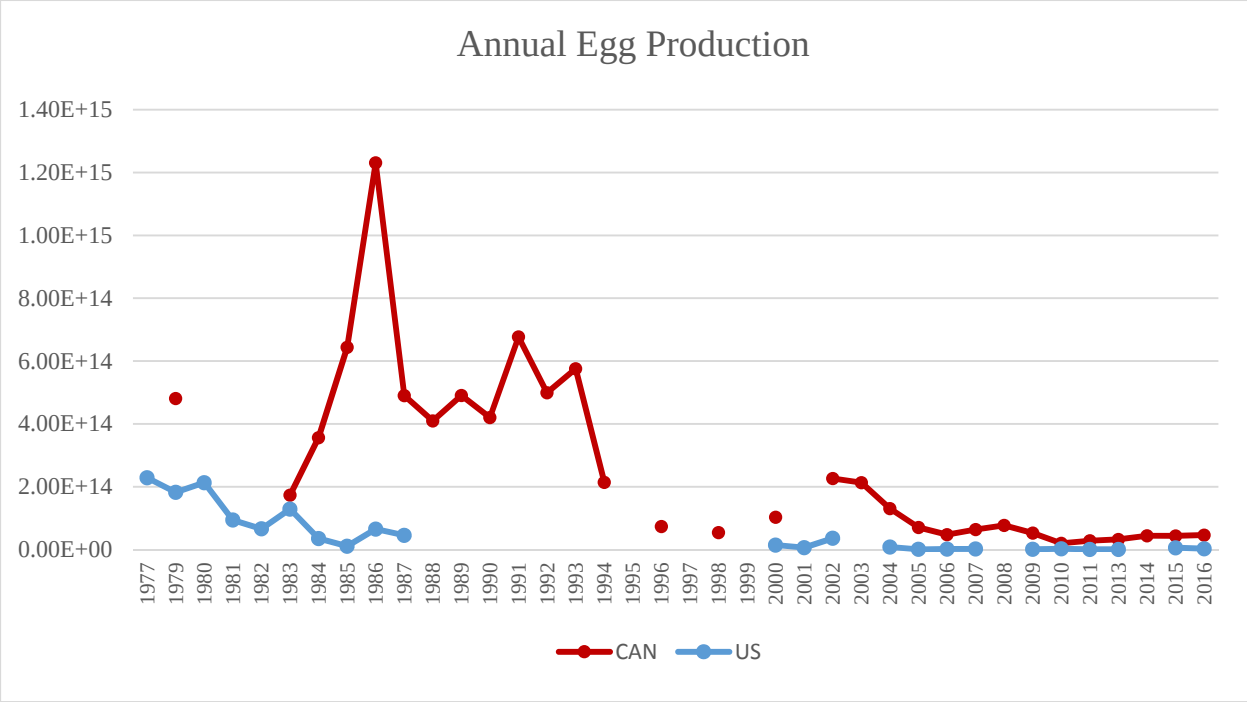
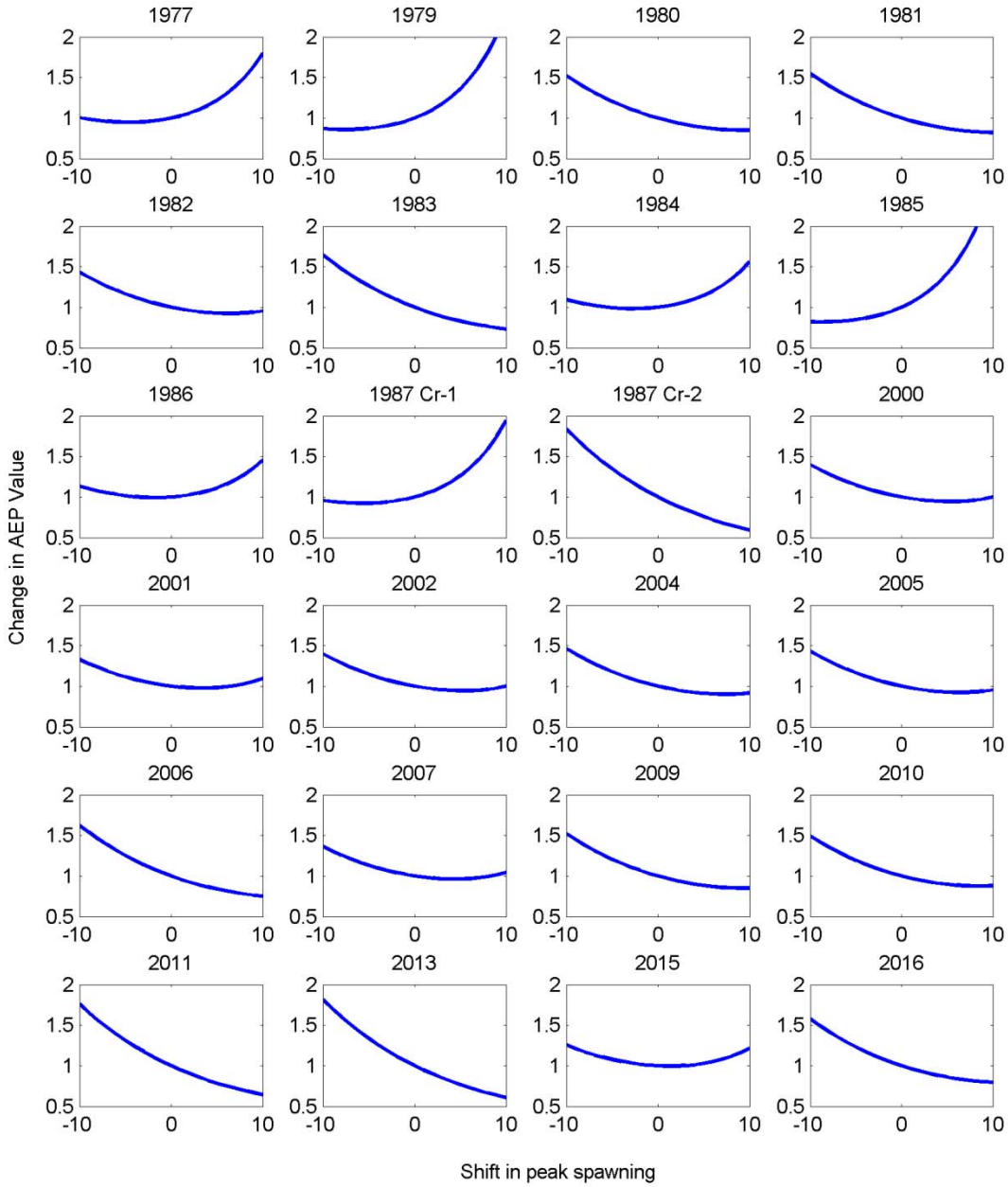


Figure 10. Sensitivity analysis evaluating the effects of a change in spawning seasonality on the Annual Egg Production value by year. Due to a lack of annual fecundity sampling a mean spawning seasonality (derived from a larval index methodology) is used in the calculations. An early (negative values-x axis) or late (positive values) spawning season can affect the index based on the timing of sampling for that year (y-axis >1 index will be higher by that scalar, y-axis<1 index will be lower).



Appendix A4: Mackerel predation estimates from predators sampled in the NEFSC bottom trawl surveys

Brian Smith and Sarah Gaichas

Summary of species interactions

The presence of Atlantic mackerel (*Scomber scombrus*) in fish stomachs collected during the NEFSC bottom trawl surveys was generally low from 1973-2016. A total of 1,284 out of 619,637 stomachs contained mackerel (including unidentified mackerel: Scombridae and *Scomber* spp.; ~0.2%). Mackerel predation was examined by estimating per capita consumption (by evacuation rate method) and generating predation indices including a predation pressure index (Richards and Jacobson 2016), and percent diet composition by mass, frequency of occurrence, and prey number to potentially scale mackerel abundance. These indices did reveal some trends, most notably was a recent decline in each predation index from the early 2000s to the present (Figs 1 & 2). However, there may be factors other than mackerel abundance driving this trend including the lack of sampling the complete predator field, and for those predators sampled, other non-mackerel prey may be more accessible (see below).

Other predators of mackerel are not represented in the NEFSC food habits database, including highly migratory species, marine mammals, and seabirds. Consumption from these predators is more difficult to estimate due to incomplete information on population levels and annual diet information. Despite these incomplete estimates of mackerel predation, time series trends were observed and they appeared to contrast survey indices of mackerel abundance.

Introduction

Fish diet data from NEFSC bottom trawl surveys were evaluated initially for 17 mackerel predators (Table 1). The total amount of food eaten and the type of food eaten were the primary diet data examined. From these basic food habits data, diet composition of mackerel by mass, frequency of occurrence, and prey number were calculated. With additional interests, per capita consumption (e.g. NEFSC 2012; NEFSC 2014) and a predation pressure index (Richards and Jacobson 2016) were calculated similar to previous forage fish and shrimp stock assessments.

Methods

Every predator that contained mackerel was identified from the NEFSC Food Habits Database (FHDBS). From this list, predators that were sampled regularly each decade (1973-2016), and were not suspected of accidental mackerel feeding were included (17 predators). Diet data were only available for the northeast U.S. shelf and treated as one geographic unit.

Estimates of per capita consumption were calculated on a seasonal basis (two 6 month periods) for each predator and summed for each annum. Although diet data collections for some predators started quantitatively in 1973 and extend to the present (through 2016), not all mackerel predators were sampled during the full extent of this sampling program. Stomach sampling for most species began in 1977 and extends through 2016. For more details on the food habits sampling protocols and approaches, see Link and Almeida (2000) and Smith and

Link (2010). This sampling program was part of the NEFSC bottom trawl survey program; further details of the survey program can be found in Azarovitz (1981), NEFC (1988), and Reid et al. (1999).

Basic Food Habits Data

To estimate mean total stomach contents (S_i), each mackerel predator had the total amount of food eaten (as observed from food habits sampling) calculated for each temporal (t, fall or spring; year) scheme and was inclusive of empty stomachs. Mean total stomach contents was a sum of all prey items across each predator's stomachs. Mean mackerel amounts were weighted by the number of predator at length per tow and by the total number of each predator collected per tow. Means were the mean weight of mackerel per individual predator. Units for this estimate are in grams (g). These estimates were taken as proportions of mackerel per mean total stomach contents for each temporal scheme (fall or spring).

Per Capita Consumption Rates

To estimate per capita consumption, the gastric evacuation rate method was used (Eggers 1977, Elliott and Persson 1978). Units are in g year^{-1}. This method requires two variables and two parameters. The daily per capita consumption rate, C_{it} is calculated as:

$$C_{it} = 24 \cdot E_{it} \cdot \overline{S_{it}}^{\gamma} \quad ,$$

where 24 is the number of hours in a day. The evacuation rate E_{it} is:

$$E_{it} = \alpha e^{\beta T} \quad ,$$

and is formulated such that estimates of mean total stomach contents (S_i) and ambient temperature (T; here used as bottom temperature from the NEFSC bottom trawl surveys associated with the presence of each predator [Taylor and Bascuñán 2000, Taylor et al. 2005]) are the only data required. The parameters α and β were set as 0.002 and 0.115 for the elasmobranch predators respectively and 0.004 and 0.115 for the teleost predators respectively (Tsou and Collie 2001a, 2001b, Overholtz et al. 1999, 2000). The parameter γ is a shape function and is typically set to 1 (Gerking 1994).

Scaling Per Capita Consumption

Following the estimation of per capita consumption rates for each predator and temporal (t) scheme, those estimates were scaled up to a seasonal estimate ($C'_{it} = C_{fall}$ or C_{spring}) by multiplying the number of days in each half year:

$$C'_{it} = C_{it} \cdot 182.5 \quad .$$

These were then multiplied by the diet composition D_{ijt} that was mackerel (taken as a proportion), to estimate the seasonal per capita consumption of mackerel C_{ijt}:

$$C_{ijt} = C'_{it} \cdot D_{ijt} \quad .$$

These were then summed to provide an annual estimate, C'_{ij}:

$$C'_{ij} = C_{ij,fall} + C_{ij,spring} \quad .$$

Predation pressure and other diet indices

For the 17 predators considered, spiny dogfish (*Squalus acanthius)* was responsible for 67 % of all mackerel prey occurrences in FHDBS; thus, the following indices were limited to spiny dogfish predation of mackerel. Following the methods outlined above for annual per capita consumption, estimates were also calculated for five additional prey (sand lance *Ammodytes* spp., Atlantic herring *Clupea harengus*, Loligo squid *Loligo* spp., silver hake *Merluccius bilinearis*, and unidentified fishes) to examine potential prey switching, specifically for spiny dogfish.

An index of predation pressure was created following the methods of Richards and Jacobson (2016). Here, the diet index of frequency of occurrence of mackerel is used to weight the time series of predator biomass or abundance of spiny dogfish. Richards and Jacobson (2016) applied this method with predator biomass, whereas the current work explored abundance in addition to biomass. Predation pressure index (PPI) is equal to

$$PPI_i = \sum_j A_{ij} \times FO_{ij} \quad ,$$

where A_{ij} is the predator biomass or abundance index (stratified mean amount per tow) from NEFSC fall bottom trawl surveys for the entire shelf region. The FO_{ij} is the annual percent frequency of occurrence of mackerel per predator equal to

$$FO_{ij} = \frac{\sum_i N_{ij}}{\sum_i T_{ij}} \times 100 \quad ,$$

where N_{ij} is the number of stomachs per year and predator containing mackerel, and T_{ij} is the total number of stomachs per year and predator sampled.

The remaining two diet indices: percent diet composition by weight and prey number were described above with the calculation of per capita consumption (diet composition by weight) or are detailed here. Percent diet composition by number (NB_{ij}) is similar in form to FO_{ij} with two exceptions. Instead of number of stomachs with mackerel (N_{ij}), the number of mackerel observed (G_{ij}) is used, and the total number of prey observed (H_{ij}) replaces the total number of stomachs sampled (T_{ij}) as

$$NB_{ij} = \frac{\sum_i G_{ij}}{\sum_i H_{ij}} \times 100 \quad .$$

When prey number was null for mackerel and non mackerel prey, prey number was assumed to equal one.

Results

Total per capita consumption for the 17 fish predators was variable from 1973-2016 with 0 to 536 g of mackerel eaten per individual per year (Fig. 1; time series average equaled 139 g). Notably in recent years, a decline in mackerel consumption was observed from ~2000 to the present (2016). Similarly, this recent decline in predation was also seen in the four other mackerel predation indices examined for spiny dogfish: percent diet compositions by weight, frequency of occurrence, and prey number, and the predation pressure index (Fig. 2). Interestingly, when considering other prey, spiny dogfish show variability in non-mackerel prey including Atlantic herring, Loligo squid, and unidentified fishes, and silver hake over time (Fig. 3). This suggests spiny dogfish, similar to other generalist predators, switches among prey as the prey field changes, either because some prey are more preferred, more easily captured, or both.

In conclusion, the diet data explored were not considered adequate by the working group to formally incorporate within an estimate of annual consumption of mackerel or as an index of abundance at this time. The exclusion of other known mackerel predators due to limited diet data availability coupled with the limited spatial extent of the existing diet data (primarily U.S. waters) limited the use of these data.

References

Azarovitz, T.R. 1981. A brief historical review of the Woods Hole Laboratory trawl survey time series. In: Doubleday WG; Rivard D., eds. Bottom trawl surveys. Can Spec. Publ. Fish. Aquat. Sci. 58; p 62-67.

Eggers, D.M. 1977. Factors in interpreting data obtain by diel sampling of fish stomachs. J. Fish. Res. Board Can. 34:290-294.

Elliot, J.M., Persson, L. 1978. The estimation of daily rates of food consumption for fish. J. Anim. Ecol. 47:977-991.

Gerking, S.D. 1994. Feeding ecology of fish. San Diego [CA]: Academic Press.

Link, J.S., Almeida, F.P. 2000. An overview and history of the food web dynamics program of the Northeast Fisheries Science Center, Woods Hole, MA. NOAA Tech. Memo. NMFS-NE-159, 60 p.

Northeast Fisheries Center (NEFC). 1988. An evaluation of the bottom trawl survey program of the Northeast Fisheries Center. NOAA Tech. Memo. NMFS-F/NEC-52, 83 p.

Northeast Fisheries Science Center (NEFSC). 2012. 54th Northeast Regional Stock Assessment Workshop (54th SAW) Assessment Report. US Dept. Commer. NEFSC Ref. Doc. 12-18; 600 p.

Northeast Fisheries Science Center (NEFSC). 2014. 58th Northeast Regional Stock Assessment Workshop (58th SAW) Assessment Report. US Dept. Commer. NEFSC Ref Doc. 14-04; 784 p.

Overholtz, W.J., Link, J.S., Suslowicz, L.E. 1999. Consumption and harvest of pelagic fishes in the Gulf of Maine-Georges Bank ecosystem: Implications for fishery management. Proceedings of the 16th Lowell Wakefield Fisheries Symposium – Ecosystem Considerations in Fisheries Management. AK-SG-99-01:163-186.

Overholtz, W.J., Link, J.S., Suslowicz, L.E. 2000. The impact and implications of fish production on pelagic fish and squid on the eastern USA shelf. ICES J. Mar. Sci. 57:1147-1159.

Reid, R.N., Almeida, F.P., Zetlen, C.A. 1999. Essential fish habit source document: fishery-independent surveys, data sources, and methods. NOAA Tech. Memo. NMFS-NE-122, 39 p.

Richards, R.A., Jacobson, L.D. 2016. A simple predation pressure index for modeling changes in natural mortality: Application to Gulf of Maine northern shrimp stock assessment. Fish. Res. 179:224-236.

Smith, B.E., Link, J.S. 2010. The trophic dynamics of 50 finfish and 2 squid species on the northeast US continental shelf. NOAA Tech Memo. NMFS-NE-216, 640 p.

Taylor, M.H., Bascuñán, C. 2000. CTD data collection on Northeast Fisheries Science Center Cruises: Standard Operating Procedures. NEFSC Ref. Doc. 00-11; 28 p.

Taylor, M.H., Bascuñán, C., Manning, J.P. 2005. Description of the 2004 oceanographic conditions on the northeast continental shelf. NEFSC Ref. Doc. 05-03; 90 p.

Tsou, T.S., Collie, J.S. 2001a. Estimating predation mortality in the Georges Bank fish community. Can. J. Fish. Aquat. Sci. 58:908-922.

Tsou, T.S., Collie, J.S. 2001b. Predation-mediated recruitment in the Georges Bank fish community. ICES J. Mar. Sci. 58:994-1001.

Tables

Table 1. Atlantic mackerel (*Scomber scombrus*) predators from the NEFSC Food Habits Database included in response to TOR 1.

Common Name	Species
Smooth dogfish	*Mustelus canis*
Spiny dogfish	*Squalus acanthias*
Barndoor skate	*Dipturus laevis*
Winter skate	*Leucoraja ocellata*
Thorny skate	*Amblyraja radiata*
Silver hake	*Merluccius bilinearis*
Atlantic cod	*Gadus morhua*
Pollock	*Pollachius virens*
White hake	*Urophycis tenuis*
Red hake	*Urophycis chuss*
Spotted hake	*Urophycis regia*
Atlantic halibut	*Hippoglossus hippoglossus*
Summer flounder	*Paralichthys dentatus*
Bluefish	*Pomatomus saltatrix*
Longhorn sculpin	*Myoxocephalus octodecemspinosus*
Sea raven	*Hemitripterus americanus*
Goosefish	*Lophius americanus*

Figures

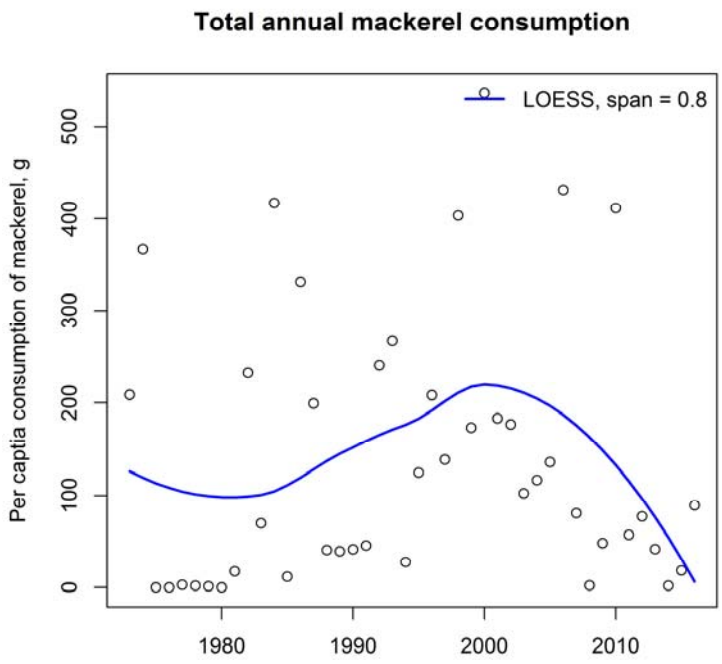


Figure 1. Total annual per capita consumption of mackerel for 17 predators in NEFSC Food Habits Database.

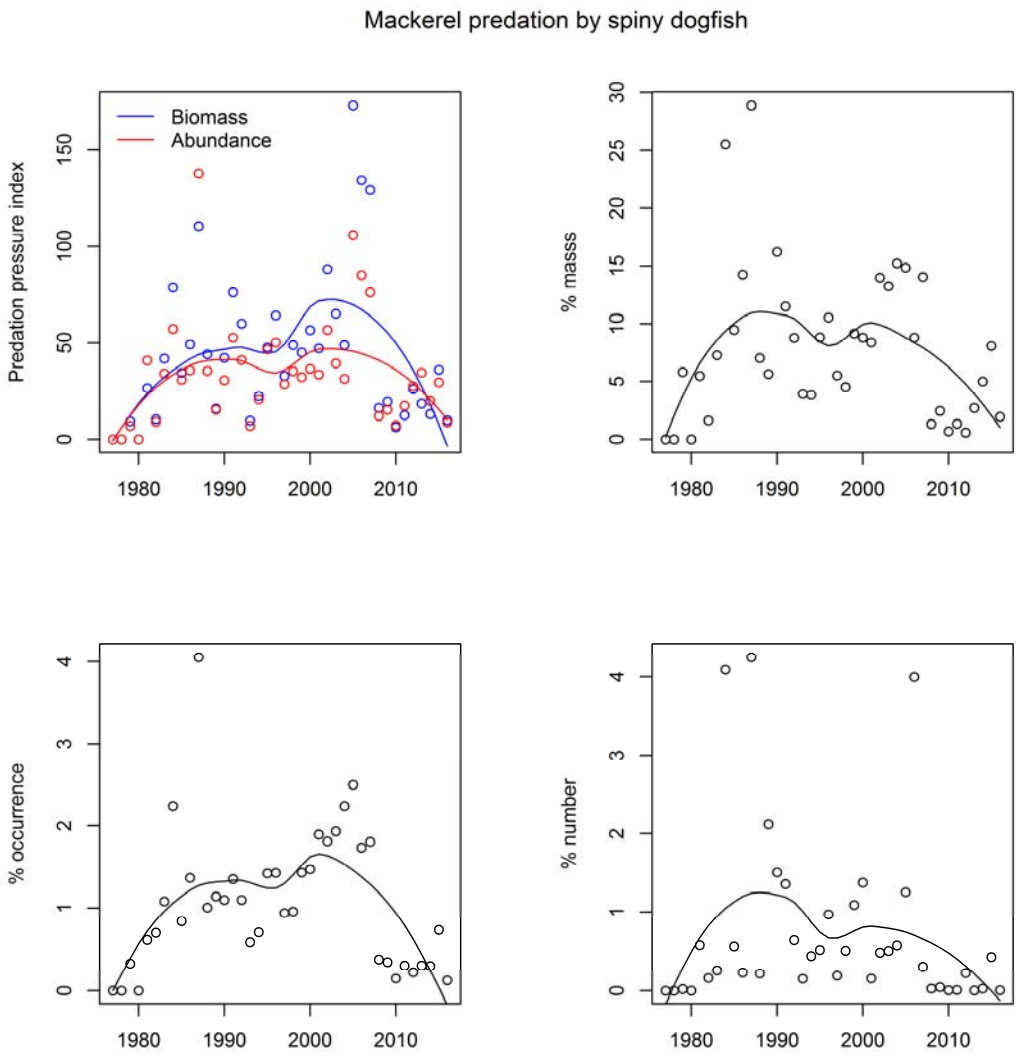


Figure 2. Mackerel predation indices for spiny dogfish: predation pressure index, and percent diet composition by mass, frequency of occurrence, and prey number. Smoother is LOESS, span = 0.8.

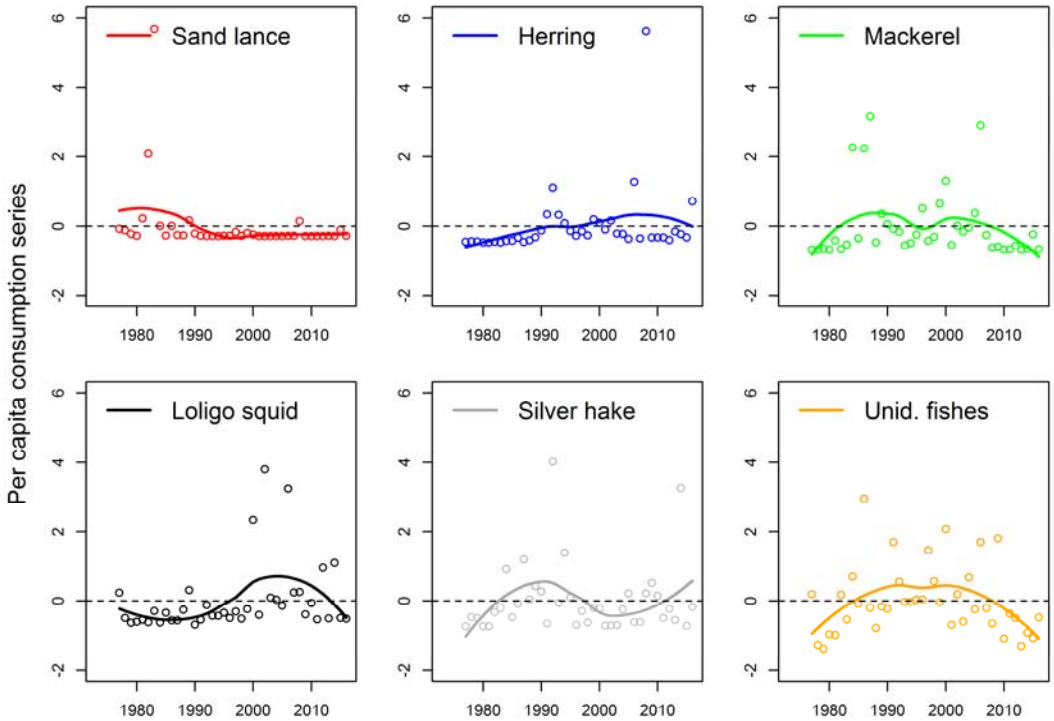


Figure 3. Z-scored annual per capita consumption of mackerel and non-mackerel prey for spiny dogfish. Smoother is LOESS, span = 0.8.

Appendix A5: Spatial patterns in the spring NEFSC survey for Atlantic mackerel

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Terms of Reference Addressed

1. Spatial and ecosystem influences on stock dynamics: a. Evaluate possible spatial influences on the stock dynamics. Recommend any need to modify the current stock definition for future stock assessments.
3. Evaluate fishery independent and fishery dependent indices being used in the assessment (e.g., indices of relative or absolute abundance, recruitment, state surveys, age-length data, etc.). Characterize the uncertainty and any bias in these sources of data

Introduction

Numerous papers have evaluated changes in the spatial distribution of Atlantic mackerel in the Northwest Atlantic Ocean using Northeast Fisheries Science Center (NEFSC) bottom trawl survey data. Murawski and Mountain (1990) found no link between the mean latitude of mackerel and several predictor variables including abundance, bottom temperature and surface temperature when analyzing shelf wide NEFSC spring survey data, 1968–1990. However, these same authors did find a significant relationship between mean latitude and surface temperature when the study area was restricted to the Mid-Atlantic Bight and the period 1980–1989 (Mountain and Murawski, 1992). Overholtz et al. (2011) noted a northeast shift in the center of mackerel distributions using spring NEFSC survey data for the period 1968–2008. A highly cited time-series analysis (Nye et al., 2009) found no significant along shelf movement, but an increase in area occupancy and a decrease in depth using shelf-wide NEFSC spring survey data for 1968–2007. In a more recent time-series analysis using stock assessment boundaries and data for 1968–2015, I found a significant increase in the mean latitude of mackerel and area occupancy, but no change in depth (Appendix 1). The differences between these two time-series analyses illustrate the importance of methodological decisions such as the choice of survey strata (i.e., footprint), length of the time-series, etc.

Objective

This working paper addresses TORs 1 & 3 through several analyses:

1. NEFSC spring survey catch of mackerel in the Gulf of Maine (GOM) over the period 1968–2016 was examined to address the current stock definition.
2. Several spatial indicators (Woillez et al., 2009) were calculated to provide summary statistics on spatial distribution of mackerel. A previous analysis of mackerel spatial distribution using stock assessment boundaries (Appendix 1) found a significant increase in mean latitude, a decrease in mean depth and an increase in area occupancy over the course of the spring NEFSC survey, 1968–2015. In the present analysis, strata and the outermost inshore strata were added (Figure 1) to investigate whether these trends persist with the additional strata.

3. The effect of survey timing on each of the spatial indices was examined. A recent analysis of spatial distribution of Northwest Atlantic groundfish (Adams et al., in review) found a significant effect of survey timing on spatial indices for stocks that exhibit migratory patterns. A similar analysis was repeated here to determine whether mackerel fall into this category.
4. Correlations between the various spatial indices and the NEFSC survey abundance index for mackerel were calculated to address potential bias in the latter. Survey timing was also included in this analysis.
5. Effect of location and date on mackerel presence/absence was examined with a generalized additive model (GAM) as an alternative spatial model.

Methods/Results

Data Preparation

Data were pulled using SAGA version 6.12 with TOGA ≤ 132X and strata shown in Figure 1. Calibration factors of 1.18 and 0.87 for numbers and weight, respectively, were applied to data for 2009–2016.

Data were prepared for spatial analysis using the methods described in Adams (2017). Briefly, longitude and latitude for each trawl station were converted to Euclidean space. Areas of influence for each station were calculated with a Dirichlet tessellation. Spatial indices calculated were: the center of gravity (CG) and its variance (inertia); abundance weighted mean depth of occurrence (mean depth); and the positive area (PA). This was done for all mackerel (hereafter referred to as the stock, even though this analysis did not use stock boundaries) as well as the immature and mature components. An L50 of 25 cm (Kiersten Curti, pers. comm.) was used such that < 25 cm = immature and ≥ 25 cm = mature.

Positive tows in the GOM

Figure 2 shows that there were only four years in which the NEFSC survey caught mackerel in the GOM during the period 1968–1990. Beginning in 1991 the proportion of positive tows averaged 12% over the next decade. After four years of no mackerel, the period of 2006–2009 also averaged 12% positive tows. Over the last seven years (2010–2016) the proportion of positive tows has increased to an average of 38%, or 41% if 2014 is omitted.

There were five years in which positive tows were made up exclusively of mature mackerel, and four years which were made up exclusively of immature mackerel. Mature mackerel have been in a majority of positive tows in five of the seven most recent years.

Spatial indices

Numerous trends are suggested by the CG and inertia maps for each year provided in Appendix 2. For example, there is an apparent northeastern shift in the CG over the course of the times series, with the two most extreme northeast points occurring in 2012 and 2015. This trend is summarized in Figure 3.

Ideally, a time-series analysis would be done to confirm the aforementioned trends. Such an analysis should have an identical survey footprint in every year analyzed (Adams, 2017). An alternative approach is to drop years from the analysis in which all strata are not sampled (Adams et al., in review; Appendix 1, this document). Applying the latter criterion to the strata chosen for this analysis would have resulted in only ten of 49 years having all strata. In spite of these concerns, a time-series analysis was done, with the caveat that the results should be

considered provisional. Regression coefficients are not provided to emphasize this point. Figure 4 shows a significant north and east shift in the CG over the course of the time-series for the stock, as well as the immature and mature components. A similar increase in area occupancy was also found. A decrease in depth was also observed for the mature component. However, this trend was barely significant ($p = 0.0495$), suggesting that it should be viewed with additional caution beyond the provisional status described above.

It is also useful to compare the trends of the present analysis with the previous analysis that used current stock boundaries (Appendix 1). Both analyses found a significant increase in the YCG and area occupancy (Table 1 & Appendix 1 Table 1). As for the XCG, the previous analysis found no significant change, whereas the present analysis found a significant increase (i.e., eastward shift). The additional data point for 2016 has decreased relative to 2015 (Figure 4), suggesting that the significant eastward shift in the present analysis is due to the addition of the GOM strata. Finally, the barely significant decrease in depth in the previous analysis is no longer significant in the present analysis, despite the 2016 data point being shallower relative to 2015 (Figure 4). This suggests that the addition of the GOM strata and/or the inshore strata has mitigated this trend.

Effect of survey timing on spatial indices

As a preliminary, the spring survey mean day-of-year using current stock boundaries and the strata in this spatial analysis are compared in Figure 5. The time-series means are 95.7 and 94.9, respectively.

The effect of survey timing on spatial indices was investigated using linear regression and GAM. For the latter, an identity link function and Gaussian distribution were used to facilitate comparison with the linear models. GAM significance level was set at $\alpha = 0.01$ (Wood, 2006). To differentiate between models an F-test was done with significance levels set at the usual $\alpha = 0.05$. ΔAIC values were also calculated.

Results for linear and GAM models are summarized in Tables 1 and 2, respectively. For the stock there was a significant nonlinear relationship between depth and survey mean day-of-year (Table 2; Figure 6a), with a peak around day 111 (April 21). There was also a significant nonlinear relationship between survey mean day-of-year and area occupancy: the PA peaked around mean day-of-year 95 (April 5), decreased to day 109 (April 19), then increased again after that (Table 2, Figure 6a). However, the latter increase was driven by two years, 2014 and 2016, when survey mean day-of-year were 122 and 130, respectively.

Survey timing had no effect on any spatial index for the immature component (Tables 1 and 2).

For the mature component there was a significant linear relationship between survey mean day-of-year and both the XCG and YCG, such that mature mackerel were found farther northeast as survey mean day-of year increased (Table 1; Figure 5b). There was also a significant nonlinear relationship between depth and survey mean day-of-year (Table 2; Figure 6b), with a peak around day 111 (April 21).

Correlations with the survey abundance index

As a preliminary, the stratified mean number per tow using current stock boundaries and the strata in this spatial analysis are compared in Figure 7. Trends are almost identical, with the spatial strata index generally being lower, except for a few years early in the time series.

Correlations between the various spatial indices and the spatial strata abundance index were calculated, as well as for the survey mean day-of-year and the abundance index. An additional calculation was also done for the positive area. In a simulation study, Rindorf and Lewy (2012) found that spurious relationships between abundance and indices such as the proportion of positive tows may be generated when no such relationship exists if the data have a negative binomial distribution and the mean number per tow is ≤ 10. Adams et al. (in review) confirmed this effect with empirical data, finding spurious relationships between abundance and the PA for groundfish stocks with relatively low abundance indices. Thus, the abundance-PA correlation was also calculated using only years in which the former was > 10.

Table 3 shows a significant positive correlation between the abundance index and the CG, indicating that years with high abundance are associated with mean locations of the population that are more northeast. This trend is driven by the mature component. There also appears to be positive correlation between the abundance index and area occupancy; however, when years of low abundance are removed this relationship only exists for the immature component.

Effect of location and date on mackerel presence

Plots of catch biomass, ordered by consecutive tow number (Appendix 3), suggested that it may be possible to model the probability and magnitude of a tow based on the location and magnitude of the previous tow.

As a first step in model building, the effect of location and date on the presence/absence of mackerel was investigated with a GAM. In this case a binomial error distribution with a logit link function was used. Cubic regression splines (Wood, 2006) was chosen as a smoother, with a maximum of 5 degrees of freedom (i.e., knots (k) = 5). Additionally, a $\lambda = 1.4$ was used to place a heavier penalty on each degree of freedom to counteract overfitting (Sagarese et al., 2014). As above, significance level was set at $\alpha = 0.01$.

Table 4 shows that there was a significant relationship between mackerel presence for geographically referenced longitude and latitude in 53% and 78% of years, respectively. There was a significant relationship between mackerel presence and survey day-of-year in 24% of years.

This analysis is ongoing.

Conclusions

Given the increasing proportion of positive tows in the GOM it is suggested the stock boundaries for mackerel be revised to include GOM strata.

The proportion of positive tows since 2010 (with the exception of 2014) has been higher than all other years in the time series. However, the proportion of positive tows for 2009 and 2014 were lower than in 1996 and 2008, indicating the higher proportion in recent years is not just a Bigelow effect. Nevertheless, given the lack of a length-based calibration, it is suggested that the Bigelow data be treated as a separate series.

A comparison of my previous stock boundary analysis with the present spatial analysis illustrate that some signals are strong enough to be impervious to inconsistent survey footprints, while other results should be considered analysis-specific. Increasing YCG and area occupancy over the course of the times series fall into the former category, while eastward movement and decreasing depth fall into the latter category.

Survey timing has differing effects on spatial indices, depending on whether one is looking at the immature component, the mature component, or the stock as a whole. There was no effect of mean day-of-year on spatial indices for the immature component. For the mature component, the positive relationship between mean day-of-year and the CG illustrates that inferences based on linear relationships should be examined carefully: the two recent late years (2014 & 2016) had CGs that fit almost exactly on the trend line, and were not outliers as one might guess. The nonlinear relationship between mean day-of-year and depth for both the mature component and the stock as a whole suggests that changes in depth distribution should be considered in conjunction with survey timing (along with the footprint caveat described above). Similarly, the nonlinear relationship between mean day-of-year and the PA for mackerel suggests that area occupancy should also be considered in conjunction with survey timing, particularly given that the late timing increase is based on two data points.

Years with a relatively higher stratified mean number per tow are associated with mean locations of the population that are more northeast. This trend is driven by the mature component. The relationship between the abundance index and the number of positive tows appears to be spurious.

Modeling the probability and magnitude of a tow based on the location and magnitude of the previous tow is ongoing. In the first step a significant relationship between mackerel presence and location was found. Specifically, mackerel presence was related to latitude in 78% of years, and longitude in 53% of years. Survey day-of-year was related to mackerel presence in only 24% of years.

References

Adams CF. 2017. Age-specific differences in the seasonal spatial distribution of butterfish (*Peprilus triacanthus*). ICES Journal of Marine Science 74:170–179

Adams CF, Alade LA, Legault CM, O'Brien L, Palmer MC, Sosebee KA, Traver ML. In review. Seasonal trends in the spatial distribution of Northwest Atlantic groundfish stocks over the last half-century. ICES Journal of Marine Science

Mountain DG, Murawski SA. 1992. Variation in the distribution of fish stocks on the northeast continental shelf in relation to their environment, 1980–1989. ICES Marine Science Symposium 195:424–432

Murawski SA, Mountain DG. 1990. Climate change and marine fish distributions: analogies from seasonal and annual variability. ICES Document CM 1990/C: 36. 24 pp

Nye JA, Link JS, Hare JA, Overholtz WJ. 2009. Changing spatial distribution of fish stocks in relation to climate and population size on the Northeast United States continental shelf. Marine Ecology Progress Series 393:111–129

Overholtz WJ, Hare JA, Keith CM. 2011. Impacts of interannual environmental forcing and climate change on the distribution of Atlantic mackerel on the U.S. Northeast Continental Shelf. Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science 3:219–232

Rindorf A, Lewy P. 2012. Estimating the relationship between abundance and distribution. Canadian Journal of Fisheries and Aquatic Sciences 69:382–397

Sagarese SR, Frisk MG, Cerrato RM, Sosebee KA, Musick JA, Rago PJ. 2014. Application of generalized additive models to examine ontogenetic and seasonal distributions of spiny dogfish (*Squalus acanthias*) in the Northeast (US) shelf large marine ecosystem. Canadian Journal of Fisheries and Aquatic Sciences 71:847–877

Woillez M, Rivoirard J, Petitgas P. 2009. Notes on survey-based spatial indicators for monitoring fish populations. Aquatic Living Resources 22:155–164

Wood SN. 2006. Generalized Additive Models: An Introduction with R. Chapman and Hall/CRC Press

Table 1. Slope (β), standard error, t-value and p-value for linear regressions of Atlantic mackerel center of gravity (XCG, YCG), inertia, depth and positive area (PA) as a function of survey mean day-of-year. P-values < 0.05 are in bold.

	Stock				Immature component				Mature component			
	β	s.e.	t	p	β	s.e.	t	p	β	s.e.	t	p
XCG	3.23	1.88	1.72	0.092	1.50	2.28	0.66	0.512	4.30	1.85	2.33	**0.024**
YCG	3.03	1.65	1.84	0.072	1.50	2.04	0.74	0.466	3.77	1.86	2.02	**0.049**
Inertia	366.87	347.62	1.06	0.297	404.37	313.64	1.29	0.204	259.67	499.23	0.52	0.605
Depth	1.18	0.28	4.22	**< 0.001**	0.25	0.26	0.97	0.336	1.08	0.44	2.48	**0.017**
PA	355.55	353.68	1.01	0.320	-196.43	268.99	-0.73	0.469	480.42	296.36	1.62	0.112

Table 2. Effective degrees of freedom and p-value for GAM fits of Atlantic mackerel center of gravity (XCG, YCG), inertia, depth and positive area (PA) as a function of survey mean day-of-year. P-values < 0.01 are in bold. The ΔAIC and F-test values are provided for cases where the GAM is significant. P-values < 0.05 for the latter are in bold

	Stock				Immature component				Mature component			
	edf	p	ΔAIC	F.test	edf	p	ΔAIC	F.test	edf	p	ΔAIC	F.test
XCG	3.26	0.121			4.23	0.132			3.17	0.036		
YCG	3.62	0.026			5.54	0.036			3.42	0.022		
Inertia	1.38	0.417			2.72	0.024			1.00	0.605		
Depth	3.54	**0.002**	6.46	**0.020**	1.00	0.336			2.52	**0.007**	5.78	**0.020**
PA	3.99	**0.009**	12.06	**0.002**	3.72	0.047			3.71	0.017		

Table 3. Pearson's *r* and asymptotic *p*-values for correlations between the NEFSC stratified mean number of mackerel per tow and the center of gravity (XCG, YCG), inertia, depth, positive area (PA) and survey mean day-of-year. PA.sub reports *r* and *p*-values for years when the abundance index was > 10. Sample sizes for the latter were: stock (n = 31); immature (n = 14); mature (n = 18). The abundance index was log-transformed for all calculations to meet the assumption of normality. *P*-values < 0.05 are in bold.

	Stock		Immature		Mature	
	r	*p*	*r*	*p*	*r*	*p*
XCG	0.29	**0.045**	0.23	0.119	0.30	**0.039**
YCG	0.43	**0.002**	0.27	0.062	0.45	**0.001**
Inertia	-0.08	0.598	-0.04	0.770	-0.07	0.624
Depth	-0.28	0.056	-0.17	0.232	-0.28	0.052
PA	0.66	**< 0.001**	0.72	**< 0.001**	0.56	**< 0.001**
PA.sub	0.28	0.124	0.63	**0.016**	0.05	0.851
Mean.doy	-0.19	0.198	-0.24	0.097	-0.10	0.489

Table 4. Effective degrees of freedom and *p*-value for GAM fits of Atlantic mackerel presence/absence as a function of geographically referenced longitude (X) and latitude (Y), and survey day-of-year. Fits that reduced to a linear model are highlighted in gray. *P*-values < 0.01 are in bold.

	X		Y		day-of-year	
Year	edf	*p*	edf	*p*	edf	*p*
1968	2.08	0.127	1.00	0.916	2.85	0.128
1969	3.60	0.020	1.00	**< 0.001**	1.00	0.922
1970	1.00	0.014	2.32	**0.006**	1.00	**0.005**
1971	2.62	0.224	2.91	0.081	1.48	0.428
1972	3.54	0.015	2.96	0.011	1.00	0.020
1973	2.43	**< 0.001**	2.93	**< 0.001**	1.00	**0.001**
1974	1.00	**0.002**	2.47	**0.004**	1.13	**< 0.001**
1975	2.53	**< 0.001**	1.56	**0.001**	1.00	0.538
1976	1.00	**0.006**	2.94	**< 0.001**	1.56	0.212
1977	3.91	**< 0.001**	3.65	**< 0.001**	1.00	0.483
1978	2.86	**0.003**	1.96	**0.002**	1.00	0.307
1979	1.00	0.147	2.39	**< 0.001**	1.93	0.023
1980	3.94	0.029	2.51	**< 0.001**	1.07	0.426
1981	3.99	**< 0.001**	3.29	**< 0.001**	1.00	**< 0.001**
1982	3.88	0.026	2.91	0.131	1.00	0.477
1983	1.00	0.398	2.84	0.016	1.00	0.195
1984	1.00	**0.002**	1.00	0.104	2.17	**< 0.001**
1985	1.00	0.818	1.57	**0.003**	3.00	0.028
1986	1.00	0.868	1.94	**0.007**	1.77	0.058
1987	1.52	0.185	2.64	**0.001**	1.00	0.019
1988	2.54	0.035	2.80	**< 0.001**	2.84	0.222
1989	1.00	0.087	2.79	0.069	1.00	0.085
1990	2.78	**0.003**	2.56	**0.002**	1.00	0.363
1991	3.64	**< 0.001**	3.30	**< 0.001**	1.50	0.075
1992	1.00	0.034	2.62	**< 0.001**	1.00	**0.002**
1993	2.82	**< 0.001**	2.67	**< 0.001**	4.00	**< 0.001**
1994	1.78	**< 0.001**	2.07	**< 0.001**	3.02	0.060
1995	3.53	0.021	2.97	0.026	1.91	0.214
1996	1.53	0.052	3.71	**< 0.001**	1.00	0.067
1997	3.86	**0.009**	2.74	**0.001**	1.00	0.315
1998	3.64	**0.003**	2.16	0.117	1.00	0.969
1999	1.35	0.229	2.34	**< 0.001**	1.48	0.324
2000	3.96	**< 0.001**	2.14	**0.002**	1.85	**0.001**
2001	1.81	0.185	2.26	**0.002**	3.54	0.043
2002	1.00	**0.001**	3.12	**< 0.001**	1.00	0.011
2003	3.93	**< 0.001**	2.82	**< 0.001**	1.05	0.258
2004	1.00	0.017	2.73	**< 0.001**	1.00	0.319
2005	2.98	**0.006**	2.74	**0.002**	1.86	0.042
2006	2.43	**0.007**	1.88	**0.001**	1.75	**0.008**
2007	1.42	0.151	2.06	0.056	3.47	**0.005**
2008	1.00	0.045	3.41	**0.001**	3.12	0.221

Table 4 continued.

	X		Y		day-of-year	
Year	edf	*p*	edf	*p*	edf	*p*
2009	3.73	**< 0.001**	3.53	**< 0.001**	3.36	0.026
2010	3.45	**< 0.001**	3.92	**< 0.001**	1.00	0.025
2011	2.97	**0.006**	3.25	**0.001**	3.78	**0.006**
2012	2.75	**< 0.001**	3.67	**< 0.001**	2.17	0.066
2013	3.84	**< 0.001**	1.00	**0.002**	1.52	0.499
2014	1.00	0.977	1.00	0.608	3.49	0.215
2015	3.05	**< 0.001**	3.92	**0.007**	1.82	**0.002**
2016	3.73	**< 0.001**	2.77	**0.000**	1.42	0.598

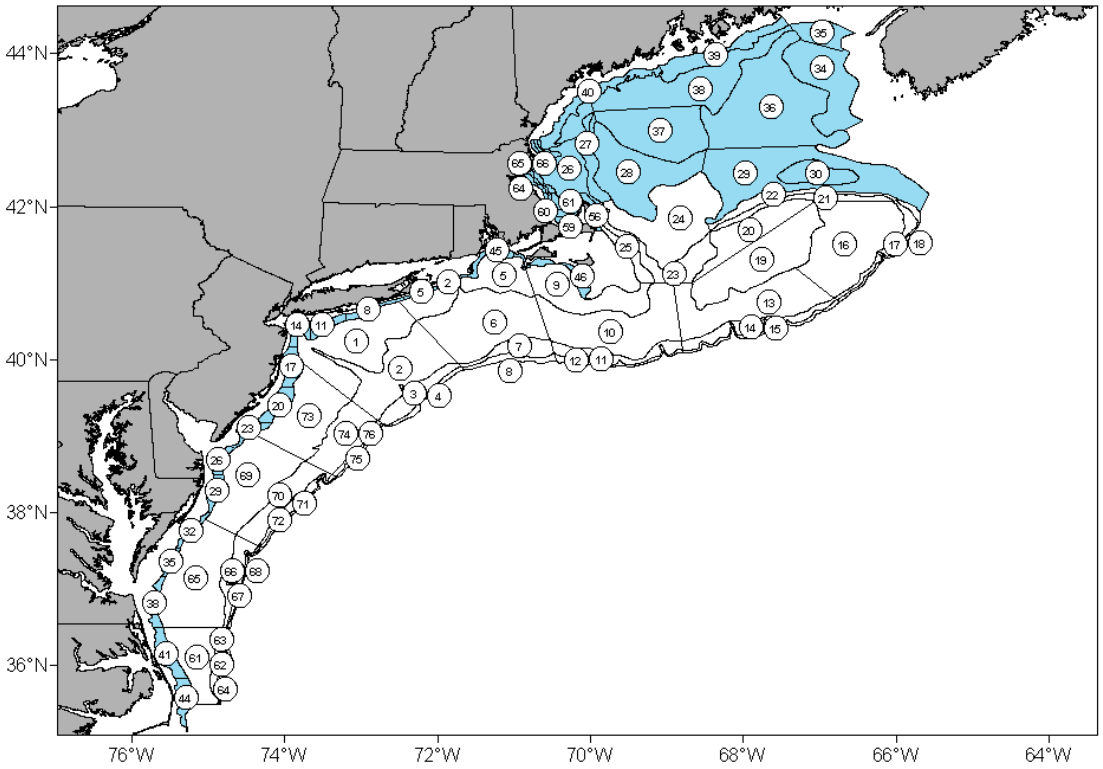


Figure 1. Current mackerel assessment strata (white) and additional strata used in this analysis (blue). The latter includes Gulf of Maine strata (26–30, 34–40) and the outermost inshore strata (2, 5, 8, 11, 14, 17, 20, 23, 26, 29, 32, 35, 38, 41, 44-46, 56, 59-61, 64-66)

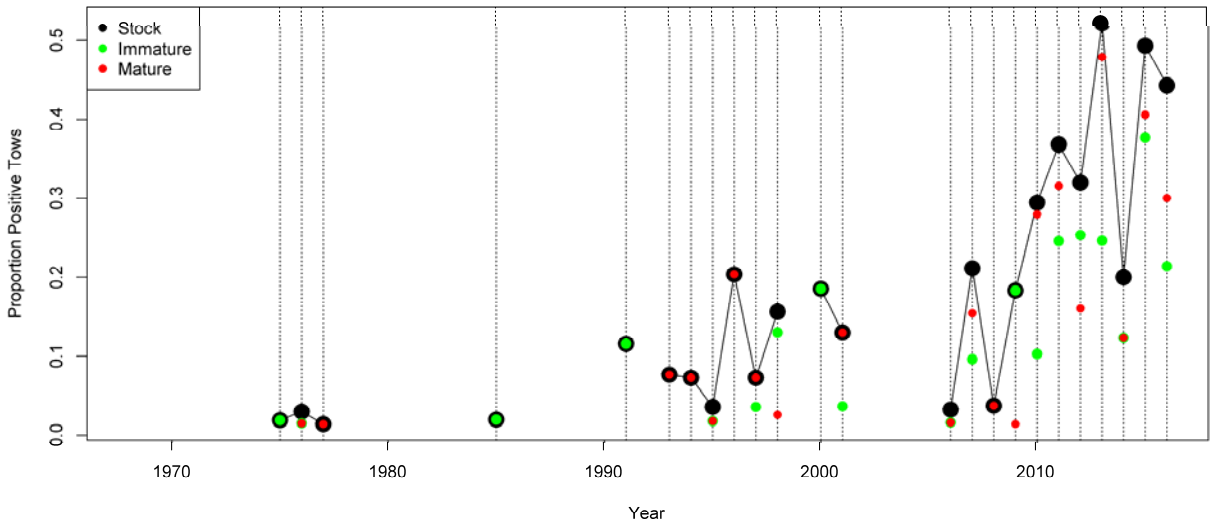


Figure 2. Proportion of positive tows for mackerel in the Gulf of Maine. Vertical lines are provided for years with positive tows to aid in visualization.

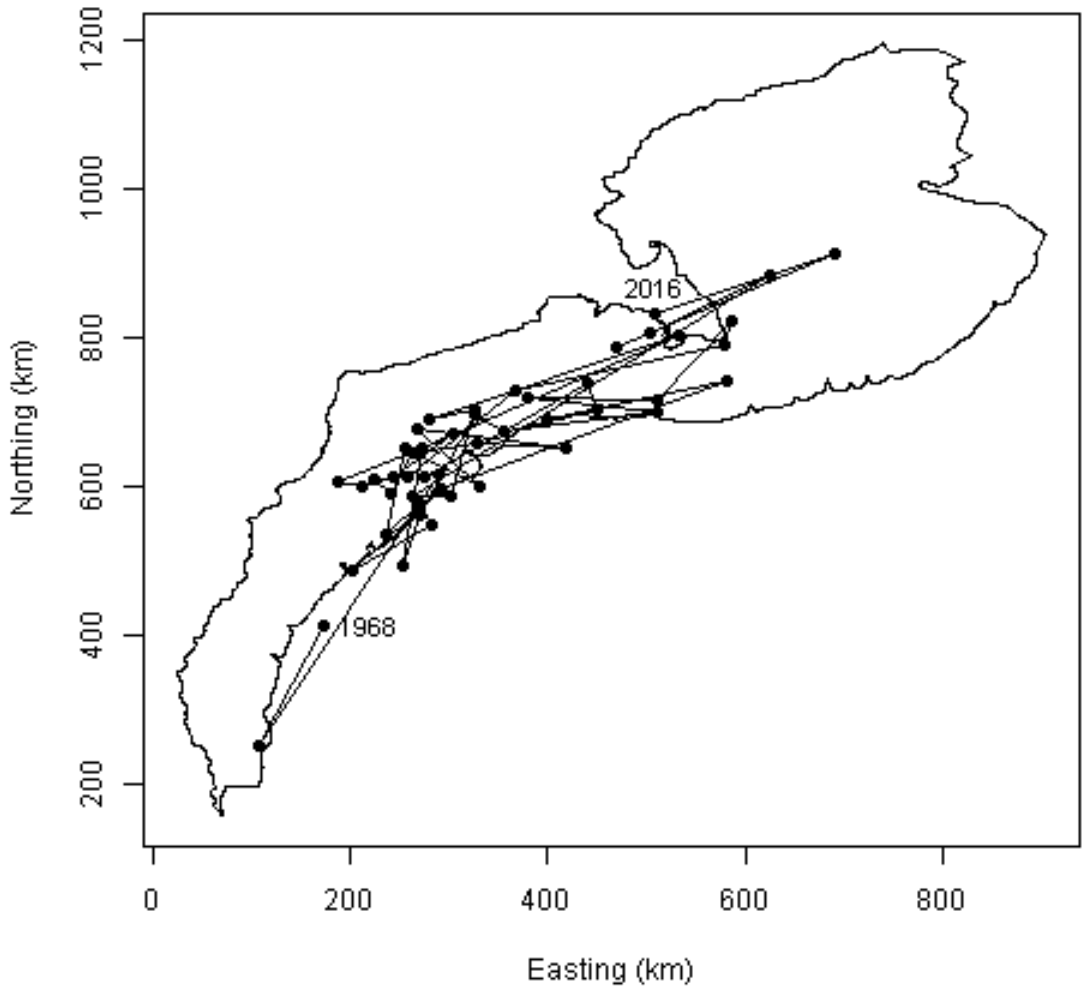


Figure 3. Centers of gravity for Atlantic mackerel, spring 1968–2016

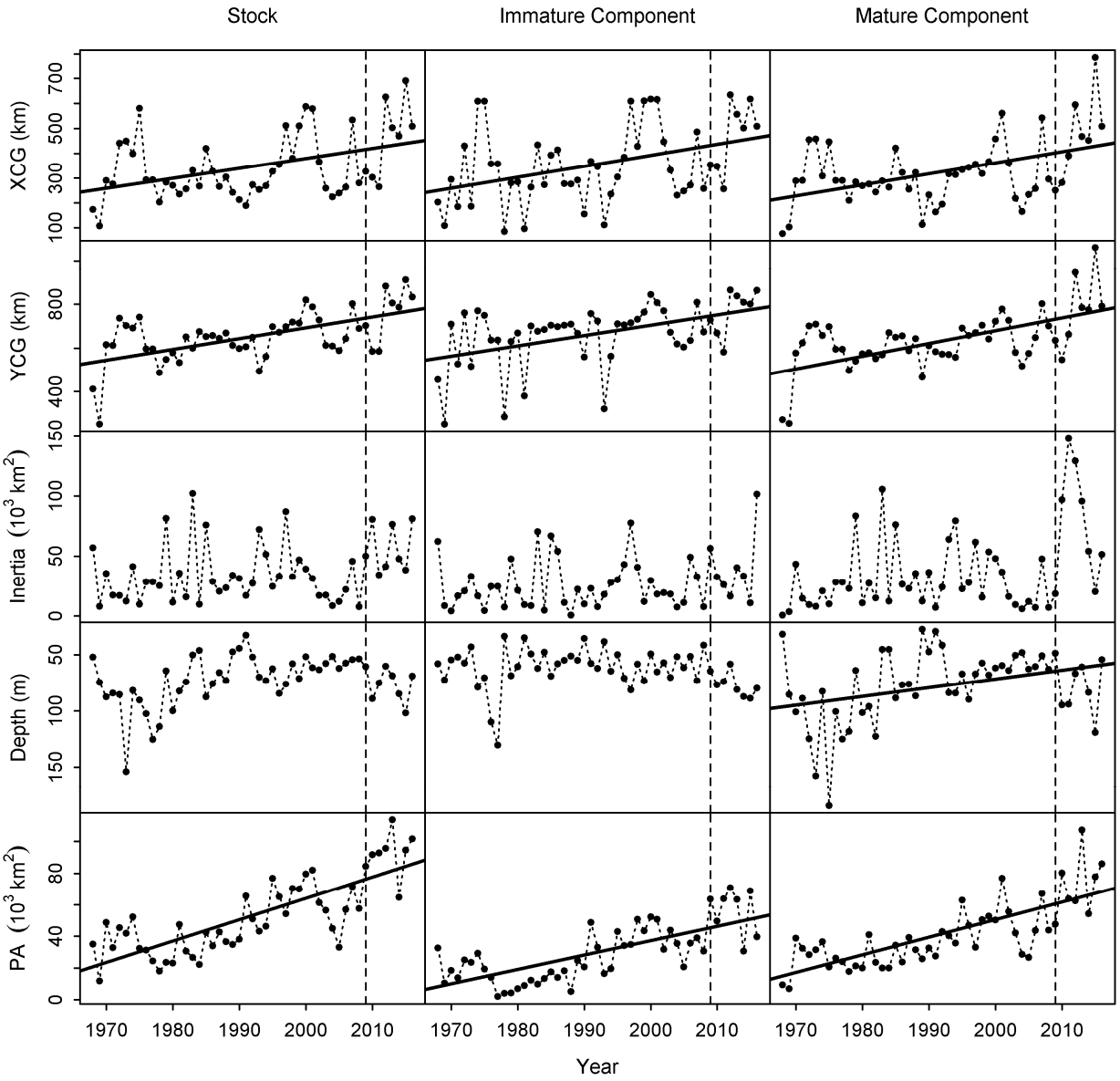


Figure 4. Spring time series of spatial indicators for Atlantic mackerel. Solid lines indicate a significant linear fit at the level of $\alpha = 0.05$. A vertical dashed line is provided to aid in tracking the year 2009.

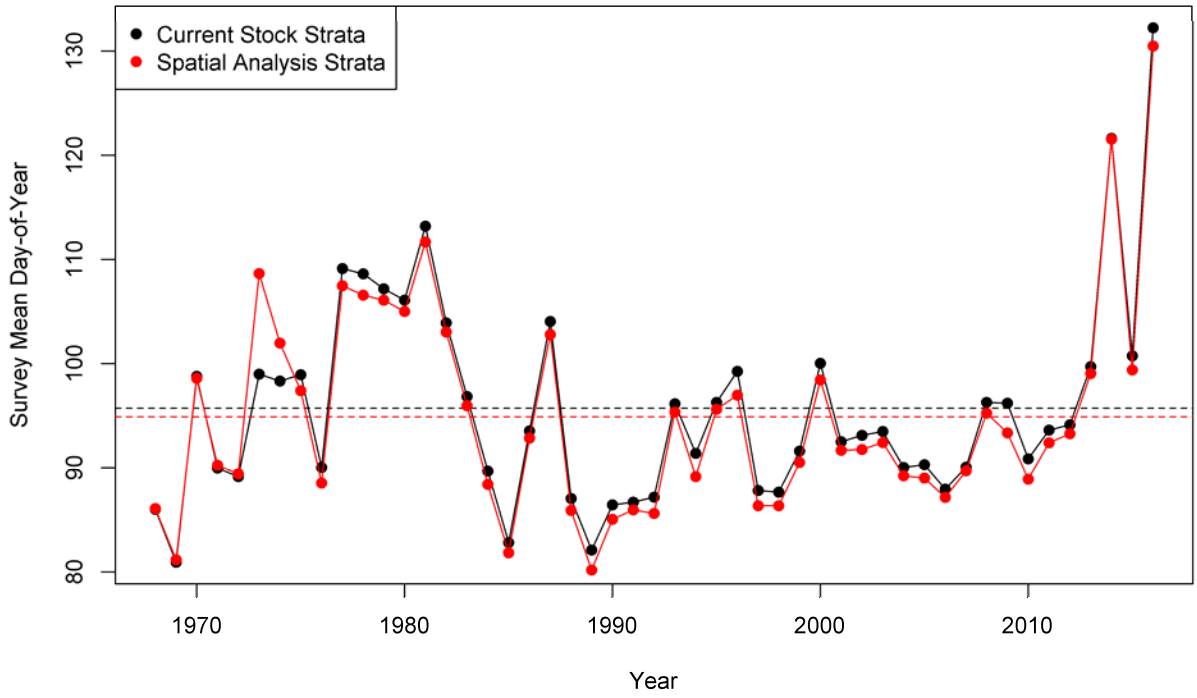


Figure 5. NEFSC spring survey mean day-of-year, 1968–2016.

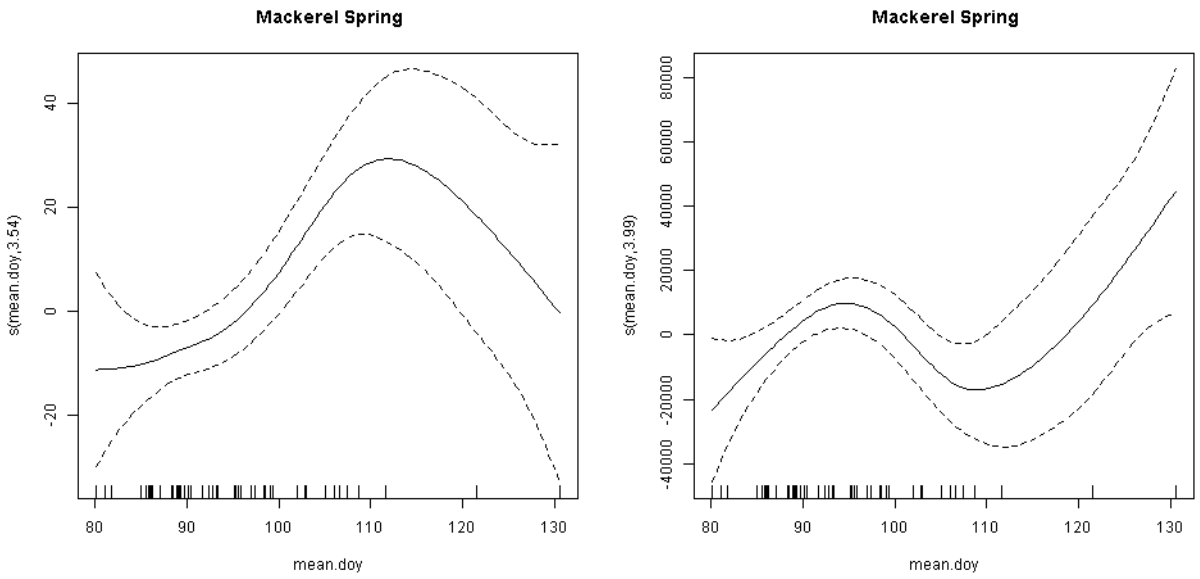


Figure 6a. Significant nonlinear fits of mackerel depth (left) and PA (right) to survey mean day-of-year (see Table 2).

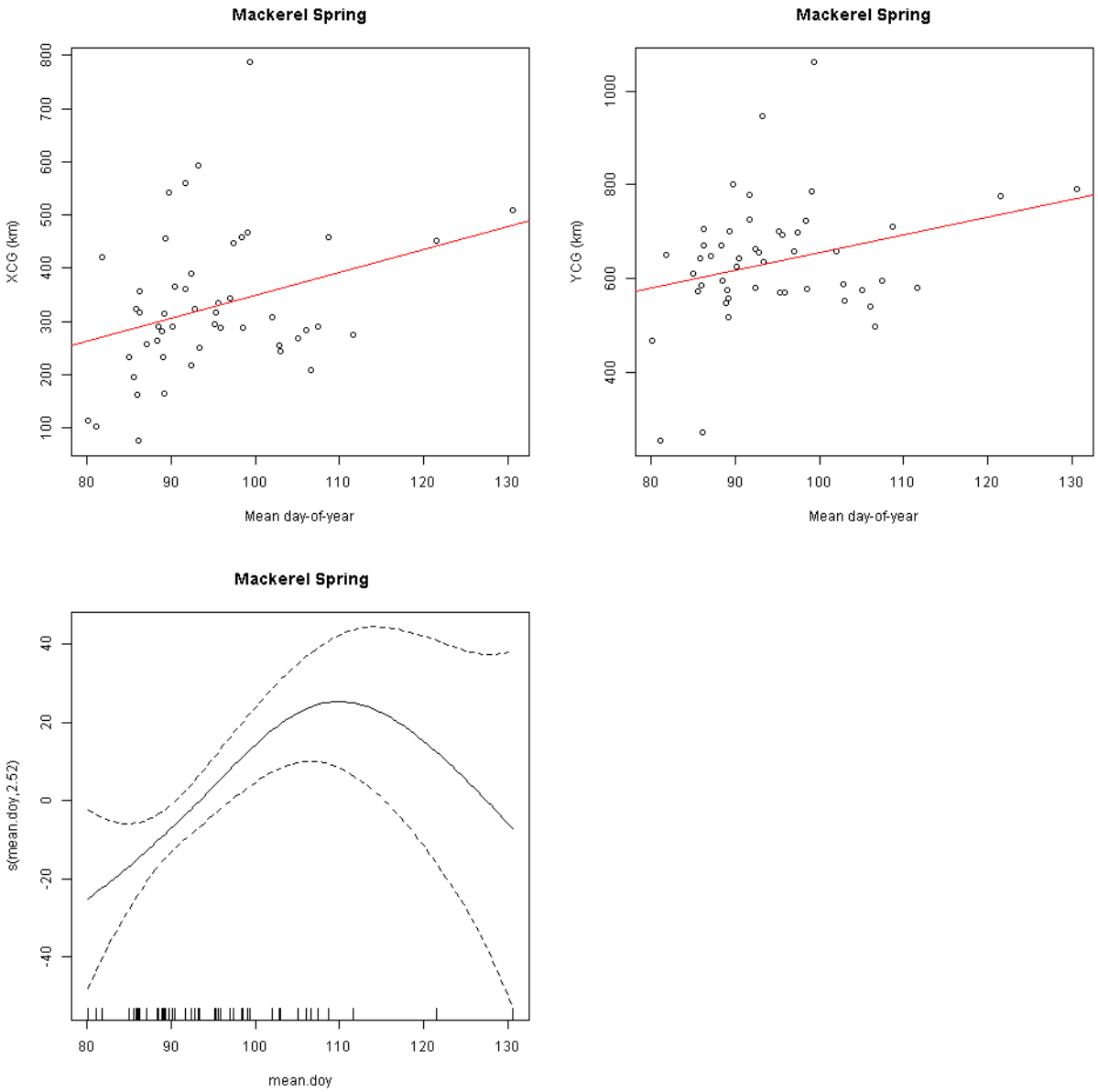


Figure 6b. Significant linear fits of mature mackerel XCG (upper left) and YCG (upper right) to survey mean day-of-year (see Table 1). Significant nonlinear fit of mature mackerel depth (lower left) to survey mean day-of-year (see Table 2).

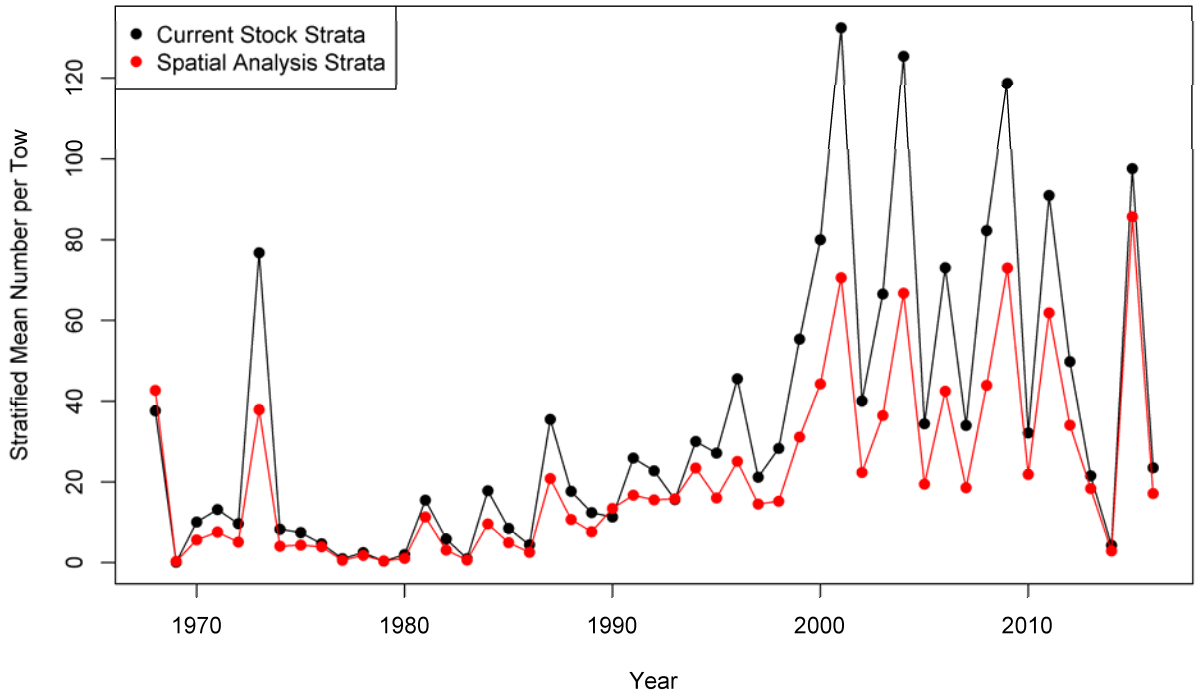


Figure 7. NEFSC stratified mean number per tow for mackerel, spring 1968–2016.

Appendix 1

Preliminary analysis of mackerel spatial distribution
Provided to mackerel WG 12/1/2015
Minor edits 4/12/2017

Preliminary analysis of mackerel spatial distribution
12/1/2015, updated 4/12/2017 with Adams (2017) citation & previously unpublished positive area text, results & Figure

Summary
- Calculated center of gravity (CG), inertia (variance) and abundance weighted mean depth of occurrence
- Regression of XCG, YCG, inertia and depth as a function of year; if the regression was significant, but failed a Durbin-Watson test for serial correlation, an autoregressive (AR) model was used instead
- Significant increase in YCG over the course of the time series after correction with an AR model (Table 1; Figure 1)
- Barely significant decrease in depth over the course of the time series after correction with an AR model (Table 1: Figure 2)
- Increasing trend in XCG over the course of the time series no longer significant after correction with an AR model (Table 1; Figure 3)
- Significant increase in area occupancy over the course of the time series after correction with an AR model (Table 1; Figure 4)

Data & methods
- Spring NEFSC survey data, 1968-2015, using SAGA parameters & stock boundaries you gave me
- It is important to have the same footprint of survey strata throughout the time series. In my butterfish analysis I achieved this by dropping the few assessment strata that were not sampled throughout the time series. In this mackerel analysis, my objective was to maintain stock strata/boundaries. Twelve years were excluded from analysis due to certain strata not being sampled in those years (see accompanying file "missing strata.xlsx"). Exclusion of these strata had no effect on significance vs. non-significance.
- For further methodological details see Adams (2017)

Comparison with previous studies
CG

There are some minor differences as compared with Nye et al. (2009) and Walsh et al. (2015). Nye et al. found no significant poleward (i.e., along shelf) movement in the southern ecoregion, 1968-2007; whereas Walsh at al. reported significant along-shelf and cross-shelf movement for adults in the spring 1999-2008 (EcoMon) vs. the 1977-1987 (MARMAP) data. Using the stock assessment boundaries, I found significant northward (YCG) movement over time but no significant change in the XCG.

Depth

With respect to depth, Nye et al. found a significant decrease in depth, while Walsh et al. reported no difference in depth for adults between the two spring time periods. Given the significance level ($p = 0.049$) for my analysis the results should be considered provisional.

Future work
- Age based analysis

- Length-based calibration
- Area occupancy (after calculating areas of influence)

Table 1. Slope (β), standard error, t-value and p-value for linear regressions (left) of Atlantic mackerel center of gravity (XCG, YCG), inertia, depth and positive area (PA) as a function of year. Significant linear regressions that failed a Durbin-Watson test for serial correlation were fit with an autoregressive AR model (right). P-values < 0.05 are in bold.

	Linear regression				AR model			
	β	s.e.	t-value	p-value	β	s.e.	t-value	p-value
XCG	3.25	1.43	2.27	**0.030**	3.70	1.96	1.88	0.068
YCG	3.39	1.10	3.09	**0.004**	3.60	1.49	2.41	**0.022**
Inertia	34.10	233.96	0.15	0.885				
Depth	-1.11	0.29	-3.80	< **0.001**	-0.91	0.44	-2.05	**0.049**
PA	839.01	143.51	5.85	< **0.001**	808.68	204.41	3.96	< **0.001**

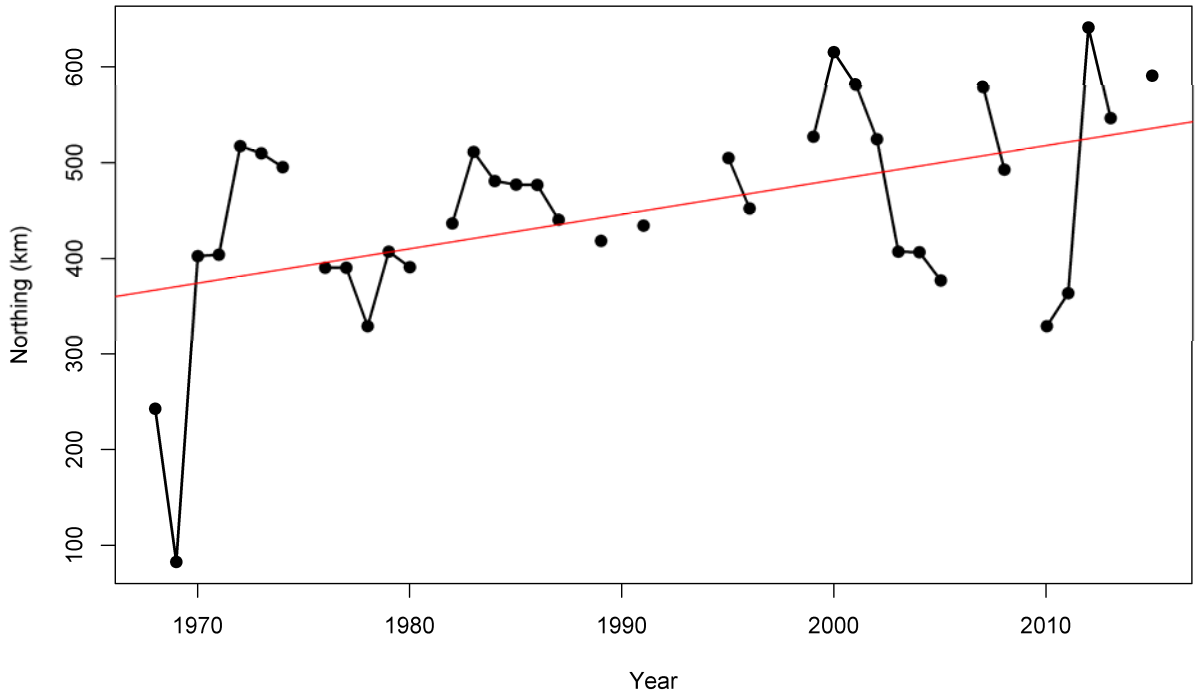


Figure 1. Time series of the latitude component of the center of gravity for Atlantic mackerel using spring NEFSC survey data, 1968-2015. Red line is the linear fit using an autoregressive model

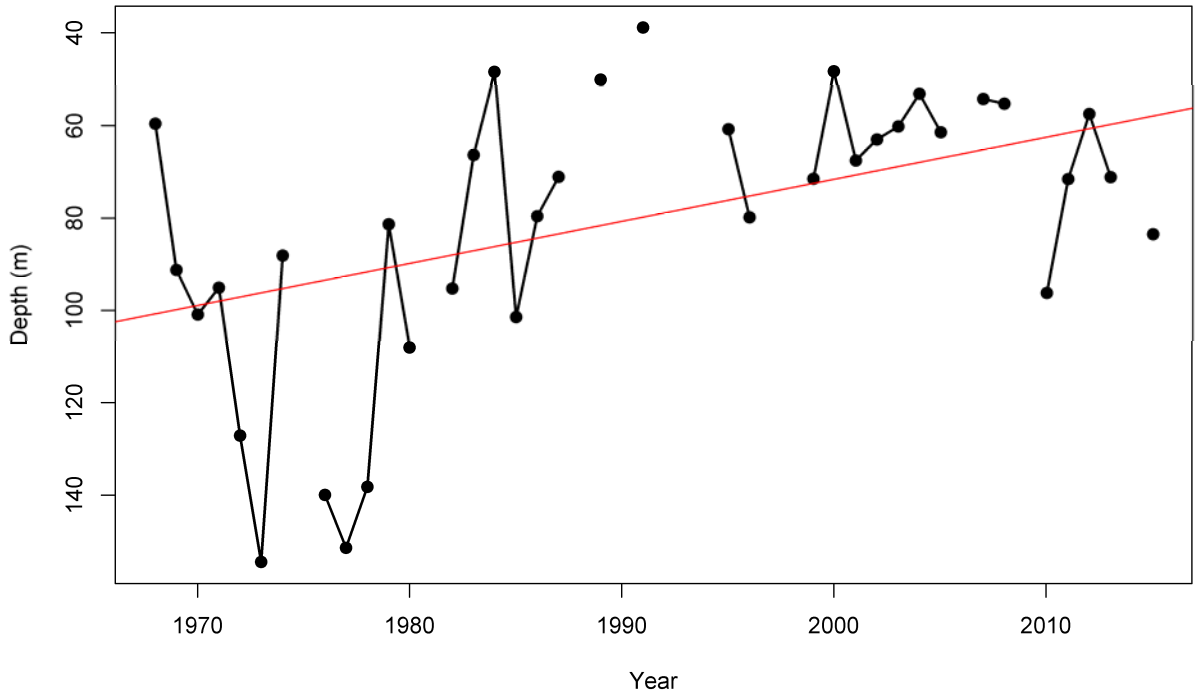


Figure 2. Time series of the abundance weighted mean depth of occurrence for Atlantic mackerel using spring NEFSC survey data, 1968-2015. Red line is the linear fit using an autoregressive model.

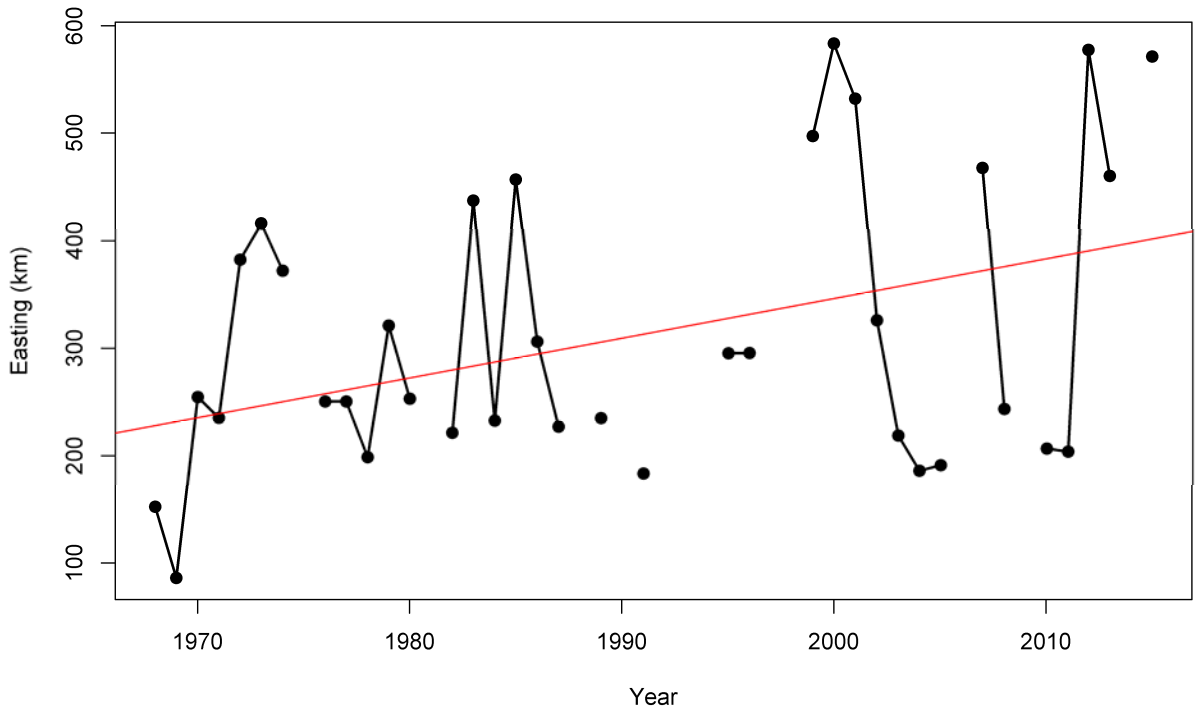


Figure 3. Time series of the longitude component of the center of gravity for Atlantic mackerel using spring NEFSC survey data, 1968-2015. Red line is the linear fit using an autoregressive model

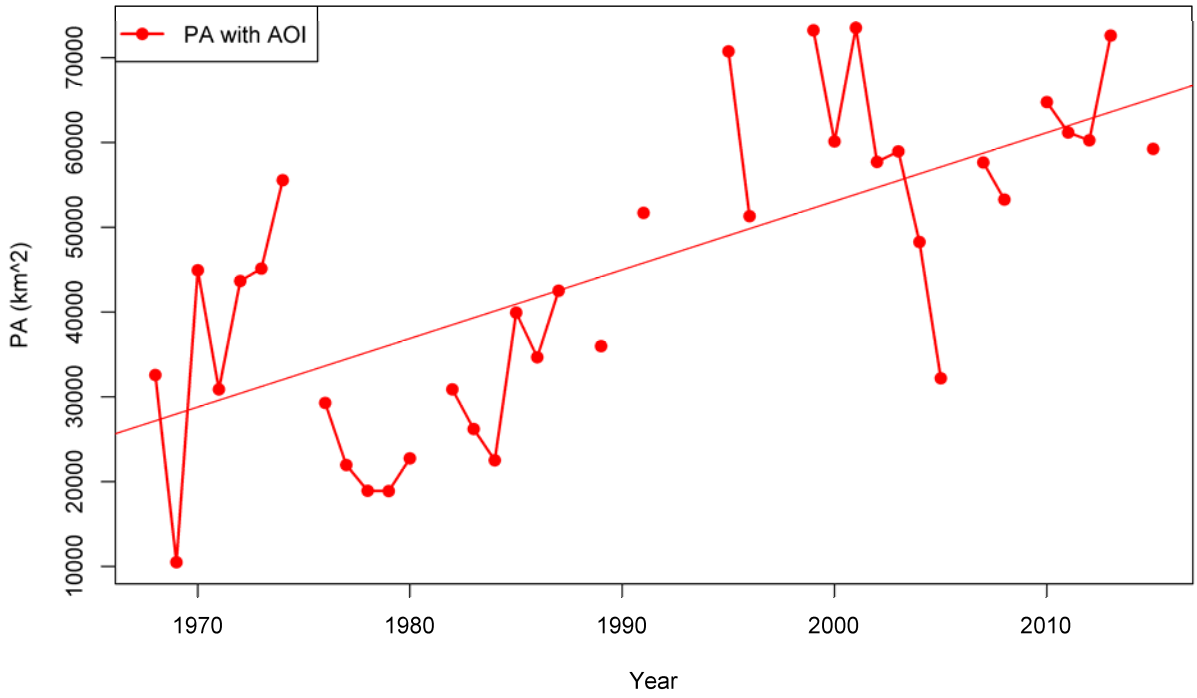
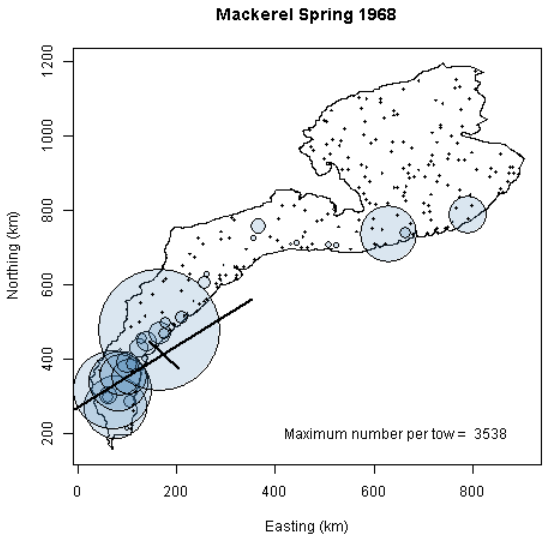
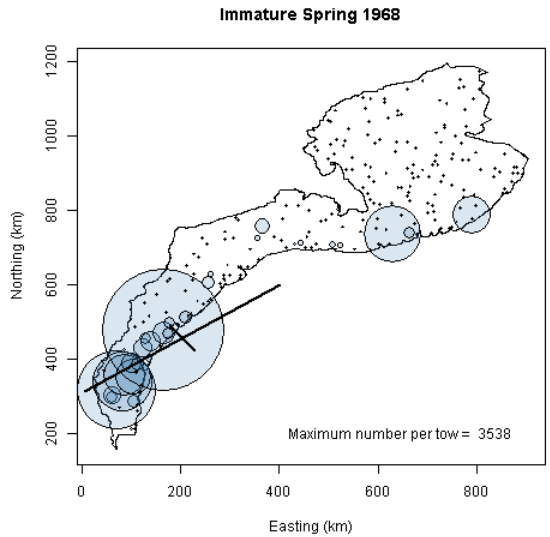


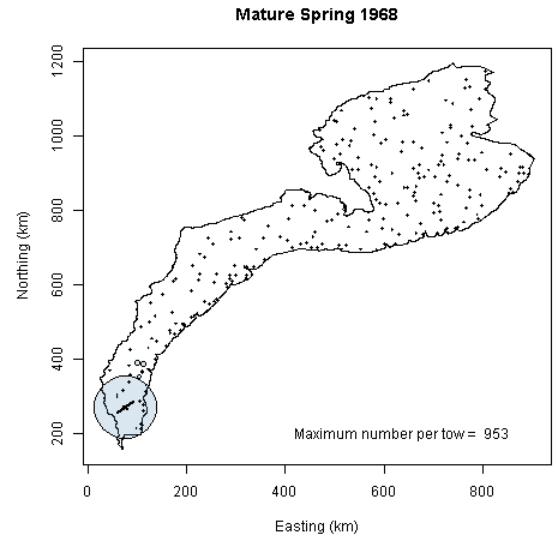
Figure 4. Time series of positive tows, weighted with areas of influence, for Atlantic mackerel using spring NEFSC survey data, 1968-2015. Red line is the linear fit using an autoregressive model.

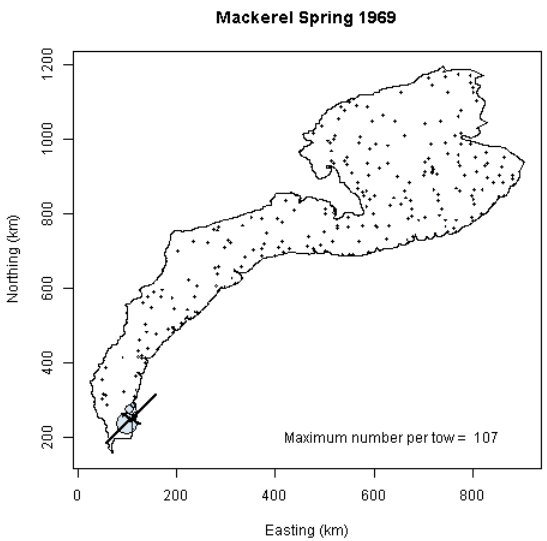
Appendix 2

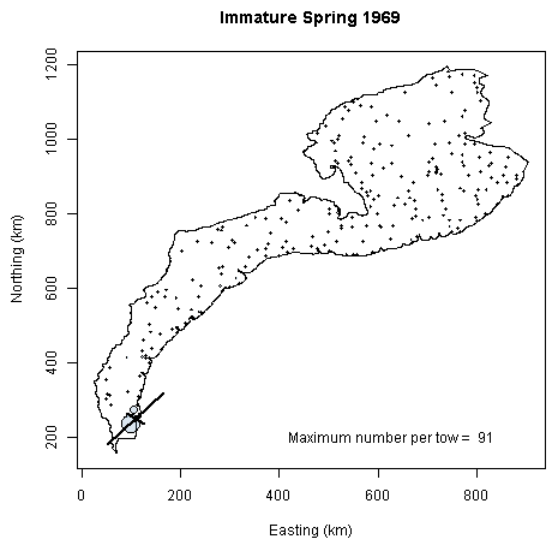
Center of gravity and inertia maps for Atlantic mackerel, based on spring NEFSC survey data catch numbers, 1968–2016

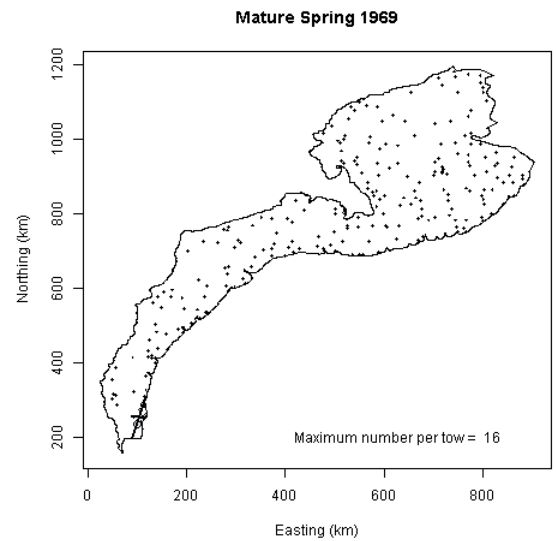

Mackerel Spring 1968
Maximum number per tow = 3538
Northing (km)
Easting (km)

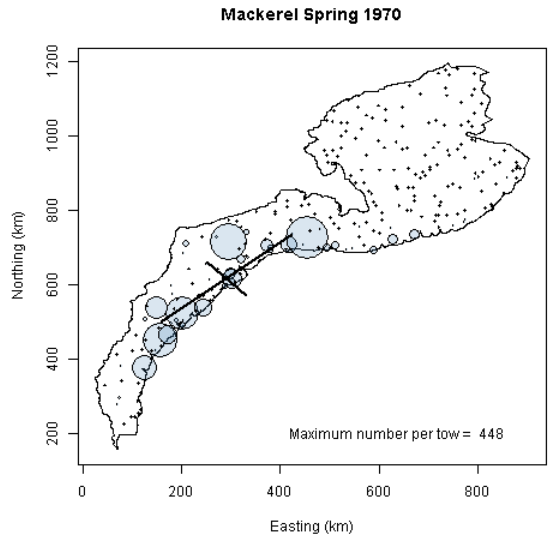

Immature Spring 1968
Maximum number per tow = 3538
Northing (km)
Easting (km)

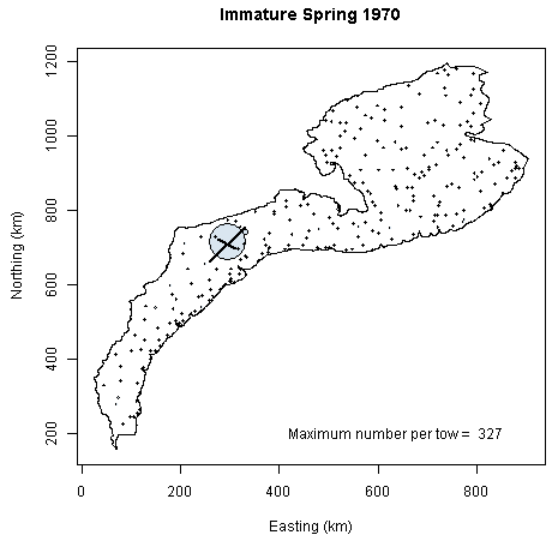

Mature Spring 1968
Maximum number per tow = 953
Northing (km)
Easting (km)

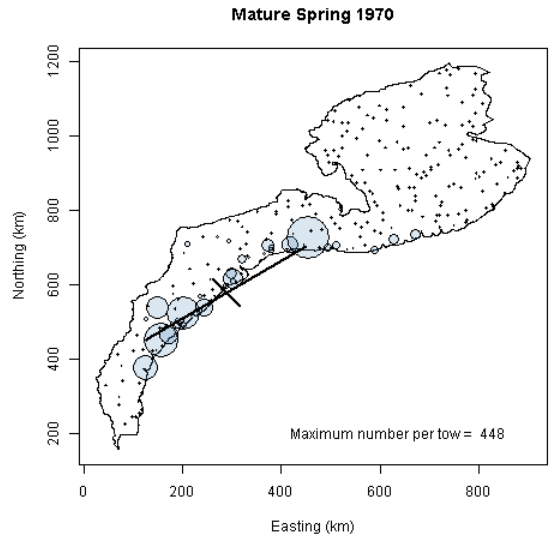

Mackerel Spring 1969
Maximum number per tow = 107
Northing (km)
Easting (km)

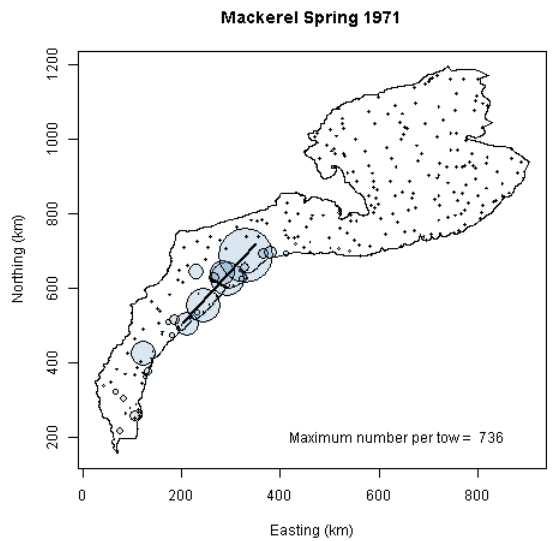

Immature Spring 1969
Maximum number per tow = 91
Northing (km)
Easting (km)

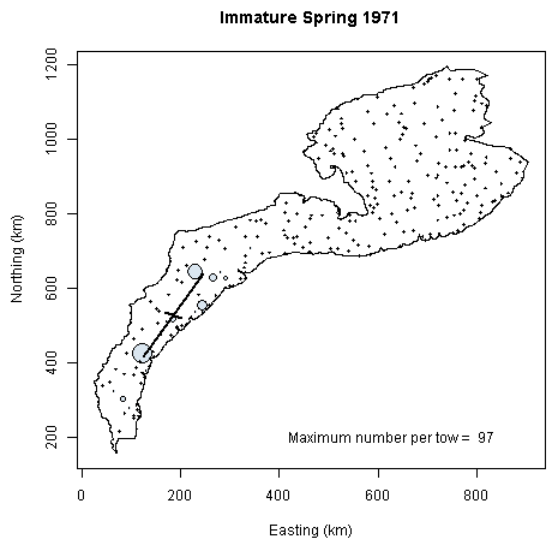

Mature Spring 1969
Maximum number per tow = 16
Northing (km)
Easting (km)

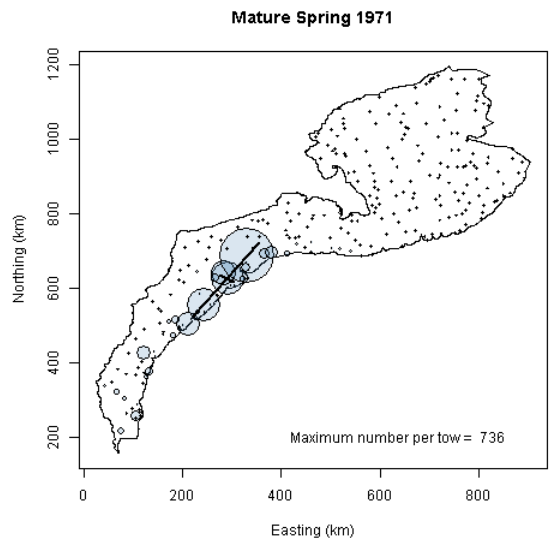

Mackerel Spring 1970
Maximum number per tow = 448
Northing (km)
Easting (km)

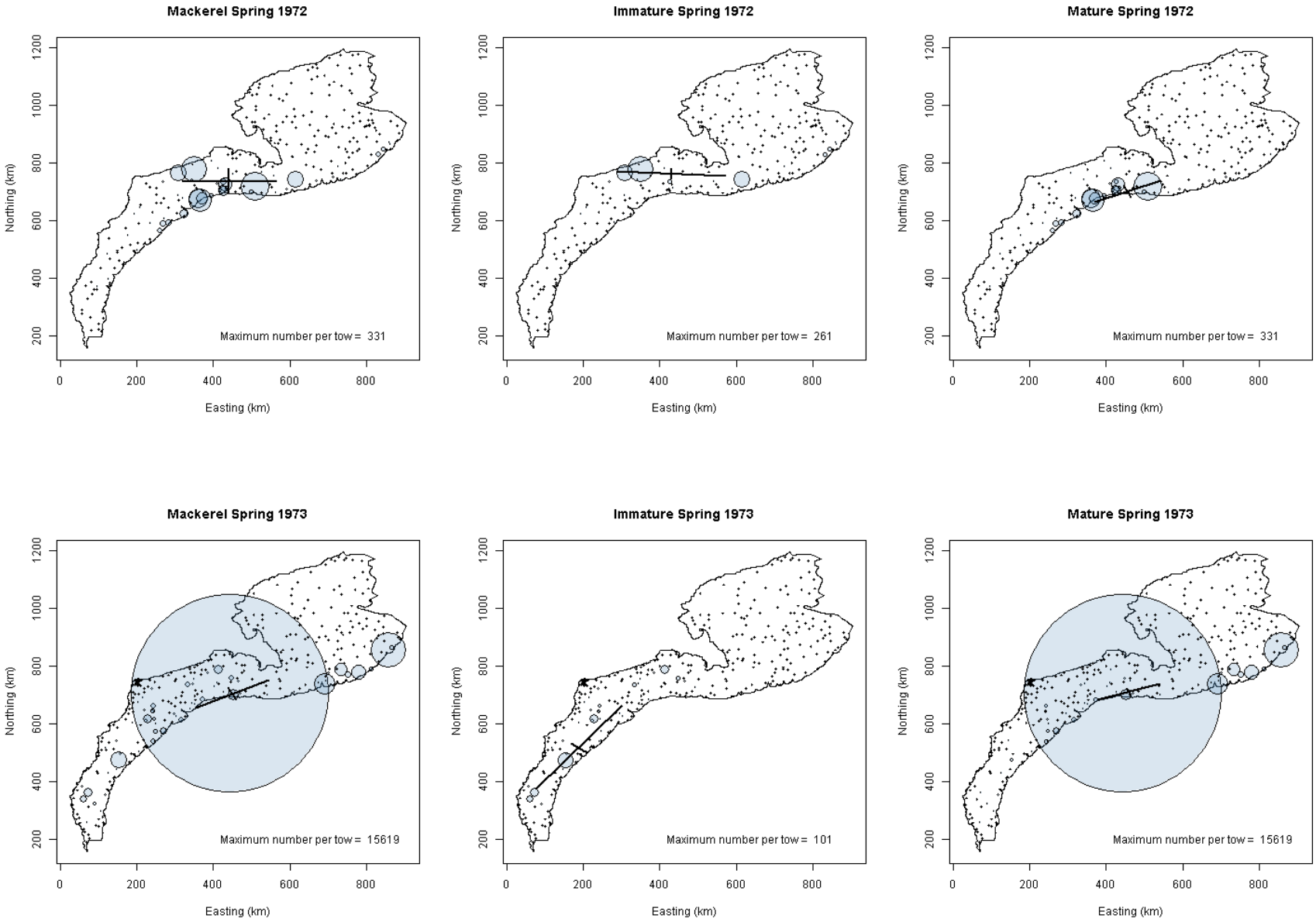

Immature Spring 1970
Maximum number per tow = 327
Northing (km)
Easting (km)

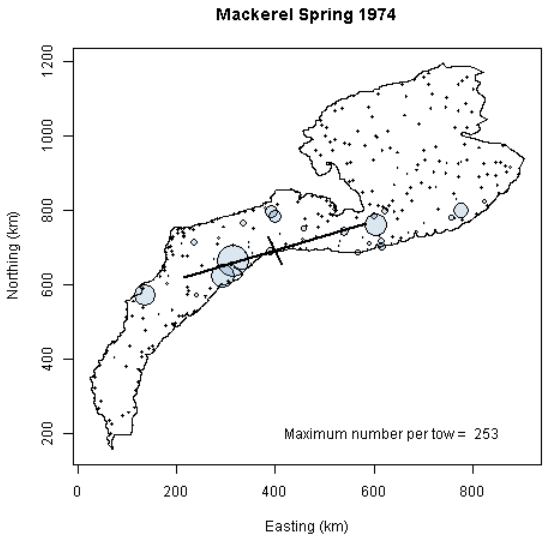

Mature Spring 1970
Maximum number per tow = 448
Northing (km)
Easting (km)

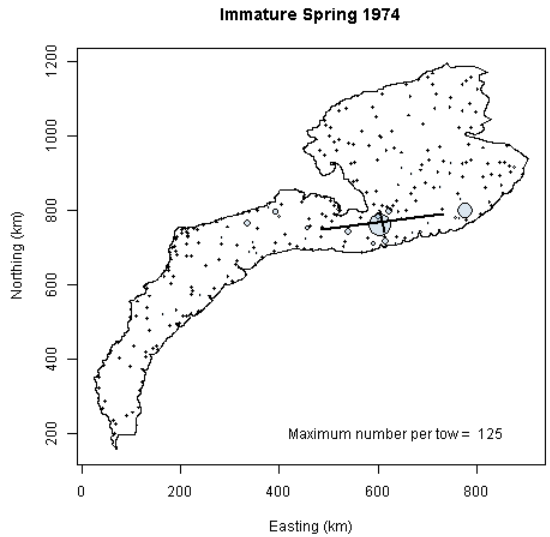

Mackerel Spring 1971
Maximum number per tow = 736
Northing (km)
Easting (km)

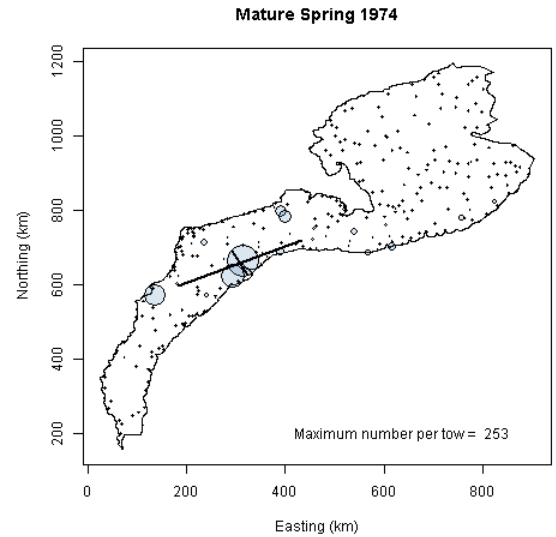

Immature Spring 1971
Maximum number per tow = 97
Northing (km)
Easting (km)

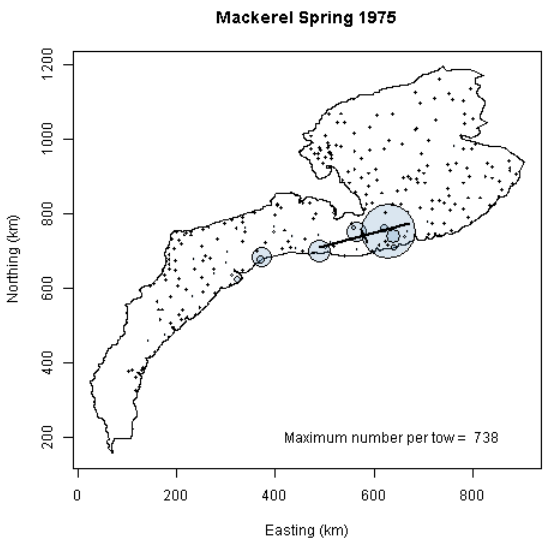

Mature Spring 1971
Maximum number per tow = 736
Northing (km)
Easting (km)

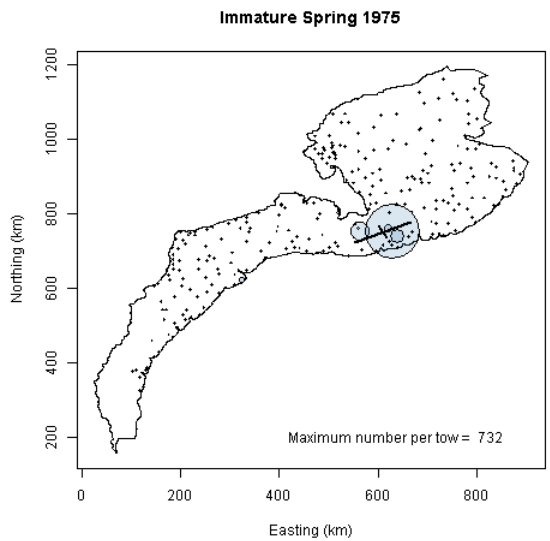

Mackerel Spring 1972
Maximum number per tow = 331
Immature Spring 1972
Maximum number per tow = 261
Mature Spring 1972
Maximum number per tow = 331
Mackerel Spring 1973
Maximum number per tow = 15619
Immature Spring 1973
Maximum number per tow = 101
Mature Spring 1973
Maximum number per tow = 15619
Northing (km)
Easting (km)
0
200
400
600
800
1000
1200

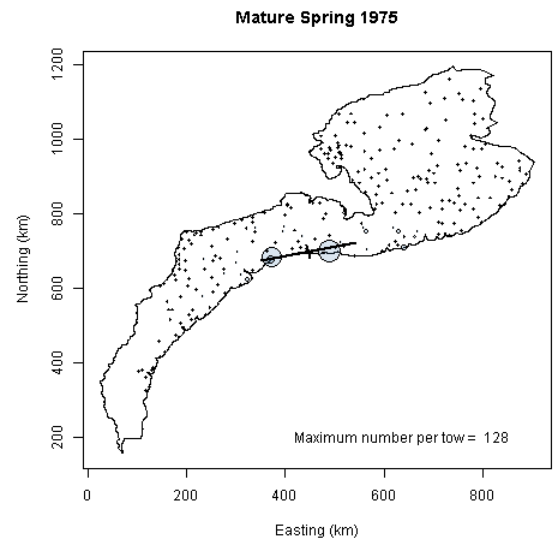

Mackerel Spring 1974
Maximum number per tow = 253
Northing (km)
Easting (km)

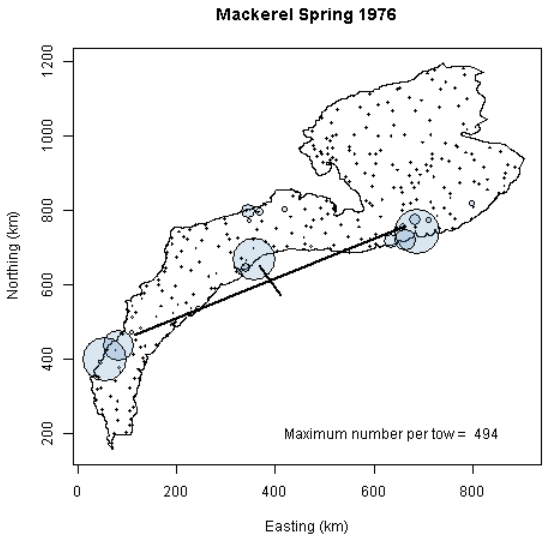

Immature Spring 1974
Maximum number per tow = 125
Northing (km)
Easting (km)

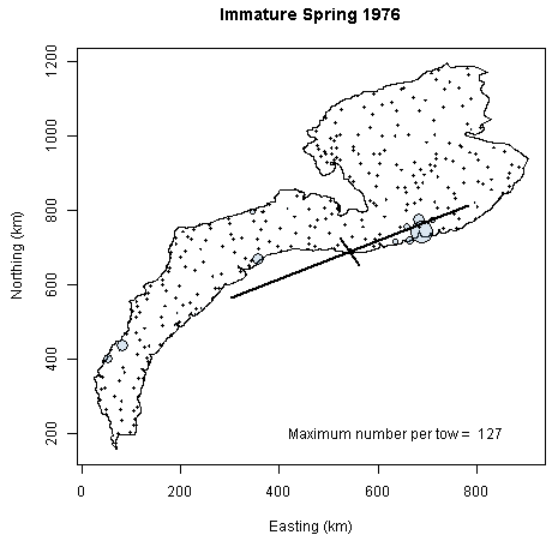

Mature Spring 1974
Maximum number per tow = 253
Northing (km)
Easting (km)

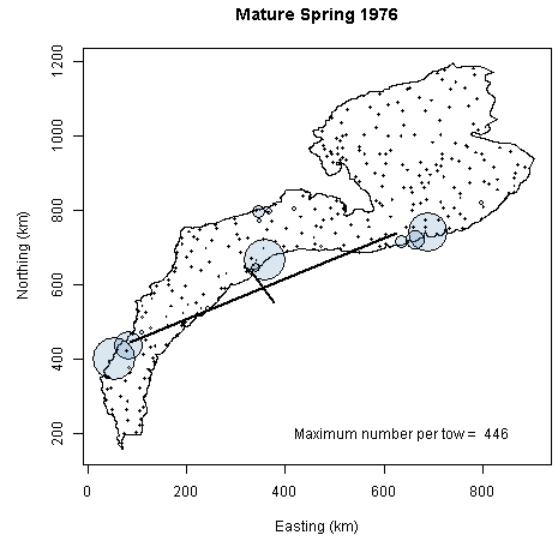

Mackerel Spring 1975
Maximum number per tow = 738
Northing (km)
Easting (km)

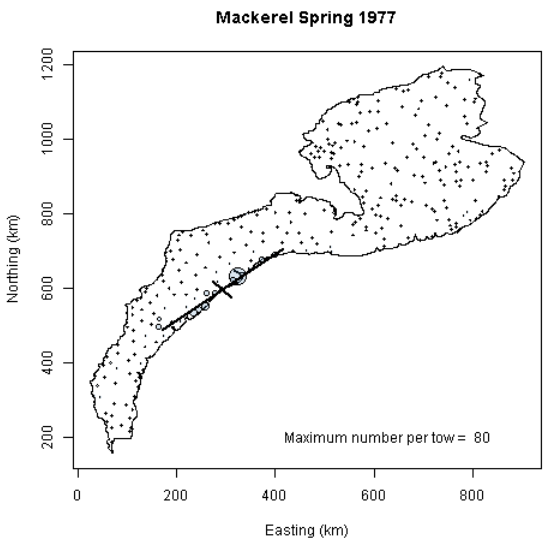

Immature Spring 1975
Maximum number per tow = 732
Northing (km)
Easting (km)

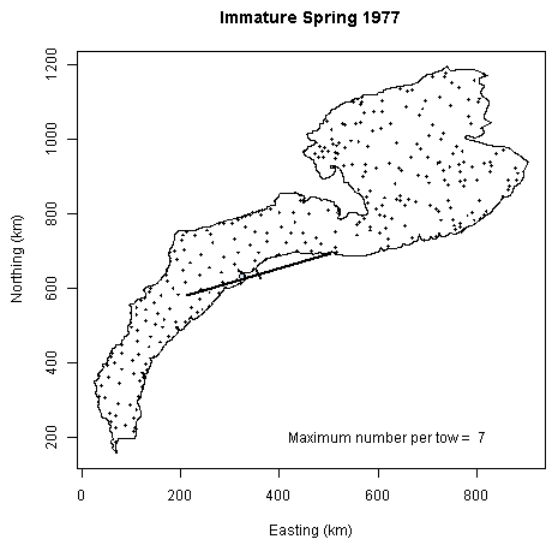

Mature Spring 1975
Maximum number per tow = 128
Northing (km)
Easting (km)

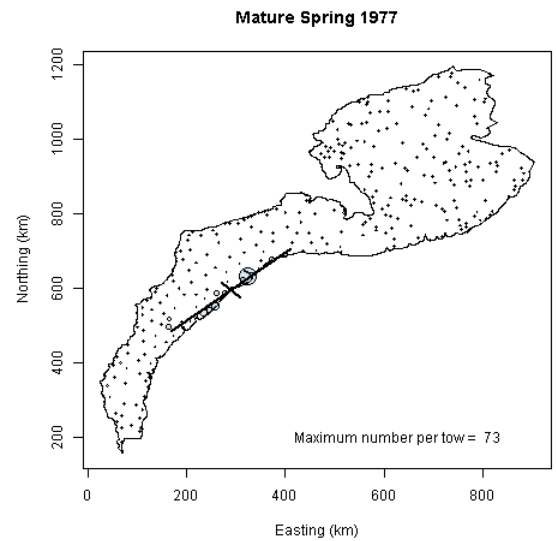

Mackerel Spring 1976
Maximum number per tow = 494
Northing (km)
Easting (km)

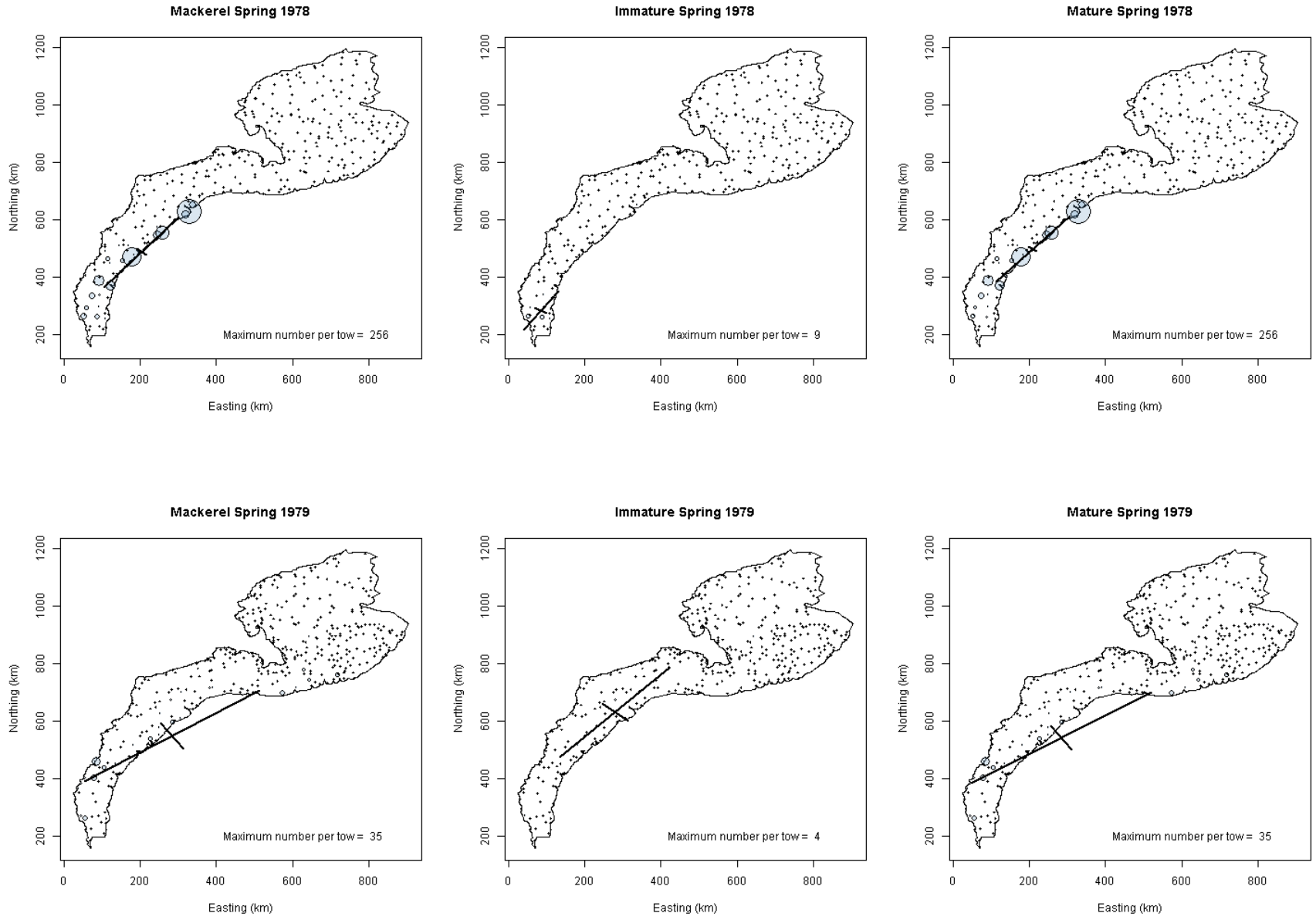

Immature Spring 1976
Maximum number per tow = 127
Northing (km)
Easting (km)

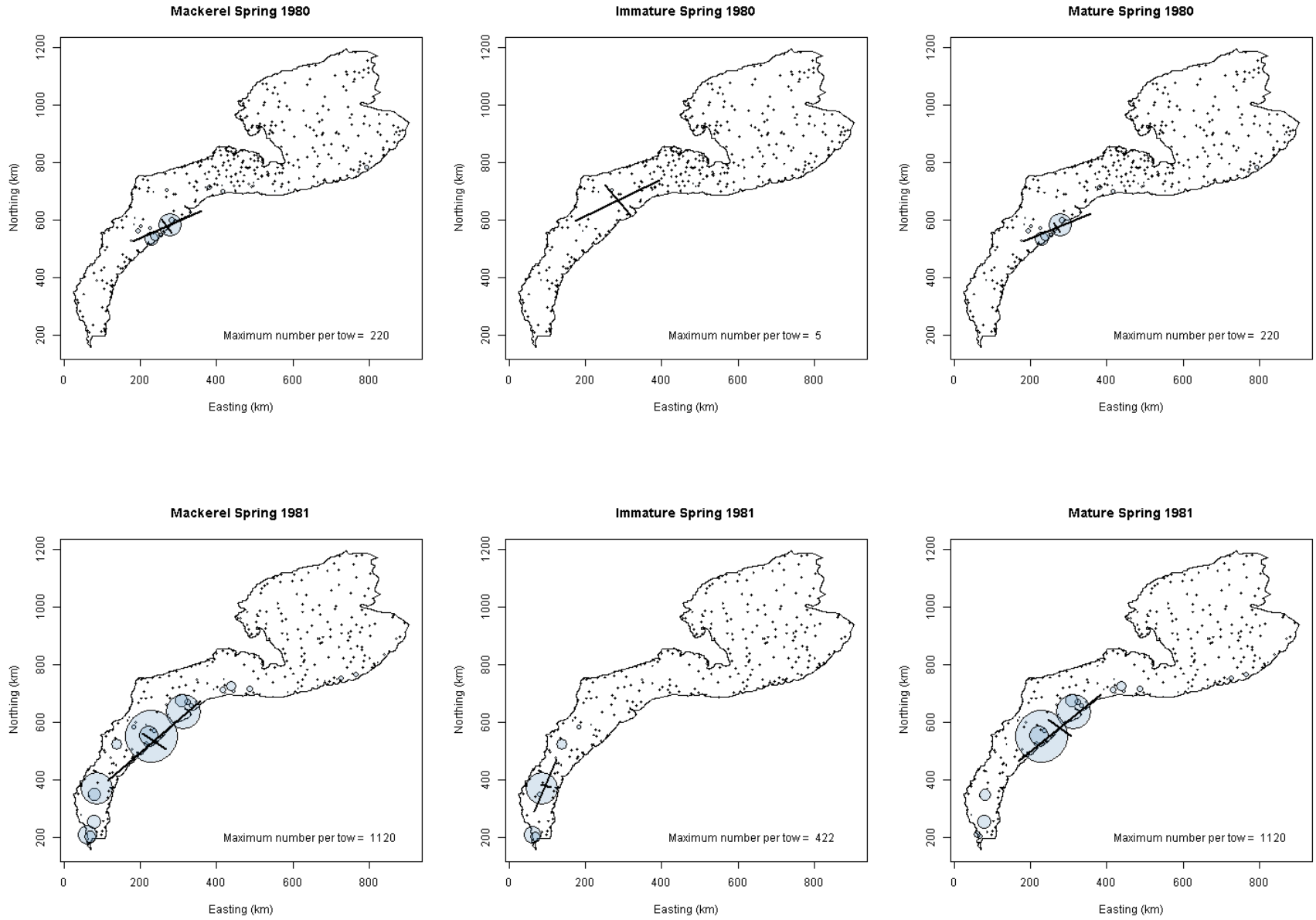

Mature Spring 1976
Maximum number per tow = 446
Northing (km)
Easting (km)

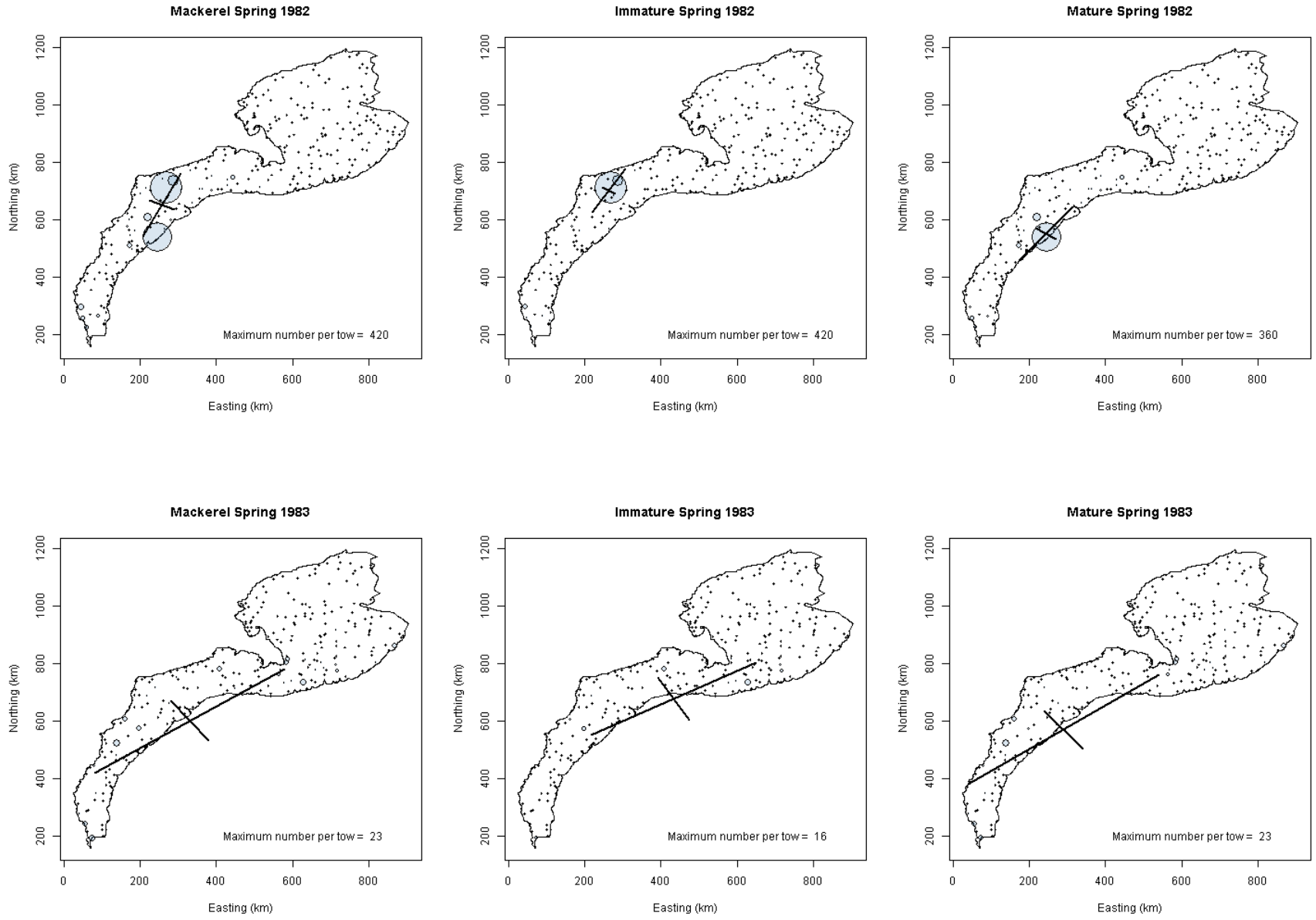

Mackerel Spring 1977
Maximum number per tow = 80
Northing (km)
Easting (km)

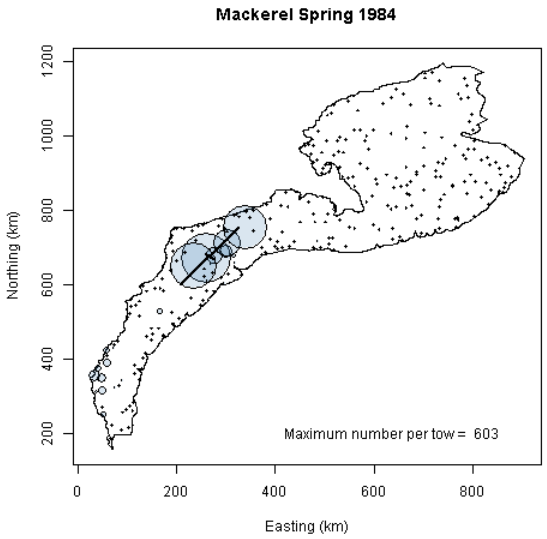

Immature Spring 1977
Maximum number per tow = 7
Northing (km)
Easting (km)

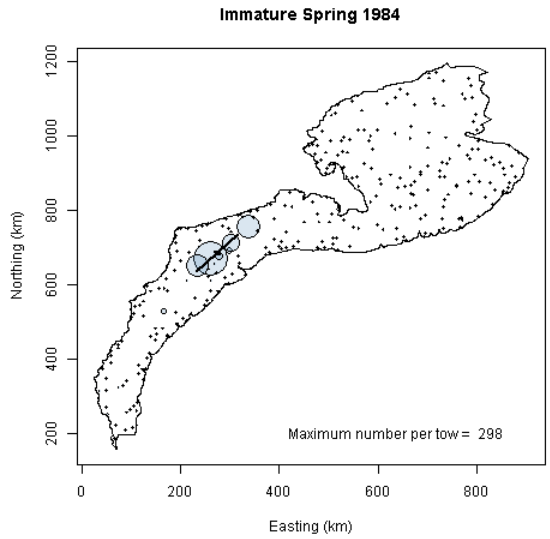

Mature Spring 1977
Maximum number per tow = 73
Northing (km)
Easting (km)

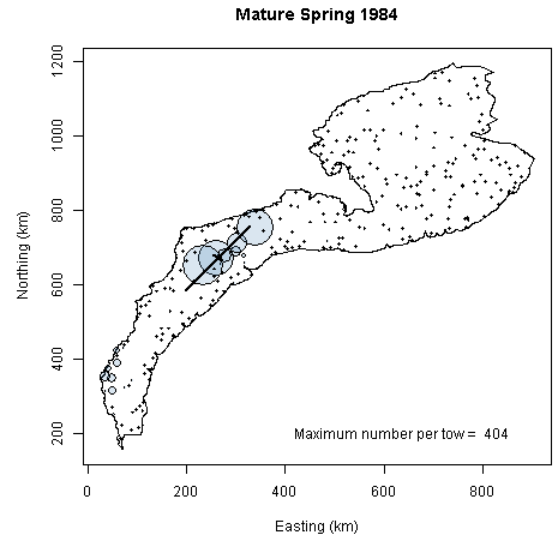

Mackerel Spring 1978
Maximum number per tow = 256
Immature Spring 1978
Maximum number per tow = 9
Mature Spring 1978
Maximum number per tow = 256
Mackerel Spring 1979
Maximum number per tow = 35
Immature Spring 1979
Maximum number per tow = 4
Mature Spring 1979
Maximum number per tow = 35
Northing (km)
Easting (km)
0
200
400
600
800
1000
1200

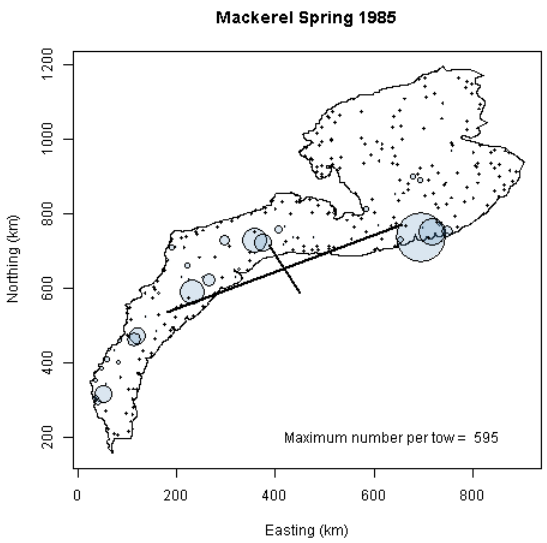

Mackerel Spring 1980
Maximum number per tow = 220
Immature Spring 1980
Maximum number per tow = 5
Mature Spring 1980
Maximum number per tow = 220
Mackerel Spring 1981
Maximum number per tow = 1120
Immature Spring 1981
Maximum number per tow = 422
Mature Spring 1981
Maximum number per tow = 1120
Northing (km)
Easting (km)
200
400
600
800
1000
1200
0

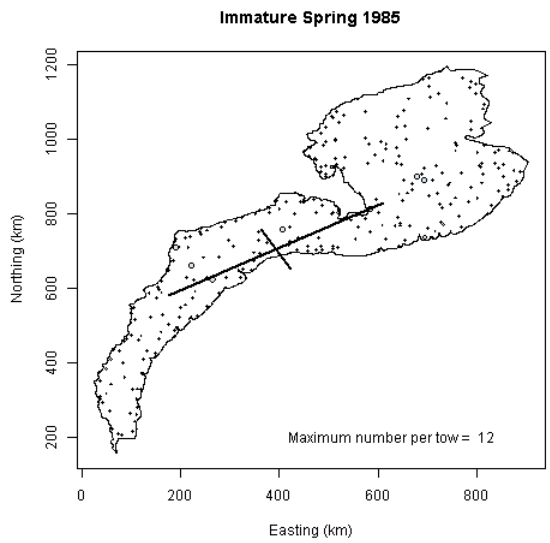

Mackerel Spring 1982
Maximum number per tow = 420
Immature Spring 1982
Maximum number per tow = 420
Mature Spring 1982
Maximum number per tow = 360
Mackerel Spring 1983
Maximum number per tow = 23
Immature Spring 1983
Maximum number per tow = 16
Mature Spring 1983
Maximum number per tow = 23
Northing (km)
Easting (km)
200
400
600
800
1000
1200
0
200
400
600
800

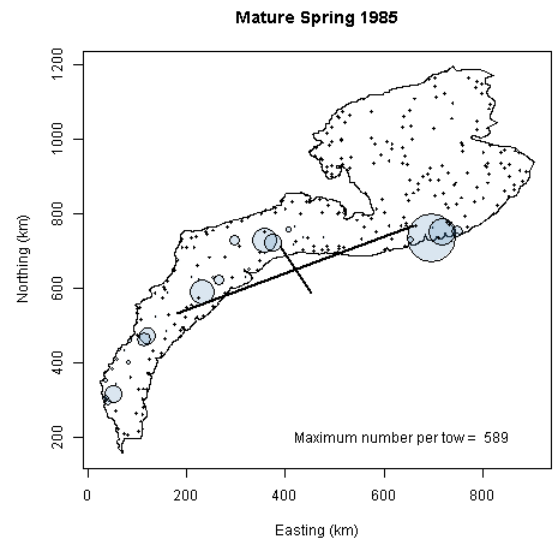

Mackerel Spring 1984
Maximum number per tow = 603
Northing (km)
Easting (km)

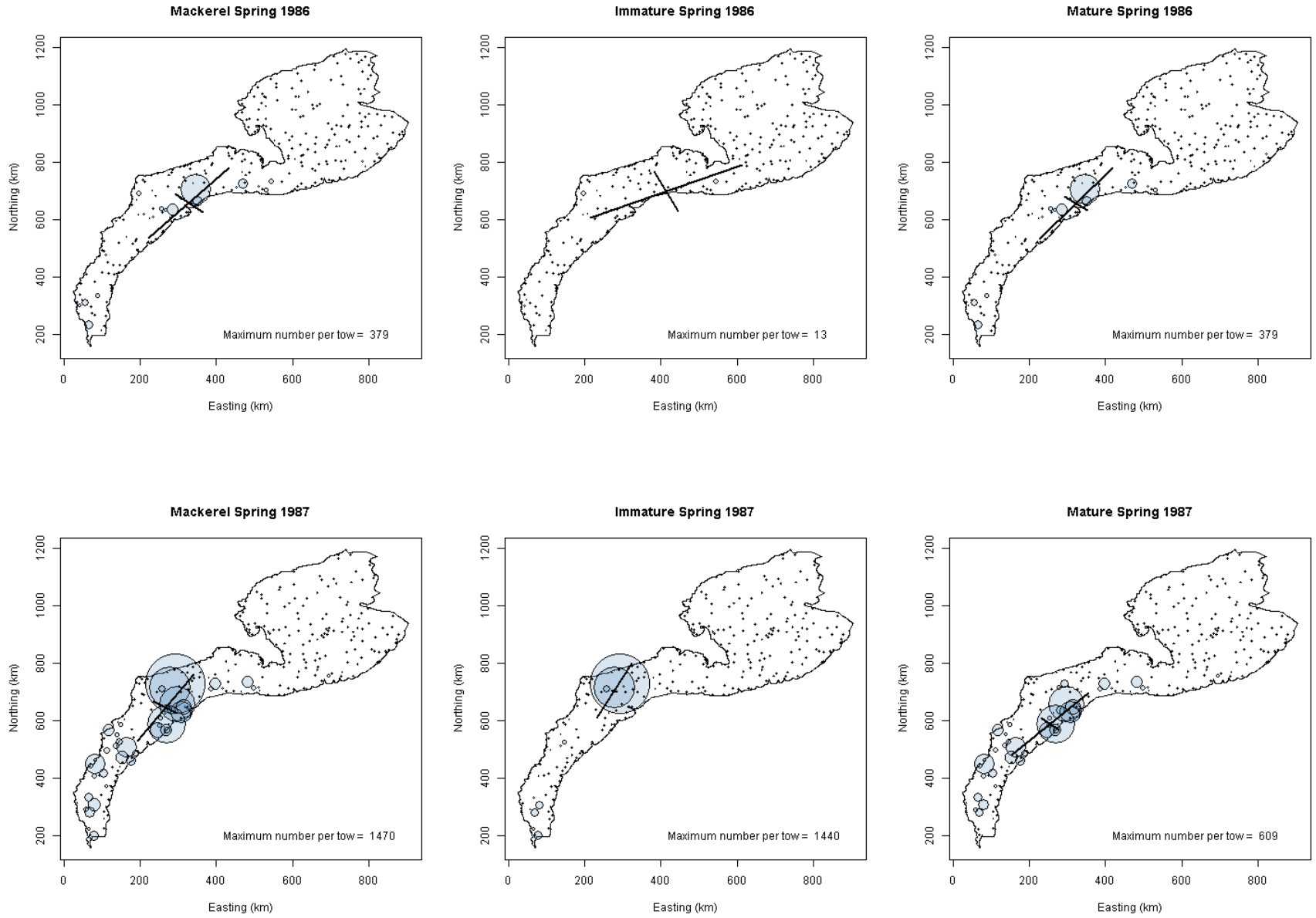

Immature Spring 1984
Maximum number per tow = 298
Northing (km)
Easting (km)

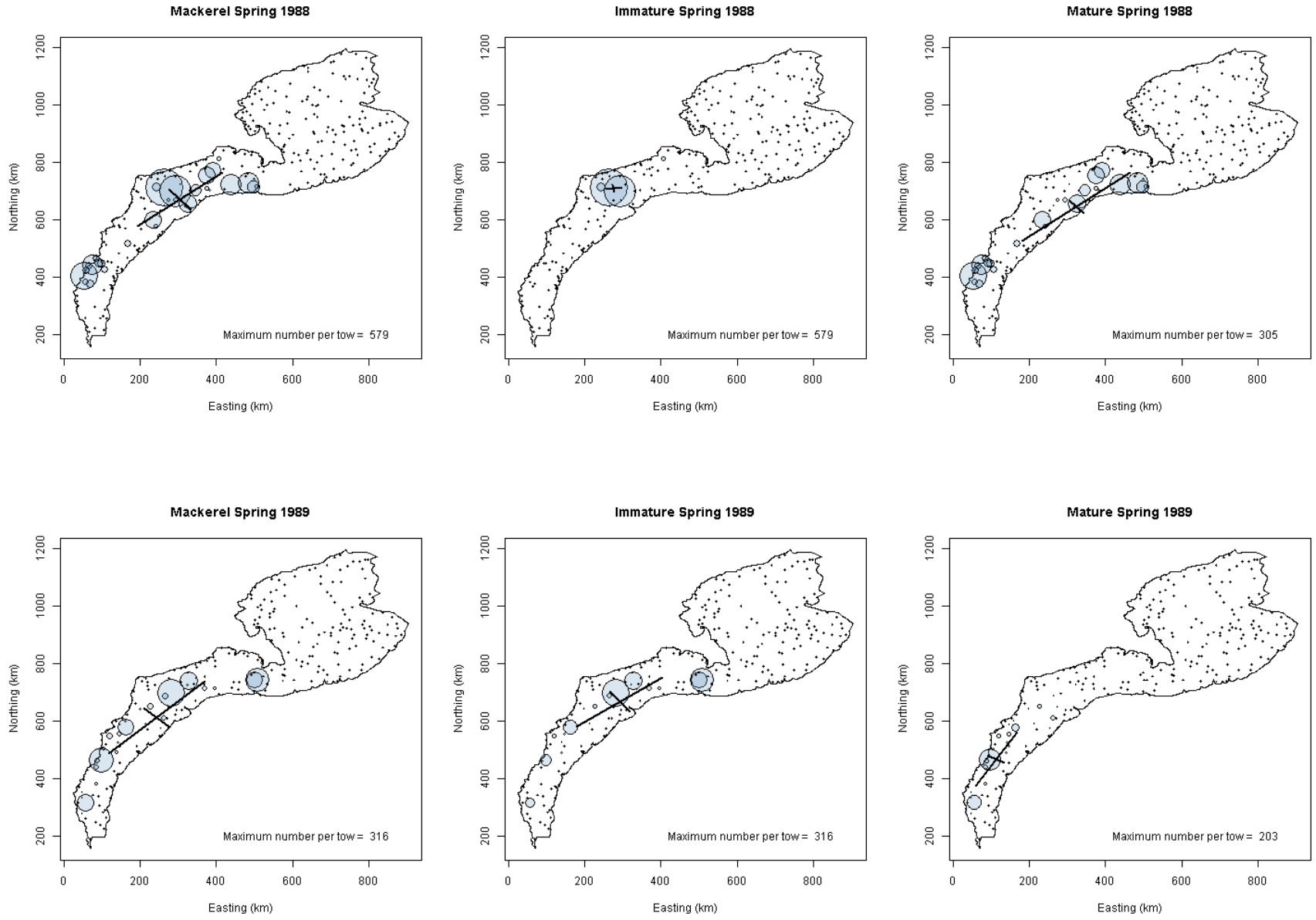

Mature Spring 1984
Maximum number per tow = 404
Northing (km)
Easting (km)

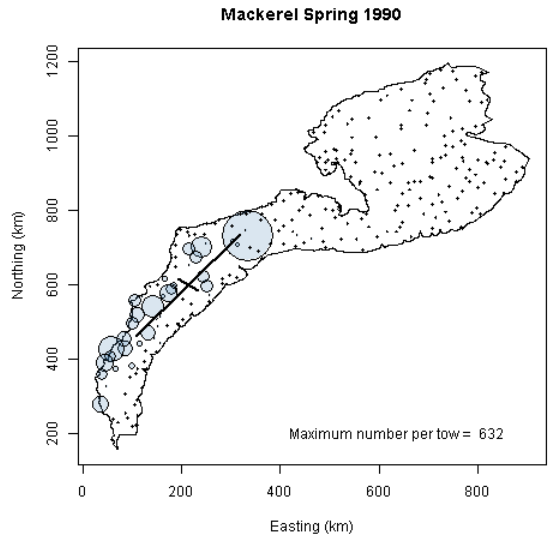

Mackerel Spring 1985
Maximum number per tow = 595
Northing (km)
Easting (km)

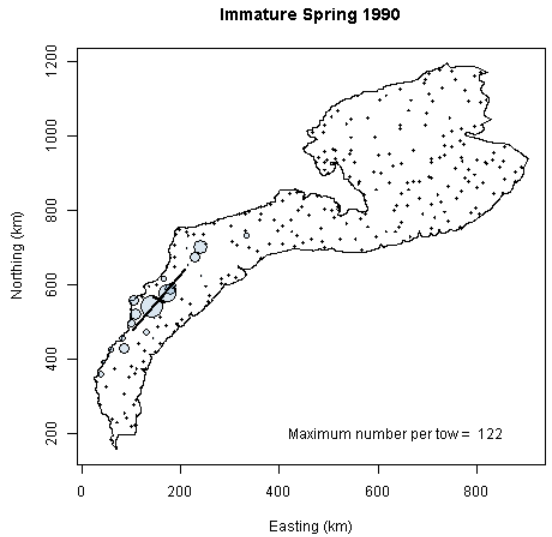

Immature Spring 1985
Maximum number per tow = 12
Northing (km)
Easting (km)

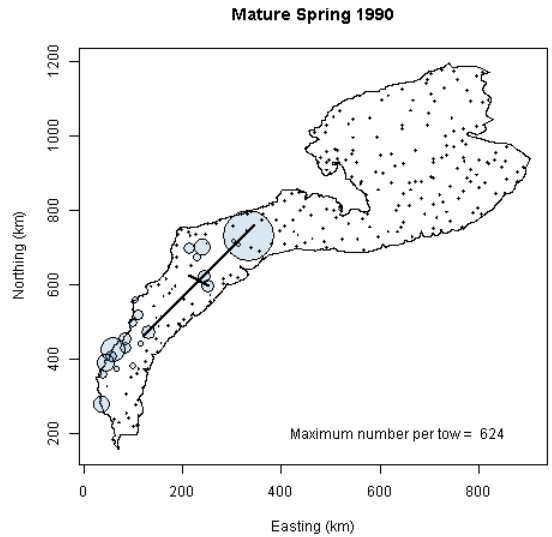

Mature Spring 1985
Maximum number per tow = 589
Northing (km)
Easting (km)

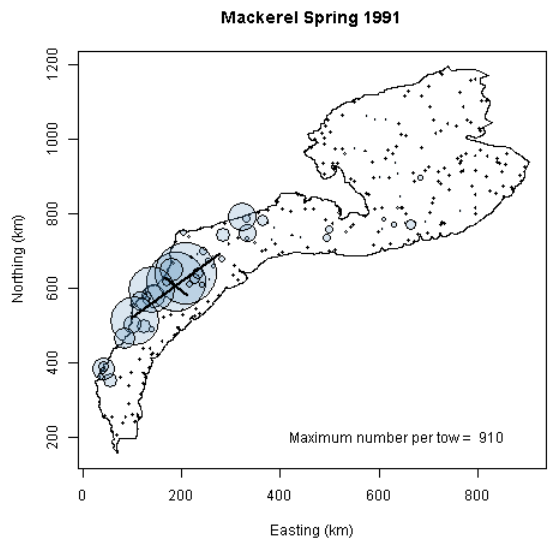

Mackerel Spring 1986
Maximum number per tow = 379
Immature Spring 1986
Maximum number per tow = 13
Mature Spring 1986
Maximum number per tow = 379
Mackerel Spring 1987
Maximum number per tow = 1470
Immature Spring 1987
Maximum number per tow = 1440
Mature Spring 1987
Maximum number per tow = 609
Northing (km)
Easting (km)
0
200
400
600
800
1000
1200

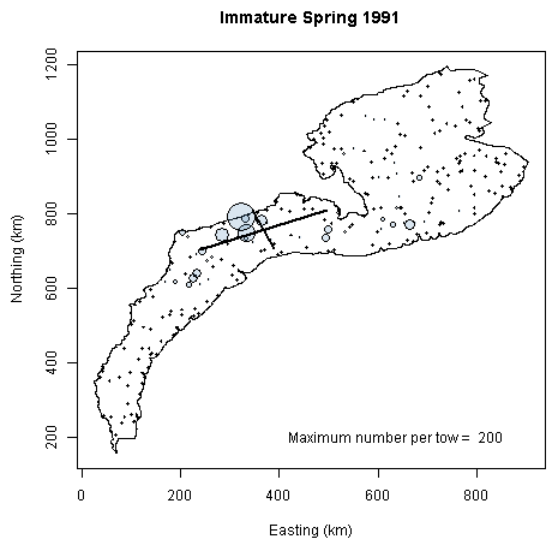

Mackerel Spring 1988
Maximum number per tow = 579
Immature Spring 1988
Maximum number per tow = 579
Mature Spring 1988
Maximum number per tow = 305
Mackerel Spring 1989
Maximum number per tow = 316
Immature Spring 1989
Maximum number per tow = 316
Mature Spring 1989
Maximum number per tow = 203
Northing (km)
Easting (km)
200
400
600
800
1000
1200
0
200
400
600
800

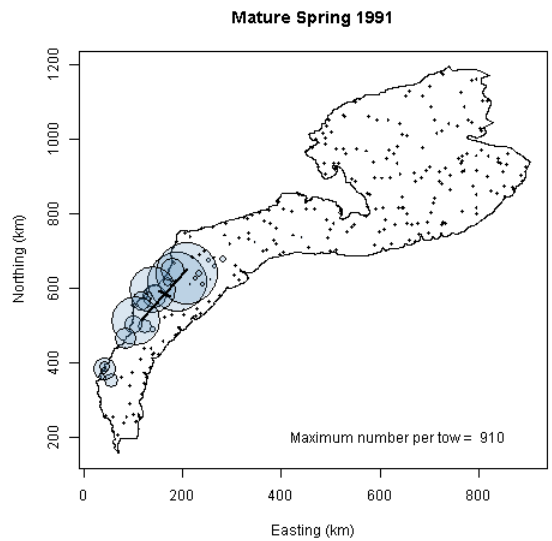

Mackerel Spring 1990
Maximum number per tow = 632
Northing (km)
Easting (km)

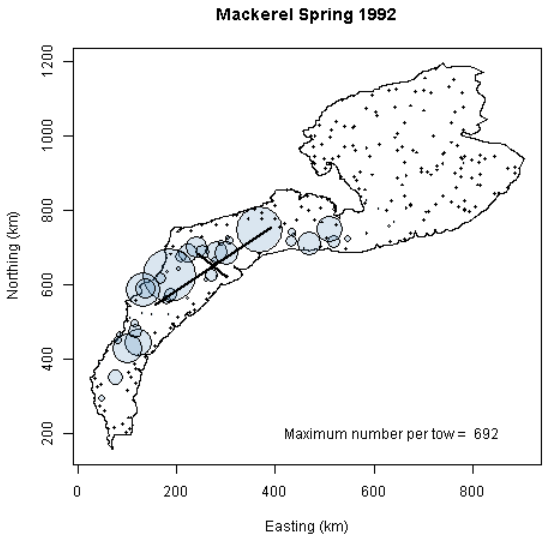

Immature Spring 1990
Maximum number per tow = 122
Northing (km)
Easting (km)

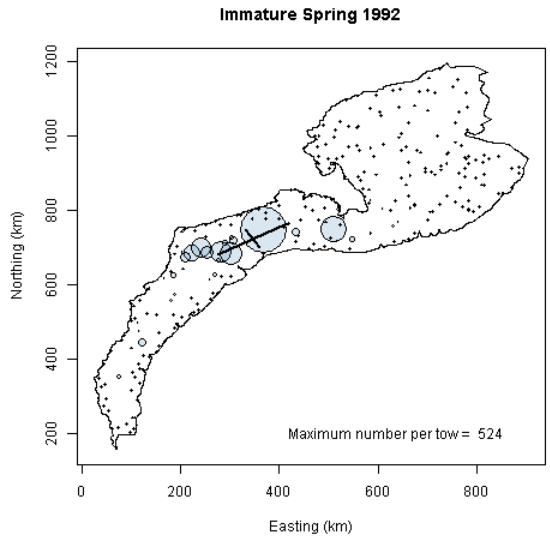

Mature Spring 1990
Maximum number per tow = 624
Northing (km)
Easting (km)

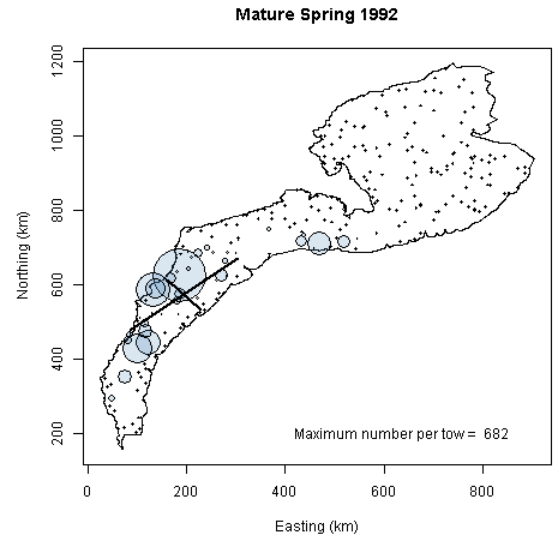

Mackerel Spring 1991
Maximum number per tow = 910
Northing (km)
Easting (km)

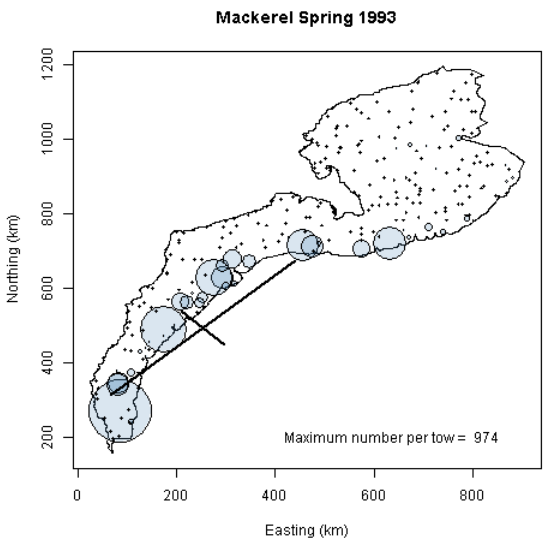

Immature Spring 1991
Maximum number per tow = 200
Northing (km)
Easting (km)

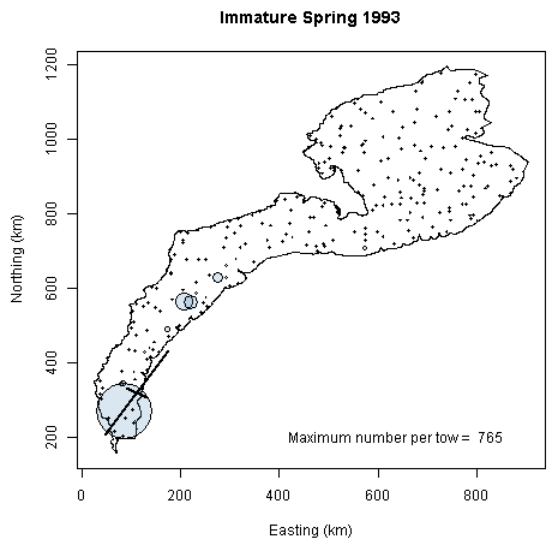

Mature Spring 1991
Maximum number per tow = 910
Northing (km)
Easting (km)

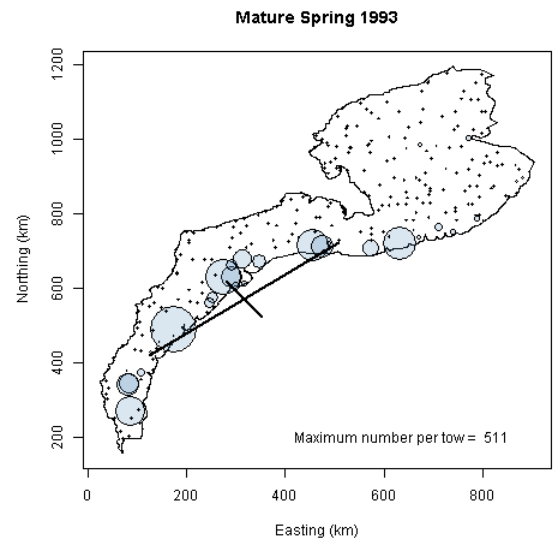

Mackerel Spring 1992
Maximum number per tow = 692
Northing (km)
Easting (km)

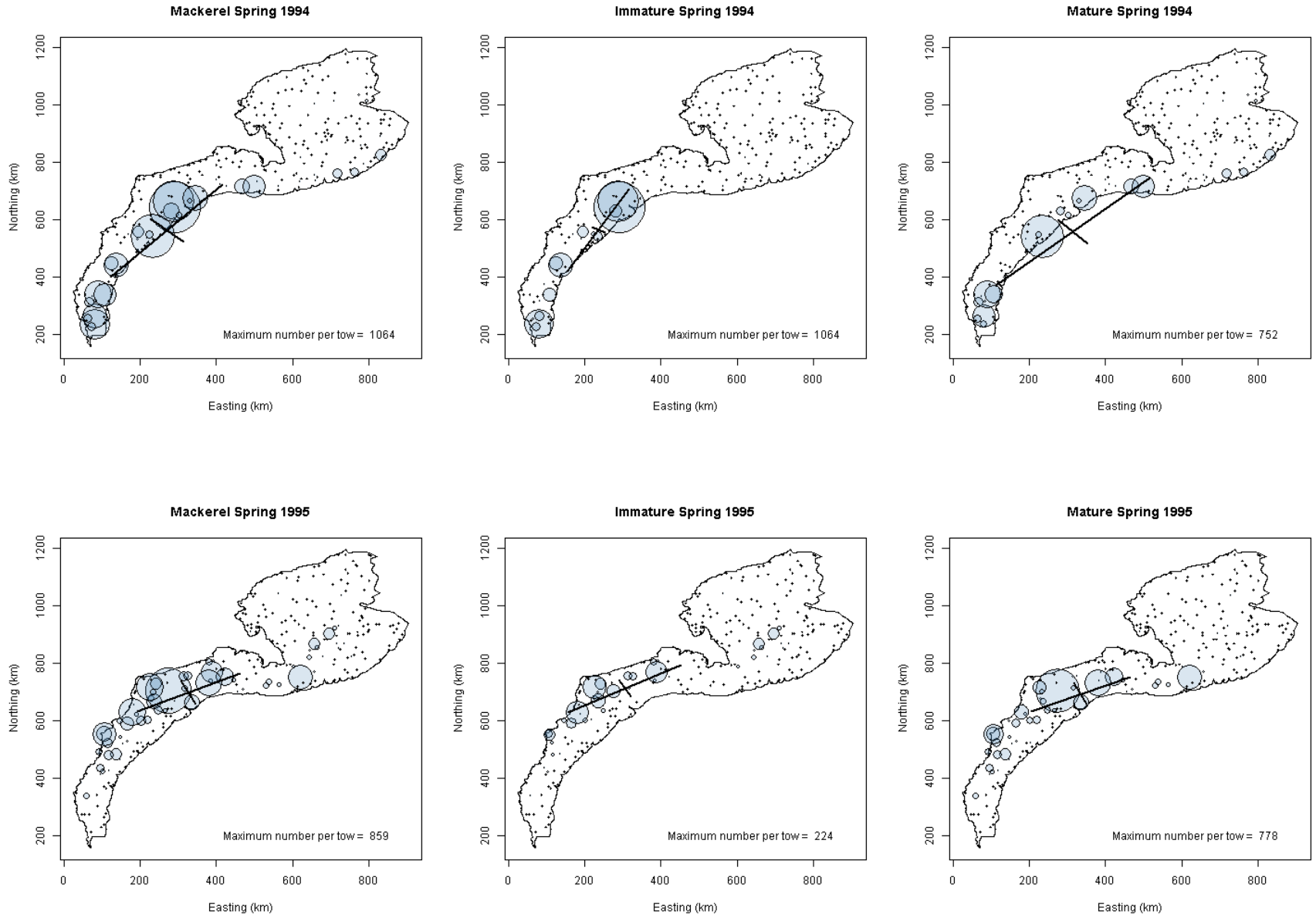

Immature Spring 1992
Maximum number per tow = 524
Northing (km)
Easting (km)

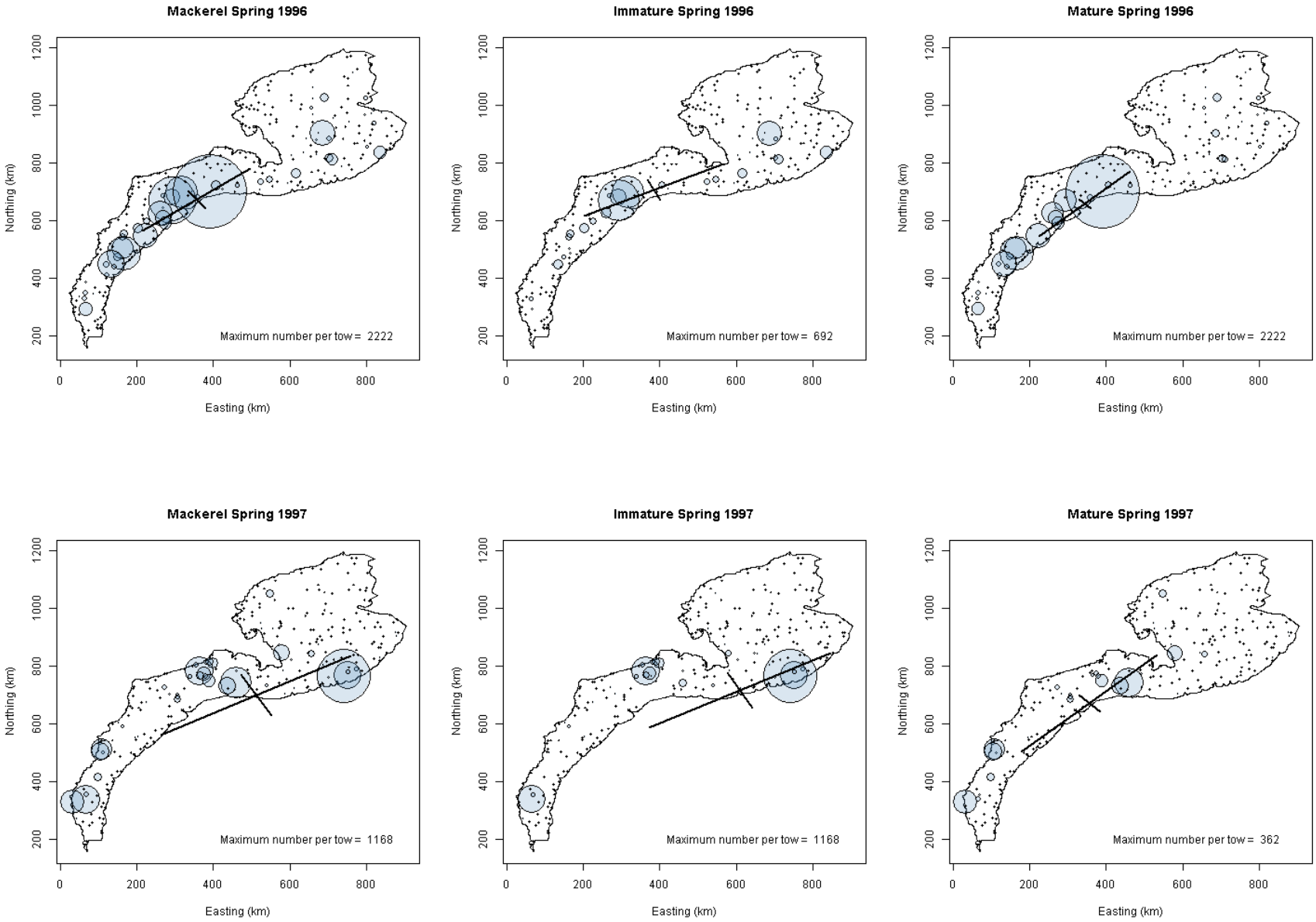

Mature Spring 1992
Maximum number per tow = 682
Northing (km)
Easting (km)

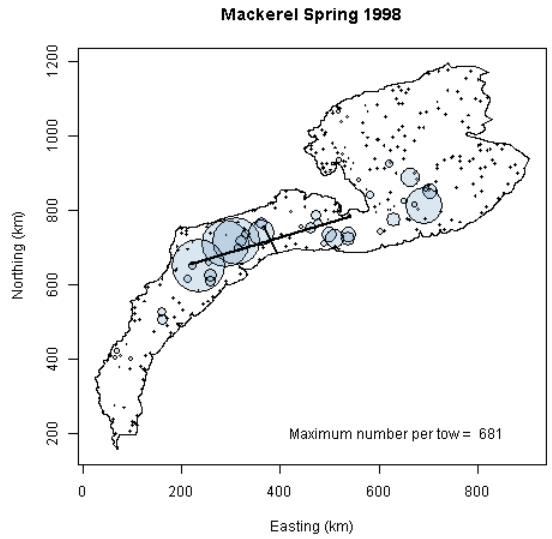

Mackerel Spring 1993
Maximum number per tow = 974
Northing (km)
Easting (km)

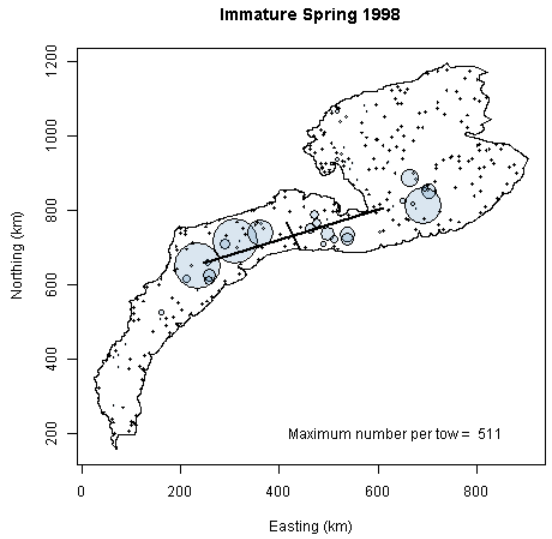

Immature Spring 1993
Maximum number per tow = 765
Northing (km)
Easting (km)

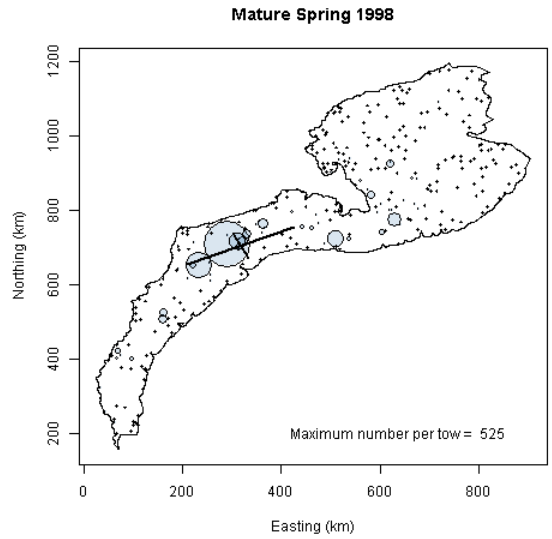

Mature Spring 1993
Maximum number per tow = 511
Northing (km)
Easting (km)

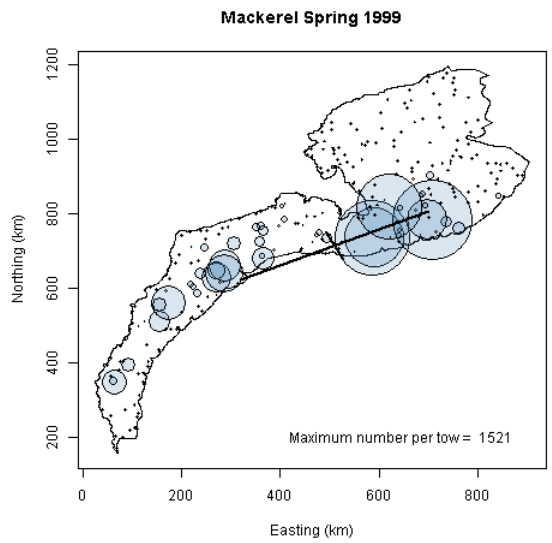

Mackerel Spring 1994
Maximum number per tow = 1064
Immature Spring 1994
Maximum number per tow = 1064
Mature Spring 1994
Maximum number per tow = 752
Mackerel Spring 1995
Maximum number per tow = 859
Immature Spring 1995
Maximum number per tow = 224
Mature Spring 1995
Maximum number per tow = 778
Northing (km)
Easting (km)
0
200
400
600
800
1000
1200

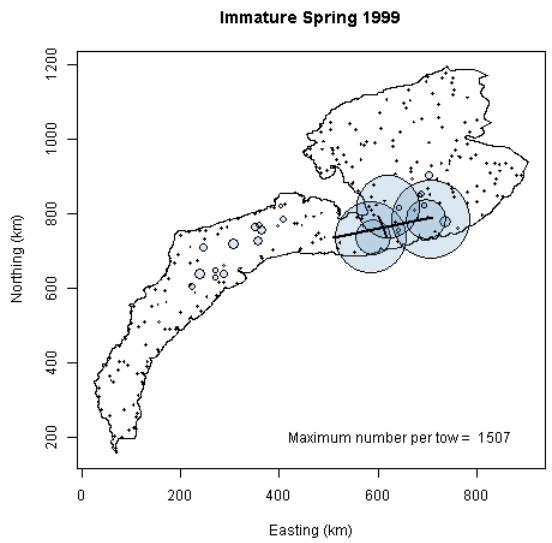

Mackerel Spring 1996
Maximum number per tow = 2222
Immature Spring 1996
Maximum number per tow = 692
Mature Spring 1996
Maximum number per tow = 2222
Mackerel Spring 1997
Maximum number per tow = 1168
Immature Spring 1997
Maximum number per tow = 1168
Mature Spring 1997
Maximum number per tow = 362
Northing (km)
Easting (km)
0
200
400
600
800
1000
1200

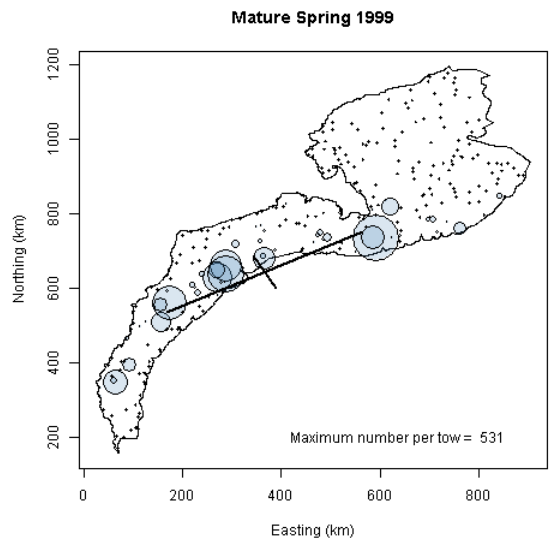

Mackerel Spring 1998
Maximum number per tow = 681
Northing (km)
Easting (km)

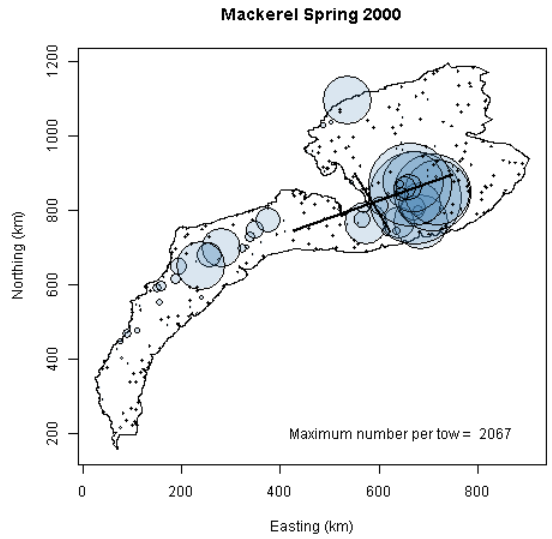

Immature Spring 1998
Maximum number per tow = 511
Northing (km)
Easting (km)

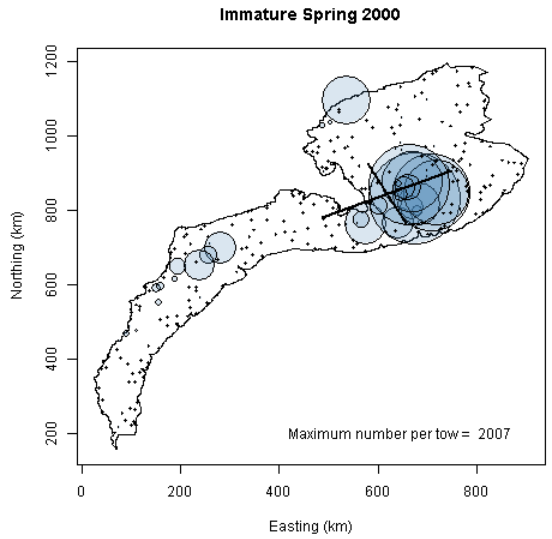

Mature Spring 1998
Maximum number per tow = 525
Northing (km)
Easting (km)

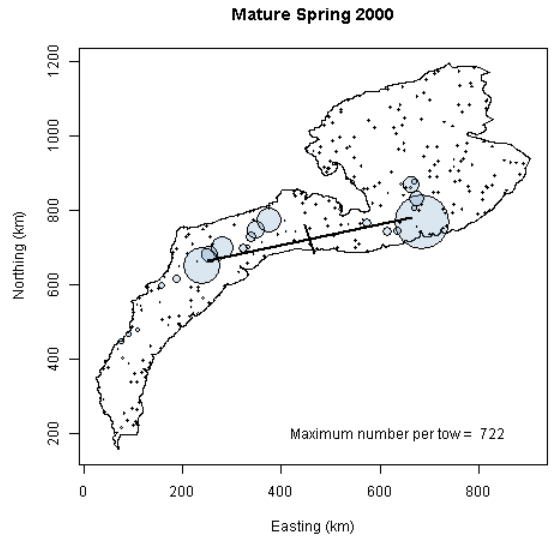

Mackerel Spring 1999
Maximum number per tow = 1521
Northing (km)
Easting (km)

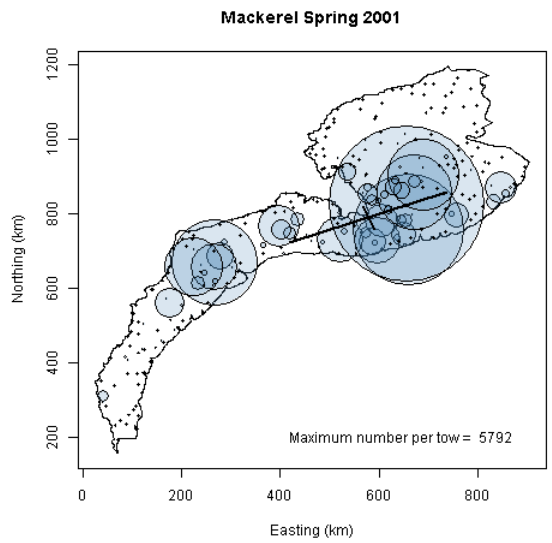

Immature Spring 1999
Maximum number per tow = 1507
Northing (km)
Easting (km)

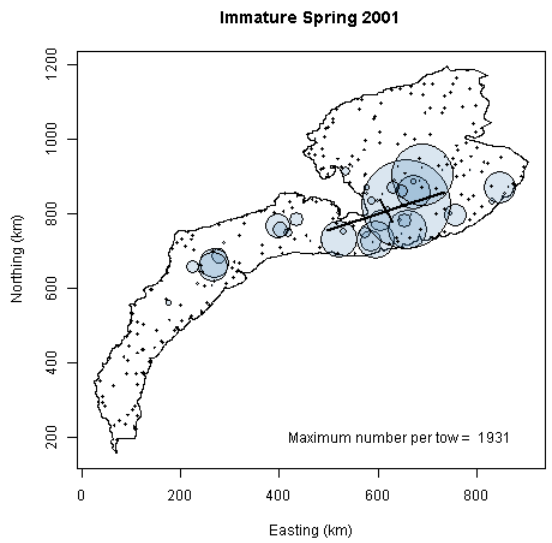

Mature Spring 1999
Maximum number per tow = 531
Northing (km)
Easting (km)

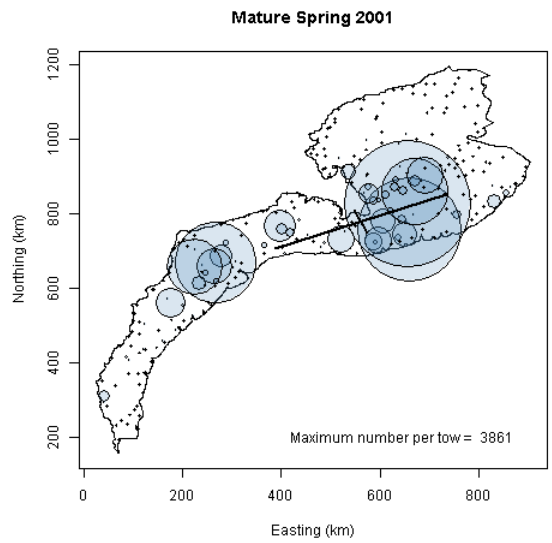

Mackerel Spring 2000
Maximum number per tow = 2067
Northing (km)
Easting (km)

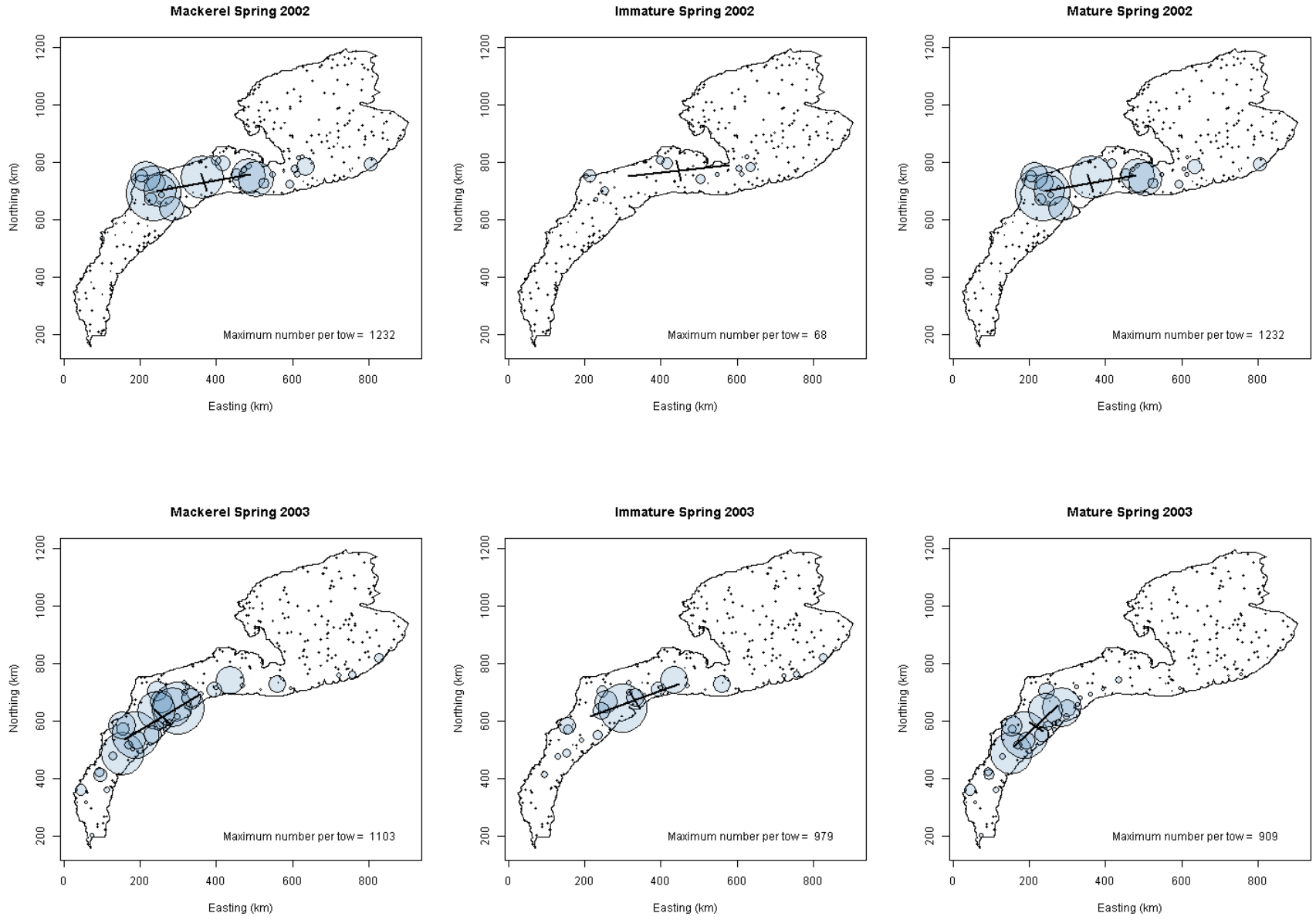

Immature Spring 2000
Maximum number per tow = 2007
Northing (km)
Easting (km)

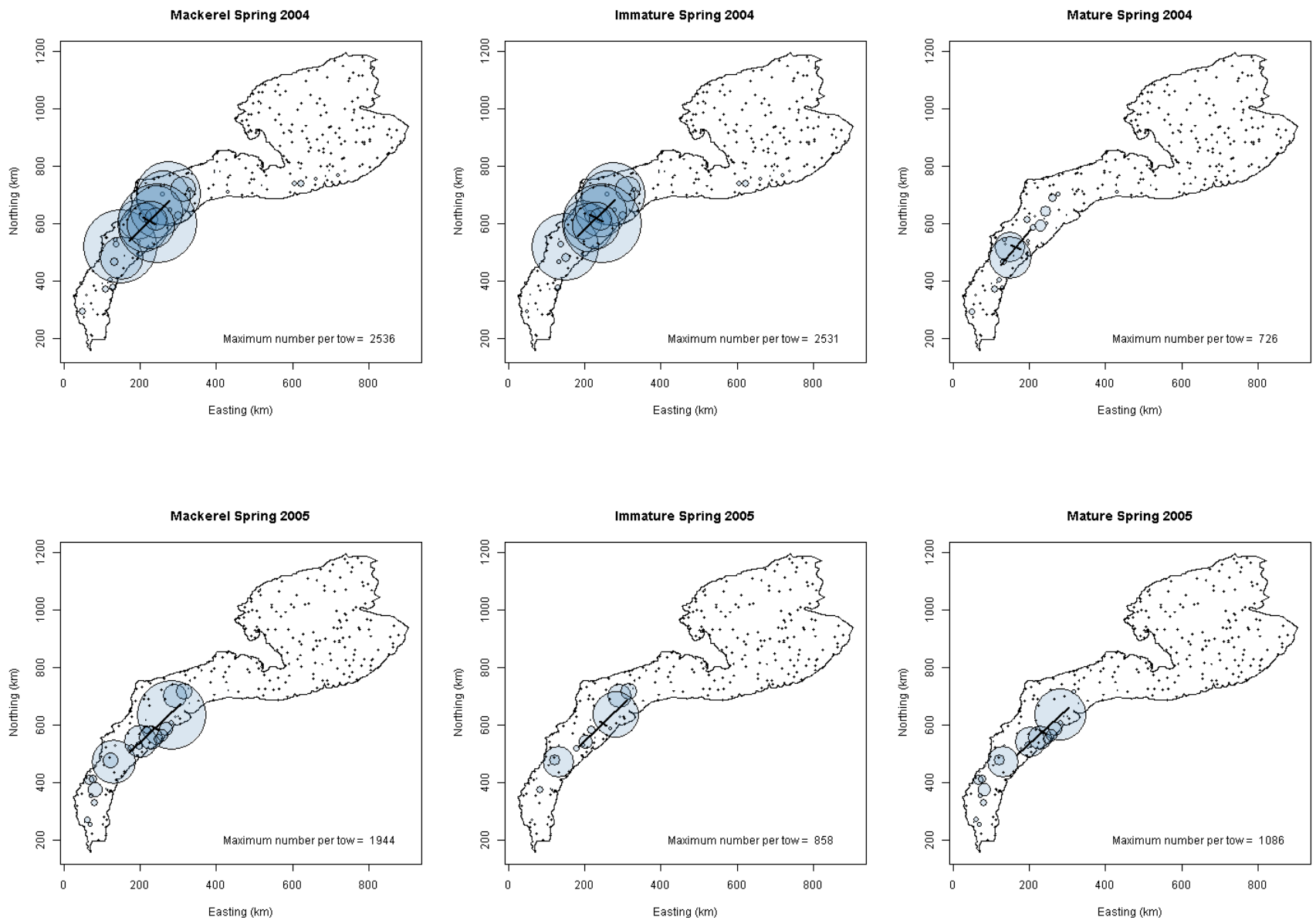

Mature Spring 2000
Maximum number per tow = 722
Northing (km)
Easting (km)

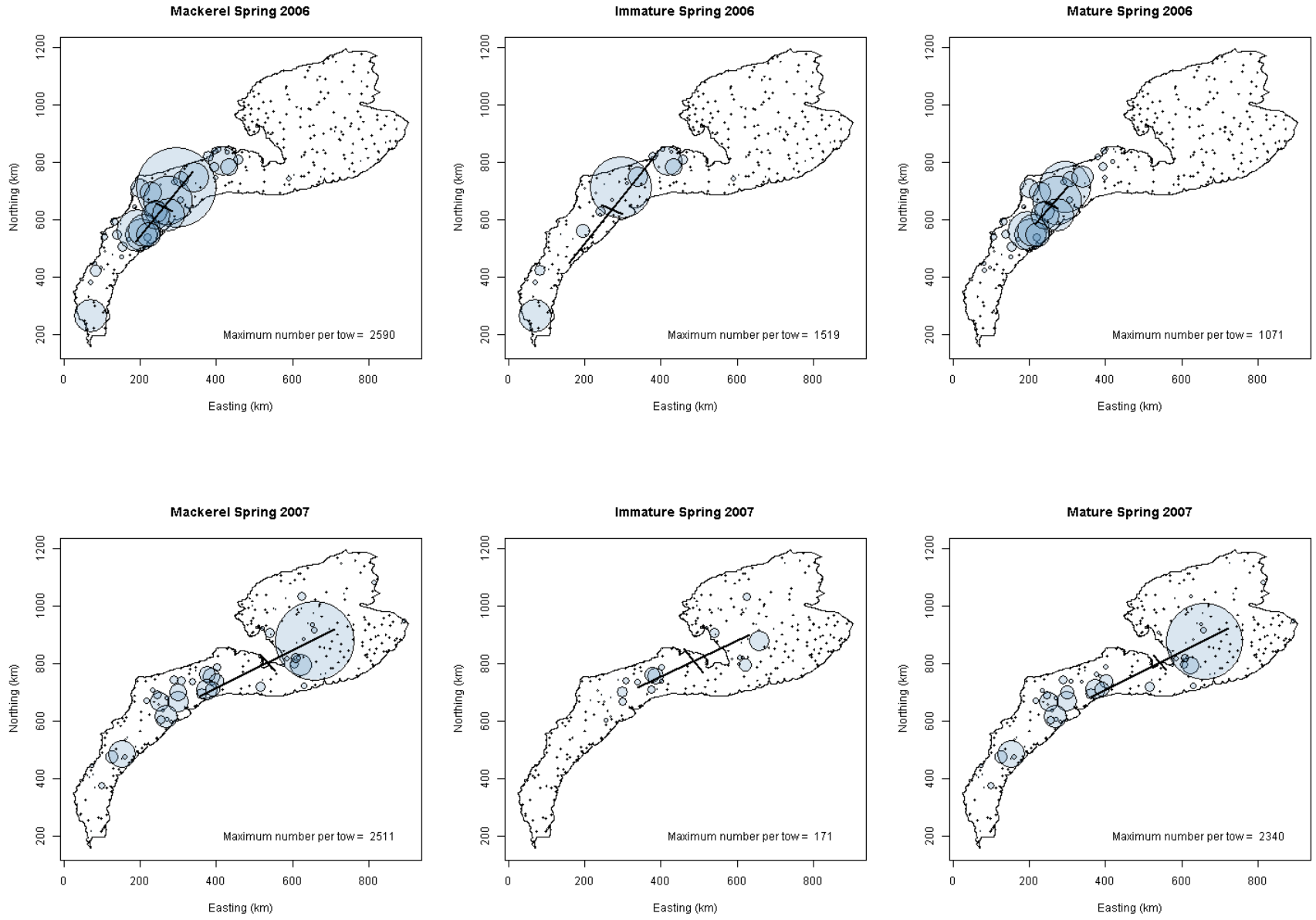

Mackerel Spring 2001
Maximum number per tow = 5792
Northing (km)
Easting (km)

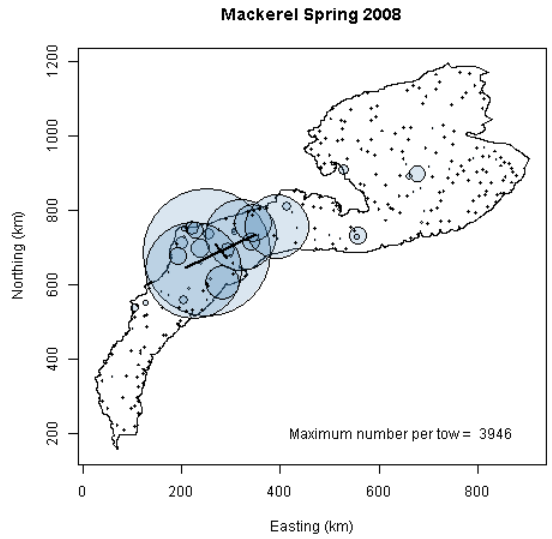

Immature Spring 2001
Maximum number per tow = 1931
Northing (km)
Easting (km)

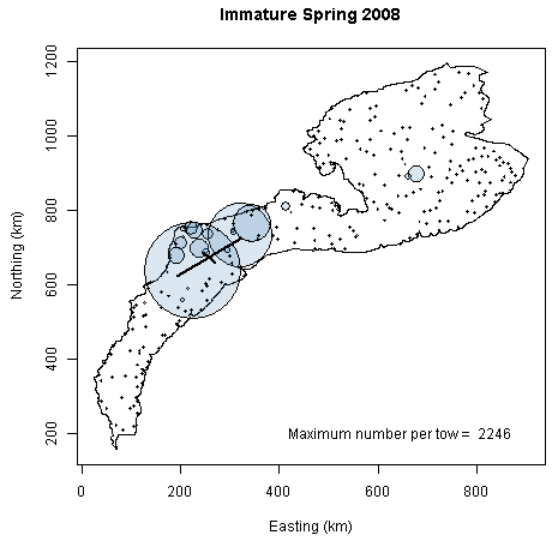

Mature Spring 2001
Maximum number per tow = 3861
Northing (km)
Easting (km)

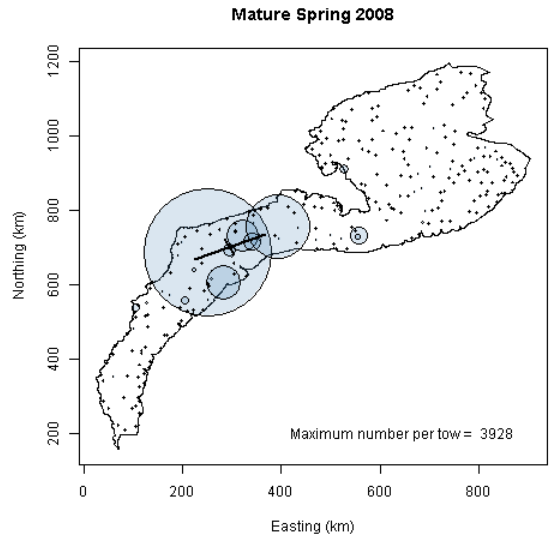

Mackerel Spring 2002
Maximum number per tow = 1232
Immature Spring 2002
Maximum number per tow = 68
Mature Spring 2002
Maximum number per tow = 1232
Mackerel Spring 2003
Maximum number per tow = 1103
Immature Spring 2003
Maximum number per tow = 979
Mature Spring 2003
Maximum number per tow = 909
Northing (km)
Easting (km)
200
400
600
800
1000
1200
0
200
400
600
800

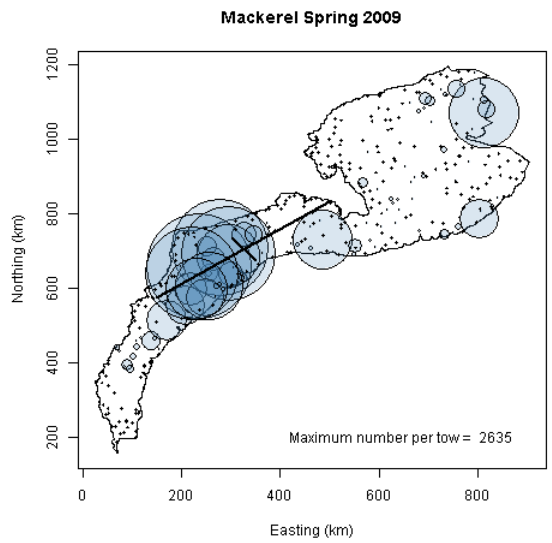

Mackerel Spring 2004
Maximum number per tow = 2536
Immature Spring 2004
Maximum number per tow = 2531
Mature Spring 2004
Maximum number per tow = 726
Mackerel Spring 2005
Maximum number per tow = 1944
Immature Spring 2005
Maximum number per tow = 858
Mature Spring 2005
Maximum number per tow = 1086
Northing (km)
Easting (km)
0
200
400
600
800
1000
1200

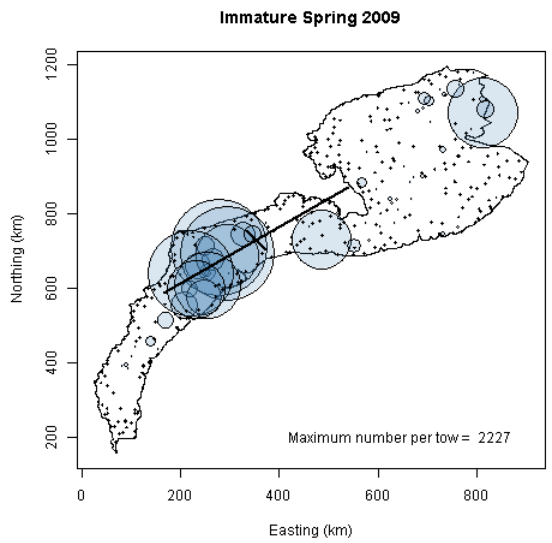

Mackerel Spring 2006
Maximum number per tow = 2590
Immature Spring 2006
Maximum number per tow = 1519
Mature Spring 2006
Maximum number per tow = 1071
Mackerel Spring 2007
Maximum number per tow = 2511
Immature Spring 2007
Maximum number per tow = 171
Mature Spring 2007
Maximum number per tow = 2340
Northing (km)
Easting (km)
0
200
400
600
800
1000
1200

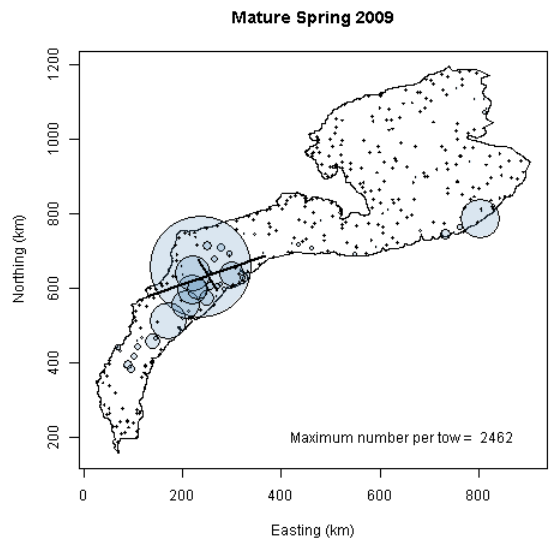

Mackerel Spring 2008
Maximum number per tow = 3946
Northing (km)
Easting (km)

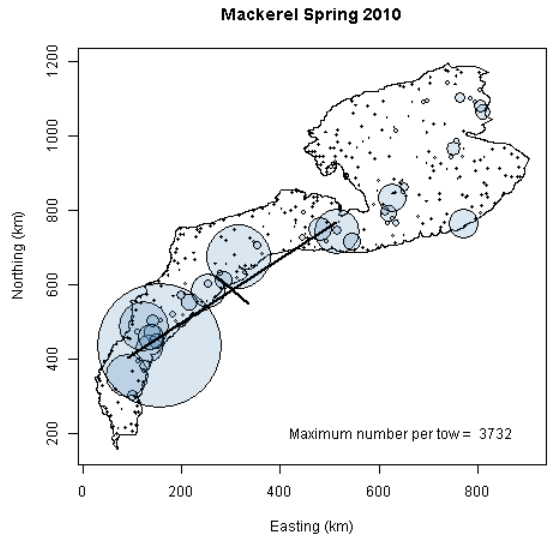

Immature Spring 2008
Maximum number per tow = 2246
Northing (km)
Easting (km)

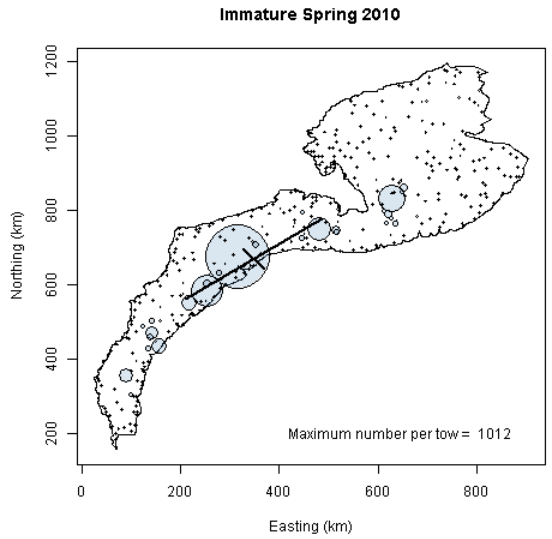

Mature Spring 2008
Maximum number per tow = 3928
Northing (km)
Easting (km)

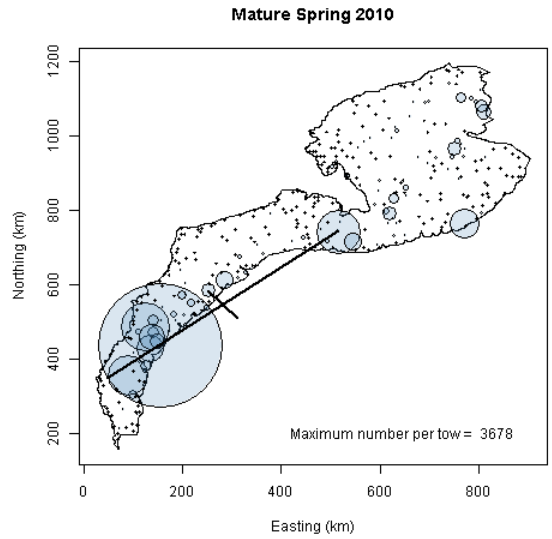

Mackerel Spring 2009
Maximum number per tow = 2635
Northing (km)
Easting (km)

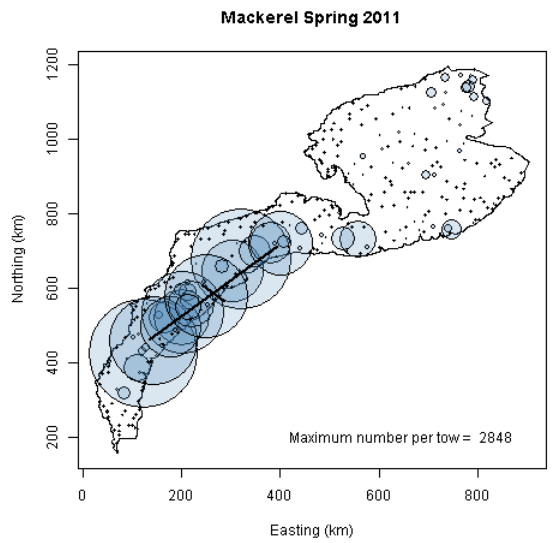

Immature Spring 2009
Maximum number per tow = 2227
Northing (km)
Easting (km)

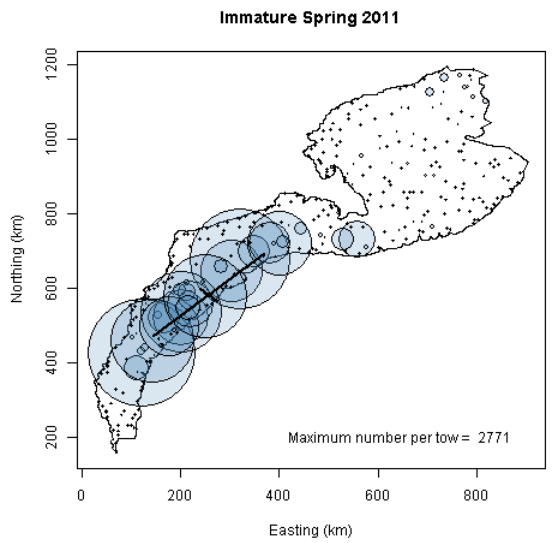

Mature Spring 2009
Maximum number per tow = 2462
Northing (km)
Easting (km)

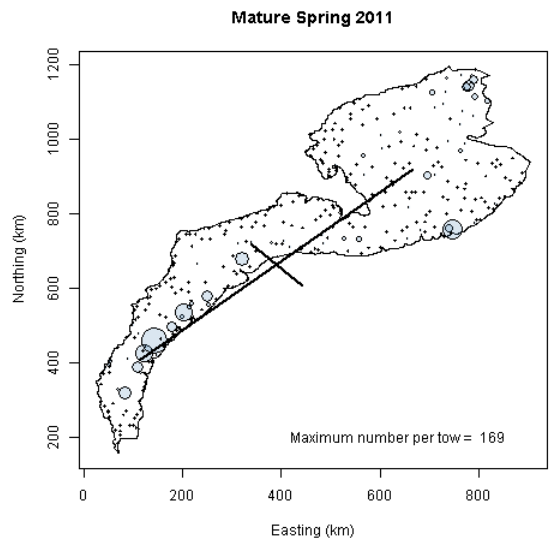

Mackerel Spring 2010
Maximum number per tow = 3732
Northing (km)
Easting (km)

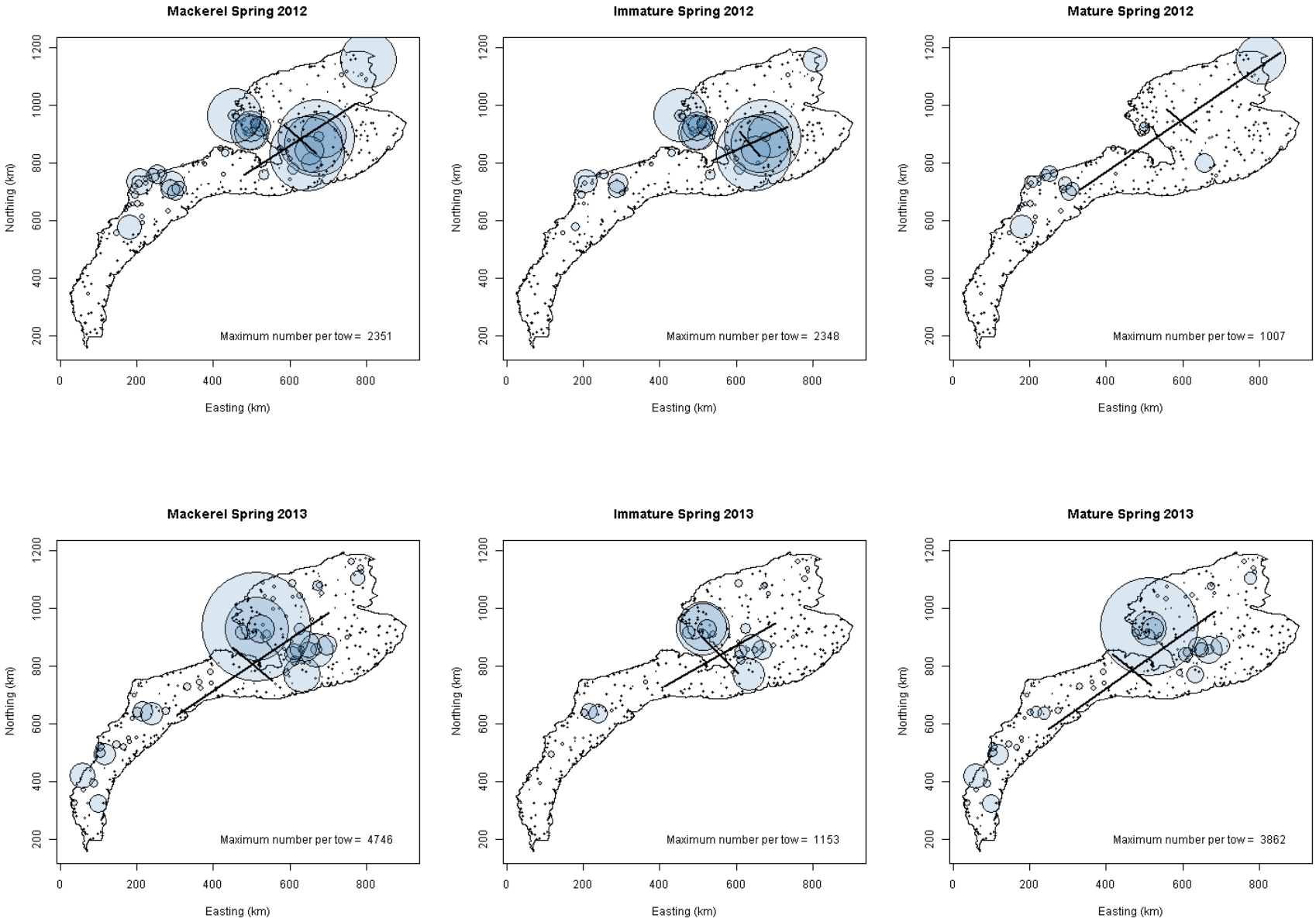

Immature Spring 2010
Maximum number per tow = 1012
Northing (km)
Easting (km)

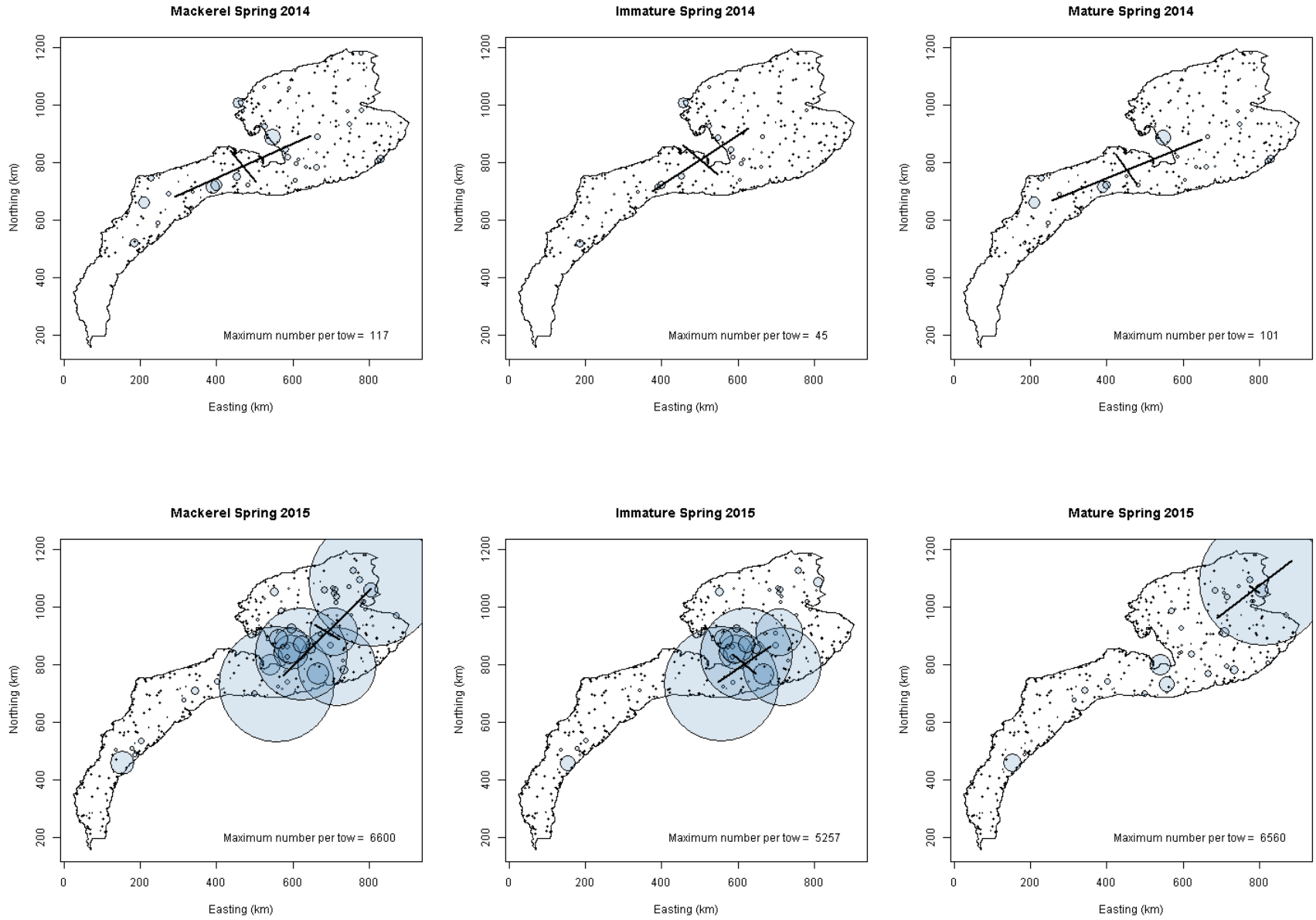

Mature Spring 2010
Maximum number per tow = 3678
Northing (km)
Easting (km)

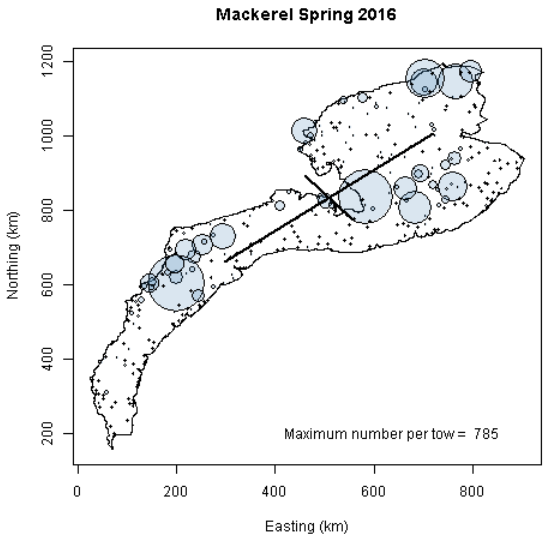

Mackerel Spring 2011
Maximum number per tow = 2848
Northing (km)
Easting (km)

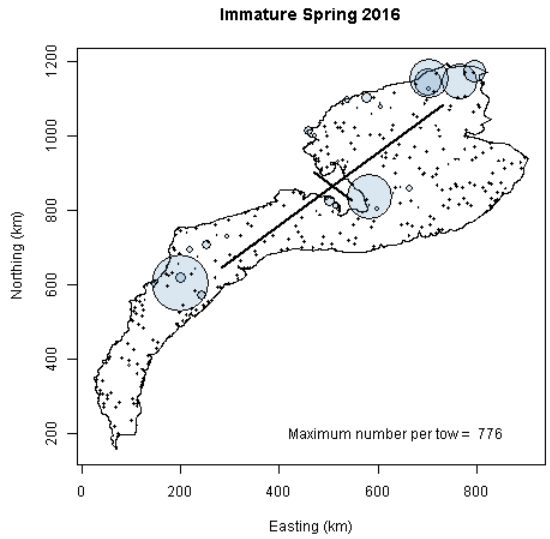

Immature Spring 2011
Maximum number per tow = 2771
Northing (km)
Easting (km)

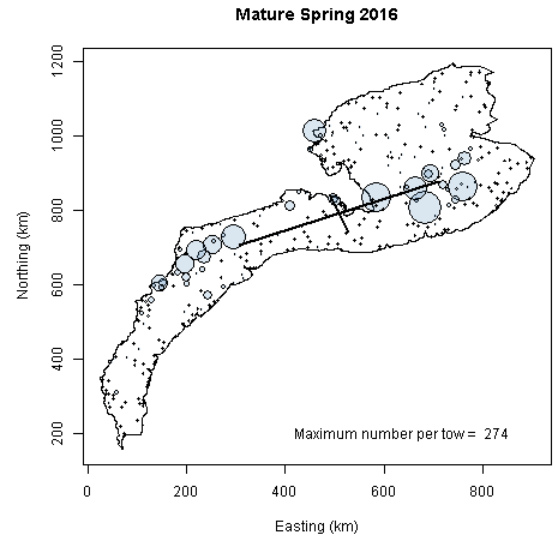

Mature Spring 2011
Maximum number per tow = 169
Northing (km)
Easting (km)


Mackerel Spring 2012
Maximum number per tow = 2351
Immature Spring 2012
Maximum number per tow = 2348
Mature Spring 2012
Maximum number per tow = 1007
Mackerel Spring 2013
Maximum number per tow = 4746
Immature Spring 2013
Maximum number per tow = 1153
Mature Spring 2013
Maximum number per tow = 3862
Northing (km)
Easting (km)
0
200
400
600
800
1000
1200


Mackerel Spring 2014
Maximum number per tow = 117
Immature Spring 2014
Maximum number per tow = 45
Mature Spring 2014
Maximum number per tow = 101
Mackerel Spring 2015
Maximum number per tow = 6600
Immature Spring 2015
Maximum number per tow = 5257
Mature Spring 2015
Maximum number per tow = 6560
Northing (km)
Easting (km)
0
200
400
600
800
1000
1200

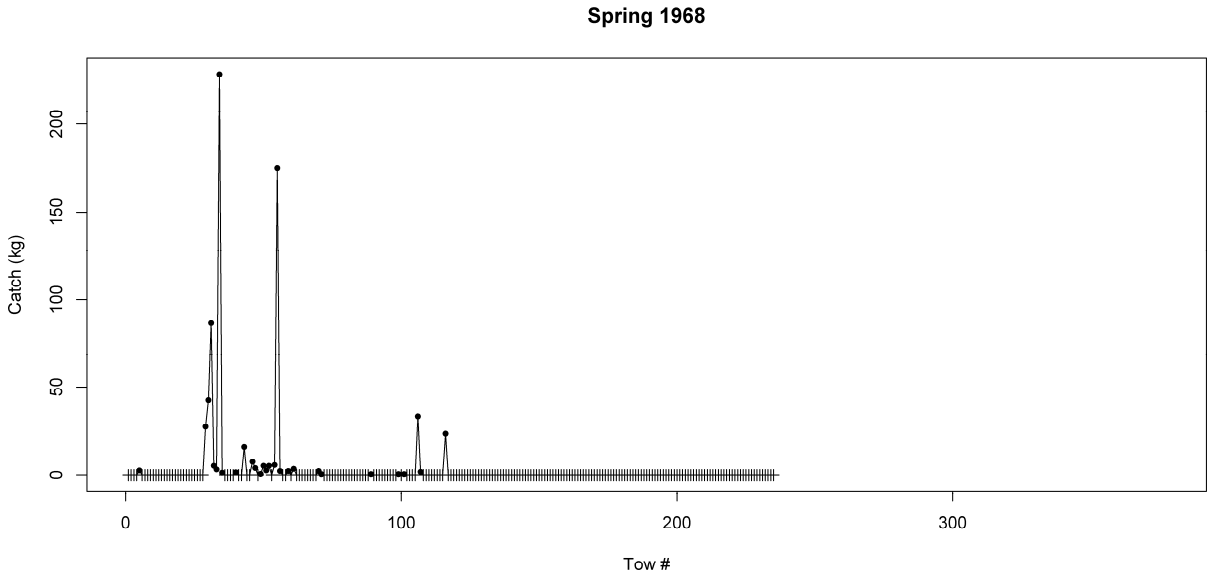

Mackerel Spring 2016
Maximum number per tow = 785
Northing (km)
Easting (km)
200
400
600
800
1000
1200
0
200
400
600
800

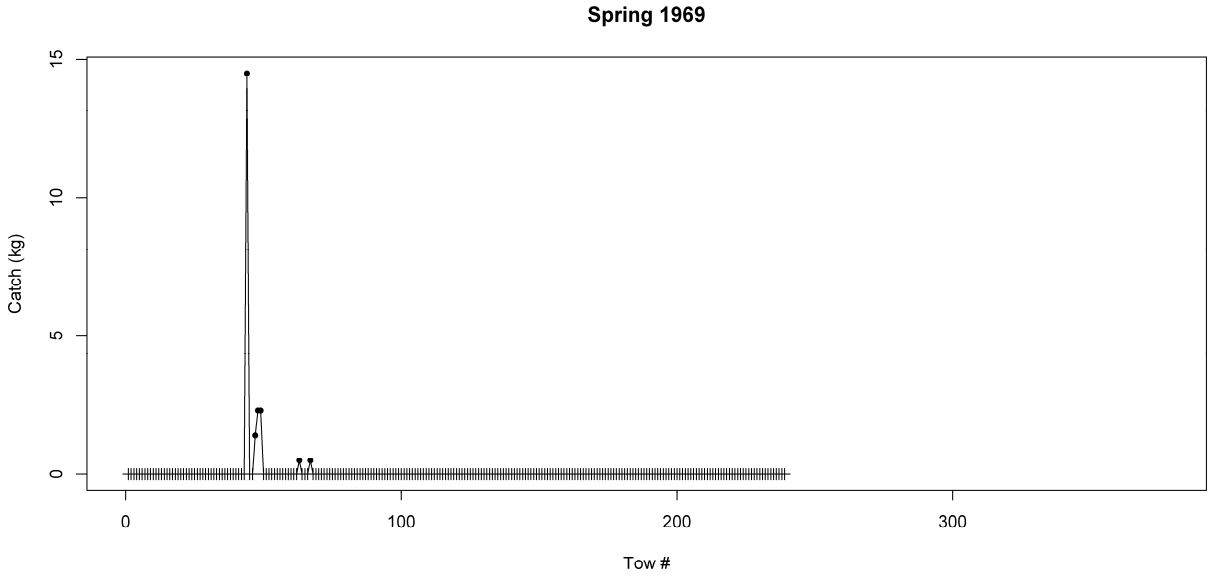

Immature Spring 2016
Maximum number per tow = 776
Northing (km)
Easting (km)
200
400
600
800
1000
1200
0
200
400
600
800

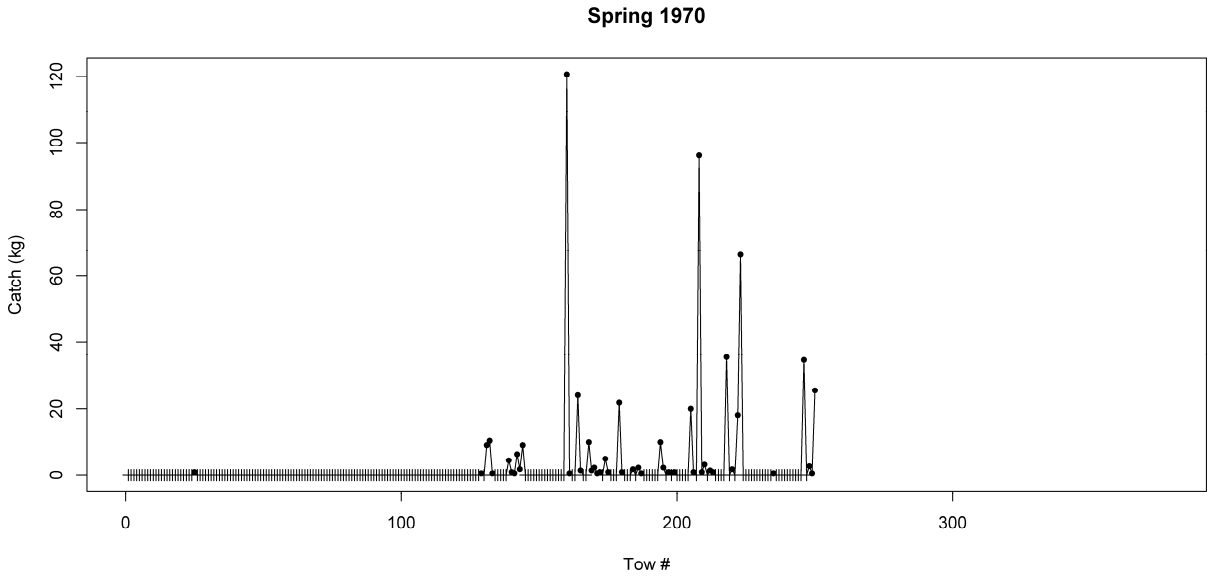

Mature Spring 2016
Maximum number per tow = 274
Northing (km)
Easting (km)
200
400
600
800
1000
1200
0
200
400
600
800

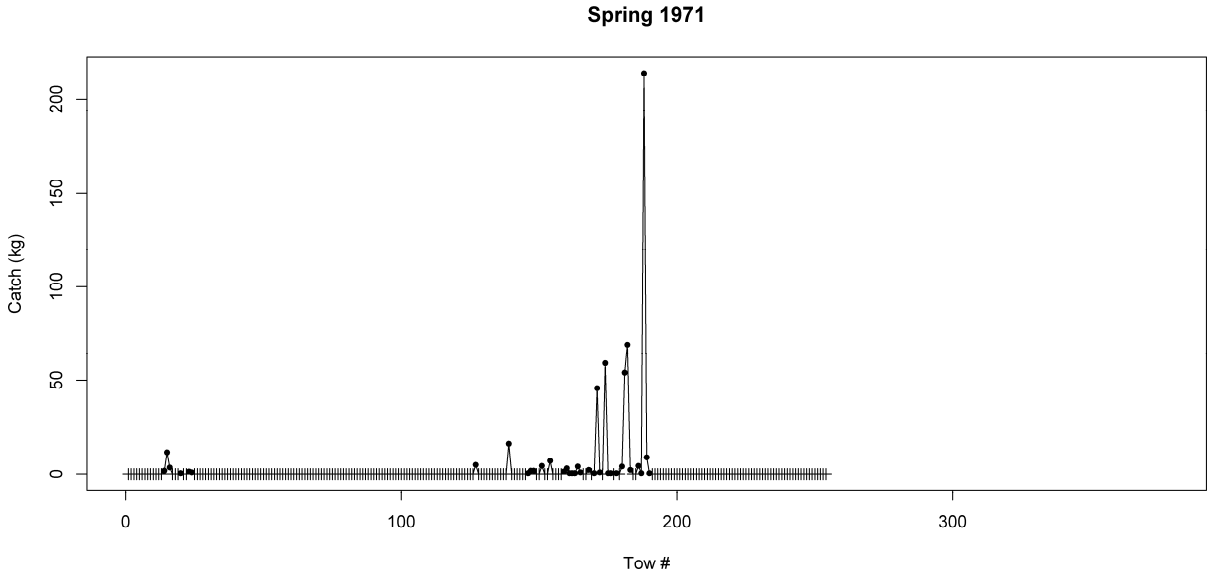
Appendix 3

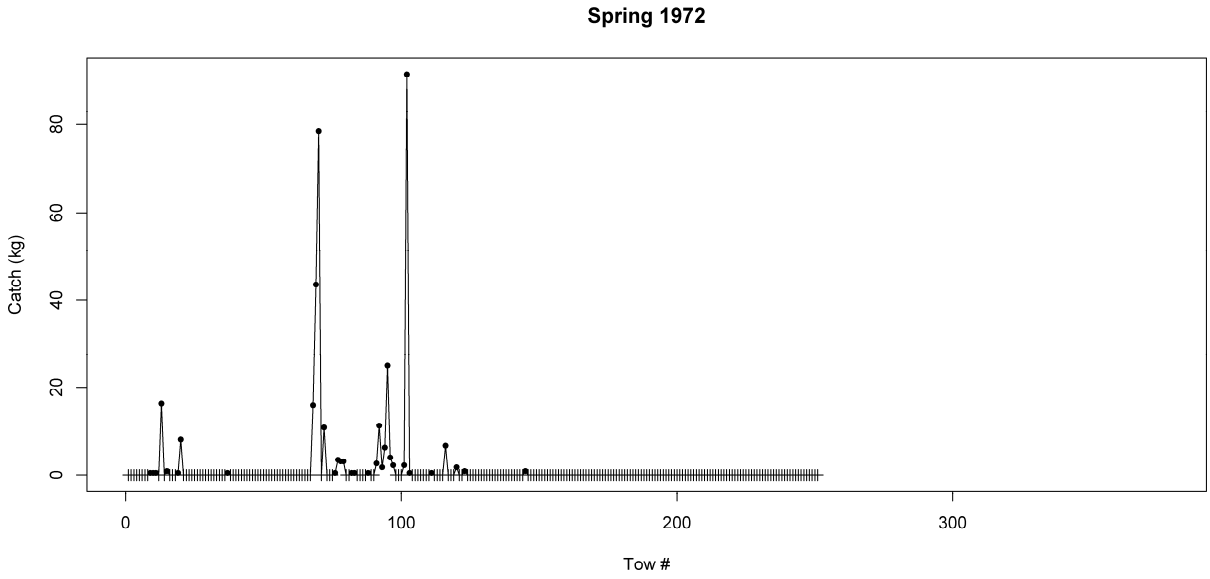
Plots of Atlantic mackerel catch biomass in the NEFSC spring survey, 1968–2016, ordered by consecutive tow number

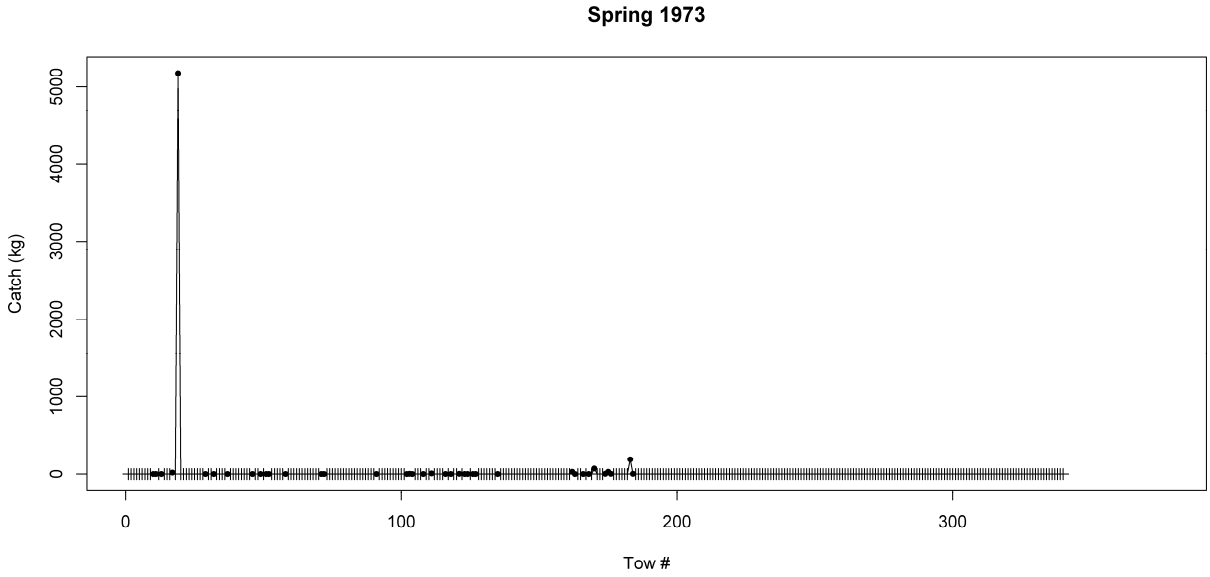

Spring 1968
Catch (kg)
0
50
100
150
200
0
100
200
300
Tow #

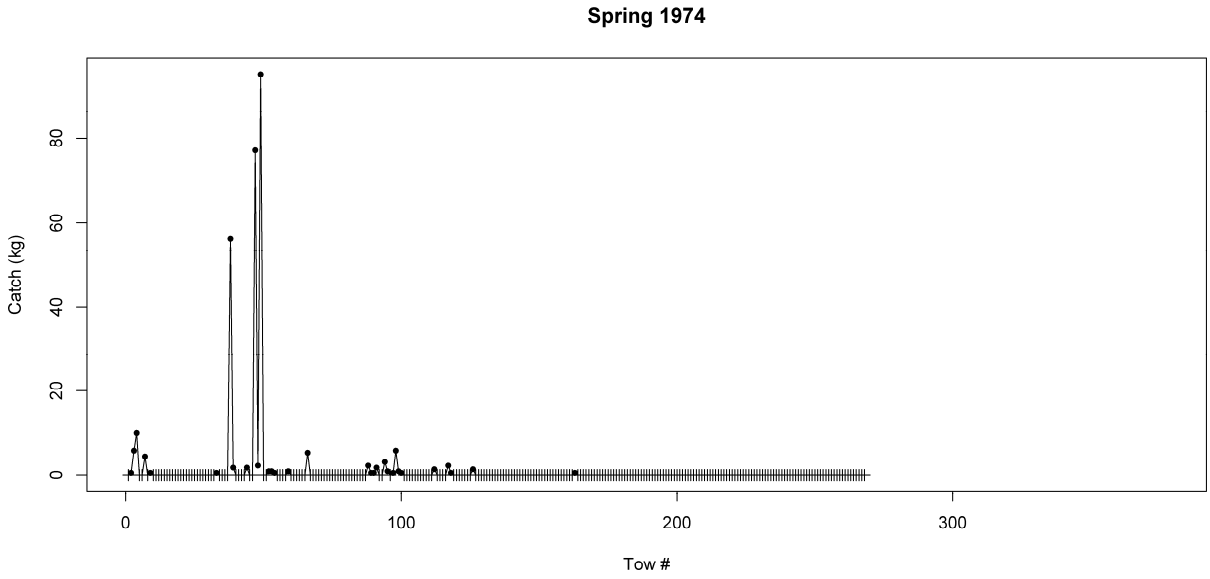

Spring 1969
Catch (kg)
0
5
10
15
0
100
200
300
Tow #

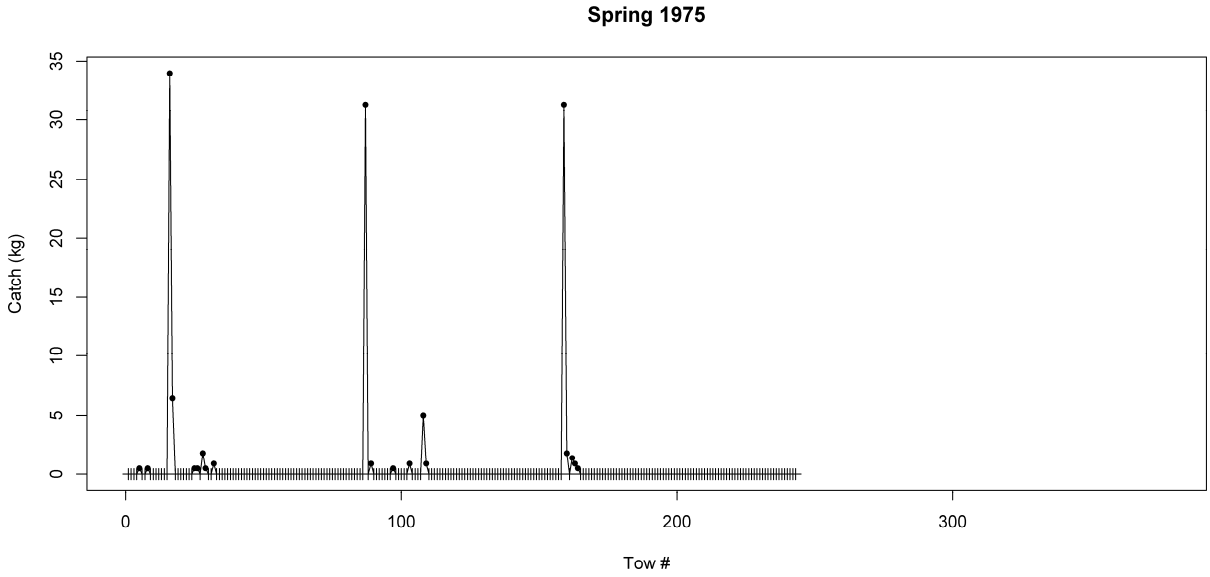

Spring 1970
Catch (kg)
0
20
40
60
80
100
120
0
100
200
300
Tow #

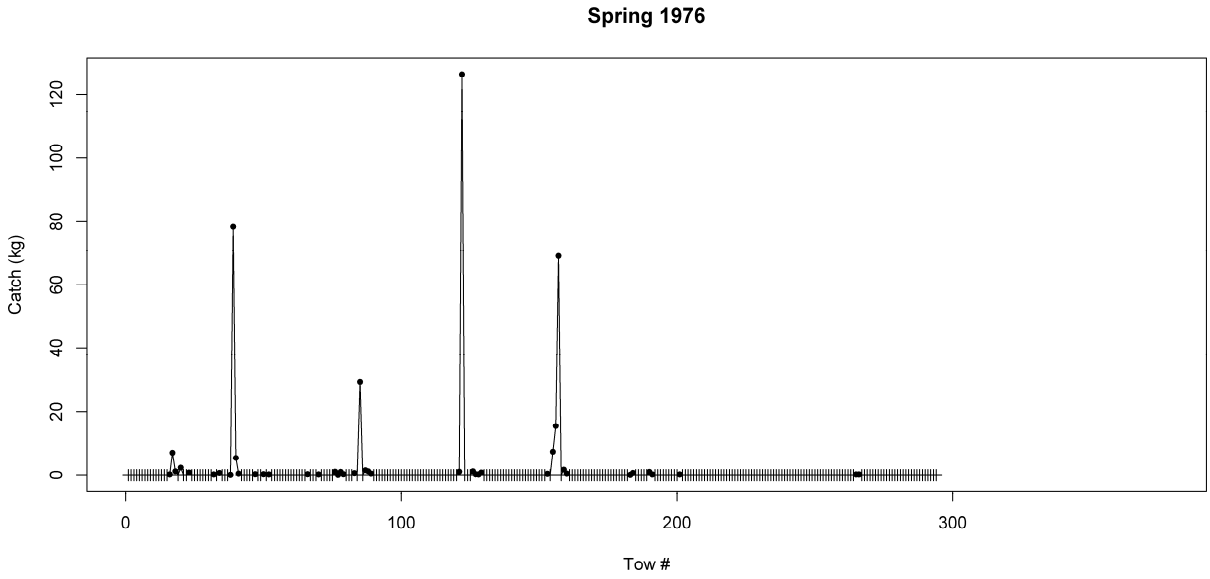

Spring 1971
Catch (kg)
0
50
100
150
200
0
100
200
300
Tow #

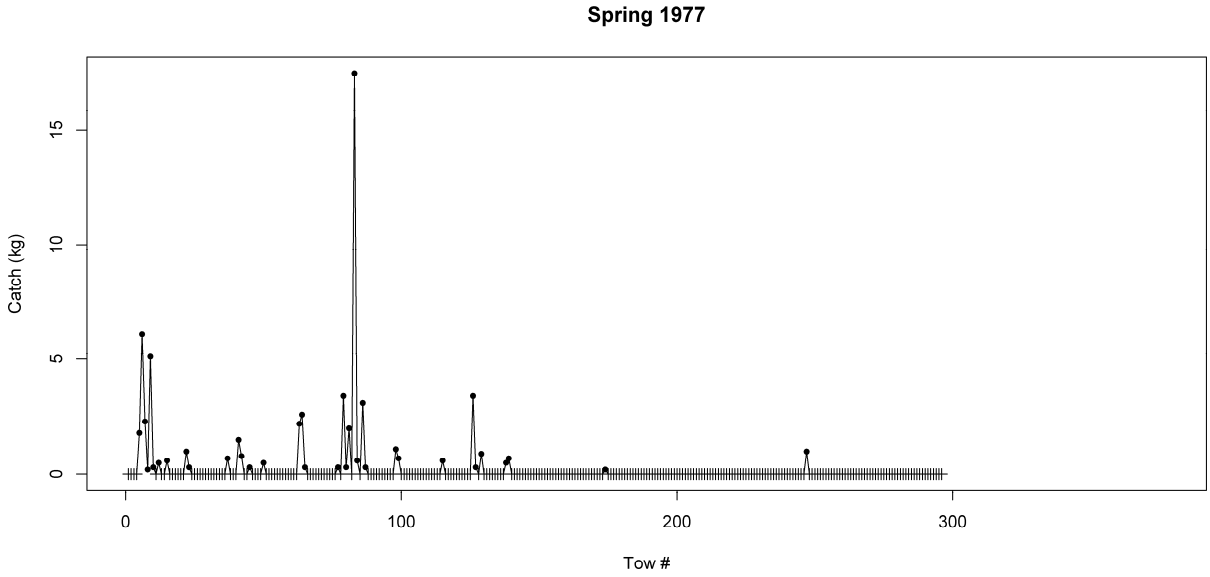

Spring 1972
Catch (kg)
0
20
40
60
80
0
100
200
300
Tow #

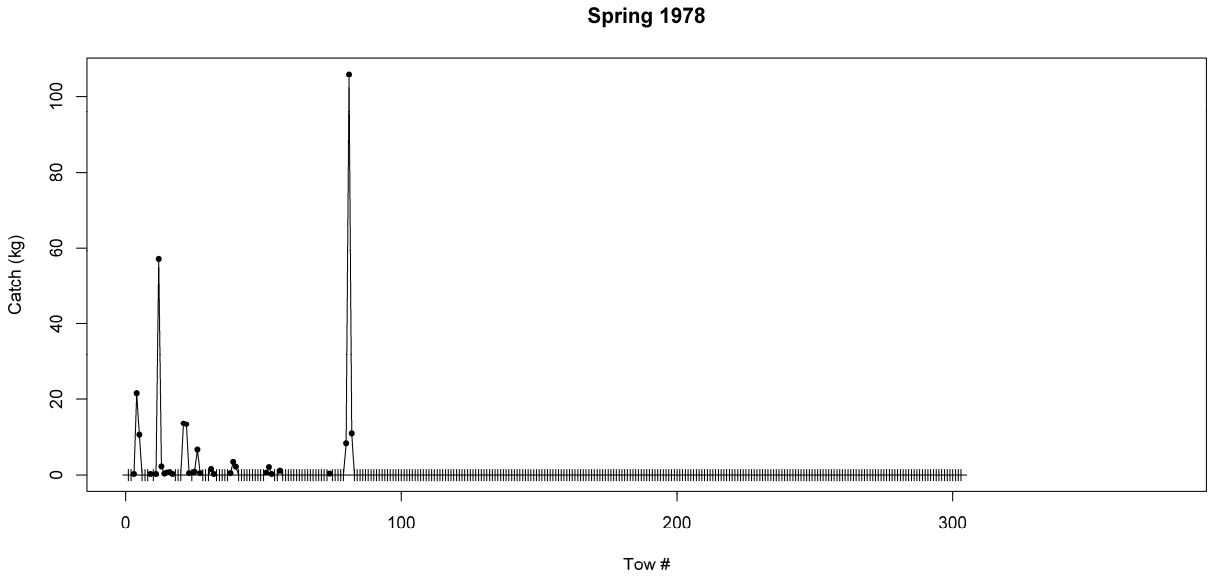

Spring 1973
Catch (kg)
0
1000
2000
3000
4000
5000
0
100
200
300
Tow #

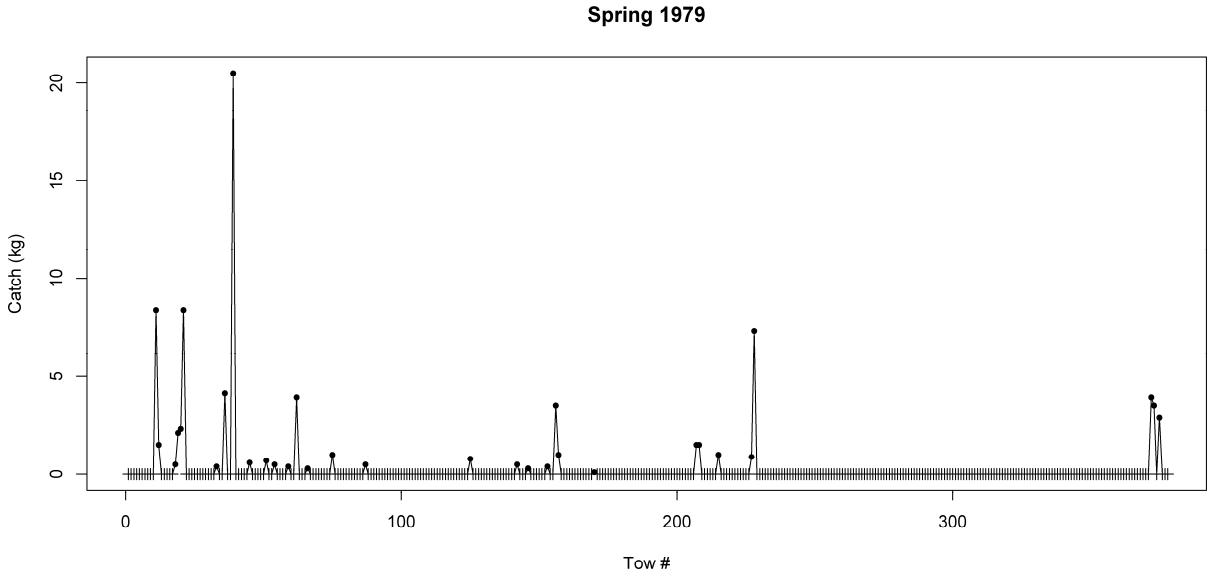

Spring 1974
Catch (kg)
0
20
40
60
80
0
100
200
300
Tow #

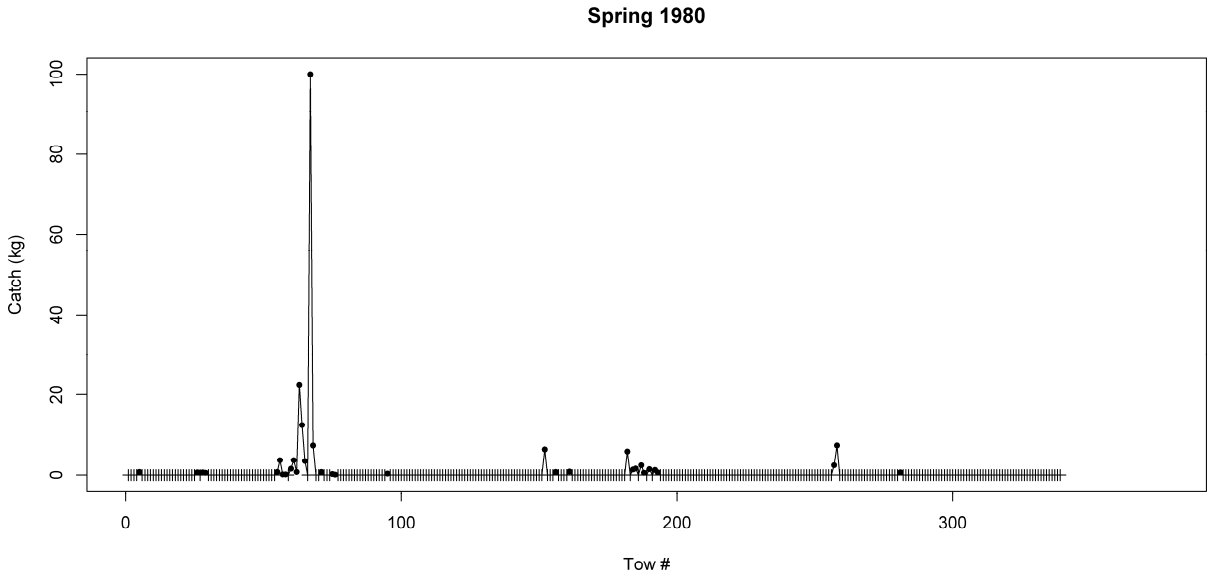

Spring 1975
Catch (kg)
0
5
10
15
20
25
30
35
0
100
200
300
Tow #

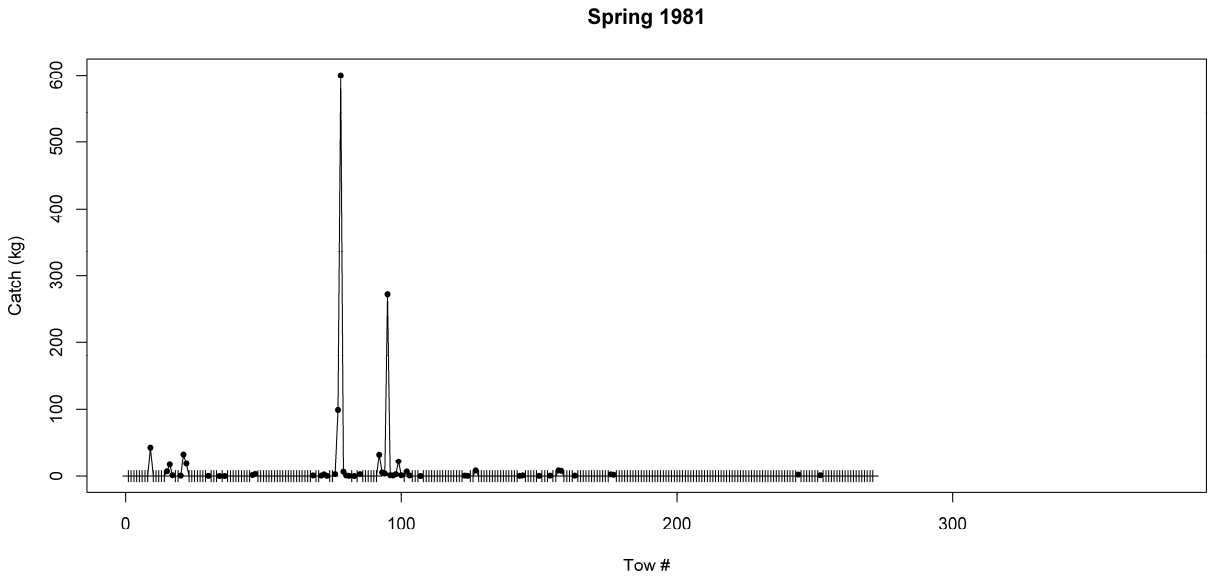

Spring 1976
Catch (kg)
0
20
40
60
80
100
120
0
100
200
300
Tow #

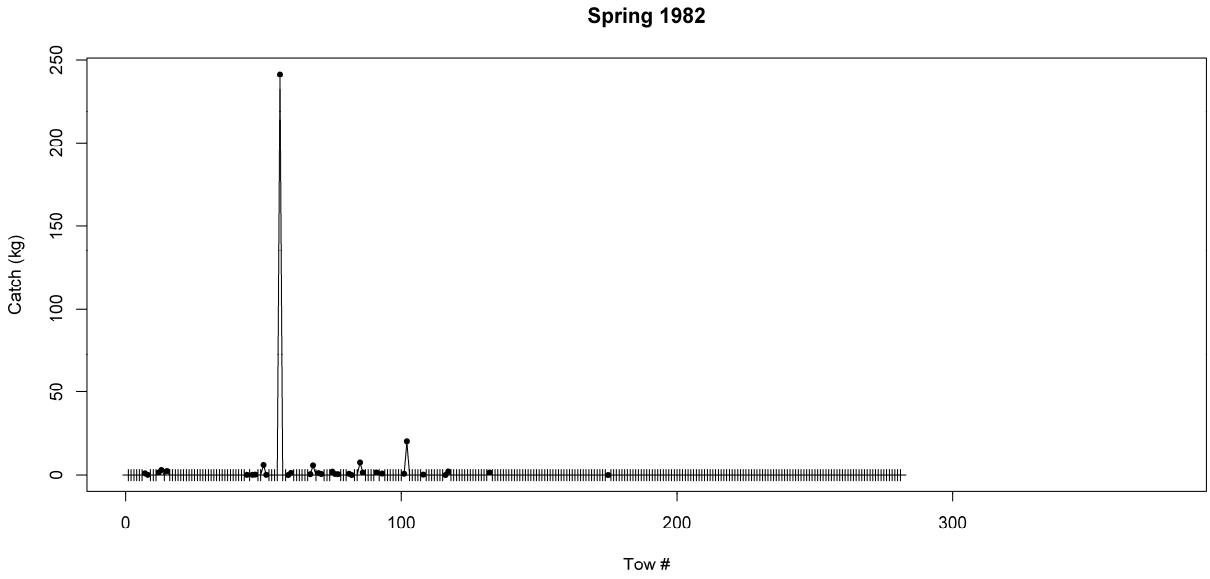

Spring 1977
Catch (kg)
0
5
10
15
0
100
200
300
Tow #

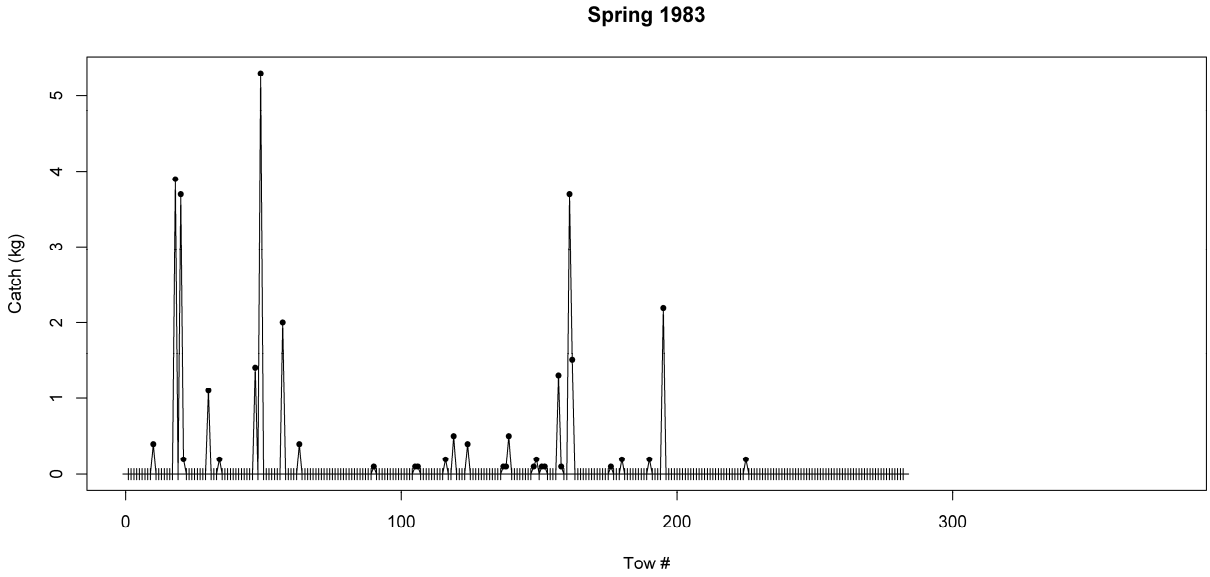

Spring 1978
Catch (kg)
0
20
40
60
80
100
0
100
200
300
Tow #

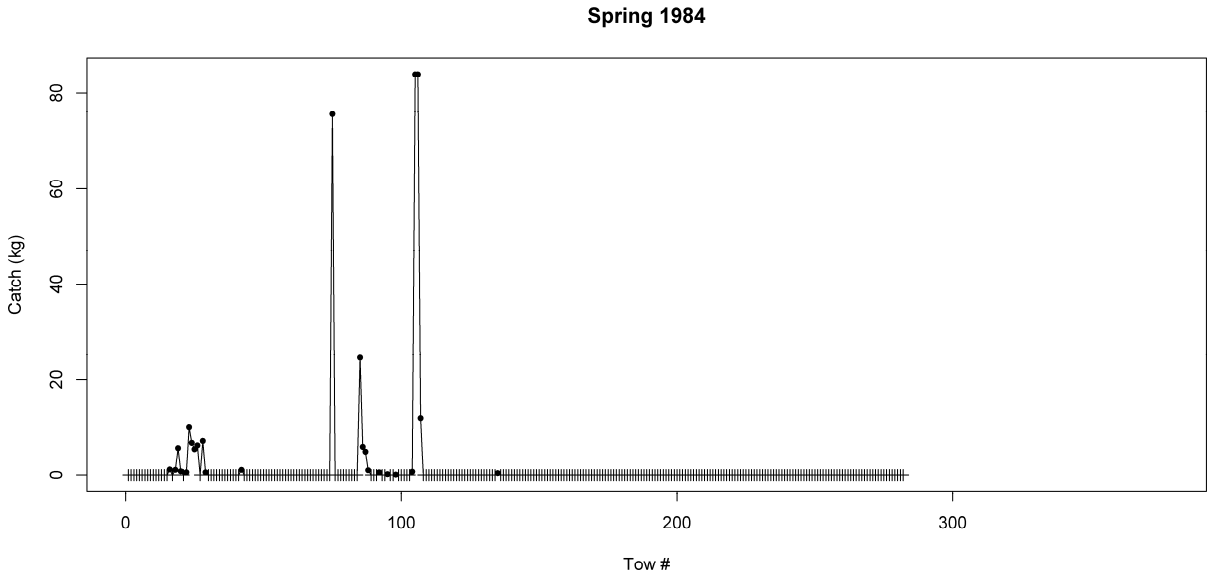

Spring 1979
Catch (kg)
0
5
10
15
20
0
100
200
300
Tow #

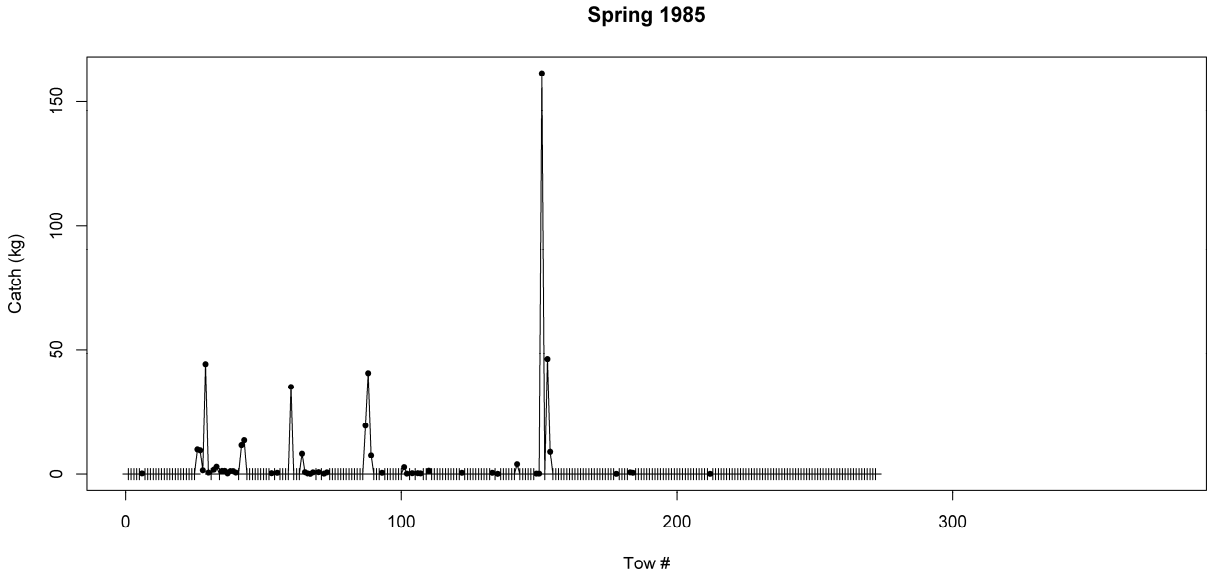

Spring 1980
Catch (kg)
0
20
40
60
80
100
0
100
200
300
Tow #

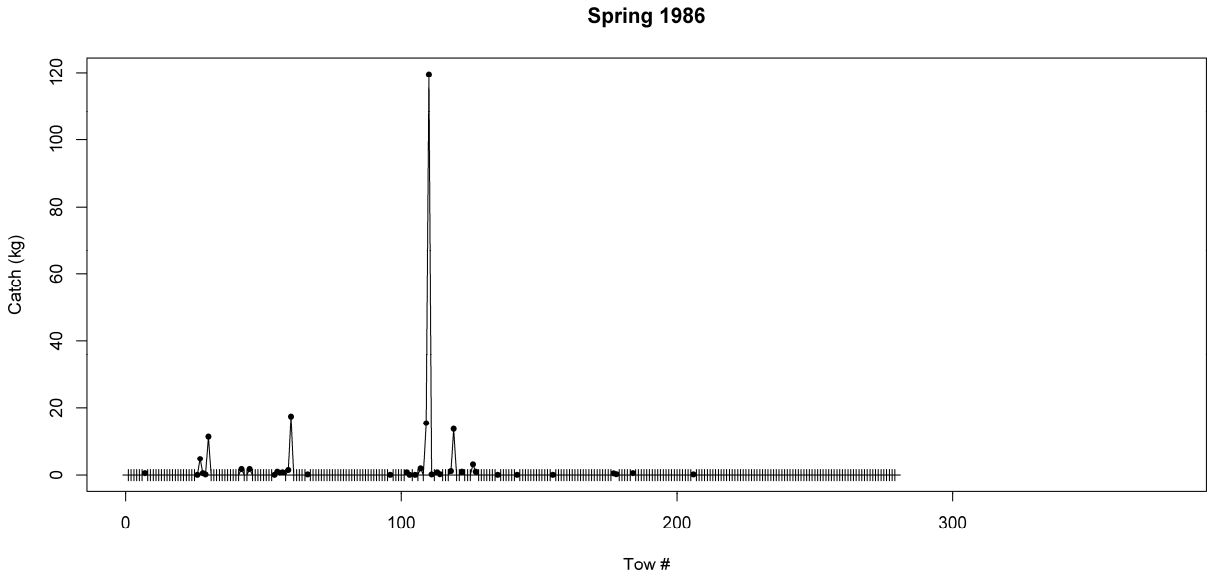

Spring 1981
Catch (kg)
0
100
200
300
400
500
600
0
100
200
300
Tow #

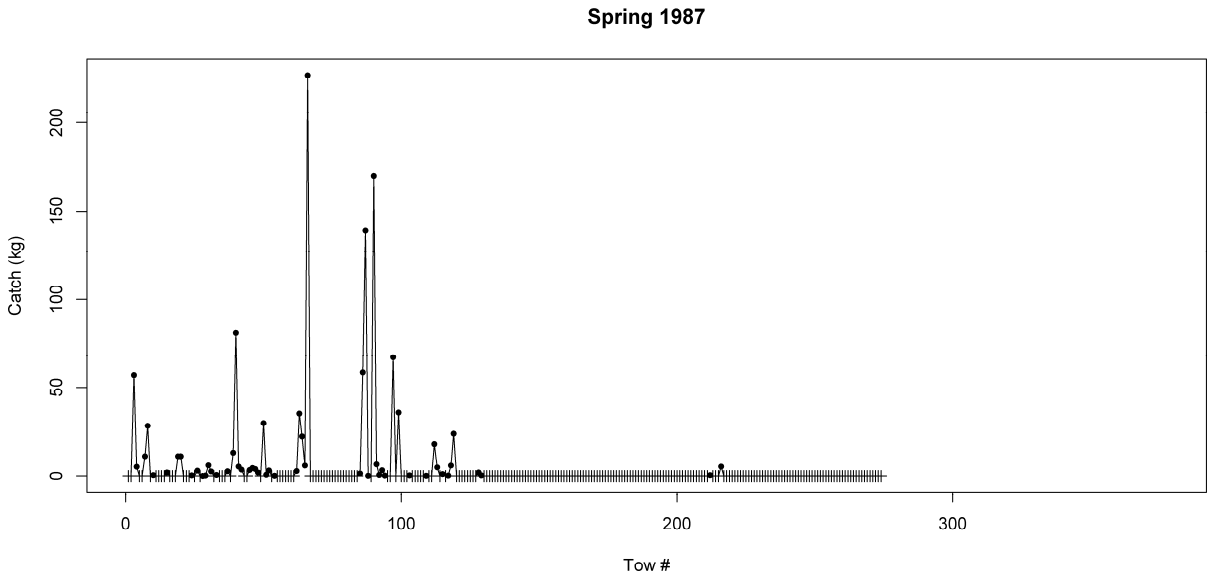

Spring 1982
Catch (kg)
0
50
100
150
200
250
0
100
200
300
Tow #

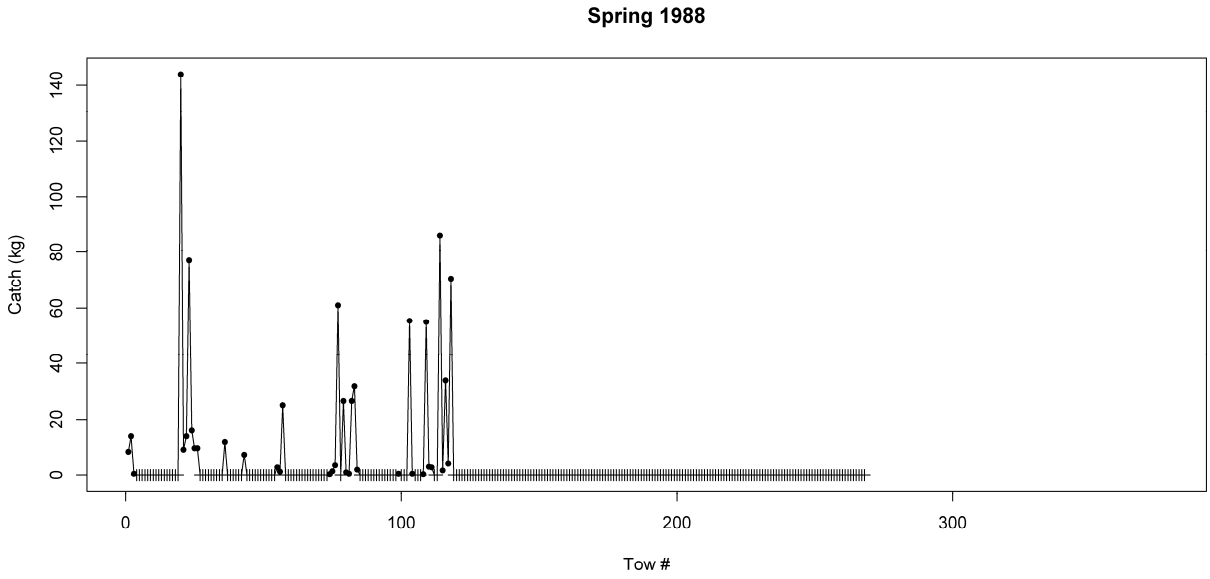

Spring 1983
Catch (kg)
0
1
2
3
4
5
0
100
200
300
Tow #

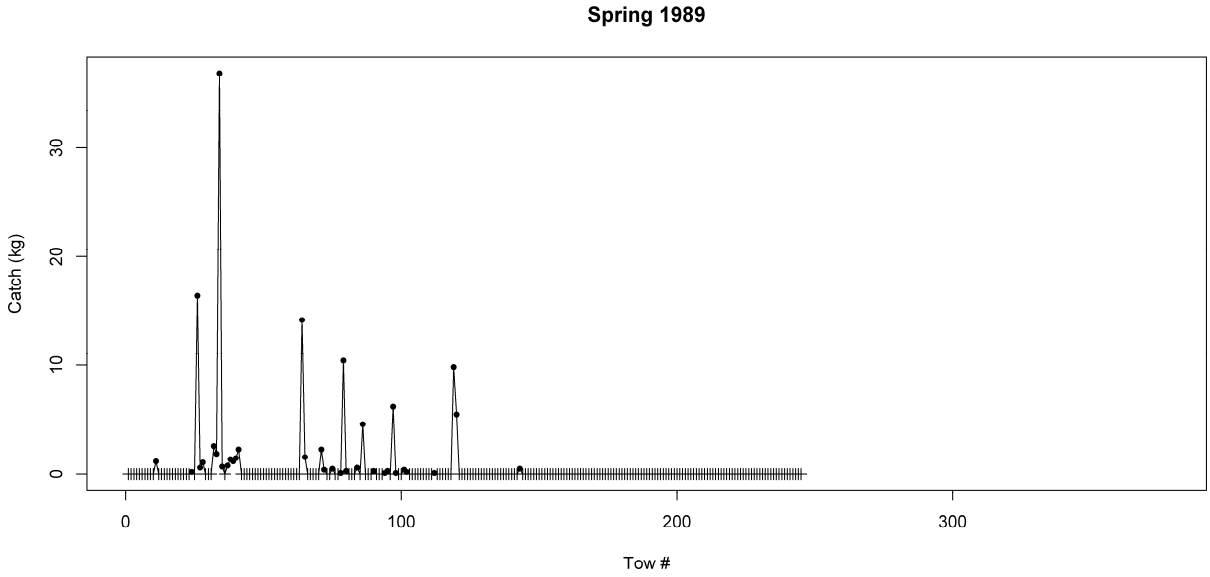

Spring 1984
Catch (kg)
0
20
40
60
80
0
100
200
300
Tow #

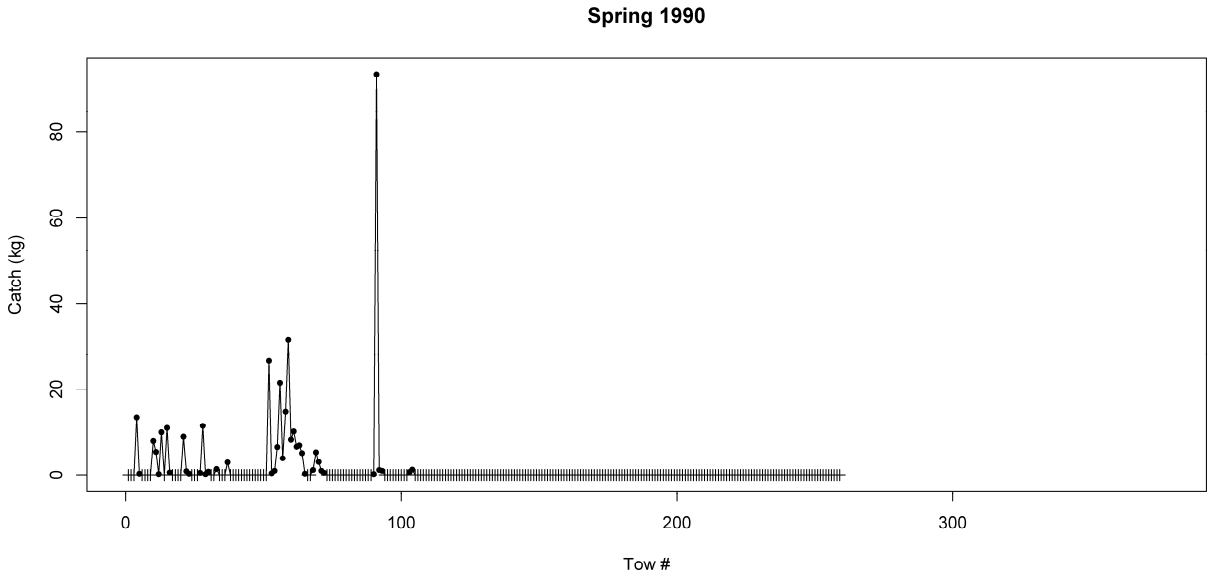

Spring 1985
Catch (kg)
0
50
100
150
0
100
200
300
Tow #

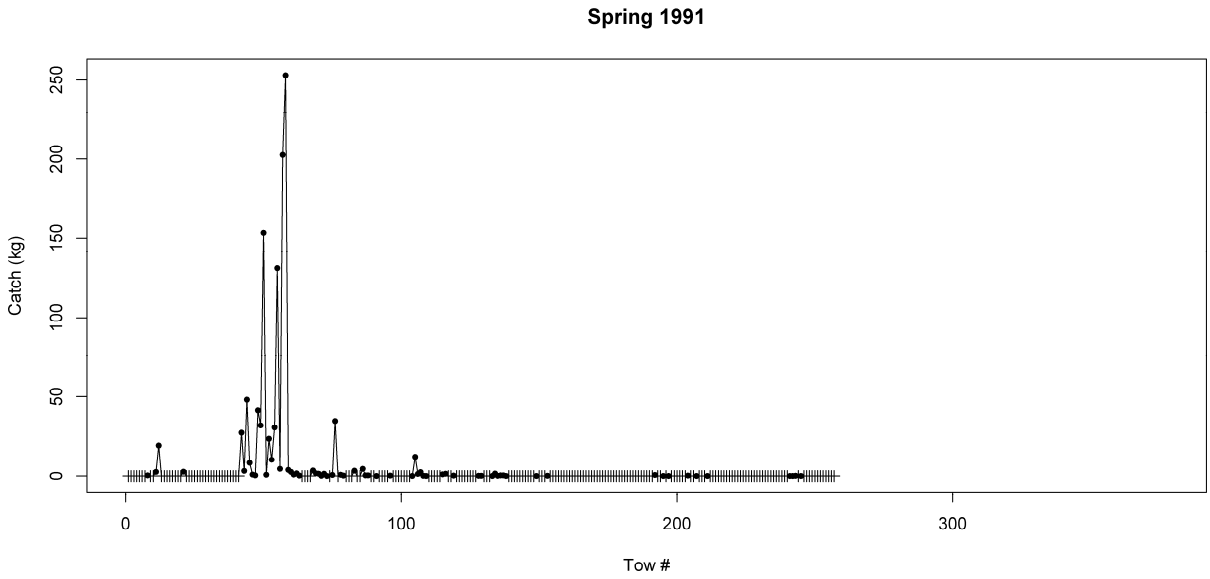

Spring 1986
Catch (kg)
0
20
40
60
80
100
120
0
100
200
300
Tow #

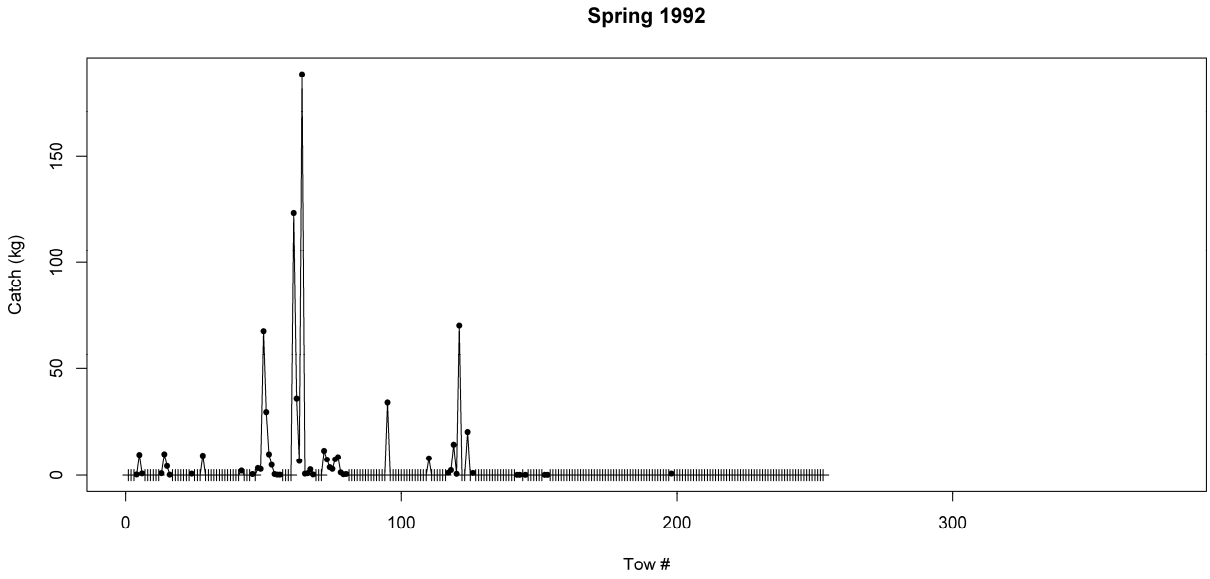

Spring 1987
Catch (kg)
0
50
100
150
200
0
100
200
300
Tow #

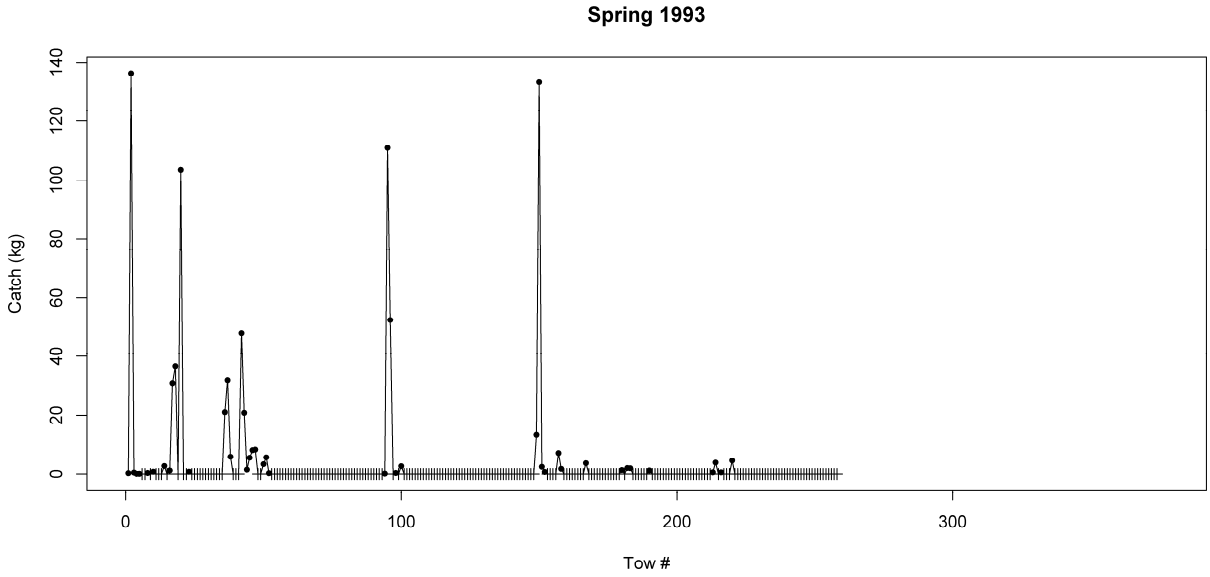

Spring 1988
Catch (kg)
0
20
40
60
80
100
120
140
0
100
200
300
Tow #

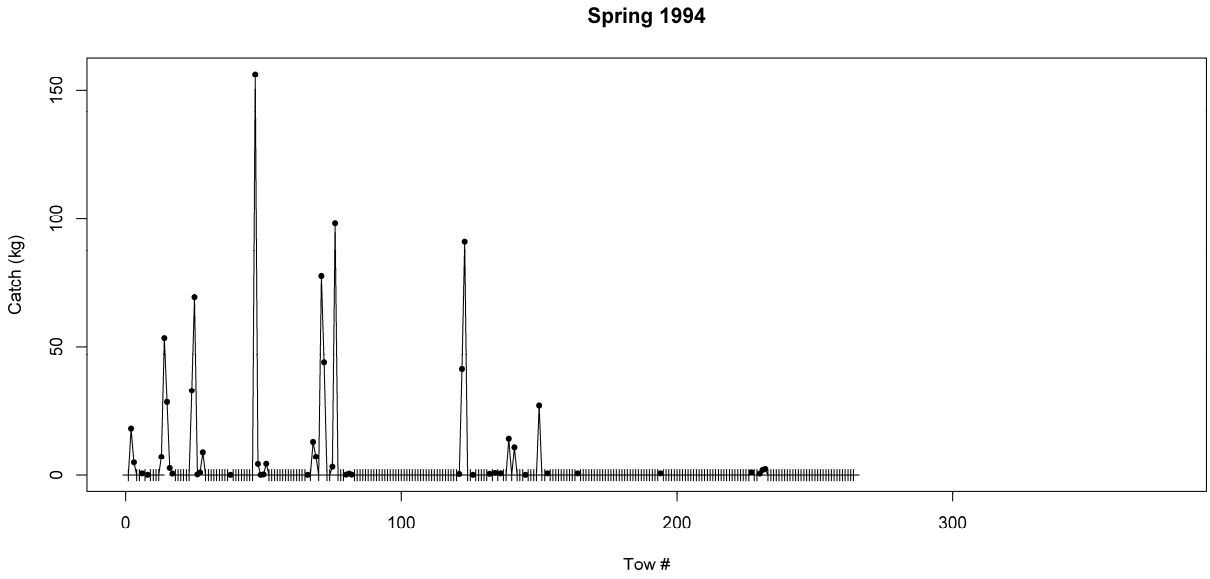

Spring 1989
Catch (kg)
0
10
20
30
0
100
200
300
Tow #

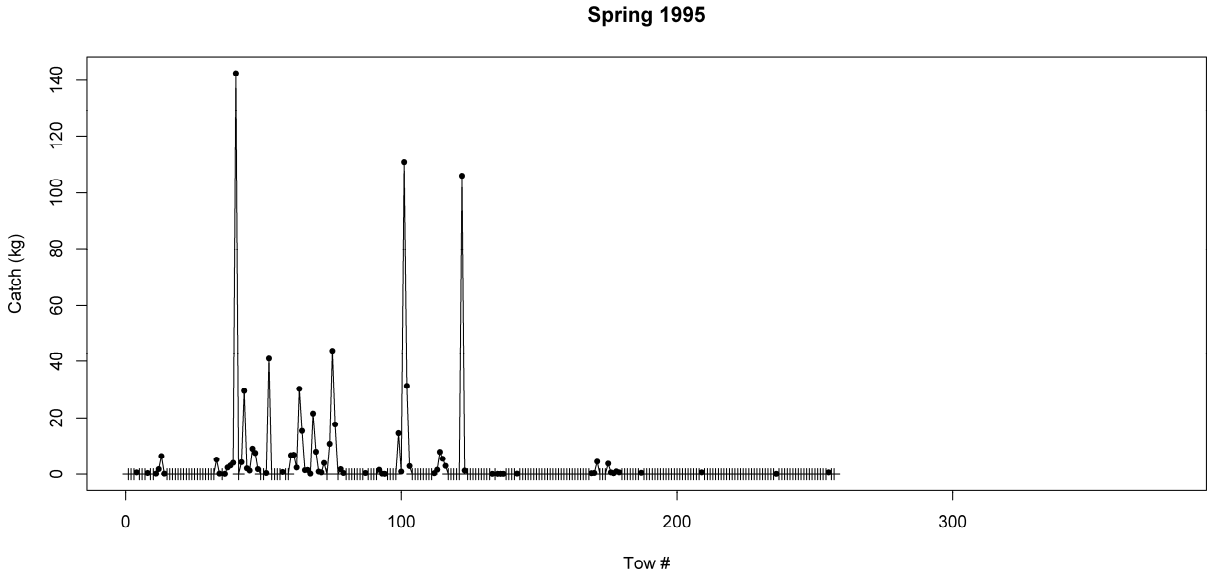

Spring 1990
Catch (kg)
0
20
40
60
80
0
100
200
300
Tow #

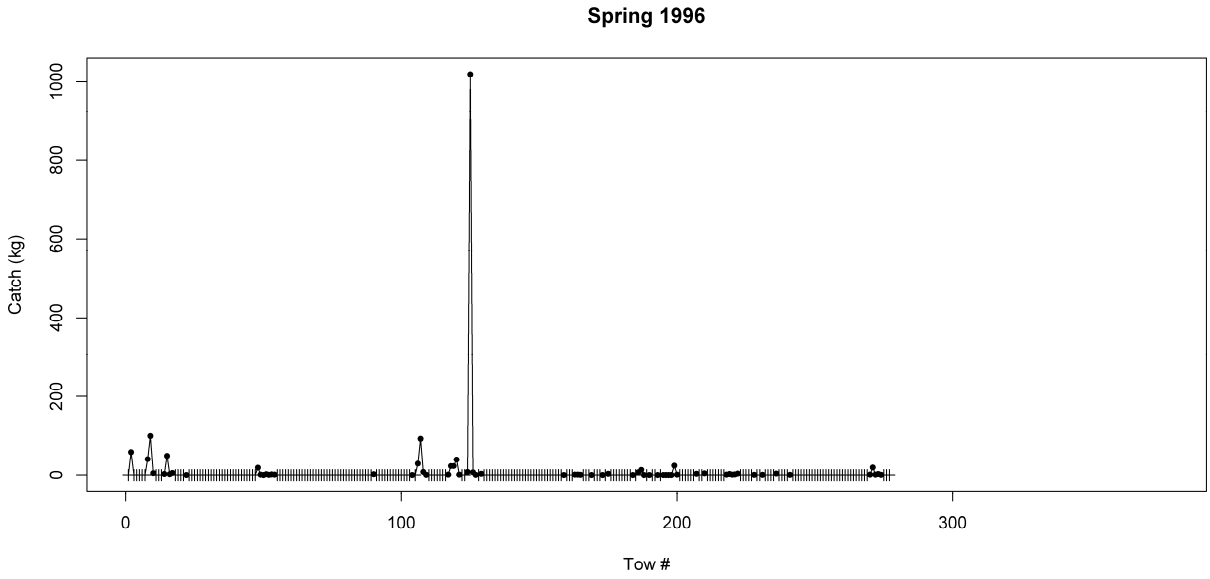

Spring 1991
Catch (kg)
0
50
100
150
200
250
0
100
200
300
Tow #

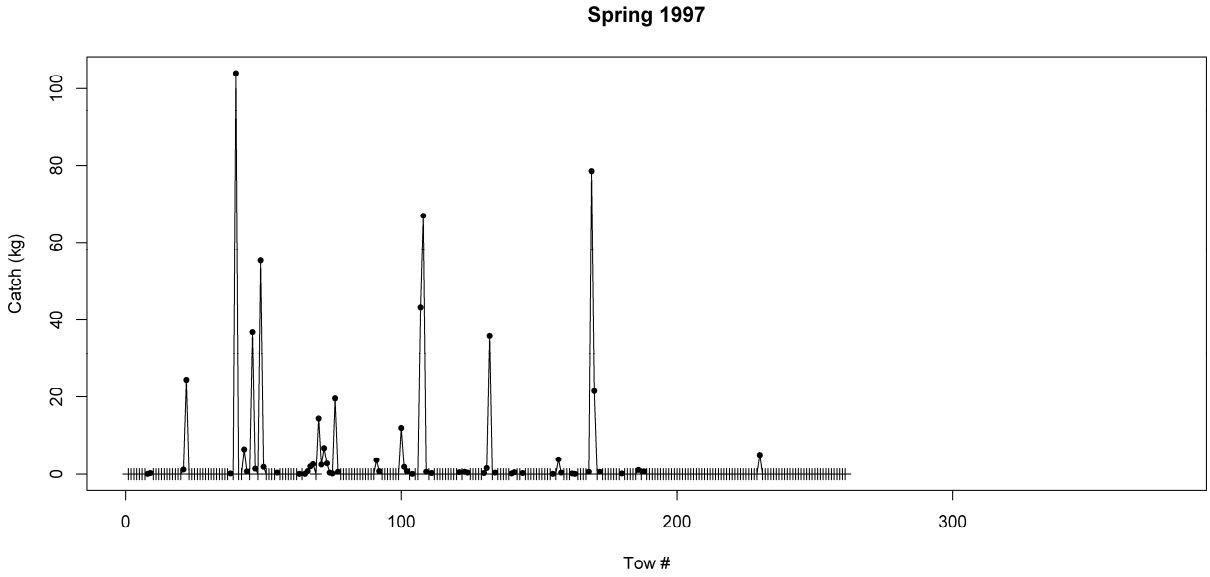

Spring 1992
Catch (kg)
0
50
100
150
0
100
200
300
Tow #

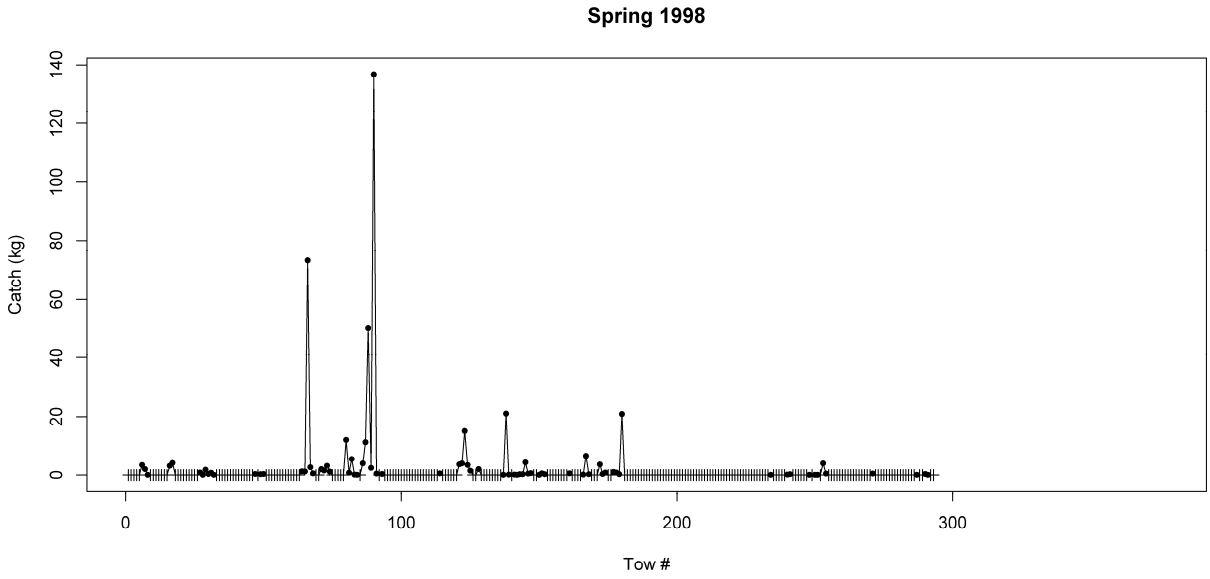

Spring 1993
Catch (kg)
0
20
40
60
80
100
120
140
0
100
200
300
Tow #

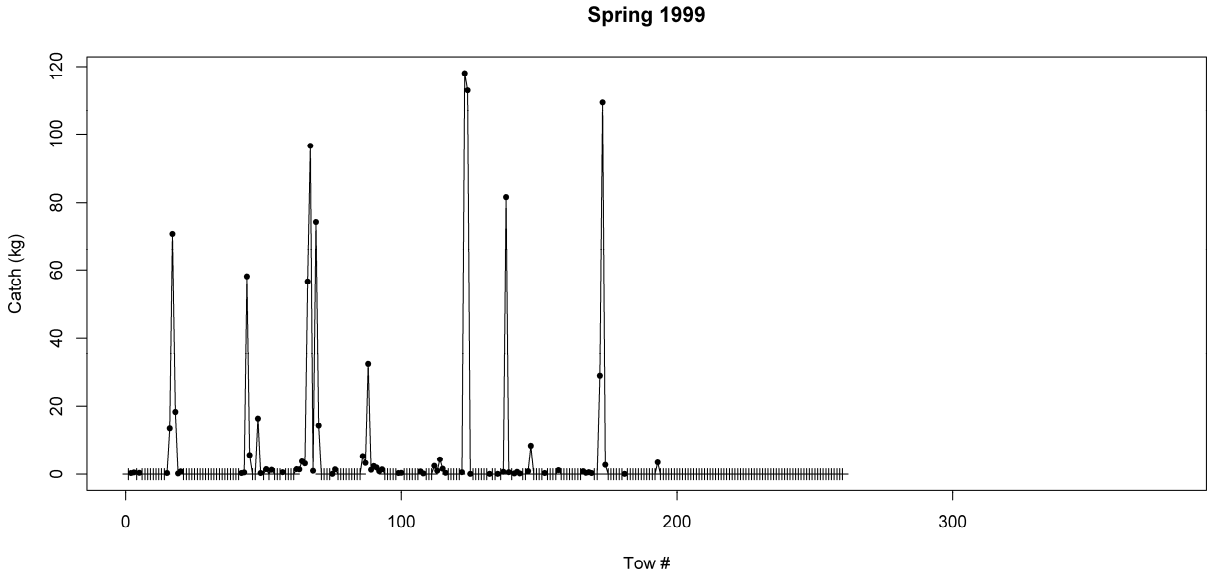

Spring 1994
Catch (kg)
0
50
100
150
0
100
200
300
Tow #

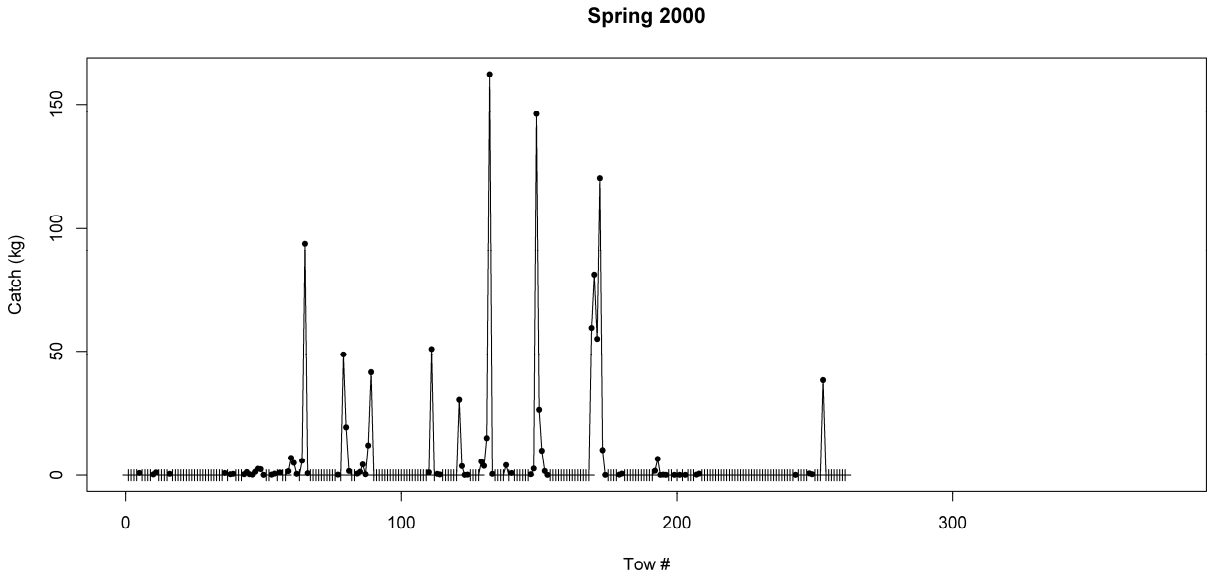

Spring 1995
Catch (kg)
0
20
40
60
80
100
120
140
0
100
200
300
Tow #

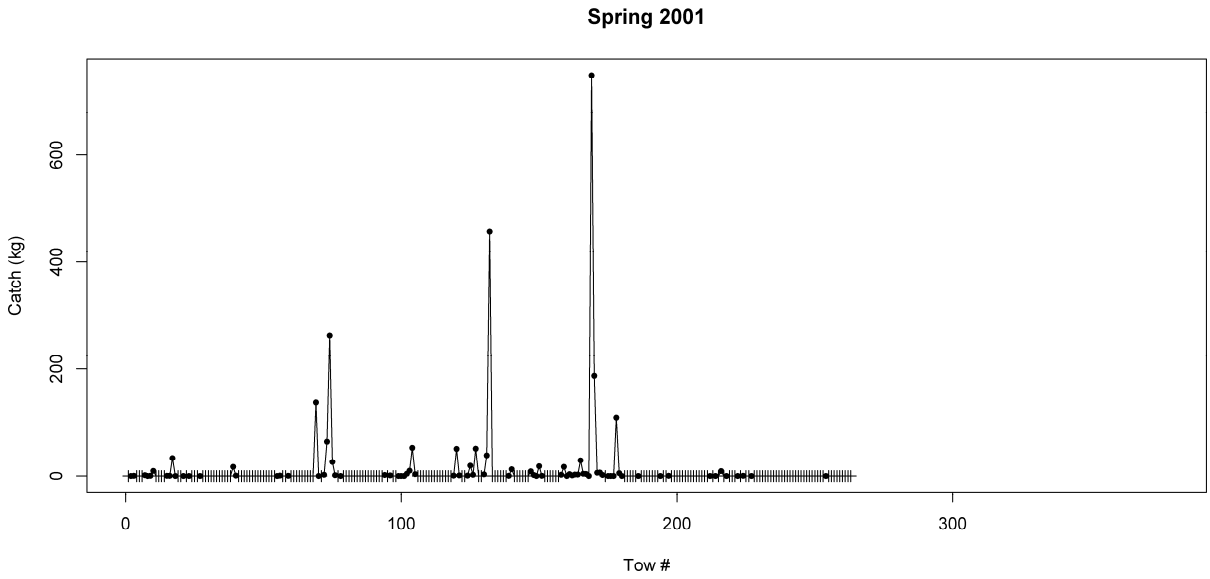

Spring 1996
Catch (kg)
0
200
400
600
800
1000
0
100
200
300
Tow #

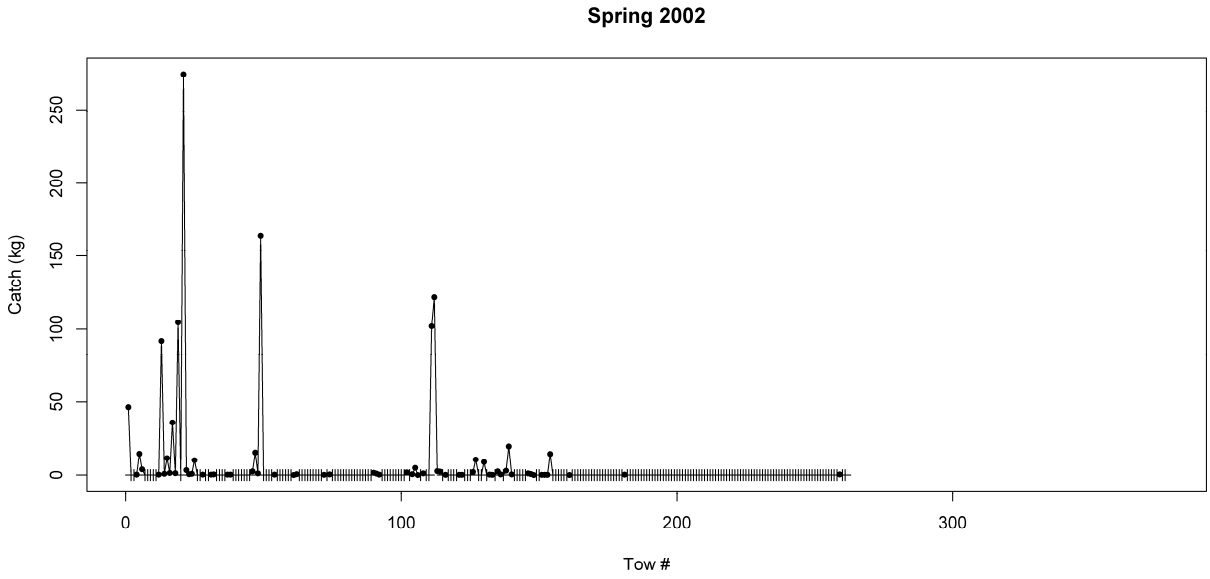

Spring 1997
Catch (kg)
0
20
40
60
80
100
0
100
200
300
Tow #

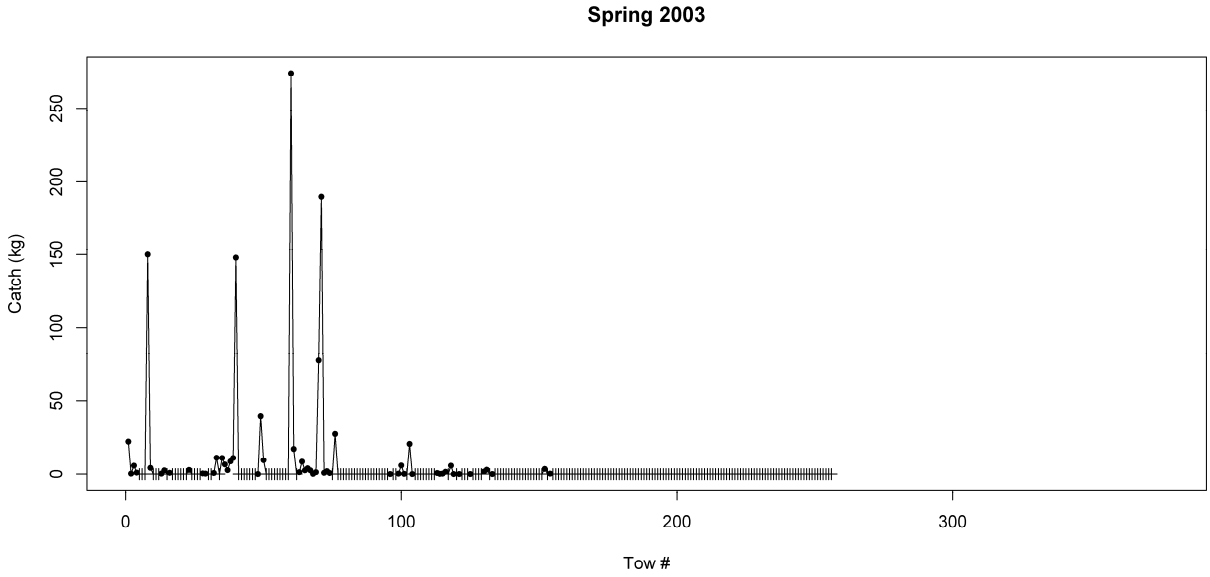

Spring 1998
Catch (kg)
0
20
40
60
80
100
120
140
0
100
200
300
Tow #

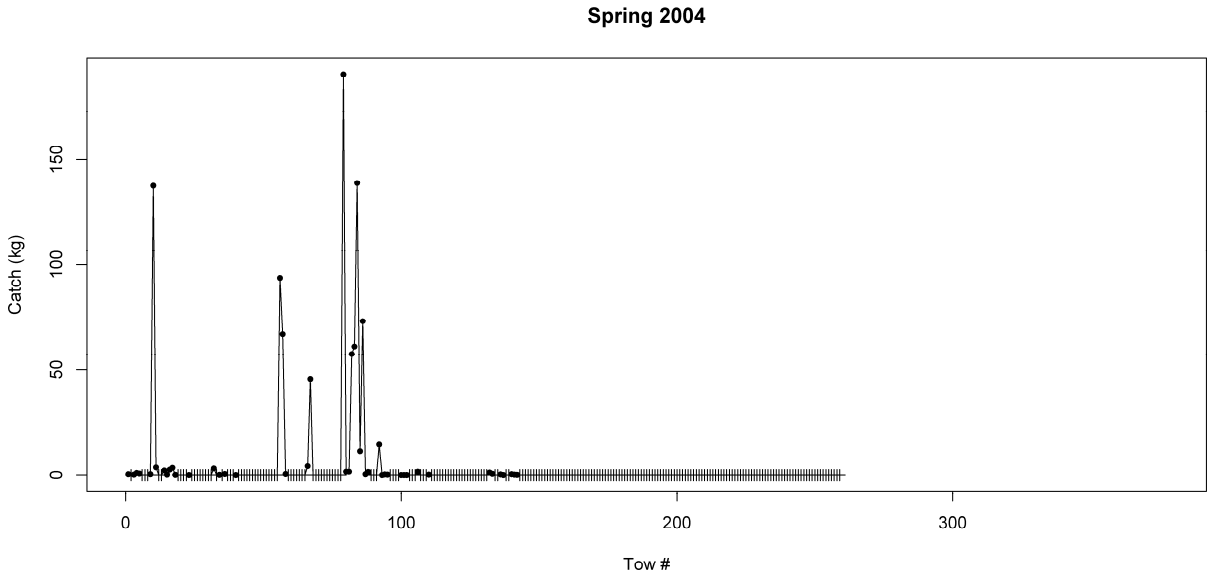

Spring 1999
Catch (kg)
0
20
40
60
80
100
120
0
100
200
300
Tow #

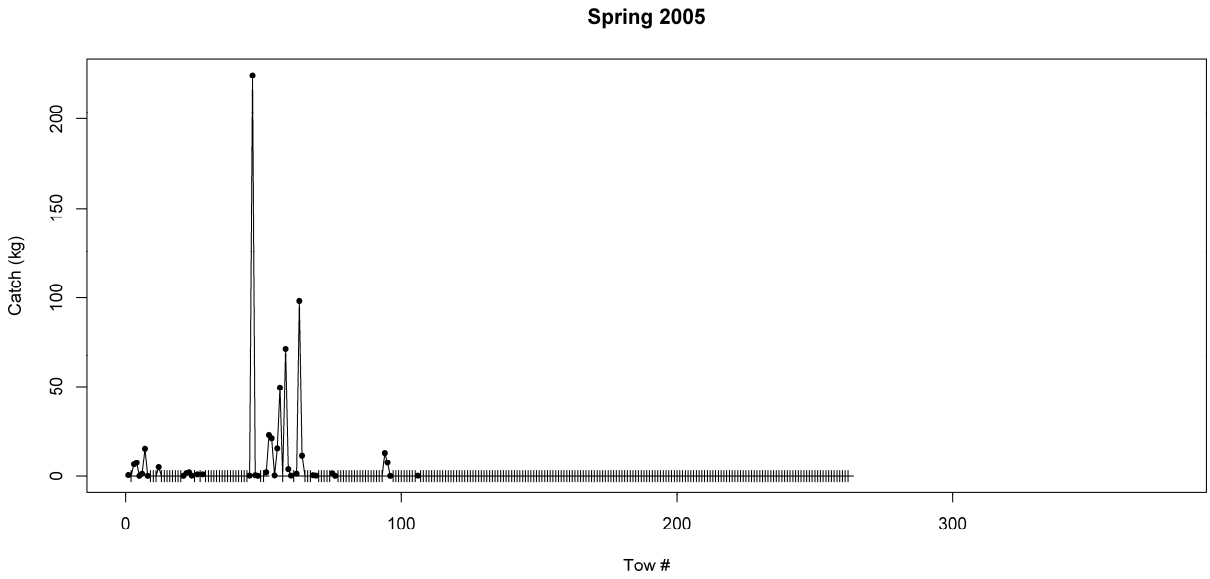

Spring 2000
Catch (kg)
0
50
100
150
0
100
200
300
Tow #

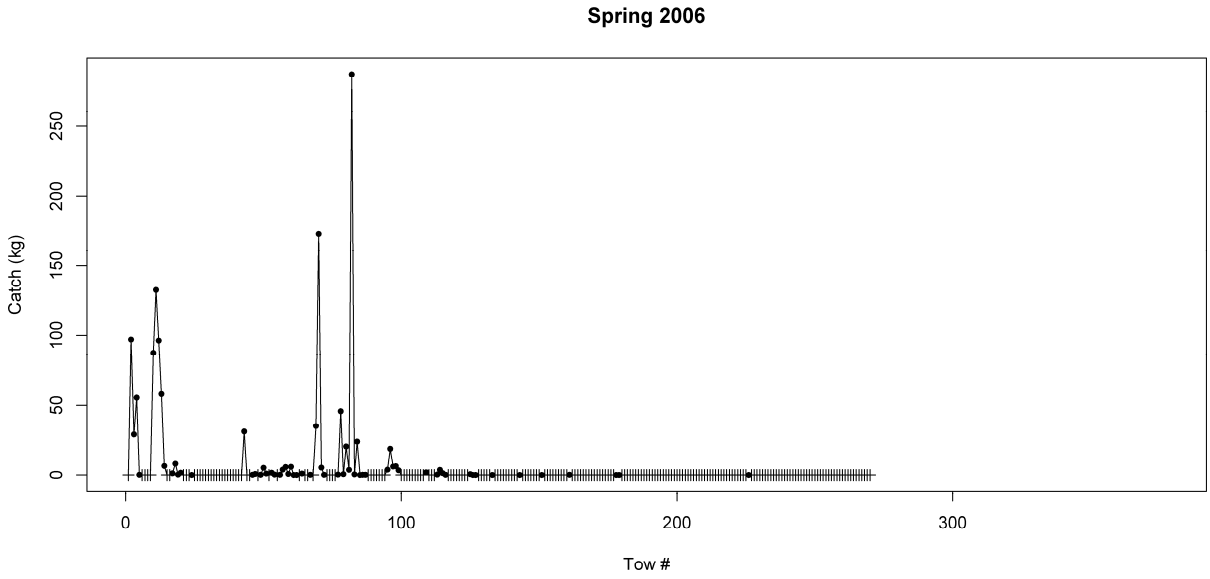

Spring 2001
Catch (kg)
0
200
400
600
0
100
200
300
Tow #


Spring 2002
Catch (kg)
0
50
100
150
200
250
0
100
200
300
Tow #


Spring 2003
Catch (kg)
0
50
100
150
200
250
0
100
200
300
Tow #


Spring 2004
Catch (kg)
0
50
100
150
0
100
200
300
Tow #


Spring 2005
Catch (kg)
0
50
100
150
200
0
100
200
300
Tow #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Catch (kg)
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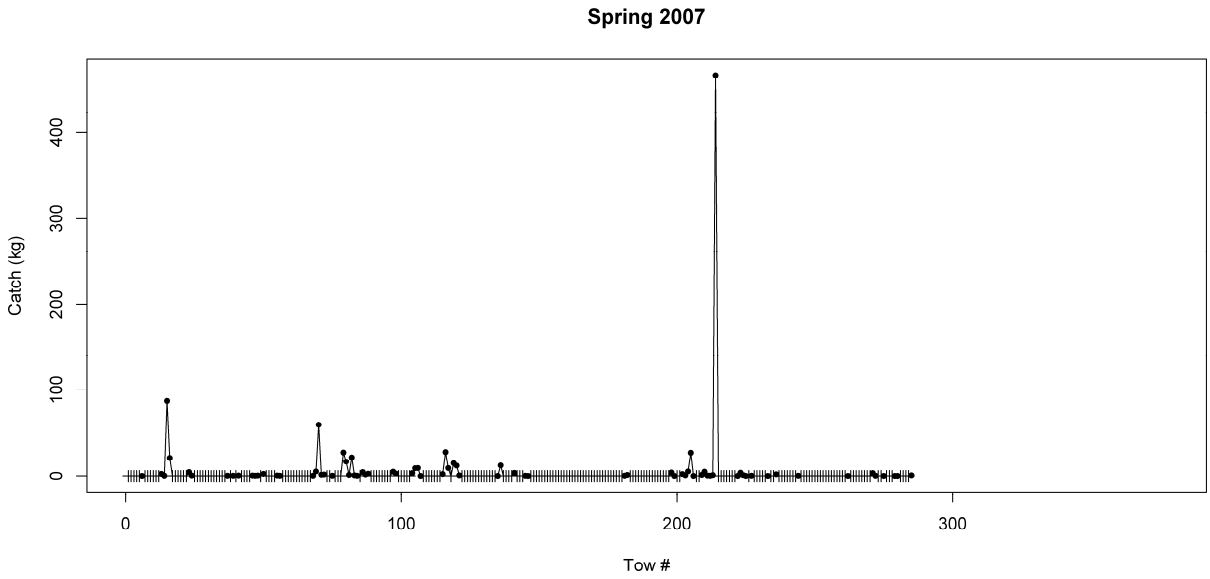
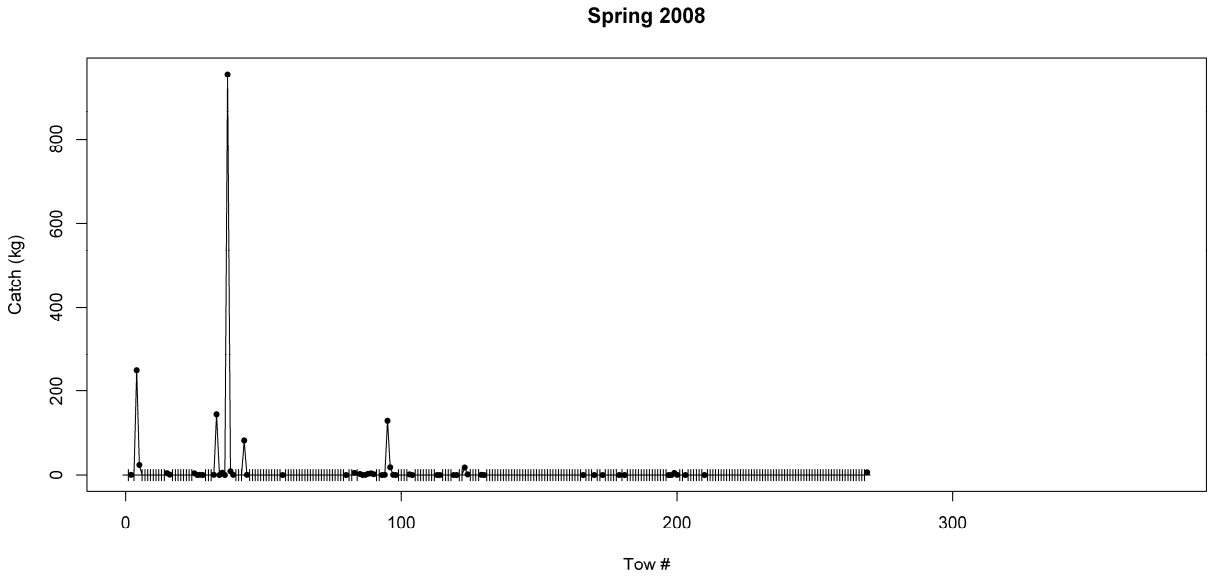
50
100
150
200
250
0
100
200
300
Tow #


Spring 2007
Catch (kg)
0
100
200
300
400
0
100
200
300
Tow #


Spring 2008
Catch (kg)
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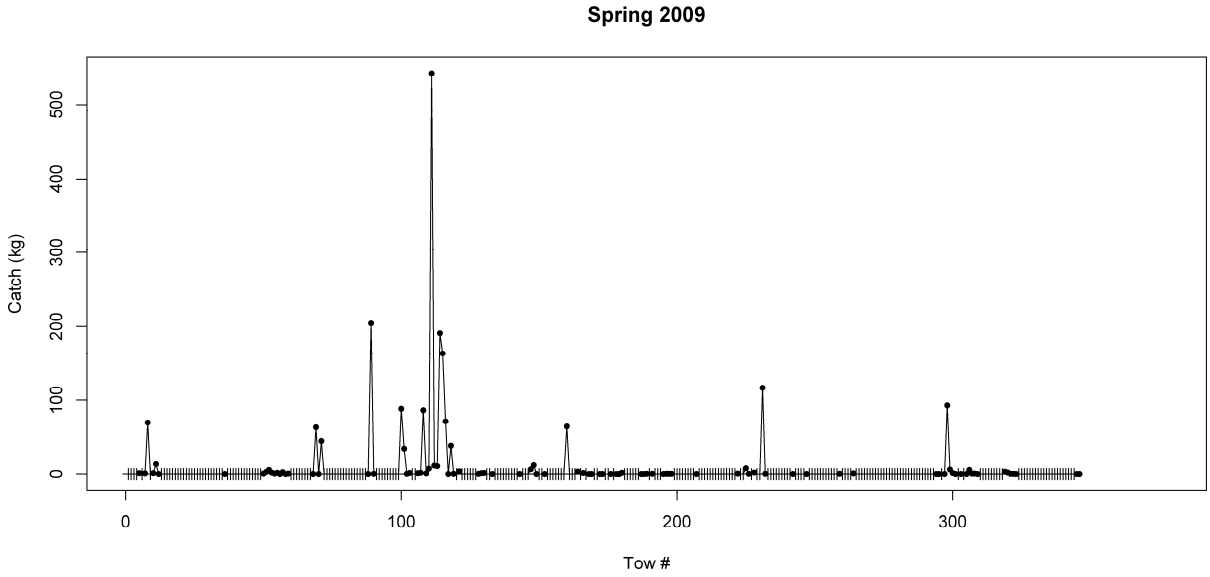
200
400
600
800
0
100
200
300
Tow #


Spring 2009
Catch (kg)
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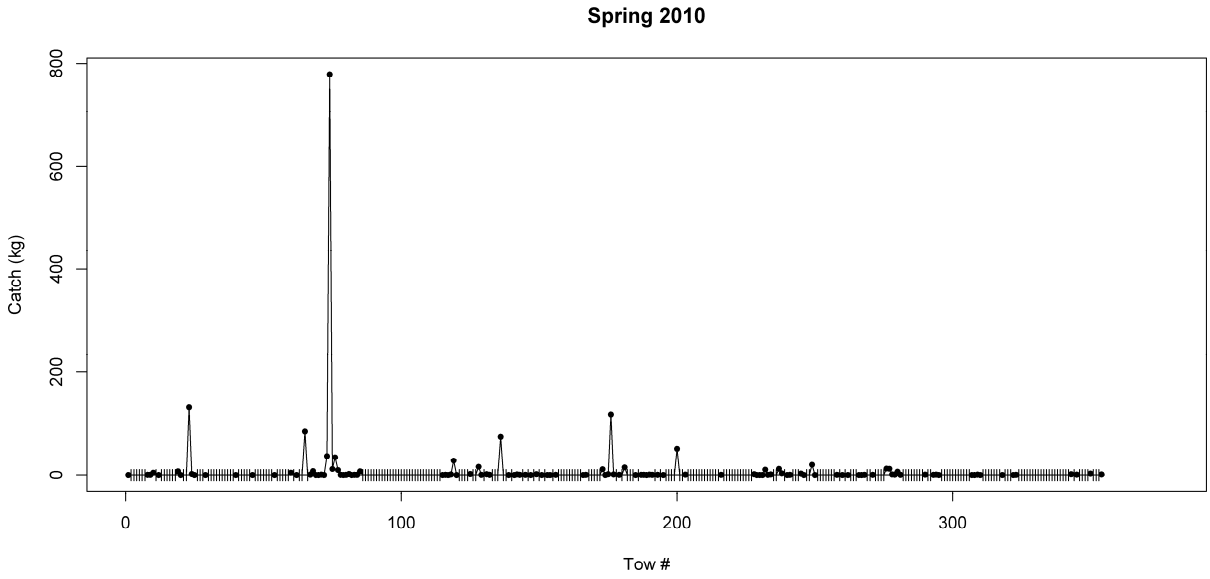
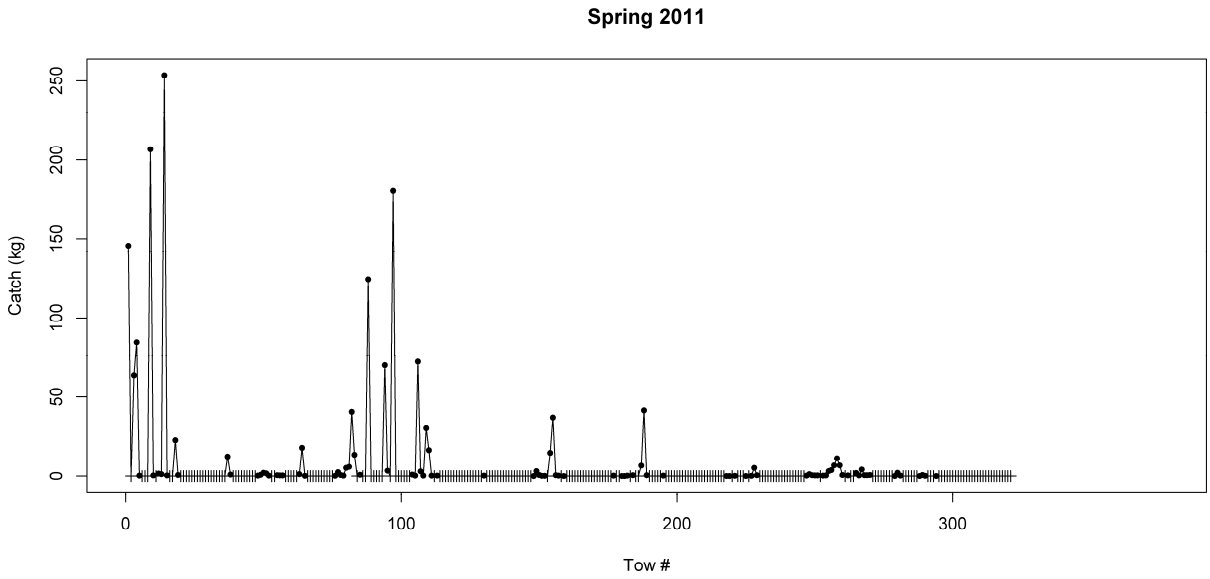
100
200
300
400
500
0
100
200
300
Tow #


Spring 2010
Catch (kg)
0
200
400
600
800
0
100
200
300
Tow #


Spring 2011
Catch (kg)
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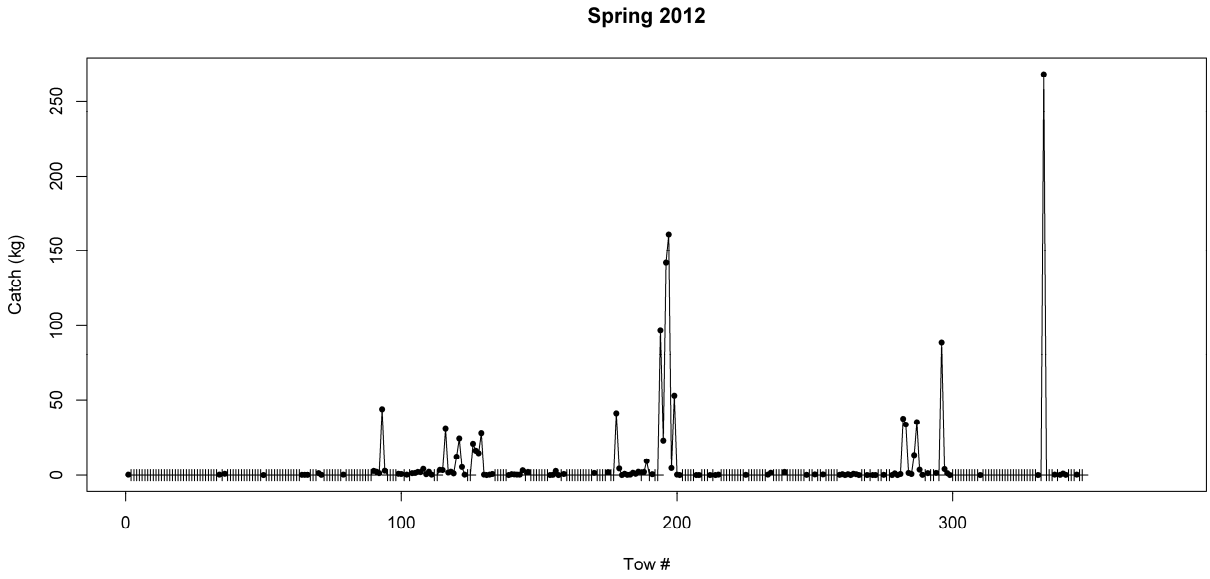
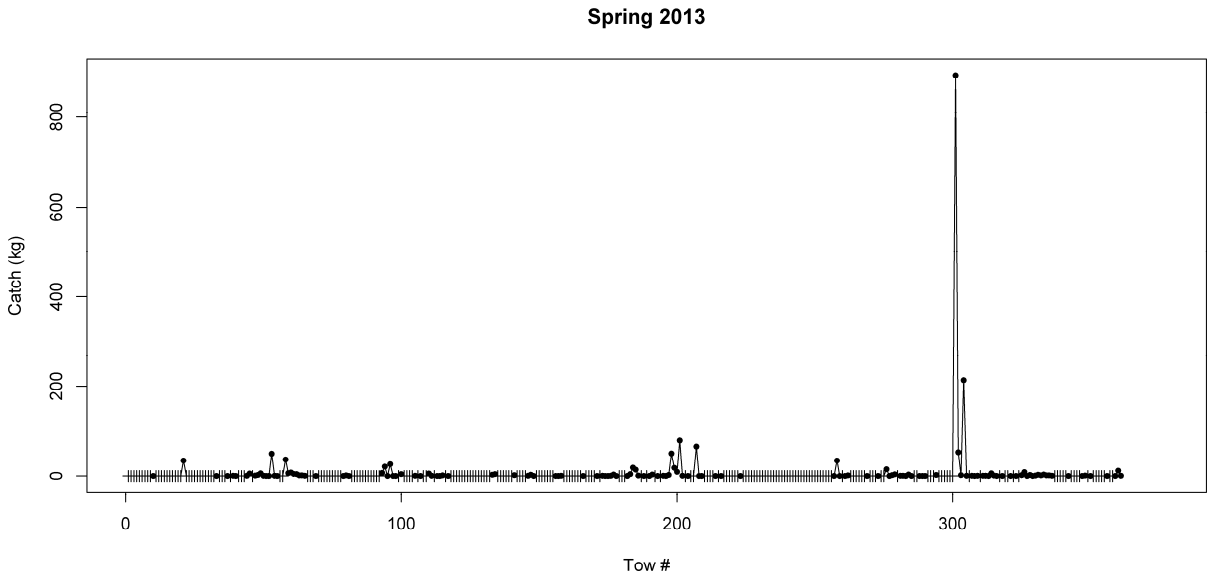
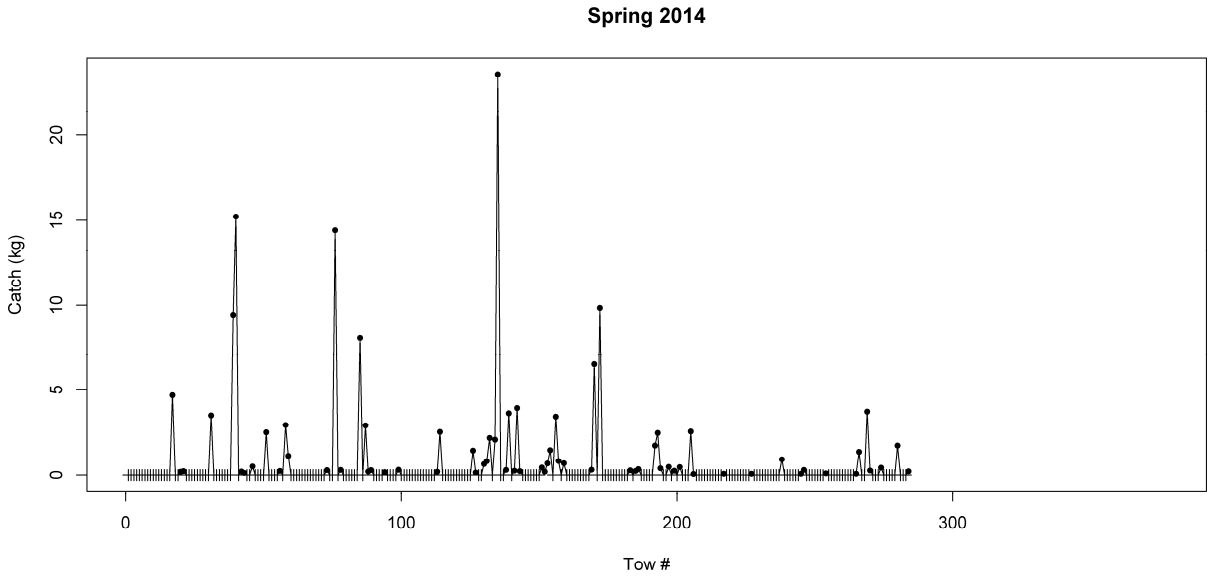
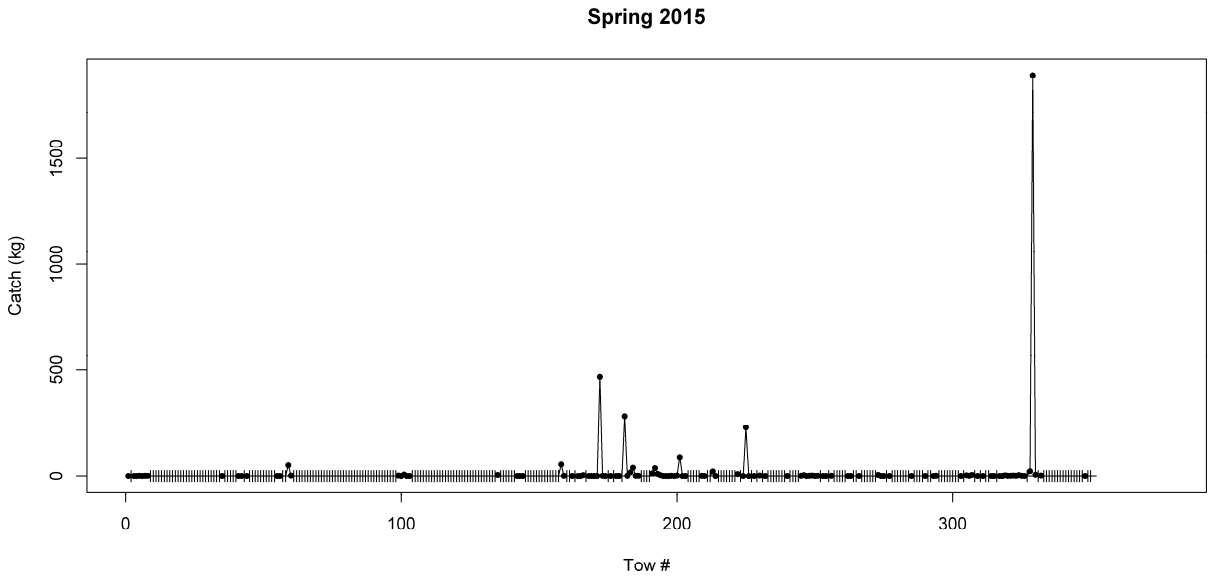
50
100
150
200
250
0
100
200
300
Tow #


Spring 2012
Catch (kg)
0
50
100
150
200
250
0
100
200
300
Tow #


Spring 2013
Catch (kg)
0
200
400
600
800
0
100
200
300
Tow #


Spring 2014
Catch (kg)
0
5
10
15
20
0
100
200
300
Tow #


Spring 2015
Catch (kg)
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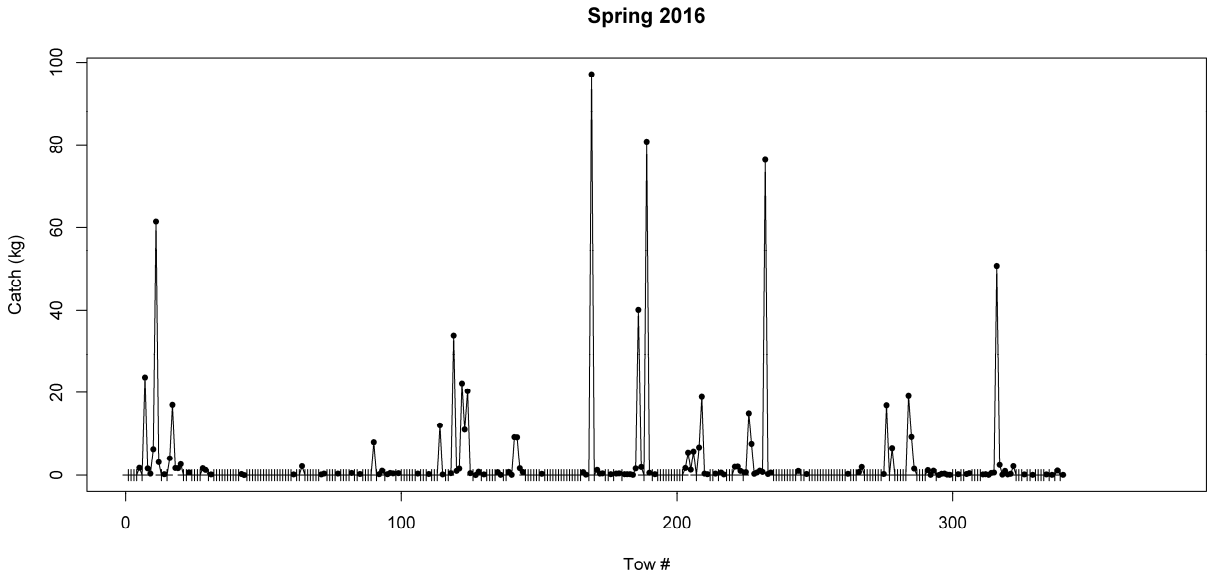
500
1000
1500
0
100
200
300
Tow #


Spring 2016
Catch (kg)
0
20
40
60
80
100
0
100
200
300
Tow #

Appendix A6: Changes in the spatial structure of Atlantic Mackerel and thermal habitat during the spring NEFSC bottom trawl survey and a winter habitat model accounting for movement constraints. Part I. changes in spatial structure.

Manderson, John P[1], Kohut Josh[2], Pessutti Jeff[1], Dimitris Politikos[3], William K Bright[4], Peter Moore[5], Mitch Roffer[6], Laura Nazarro[2], Enrigue Curchister[3], Greg Didomenico[7]

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[2] Center of Ocean Observing Leadership, Rutgers University
[3] Department of Environmental Sciences, Rutgers University
[4] Loper-Bright Enterprises Inc.
[5] The Mid-Atlantic Coastal Ocean Observing System (MARACOOS)
[6] Roffer's Ocean Fishing Forecasting Service, Inc. (ROFFS™)
[7] Garden State Seafood Association

Summary: We analyzed the spatial structure of Atlantic Mackerel distributions, habitat associations and thermal habitat during the spring NEFSC bottom trawl survey from 1968 to 2015. Further we developed a thermal habitat model accounting movement constraints that could be used to estimate the proportion habitat surveyed, a substitute for population availability. This work is described in 2 working papers. This first working paper describes changes in the spatial structure of Atlantic Mackerel and thermal habitat during the spring NEFSC bottom trawl survey

Spatial indicators of population distribution indicated that as areas occupied by mackerel increased from 1980-2015, centers of gravity gradually shifted to the northeast at an average rate of ~ 11 km yr^{-1} for immature mackerel (*≤25 cm*) and nearly 15 km yr^{-1} for mature fish (>25 cm) which grew more rare in survey collections over time. Thermal habitat preferred by mackerel during the winter (5.5°C -9.5°C) and available in the spring survey also expanded and shifted to the northeast. However these changes in habitat area and location occurred at later in time and at a slower rate than for the fish. This result indicated that a simple thermal habitat model cannot be applied to develop a estimate of the availability of Mackerel to the survey.

As the area occupied by mackerel increased, trends in aggregation indices suggested that small and or lower density schools of fish probably became more prevalent in the spring NEFSC survey over time. Analyses suggested that survey indices of abundance increased and larger size fish became more rare as the area occupied by the stock increased, the animals became less aggregated and centers of gravity shifted to the northeast. In contrast, US fishery landings were highest during years when the fish were aggregated in smaller areas of occupation to the southwest during the spring NEFSC survey. Spatial analysis and a review of literature describing school structure of Atlantic Mackerel and other small pelagic fishes suggests that indices of abundance developed from the spring NEFSC bottom trawl are proportional to the number of schools of mackerel but not the size of the population since the standardized bottom trawls do not effectively measure school volumes and/or concentrations of fish in those volumes. In

contrast, Fishery landings appear to fluctuate primarily in concert with the availability of large volume rich mackerel schools in the mid-Atlantic Bight.

Introduction & Rational

A Virtual Population Analysis model was put forward for review in the 2010 Transboundary Resources Assessment of Northwest Atlantic Mackerel (Deroba et al. 2010). Early model runs produced significant retrospective patterns indicating that processes underlying mackerel population dynamics and /or errors in observations of state variables that were assumed to be stationary had changed over time. To reduce the retrospective pattern the working group chose to break the spring NEFSC trawl survey time series into 3 segments. When this was done, model based estimates of age specific catchability for the segments increased 78 to 50 fold over time for age 1-3 fish. Segmentation of the spring NEFSC survey time series did not eliminate the retrospective pattern and model based catchability estimates could not be explained. Furthermore, the model could not resolve conflicting trends in survey catches, age structure and fishery landings. The objective of this working paper is to inform discussions of catchability of fish in the spring NEFSC bottom trawl survey. We analyze changes in mackerel distribution and habitat and provide a habitat model based estimate of population availability to the survey, the component of catchability most likely to change over time (Wilberg et al. 2012). The working paper which has 2 parts is designed to inform the 3rd term of reference of SAW/SARC–64 which is to describe "oceanographic data pertaining to Atlantic mackerel distribution, availability, and stock characteristics and if possible, integrate the results into the stock assessment".

We took the following 6 steps to meet our objectives. In this working paper we 1) review of scientific literature describing Atlantic Mackerel behavior and habitat ecology relevant to the interpretation of NEFSC spring bottom trawl survey. In step 2 we apply spatial indicators to describe changes in the spatial structure of immature and mature mackerel in the survey from 1968 to 2016. We apply the same indictors to habitat defined by *insitu* temperatures measured during the surveys to determine whether changes in habitat distributions matched changes in fish distributions. In step 3, we examined relationships of indicators of the spatial structure of mackerel and thermal habitat to survey based indices of abundance, size structure and US fisheries landings. In the second working paper we summarize the final 3 steps which include 4) an in depth habitat analysis of Atlantic mackerel in US waters 5) the development and evaluation of a winter habitat model accounting for spatial constraints on overwintering migration and finally 6) application of the model to estimate the proportion habitat sampled on the spring NEFSC survey.

Step 1: ***Atlantic Mackerel behavior and habitat ecology relevant to catchability and interpretation of the NEFSC spring bottom trawl survey***

The NEFSC spring bottom trawl surveys occur from March through May, with most tows completed in March (23%) and April (71%). The availability of mackerel to the survey is therefore determined by behaviors associated with the timing and location of migration during the late fall and winter, overwintering habitat, and spring migration.

North West (NW) Atlantic Mackerel range from Newfoundland, Canada to Cape Hattaras, North Carolina. The species also occurs in the Northeast (NE) Atlantic from the west coast of Greenland to the Gulf of Cadiz. There is, however, no evidence of significant mixing of NW and NE Atlantic Mackerel (Nesbo et al. 2000, Rodríguez-Ezpeleta et al. 2016) reviewed by (Jansen and Gislason 2013). Mackerel are a fast swimming pelagic fish (Individual cruising speed ~ 3.5 body lengths per second [BL s^{-1}]; burst speed ~18 BL sec^{-1}; school speeds of ~6 m s^{-1}) that occupy habitats from the nearshore continental shelf to the continental slope (He and Wardle 1988, Wardle and He 1988, Godø et al. 2004). Mackerel can also traverse deep ocean habitats (Astthorsson et al. 2012, ICES 2014a). Mackerel habitat preferences vary by life history stage, life history process and season, and process specific physiological requirements and rates appear to be met and controlled through behavioral habitat selection for abiotic and biological properties and processes in the water column. Seawater temperature appears to be particularly important (Castonguay et al. 1992, Reid et al. 1997, Bruge et al. 2016, and many others). The complex pelagic habitat ecology of mackerel is reflected in highly plastic patterns of migration, geographic distribution, schooling and life history event schedules (Neill 1984, Walsh et al. 1995, Reid et al. 1997, Bruge et al. 2016). Throughout recorded history Atlantic Mackerel have exhibited dramatic fluctuations in local abundance. Some of the earliest fishery gear restrictions were imposed in the US during the 17th century in response to the disappearance of Mackerel in coastal Massachussetts waters (Stansby and Lemon 1941, Hoy and Clark 1967). In recent years and on both sides of the North Atlantic mackerel have exhibited dramatic changes in geographic distribution and productivity attributed to anthropogenic climate change (Overholtz et al. 2011, Astthorsson et al. 2012, Radlinski et al. 2013, Jansen et al. 2016). These impacts included recent distribution shifts observed in the NOAA/NEFSC spring bottom trawl survey that have been associated with changes in seawater temperature (Overholtz et al. 2011, Radlinski et al. 2013).

North West Atlantic Mackerel are believed to be composed of two contingents; a southern contingent that spawns on the south side of Long Island and the western Gulf of Maine in April and May and a northern contingent that spawns in the Gulf of Saint Lawrence during July (Sette 1950, Ware 1977, Morse 1980). When the animals reach spawning grounds they have low fat reserves in somatic tissues ranging from 3-5%. This poor condition, which results from the energetic demands of spring migration and the mobilization of lipids from somatic tissues to gametes, can produce significant mortality on spawning grounds (Grégoire 2006). After spawning the southern contingent uses summer feeding habitats in the coastal waters of the Gulf of Maine and Georges Bank. From October through December, the southern contingent aggregates to feed in the southern gulf of Maine where a late fall fishery occurs (Sette 1950, Bright WM Pers Comm.). Somatic fat peaks annually during this late Fall period (20->30% by weight) and the fish are valuable in international markets (Grégoire and Lévesque 1994, G Goodwin, Seafreeze LTD Pers Comm). As winter progresses, the fish in western Gulf of Maine move along the continental shelf to the southwest into Southern New England and the Mid-Atlantic Bight where they have supported an important winter fishery since the 19th century (Pierce 1934). Typically the largest fish migrate close to the coast and,

during some winters, these fish can occur as far to the southwest as Cape Hatteras. A portion of the northern spawning contingent spends the summer in Canadian waters on the Nova Scotia shelf, the northern Gulf of Saint Lawrence and Newfoundland. Some fish that spend the summer in Canadian waters move to deep water (~200 meters) overwintering habitats including areas on the outer edge of Nova Scotia Shelf (Sette 1950, Grégoire et al. 2014). A portion of the northern contingent also moves south to mix with the southern contingent in the Gulf of Maine during the summer. These fish from the northern contingent are also believed to migrate into the southern New England-Mid Atlantic Bight region during the winter.

During winter and early spring NW and NE Atlantic Mackerel occur in high concentrations in relatively cold bottom water ranging from approximately 5°C -7°C (Giedz 1988, D'Amours and Castonguay 1992, Jansen et al. 2015). The fish become progressively lean during the winter and feeding activity is presumed to be low. The fish may occupy cold water to conserve energy through the winter when primary productivity is low. Fish begin to migrate to the northeast in the early spring along multiple pathways including the shallow nearshore continental shelf and inner edge of the continental slope (Sette 1950, Christensen and Clifford 1980). The speed and direction of migration appears to be temperature dependent and migration can shift between nearshore and offshore pathways (Reid et al. 1997). Fish are believed to follow the 7°C isotherm northeast to arrive on spawning grounds in the spring and early summer (Hoy and Clark 1967, Ware and Lambert 1985). Mackerel are also reported to use downstream circulation pathways to conserve energy during long distance migration (Sette 1950, Ware and Lambert 1985, Castonguay and Gilbert 1995, Reid et al. 1997, Nøttestad et al. 2016).

This literature review indicates that the habitat ecology relevant to the spring NEFSC bottom trawl survey is complex. The availability and distribution of fish within survey which occurs during the winter-spring ocean transition appears to be a function of the development of relatively cold water 5-7°C during the late fall and winter before the survey takes place which can provide access to the mid-Atlantic Bight and an energy saving overwintering refuge. Availability and detectability during the bottom trawl survey may also be affected by shift in behavior from overwintering, and possibly torpor, to active migration to spawning grounds.

A note on the detectability of mackerel in bottom trawls

The fast-swimming pelagic lifestyle and schooling behavior of Atlantic mackerel has significant impacts on the detectability of the fish in bottom trawls used in fishery independent (FI) surveys and the degree to which indices derived from them are proportional to population size. FI surveys use random sampling, relatively small demersal trawls towed at slow speeds for short durations that select slower swimming, small juvenile fish and larger fish in poor condition (Slotte et al. 2007). Since the animals are fully pelagic and meet ecological requirements by selecting water column features including those allowing them to avoid predators, net efficiency (=detectability) appears to be low and variable and has been estimated to range from 0.009 to 0.0248 (Massé et al. 1996, Harley et al. 2001, DFO, 2008). During the winter mackerel are

associated with cold bottom water on both sides of the Atlantic and exhibit diving behavior in response to approaching trawlers (Slotte et al. 2007). As a result, Jansen et al. (2015) concluded that winter trawl surveys can provide useful indices of juvenile recruitment for stock assessments as long the data are carefully interpreted. Their analysis of combined fishery hydroacoustic and trawl data indicated that bigger schools of mackerel are more closely associated with the seabed than smaller schools. On the basis of this finding (Jansen et al. 2015) concluded that net efficiency was positively density dependent and that square or cube root transformation of bottom trawl survey data was required for developing indices of juvenile recruit abundance useful for population assessments (ICES 2014b). However, mackerel exhibit complex schooling behavior that may be related to changes in the biotic and abiotic environment and/or population size (Glass et al. 1986, Reid et al. 1997, Petitgas et al. 2001). Stratified random bottom trawl surveys do not measure the 3 dimensional structure of schools of pelagic fish, including volumes and concentrations of fish within volumes (Jech and McQuinn 2016).

Step 2: Changes in the spatial structure of NE Atlantic Mackerel and thermal habitat in the Spring NEFSC bottom trawl survey from 1968 to 2016.

Methods: To analyze the spatial structure of Atlantic Mackerel collected in the spring NEFSC bottom trawl survey we divided fish into immature and mature size classes. The maturity classes were divided at 25 cm total length based on bootstrapped logistic regression of size and maturity data collected on the NEFSC survey (Appendix 1).

We applied survey-based spatial indicators to Spring NEFSC bottom trawl survey data to identify changes in location (centre of gravity, global index of collocation of mature and immature fish) and space occupation (inertia, isotropy, positive area, spreading area, and positive area:spreading area ratio, microstructure and number of patches) of immature and mature Atlantic Mackerel from 1968-2015 (Table 1, (Woillez et al. 2007, Woillez et al. 2009)). Null densities and the shape of the study domain do not affect these indicators. We chose a support size of ~20 km (~10 nautical miles, nm) which is close to the median nearest neighbor distance between stations in the spring NEFSC survey. We also chose ~100 km (50 nm) as the limit of sample influence for the calculation of the microstructure index. Because the indicators are dependent on parameter values, the focus on our analysis is focused on relative changes in indicator values over time not absolute values. To account for changes in the spatial patterns of sampling over time we also developed indicators for the center of gravity, inertia, isotropy and positive area of the NEFSC survey itself. We used the same parameter values for all of the spatial indicator calculations.

Results: Many of the spatial indicators of location, space use and occupation for immature and mature Atlantic mackerel varied systematically over time with long term trends in frequency of occurrence (Fig. 1) and abundance (see below).

Frequencies of occurrence of immature and mature Atlantic mackerel in the NEFSC spring bottom trawl survey ranged from less than 3% in the late 1970s and early 1980s to

over 19% in 2012. A secondary peak occurred in 2000-2001. The highest frequencies occurred in 2012-2013 (Fig. 1).

Centers of gravity (CG) for immature and mature fish shifted to the northeast over time and distance of CGs from Cape Hatteras was correlated with changes in frequencies of occurrence (Fig. 2; Rho Immature fish 0.533, p= 0.0001; Mature fish 0.457, p=0.001). Centers of gravity (CG) for fish were probably not influenced by changes in the survey as CGs for the survey that varied little over time. There was a slight decrease in the survey CG in the early 1980s when a relatively large number of stations were sampled south of Cape Hatteras. The survey CG was also relatively high in 2014 when the southern mid-Atlantic Bight was not sampled.

The CG of immature fish shifted at an average rate of ~ 10.8 km yr^{-1} toward the north east from 1980 to 2016 (SD=2.62 km yr^{-1}, p= 0.0002). Mature fish shifted to the northeast at a slightly more rapid rate (14.7 km yr^{-1}; SD= 2.803, p=8.2e-06). While the long term trend in CGs for both maturity classes was to the northeast the progression was variable. Centers of gravity were farthest southwest for the maturity classes in the 1960s, late 1970-early 1980s, 1993-1994, 2004-2005 and 2010-2011. Centers of gravity were farthest northeast during the springs of 1975, 2000, 2007, and consistently from 2012-2016. Prior to the late 1990s fish were rarely collected in the Gulf of Maine during the survey. From 2007 to 2016, both maturity classes were common in the northern Gulf of Maine adjacent to the mouth of the Bay of Fundy.

The spatial overlap of immature and mature fish in the survey was variable but collocation scores were consistently high (≥0.8) from 2000 to the 2016 (Fig. 3). During 10 of the 11 years when collocation scores were <0.8, the median centers of gravity for mature fish was 160 km southwest of the CG for immature fish (range=-9k to 423km). This pattern is consistent with published work and fishery observations indicating that larger fish migrate longer distances and that the nearshore runs of large fish that moved southwest into the southern Mid Atlantic Bight disappeared around 2000 ((N√∏ttestad et al. 1999); see SARC 64 WP "Fishing industry perspectives on the socioecological factors driving catchability and landings of Atlantic Mackerel in US waters"). Fish older than age 3 were also rare in the survey after 2000.

Inertia's (~variance) around centers of gravity were variable and often high when centers of gravity for fish were farthest from Cape Hattaras. (Figs 3,4) The isotrophy of fish was only slightly lower than the isotrophy for the survey, indicating that mackerel distributions were generally aligned with the principal southwest-northeast axis of the survey (Fig 5).

Estimates for the area surveyed were stable over time with tow exceptions (Figs. 6 & 7). The area estimate for the survey was smallest during 2014 when the southern part of the mid-Atlantic Bight was left unsampled. Estimates of approximate area surveyed were highest during the early to mid 1980s when large numbers of samples were collected south of Cape Hatteras.

Indicators measuring patterns in the area occupied by mature and immature mackerel increased gradually from 1980 to the present in a manner that matched frequency of occurrence and the northeastward movements of centers of gravity (Figs 6,7). Areas occupied by immature fish were always larger than areas occupied by mature fish. From 1977-1983 only about 2% of the area surveyed was occupied by immature fish, while adult fish occupied only 1% of the area. Area occupancy reached secondary peaks for immature fish in 2000 (19% of the area surveyed), and for mature fish in 2001 (16% of the areas surveyed). Area occupied then declined to approximately %10 for the two size classes from 2002-2008. Since 2008 immature and mature fish have occupied ~ 23% and 15% of the area surveyed.

Spreading area (SA) which weights area occupied by catch densities exhibited trends similar to positive areas but increased at rates that were ~10% of the rate of increase of area occupied (Fig. 6). PA:SA ratios were variable, but the faster rate of increase in the area of presence (PA) than in the area occupied weighted by densities (SA) was evident in the trend in the index. This suggests that fish occupied new areas at relatively small school sizes and/or fish densities. This interpretation is supported by trends in the microstructure index that indicated that heterogeneity in catch densities at spatial grains less than 50 nm gradually decreased from 1980 onward (Fig. 8). This pattern was relatively strong for mature mackerel.

The number of large patches containing >10% of mackerel ranged from 1 to 4 for immature fish and 1 to 3 for mature fish (Fig. 9) . The indicator was variable. However, mackerel occurred at significant densities in more that one patch more frequently after after 1991.

2c Analysis of changes in thermal habitat location and areas

Methods: For analysis of thermal habitat in the spring NEFSC survey we identified temperature associations of immature and mature mackerel mackerel using single factor quotient analysis and bottom temperatures measured *in situ* (See WP part 2). Mature and immature mackerel where more abundant in temperatures ranging from 5.5°C to 9.5°C than expected by chance in the spring NEFSC survey (appendix fig.2). Quotients and weighted average temperatures computed annually indicated that this temperature association did not change over the years of the spring survey.

We classified survey stations on the basis of whether bottom temperatures measured *in situ* were within (=1) and outside (=0) the "preferred" temperature range (5.5C- 9.5C). To identify changes in the location and surface areas of thermal habitat, we applied the same spatial indices with support sizes above to the classified stations.

Results: Thermal habitat available during the surveys shifted to the northeast but later in time and a slower rate than distributions of Atlantic Mackerel. Centers of gravity for preferred temperatures began to shift persistently northeastward in 1990 at an average rate of 5.0 km y^{-1} (+/-1.2 km y^{-1}; P=0.0004). CGs for thermal habitat during the survey were northeast of CGs of Mackerel from 1968 to 1997 (Fig. 9). CGs for thermal habitat

were south of CGs for immature mackerel periodically from 2000-2016. Thermal habitat was located to the south of mature mackerel CGs in 2007, 2012, and 2014.

The area of thermal habitat was variable (Fig. 10). Habitat areas were approximately 4 times larger (2.5% & 97.5 % quantiles 1.51, 20.69) than areas occupied by immature mackerel and 7 times larger than areas occupied by mature mackerel (2.5% & 97.5 % quantiles 2.43, 77.89).

Differences is the speed and timing of the northeast shift in thermal habitat and the large areas of thermal habitat when compared to shifts in CGs and areas occupied by fish indicated mackerel distributions were probably not limited by the availability of thermal habitat during the survey period.

2d) Principal components analysis of spatial indices for mackerel and thermal habitat and their relationship to abundance and size structure in the NEFSC survey and landings.

Methods: We performed principal components analysis (PCA) on the time series of spatial indicators to construct composite, orthogonal indices of the spatial structure of mackerel distributions that we could relate to indices of abundance and size structure during the survey and US landings. PCA was performed using all spatial indicators for mackerel and thermal habitat described above. Indices were re-scaled to have a unit variance before the PCA was performed.

To identify significant relationships between indices of abundance developed from the NEFSC spring bottom trawl survey, US fishery landings and the indicators of spatial structure we applied generalized additive modeling and a backward selection approach to select among the first 5 principal components. We extracted Indices of abundance, and size structure as well as fishery landings from the Atlantic Mackerel Update assessment for 2017 (https://static1.squarespace.com/static/511cdc7fe4b00307a2628ac6/t/5720e48dab48de3e8ab30892/1461773454206/mackerel_data_update_2016.pdf).
Backward selection was performed using the technique of multi-model inference using AICc for low sample sizes to compute evidence ratios (Burnham and Anderson 2002). The best model was identified as the one with the lowest evidence ratio. Partial deviance plots of the best models were inspected to determine whether effects of independent variables on dependent variables were more than just marginal. We considered effects marginal when 2 SE confidence bands included 0 throughout the data range. We used the BIOENV procedure (Clarke and Ainsworth 1993) to identify changes in the size structure of mackerel collected in the NEFSC survey correlated with changes in the spatial structure of the population as represented by the principal components This approach allowed us to identify the subset of PCs that produced a Euclidean distance matrix with the highest spearman correlation to a Bray-Curtis dissimilarity matrix derived from abundances of fish in 1 cm size classes in each year of the spring bottom trawl survey.

Results: Five principal components accounted for nearly 80% of the variance in the spatial indicators (Table 2). Principal component 1 accounted for 37% of the variance and was defined by area of occupation, frequency of occurrence, spreading areas, distances of centers of gravity from Cape Hatteras for immature and mature fish, the PA:SA ratio for mature fish and the area of thermal habitat. Correlations of these indices with PC1 were all higher than 0.62. Inertia, number of patches, microstructure were all negatively correlated with PCA 2 which accounted for an additional 18% of the variance. PC3 was negatively related to the PA:SA ratio for immature fish. Spreading area for mature fish, the PA:SA ratio for mature fish, and habitat area were also correlated with PC3 but less so than with PC1. PC 4 & 5 accounted for less than 7% of the variance. The index of collocation of mature and immature mackerel was negatively related to axis 4 while the distance of the center of gravity for thermal habitat was positively related to the axis. As PC5 scores increased, the center of gravity for habitat shifted southwest and the number of patches increased.

GAM models that included PC1 explained NEFSC survey indices of abundance by weight and number (*Table 3*). In both cases the indices of abundance increased as the indices of area occupied increased and the center of gravity for mackerel shifted to the northeast with increasing PC1 scores (*Fig. 11*). While the evidence ratio for the model for the survey index by number were slightly lower when PC3 and PC5 were included, effects were marginal based on inspection of partial deviance plots. The effect of PC2 on the index of abundance by weight was also marginal. The index of abundance by weight was slightly higher in the middle of the range of PC5 scores. Dissimilarities in annual patterns of size structure for mackerel in the survey were also correlated with PC1 ($r^{2=}0.3381$, $P<0.001$) but not the other PCs (*Fig. 12*). Large sizes of fish occurred in the survey during springs when the area occupied was relatively small and CGs were relatively near to Cape Hatteras.

In contrast with survey abundance indices, landings of mackerel in the US fishery, t typically largest in Southern New England and the middle Atlantic Bight during the winter and early spring, were high when the area occupied by mackerel was small and center of gravity was located to the southwest during the NEFSC spring survey (high PC1 scores) (Fig 13). Landings also decreased as PC3 increased. Landings tended to be highest during years when both the PA:SA ratio and microstructure index for immature fish were high.

Conclusions

Our suggests that the structure of mackerel distributions in the NEFSC spring survey has changed since the 1980s. Areas occupied and frequency of occurrence for immature and mature fish increased as centers of gravity have shifted northeast. Mature fish, that often occupied areas well to the southwest of immature fish before 2000, have shifted northeast at a faster rate and now show higher overlap with immature fish. These changes have accompanied decreases in aggregation and the heterogeneity of mackerel catch densities at relatively fine scales. Mackerel may become more dispersed with small schools with perhaps lower densities of fish occupying new areas. These changes have been

accompanied by increases in indices of abundance and size truncation within the survey. In contrast US Fishery landings, typically high during the winter, were highest during years when mackerel were aggregated in smaller areas located southwest in the mid-Atlantic Bight during the NEFSC survey. These results indicate that stratified random bottom trawl surveys may be useful for measuring the numbers of schools of mackerel. However since they do measure school volumes or concentrations of fish within volumes the relationship between bottom trawl survey abundance indices and population size are probably complex and non-intuitive.

During the survey, changes in the location and area of preferred winter thermal habitat occurred later and more slowly than changes in mackerel distributions. Shifts in winter distributions of Atlantic Mackerel in US waters have often been reported and are usually attributed to changes in bottom water temperature (Sette 1950, Taylor et al. 1957, Anderson and Almeida 1977, Overholtz et al. 2011). The presented we presented in working paper indicates that spatial distributions of mackerel in the NEFSC bottom trawl survey are not a simple function of contemporaneous distributions of water temperature.

Table. 1 Spatial indicators summarizing changes in spatial distributions of immature and mature Atlantic Mackerel in the spring NEFSC bottom trawl survey over time (Woillez et al. 2007, Woillez et al. 2009). Indicators were also calculated for the survey to account for changes in the survey and COG and positive area were calculated for thermal habitat.

Indicator	Interpretation
Center of gravity (CG)	Mean location of distribution (Kilometers from Cape Hatteras, NC)
Inertia (I)	Spatial dispersion around CG (nm)
Global index of collocation (GIC)	Similarity in spatial occupation patterns of immature (*≤25 cm*) and mature (> 25 cm) size classes of fish
Isotropy	Elongation of population in space
Positive area (PA)	Area (nm^2) occupied by each maturity classes
Spreading area (SA)	Area occupied by maturity classes weighted by catch densities (nm^2)
Degree of aggregation (PA/SA)	PA/SA measures how evenly population densities are distributed in the area occupied. When PA/SA = 1 population densities are spread evenly across the area. As PA/SA increases high density patches of small area occur within the broader area occupied.
Microstructure	Heterogeneity in catch densities below chosen lag scale (50 nm). 0=low, 1=high
Number of patches with >10% of density	Number of large patches of fish.

Table 2. Principal Components analysis of spatial indicators of Atlantic Mackerel distributions and thermal habitat during the spring NEFSC bottom trawl survey.

	PC1	PC2	PC3	PC4	PC5	PC6
Standard deviation	2.61	1.84	1.52	1.13	1.05	0.95
Proportion of Variance	0.36	0.18	0.12	0.07	0.06	0.05
Cumulative Proportion	0.36	0.54	0.66	0.72	0.78	0.83
Contribution of variable						
Correlation of variable						
Positive Area (I)	**13.07**	0.02	0.00	0.03	3.22	2.21
	0.94	0.03	0.00	-0.02	0.19	-0.14
Frequency (I)	**12.88**	0.00	0.02	0.17	3.51	2.64
	0.94	0.01	0.02	-0.05	0.20	-0.15
Positive Area (M)	**11.54**	0.00	0.00	3.81	0.12	6.08
	0.89	0.01	-0.01	-0.22	0.04	-0.23
Spreading Area (I)	**9.66**	0.10	8.82	0.57	0.63	0.12
	0.81	0.06	0.45	-0.09	0.08	0.03
Frequency (M)	**9.10**	0.48	0.93	2.74	0.01	0.12
	0.79	0.13	0.15	0.19	-0.01	-0.03
CG (M)	**8.87**	0.55	2.84	0.54	5.48	10.60
	0.78	0.14	-0.26	-0.08	-0.25	0.31
CG (I)	**7.79**	0.21	3.72	5.25	0.62	13.55
	0.73	0.08	-0.29	0.26	-0.08	0.35
Spreading Area (M)	**7.39**	0.93	**10.18**	0.17	3.12	2.98
	0.71	0.18	**0.48**	-0.05	-0.19	-0.16
PA:SA (M)	**6.19**	0.06	**11.38**	4.29	6.07	4.88
	0.65	-0.05	**-0.51**	-0.23	0.26	-0.21
Positive Area habitat	**5.66**	0.01	**4.89**	0.04	0.18	24.03
	0.62	-0.02	**-0.34**	0.02	-0.04	0.47
PA:SA (I)	1.77	0.19	**20.63**	5.39	0.38	10.37
	0.35	0.08	**-0.69**	0.26	0.07	-0.31
Inertia (M)	1.28	**18.16**	1.57	1.93	5.88	1.40
	0.30	**-0.78**	0.19	0.16	-0.26	-0.11
GCI	1.26	0.67	0.57	**37.80**	19.71	1.18
	0.29	-0.15	0.11	**-0.70**	-0.47	0.10
CG habitat	1.05	0.04	0.99	**26.87**	**29.39**	2.47
	0.27	-0.04	-0.15	**0.59**	**-0.57**	-0.15
Number Patches (I)	0.75	**14.80**	2.12	2.70	**17.19**	6.65
	0.23	**-0.71**	0.22	0.19	**0.44**	0.25
Microstructure (M)	0.64	**16.34**	8.90	1.38	0.13	2.13
	-0.21	**-0.74**	-0.45	-0.13	-0.04	-0.14
Inertia (I)	0.63	**20.81**	1.20	0.82	1.53	4.23
	0.21	**-0.84**	0.17	0.10	0.13	0.20

Microstructure (I)	0.24	**11.91**	**14.09**	5.06	1.06	0.02
	-0.13	**-0.63**	**-0.57**	-0.25	-0.11	-0.01
Number Patches (M)	0.23	**14.70**	7.17	0.45	1.75	4.34
	0.13	**-0.70**	0.41	0.08	-0.14	-0.20

Table 3. Results of generalized additive modeling (GAM) of the relationship between indices of abundance derived from the NEFSC bottom trawl survey and US landings and principal components derived from indicators of spatial structure of mackerel and thermal habitat during the survey (see Table 2). AICc is the Akaike Information Criterion corrected for small sample sizes

Dependent variable /independent variables	Residual Deviance	Deviance explained (%)	AICc	Log Likelihood	Δ AIC	Relative Likelihood	AIC Wt.	Evidence Ratio
Abundance Index (N)								
PC1+PC3+PC5	32947	39.3	448.9	-216.5	0.0	1.0	0.3	1.0
PC1+PC5	25233	53.5	449.1	-210.3	0.2	0.9	0.3	1.1
PC1+PC3	38543	29.0	449.8	-220.1	0.9	0.6	0.2	1.6
PC1+PC3+PC4+PC5	32830	39.5	450.9	-216.4	2.0	0.4	0.1	2.7
~1	54256	0.0	460.2	-227.9	11.3	0.0	0.0	279.6
PC3+PC5	46701	13.9	460.8	-224.5	11.9	0.0	0.0	380.1
PC1+PC2+PC3+PC4+PC5	14296	73.7	462.9	-197.3	14.0	0.0	0.0	1100.6
Abundance Index (W)								
PC1+PC2+PC5	739	42.2	281.2	-129.1	0.0	1.0	0.4	1.0
PC1+PC5	916	28.3	282.5	-134.1	1.3	0.5	0.2	1.9
PC1+PC2+PC4+PC5	708	44.6	283.6	-128.2	2.4	0.3	0.1	3.4
PC1+PC2	982	23.2	283.8	-135.7	2.6	0.3	0.1	3.6
PC2+PC5	908	29.0	285.1	-133.9	3.9	0.1	0.1	7.0
~1	1279	0.0	287.8	-141.7	6.6	0.0	0.0	27.1
PC1+PC2+PC3+PC4+PC5	571	55.4	292.1	-123.2	11.0	0.0	0.0	240.2
US Landings								
PC1+PC3	1.85E+12	30.3	1268.4	-626.9	0.0	1.0	0.5	1.0
PC1+PC2+PC3	1.80E+12	32.4	1270.0	-626.2	1.7	0.4	0.2	2.3
PC1+PC2+PC3+PC5	1.77E+12	33.3	1272.0	-625.9	3.6	0.2	0.1	6.1
PC1+PC2	2.02E+12	23.9	1272.5	-628.9	4.1	0.1	0.1	7.7
PC2+PC3	2.40E+12	9.8	1274.6	-632.8	6.3	0.0	0.0	22.9

~1	2.66E+12	0.0	1274.7	-635.2	6.3	0.0	0.0	23.2
PC1+PC2+PC3+PC4+PC5	1.76E+12	33.8	1275.1	-625.7	6.8	0.0	0.0	29.4

Literature cited

Anderson, E. D., and F. P. Almeida. 1977. Distribution of Atlantic mackerel in ICNAF Subarea 5 and Statistical Area 6 based on research vessel spring bottom trawl surveys, 1968-76. Int. Comm. Northw. Atlant. Fish., Sei. Pap., **2**:33-44.

Astthorsson, O. S., H. Valdimarsson, A. Gudmundsdottir, and G. J. Óskarsson. 2012. Climate-related variations in the occurrence and distribution of mackerel (Scomber scombrus) in Icelandic waters. ICES Journal of Marine Science **69**:1289-1297.

Bruge, A., P. Alvarez, A. Fontán, U. Cotano, and G. Chust. 2016. Thermal Niche Tracking and Future Distribution of Atlantic Mackerel Spawning in Response to Ocean Warming. Frontiers in Marine Science **3**:86.

Burnham, K. P., and D. R. Anderson. 2002. Model Selection and Multimodel Inference: A Practical Information-Theoretic Approach. Springer.

Castonguay, M., and D. Gilbert. 1995. Effects of tidal streams on migrating Atlantic mackerel, Scomber scombrus L. ICES Journal of Marine Science: Journal du Conseil **52**:941-954.

Castonguay, M., G. A. Rose, and W. C. Leggett. 1992. Onshore Movements of Atlantic Mackerel (Scomber scombrus) in the Northern Gulf of St. Lawrence: Associations with Wind-Forced Advections of Warmed Surface Waters. Canadian Journal of Fisheries and Aquatic Sciences **49**:2232-2241.

Christensen, D. J., and W. J. Clifford. 1980. The 1978 spring recreational catch of Atlantic Mackerel, Scombe scombrus, off the Middle Atlantic regions. Fishery Bulletin **78**:799-805.

Clarke, K. R., and M. Ainsworth. 1993. A method of linking multivariate community structure to environmental variables. Marine Ecology Progress Series **92**:205-219.

D'Amours, D., and M. Castonguay. 1992. Spring migration of Atlantic mackerel, Scomber scombrus, in relation to water temperature through Cabot Strait (Gulf of St. Lawrence). Environmental Biology of Fishes **34**:393-399.

Deroba, J., G. Shepherd, F. Gregoire, J. Nieland, and P. Rago. 2010. Stock Assessment of Atlantic Mackerel in the Northwest Atlantic for 2010.

Giedz, M. 1988. Investigations into the relationship between shelf bottom temperamre and the mackerel C.P.U.E. on the U.S. Atlantic shelf in years 1985-1987. ICES CM 1988/H:69: 14 p.

Glass, C. W., C. S. Wardle, and W. R. Mojsiewicz. 1986. A light intensity threshold for schooling in the Atlantic mackerel, Scomber scombrus. Journal of Fish Biology **29**:71-81.

Godø, O. R., V. Hjellvik, S. A. Iversen, A. Slotte, E. Tenningen, and T. Torkelsen. 2004. Behaviour of mackerel schools during summer feeding migration in the Norwegian Sea, as observed from fishing vessel sonars. ICES Journal of Marine Science **61**:1093-1099.

Grégoire, F., H. Dionne , and C. Lévesque. 1994. Fat content of Atlantic mackerel (Scomber scombrus L.) in 1991 and 1992 Can. Ind. Rep. of Fish. and Aquat. Sci **220**:ix + 69.

Grégoire, F. o. 2006. Vertical distribution of the midwater trawl catches of Atlantic mackerel (Scomber scombrus L.) in relation with water temperature.

Grégoire, F. o., L. Girard, and M. l. Boudreau. 2014. La pêche au maquereau bleu (Scomber scombrus L.) dans les sous-régions 3 et 4 de l'OPANO en 2013. Secr. can. de consult. sci. du MPO. Doc. de rech.

Harley, S. J., R. A. Myers, and A. Dunn. 2001. Is catch-per-unit-effort proportional to abundance? Canadian Journal of Fisheries and Aquatic Sciences **58**:1760-1772.

He, P., and C. S. Wardle. 1988. Endurance at intermediate swimming speeds of Atlantic mackerel, Scomber scombrus L., herring, Clupea harengus L., and saithe, Pollachius virens L. Journal of Fish Biology **33**:255-266.

Hoy, D. L., and G. M. Clark. 1967. Atlantic Mackerel Fishery, 1804 - 1965. United States Department of The Interior.

ICES. 2014a. 15 NWWF Report - Section 13: Overview on ecosystem, fisheries and management in greenland waters., International Council for the Exploration of the Sea.

ICES. 2014b. Report of the Benchmark Workshop on Pelagic Stocks (WKPELA).

Jansen, T., and H. Gislason. 2013. Population Structure of Atlantic Mackerel (<italic>Scomber scombrus</italic>). PLoS ONE **8**:e64744.

Jansen, T., K. Kristensen, J. van der Kooij, S. Post, A. Campbell, K. R. Utne, P. Carrera, J. A. Jacobsen, A. Gudmundssdottir, B. A. Roel, and E. M. C. Hatfield. 2015. Nursery areas and recruitment variation of Northeast Atlantic mackerel (Scomber scombrus). ICES Journal of Marine Science: Journal du Conseil **72**:1779-1789.

Jansen, T., S. Post, T. Kristiansen, G. J. Óskarsson, J. Boje, B. R. MacKenzie, M. Broberg, and H. Siegstad. 2016. Ocean warming expands habitat of a rich natural resource and benefits a national economy. Ecological Applications **26**:2021-2032.

Jech, J. M., and I. H. McQuinn. 2016. Towards a balanced presentation and objective interpretation of acoustic and trawl survey data, with specific reference to the eastern Scotian Shelf. Canadian Journal of Fisheries and Aquatic Sciences **73**:1914-1921.

Massé, J., C. Koutsikopoulos, and W. Patty. 1996. The structure and spatial distribution of pelagic fish schools in multispecies clusters: an acoustic study. ICES Journal of Marine Science **53**:155-160.

Morse, W. W. 1980. SPAWNING AND FECUNDITY OF ATLANTIC MACKEREL, SCOMBER SCOMBRUS, IN THE MIDDLE ATLANTIC BIGHT. Fishery Bulletin **78**:23.

N√∏ttestad, L., J. Giske, J. C. Holst, and G. Huse. 1999. A length-based hypothesis for feeding migrations in pelagic fish. Canadian Journal of Fisheries and Aquatic Sciences **56**:26-34.

Neill, W. H. 1984. Behavioural enviroregulation's role in fish migration. Pages 61–66. *in* J. D. McCleave, G. P. Arnold, J. J. Dodson, and W. H. Neill, editors. Mechanisms of migration in fishes. Plenum Press, New York.

Nesbo, C. L., E. K. Rueness, S. A. Iversen, D. W. Skagen, and K. S. Jakobsen. 2000. Phylogeography and Population History of Atlantic Mackerel (Scomber scombrus L.): A Genealogical Approach Reveals Genetic Structuring among the Eastern Atlantic Stocks. Proceedings: Biological Sciences **267**:281-292.

Nøttestad, L., J. Diaz, H. Penã, H. Søiland, G. Huse, and A. Fernö. 2016. Feeding strategy of mackerel in the Norwegian Sea relative to currents, temperature, and prey. ICES Journal of Marine Science: Journal du Conseil **73**:1127-1137.

Overholtz, W. J., J. A. Hare, and C. M. Keith. 2011. Impacts of interannual environmental forcing and climate change on the distribution of Atlantic mackerel on the U.S. Northeast Continental Shelf. . Marine and Coastal Fisheries **2**:219-232.

Petitgas, P., D. Reid, P. Carrera, M. Iglesias, S. Georgakarakos, B. Liorzou, and J. Massé. 2001. On the relation between schools, clusters of schools, and abundance in pelagic fish stocks. ICES Journal of Marine Science **58**:1150-1160.

Pierce, W. G. 1934. Goin' Fishin'. The story of the deep-sea fisherman of New England. The Southworth-Anthoensen Press, Portland Maine.

Radlinski, M. K., M. A. Sundermeyer, J. J. Bisagni, and S. X. Cadrin. 2013. Spatial and temporal distribution of Atlantic mackerel (Scomber scombrus) along the northeast coast of the United States, 1985–1999. ICES Journal of Marine Science: Journal du Conseil **70**:1151-1161.

Reid, D. G., W. R. Turrell, M. Walsh, and A. Corten. 1997. Cross-shelf processes north of Scotland in relation to the southerly migration of Western mackerel. ICES Journal of Marine Science: Journal du Conseil **54**:168-178.

Rodríguez-Ezpeleta, N., I. R. Bradbury, I. Mendibil, P. Álvarez, U. Cotano, and X. Irigoien. 2016. Population structure of Atlantic mackerel inferred from RAD-seq-derived SNP markers: effects of sequence clustering parameters and hierarchical SNP selection. Molecular Ecology Resources **16**:991-1001.

Sette, O. E. 1950. Biology of Atlantic mackerel (Scomber scombrus) of North America. Part II. Migrations and habits. . U.S. Fish Wildl. Serv. Fish. Bull. **51**:251-358.

Slotte, A., D. Skagen, and S. A. Iversen. 2007. Size of mackerel in research vessel trawls and commercial purse-seine catches: implications for acoustic estimation of biomass. ICES Journal of Marine Science: Journal du Conseil **64**:989-994.

Stansby, M. E., and J. M. Lemon. 1941. Studies on the handling of fresh mackerel (Scomber scomber). United States Department of the Interior, Fish and Wildlife Serviece.

Taylor, C., H. B. Bigelow, and H. W. Graham. 1957. CLIMATIC TRENDS AND THE DISTRIBUTION OF MARINE ANIMALS IN NEW ENGLAND. Fishery Bulletin **115**:293-345.

Walsh, M., D. G. Reid, and W. R. Turrell. 1995. Understanding mackerel migration off Scotland: Tracking with echosounders and commercial data, and including environmental correlates and behaviour. ICES Journal of Marine Science: Journal du Conseil **52**:925-939.

Wardle, C. S., and P. He. 1988. Burst swimming speeds of mackerel, Scomber scombrus L. Journal of Fish Biology **32**:471-478.

Ware, D. M. 1977. Spawning Time and Egg Size of Atlantic Mackerel, Scomber scombrus, in Relation to the Plankton. Journal of the Fisheries Research Board of Canada **34**:2308-2315.

Ware, D. M., and T. C. Lambert. 1985. Early Life History of Atlantic Mackerel (Scomber scombrus) in the Southern Gulf of St. Lawrence. Canadian Journal of Fisheries and Aquatic Sciences **42**:577-592.

Wilberg, M. J., J. T. Thorson, B. C. Linton, and J. Berkson. 2012. Incorporating Time-Varying Catchability into Population Dynamic Stock Assessment Models. Reviews in Fisheries Science **18**:7–24.

Woillez, M., J.-C. Poulard, J. Rivoirard, P. Petitgas, and N. Bez. 2007. Indices for capturing spatial patterns and their evolution in time, with application to European hake (Merluccius merluccius) in the Bay of Biscay. ICES Journal of Marine Science: Journal du Conseil **64**:537-550.

Woillez, M., J. Rivoirard, and P. Petitgas. 2009. Notes on survey-based spatial indicators for monitoring fish populations. Aquatic Living Resources **22**:155 - 164.

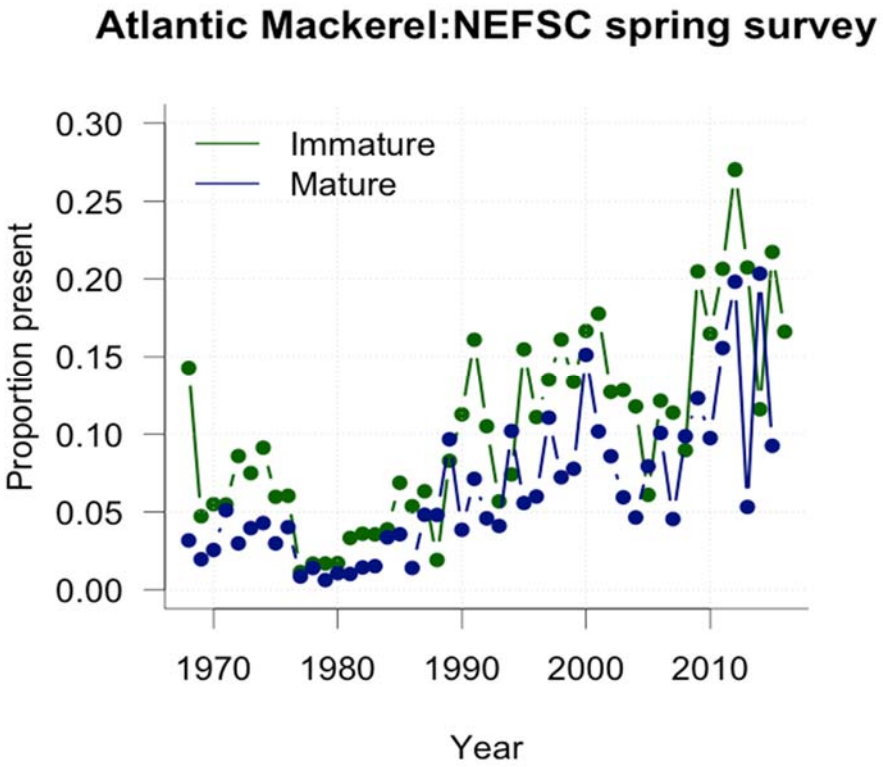


Figure 1. Frequencies of occurrence for immature (≤25 cm) and mature (>25cm) Atlantic Mackerel in the Spring NEFSC bottom trawl survey

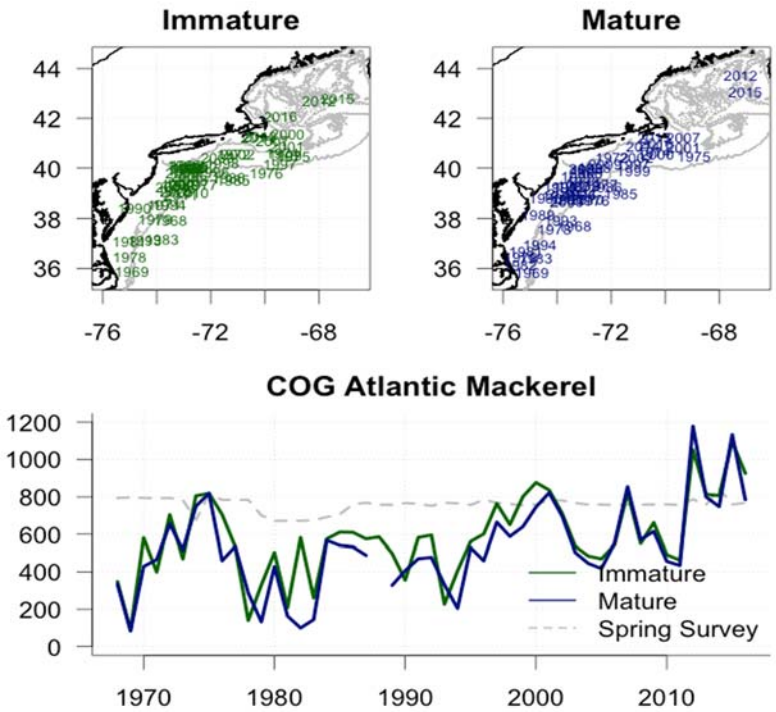


Figure 2. Centers of Gravity for immature (≤25 cm) and mature (>25cm) Atlantic Mackerel in the Spring NEFSC bottom trawl survey. Top. Maps of latitudes and longitudes of CGs. Bottom. Distance from Cape Hattaras in kilometers of CGs for mature and immature mackerel and for the NEFSC survey

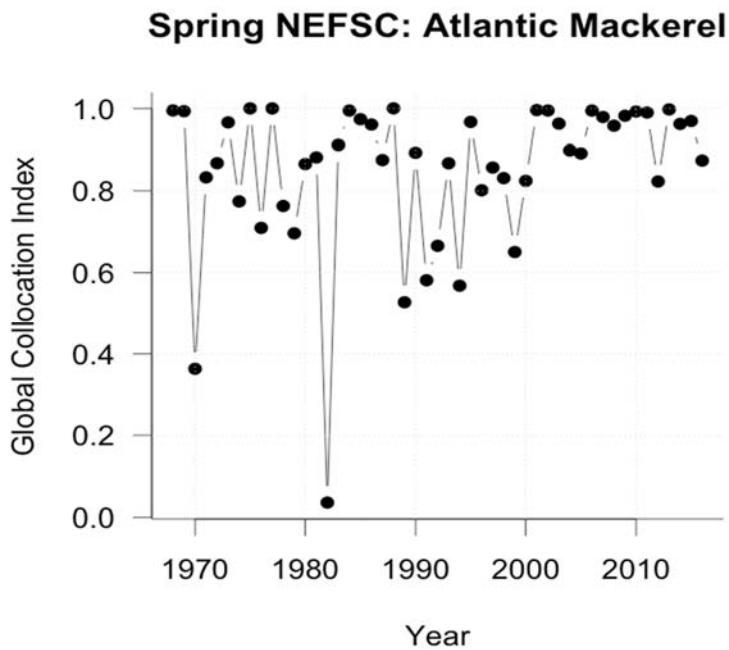


Figure 3. Collocation (GIC) of immature (≤25 cm) and mature (>25cm) Atlantic Mackerel was variable, but consistently high in the Spring NEFSC bottom trawl survey from 2000-2016. A GIC of 1 indicates perfect spatial overlap while lower values indicate less spatial overlap

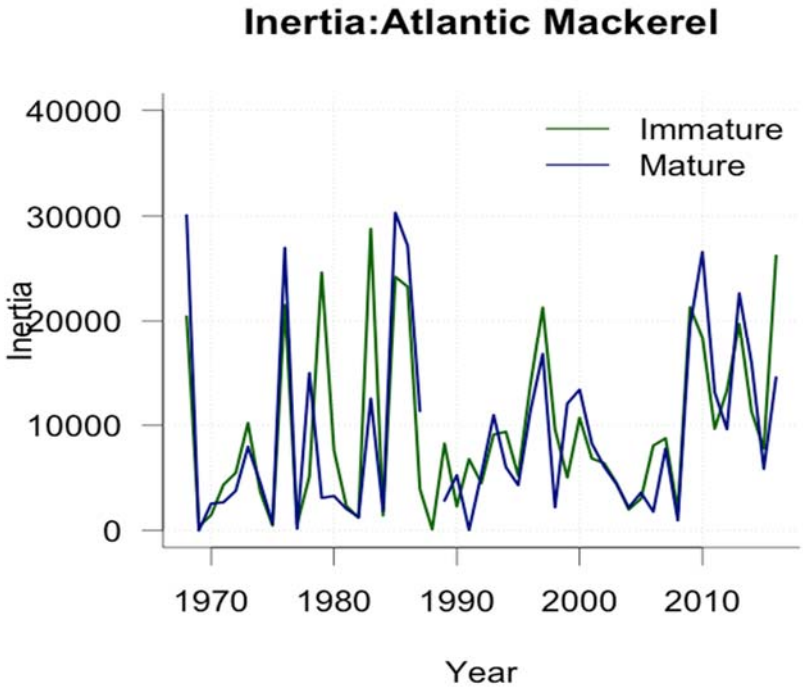


Figure 4. Inertia for immature (≤25 cm) and mature (>25cm) Atlantic Mackerel was variable in the Spring NEFSC bottom trawl survey from 2000-2016.

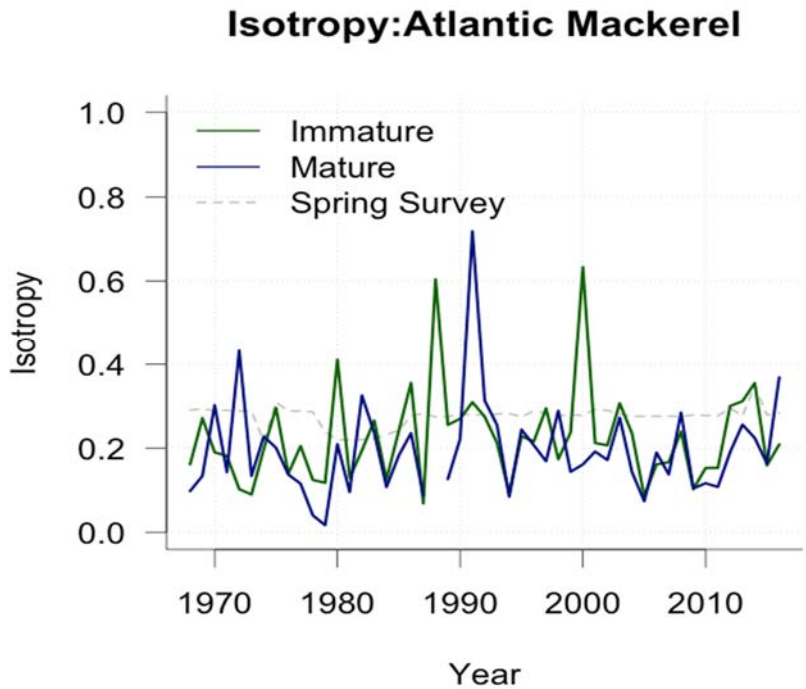


Figure 5. Isotropy for immature (≤25 cm) and mature (>25cm) Atlantic Mackerel was variable and similar to stations in the Spring NEFSC bottom trawl survey from 2000-2016.

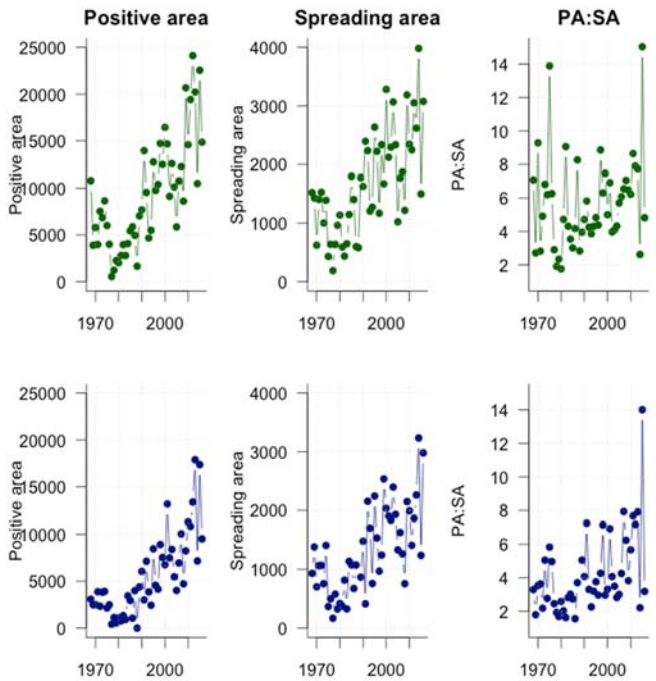


Figure 6. Indicators of area occupied for immature (≤25 cm; top panels) and mature (>25cm; bottom panels) Atlantic Mackerel in the Spring NEFSC bottom trawl survey from 1968 -2016. Positive area (PA) only accounts for the presence of fish while spreading area (SA) takes into account catch density. The ratio of PA:SA is a global indicator of fish aggregation. When PA:SA = 1 fish densities are the same across the occupied area. As PA:SA increases fish occur in high densities concentrations in areas smaller than areas where fish are just present.

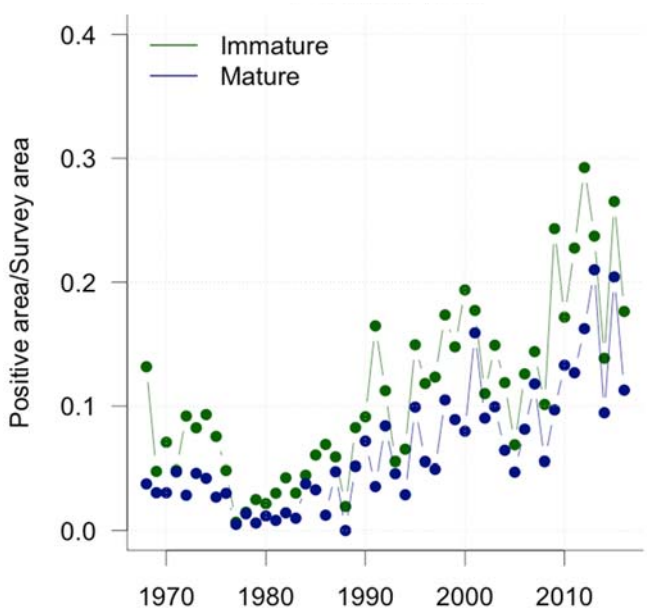


Figure 7. Positive area for immature (≤25 cm) and mature (>25cm) Atlantic Mackerel in the Spring NEFSC bottom trawl survey (Fig. 7, left panels) standardized by area surveyed calculated using the same algorithm (Fig. 6)

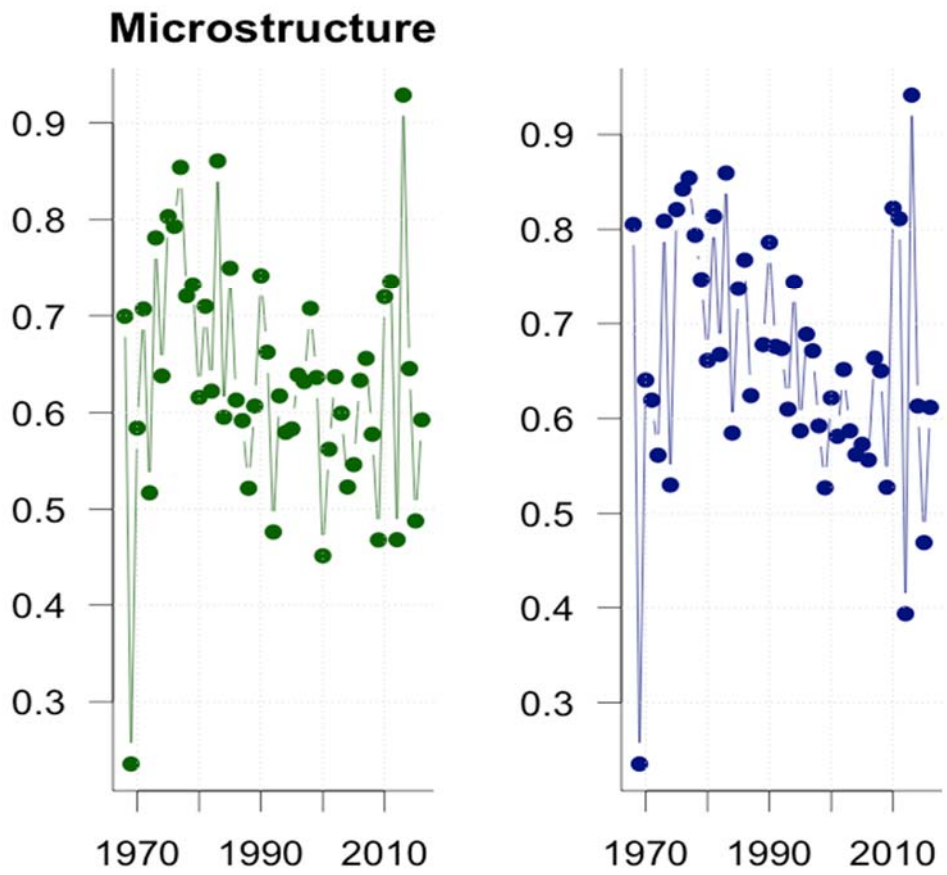


Figure 8. Tends in the microstructure indicators indicating that heterogeneity in catch densities for immature (≤25 cm; Left) and mature (>25cm; Right) Atlantic Mackerel at spatial grains less than 50 nm declined over time in the Spring NEFSC bottom trawl survey from 1980 onward. When the indicator is 1 densities are heterogeneous. As the indicator decreases densities at grains less than 50 nm become more homogeneous.

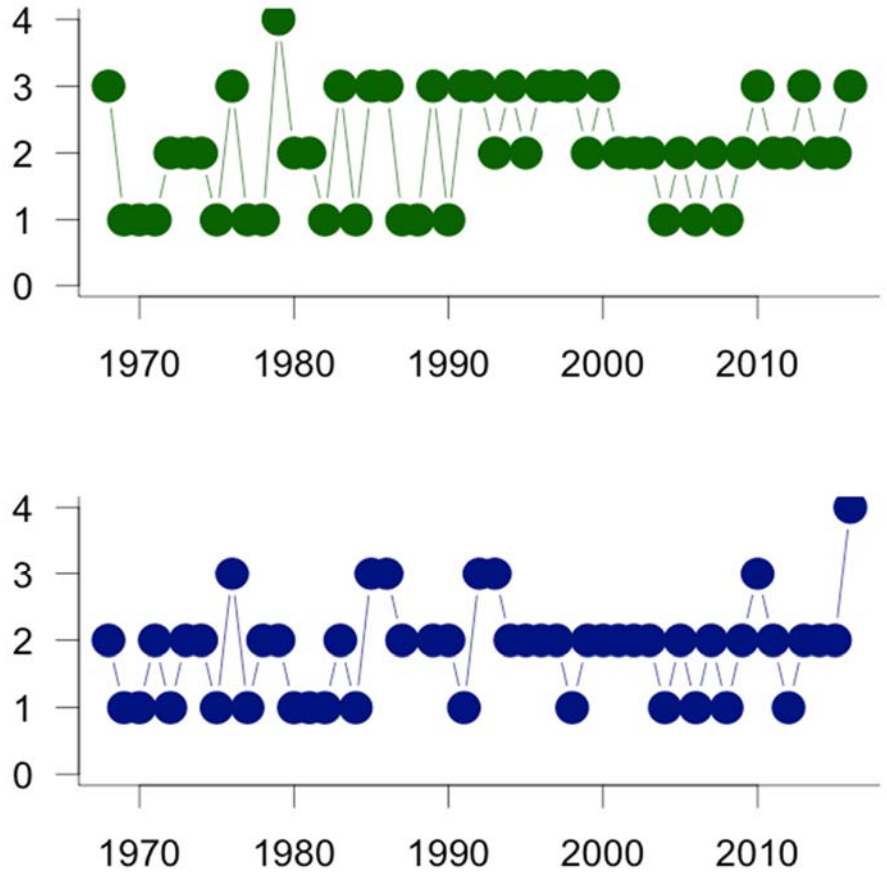


Figure 9. Number of patches with more than 10% of catch densities for immature (top) and mature (bottom) mackerel during the spring NEFSC trawl survey.

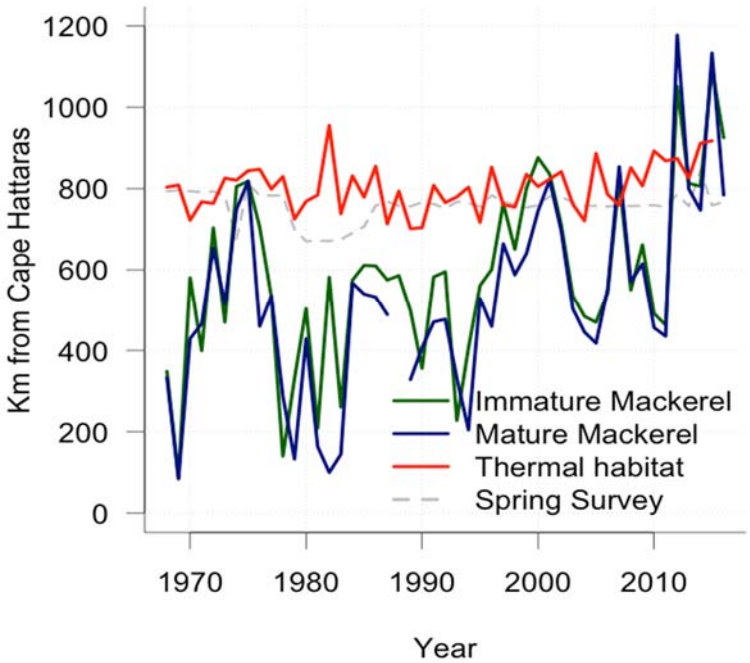


Figure 9. Center of gravity of thermal habitat preferred by Atlantic Mackerel (5.5C - 9.5C red line) compared to COGs for immature and mature mackerel and stations in the spring NEFSC bottom trawl survey.

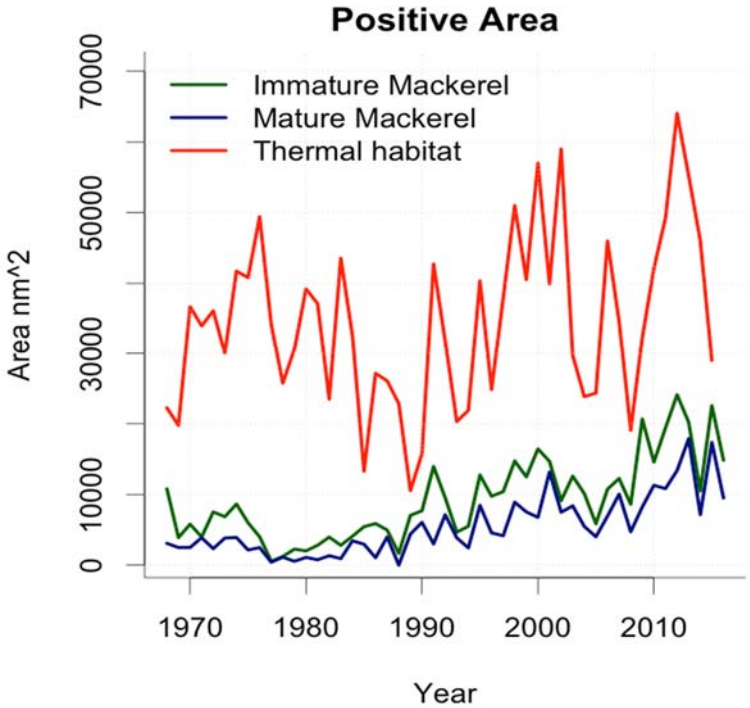


Figure 10. Positive areas for thermal habitat preferred by Atlantic Mackerel (5.5C - 9.5C red line) compared to PAs for immature and mature mackerel in the spring NEFSC bottom trawl survey.

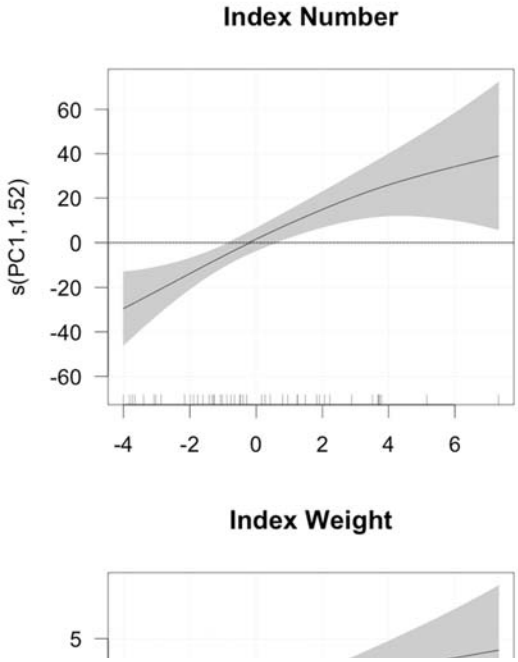
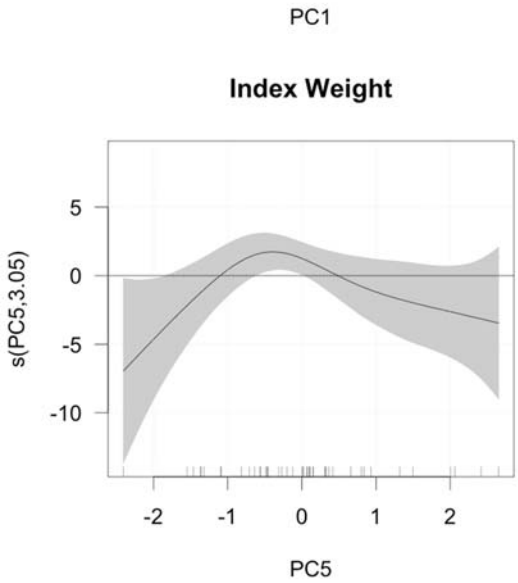


Figure 11. Deviance plots from generalized additive models of relationships of the index of abundance for Atlantic Mackerel by number (top) and weight in the NEFSC survey with the first PCA for the spatial indicators (middle). Indices increased as the area occupied, frequency of occurrence and distance from Cape Hattaras increased. The relationship between PCA 5 (+correlated with number of patches, -correlated with distance of habitat CG from Cape Hattaras) and the index of abundance by weight is indicated at the bottom. The results of the PCA are described in Table 2, while the GAM results are described in Table 3.



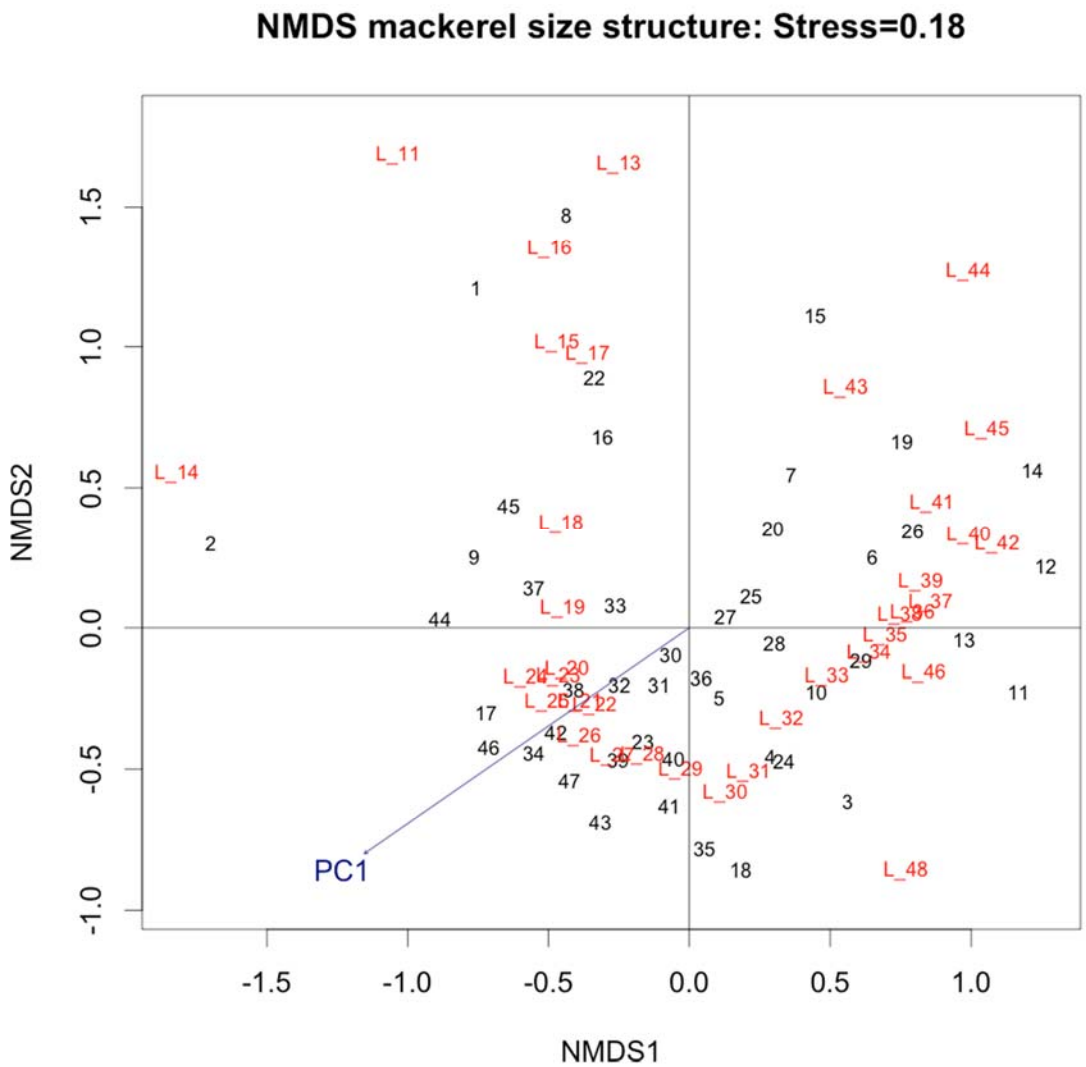
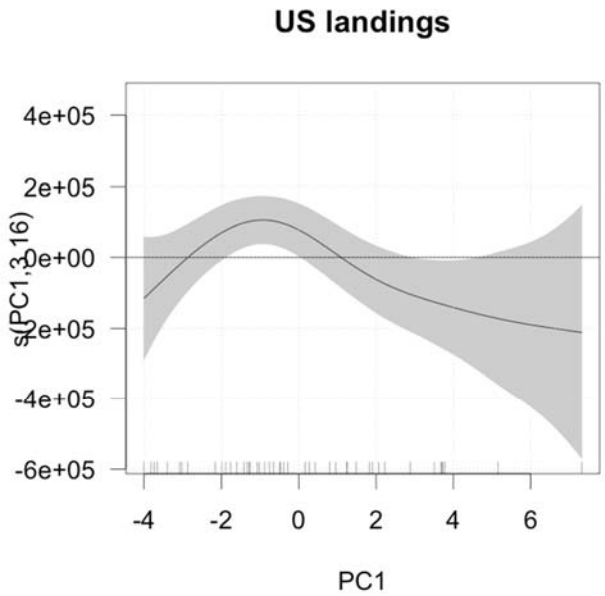
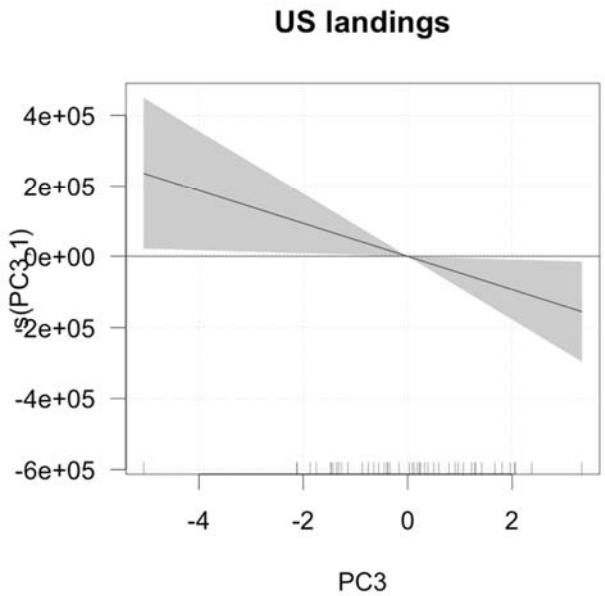


Figure 12. Nonmetric Multidimensional scaling plot of the relationship between size structure of fish collected in the NEFSC survey and the first principal component (blue arrow) of the spatial indicators, for which scores increased as areas of occupation and distance from Cape Hatteras increased. Red letters are length (L) classes in 1 cm intervals. Black numbers are year number from 1968. Only the first principal component was significantly correlated with changes in size structure using the BIOENV procedure.





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Additional Analysis

Analysis of size at maturity to divide mackerel into immature and mature size classes

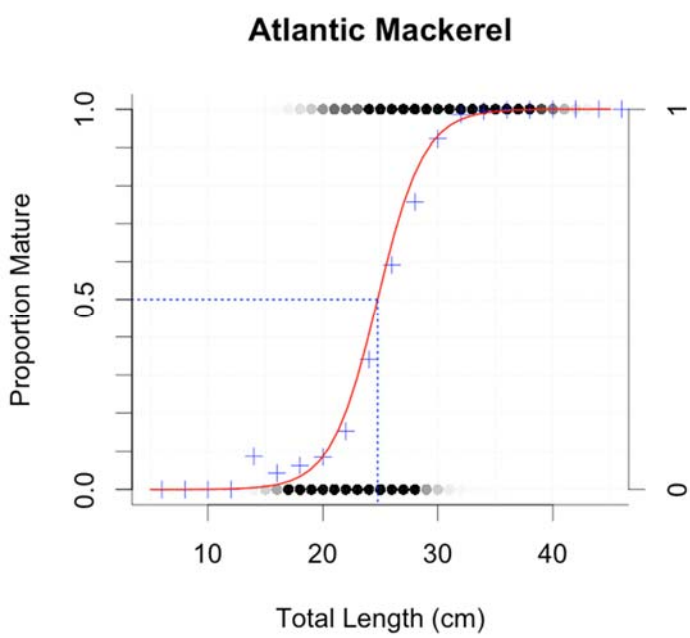
We used mackerel size and maturity data collected in the spring NEFSC bottom trawl survey and bootstrapped logistic regression to determine the length at 50% maturity and a threshold to classify immature and mature fish based on length. Differences in size at maturity between sexes were explored but proved not to be significant (length*sex interaction, p=0.092). The median length of 50% maturity (95% confidence intervals) calculated using bootstrapped regression (N=1000) was ~25 cm.

Bootstrapped coefficients

	Bootstrapped SD	50%	2.5%	97.5%
(Intercept)	0.173	-12.272	-12.612	-11.951
#LENGTH	0.007	0.496	0.483	0.508

Length at 50% maturity

50%	2.5%	97.5%
24.76	24.67	24.85



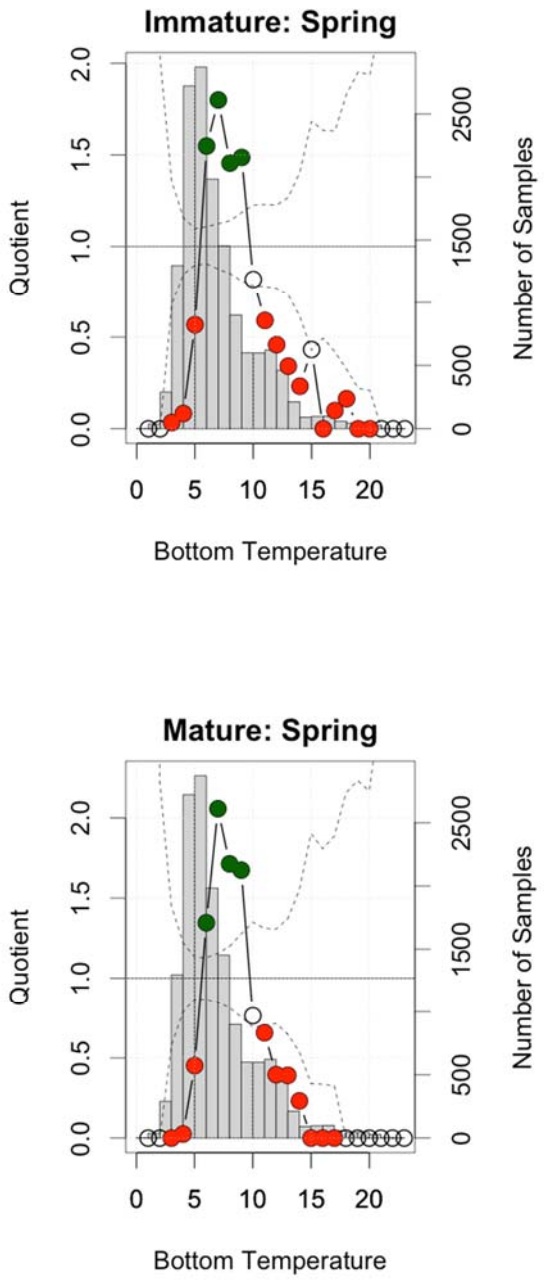
Appendix Figure 2. Logisttic regression relating the maturity to body size for Atlantic Mackerel collected in the spring NEFSC bottom trawl survey.

Analysis of habitat associations

We used single variable quotient analysis to identify environmental variables useful for describing habitat associations of mature and immature mackerel during the spring NEFSC survey (van der Lingen et al. 2001, Bernal, 2007 #3151). Quotients (Qi) were calculated by dividing the percent of total catch in each environmental variable bin by the percent of stations in each bin. Median and 97.5% confidence intervals for "null" quotients were calculated by bootstrapping (N=999) random associations of the environmental variable and catch. Quotient values above confidence intervals of bootstrapped "null" values indicated positive association of fish along the range of the specific variable while quotients falling below confidence intervals indicated avoidance of the range.

We tested for associations of fish with bottom depth and surface and bottom temperatures and salinities measured insitu at spring survey stations (N=17003). Insitu measurements of these environmental variables were made at more than 43% of the stations. We also examined the strength of mackerel associations with primary productivity, frontal gradient strength and optical wavelengths that alias colored organic matter (A443) and particulate organic carbon (POC) measured by the MODIS satellite {Blondeau-Patissier, 2014 #3851. We used MODIS data aggregated at a daily time step from 2003-2016, and made available by the mid-Atlantic Regional Association Coastal Ocean Observing System and the Ocean Exploration, Remote Sensing and Biogeography Laboratory at the University of Delaware (http://basin.ceoe.udel.edu/thredds/dodsC/Aqua1DayAggregate.nc). Frontal gradient strength was computed as described in {Oliver, 2008 #2517} on the basis of surface temperature and normalized water-leaving radiance at 443nm (an alias for CDOM) and 555 nm (an alias for Algae). We used the median of satellite measurements made within a 2000 meter (~1 nm) diameter buffer surrounding each station. A total of 4819 spring NEFSC survey samples were collected over the period of MODIS sampling. Of these 31% to 45 % could be matched to satellite measurements.

Quotient analysis indicated that immature and mature mackerel in spring trawl collections were associated with bottom water temperatures ranging between 6 and 9 degrees°C salinities greater than 33 PSU and water depths greater than 25 meters. We were not able to use the available data to identify significant associations of trawled mackerel with chlorophyll, particulate organic carbon, CDOM, or frontal gradient strengths measured by satellites. Associations were strongest with bottom temperature. More detailed results are shown in the 2nd part of this working paper.



Appendix Figure 3. Single factor quotient analysis for immature (top) and mature (bottom) size classes of Atlantic mackerel during the spring NEFSC survey. Colored dots indicate whether abundances in the 1°C temperature bin is greater than (green; positive association), equal too (white) or lower than (red; avoidance) expected by chance randomization of the dataset (dotted lines). Grey bars are the histogram of bottom temperatures measured at the survey stations.

van der Lingen, C. D., L. Hutchings, D. Merkle, J. J. van der Westhuizen, and J. Nelson. 2001. Comparative spawning habitats of anchovy (*Engraulis capensis*) and sardine (Sardinops sagax) in the southern Benguela upwelling ecosystem. University of Alaska Sea Grant, Fairbanks, USA.

Appendix A7: ***Winter habitat for juvenile and adult North West Atlantic Mackerel and its value for for estimating availability to the spring NEFSC bottom trawl survey***.

Manderson, John P[1], Pessutti Jeff[1], Laura Nazarro[2], William K Bright[4], Kohut Josh[2], Dimitris Politikos[3], Peter Moore[5], Mitch Roffer[6], Enrigue Curchister[3], Greg Didomenico[7]

[1] NOAA Northeast Fisheries Science Center
[2] Center of Ocean Observing Leadership, Rutgers University
[3] Department of Environmental Sciences, Rutgers University
[4] Loper-Bright Enterprises Inc.
[5] The Mid-Atlantic Coastal Ocean Observing System (MARACOOS)
[6] Roffer's Ocean Fishing Forecasting Service, Inc. (ROFFS™)
[7] Garden State Seafood Association

RATIONAL AND RELEVANT RESULTS

Catchability of juvenile and adult Atlantic mackerel in spring NEFSC bottom trawl surveys has been an important source of uncertainty in population assessments. Analyses indicate that mackerel have shifted distributions as a result of changing habitat conditions, particularly ocean temperatures (Overholtz et al. 2011, Radlinski et al. 2013, Bruge et al. 2016, Henderson et al. 2017). Systematic habitat shifts can cause changes in populations availability and thus catchability in fishery independent surveys used to inform population assessments (Link et al. 2011). Systematic shifts are one potential cause of retrospective patterns that have appeared in recent Atlantic Mackerel assessments (Deroba et al. 2010).

Indices of age specific mackerel abundance measured in the NEFSC spring bottom trawl conducted from March through April for nearly 5 decades have been used to inform assessments. The spring survey conducted when bottom temperatures on the Northeast shelf are coldest (Richaud et al. 2016) describes the abundance of trawlable age classes of mackerel during the overwintering period, and the beginning of spring migration. To provide an environmentally explicit proxy for population availability to spring NEFSCS bottom trawl surveys we developed model based estimates of proportions of available winter habitat in the northwest Atlantic sampled on the surveys. The model was developed using habitat analysis and collaborative field research conducted by NEFSC cooperative research staff and industry partners.

The final winter habitat model integrated temperature preferences with movement constraints associated with habitat connectivity along fall to winter migration pathways. We used the model to estimate that from 1980 to 2015 69% (2.5 & 97.5% quantiles = 45% & 89%) of the habitat available within the model domain was sampled by the spring NEFSC survey (Fig. 5). The proportion of winter habitat sampled did not vary systematically over time. Spatio-temporal distributions of winter habitat simulated by the model were consistent with mackerel distributions

in US fishery catches and fisheries independent trawl surveys including a winter survey of the Canadian Nova Scotian Shelf (Grégoire et al. 2014).

However, spatial analysis of centers of gravity and areas for habitat classified using our model and *in situ* temperatures along with fish collected in the spring NEFSC survey indicated that that northeastward shifts and increases winter habitat area occurred later and at much slower rates than for mackerel. We propose two alternative, non-mutually exclusive hypotheses that could account for this result. First winter habitat for primarily controls distributions of juvenile and adult mackerel in the spring survey and our model poorly defines it. Alternatively, changes in habitat conditions required for successful completion of other important life history processes, such as spawning and larval development that incentivize migration patterns are primary drivers of shifts in winter distributions and winter habitat availability is of secondary importance. The fact that Atlantic mackerel eggs and larvae have become relatively rate on Mid Atlantic Bight spawning and nursery ground since 2005 (Richardson et al., 2017) is one piece of circumstantial evidence supporting second alternative that is consistent with the mixed school feedback mechanism proposed by Bakun (Bakun 2001, Bakun and Cury 1999)

SPECIFIC METHODS AND RESULTS

Habitat analysis*:*

Methods: To develop a baseline winter habitat for juvenile and adult mackerel we used collections of fish and environmental data measured *insitu* and by satellite during the spring NEFSC survey. Abundance per tow was calculated for fish divided at 25 cm total length; the size of maturity for 50% of fish based on analysis of size at maturity. The habitat characteristics considered included surface and bottom temperature and salinity, along with bottom depth measured *insitu*. We also used MODIS satellite measurements of primary productivity, frontal gradient strengths and optical wavelengths aliasing colored organic matter (A443) and particulate organic carbon (POC) available from (http://basin.ceoe.udel.edu/thredds/dodsC/Aqua1DayAggregate.nc) (Blondeau-Patissier et al. 2014). We extracted median values for satellite data aggregated at a daily time step from 2003-2016 within 2000 meter (~1 nm) diameter buffers surrounding each survey sample. Nearly 5000 samples were collected during the MODIS period. Of these only 31% to 45 % could be matched to satellite measurements due to cloud interference.

We first applied single factor quotient analysis (van der Lingen et al. 2001, Bernal, 2007 #3151) to identify significant associations of mackerel with ranges of specific environmental variables. We then determined the relative importance of significant variables using the method of (Thuiller 2013, Thuiller et al. 2016) which compares relative out of sample prediction accuracy of 10 fold cross validated GAMs. Here we only analyzed samples complete for all significant habitat variables.

Results: Quotient analysis indicated that mackerel associations with depth and bottom and surface temperature and salinity were greater than by chance (Table 1).

We did not detect significant associations of mackerel with any of the ocean features measured by MODIS satellite.

Prediction accuracy was two fold higher for bottom temperature than for the other significant variables (Fig. 1). Associations of mackerel with the other variables occurred over relatively broad ranges, were relatively uninformative, or conflicted with fishery data (Table 1.). While fish were collected in a specific depth range in the NEFSC survey fishery catches of mackerel occur in the shallow nearshore as well as the outer edge of the continental shelf and shelf slope sea (Axelson et al. 2017). Preferred sea surface temperatures were nearly identical to preferred bottom temperatures, as expected during the spring survey when the ocean is well mixed. Fish were associated with a relatively narrow range of salinities in the survey but the fishery catches on the outer edge of the continental shelf occur at higher salinities. We believed that incorporating variables other than bottom temperature in the model would constrain it from projecting winter habitat into areas and times fish are known to occur.

Mature and immature size classes of mackerel were positively associated with nearly identical bottom water temperatures ranging from ~5.5° to 9.5°C. (Fig. 2). This range is similar to winter thermal habitat preferences reported for fish throughout the Atlantic (Giedz 1988, D'Amours and Castonguay 1992, Jansen et al. 2015). Fishery reports, comparison of mackerel sizes in fall and subsequent spring surveys, and annual cycles of tissue fat content (Grégoire and Lévesque 1994) suggest that during winter, mackerel are strongly associated with cold bottom water, don't grow significantly and are relatively inactive including showing reduced feeding activity. Mackerel may become hypometabolic in winter habitats in order to conserve resources for extensive spring migration and spawning. If this is the case a thermal habitat model may be sufficient for developing a first order approximation of overwintering habitat dynamics for juvenile and adult Atlantic mackerel.

Collaborative model evaluation & refinement with the winter trawl fishery

Methods: We collaborated with members of the winter trawl fishery to evaluate and refine the winter habitat model. We applied two approaches. In both we used bottom temperatures from a data assimilative operational numerical ocean model to project estimates of winter temperatures preferred by mackerel in space and time on the continental shelf in Southern New England and the Mid Atlantic Bight (Wilkin and Hunter 2013) (http://tds.marine.rutgers.edu/thredds/dodsC/roms/espresso/2013_da/avg/ESPRESSO_Real-Time_v2_Averages_Best).

We used habitat hindcasting to determine whether fishery catches of mackerel greater than 1,000 lbs and recorded by fishery observers or electronically by captains in the NEFSC fishery study fleet were made within or outside preferred habitat. We only analyzed catches made during winter which we defined as the period from January 1 through April 15. We applied an *exact binomial tests* to

determine the strength of association of fishery catches with thermal habitat classified as preferred, cold and warm based on the quotient analysis of the NEFSC spring trawl survey. Null expectations for the tests were developed by calculating the proportion of temperatures within the model domain in each thermal habitat class from January 1 through April 15 in 2014-2017.

We also evaluated the model in the field by providing habitat nowcasts to several NEFSC study fleet captains (N=3) throughout the winter fishing seasons of 2014-2015 and 2016-2017. To evaluate and improve habitat nowcast accuracy several modifications, including the substitution of continuous thermal responses, were tried during the two years based on suggestions and observations of individual industry collaborators and the lead scientist. Data from vessels with access to model nowcasts were not included in the *exact binomial tests* applied in the first approach.

Results: From January 1, 2014 and April 7, 2017, 132 fishery tows producing over 1000 lbs of mackerel were made within 10 km and 12 hours of bottom temperatures hindcast by the ROMs (Table 2; Fig 3). Frequencies of tows were much higher than expected in the preferred habitat and much lower than expected in colder water. Frequencies of catch in warmer water were not different than expected based on model based estimates of the relative availability of warmer water during the winter.

Active field research with NEFSC study fleet collaborators and observation of habitat and fleet dynamics confirmed that fish were observed and catches were made in bottom water temperatures ranging from 5°C - 10°C. However, the field research revealed that mackerel were unable to occupy preferred thermal habitat unless that habitat had been connected to suitable habitat north and east along the winter migration route. Thus habitat connectivity along the migration route appeared to be an important determinant of geographic patterns of winter catches and habitat occupancy.

Development of a winter habitat model accounting for habitat connectivity

Methods: To develop a winter habitat model accounting for habitat connectivity we used daily estimates of bottom water temperature from an implementation of ROMS that had a domain covering the path of the Gulf Stream and the northeast US continental shelf (Kang and Curchitser 2013). The model has horizontal grain of approximately 7 km (720 x 360 grid points), 40 vertical levels and a minimum depth of 10m. Its bathymetry is derived from the 1 min resolution Shuttle Radar Topography Mission (Farr et al. 2007). Oceanic boundary forcing and initial conditions are determined by reanalysis data of Simple Ocean Data Assimilation v3.0.0 (Carton and Giese 2008). The Coordinated Ocean-ice Reference Experiments (CORE.v2) dataset supplies the model with air temperature, sea level pressure, humidity, wind, solar radiation, and precipitation. Modern Era Retrospective Analysis for Research and Applications (MERRA) reanalysis (Rienecker et al. 2011) is also used. Bias associated with inadequate representation of cloud cover in

MERRA was dealt with by correcting short-wave radiation. The NW Atlantic ROMS model has been validated using a 50-year (1958–2007) hindcast simulation (Kang and Curchitser 2013, Kang and Curchitser 2015, Kang et al. 2016).

For our application we extracted data from the portion of the ROMS domain north of 34°N where bottom depths were < 1000 meters (*Fig. 4*). We selected this area based on reported distribution limits of Atlantic mackerel (Froese 2017). Comparison of bottom temperatures measured *insitu* and extracted from the ROMs for spring survey samples indicated that modeled bottom temperatures had a warm bias of ~0.45° C . Therefore we applied a -0.45°C correction to estimates of the temperature ranges preferred by mackerel during the winter and late fall (see below). We used Lambert equal area projection for all grid calculations.

We constructed environmentally explicit estimates of late fall spatial distributions of fish for each year to constrain the daily development of winter habitat in our model (e.g. fig. 4). We defined fall distributions based on environmental conditions identified with single factor quotient analysis of mackerel catches made from October 1- December 31 in 15 state and federal fishery independent surveys included in the NOAA Northeast US Essential Fish Habitat Geodatabase. These conditions were applied to ROMS output on December 1 for the years 1979-2014 to describe late fall mackerel distributions.

ROMS bottom temperatures for each day from December 2 to the end of the NEFSC spring bottom trawl survey in the subsequent year (1980-2015) were classified to develop grids of preferred (=1, 5-10°c, with bias adjustment) and avoided witner habitat (=0, <5°C, >10°C). Connectivity grids were also developed for each day by identifying and aggregating pixels of preferred habitat adjacent to the previous days preferred habitat beginning with December 1 late fall distributions. We multiplied each days winter habitat grid by its connectivity grid to eliminate thermal habitat that had developed noncontiguously. These computations were carried out for each successive day through the end of the NEFSC spring bottom trawl survey in each year. Habitat grids defined by preferred temperatures and the connectivity constraint for the days of the NEFSC spring survey from 1981-2015 were used to compute annual estimates of the proportion of thermal habitat sampled in each survey using the equation below (e.g. Fig. 4).

The proportion of available thermal habitat surveyed (ρ_H) was calculated in a manner that accounted for the survey design using the following equation:

Equation 1

$$\rho_H = \sum_{k=1}^{o} \frac{HSI_{k_{j,i}} * \frac{Area\ of\ strata_k}{n}}{\sum_{j=1}^{n} HSI_{j,i} * Area_{\ j}}$$

Here the habitat suitability value (*HSI*; 0 or 1) for sample *k*, occurring at location *j* on day *i* is extrapolated to the area sample *k* represents in the survey (e.g. Fig. 4). This is achieved by dividing the *Area of the strata* (km^2) in which sample *k* occurs by the total number of samples (*n*) in the strata. This area is then multiplied this area by sample *k's HSI* (0-1). The habitat suitability weighted area of sample *k* is then divided by the sum of *HSI* values for all locations *j=1..n* within the model domain for the day of sampling (*i)* multiplied by the surface areas of all ~pixels in the model. The surface area of model pixels is ~49 km^2 ($Area_j$) as defined by the resolution of the ROMS bottom temperature hindcast. The result is the proportion of the total habitat suitability weighted area available in the model domain represented by sample *k.* The total proportion of available habitat suitability sampled on a survey (ρ_H) is then the sum of the proportion of available habitat suitability sampled for each station in the survey (k=1…o).

Results: The quotient analysis of fall collections included in EFH GEO database indicated that mackerel were positively associated with latitudes north of 41.8, depths from 40 - 160 meters and bottom water temperatures ranging from 9°C to 13°C. To develop potential late fall distributions of mackerel on December 1 we selected areas of the ROMS with latitudes > 41.5, depths< 160M and temperatures ranging from 9°C to 13°C. The -0.45°C model bias adjustment was applied to the temperature range.

The final winter habitat model incorporating thermal habitat connectivity along fall and winter migration pathways was used to estimate that an average of 69% (2.5 & 97.5% quantiles = 45% & 89%) of winter habitat available within the model domain was sampled by the NEFSC survey between 1980 and 2016 (Fig. 5). The model based estimates did not vary systematically over the time period.

Evaluation of whether shifts in mackerel distributions are explained by changes in modeled or measured winter habitat distributions

Methods: To determine whether mackerel distribution shifts were explained by measured or modeled shifts in winter habitat we computed centers of gravity and area occupied by modeled habitat using the methods of Woillez (Woillez et al. 2007, Woillez et al. 2009) as described in detail in Manderson et al. (2017) (Appendix ?). We analysed the model data using the exact same constraints used in the analysis presented in Manderson et al. (2017). We then compared time series of centers of gravity and area occupied by fish and measured and modeled habitat, visually and with cross correlation function analysis (ccf).

Results: Centers of gravities and areas of habitat hindcast by the model for the survey were reasonable similar to habitat classified based on temperatures measured *insitu (Fig.6)*. They were most similar from 1990-2000, and relatively dissimilar before and after that period. The model did not to capture the gradual northeastward shift of winter habitat (5 km y^{-1}) defined by *in situ* temperatures that

began in 1990. However the rapid northeastward shifts (11-15 km y^{-1}) in mackerel distributions from 1980 to 2016 were not matched either measured modeled or winter habitat. We found only a weakly significant correlation (0.334) at a time lag of 0 between centers of gravity for mackerel and winter habitat defined by *insitu* temperatures in ccf analysis. Furthermore the areas occupied by mackerel were relatively small when compared with winter habitat areas suggesting that other factors constrain distributions.

We propose two alternative but non-mutually exclusive hypotheses that could account for this result. First winter habitat may indeed primarily control distributions of juvenile and adult mackerel in the spring survey but our model poorly defines it. Alternatively, changes in habitat conditions required for successful completion of other important life history processes, such as spawning and larval development that incentivize specific migration patterns are the primary drivers of winter distribution shifts and winter habitat availability is of secondary importance. The fact that Atlantic mackerel eggs and larvae have become relatively rare on historically important Mid Atlantic Bight spawning and nursery grounds since 2005 (Richardson et al., 2017) is one piece of circumstantial evidence that supports the alternative hypothesis which is consistent with the mixed school feedback mechanism for pelagic schooling fish proposed by Bakun (Bakun 2001, Bakun and Cury 1999)

Liturature Cited

Axelson, L., W. K. Bright, G. Goodwin, J. Hoey, J. Knight, M. Lapp, J. P. Manderson, G. McCallig, B. P. Mitchell, P. Moore, R. Mullen, G. O'Neill, W. Reichle, J. Rhule, C. Sarro, and P. Quinn. 2017. Fishing industry perspectives on the socioecological factors driving catchability and landings of Atlantic Mackerel in US waters

Bakun, A. 2001. School-mix feed back : a different way to think about low frequency variability in large mobile fish populations. Progress In Oceanography **49** 485-511.

Bakun, A., and P. Cury. 1999. The "school trap": a mechanism promoting large-amplitude out-of-phase population oscillations of small pelagic fish species. Ecology Letters **2**:349-351.

Blondeau-Patissier, D., J. F. R. Gower, A. G. Dekker, S. R. Phinn, and V. E. Brando. 2014. A review of ocean color remote sensing methods and statistical techniques for the detection, mapping and analysis of phytoplankton blooms in coastal and open oceans. Progress In Oceanography **123**:123-144.

Bruge, A., P. Alvarez, A. Fontán, U. Cotano, and G. Chust. 2016. Thermal Niche Tracking and Future Distribution of Atlantic Mackerel Spawning in Response to Ocean Warming. Frontiers in Marine Science **3**:86.

Carton, J. A., and B. S. Giese. 2008. A Reanalysis of Ocean Climate Using Simple Ocean Data Assimilation (SODA). Monthly Weather Review **136**:2999-3017.

D'Amours, D., and M. Castonguay. 1992. Spring migration of Atlantic mackerel, Scomber scombrus, in relation to water temperature through Cabot Strait (Gulf of St. Lawrence). Environmental Biology of Fishes **34**:393-399.

Deroba, J., G. Shepherd, F. Gregoire, J. Nieland, and P. Rago. 2010. Stock Assessment of Atlantic Mackerel in the Northwest Atlantic for 2010.

Farr, T. G., P. A. Rosen, E. Caro, R. Crippen, R. Duren, S. Hensley, M. Kobrick, M. Paller, E. Rodriguez, L. Roth, D. Seal, S. Shaffer, J. Shimada, J. Umland, M. Werner, M. Oskin, D. Burbank, and D. Alsdorf. 2007. The Shuttle Radar Topography Mission. Rev. Geophys. **45**:RG2004.

Froese, R. 2017. FishBase. World Wide Web electronic publication.

Giedz, M. 1988. Investigations into the relationship between shelf bottom temperamre and the mackerel C.P.U.E. on the U.S. Atlantic shelf in years 1985-1987. ICES CM 1988/H:69: 14 p.

Grégoire, F., L. Girard, and B. Boudreau. 2014. La pêche au maquereau bleu (Scomber scombrus L.) dans les sous-régions 3 et 4 de l'OPANO en 2013. Fisheries and Oceans Canada.

Grégoire, F., H. Dionne , and C. Lévesque. 1994. Fat content of Atlantic mackerel (Scomber scombrus L.) in 1991 and 1992 Can. Ind. Rep. of Fish. and Aquat. Sci **220**:ix + 69.

Henderson, M. E., K. E. Mills, A. C. Thomas, A. J. Pershing, and J. A. Nye. 2017. Effects of spring onset and summer duration on fish species distribution and biomass along the Northeast United States continental shelf. Reviews in Fish Biology and Fisheries **27**:411-424.

Jansen, T., K. Kristensen, J. van der Kooij, S. Post, A. Campbell, K. R. Utne, P. Carrera, J. A. Jacobsen, A. Gudmundssdottir, B. A. Roel, and E. M. C. Hatfield. 2015. Nursery areas and recruitment variation of Northeast Atlantic mackerel (Scomber scombrus). ICES Journal of Marine Science: Journal du Conseil **72**:1779-1789.

Kang, D., and E. N. Curchitser. 2013. Gulf Stream eddy characteristics in a high-resolution ocean model. Journal of Geophysical Research: Oceans **118**:4474-4487.

Kang, D., and E. N. Curchitser. 2015. Energetics of eddy–mean flow interactions in the Gulf Stream region. JOURNAL OF PHYSICAL OCEANOGRAPHY **45**:1103-1120.

Kang, D., E. N. Curchitser, and A. Rosati. 2016. Seasonal variability of the Gulf Stream kinetic energy. JOURNAL OF PHYSICAL OCEANOGRAPHY **46**:1189-1207.

Link, J. S., J. A. Nye, and J. A. Hare. 2011. Guidelines for incorporating fish distribution shifts into a fisheries management context. FISH and FISHERIES:no-no.

Manderson, J. P., J. Kohut, J. Pessutti, P. Dimitris, W. K. Bright, P. Moore, M. Roffer, L. Nazarro, E. Curchister, and G. Didomenico. 2017. Changes in the spatial structure of Atlantic Mackerel and thermal habitat during the spring NEFSC bottom trawl survey and a winter habitat model accounting for movement constraints. Part I. changes in spatial structure. Working Paper submitted to the Altantic Mackerel Assessment Working Group.

Overholtz, W. J., J. A. Hare, and C. M. Keith. 2011. Impacts of interannual environmental forcing and climate change on the distribution of Atlantic mackerel on the U.S. Northeast Continental Shelf. . Marine and Coastal Fisheries **2**:219-232.

Radlinski, M. K., M. A. Sundermeyer, J. J. Bisagni, and S. X. Cadrin. 2013. Spatial and temporal distribution of Atlantic mackerel (Scomber scombrus) along the northeast coast of the United States, 1985–1999. ICES Journal of Marine Science: Journal du Conseil **70**:1151-1161.

Richaud, B., Y.-O. Kwon, T. M. Joyce, P. S. Fratantoni, and S. J. Lentz. 2016. Surface and bottom temperature and salinity climatology along the continental shelf off the Canadian and U.S. East Coasts. Continental Shelf Research **124**:165-181.

Rienecker, M. M., M. J. Suarez, R. Gelaro, R. Todling, J. Bacmeister, E. Liu, M. G. Bosilovich, S. D. Schubert, L. Takacs, G. K. Kim, and a. others. 2011. MERRA: NASA's modern-era retrospective analysis for research and applications. Journal of Climate **24**:3624-3648.

Thuiller, W. 2013. On the importance of edaphic variables to predict plant species distributions – limits and prospects. Journal of Vegetation Science **24**:591-592.

Thuiller, W., D. Georges, R. Engler, and F. Breiner. 2016. biomod2: Ensemble Platform for Species Distribution Modeling. . R package version.

van der Lingen, C. D., L. Hutchings, D. Merkle, J. J. van der Westhuizen, and J. Nelson. 2001. Comparative spawning habitats of anchovy (Engraulis capensis) and sardine (Sardinops sagax) in the southern Benguela upwelling ecosystem. University of Alaska Sea Grant, Fairbanks, USA.

Wilkin, J. L., and E. J. Hunter. 2013. An assessment of the skill of real-time models of Mid-Atlantic Bight continental shelf circulation. J. Geophys. Res. Oceans **118**:2919–2933

Woillez, M., J.-C. Poulard, J. Rivoirard, P. Petitgas, and N. Bez. 2007. Indices for capturing spatial patterns and their evolution in time, with application to European hake (Merluccius merluccius) in the Bay of Biscay. ICES Journal of Marine Science: Journal du Conseil **64**:537-550.

Woillez, M., J. Rivoirard, and P. Petitgas. 2009. Notes on survey-based spatial indicators for monitoring fish populations. Aquatic Living Resources **22**:155 - 164.

Table 1. Results of single factor quotient analysis relating the catch densities of immature (I) and mature (M) mackerel in the spring NEFSC trawl survey and environmental variation measured *in situ* or with MODIS satellite.

Variable	Maturity Class (N samples)	Location Measured	Significant Association	Range of association	Range of avoidance	Data Range
Depth	I (16972)	*in situ*	Yes	35-90	≤ 25	5-494 M
Depth	M (16972)	*in situ*	Yes	30-80	≤ 15	
Bottom Temperature	I (14525)	*in situ*	Yes	6-9	≤ 5, ≥ 11	0-22.7°C
Bottom Temperature	M (7296)	*in situ*	Yes	6-9	≤ 5, ≥ 11	
Bottom Salinity	I (7296)	*in situ*	Yes	33-34.5	≤ 32, ≥ 36	23-37 PSU
Bottom Salinity	M (7296)	*in situ*	Yes	33.5-34	≤ 33, ≥ 36	
Surface Temperature	I (14868)	*in situ*	Yes	6-8	≤ 5, ≥ 11	0-23.8°C
Surface temperature	M(14868)	*in situ*	Yes	6-8	≤ 5, ≥ 13	
Surface Salinity	I (7431)	*in situ*	Yes	33-34	≤ 32, ≥ 36	16-36.5 PSU
Surface Salinity	M (7431)	*in situ*	Yes	33-34	≤ 33, ≥ 36	
Solar elevation	I (17003)	Computed	No			-62.5-71.6°
Solar elevation	M (17003)	Computed	Marginal	10-15	-15--25	
Log Chlorophyll	I (1484)	Satellite	No			0.2-4.6
Log Chlorophyll	M (1484)	Satellite	No			
Log POC	I (2163)	Satellite	No			3.9-9.5
Log POC	M(2163)	Satellite	No			
Log A433	I (2163)	Satellite	No			-3.5-1.7
Log A433	M(2163)	Satellite	No			
Log Gradient Strength	I (1574)	Satellite	No			0-1.4
Log Gradient Strength	M(1574)	Satellite	No			

Table 2. Catches of mackerel in the winter fishery were significantly less likely in cold bottom water temperatures than expected and more likely than expected in preferred temperatures(*) based on exact binomial tests of frequencies of mackerel catches > 1000 lbs. The proportion of catches in warm bottom water was not different than expected. Preferred temperatures were those identified with quotient analysis. Bottom temperatures estimated for the Expresso ROMS domain from Jan. 1 – April 13 in 2014-2017 were used to estimate catch temperatures and expectation (Wilkin and Hunter 2013).

Bottom temperature	Expectation within ROMS domain	Proportion of tows (N=132) (95% Confidence intervals)	P-value
5°-10°C*	0.2631	0.7121 (0.6269-0.7876)	2.2e-16
< 5°C	0.5829	0.0833 (0.0423-0.1442)	2.2e-16
>10°C	0.1540	0.2045 (0.1393-0.2835)	0.1162

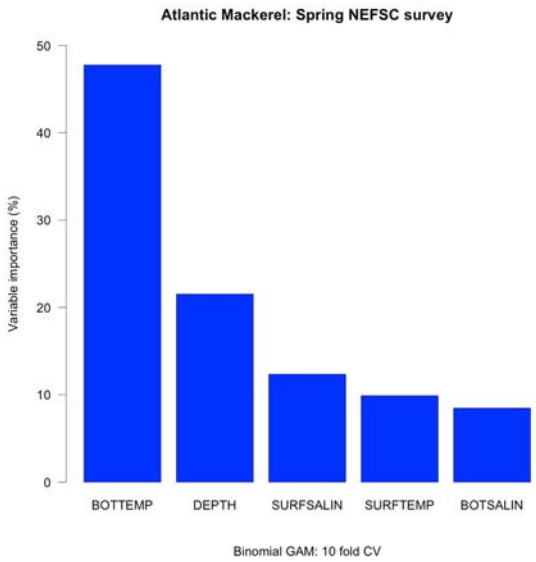


Figure 1. Relative Importance of habitat variables identified as significant in single factor quotient analysis applied to NEFSC bottom trawls survey collections of Atlantic Mackerel. The analysis used the methods of {Thuiller, 2013 #4223;Thuiller, 2016 #4227} which compare correlations of observations with predictions from 10 fold cross validated GAMs.

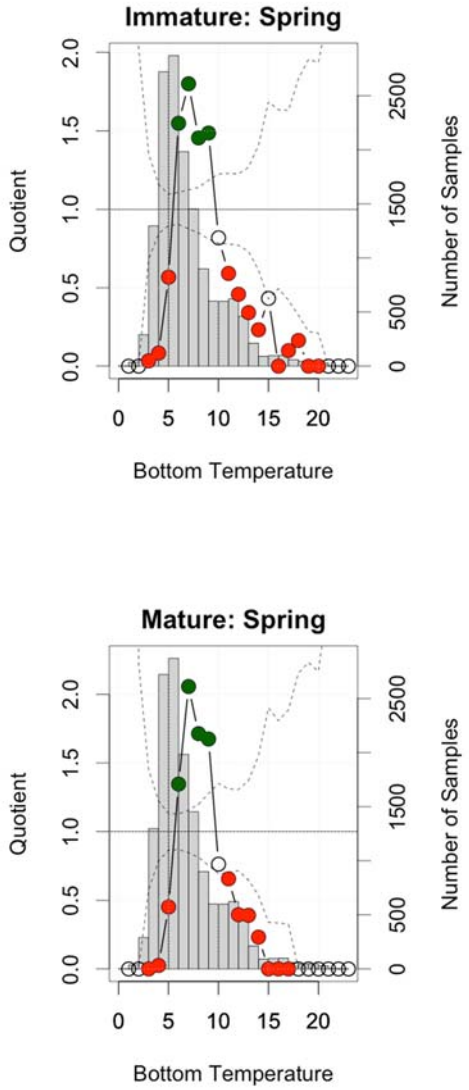


Figure 2. Single factor quotient analysis indicated that immature (top) and mature (bottom) size classes of Atlantic mackerel were positively associated with temperatures of 5.5-9.5°C and 5.7-9.5°C, (green dots) respectively during the spring bottom trawl survey. Dot indicate whether abundances in 1°C temperature bin was greater than (green; positive association), equal to (white, no effect) or lower than (red; avoidance) expected by chance based on randomization of the data (N=999). Dotted lines are 2 standard errors confidence bands for null quotients developed by data randomization. The histogram of bottom temperatures measured at the survey stations is indicated in grey.

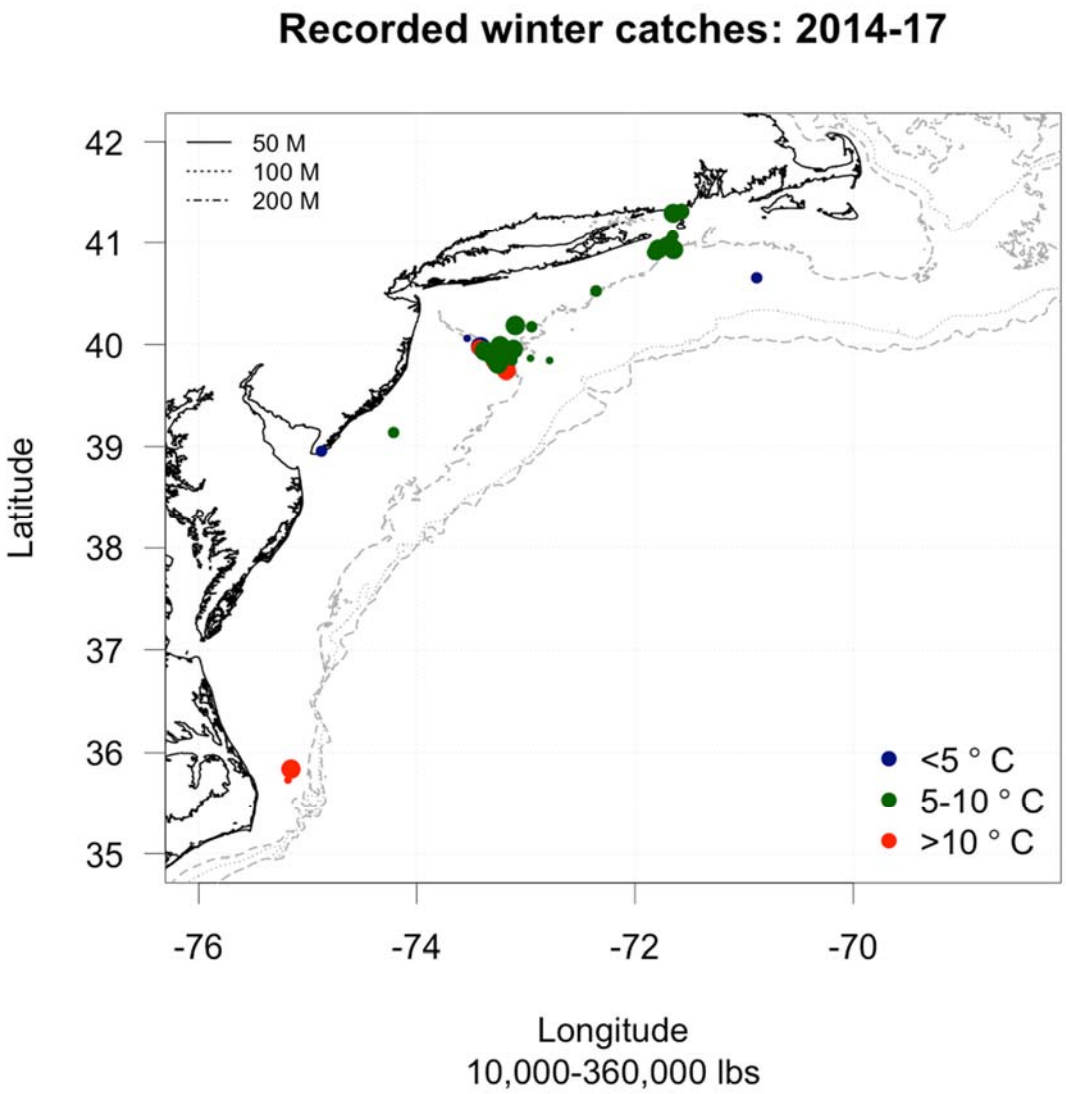


Figure 3. Locations and thermal habitat for fishery catches (N=134) of mackerel > 1000 lbs during the winter (January 1- April 15) from 2014 through 2017. Thermal habitats was classified based on the results of single factor quotient analysis (Fig 2) and water temperatures hindcast by Expresso ROMS within 10 km and 12 hours of tows. 8% of tows (N= 11) occurred in bottom water colder than 5°C, 20% of tows occurred in bottom water warmer than 10°C and 71% (N= 94) occurred in the preferred temperatures (See Table 2).

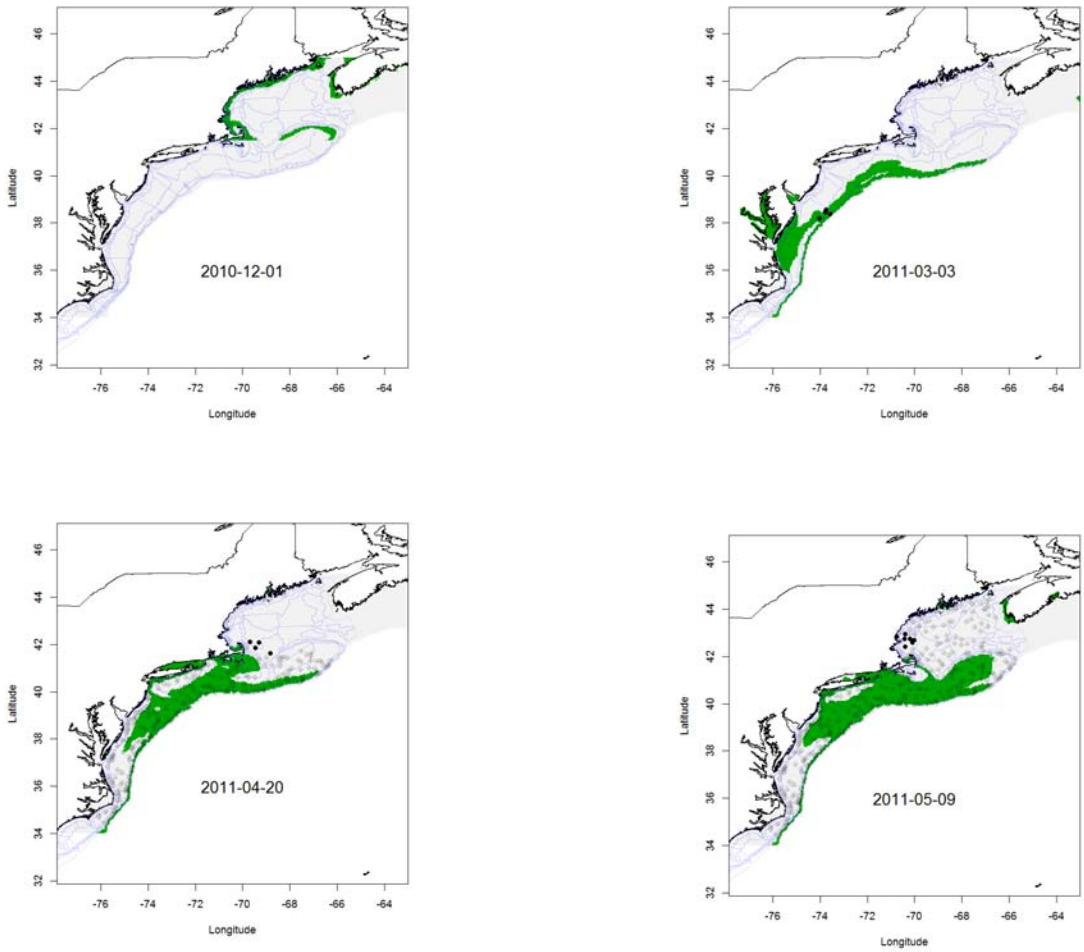


Figure 4. Portion of the NW Atlantic ROMs model domain used to develop the habitat model with movement constraints. (Top left) Initial fall distributions of Atlantic mackerel on December 1 2010 are defined by the green area where latitude is > 41.5°N, depths < 160M, and bottom temperatures range from 8-12°C (with model bias adjustment). Grids defined by the same conditions constructed for each year were used to set initial conditions to account for movement constraints associated with habitat connectivity along fall-winter migration pathways (See method). Thre remaining projections are selected daily estimates of preferred habitat (green) for the beginning (March 3), middle (April 20) and end (May 9) of the 2011 NEFSC bottom trawl survey. Closed circles are survey samples taken on the day of the habitat projection while open circles are the samples completed before that date. Samples falling within the preferred habitat (Black dots within green areas) have an HSI =1 while those falling outside are assigned and HSI =0 in equation 1. Survey strata used in area calculations in equation 1 are depicted by blue lines

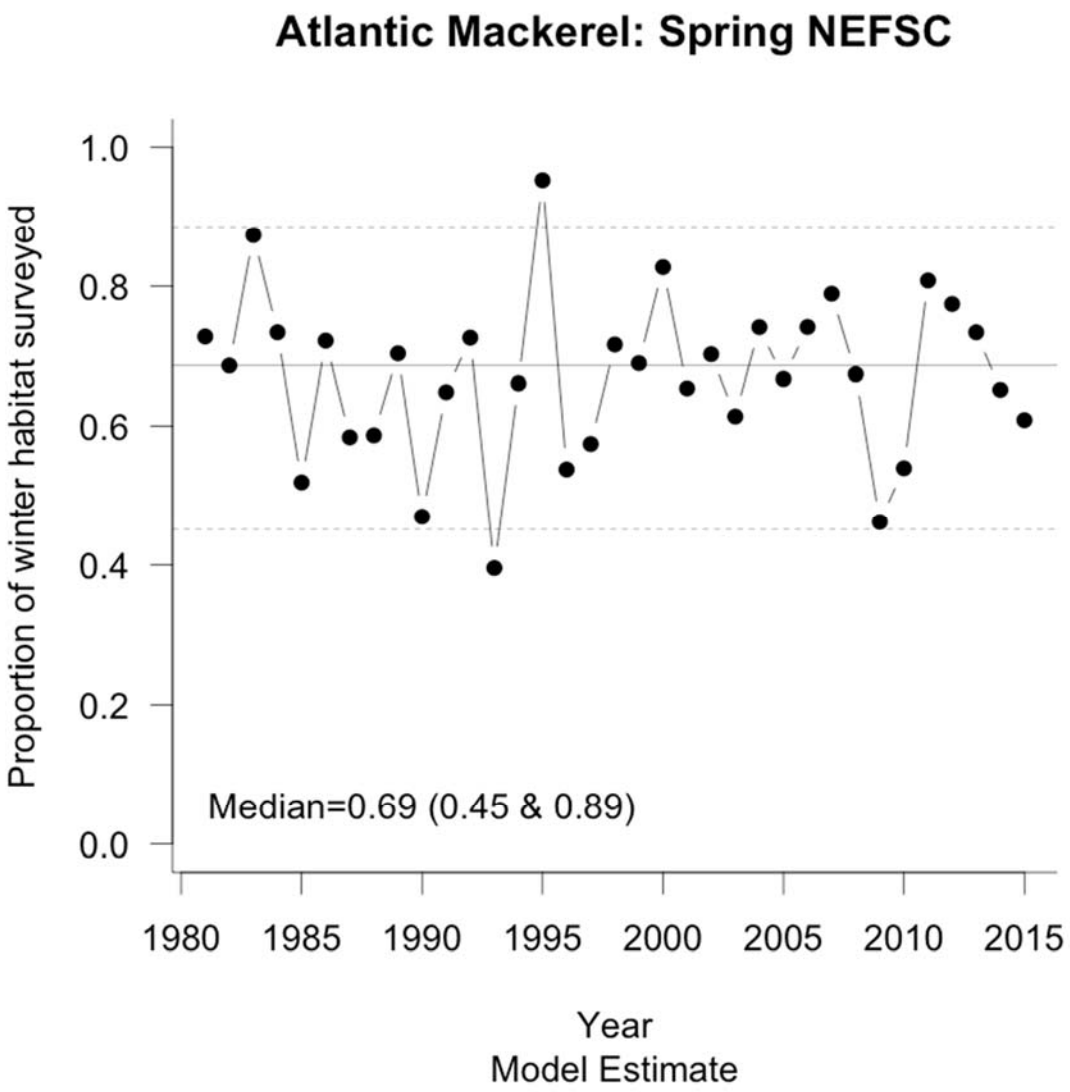


Figure **5.** Model based estimates of the proportion of winter habitat surveyed in the spring NEFCS bottom trawl survey from 1980-2016 computed using habitat projections (e.g. Fig. 4) and equation 1.

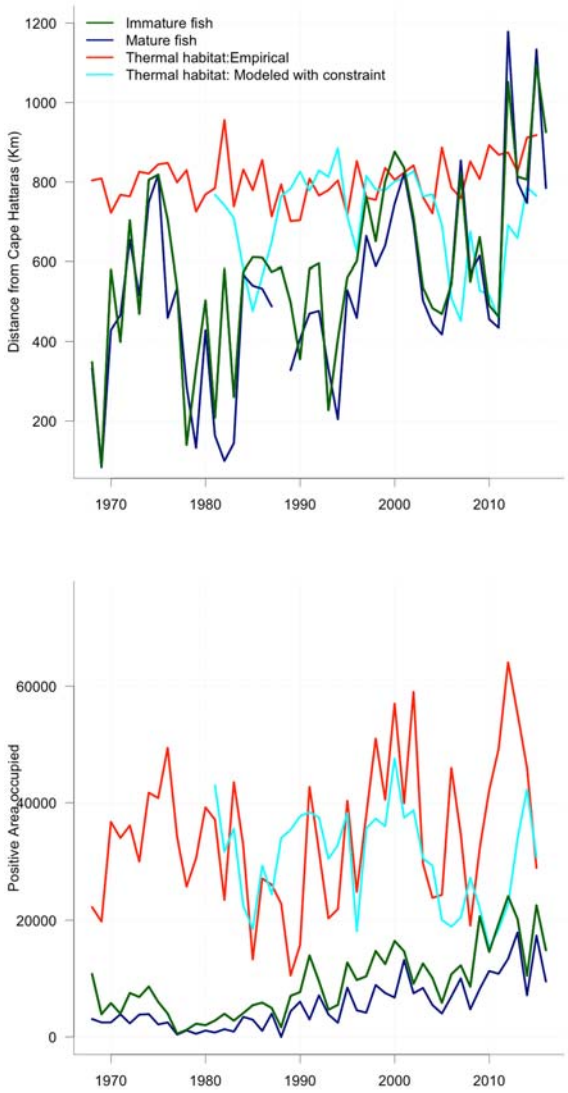


Figure 6**.** Distances of centers of gravity from Cape Hatteras (top) and relative areas of occupation (bottom) for juvenile and adult mackerel and habitat classified based on bottom temperatures measured *insitu* (empirical) and hindcast using the habitat model that incorporated movement constraints. Spatial indices were calculated using the methods of {Woillez, 2007 #3778;Woillez, 2009 #3779} as described in detail in {Manderson, 2017 #4298} (Appendix ?)

Appendix A8: Change in the spatial distribution of mackerel habitat during spring

Kevin Friedland, James Manning, John Manderson, and Ryan Morse

A random forest model using both static and dynamics variables was developed for Atlantic mackerel on the Northeast Shelf. Prior to final model formalization eight variable classes were evaluated to determine which variables from each set would appear to have the highest explanatory power for the distribution of mackerel catch biomass, assuming catch biomass is reflective of the relative value of a location as habitat. The data time series went from 1992 to 2016 limited by the availability of the salinity data collected on the NEFSC bottom trawl survey. The variable groups were as follows; an individual random forest was fit for each group:

Station salinity, surface and bottom, dynamic, 2 variables
Station temperature, surface and bottom, dynamic, 2 variables
Static variables, including bottom complexity, 22 variables
Satellite chlorophyll frontal magnitude, climatology, 12 variables
Satellite chlorophyll, climatology, 12 variables
Satellite SST frontal magnitude, climatology, 12 variables
Satellite SST, climatology, 12 variables
Zooplankton bio-volume and taxa abundance, dynamic, 19 variables

The variables with the highest % increase in MSE, either the top one or two variables, were combined with station depth as the predictor variables used to fit the final random forest model. So, the model included:

Station depth
Station salinity, top variable
Station temperature, top variable
Static variables, top two variables
Satellite chlorophyll frontal magnitude, top variable
Satellite chlorophyll, top variable
Satellite SST frontal magnitude, top variable
Satellite SST, top variable
Zooplankton, top two variable

Biomass was $\log_{10}$ transformed before the model was fit, 300 trees were fit during the training process yielding a model with the following variables: chl_r_clim_08, SURFSALIN, DEPTH, ST_SD, sst_f_clim_s_03, zoo_spr_ann_cirr, sst_r_clim_s_07, rast_plcurv20km, chl_f_clim_s_03, rast_soft_sed, and zoo_spr_ann_echino (see appendix 1 for variable definition details). The relative rank of these variables are shown in Figure 1 with the percent increase of MSE and the increase in Node Purity for each variable. The variables are sorted from the highest to lowest $IncMSE. The model was used to compute predicted values, which are compared to observed values in Figure 2. The mean square error of the predicted values was 0.025 and the pseudo r^2 was 0.83. Data for each model variable over a 0.1° grid of the Northeast Shelf (see appendix 2) was selected for each of the model year 1992-2016. The

annual habitat predictions were projected on a raster each year; any missing data was filled using ordinary Kriging. The time series of rasters were put into a raster stack and linear trend was estimated for each grid location. The distribution of these trend estimates are shown in Figure 3, noting that the area that trend estimates are shown is limited to the parts of the ecosystem within the 99% kernel density distribution for mackerel over the time period (see appendix 3).

The main findings include the suggestion from this model that over time, the outer continental shelf in the Middle Atlantic Bight has declined as spring mackerel habitat while the inner shelf of the Bight has increased in its habitat score. And, the habitat scores have increased over much the Gulf of Maine and Georges Bank areas. These observations would be consistent with two assertions: 1) the shift in habitat in the Middle Atlantic Bight may reflect a change in the availability of mackerel to the spring time frame bottom travel survey. The bulk of the mackerel population may have been distributed at the shelf break front or further east in the early segment of the time series and was less available. In recent years, with the increase in habitat on the shelf proper, more of the fish are available to the survey, regardless of stock abundance. And 2), the increase in habitat in the Gulf of Maine and George Bank area represents a possible conduit between the Canadian resource and the Middle Atlantic Bight stock area, perhaps explaining the occurrence of these fish in US waters.

Figure 1. Sorted percent increase of MSE and the increase in Node Purity for each variable in the random forest model.

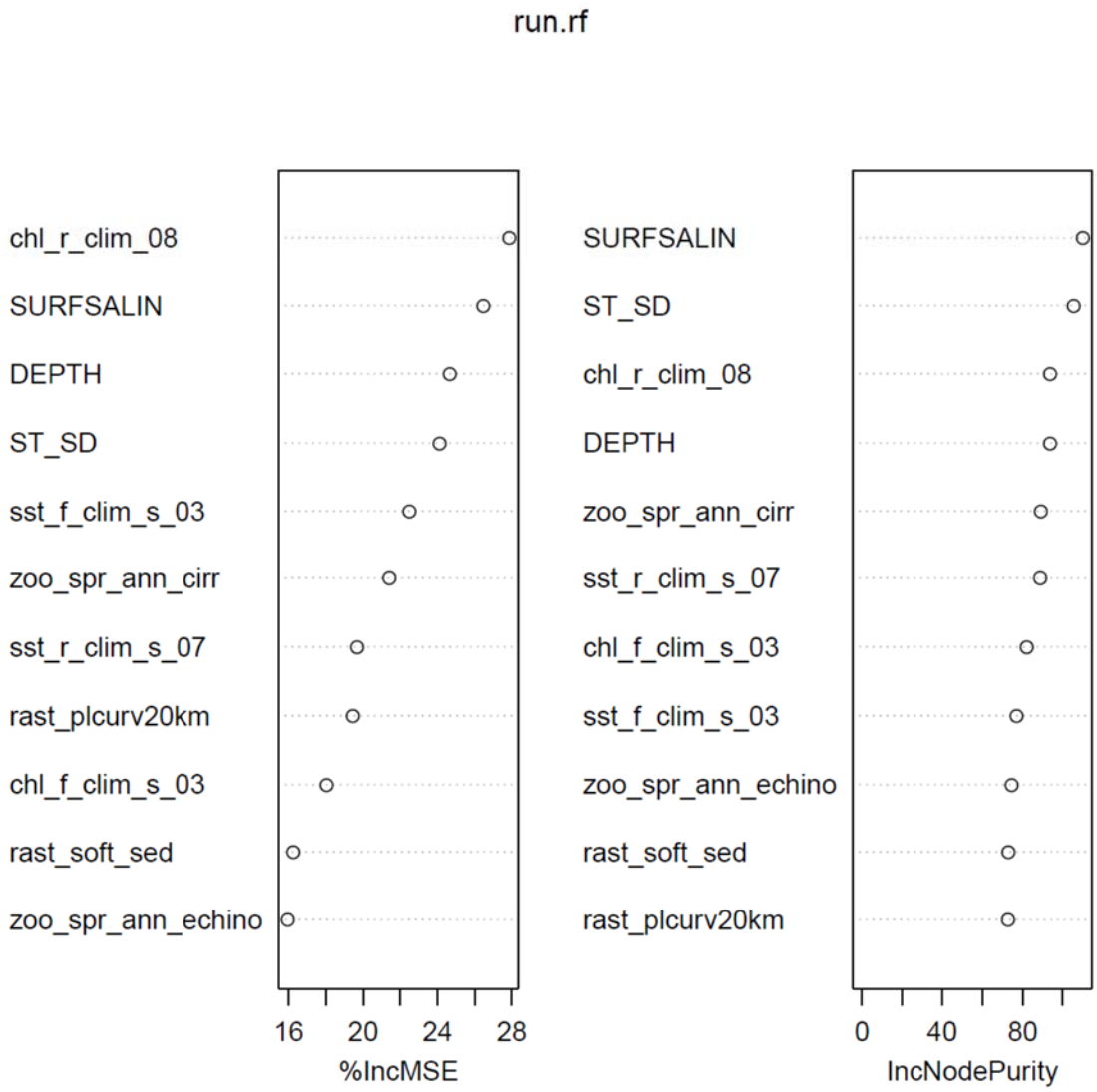


Figure 2. Final model predicted versus observed, red line marks 1:1 or predicted equal observed values.

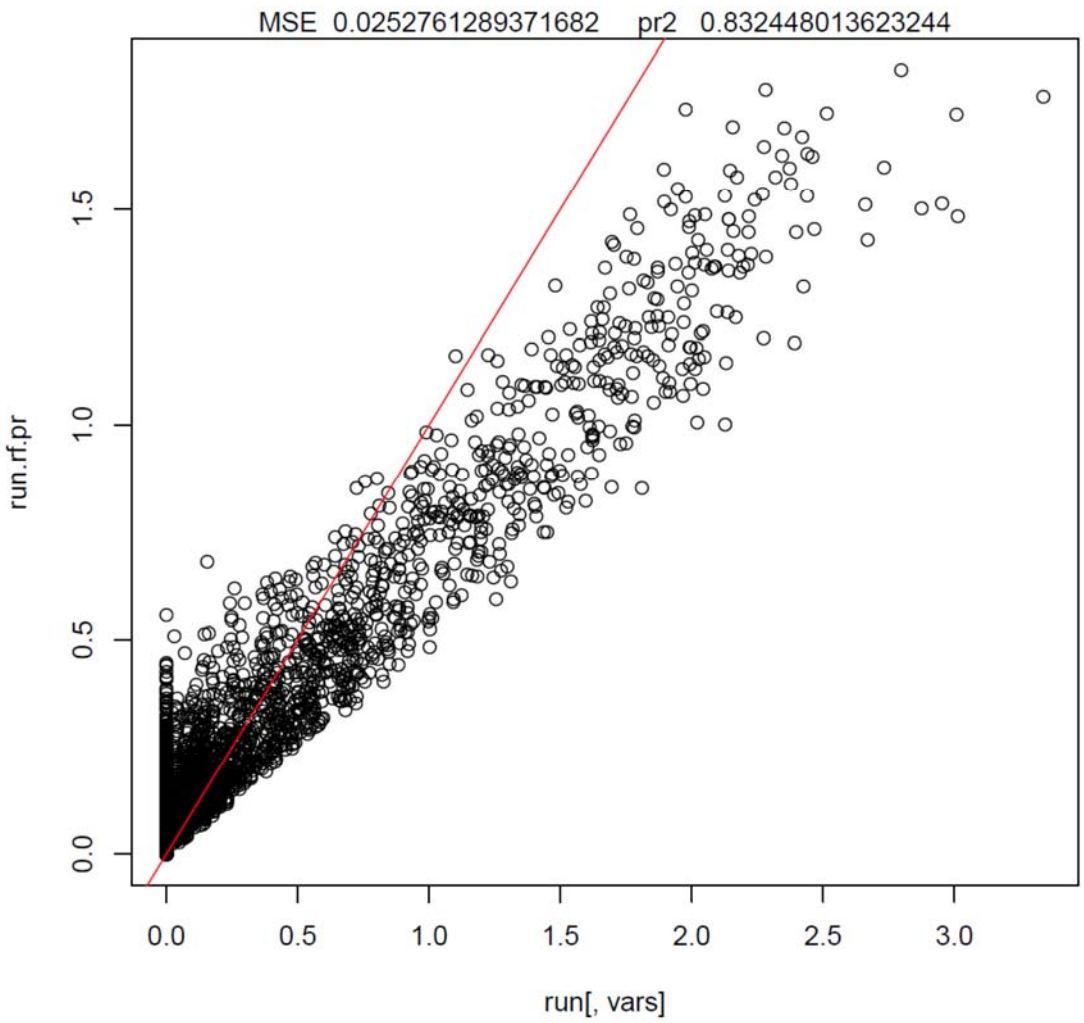
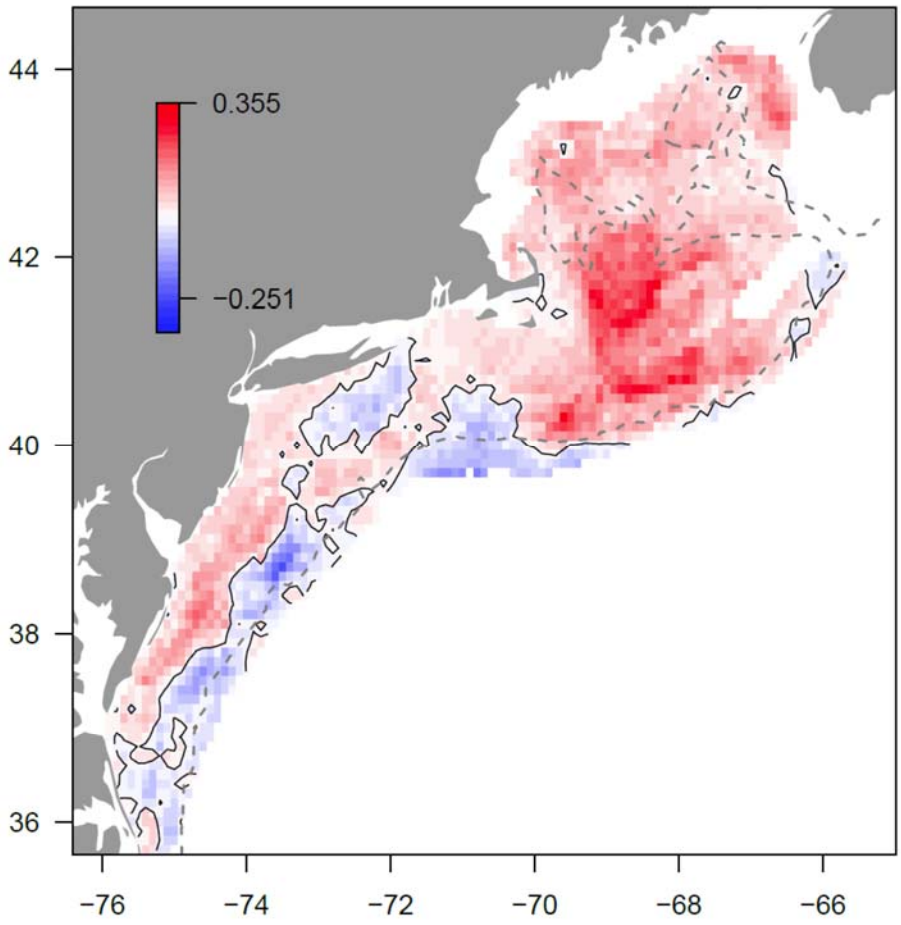


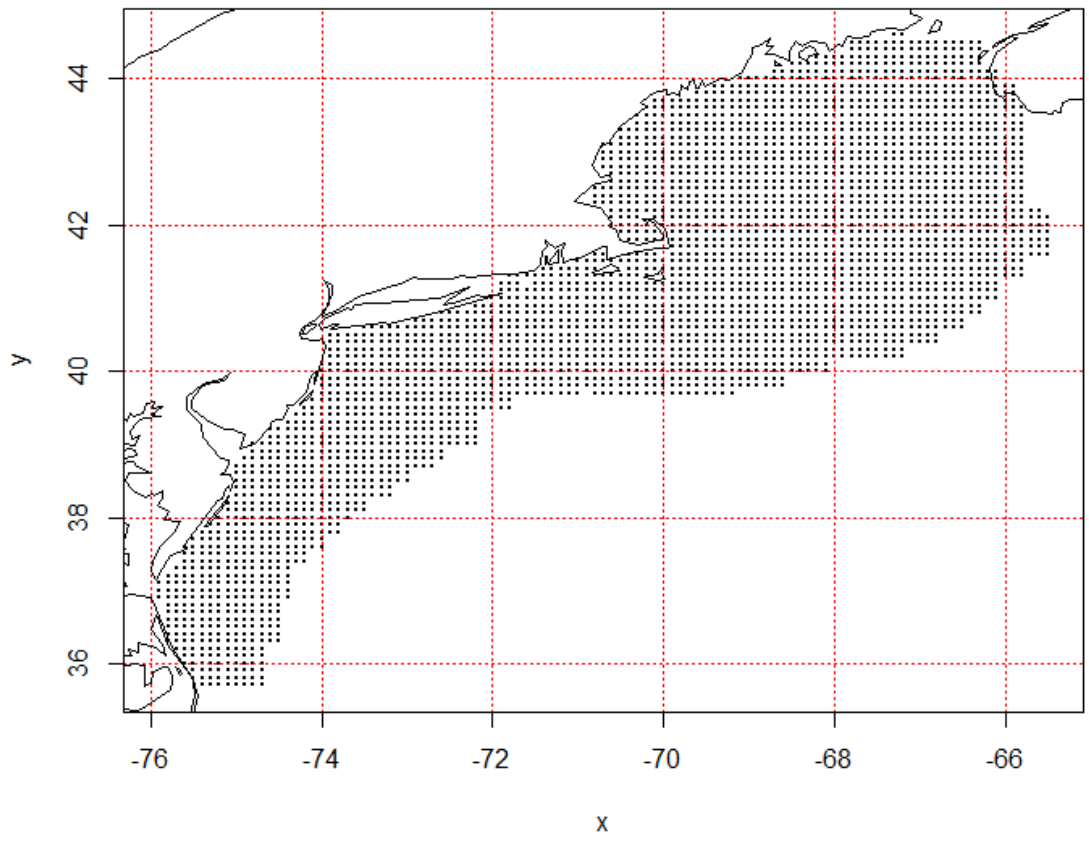
Figure 3. Linear trend over the time series 1992-2016 for mackerel spring habitat constrained within the area of the 99% kernel density distribution of species occurrence. The line marks the 0 isotrend line.



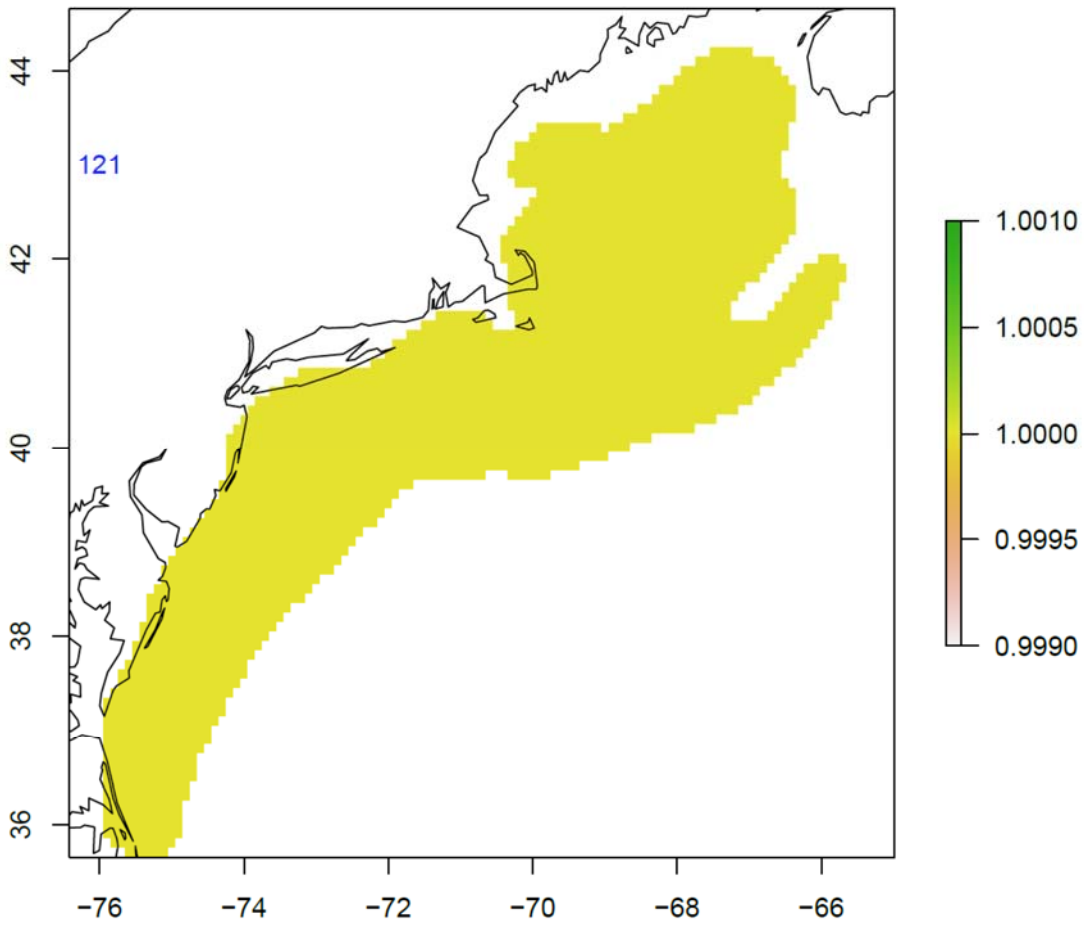
Appendix 1. Predictor variable details.

Variable	**Annual or climatology**	**Description**
chl_r_clim_08	Climatology	August chlorophyll concentration
SURFSALIN	Annual	Station surface salinity
DEPTH	Climatology	Depth
ST_SD	Annual	Station surface temperature
sst_f_clim_s_03	Climatology	March satellite SST gradient magnitude sampled after 5-day drift
zoo_spr_ann_cirr	Annual	Cirripedia per 100m3 of water volume
sst_r_clim_s_07	Climatology	July satellite SST sampled after 5-day drift
rast_plcurv20km	Climatology	Planform curvature 20km
chl_f_clim_s_03	Climatology	March chlorophyll gradient magnitude sampled after 5-day drift
rast_soft_sed	Climatology	Soft sediment distribution
zoo_spr_ann_echino	Annual	Echinodermata per 100m3 of water volume

Appendix 2. NES grid at 0.1 degree resolution.



Appendix 3. Kernel density distribution of mackerel during spring at the 99% level.



Appendix A9: Physical conditions and lower trophic level ecology in the Atlantic mackerel spawning areas in US and Canadian waters

Kevin Friedland, Conor McManus, Ryan Morse, Martin Castonguay

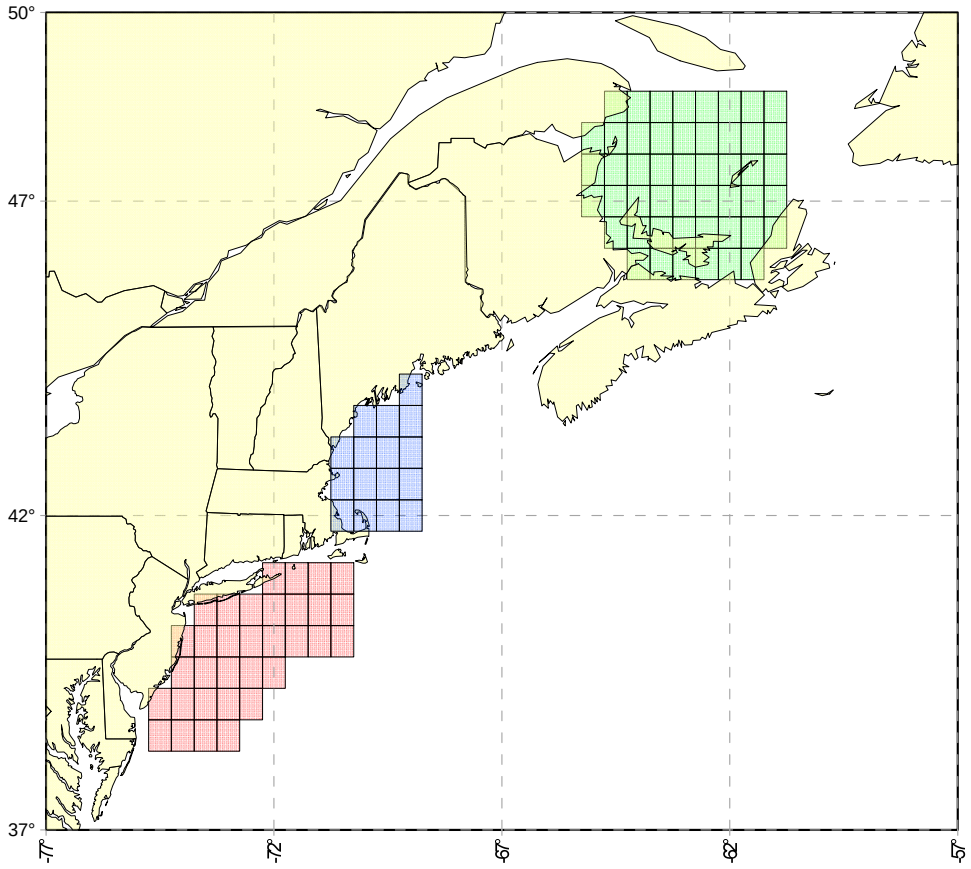
This working paper reviews samples and data to be used in an analysis of selected physical forcing variables and variables related to lower trophic level status in the putative spawning/stocks areas for Atlantic mackerel in the United States and Canada. The data are intended to address term of reference 1b:

1. Spatial and ecosystem influences on stock dynamics:

b. Describe data (e.g., oceanographic, habitat, or species interactions) that might pertain to Atlantic mackerel distribution and availability. If possible, integrate the results into the stock assessment (TOR-

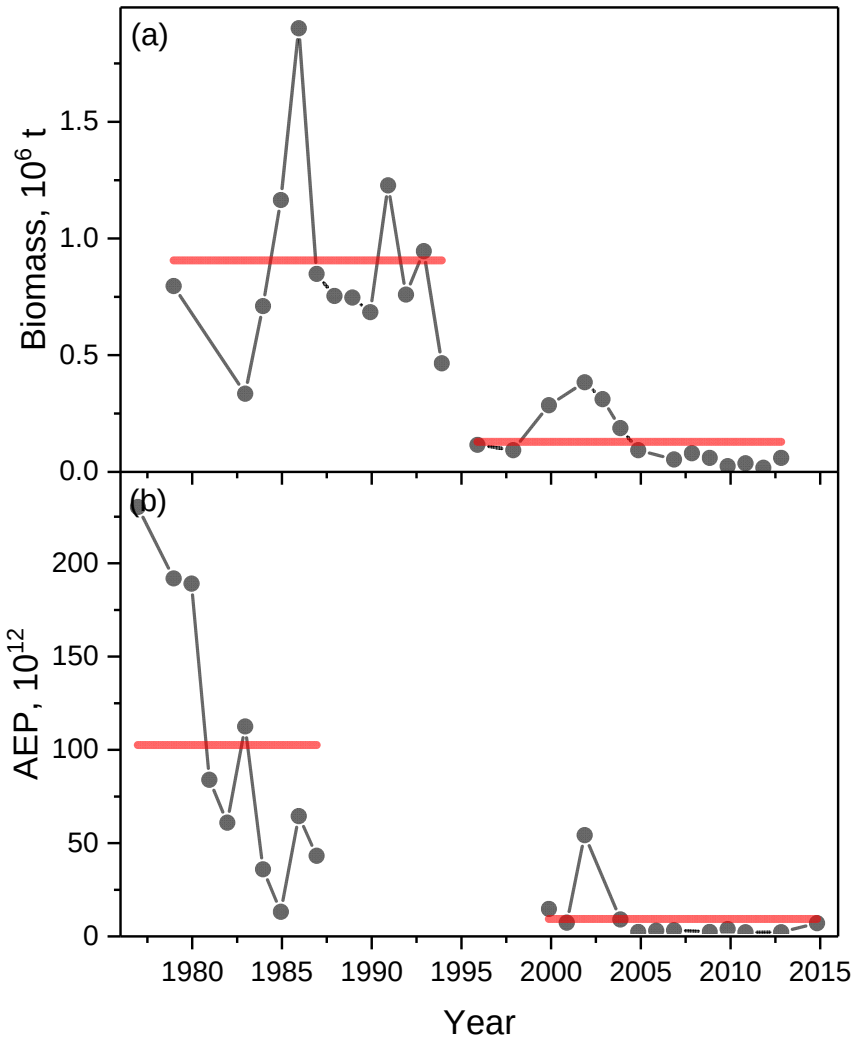
Study area

Map of study area showing grid locations for index areas in the Gulf of St. Lawrence, Gulf of Maine, and Middle Atlantic Bight.



Stock abundance indicators

Abundance (biomass, t) index for mackerel in the Gulf of St. Lawrence (a) is based on two estimation procedures, see figure 10 in DFO (DFO, 2014) . Abundance of mackerel in the Middle Atlantic Bight is represented by an Annual Egg Production index calculated from the raw egg numbers collected during the May-June surveys (b). The calculations account for egg incubation time in the estimates of daily egg production on area sampled basis (L. Carter, per comm).



Index periods for high and low recruitment regimes in the Gulf of St. Lawrence and Middle Atlantic Bight

For subsequent analyses, data are summarized for two time periods to contrast the conditions associated with high and low stock abundance and the assumed recruitment levels that produced these stock levels. The index for the MAB is applied to the Gulf of Maine area.

MAB

Abundance	Start	End
High	1977	1987
Low	2000	2015

GSL

Abundance	Start	End
High	1979	1994
Low	1996	2013

Sea surface temperature

SST was derived from the extended reconstructed sea surface temperature (ERSST, version 4) dataset. This dataset is based on the SST compilation of the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) SST dataset and represents interpolation procedures that reconstructs SST fields in regions with sparse data (Huang *et al.*, 2015; Liu *et al.*, 2015; Huang *et al.*, 2016).

Grid cells (longitude, latitude) used to represent the Gulf of St Lawrence, Gulf of Maine, and Middle Atlantic Bight SST index areas.

GSL

-64	46
-64	48
-62	46
-62	48

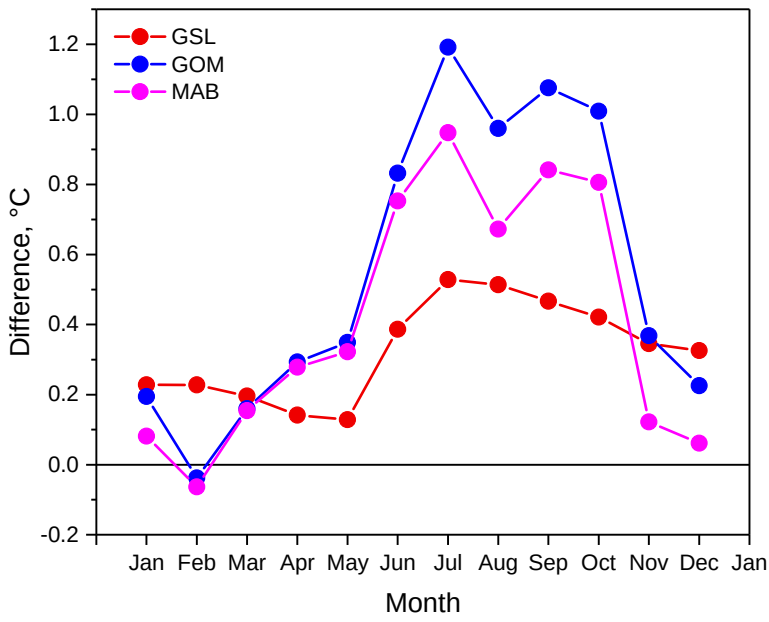
GOM

-68	42
-68	44
-70	42
-70	44

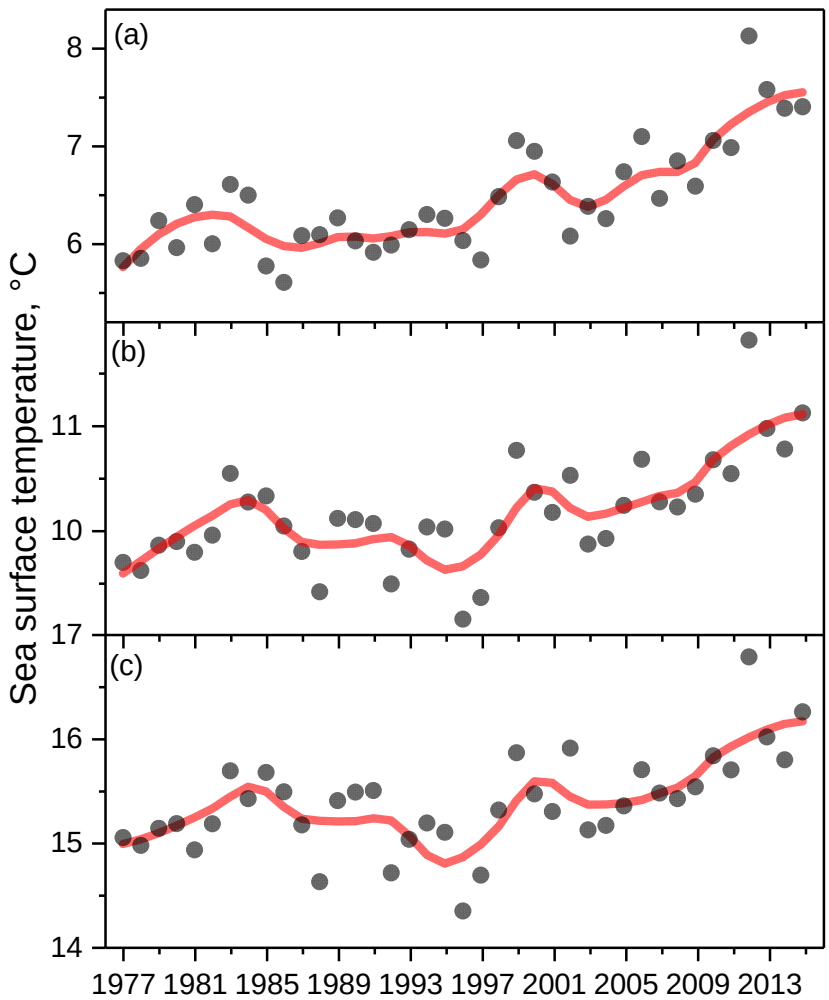
MAB

-74	38
-74	49
-72	40
-70	40

The figure below shows the difference in mean SST between abundance index time periods for the Gulf of St. Lawrence, Gulf of Maine, and Middle Atlantic Bight. The positive difference in all areas shows that temperature was higher in the index areas during the more recent time period of low stock abundance than during the earlier period associated with higher stock abundance, the largest differences associated with the summer into fall months.



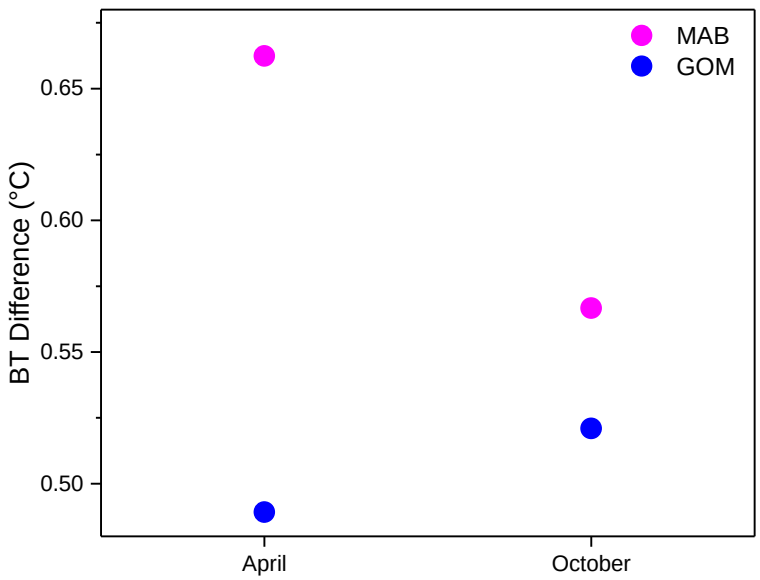
The figure below shows the time series of annual mean SST for the Gulf of St. Lawrence (a), Gulf of Maine (b), and Middle Atlantic Bight (c). The most rapid change in SST has occurred in recent years. For example, the overall mean SST changed from approximately 6.0 to 7.5°C in the GSL suggesting a change of 1.5°C, however, when comparing the index periods the SST change in the GSL is more on the order of 0.5°C. Red lines are loess smoothing with span of 0.3.



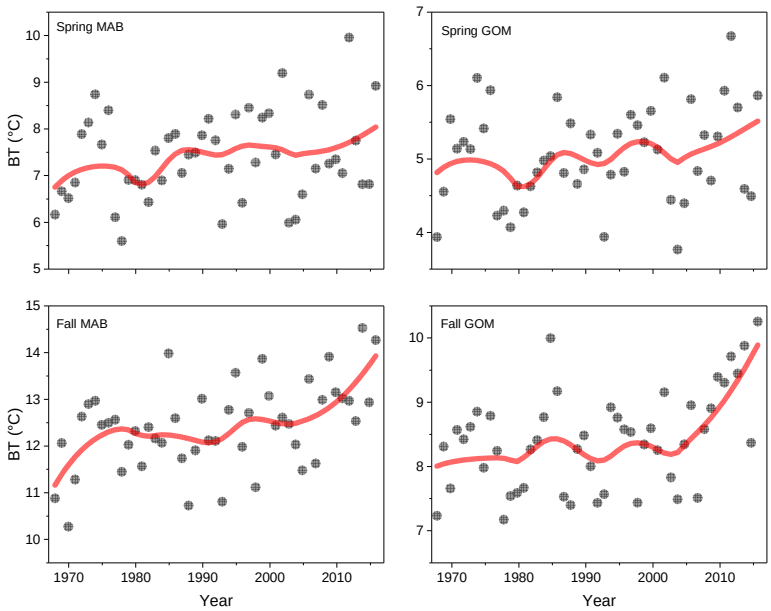
Bottom Temperature

The following describes changes in interpolated bottom temperature fields for the Northeast Shelf that correlate to the spring and fall survey time windows based on station data from the NEFSC bottom trawl survey.

The figure below shows the difference in mean BT between abundance index time periods for the Gulf of Maine and Middle Atlantic Bight for the two time periods of the trawl survey. The positive differences in both areas shows that temperature was higher in the index areas during the more recent time period of low stock abundance than during the earlier period associated with higher stock abundance.



The figure below shows the time series of annual mean BT for the Gulf of Maine and Middle Atlantic Bight during spring and fall time frames. The increase in temperature has been more gradual during the spring as compared to the fall time series which shows a more dramatic increase temperature in recent years. Red lines are loess smoothing with span of 0.3.



Wind

Surface or near the surface (.995 sigma level) monthly zonal wind speeds (m sec^{-1}), which are also referred to as the u-vector or the east–west component of the wind, and meridional wind speeds, or the v-vector or the north–south component of the wind, were extracted from the NCEP/NCAR reanalysis project dataset (Kalnay *et al.*, 1996). Vector wind speeds are represented as wind speed and Meridional Circulation Index (MCI) from (Francis & Vavrus, 2015).

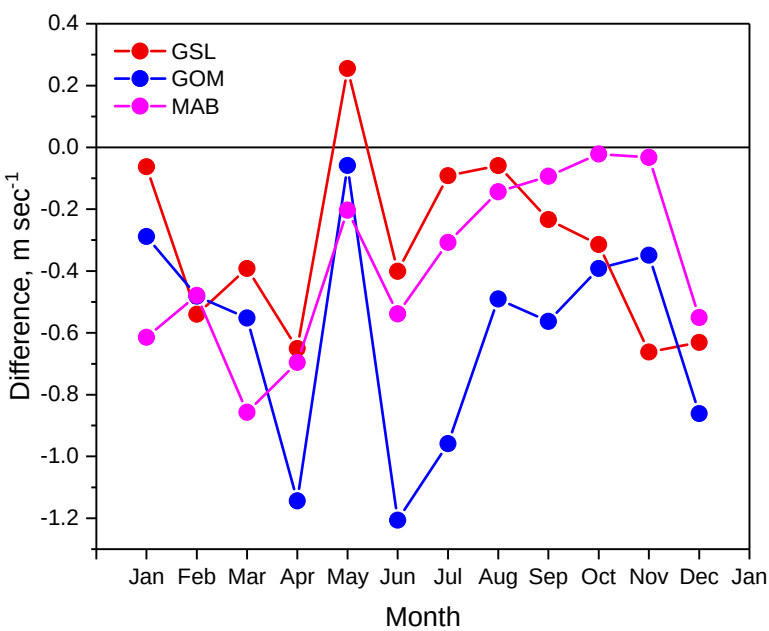
Wind speed:

$$ws = \sqrt{(u^2 + v^2)}$$

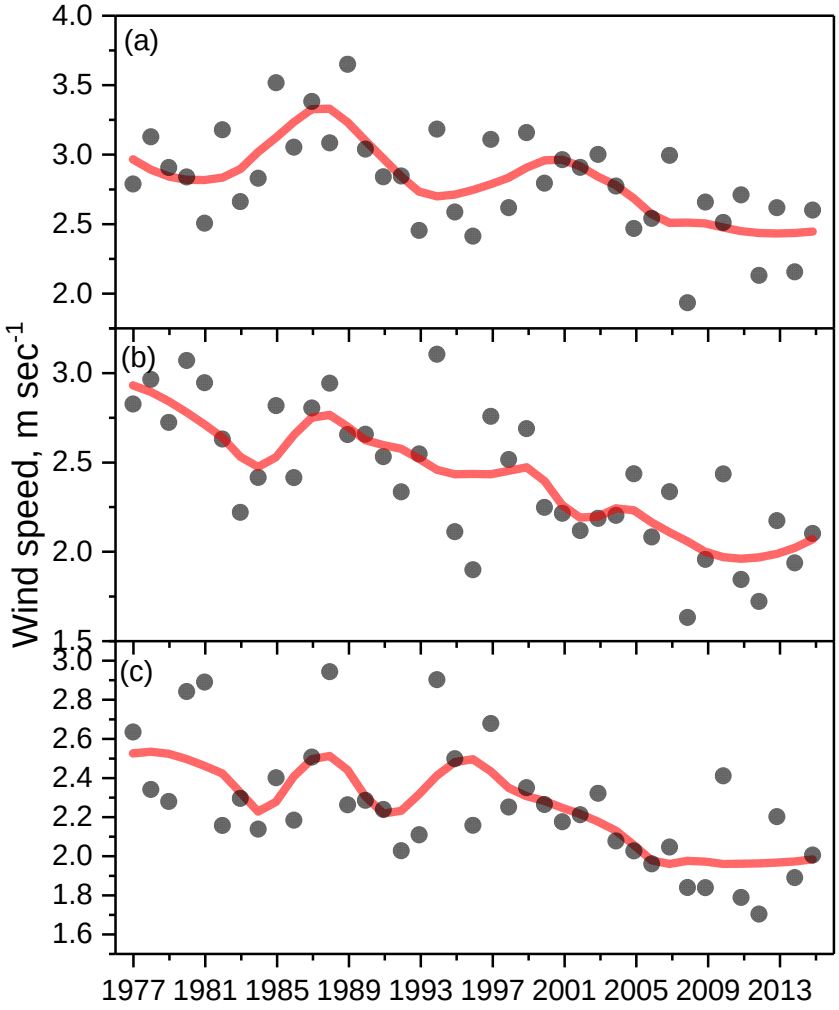
The MCI index:

$$mci = (v \times |v|) \div (u^2 + v^2)$$

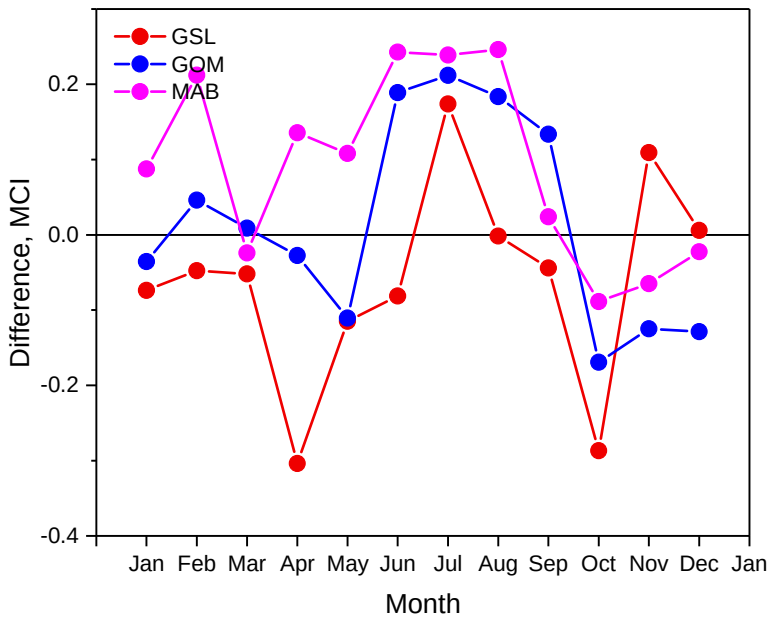
The figure below shows the difference in mean wind speed between abundance index time periods for the Gulf of St. Lawrence, Gulf of Maine, and Middle Atlantic Bight. The negative difference in all areas shows that wind speed was lower in the index areas during the more recent time period of low stock abundance than during the earlier period associated with higher stock abundance. Largest relative time period differences vary by season depending on the region: MAB is spring, GOM is spring and summer, and GSL is spring and fall.



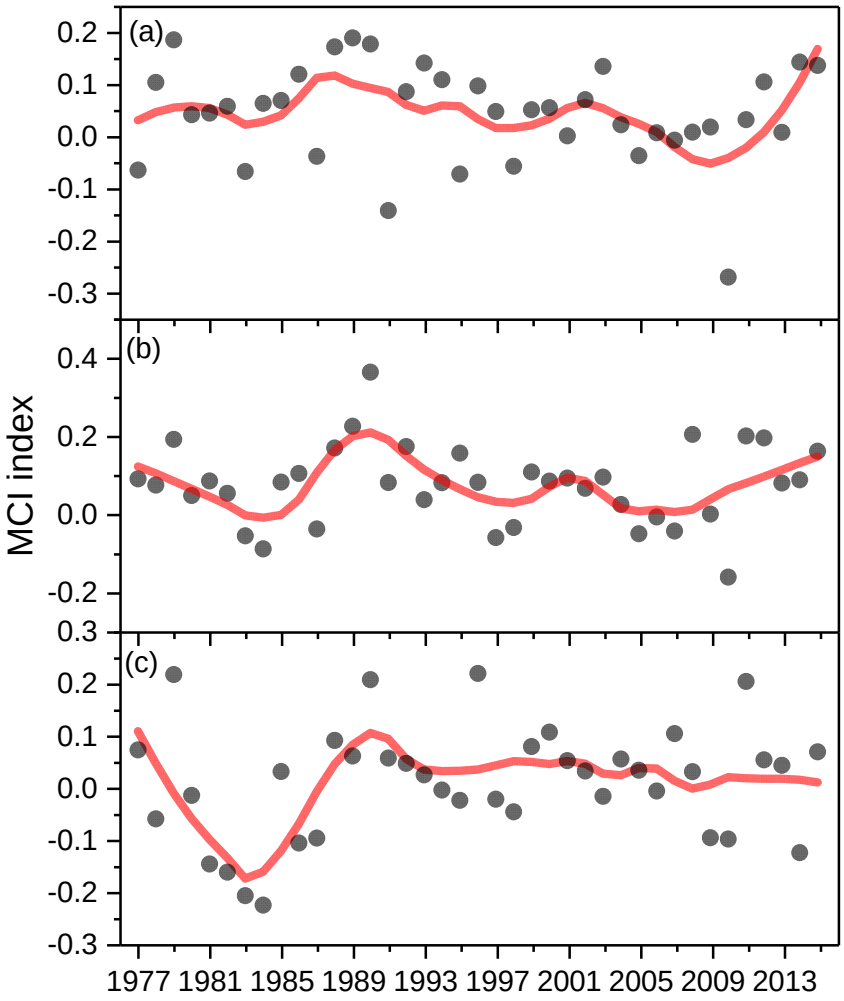
The figure below shows the time series of annual mean wind speed for the Gulf of St. Lawrence (a), Gulf of Maine (b), and Middle Atlantic Bight (c). The most rapid change in wind speed has occurred in recent years. For example, the overall mean wind speed changed from approximately 3.0 to 2.0 m sec-1 in the Gulf of Maine, which appear to be the most substantial change among the three areas. Red lines are loess smoothing with span of 0.3.



The figure below shows the difference in mean MCI between abundance index time periods for the Gulf of St. Lawrence, Gulf of Maine, and Middle Atlantic Bight. The only pattern common to all three areas is a tendency for MCI to have increased during the summer months.



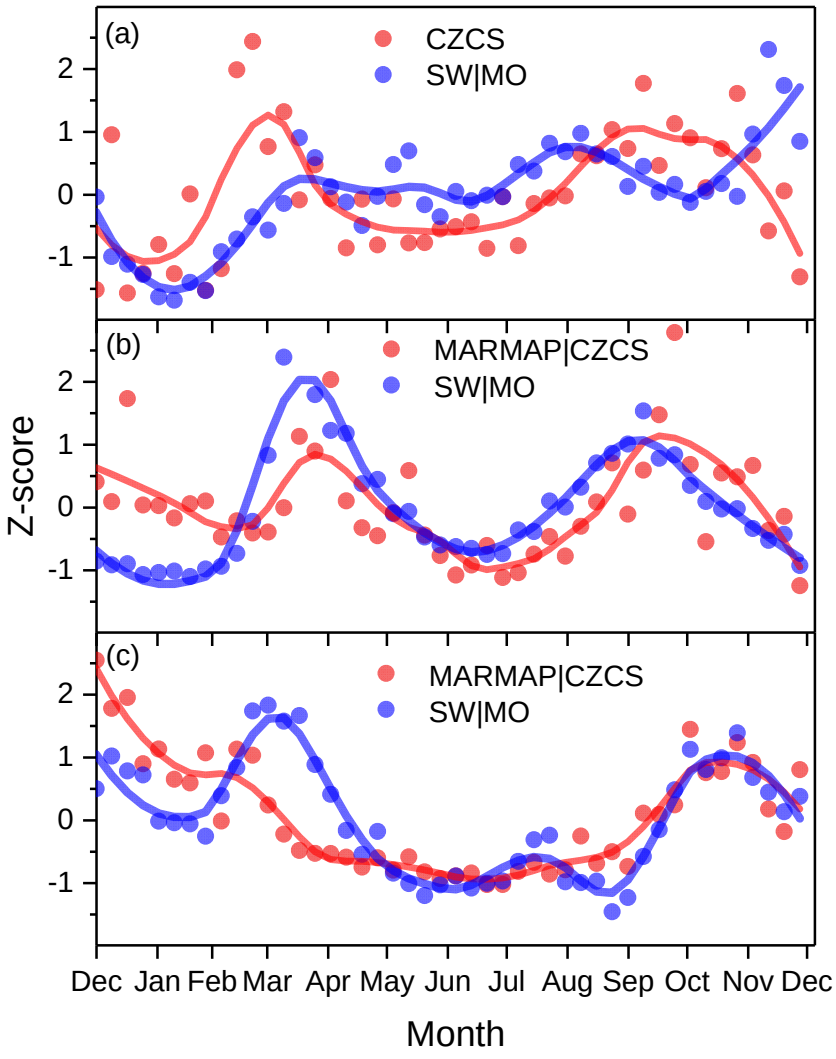
The figure below shows the time series of annual mean MCI for the Gulf of St. Lawrence (a), Gulf of Maine (b), and Middle Atlantic Bight (c). There is little trend in MCI over the annual cycle of wind directions each year. Red lines are loess smoothing with span of 0.3.



Chlorophyll concentration

Surface chlorophyll concentration was derived from various data collection program including both in situ and satellite methods. MARMAP chlorophyll concentration (mg m^{-3}, [Chl]) was measured fluorometrically using the method from Yentch and Menzel (Yentsch & Menzel, 1963; O'Reilly & Zetlin, 1988). Coastal Zone Color Scanner chlorophyll concentration (mg m^{-3}) was derived from the CZCS sensor (Gregg & Conkright, 2002) available from the Ocean Color Website (https://oceancolor.gsfc.nasa.gov/). SeaWiFS and MODIS chlorophyll concentration (mg m^{-3}) was derived from the SeaWiFS and MODIS sensors available from the Ocean Color Website (https://oceancolor.gsfc.nasa.gov/).

The figure below shows the difference in [Chl] Z-score between mackerel abundance index time periods for the Gulf of St. Lawrence (a), Gulf of Maine (b), and Middle Atlantic Bight (c). The high mackerel abundance time period is represented by data from the CZCS sensor and MARMAP samples; the low abundance time period is represented by data from the SW and MO sensors. In all three areas spring bloom [Chl] was relatively higher than winter [Chl] during the more recent time period of low mackerel abundance and in the early time period of low mackerel abundance it appear winter [Chl] was relatively higher. Red and blue lines are loess smoothing with span of 0.3.



Zooplankton abundance

Zooplankton biovolume, which is a proxy for biomass, was derived from sampling performed by shipboard surveys of the U.S. Northeast Shelf ecosystem. From 1977-1987, the MArine Resources Monitoring, Assessment, and Prediction (MARMAP) program conducted intensive surveys from Cape Hatteras, North Carolina to Nova Scotia. These efforts continued at a reduced level through the 1990s and are ongoing today as the Ecosystem Monitoring program (EcoMon). Currently, the EcoMon program tries to collect 120 plankton samples 6 times a year over the Northeast U.S. Shelf ecosystem. Sample tows are oblique paired 61 cm diameter bongo trawls made with a 335 µm mesh to a maximum depth of 200 m distributed in a stratified random sampling design. Biovolume was determined by measuring the settled volume of the sample (Harris *et al.*, 2000). Zooplankton were identified to the lowest taxonomic level possible, resulting in taxa-specific data on abundance and distribution (Meise & OReilly, 1996; Kane, 2007)

High abundance zooplankton taxa in the Middle Atlantic Bight and Gulf of Maine index areas, average annual abundance provided, number $100m^3$.

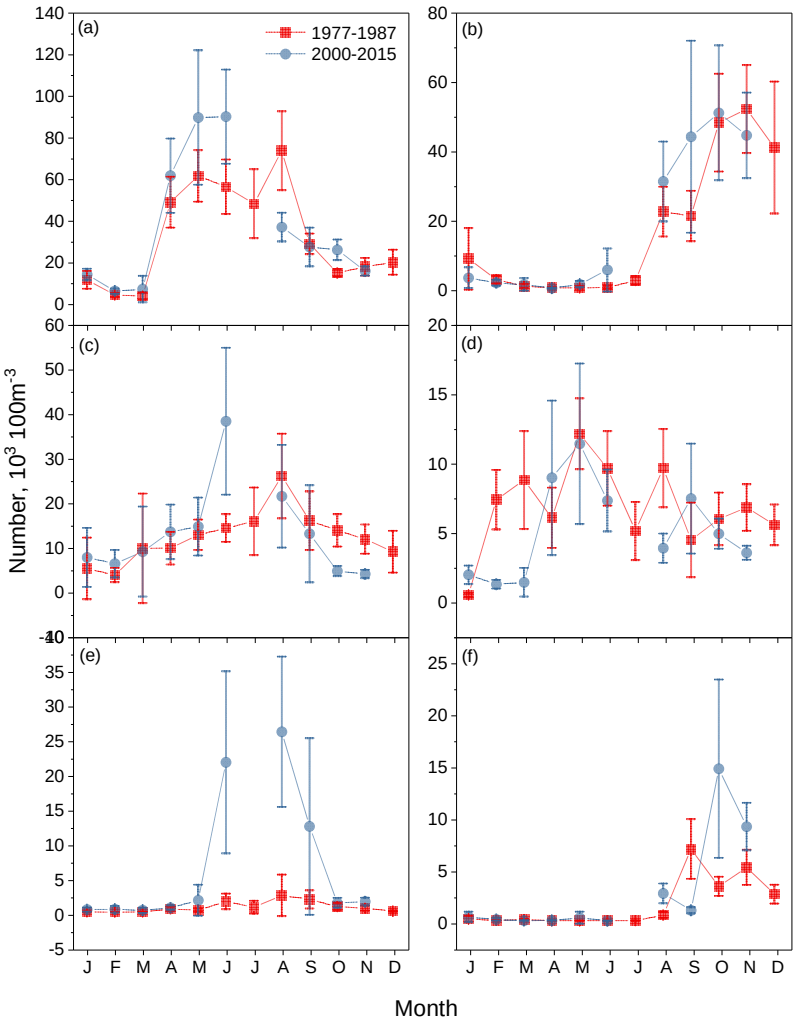
MAB

Taxa	100m^3
Centropages typicus	36965
Pseudocalanus spp.	17983
Calanus finmarchicus	13223
Temora longicornis	11487
Paracalanus parvus	4079
Centropages hamatus	2464

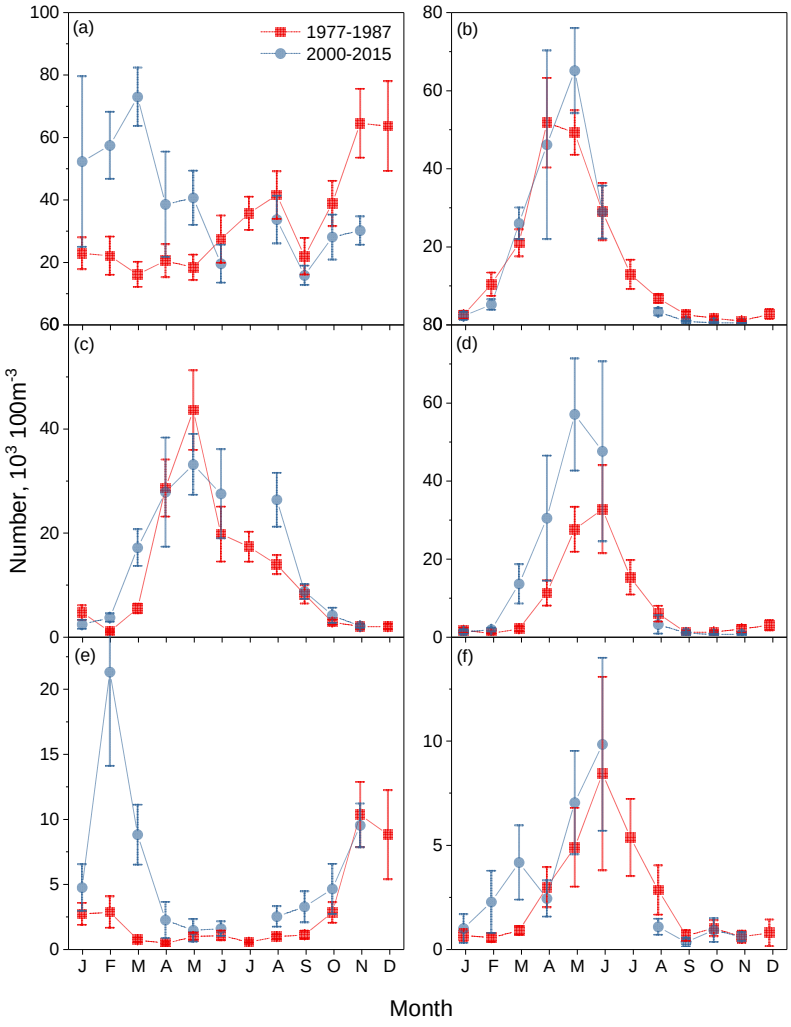
GOM

Taxa	100m^3
Calanus finmarchicus	31101
Centropages typicus	29216
Pseudocalanus spp.	13563
Metridia lucens	5962
Temora longicornis	4364
Paracalanus parvus	3198

Monthly zooplankton abundances during low and high abundance time periods in the GOM for species *Calanus finmarchicus* (a), *Centropages typicus* (b), *Pseudocalanus spp.* (c), *Metridia lucens* (d), *Temora longicornis* (e), and *Paracalanus parvus* (f) are presented below. With the exception of *Metridia lucens*, all taxa showed higher abundances in the more recent high mackerel period during variably the spring through fall months. Error bars are 95% confidence intervals.



Monthly zooplankton abundance during low and high mackerel abundance time periods in the MAB for species *Centropages typicus* (a), *Pseudocalanus spp.* (b), *Calanus finmarchicus* (c), *Temora longicornis* (d), *Paracalanus parvus* (e), and *Centropages hamatus* (f). The taxa *Centropages typicus*, the most abundant species in the MAB, shows a dramatic increase in abundance during winter into the spring month and a decrease in abundance during summer during the two time periods. Neither *Pseudocalanus spp.* nor *Calanus finmarchicus* show much change between the two time periods, however *Temora longicornis*, *Paracalanus parvus*, and *Centropages hamatus* reflect the same increase in winter abundance seen in *Centropages typicus.* Error bars are 95% confidence intervals.



Conclusions

There has been dramatic changes in the physical environment in areas supporting mackerel populations in the NW Atlantic where increased temperatures, especially during summer into fall, appear to be associated with lower recruitment and stock abundance. In addition to change in temperature, there has also been a change in the wind regime during spring into summer, with wind speed decreasing on the order of one third fold. The change in wind speed during these time periods may impact the dynamics of water column stability with associated effects on nutrients and phytoplankton bloom development and the transport and feeding of early life history stages of mackerel and other species. There have also been changes in secondary production in the Gulf of Maine and Middle Atlantic Bight. In the GOM, an enhanced spring bloom seems to be related to a bottom up effect on the production of the main zooplankton species in the area. However, in the MAB, the change in zooplankton abundance may be related to top down effects on the levels of [Chl]. The mechanistic effects of these physical and biological changes on mackerel are not immediately clear, noting that the effects on the distribution of the species and recruitment success are consistent with difference aspects of the data.

References

DFO (2014) Assessment of the Atlantic Mackerel stock for the Northwest Atlantic (Subareas 3 and 4) in 2013. *DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2014/030*,

Francis, J.A. & Vavrus, S.J. (2015) Evidence for a wavier jet stream in response to rapid Arctic warming. *Environmental Research Letters*, **10**

Gregg, W.W. & Conkright, M.E. (2002) Decadal changes in global ocean chlorophyll. *Geophysical Research Letters*, **29**

Harris, R.P., Wiebe, P.H., Lenz, J., Skjldal, H.R. & Huntley, M. (2000) *ICES Zooplankton Methodology Manual*. Academic Press.

Huang, B., Thorne, P.W., Smith, T.M., Liu, W., Lawrimore, J., Banzon, V.F., Zhang, H.M., Peterson, T.C. & Menne, M. (2016) Further Exploring and Quantifying Uncertainties for Extended Reconstructed Sea Surface Temperature (ERSST) Version 4 (v4). *Journal of Climate*, **29**, 3119-3142.

Huang, B.Y., Banzon, V.F., Freeman, E., Lawrimore, J., Liu, W., Peterson, T.C., Smith, T.M., Thorne, P.W., Woodruff, S.D. & Zhang, H.M. (2015) Extended Reconstructed Sea Surface Temperature Version 4 (ERSST.v4). Part I: Upgrades and Intercomparisons. *Journal of Climate*, **28**, 911-930.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K.C., Ropelewski, C., Wang, J., Leetmaa, A., Reynolds, R., Jenne, R. & Joseph, D. (1996) The NCEP/NCAR 40-year reanalysis project. *Bulletin of the American Meteorological Society*, **77**, 437-471.

Kane, J. (2007) Zooplankton abundance trends on Georges Bank, 1977-2004. *Ices Journal of Marine Science*, **64**, 909-919.

Liu, W., Huang, B.Y., Thorne, P.W., Banzon, V.F., Zhang, H.M., Freeman, E., Lawrimore, J., Peterson, T.C., Smith, T.M. & Woodruff, S.D. (2015) Extended Reconstructed Sea Surface Temperature Version 4 (ERSST.v4): Part II. Parametric and Structural Uncertainty Estimations. *Journal of Climate*, **28**, 931-951.

Meise, C.J. & OReilly, J.E. (1996) Spatial and seasonal patterns in abundance and age-composition of Calanus finmarchicus in the Gulf of Maine and on Georges Bank: 1977-1987. *Deep-Sea Research Part Ii-Topical Studies in Oceanography*, **43**, 1473-&.

O'Reilly, J.E. & Zetlin, C. (1988) Seasonal, horizontal, and vertical distribution of phytoplankton chlorophyll a in the Northeast U.S. Continental Shelf Ecosystem. **NOAA/National Marine Fisheries Service, NOAA Technical Report NMFS 139**

Yentsch, C.S. & Menzel, D.W. (1963) A method for the determination of phytoplankton chlorophyll and phaeophytin by fluorescence. *Deep Sea Research and Oceanographic Abstracts*, **10**, 221-231.

Appendix A10:
Fishing industry perspectives on the socioecological factors driving catchability and landings of Atlantic Mackerel in US waters

Submitted by: Northeast Fisheries Cooperative Research Program & Fishing Industry Partners

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ABSTRACT
Recent US assessments of Atlantic mackerel have been highly uncertain. Assessment models have indicated that dramatic changes have occurred in the catchability of mackerel in the federal bottom trawl survey or in other unknown population processes that are difficult to explain. As a result US landings have often been treated as an important indicator of the scale of the mackerel population and have been used to develop harvest policy. Daily engagement with the task of catching mackerel to meet demand in global markets within the context of management regulations gives fisherman and their associates them expert and practical insights into the topics of population availability and the detectability of Atlantic Mackerel in US waters, as well as the regulatory and economic drivers of US landings. We summarize perspectives of expert mackerel fisherman on these topics in an effort to provide information we hope will be valuable to discussions in, and improve the accuracy of the 2017 Atlantic Mackerel Assessment.

Following an introduction, methods and a discussion of limits to the scope of fisheries observations in sections 1-3, we summarize fishery knowledge about the factors affecting the catchability of mackerel (4). We discuss patterns of migration and distribution including changes seen by the fishery over the past 35 years (4.1). This is followed by a description of the methods fisherman use to search for fish at broad to fine scales, including the way fishery hydroacoutics can be used to identify and distinguished

mackerel from other species (4.2.2). We also describe observations of structure of mackerel schools and how school structure has changed over time. In section 4.2.2 we discuss trawl gear, tows speed and duration, estimates of the efficiency of commercial trawls for catching mackerel.

In section 5 we provide a brief history of US mackerel landings, including changes in fishing technology and the development of governance of the mackerel fishery. This section includes a description of regulatory constraints impacting recent mackerel landings (5.2), including the effects of spatial management regulations and catch caps. Finally, Markets and market forces on landings are summarized in section 5.3.

1) INTRODUCTION

The accuracy and credibility of fish population assessment and fishery management measures can be increased by integrating the knowledge of fishing industry experts (Bergmann et al. 2004, Stephenson et al. 2016, DeCelles et al. 2017, Yates 2014). Fishermen can provide detailed information acquired in daily fishing operations about the movements and habitat associations of the animals they target; knowledge they share within their communities. They have deep understanding about the ways the capture efficiency of fishing gear is determined by fish behavior, gear design and performance. Fishermen can therefore provide insights into the two components of catchability; population availability and detectability (= net efficiency). Furthermore fishermen, fish processors and dealers possess an in depth understanding of the economic and regulatory incentives and constraints imposed on fishing operations and fishery landings. The accuracy of interpretations of fishery land[illegible] often used in assessments and fishery policy making to infer the scale of fish populations, can be improved by considering the knowledge of fishing industry experts.

Atlantic mackerel have supported an important but ephemeral fishery on the east coast of the US since the early 19th century. Mackerel are a fast swimming, schooling, boreal pelagic fish. Their complex habitat ecology which is coupled to dynamic properties and processes in the water column is reflected in highly plastic patterns of schooling, migration and geographic distribution (Neill 1984, Walsh et al. 1995, Reid et al. 1997, Bruge et al. 2016). These characteristics make Atlantic mackerel populations notoriously difficult to assess. Recent US assessment models have produced strong retrospective patterns indicating that processes underlying mackerel population dynamics and/or observations of them that were assumed to be stationary, changed over time (Deroba et al. 2010, Hurtado-Ferro et al. 2014, Legault 2009). In the 2010 Transboundary Assessment, these retrospective patterns were addressed by splitting the NEFSC bottom trawl survey time series into three segments (Deroba et al. 2010). This approach produced model based estimates of survey catchability that increased substantially over time and could not be explained. Further the model could not resolve conflicting trends in US fisheries landings and abundance indices and age class structure developed from the spring NEFSC bottom trawl survey. The model was rejected by the Stock Assessment Review Committee and could not be used to develop fishery reference points. The Mid-Atlantic Fisheries Management Council (MAFMC) therefore developed a harvest policy based upon US commercial fisheries landings combined with estimates

of recreational and Canadian catch. Using landings to develop harvest policy assumes that landings primarily reflect the health of fish populations including its size and age class structure.

This working paper summarizes knowledge of fishing industry experts about a) factors affecting catchability of Atlantic mackerel in the North West Atlantic and b) socioeconomic drivers of landings. Given the high level of uncertainty in assessment model based catchability estimates and the historic importance of fishery landings in developing harvest policy for Atlantic mackerel we believe that a summary of fishing industry perspectives on catchability and landings could help to improve the accuracy of the 2017 assessment.

2) METHODS

Three sources of information were used to develop this document. We synthesized information collected at two *Atlantic Mackerel Population Ecology and Fishery: Industry & Science Perspectives Workshops* held in Point Judith, Rhode Island in December of 2015 and 2016. We also conducted unstructured and structured interviews of fishing industry experts over two years. Structured interviews were performed to clarify information after synthesizing information gathered in the workshops and extensive unstructured interviews. The experts included fishermen, processors and dealers who sell mackerel in national and international markets as well as government liaisons.

For the structured interviews we developed a questionnaire (*appendix 1*) covering a range of topics from personal fishing experience and practice, to fish behavior and markets. Six fishermen were selected based on their experience in the mackerel fishery. All six members are active industry collaborators in the NEFSC Cooperative Research Program. The captains were given the questionnaire for review before the interviews were conducted. The interviews were conducted in person, over the phone and/or by email correspondence. Two fishermen who fish for mackerel using small-mesh bottom trawls, one who fish a single mid-water trawl and three who fish using paired mid-water trawls participated in the semi-structured interviews. One of the small mesh bottom trawl fishermen also participated in the nearshore gillnet fishery in the 1960s and 1970s and one midwater trawler had once worked on a purse seiner. These fishermen along with others interviewed more informally provided a diverse view of the fishery. However all fished primarily onboard commercial trawlers. We were not able to formally interview fishermen participating in the inshore jig fishery that recently developed in 2013-2014 in the Gulf of Maine or the winter for-hire rod and reel fishery in the southern part of the mid-Atlantic. Jig fishery landings are included in the coastal rod and reel and handline landings of mackerel. These landings increased from 188,637 lbs in 2013 to 647,411 lbs in 2014 and were nearly 2 million lbs in 2016. Assuming that the jig fishery is responsible for significant portion of these landings the fishery is not insignificant. The perspectives of participants in that fishery are not included here.

To create this summary document we compiled and synthesized information from the workshops, unstructured and structured interviews into draft sections on specific topics. Industry experts then reviewed each individual section and their comments were

integrated into a draft of the entire document. This draft was then sent to five industry partners for final review. To the best of our knowledge this final draft accurately reflects the perspectives of most of the Mackerel fishery.

3) SCOPE OF FISHERY OBSERVATIONS

Fishery observations are necessarily limited by the scope of fishing activities in space and time. The spatial and temporal scope of fishery observations is a complex function of interdependent factors including market values of species and alternative species which are size and condition dependent, as well as economic, logistical and regulatory constraints. Until 2014, most large landings mackerel have been made in southern New England and the mid-Atlantic Bight during the winter and early spring. After 2014 a Research Set Aside (RSA) quota provided a bycatch buffer for herring that allowed the industry to resume fishing for high value mackerel in the western Gulf of Maine during the fall (see below). Mackerel are also sometimes landed in the Gulf of Maine during the summer by trawlers working the western side of Georges Bank or by the coastal jig fishery. The observations summarized in this document reflect the perspectives of fishermen who have fished for mackerel primarily in the fall, winter and spring mostly with trawl gear and within the contraints of regulations since the 1950s.

4) CATCHABILITY

4.1) Availability: Mackerel migration and distribution as viewed by the fishery

Mackerel that spend summers in US waters use nearshore coastal waters in Maine, New Hampshire and Massachusetts. They aggregate in the fall to feed at depths of 10-20 fathoms (20-40M) in the western Gulf of Maine in the vicinity of Stellwagen Bank before migrating to overwintering habitats. Fishermen have also observed aggregations of mackerel off Halifax, Nova Scotia in the summer that move down the Bay of Fundy into the Gulf of Maine during the fall. Coastal waters around Cape Cod, Nantucket and Martha's Vineyard are thought to serve as the primary migration pathway for mackerel from the Gulf of Maine into Southern New England Waters during the fall and winter. Fishermen have also observed mackerel moving through the Cape Cod Canal into Buzzards Bay and along the continental shelf break.

Before 1990 large fish migrated first in shallow coastal water (< 10 fathoms = 18M), as early as November, from the Gulf of Maine into Southern New England. Winter migration into Southern New England waters occurred earlier during years when fall seasons were cold and stormy. Historically, large fish migrated south along the New York and New Jersey coasts to gather outside Chesapeake Bay by late February/early March. During some years fish moved as far south as Cape Hatteras. Since 2000, large schools of mackerel have not moved into Southern New England until after the first of January. Fishermen reported a second run of fish into Southern New England and the Mid-Atlantic Bight that occurs in deeper water. This second run that included smaller individuals than the inshore run, moved south into the region at depths of 30-50 fathoms (55-90 M) several months after the inshore run of large fish (~January). In some years these fish moved as far south as Chesapeake Bay where they presumably mixed with fish from the inshore run. In more recent years these fish aggregated to the north in the vicinity of the Hudson Shelf Valley. Most of the mackerel migrating along the shelf

break into the mid-Atlantic Bight are thought to remain associated with the shelf break or slope during the winter. They can form aggregations in canyons south of Spencer's Canyon where they are caught incidentally in the winter small mesh trawl fishery.

Mackerel begin to migrate north in late March and April. Fishermen who participated in inshore gillnet fisheries report the existence of a run of large fish that would migrate north along the coasts of Virginia, New Jersey and New York in shallow water just outside the surf zone. These fish remained high in the water column and were not available to trawl gear. They were accessible with gillnets and rod and reel. These fish have been monitored in the past (Christensen and Clifford 1980). Another body of fish that included smaller individuals migrated north in deeper water. If this run began the migration in the vicinity of Chesapeake Bay, they moved 10 fathoms (~20M) deeper with every 100 nautical miles (185km) of migration. By the time they reached the Hudson Canyon they were near the shelf break. These fish were more strongly associated with the seabed than the inshore run and could be caught by trawlers. Some of these fish are believed to move back inshore from the southern New England canyons to migrate into the Gulf of Maine through Nantucket Sound and the Great South Channel. Other mackerel remain along the shelfbreak to migrate east to the northeast peak of Georges Bank. Several fisherman report that they catch mackerel in the New England canyons, including Oceanographers, Gilbert, and Lydonia in late March and April while the main bodies of fish are to the southwest. These fish have a "skinnier" body morphology than most mackerel and are trawled in waters as deep as 150 fathoms (275M). The fisherman interviewed speculated that this may be evidence for a a fourth body of fish that moves into the canyons from deeper water or perhaps from the northeast.

Fishermen have observed important changes in the distribution and movement patterns of mackerel which they attribute to changes in the environment (temperature, prey availability, predator distributions and abundance, particularly spiny dogfish, and nearshore water quality). Some fishermen believe these environmental changes are cyclic while others believe them to be persistent. The run of large fish moving in shallow water along the coast as far south as Cape Hatteras was available to the winter fishery in the 1970s and 1980s. As this coastal run of large fish began to diminish in the 1980s and 1990s, the fishery shifted its focus to the second run of fish that occurred on the continental shelf in deeper water. After 1998 large fish have typically been unavailable to the mid-Atlantic Bight winter fishery in the coastal zone. However, party boat fishermen caught relatively large mackerel (300-600 gram) for several weeks in February and early March of this year (2017) close to shore (within 10 nm) in the vicinity of Ocean City, MD, Chincoteague, VA and Virginia Beach, VA. Fishermen reported that they had not seen an abundance of large mackerel in the area for the past 15 years. In recent years most catches of mackerel during the winter have occurred on the Southern New England Shelf to the north side of the Hudson Shelf Valley. It should be kept in mind that reductions in the size of fleets fishing for mackerel, spatial and temporal constraints placed upon on the fleet by regulations and the shift from a targeted to an opportunistic mackerel fishery due to regulation and economics, including the high demand for herring as bait, has limited fishery observations of mackerel in recent years.

4.2) Detectability: *"Now, mackerel think they are herring."*

4.2.1 Searching at broad scales and observations of school structure

Long and short term fishing history and reports by word of mouth within fishing social networks provide important information for determining the search patterns of fishermen for mackerel schools at large spatial scales (10s to 100s of km, 5-55nm). Once at sea, fishermen hunt for mackerel schools and only set nets when marketable quantities and sizes of fish are available in those schools. Schools can be visible at or near the surface at distances of a few km to 10s of meters (~2nm -100s of yards) particularly at night when the fish agitate phosphorescent organisms in the water and "light up". Sea-surface temperature is also an important cue at sea. All vessels are equipped with hull mounted sea-surface temperature sensors. Some vessels have temperature sensors integrated into net mensuration sensor systems deployed on fishing nets and doors. The fishermen interviewed search for mackerel in sea-surface temperatures ranging from 43-48° F (6-9°C) in the winter to the low 60s°F (~18°C) in the fall. Fishermen report that mackerel exhibit different seasonal temperature preferences. These seasonal preferences have not changed over the years.

Fishery hydroacoustics

All captains use fishery hydroacoustics to locate and identify mackerel at finer horizontal and vertical scales (meters to 100s of meters, yards-100s yards). Most vessels are equipped with sounders with multiple acoustic frequencies ranging between 38 or 50 Kilohertz (kHz) to 200 kHz. Atlantic mackerel do not have swim bladders and are therefore best detected on sounders with frequencies of 200 kHz. Because high frequency sound attenuates quickly with increasing depth, mackerel are difficult to detect in 200 kHz machines at depths much greater than 100 fathom (~200M). Mackerel are generally detected close to the bottom except during late spring when the fish spend most of their time swimming in the water column.

Fishermen use the acoustic signatures of school structure and target strengths at different frequencies to differentiate mackerel from other species. Mackerel tend form uniform schools with smooth tops that stretch along the bottom, though when they are abundant they often form columns that rise high into the water column. In contrast, herring form schools of more irregular shape that often form thin spikes into the water column. Menhaden, which can be associated with mackerel during the winter in the mid-Atlantic form distinctive ball shaped schools. Dogfish are shaped like "boomerangs" in fishery hydroacoustics. These other species have unique signatures visible on lower hydroacoustic frequencies than mackerel.

School structure

All captains interviewed agreed that mackerel school size and the ways mackerel interact with other species, especially herring, has changed over time. Fishermen were able to follow very large schools of mackerel, sometimes several square nautical miles in surface area, from Cape Cod to as far south as Virginia. Size segregation occurred between or within large schools. In schools that contained mixed sizes of mackerel, large fish usually schooled in the water column above smaller fish. Jigging with rod and reel or short test tows are used to determine the size composition of mackerel schools before trawls are set

for fishing. The last large schools of large fish (>400grams) were caught in 1998. The last large schools of smaller fish (≤400grams) were fished in 2006. During this period large pure schools of mackerel were common. When large mackerel schools mixed with herring, the mackerel would aggregate close to the seabed while herring schooled above them in the water column.

In more recent years fishermen have been observing smaller schools of mackerel, referring to them as "chips" based on signatures of small school size in fishery hydroacoutics. Sometimes, small schools of mackerel will form within larger schools of herring. These small mackerel schools can be identified with hydroacoustics. At other times mackerel freely intermingle with herring. If mackerel are freely mixing with herring captains will conduct short test tows or jig to determine how much mackerel are present and the size composition. Catches of small mackerel and herring are difficult to sort and the market for landings of mixed herring and mackerel is very limited. One fisherman observed *"Now, mackerel think they are herring"*. The observations of fishermen about the associations of herring and mackerel and schooling are consistent with the ideas of dominance in co-occurring schooling pelagic fish including herring and mackerel proposed by (Skud 1982, see also (Olafsdottir et al. 2015) and the mixed school trap hypothesis (Bakun 2001, Bakun and Cury 1999).

Mackerel exhibit seasonal changes in school structure. When fish are migrating, schools thin and segregate by size. Large fish arrive before smaller fish. Fishermen believe this pattern reflects the size dependence of swimming speeds. Schools made up of different sizes of fish that aggregate together off Halifax, Nova Scotia in the summer, the western Gulf of Maine during the fall before winter migration begins and in southern New England and the mid-Atlantic Bight during the late winter/early spring as the overwintering period ends. As stated above, schools are more strongly associated with the water column in the spring.

Mackerel tend to school more densely during the day than at night and tighter schools can form on sunny days than on cloudy days. Some fishermen believe mackerel form the densest schools just before sunset or just after sunrise. Often mackerel form dense schools on the bottom as storms approach. Schools of mackerel may break up on windy days, but will reform quickly after wind velocities decrease and/or the wind shifts direction. Marine mammals, dogfish and other predators may sometimes cause schools to disperse, while at other times they may cause the fish to form more compact schools.

4.2.2 Gear, tow speed and duriation, and other technical challenges:

"At one time it was lucrative, fun and exciting, I loved the hunt. It ain't just the money."

Nets

Most of the nets used by the captains interviewed were made primarily by three companies; Superior Trawl in Point Judith, RI, Swan Net USA in Seattle, WA and Dantrawl Incorporated in Seattle, WA. These nets are designed to take advantage of the behavior of schooling pelagic and semi-pelagic species. Though some nets are called mid-water trawls, all the nets are most efficient when fished close to or lightly touching

the bottom. The nets vary in dimension but have similar designs. The nets are built with long wings to achieve a high vertical opening in the front of the net. The wings have large meshes that gradually taper to smaller sizes toward the codend. Codends or "brailers", used for mackerel are usually made of 3" mesh. The large meshes (up to 44 feet = 13.5M) in the net wings serve multiple purposes. First the large meshes reduce the drag of the net allowing for greater towing speed. Second, the large meshes exploit schooling behavior of mackerel causing them herd into the net. Finally, the large meshes allow many other, unwanted species to escape. It can be difficult to separate sort small mackerel from herring through mechanical means and there is a limited market for mixed fish. Thus there is an economic incentive for clean catches of mackerel in addition to the regulatory imperatives related to bycatch.

Tow speed and duration

Captains interviewed tow at speeds ranging from 2.8-5 knots. Most agreed that faster tows are more effective because mackerel are strong fast swimmers. Preferred towing speeds don't change seasonally and have been consistent over the years. Some captains report that swimming speeds of mackerel schools can increase in an area as vessels increase their towing speeds. The arrival of a boat towing at a faster speed can reduce the efficiency of a boat towing at a slower speed.

The behavior of the fish and processing method used by the vessel determine tow durations. As a result, durations vary widely, ranging from ~10 minutes to several hours (average ~2 hours). When the fish are tightly schooled together, a large volume of fish can be caught over a short time and tow durations are short. Many boats are equipped with a 3rd wire system which allows fish to be viewed with profiling hydroacoustic systems. These systems scan the fishing circle of the net and allow the fish and their behavior to be observed in real time. On some vessels the nets are equipped with catch sensors that indicate the volume of fish in the codend and when the net should be retrieved. These sensor technologies are used to estimate volumes of fish in the net. Tow duration and the volume of fish brought onboard is a function of the method of shipboard processing and storage. Vessel which freeze at sea will limit catch volumes and rates to avoid exceeding processing capacity, mainly freezing rates. Vessels with refrigerated seawater systems (RSW) can put large volumes of fresh fish directly into the hold. To maintain the quality of product, RSW trawlers generally make shorter duration trips than freezer trawlers. Captains will also reduce tow durations when they are uncertain of the species composition in the area. Vessels tow for shorter durations now than in the past due to fears of exceeding bycatch limits and tripping accountability measures.

Estimates of net efficiency

The fishermen's estimates of overall net efficiency vary from 10% to as high as 80%. Based on previous experience in the more efficient purse seining fishery one captain believed his pair trawl net is probably 20%-30% efficient. Efficiencies of nets on single boat trawlers are lower because the vessels in pairs produce herding and diving behaviors in mackerel that increase net efficiency.

Despite disagreements about overall net efficiency, all captains agreed that factors affecting net efficiency are complex and contingent. Fish are sometimes easiest to catch when they occur in high densities and schools become "disoriented". However, unpredictability in school responses can make them difficult to fish and dispersed fish can be easier to capture. However, if the fish are dispersed fishing for them is unprofitable. Some believe that catches are highest when tows are made in the direction opposite the direction a mackerel school is swimming in. Smaller fish are more likely to escape through the large meshes in the wings of commercial nets and larger mackerel can exhibit better net retention though their fast swimming speeds make them difficult to capture. Fish are also easier to catch in shallower water as there is less open water above the net to escape into. Mackerel are most difficult to catch during the spring migration when they move at high speed, often well above the seabed. The presence of other species can impede or enhance mackerel catches. For example, dogfish make processing difficult and damage gear. Thus, if dogfish are abundant in an area, fishermen may not set nets even if mackerel are abundant. Predators can make schools disperse or become more concentrated. The efficiency of nets is dependent on the behavior of schools of mackerel of different sizes, size structures and concentrations. Fishermen observations are consistent with scientific literature describing the behavioral complexity of schooling pelagic fish (Couzin et al. 2006, Ward et al. 2008, Ritz et al. 2011)

Mackerel are unpredictable with respect to seasonal, geographic and depth ranges of occurrence. Fishing for them is hunting and uniquely different from fishing for many other species. On successful trips, up to 80% of the time can be spent hunting for schools and/or orienting tows to the movement of schools. If tows are not set up and executed correctly the likelihood of catching mackerel can be low even when a large school is present. All captains have made trips in which they searched for schools of mackerel but did not find them or were not able to make a tow.

5) LANDINGS

5.1 A brief history

Throughout recorded history (1804 – 2015) landings of Atlantic mackerel in US waters have been variable based on data assembled from two separate sources (Hoy and Clark 1967, Atlantic Mackerel Update assessment for 2017, https://static1.squarespace.com/static/511cdc7fe4b00307a2628ac6/t/5720e48dab48de3e8ab30892/1461773454206/mackerel_data_update_2016.pdf, Fig. 1). Five important shifts in landings can be identified using nonparametric statistical techniques for detecting of changes in scale and variability in time series (appendix 1). These are described below along with the major changes in fishing technology and fishery regulations associated with them.

Following an initial increase from 1804 to 1822, landings averaged approximately 43,000 mt (SD=16,199 mt) from 1823 to 1885. From 1804 to 1850 most fish were caught with hook and line, although pound nets, weirs and gillnets were also used. The purse seine fishery developed from 1850-1870. Until 1886 the fishery was executed exclusively with sailing or manually powered vessels and mackerel were preserved and sold salted (Pierce 1934, Sette and Needler 1934, Anderson and .J. 1980).

In 1885 landings declined and were relatively low from 1885 to 1923 (mean=9361mt; SD=4211mt). From 1886 to 1924, the industry made the transition from sail to motor powered vessels and the markets shifted from salted to fresh mackerel (Pierce 1934, Sette and Needler 1934, Anderson and .J. 1980). Landings increased from 1923-1950 (mean= 22,588 mt; SD= 5835 mt).

Modern trawling techniques became fully developed after 1949 when many technologies developed during World War 2 were commercialized (Sette and Needler 1934, Anderson and Paciorkowski 1980). These technologies included improved engine, winch and ship design and building, as well as sensors like sonar. From the mid 1950s through 1976 foreign flagged vessels from Russian, Poland, East Germany, Lithuania and the Netherlands caught most of the mackerel in US waters (see Chuksin 2006). There was a brief period from 1968-1977 when catches of mackerel by the foreign fleets were extremely high (Mean=243,301mt, SD=128,386mt. 1973 Peak = 398,000mt).

In response to the first signs of decline in mackerel population size and age class structure, quotas limiting Total Annual Landings for Foreign Fleets (TALFF) were established under the International Convention of the Northwest Atlantic Fisheries (ICNAF) beginning in 1973. In March of 1977, the Magnuson-Stevens Fishery Conservation and Management Act became effective, establishing the 200 mile exclusion zone and denying access to mackerel and other fish in US territorial waters to most foreign fishing fleets. However some TALFF quota was allocated as late as 2001.

Since 1977, reported landings have averaged 24,257mt (SD=19,163) and maxima (58,000 mt in 2006) and are similar to those of the period between 1823 and 1885 (64,000 mt in 1830; Fig. 1). However, recent landings have cycled dramatically with a ~17 year period through two peaks (1990, 2006) and two troughs (1993, 2011; Fig. 2). Thus the dynamics of landings are different now. A number of important changes occurred in the fishery and its governance during the recent period. Since the shore-side capacity to process large volumes of pelagic fish did not exist on US East Coast in the 1970s, a Joint Venture (JV) program was implemented in 1978 to allow US vessels fishing under US quota regulations to pass codends or pump mackerel to foreign vessels for processing. Since East German vessels played an important role in these JVs, the program began to wane with the fall of the Berlin Wall in November 1989. The last of the Joint Ventures dissolved in 1998, though JV quota was allocated as late as 2004. In 1979, the MAFMC developed a fisheries management plan (FMP) for Atlantic mackerel. The mackerel FMP was merged with FMPs for longfin and shortfin squid and Atlantic butterfish in 1981.

Following optimistic mackerel stock assessments in the late 1990s (Allowable Biological Catch (ABC)=1,175,500 mt in 1996), the National Marine fisheries Service encouraged capacity building in domestic vessel and shore-side infrastructure (Table 3). In response, the fishing industry invested approximately 25 million dollars in shore-side capacity and 35 million dollars in large, fast vessels capable of harvesting large quantities of mackerel between 1999 -2003. However, mackerel did not become available to the fishery in the quantities predicted. Although the ABC was predicted to be ~350,000 metric tons in

2005 and 2006, landings peaked in 2006 at 58,000 mt when the modern fleet of large vessels reached its maximum size (21 vessels; Fig 3). From 2007 to the present landings have declined averaging 27-30 % of annual quotas. The fleet has also declined in size. Since 2011, less than 7 vessels have been responsible for most of the mackerel landings.

5.2 Regulatory constraints on landings

"Less is more. Coherent multispecies ecosystem based assessments should result in fewer, more rational fishery management regulations facilitating sustainable harvest of living marine resources."

The mackerel fishery is subject to exceptional regulatory complexity because its governance has been structured based on historical seasonal fishing patterns rather than the ecology of the species. This regulatory complexity affects fishing effort by vessel capacity and gear, in both space and time. As a result effort and landings do not reflect mackerel population size or the efficiency of the fleet.

Since the 19th century, the largest catches of mackerel in US waters have occurred in the mid-Atlantic Region during the winter. As a result, the mid Atlantic Fisheries Management Council (MAFMC) developed the fisheries management plan for Atlantic mackerel. However, Atlantic mackerel have a strong ecological association with Atlantic herring. The species often co-occur in mixed schools and their population dynamics on both sides of the Atlantic are strongly coupled (e.g. Skud 1982, Olafsdottir et al. 2015) and see above). Most large capacity trawlers in the US mackerel fishery also target herring with the same gear (usually only the codends are different). However, most herring landings occur in the Gulf of Maine during the summer and nearshore Southern New England during the winter. As a result, the New England Fisheries Management Council (NEFMC) developed the fisheries management plan for Atlantic herring. In addition, the Atlantic States Marine Fisheries Commission (ASMFC) also restricts herring landings which directly impacts landings of mackerel. Thus large capacity vessels in the mackerel fishery are affected by regulations developed under two FMPs and implemented by three different fisheries management bodies.

Spatial regulations

The MAFMC currently imposes no spatial constraints on the mackerel fishery. However, because herring and mackerel often occur in mixed schools, it can be extremely difficult to trawl marketable volumes of mackerel without also catching at least some herring. Trawlers in the mackerel fishery and their landings are therefore directly restricted by spatial aspects of the Atlantic herring FMP as well as state landings restrictions for herring.

In the herring FMP, the fishing grounds are divided into four Herring Management Areas; 1A (Inshore Gulf of Maine), 1B (Offshore Gulf of Maine), 2 (South Coastal Area) and 3 (Georges Bank) (Fig 4). Management areas 1,2 and 3 were initially established in the 1993 under ASMFC Atlantic Herring Management Plan. Since ~2003, Herring Management Area 1A has been closed to directed herring fishing, with a 2,000 lb

possession limit from January through May. Since 2007 Area 1A is also closed to midwater trawlers from June through September. Area 1A is also subject to three rolling spawning closures for herring usually starting in mid-summer in the eastern Gulf or Maine and "rolling" west into October. Herring Management Area 1B is closed to directed herring (2,000 lbs possession limit) fishing from January 1st through April 30th. Since 2006, restrictions in the herring FMP that limit herring harvest, have also limited mackerel landings by midwater trawlers in Herring Management Areas 1A and 1B throughout most of the year (Table 1).

The Herring Management Area sub-Annual Catch Limits (sub-ACLs) also affect the availability of Atlantic mackerel to the trawl fishery and mackerel landings. Vessels can only possess 2,000 lbs of herring when the sub-ACL for herring is reached in a given area. In nearly every year since 2001 (the exception is 2006) at least one Herring Management Area has been effectively closed to mackerel fishing by trawlers as a result of the sub-ACL for herring (Table 2).

The Atlantic herring research set aside (RSA), incorporated in the Atlantic herring FMP as a quota set aside to fund research, auctions herring quota to fishermen to fund fisheries research. This RSA has also affected the dynamics of the mackerel fish and therefore its landings. In 2013, NEFMC reinstated the Herring RSA. Vessels purchasing herring RSA quota are allowed to fish for herring in a given Herring Management Area regardless of the status of the sub-ACL. This extra herring quota provides a bycatch buffer for vessels targeting mackerel even after the herring quota is reached. Since 2014, the herring RSA quota has permitted a fall mackerel trawl fishery to develop in Area 1B. This area which includes Stellwagen Bank has supported a productive fall mackerel fishery throughout recorded history (Pierce 1934, Sette and Needler 1934, Sette 1950 , Anderson and Paciorkowski 1980).

Groundfish closures in the Gulf of Maine and Georges Bank (Fig. 5) also restrict mackerel harvest. Five year-round closed areas were established in 1994 to supplement rolling closures first implemented in the 1970s (NEFMC, 2014). These include Closed Areas I and II on Georges Bank and the Nantucket Lightship Closure Area established in 1994. The Western GOM Closure Area and Jeffrey's Ledge were added in 1998. The Cashes Ledge Closed Area in the central Gulf of Maine was closed in 2002 (NEFMC 2014). These closed areas are not off-limits to all fishing activities. Amendment 5 to the herring FMP developed in 2015 began to allow midwater trawlers into these areas for mackerel fishing during certain periods but only if fisheries observers are present on the vessels. If an observer is not present the vessels are not allowed to cross into the groundfish closed areas.

The Northeast Canyons and Seamounts Marine National Monument created in 2016 is also a spatial restriction that affects mackerel fishing. Although this area has not traditionally produced large volumes of mackerel, there are fishermen who have caught fish relatively consistently there (Fig. 5).

*Catch Cap*s

Catch caps for a number of species also constrain the availability of mackerel to the fishery, fishing effort and landings in complex ways. Since the late 1970s, managers have periodically tried to address concerns about the health of river herring populations (alewife, blueback herring and American shad) including the effects of fisheries. In 2014 catch caps for river herring were established independent in the mackerel and herring fisheries. This has created extremely complex set of constraints because many of the same large vessels fish for both species that can form mixed schools.

In the mackerel fishery, the river herring catch cap is developed by the MAFMC as part of the Atlantic mackerel FMP and covers the entire spatial extent of the mackerel fishery for all gear types. If an observed trip lands more than 20,000 lbs of mackerel, the extrapolated river herring weight caught counts against the mackerel river herring catch cap. If the river herring catch cap in the mackerel fishery is exceeded the mackerel possession limit is decreased to 20,000 lbs. At current prices (usually ~10-15¢ per pound), fishing at this limit is not economical for large vessels.

In the Atlantic herring fishery, the river herring catch cap is developed by the NEFMC as part of the Atlantic herring FMP. There are five separate river herring catch caps in the herring fishery. These are midwater catch caps for the Gulf of Maine, Georges Bank, Southern New England/Mid-Atlantic and east of Cape Cod (Statistical Area 521) (Fig 6). There is also a separate small-mesh bottom trawl catch cap in the Southern New England/Mid-Atlantic. If an observed trip lands more than 6,600 lbs of herring, the extrapolated river herring caught counts against the herring catch cap. If one of the river herring catch cap is exceeded that specific component of the herring fishery has its possession limit decreased to 2,000 lbs. For example, if the Mid-water Southern New England/Mid-Atlantic catch cap is exceeded, midwater vessels can only possess 2,000 lbs of herring. This sets also sets a bycatch limit on the mackerel fishery because mackerel and herring form mixed schools.

When a vessel lands more than 20,000 lbs of mackerel and 6,600 lbs of herring (a common occurrence), the extrapolated river herring catch counts against both caps. This can lead to situations in which the river herring catch cap for one species directly limits the fishery for the other. Currently, the Atlantic herring Cape Cod Mid-water River Herring Catch Cap is projected to be roughly 80% of the allowable catch. The fleet has imposed a fishing moratorium on itself for fear of exceeding the Cape Cod Mid-water River Herring Catch Cap. This moratorium in response to the herring catch cap, has also terminated mackerel fishery in this area, even though the mackerel fishery is only at 42% of its river herring catch cap. Thus this self imposed moratorium is affecting US landings of mackerel.

There are also Haddock Incidental Catch Caps for the Gulf of Maine and Georges Bank stock areas in the herring fishery developed in 2006 that impact mackerel landings (Fig 7). The caps are set at 1% of the haddock Acceptable Biological Catch in each stock area for the groundfish fishing year (May 1-Apr 30). If the haddock catch cap is reached in a haddock stock area, all vessels fishing mid-water trawl gear are prohibited from possessing or landing more than 2,000 lbs of herring for the remainder of the groundfish

fishing year. In late October 2015 the Georges Bank haddock catch cap was reached, effectively closing Herring Management Area 3 until May 1, 2016. This closure in the fall of 2015 effectively eliminated the winter and spring mackerel fishery in Area 3 which includes Georges Bank and the eastern part of the southern New England shelf. This depressed mackerel landings for during the winter of 2015 and 2016.

In summary failure to account for the ecological overlap of Atlantic mackerel and Atlantic herring in the development of fisheries management has led to a complex set of spatial and temporal restrictions that have been developed and implement multiple federal and state jurisdictions. The complexity of these regulations constrain fishing effort and landings are therefor unlikely to be an accurate proxy for the biomass of the mackerel population.

5.3 Market forces

Fishermen fish for dollars, not for fish and economic demand in both domestic and global markets is an important driver of fishing effort, selectivity and landings. Captains target mackerel to meet demand in food and bait markets.

Mackerel caught for food are primarily sold fresh or frozen; sorted by size at shore side facilities or at-sea. Fish are sorted by weight classes in grams (100-200, 150-300 (avg. 215-225), 200-400 (avg. 285-320), 300-500 (avg. 385-425), 400-600 (475-525), 600-800). The fresh market is largely restricted to the USA and Canada, while frozen fish are sold world-wide into different markets demanding fish of different prices, sizes and fat contents. Large high quality fish are marketable in Europe and Asia while lower quality fish are sold in North and West Africa. Larger weight classes of mackerel with the highest fat content generally receive the highest price and are therefore preferred targets of fishermen. These fish are usually harvested in US waters during the fall and winter in the southern Gulf of Maine, Southern New England, and the mid-Atlantic Bight. Smaller fish in poorer condition command lower prices and are sold in North and West African markets including Egypt. US Supplies of fish compete with supplies from Europe as well as from new fisheries in Iceland and the west coast of Greenland which began to develop in 2007. Russia was an important food market for the global supply of high quality mackerel until the summer of 2014, when it boycotted imports of fish from countries, including the U.S, that imposed sanctions in response to the annexation of Crimea by Russia.

Bait markets for mackerel include food for aquarium and zoo animals, bait for commercial and recreational fishing of highly migratory species (HMS) or bait for lobster. Mackerel caught for bait are primarily sold fresh, frozen or salted. Aquariums and zoos use frozen fish with relatively high fat content as animal feed. Preferred characteristics of mackerel vary in bait markets that not all US dealers participate in. Leaner salted fish have a long life and retention on hooks and are therefore preferred in HMS fisheries using long lines. Frozen fish can be sold as bait to sport fishermen. The preferred size of mackerel depends on the HMS species targeted and the presumed prey size preferences of that species. The fat content and quality of mackerel decreases in the spring as feeding increases and the fish use energy stored in fats for spring migration to

spawning grounds and the production of gametes. These spring and early summer fish are of low value and are usually not targeted by fishermen. Mackerel in poor condition can be sold at the low prices as lobster bait when preferred alternatives, like herring, are rare.

ACKNOWLEDGEMENTS
We would like to thank the leadership of the Northeast Fisheries Science Center, specifically Jon Hare and Bill Karp for supporting the Climate, Ecosystem, Habitat and Assessment Steering Group CEHASG. This work grew out of a CEHASG focus on Atlantic Mackerel and the 2017 assessment. We also thank Chris Moore and the Mid Atlantic Fisheries Management Council, and Chris Roebuck (FV Karen Elizabeth) for generously supporting the *Atlantic Mackerel Population Ecology and Fishery: Industry & Science Perspectives Workshops*

LITERATURE CITED

Anderson, E. D., and Paciorkowski .J. 1980. A review of the Northwest Atlantic mackerel fishery. Rapp. P.-V. Reun. Cons. Int. Explor. Mer **177**:175-211.

Bakun, A. 2001. School-mix feed back : a different way to think about low frequency variability in large mobile fish populations. Progress In Oceanography **49** 485-511.

Bakun, A., and P. Cury. 1999. The "school trap": a mechanism promoting large-amplitude out-of-phase population oscillations of small pelagic fish species. Ecology Letters **2**:349-351.

Bergmann, M., H. Hinz, R. E. Blyth, M. J. Kaiser, S. I. Rogers, and M. Armstrong. 2004. Using knowledge from fishers and fisheries scientists to identify possible groundfish 'Essential Fish Habitats'. Fisheries Research **66**:373–379.

Bruge, A., P. Alvarez, A. Fontán, U. Cotano, and G. Chust. 2016. Thermal Niche Tracking and Future Distribution of Atlantic Mackerel Spawning in Response to Ocean Warming. Frontiers in Marine Science **3**:86.

Christensen, D. J., and W. J. Clifford. 1980. The 1978 spring recreational catch of Atlantic Mackerel, Scombe scombrus, off the Middle Atlantic regions. Fishery Bulletin **78**:799-805.

Chuksin, Y. V. 2006. From Cape Hatteras to Cabot Strait (The History of the Soviet Fishery on the Atlantic Continental Shelf of the United States and Canada).

Couzin, I. D., R. James, D. Mawdsley, D. P. Croft, and J. Krause. 2006. Social Organization and Information Transfer in Schooling Fishes. Pages 166-185 Fish Cognition and Behavior. Blackwell Publishing Ltd.

DeCelles, G. R., D. Martins, D. R. Zemeckis, and S. X. Cadrin. 2017. Using Fishermen's Ecological Knowledge to map Atlantic cod spawning grounds on Georges Bank. ICES Journal of Marine Science.

Deroba, J., G. Shepherd, F. Gregoire, J. Nieland, and P. Rago. 2010. Stock Assessment of Atlantic Mackerel in the Northwest Atlantic for 2010.

Hoy, D. L., and G. M. Clark. 1967. Atlantic Mackerel Fishery, 1804 - 1965. United States Department of The Interior.

Hurtado-Ferro, F., C. S. Szuwalski, J. L. Valero, S. C. Anderson, C. J. Cunningham, K. F. Johnson, R. Licandeo, C. R. McGilliard, C. C. Monnahan, M. L. Muradian, K. Ono, K. A. Vert-Pre, A. R. Whitten, and A. E. Punt. 2014. Looking in the rear-view mirror: bias and retrospective patterns in integrated, age-structured stock assessment models. ICES Journal of Marine Science: Journal du Conseil.

Legault, C. M. 2009. Report of the Retrospective Working Group January 14-16, 2008, Woods Hole, Massachusetts.

NEFMC. 2014. Omnibus Essential Fish Habitat Amendment 2 Draft Environmental Impact Statement (DEIS). **I-V**.

Neill, W. H. 1984. Behavioural enviroregulation's role in fish migration. Pages 61–66. *in* J. D. McCleave, G. P. Arnold, J. J. Dodson, and W. H. Neill, editors. Mechanisms of migration in fishes. Plenum Press, New York.

Olafsdottir, A. H., A. Slotte, J. A. Jacobsen, G. J. Oskarsson, K. R. Utne, and L. Nøttestad. 2015. Changes in weight-at-length and size-at-age of mature Northeast Atlantic mackerel (Scomber scombrus) from 1984 to 2013: effects of mackerel stock size and herring (Clupea harengus) stock size. ICES Journal of Marine Science: Journal du Conseil.

Pierce, W. G. 1934. Goin' Fishin'. The story of the deep-sea fisherman of New England. The Southworth-Anthoensen Press, Portland Maine.

Reid, D. G., W. R. Turrell, M. Walsh, and A. Corten. 1997. Cross-shelf processes north of Scotland in relation to the southerly migration of Western mackerel. ICES Journal of Marine Science: Journal du Conseil **54**:168-178.

Ritz, D. A., A. J. Hobday, J. C. Montgomery, and A. J. W. Ward. 2011. Chapter Four - Social Aggregation in the Pelagic Zone with Special Reference to Fish and Invertebrates. Pages 161-227 *in* L. Michael, editor. ADVANCES IN MARINE BIOLOGY. Academic Press.

Sette, O. E. 1950. Biology of Atlantic mackerel (Scomber scombrus) of North America. Part II. Migrations and habits. . U.S. Fish Wildl. Serv. Fish. Bull. **51**:251-358.

Sette, O. E., and A. W. H. Needler. 1934. Statistics of the mackerel fishery off the east coast of North America, 1804-1930. Bureau of Fisheries.

Skud, B. E. 1982. Dominance in fishes: The relation between environment and abundance. Science **216**:144.

Stephenson, R. L., S. Paul, M. A. Pastoors, M. Kraan, P. Holm, M. Wiber, S. Mackinson, D. J. Dankel, K. Brooks, and A. Benson. 2016. Integrating fishers' knowledge research in science and management. ICES Journal of Marine Science: Journal du Conseil.

Walsh, M., D. G. Reid, and W. R. Turrell. 1995. Understanding mackerel migration off Scotland: Tracking with echosounders and commercial data, and including environmental correlates and behaviour. ICES Journal of Marine Science: Journal du Conseil **52**:925-939.

Ward, A. J. W., D. J. T. Sumpter, I. D. Couzin, P. J. B. Hart, and J. Krause. 2008. Quorum decision-making facilitates information transfer in fish shoals. Proceedings of the National Academy of Sciences **105**:6948-6953.

Yates, K. L. 2014. View from the wheelhouse: perceptions on marine management from the fishing community and suggestions for improvement. Marine Policy **48**:39–50.

Table 1: The closure of specific Atlantic herring Management Areas due to exceeding either herring sub-ACL or haddock catch cap (* denotes an area that had a limited reopening).

		Year															
		2001	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**
Month	**1**																
	2												1B/2				
	3																
	4									2*				2			
	5														1B		
	6																
	7																
	8																
	9										1B	1B/3*			3		
	10											1A	3	1A/3			1A
	11	1A		1A		1A		1A	1A	1A	1A*		1A			1A/3	1B
	12		1A		1B	1B			1B								

Table 2: The current schedule of restrictions in the Atlantic herring fishery. The areas are either closed to all directed herring fishing (x), midwater trawling (y) or potentially all fishing because of spawning (z).

		Sub-Area			
		1A	**1B**	**2**	**3**
	1	x	x		
	2	x	x		
	3	x	x		
	4	x	x		
Month	**5**	x	x		
	6	y			
	7	y, z			
	8	y, z			
	9	y, z			
	10	z			
	11				
	12				

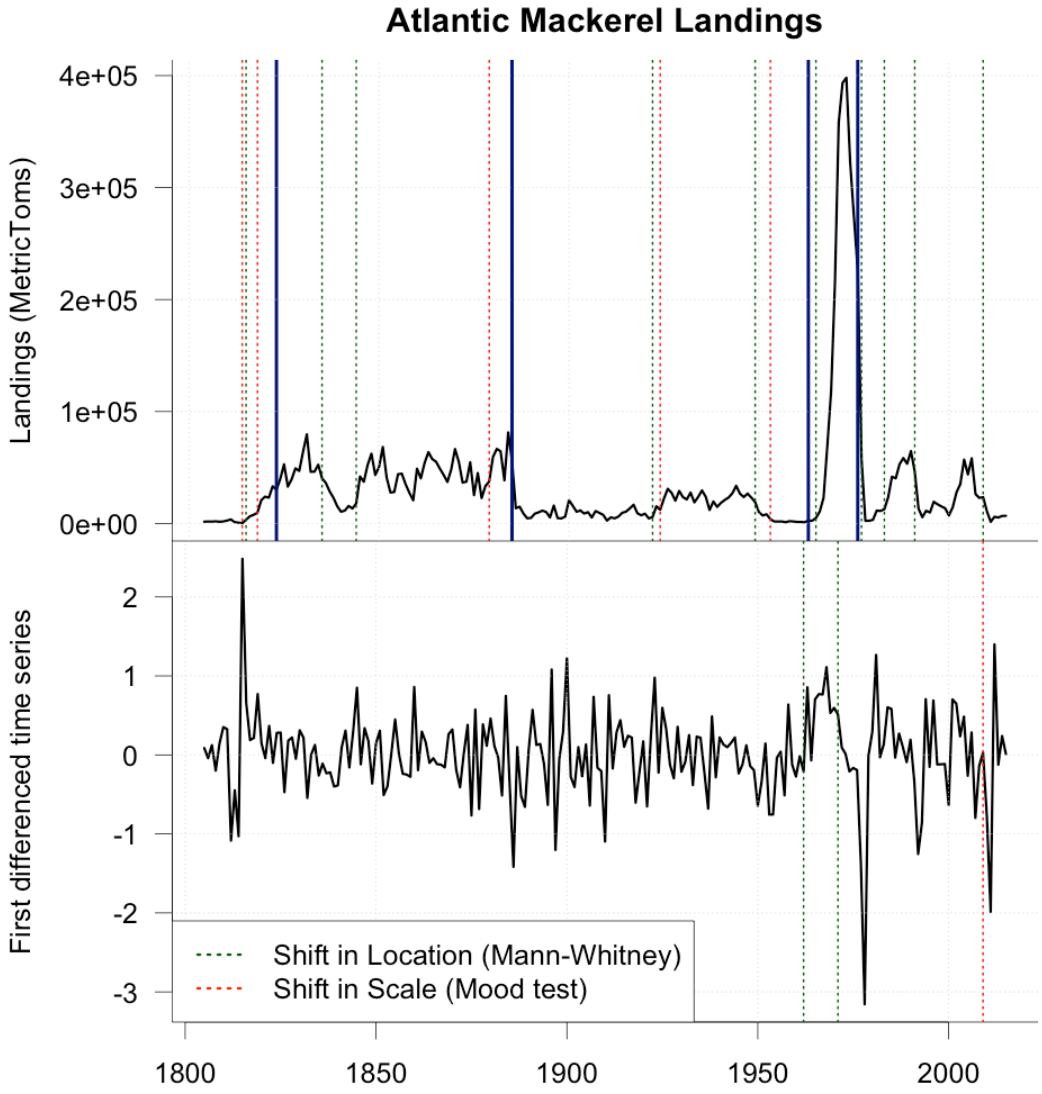

Figure 1). (*Top Panel*) Time series of US landings (in metric tons) of Mackerel from 1804 through 2016 compiled from {Hoy, 1967 #3458} and Atlantic Mackerel Update assessment for 2017 (https://static1.squarespace.com/static/511cdc7fe4b00307a2628ac6/t/5720e48dab48de3e8ab30892/1461773454206/mackerel_data_update_2016.pdf } *Bottom panel* First differenced time series of US landings. Lines indicate years identifying changes in the mean (location, Mann-Whitney test statistic) and variance (Scale, Mood test statistic) of in the landing time series using nonparametric sequential change detection {Ross, 2011 #4160;D.M., 2010 #4161; Ross, 2015 #3505}. Blue lines indicate years when both a large shifts in mean and variance occurred.

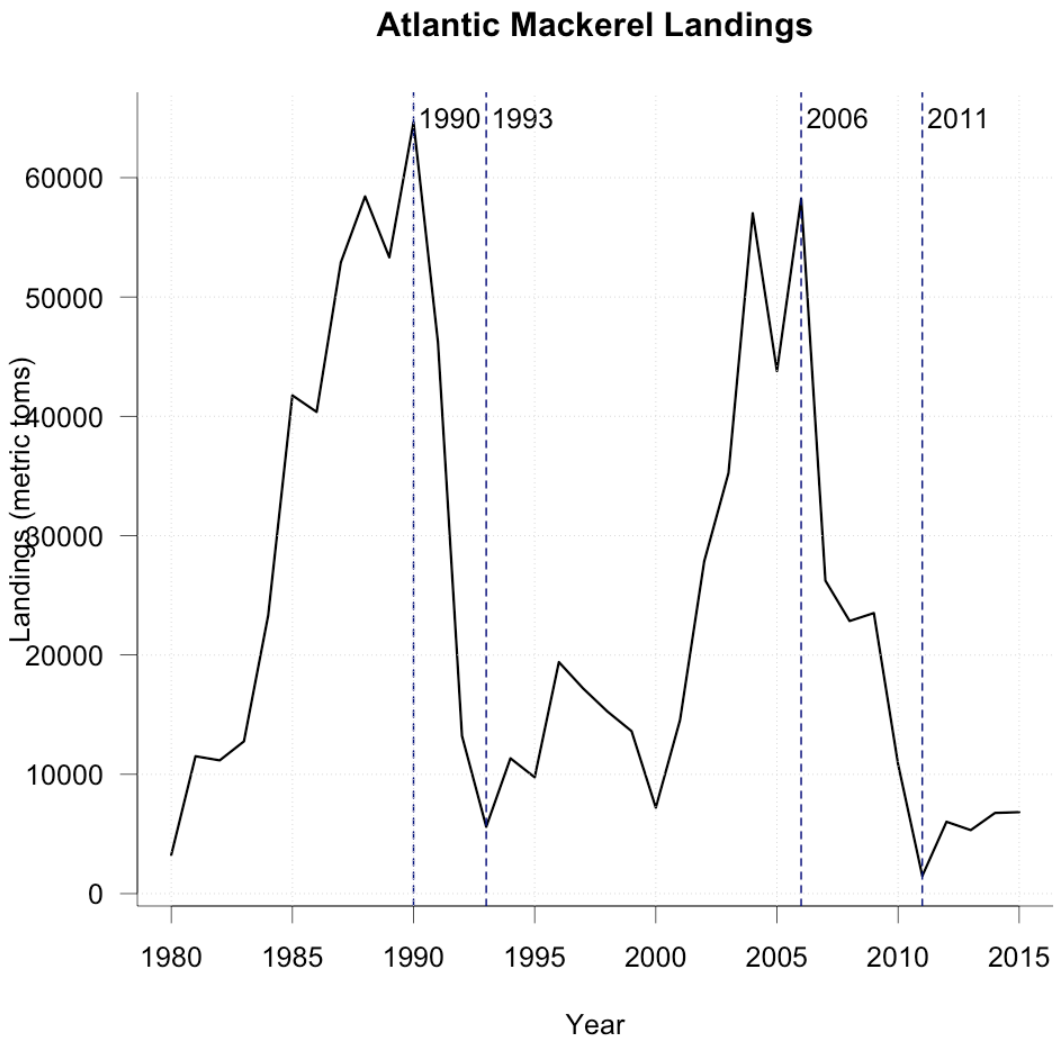

Figure 2). Time series of US landings (in metric tons) of Mackerel from 1980 through 2016 compiled from {Hoy, 1967 #3458} and Atlantic Mackerel Update assessment for 2017 (https://static1.squarespace.com/static/511cdc7fe4b00307a2628ac6/t/5720e48dab48de3e8ab30892/1461773454206/mackerel_data_update_2016.pdf } . Lines indicate peaks and troughs in the time series.

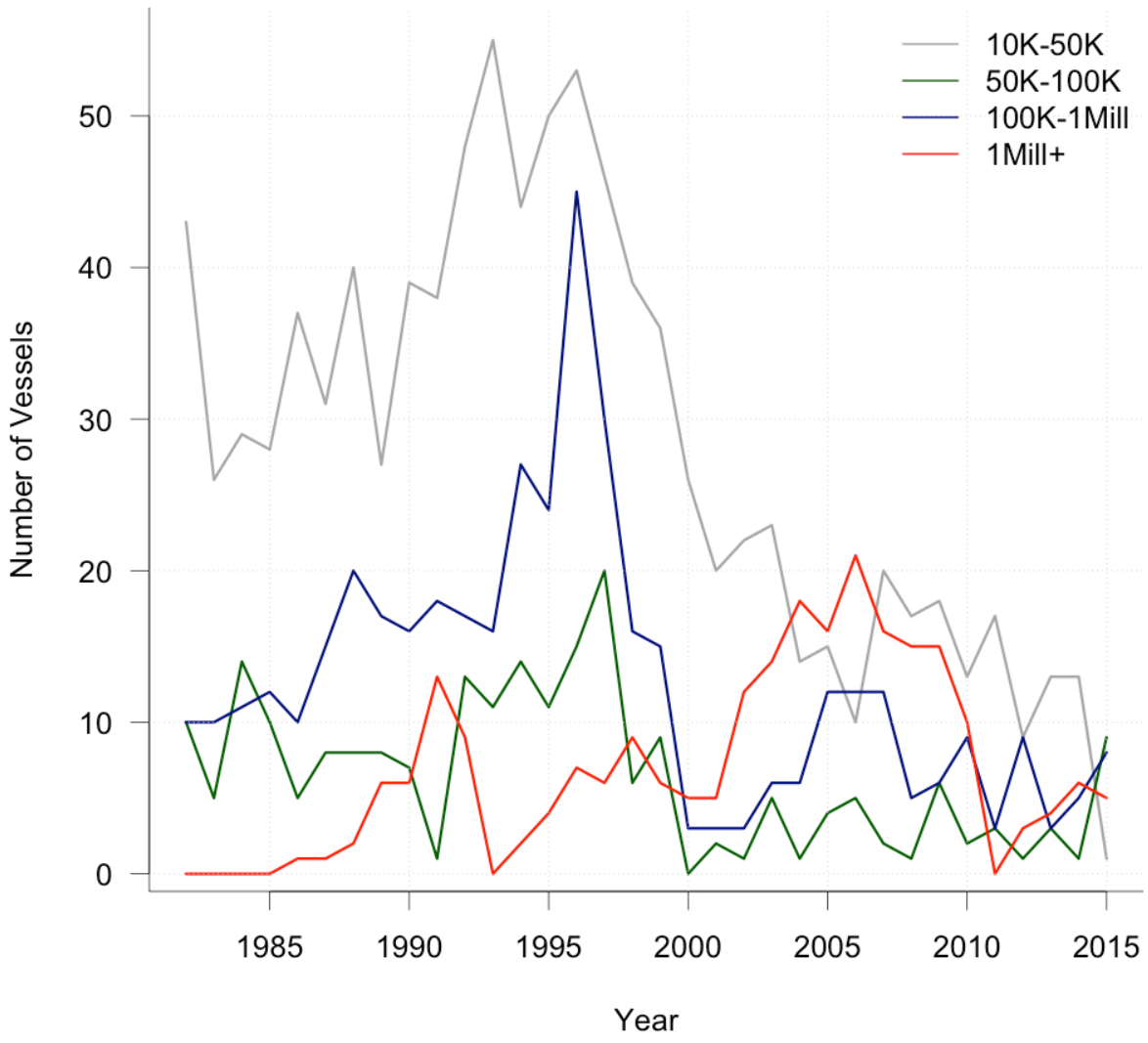

Figure 3). Number of vessels responsible for landings in different quanties of mackerel in pound categories. Data from the 2016 MAFMC Squid, Mackerel & Butterfish Fishery Performance Report (https://static1.squarespace.com/static/511cdc7fe4b00307a2628ac6/t/572ce64dc6fc08d82d934af3/1462560335098/MSB_APInfo-2016.pdf)

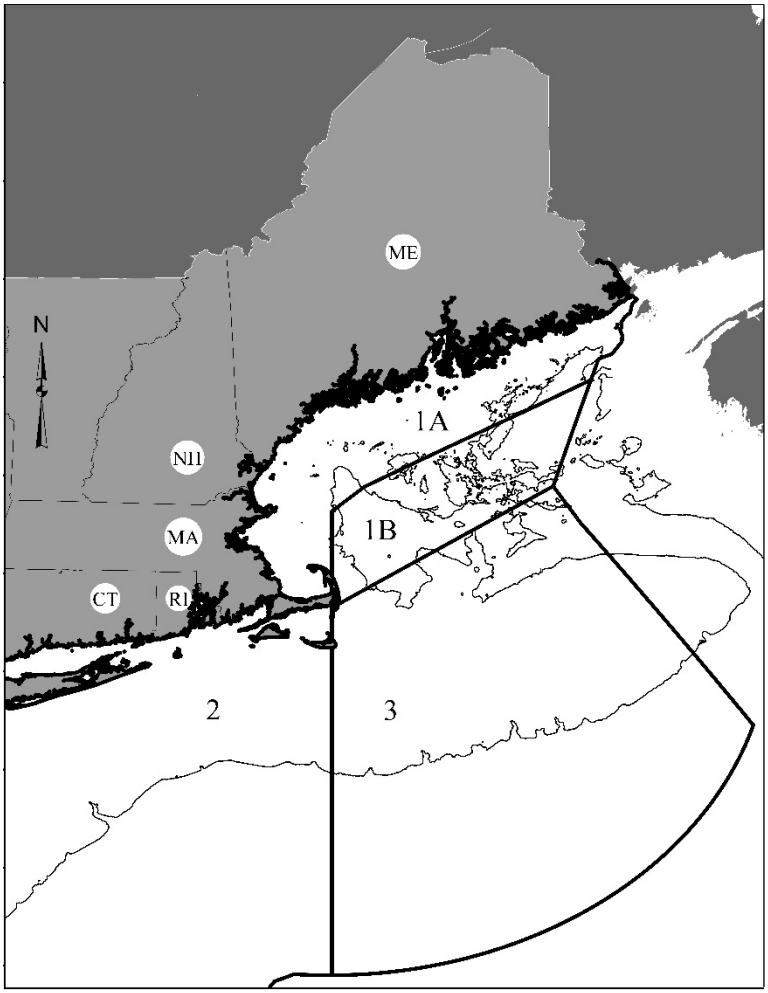

Figure 4: The division of the Atlantic herring resource into the four sub-areas, 1A (Inshore Gulf of Maine), 1B (Offshore Gulf of Maine), 2 (South Coastal Area) and 3 (Georges Bank).

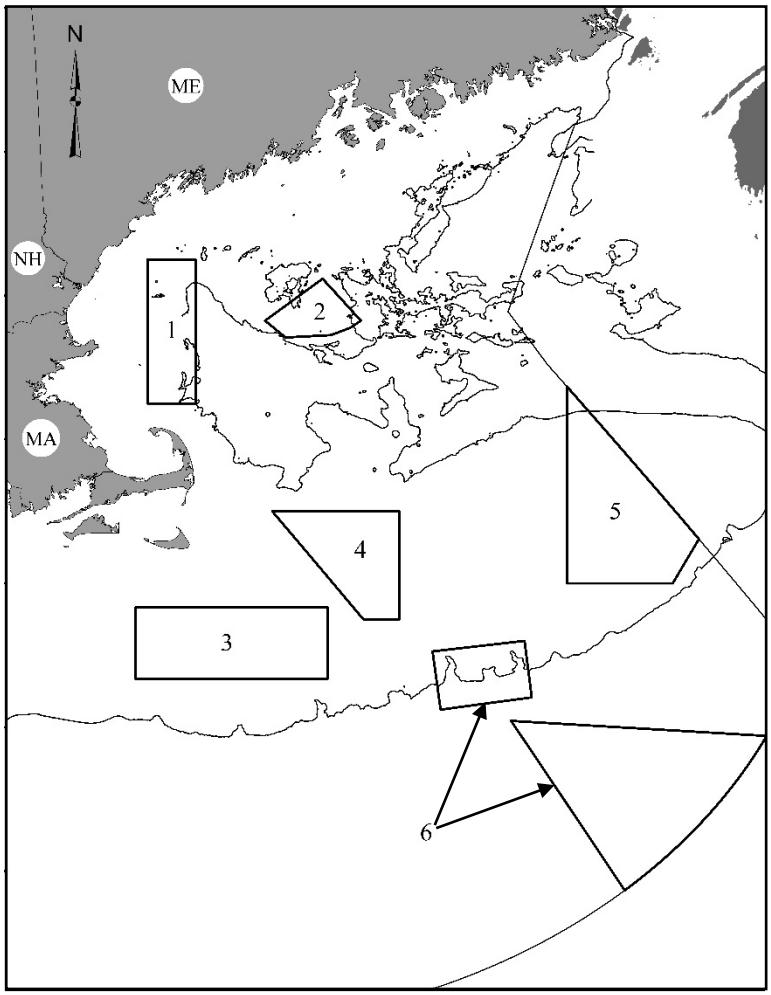

Figure 5: The five groundfish closed areas on Georges Bank and in the Gulf of Maine, Western Gulf of Maine Closed Area (1), Cashes Ledge Closed Area (2), Nantucket Lightship Closed Area (3), Closed Area I (4) and Closed Area II (5) and the Northeast Canyons and Seamounts Marine National Monument (6).

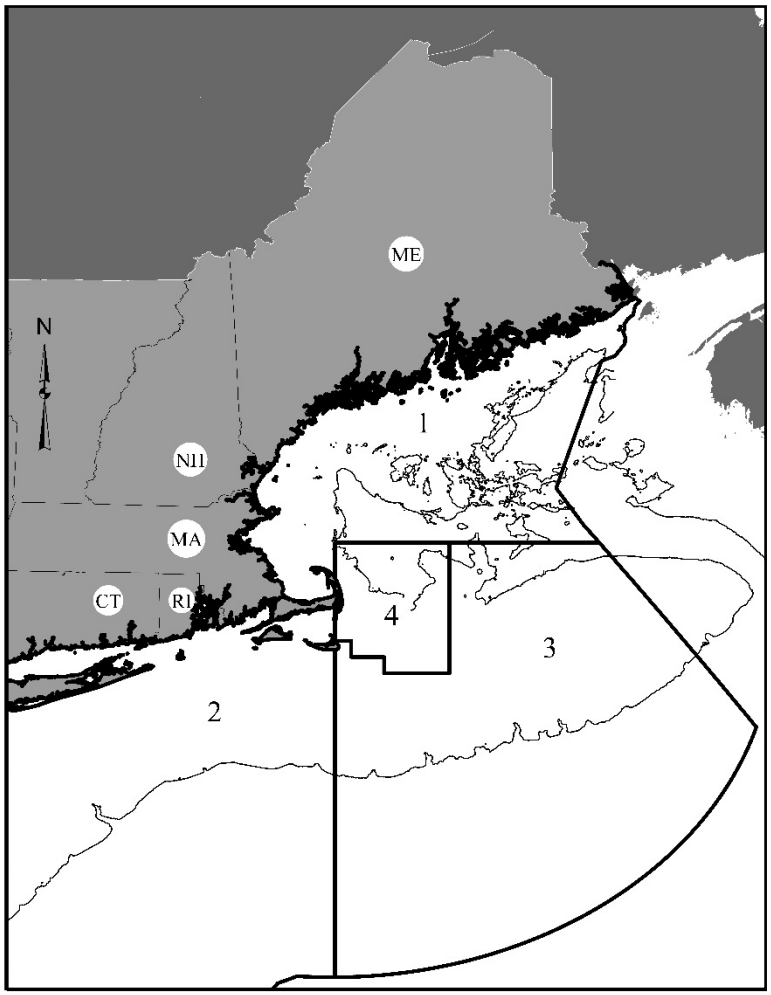

Figure 6: The four River Herring and Shad Catch Cap Areas, the Gulf of Maine Area (1), Southern New England/Mid-Atlantic Area (2), the Georges Bank Area (3) and Cape Cod Area (4). There are separate midwater and small-mesh bottom trawl river herring catch caps in Southern New England/Mid-Atlantic Area.

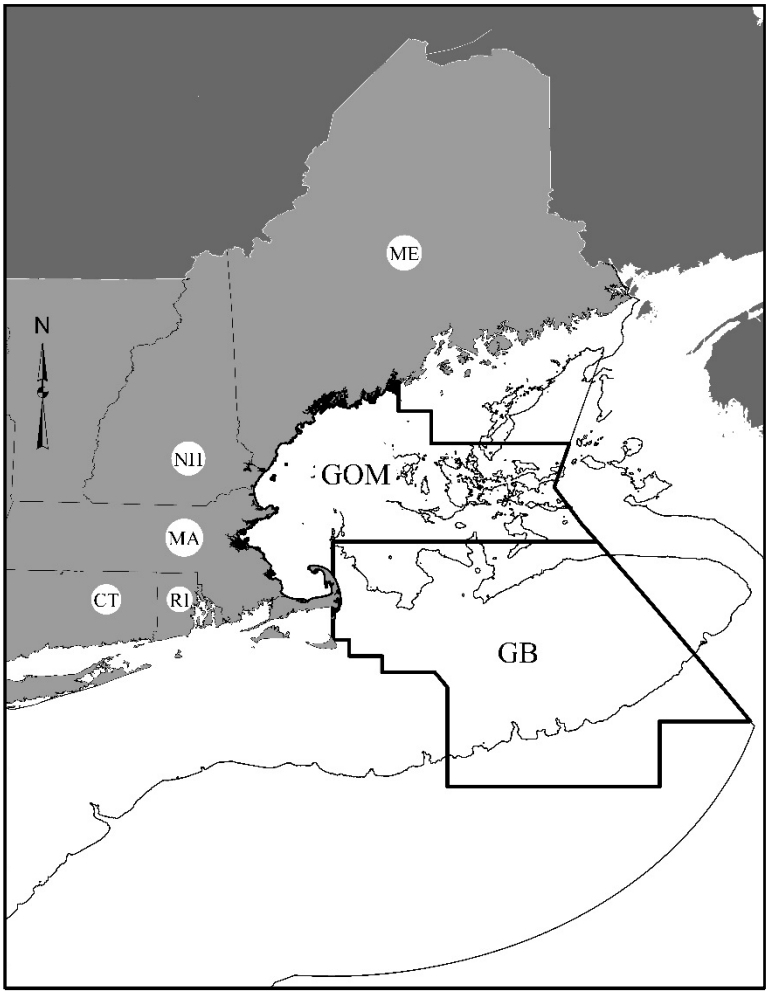

Figure 7: The two Herring Haddock Accountability Measure Area, the Gulf of Maine (GOM) and Georges Bank (GB).

Appendix 1: Questionnaire for semi-structured interviews

NAME:

Date:

Part 1: General questions:

1) How many years have you been commercial fishing?
2) Which fisheries have you participated in?
3) Do you fish for fish mackerel and herring or do you specialize in one or the other species?
4) What years have you fished for mackerel and for herring
   i) How many years were you a:
      ii) Deckhand?
      iii) Mate?
      iv) Captain?
   v) Have you stopped fishing for mackerel and herring? If yes, when did you stop? Why did you stop?
5) What types of gears did you use to fish for mackerel and herring? What years and seasons did you use the specific gears?
6) If we have left something out on this topic you think is important please explain?

Part 2: Fishing Practices:

1) Do you specifically target mackerel?
2) What factors determine whether or not you target mackerel?
3) What gear/gears do you currently use when targeting mackerel?
   i) What is the hold capacity and storage method on your boat?
   ii) Describe your gear (ie net style, mesh sizes, net height, net widths).
   iii) What sizes of fish do you prefer to target?
   iv) Has the size of fish you target changed? Why has it changed?
   v) What are your markets and how have they changed?
4) What speed do you usually tow? What are the variables that determine your tow speed?
5) How long do you typically tow on average? What are the variables that determine length of tow?
6) If we have left something out on this topic you think is important please explain?

Part 3: Targeting Mackerel: Large scale geographic distribution

1) Describe the general seasonal migration/movement patterns and how they have changed by size

2) Where do you historically find mackerel (give precise geographic locations and fathoms etc) during the
   i) Winter :
   ii) Spring:
   iii) Summer:
   iv) Fall:
3) Have traditional patterns of mackerel occurrence or migration changed?
   i) How and when have they changed
   ii) Has the location and seasons of different sizes and condition of fish (fat, feedy, etc) changed?
4) Do mackerel of different sizes/condition school together or separately in a given time and/or place? If they school differently, describe the differences (when/where) in how the different sizes of fish are distributed by in space and time.
5) What environmental factors do you think drive the southern extent of winter movements? Do they vary by the size?
6) Are there areas you expect to find mackerel over the course of a year that you are prevented from fishing by regulations? Specifically what are the areas/times and what regulations prevent you from fishing there?
7) Do you target specific sizes, and how has this changed over time? How do you know the size of fish before you shoot the net?
8) If we have left something out on this topic you think is important please explain?

PART 4: Targeting Mackerel: Fine scale habitat associations

1. What do you think are the most important habitat characteristics (temperature, salinity, depth, prey, predators, water stratification, etc) affecting distributions of mackerel?
2. Do these habitat characteristics and ranges of preference for specific characteristics change over the seasons (i.e. if temperature is important are the animals found in same temperatures in all season or do their temperature preferences change?) If habitat preference change how do they change?
3. Do these habitat characteristics and ranges of preference for specific characteristics change with fish size or condition? If they do change how do they change?
4. How are you measuring habitat characteristics you think are important and where in the water column are you measuring them. (Ie if you are measuring temperature are you measuring at the surface or net depth?)
5. Where in the water column do you fish (i.e. how close to bottom or the surface) and does this change by season? Has this changed over time?
6. Do you fish during both day and night or only during a certain part of a 24 hour day? Does this change over seasons, has this changed over the years?
7. If we have left something out on this topic you think is important please explain?

Part 5: Detecting Mackerel on acoustics:

1) Do you use acoustics to search for and identify mackerel?
2) What frequencies do you use?
3) How do you tell the difference between mackerel and other fish on your acoustics?
4) Are mackerel more bottom or water column oriented during the?
    a. Winter
    b. Summer
    c. Spring
    d. Fall
5) Have seasonal associations with the bottom or water column changed over the years?
6) Have the characteristics of mackerel schools changed over the years
7) Does mackerel distribution in the water column (i.e. bottom vs pelagic) change with mackerel school size?
8) Do other mackerel behaviors change with school size?
9) Are mackerel generally more concentrated or dispersed in different seasons of the year?
10) Have mackerel become more concentrated or dispersed over the years?
11) Are mackerel more concentrated or dispersed in the presence of herring, predators or other environmental factor and does this change seasonally? Has this changed over the years?
12) If we have left something out on this topic you think is important please explain?

Part 6: Net efficiency:

1) On average what proportion of fish available at a site where you set your net do you think you catch?
2) Does that proportion change seasonally and how does it change?
3) How does the proportion you catch change with mackerel size? Does this change by season?
4) Does the proportion you catch change with time of day?
5) Does it change with other environmental factors (eg, temperatures, predators, prey etc)?
6) Does the proportion of fish you catch change with tow speed?
7) Does this proportion change with tow length?
8) If we have left something out on this topic you think is important please explain?

Part 7: Factors driving landings:

1. Take a look at the landings figures below. Focusing on the most recent period:
    a. What years have you been actively involved in the fishery

b. What important events occurred over the time period in the figure of recent landings attached that you think have affected landings. Please describe in detail.
    i. Changes in the ocean environment
    ii. Population characteristics like body size and abundance.
    iii. Economic changes
        1. Domestic and international markets
        2. Shoreside processing capacity and location
        3. Fleet capacity
        4. Fish price
        5. Operating costs
        6. Availability and prices of alternative stocks,
    iv. Regulatory changes
        1. Quotas,
        2. Closed areas
        3. Bicatch regulations
        4. Accountability measures
        5. Others
c. If we have left something out on this topic you think is important please explain?

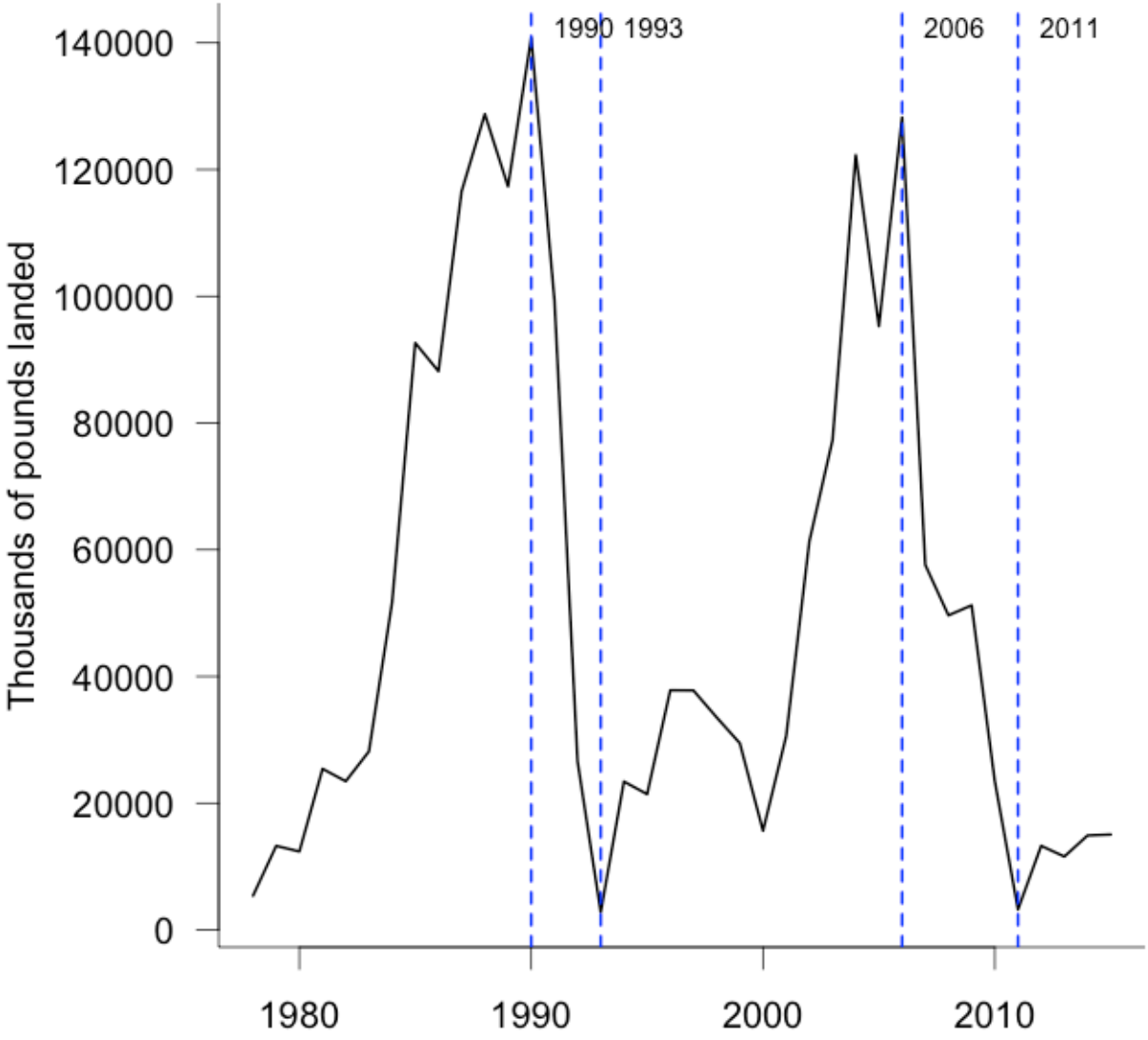

Figure 1. Recent US landings of Atlantic Mackerel

Appendix 2

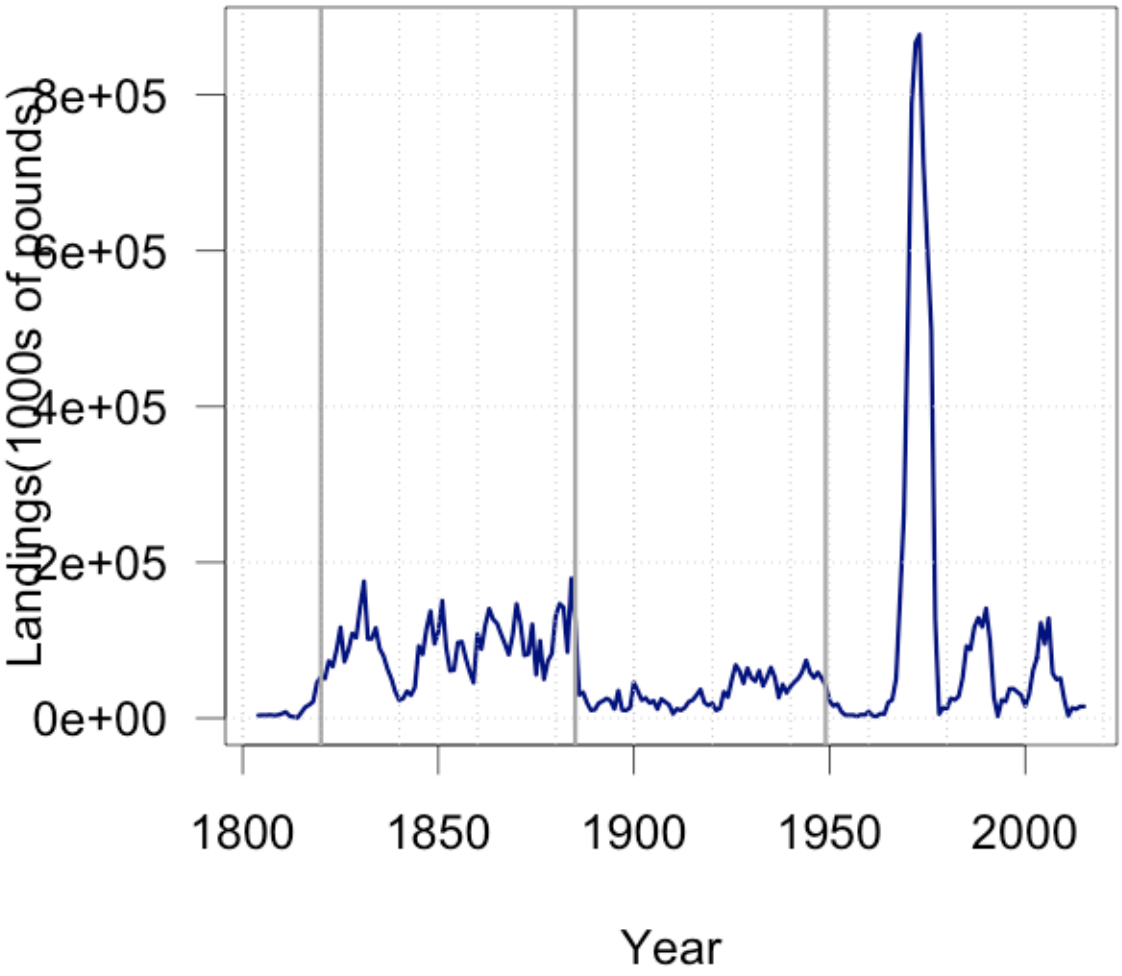

Figure . US Mackerel Landings

Appendix 2: Change detection methods applied to time series of US landings

We assembled a time series of Atlantic Mackerel Landings in US waters from 1804 through 2015 was assembled from {Hoy, 1967 #3458} and the Atlantic Mackerel Update assessment for 2017 (https://static1.squarespace.com/static/511cdc7fe4b00307a2628ac6/t/5720e48dab48de3e8ab30892/1461773454206/mackerel_data_update_2016.pdf }

*Sequential change detection*Visual inspection of the time series indicated that US landings exhibited dramatic changes in dynamics (Fig. 1). To objectively define relatively homogeneous segments of the time series we performed nonparametric sequential change detection using the cpm package in R {Ross, 2011 #3506; Ross, 2015 #3505}. The method searches sequentially along a time series for points in time that maximize differences in chosen test statistics above a threshold. We chose to apply the approach using to nonparametric statistics that did not assume a specific underlying distribution of the time series. We used the Mann-Whitney test statistic to identify the time period when the central tendency of the series changed significantly. We applied the mood test statistic to determine the scale of variability changed in the series. The analyses were performed on landings as well as first differences in log transformed landings = $\log_{10}(L_t)$- $\log10(Lt_{-1})$.

Appendix A11: Sequence of ASAP model configurations

This appendix details the sequence of model configurations explored with a start year of 1968 to arrive at the final ASAP model. Additional configurations were explored for ASAP models that began in 1981 and 1989; however, only sensitivity runs of the final model with these start years are included in the summary below. Runs 1 through 50 represented initial model development to achieve a successful configuration. In the summary table below, the following abbreviations are used: Big = Bigelow, Alb = Albatross, RMSE = Root mean square error, OFV = objective function value; obs = observed, stdev = standard deviation, B = biomass, SSB = spawning stock biomass and AEP = annual egg production.

Run	Description	Diagnostics
50	1 fishing fleet, 1 selectivity block, empirical catch, flat-topped fishery selectivity with 5^+ = 1, Fishery CV = 0.15, ESS = 75 Indices: AEP: fit to biomass, selectivity = maturity ogive, CV = obs + 0.455 Big: #/tow, CV = obs+0.45; ESS=25; selectivity: age-1 & 2==1, CV = 0.3; Alb: #/tow, CV = 0bs+1.0; ESS=25; selectivity: age-1 & 2==1, CV = 0.5 to 0.1 Recruitment penalty: Lambda = 1, CV = 1 N_{1968} deviation penalty: Lambda = 1, CV = 0.5	Starting point
51	Relax fishery selectivity: fix only age-10 at 1; Lambda=1, CV=0.9	Parameter confounding between selectivity parameters (14 selectivity parameter pairs with correlations between 0.9 – 0.96); Catch RMSE increased slightly (0.59 to 0.60); Total index RMSE decreased by 0.01; Fishery age-comp residuals did not notably change; Age-comp catch RMSE decreased slightly from 1.82 to 1.80; Slight decreases in Age-comp Big and Alb RMSE's as well; Fishery selectivity decreased for most ages, though 0.90 for age-9; Increase in maximum F from ~ 2.25 to 3.25 (but now all ages not fully selected); Index selectivities did not notably change; Negligible change in Predicted B
52	Relax fishery selectivity: fix only age-1 at 0.1, CV=0.9	OFV and RMSE's stayed the same; High correlations disappeared; Otherwise results the same
53	Run 52, but relax age-2 survey selectivity parameters (initial guesses=1, lambda=1, CV=0.99)	Index age-comp OFV decreased by 1, otherwise OFV components the same; Two parameters up against bounds: age-10 fishery selectivity=1 and Albatross age-2 selectivity=1; *Bigelow age-comps seemed to worsen a little, though only a few years of data
54	Run 53, but further relax survey selectivity	Set Bigelow selectivity CV's to 0.9; RMSE's only changed by 0.01; Age-comp RMSE's: catch increased by 0.01, Big. decreased by 0.31, and Alb. decreased by 0.01; F changed only minimally (biggest change occurred in last couple of years); Bigelow selectivity: decreased selectivity on ~ ages 4-6

Run	Description	Diagnostics
55	Run 54, but relax Alb selectivity: Alb selectivity CV's = 0.9	Index selectivity RMSE increased from 0.28 to 0.29 and fleet selectivity increased from 0.43 to 0.44; ; Age-comp RMSE's: catch stayed the same, Big decreased by 0.01, and Alb increased by 0.07; Albatross selectivity went back to being bowl shaped;
56	Modify initial parameter estimates for all Alb and Big selectivity parameters to 1	Bigelow selectivity now became bowl-shaped, and bowl on Albatross increased; ofv increased from 7675 to 7683; ofv RMSE's effectively stayed the same; No big change in residuals of Bigelow or Alb age-comps, Age-comp RMSE's for Big and Alb increased from 2.37 to 2.74 and 2.86 to 3.07, respectively; Negligible changes in F and B; As in Run 53, two parameters still up against bounds: age-10 fishery selectivity=1 and Alb age-2 selectivity=1
57	Run 55 but set Alb and Bigelow lambdas = 0 and CV's = 1	Fleet selectivity RMSE increased by 0.01 and index selectivity RMSE decreased from 0.29 to 0; Bigelow age-comp residuals seemed to get a little worse; Age-comp RMSE's for Big decreased from 2.37 to 1.95 and Alb increased from 2.86 to 2.88; Bigelow selectivity tanked for the older ages to ~ 0 with large CV's; Age-10 fishery selectivity=1; Bowl-shape increased slightly for Alb selectivity; Negligible changes to SSB and F
58	Run 55, but increase CV (CV=1.5)	CVs on Bigelow age 5+ selectivity parameters increased but values, especially for ages 8-10, did not notably change; For Alb selectivity, estimates for ages 2-9 largely stayed the same; As in Run 53, two parameters still up against bounds: age-10 fishery selectivity=1 and Alb age-2 selectivity=1; Age-comp RMSE for Bigelow decreased from 2.37 to 2.27 and for Alb increased by 0.01
59	Run 58, but fix Alb age-8 selectivity=0.28 and Big age-9 selectivity=0.296 (these were most constant parameter values when comparing Runs 55 and 58) and let age-1 parameters vary (lambda=1, CV=1.5)	3 high parameter correlations between 0.9-0.94 (age 1-3 Big selectivity); Big selectivity CV's still high for ages 5+ but had only negligible changes in value; Two parameters up against bounds: age-10 fishery selectivity and age-1 Big selectivity=1; Alb age-2 selectivity estimate now 0.997 and age-1 selectivity = 0.93; SSB and F estimates largely did not change
60	Run 55 but Alb and Big CV's for selectivity = 1	Minimal changes to selectivity estimates (max change about 0.015); Alb age-2 fishery age-10 selectivity parameters still both against bounds (= 1)
61	Run 60 but decrease Alb and Big ESS's to 5	Alb age-2 and fishery age-10 selectivity parameters still both against bounds (= 1); Catch RMSE decreased by 0.01 and index selectivity RMSE decreased from 0.18 to 0.17; Age-comp RMSE for catch decreased from 1.81 to 1.73, Big RMSE decreased from 2.35 to 1.17 and Alb RMSE decreased from 2.87 to 1.22; Magnitude of Alb and Big age-comp residuals decreased but pattern didn't really change; F decreased in last two years but otherwise didn't notably change; Bowl in Alb survey selectivity increased slightly; SSB ~ the same
61A	Run 60 but decrease Big ESS's to 15 and Alb ESS's to 10 (from 25);	Alb age-2 fishery age-10 selectivity parameters still both against bounds (== 1); Catch RMSE decreased from 0.61 to 0.59; Index total RMSE remained the same; Age-comp RMSE for catch decreased from 1.81 to 1.75, that for Big decreased from 2.35 to 1.94 and that for Alb decreased from 2.87 to 1.81; Pattern in F and B about the same; Retro converged for all runs
61B	Run 61a but fix fishery selectivity at age-10 instead of age-1	16 pairs of high correlation parameters between selectivity parameters
61C	Run61a but **fix fishery selectivity at age-6 instead of age-1**	Age-9 and 10 fishery selectivity and Age-2 Albatross selectivity up against bounds of 1; Catch RMSE decreased by 0.01; Age-comp catch RMSE increased from 1.75 to 1.77; Alb RMSE

Run	Description	Diagnostics
		increased from 1.81 to 1.83; ******* Selectivity more flat-topped even though still only fixing one age; F decreased from a maximum of over 3 to about 2.25 but pattern still the same; Bowl in Albatross selectivity less severe; Pattern in SSB the same
62	Run 60 base but **remove Alb time series** and just fit to egg and Big	Catch RMSE decreased from 0.61 to 0.52; Egg RMSE decreased from 1.3 to 1.28; otherwise RMSE's stayed the same. Total index RMSE now 1.27 because the high Alb value is removed; Small changes to fishery age-comp residuals, but nothing notable; Age-comp catch RMSE decreased from 1.81 to 1.72; Bigelow age-comp residuals stayed the same and Age-comp Big RMSE decreased slightly from 2.35 to 2.33; Negligible changes in B and F
62A	Run 62 but **fix age-6 fishery selectivity instead of age-1**	Catch RMSE decreased by 0.01 to 0.51; Egg RMSE decreased 0.01 to 1.26; Francis RMSE for catch increased from 1.72 to 1.74 and Age-comp RMSE for big increased by 0.01 from 2.33 to 2.34
63	Run 62 but decrease Big ESS from 25 to 15	Big RMSE increased by 0.01; Absolute value of Big age-comp residuals decreased (stdev decreased from 0.86 to 0.71); Age-comp RMSE for Big decreased from 2.33 to 1.93; F not quite as high in last two years, but still quite high; B the same
63A	Run 62A (fix age-6 fishery selectivity) but decrease Big ESS from 25 to 15	Index RMSE increased by 0.01 to 1.27; Big RMSE decreased from 2.34 to 1.93; ***Fishery selectivity still relatively flat-topped; Change in F and SSB negligible
64	Drop survey age-proportions and **use only Alb & Big aggregate indices** (Run 60 used as a base)	Catch RMSE decreased by 0.02 to 0.59, Egg increased by 0.02 to 1.32, Big increased 0.05 to 1.3 and Alb stayed the same; Small changes to fishery age-comp residuals (stdev decreased from 1.11 to 1.06) but not really any changes to pattern; Age-comp catch RMSE decreased from 1.81 to 1.71; Negligible changes to fishery selectivity; F pattern largely the same, but F not quite as high in last couple of years; Bowl-shaped selectivity no longer apparent for Alb
64A	Run 64 but **fix age-6 fishery selectivity instead of age-1**	Reduced catch RMSE by 0.01 and increased total index RMSE by 0.01; Did not change pattern in F but brought it down from a maximum of ~3 to a max of less than 2.5; Negligible change in SSB
65	Run 60, but use trawl survey indices based on **weight/tow** instead of number/tow (**original survey CV's**)	Need to adjust CV's: Catch RMSE = 1.24, Egg = 3.14, Big=2.17, Alb=4.03; Even with original survey CV's (and a high catch RMSE with assumed CV=0.15), model still does not want to follow Alb trends)
66	Run 65 but increase all survey CV's by a constant of 0.3	Catch ofv decreased by 17 points and aggregate index ofv decreased by 238 points. For RMSE's, catch decreased from 1.24 to 0.75, Egg decreased from 3.14 to 1.56, Big decreased from 2.17 to 1.26 and Alb decreased from 4.03 to 2.55. Some catch std. residuals are still outside of -2:2
67	Run 65 but increase Egg and Big CV's by a constant of 0.3 and Alb by a constant of 0.6	Index ofv decreased by 42 points and catch decreased by 4; RMSE's for all indices now under 2 (Egg=1.53, Big = 1.26 and Alb = 1.99); Catch RMSE = 0.65 and standardized residuals now within -2:2; Age-comp RMSE for catch = 1.84, Big = 2.45 and Alb = 5.46; Potentially some pattern in Big age-comp residuals but they're about the same as when used #/tow
68	Run 65 but increase Egg and Big CV's by a constant of 0.3 and Alb by a constant of 0.75	Index ofv decreased by 9 points; catch stayed the same; Alb RMSE decreased from 1.99 to 1.81; All other RMSE's were within 0.02 of the last run
69	Run 68 but decrease Alb and Big ESS from 25 to 10	Catch RMSE decreased from 0.63 to 0.61; May be able to decrease Catch ESS slightly, though it isn't terrible (Age-comp RMSE = 1.76); Magnitude of both Big and Alb age-comp residuals

Run	Description	Diagnostics
		decreased, though patterns are ~ the same; Age-comp Big RMSE = 1.71 (decreased from 2.45) and Alb = 3.33 (decreased from 5.46); According to McAllister & Ianelli, may be able to slightly increase Alb ESS, though likely not critical because decline in ESS between Run 68 and 69 only impacted F in the last year
69A	Run 69 but **fix fishery selectivity at age-6 instead of age-1**	Increased age comp ofv by 9 points; Catch RMSE decreased by 0.01, total index RMSE stayed the same; Age-comp catch RMSE increased by 0.02; Alb RMSE still high at 3.39; Max F decreased by ~0.5
69B	Run 69A (fix fishery selectivity at age-6 instead of age-1) but decrease Big CV (from Orig+0.3 to Orig+0.15)	Index ofv increased by only 1; Big RMSE increased from 1.25 to 1.56; F increased slightly, otherwise results ~ same
70	Run 68 but **drop survey age proportions and just use aggregate indices**	Egg RMSE increased by 0.02, catch RMSE decreased by 0.02, otherwise RMSE's stayed the same; Age-comp catch RMSE decreased from 1.84 to 1.71; F in last two years decreased, but pattern otherwise the same; ** Bigelow and Alb selectivity now decreased with age and no longer bowl-shaped; Biomass ~ the same
70A	Run 70 (drop survey age proportions and just use aggregate indices) but **fix age-6 fishery selectivity instead of 1**	Catch age comps increased by 6 points; Catch RMSE decreased by 0.01, egg RMSE increased by 0.02 but total index RMSE stayed the same; F pattern stayed the same but the maximum decreased
71	Run 69 but **drop Alb entirely** (indices include AEP, Bigelow aggregate and age-props)	Index ofv dropped from 74 to 10 and catch decreased from -84 to -86; Catch RMSE decreased 0.09 to 0.53; Egg RMSE decreased from 1.52 to 1.49 and with removal of Alb, total index RMSE decreased from 1.68 to 1.42; Age-comp catch RMSE decreased from 1.76 to 1.71; Age-comp Big RMSE only decreased 0.01 to 1.7; Negligible changes to F, Bigelow selectivity and SSB
71A	Run 71 (drop Alb entirely) but **fix age-6 fishery selectivity instead of age-1**	Again, decreases F from a max of over 3 to 2.5; Age-comp catch RMSE increased from 1.71 to 1.73
72	Run 69 but **drop Alb entirely** (Run 71) and **also drop Big age-proportions** (run with only Big aggregate data)	Aggregate index and Catch ofv's stayed the same; Catch RMSE stayed the same; Egg RMSE increased from 1.49 to 1.51 and Big decreased 0.01 to 1.25; Negligible changes in fisheries selectivity and age-comp catch RMSE stayed the same; F decreased a bit in terminal year but otherwise ~ the same; Big selectivity decreased more with increasing age (instead of flattening at older ages); B ~ the same
72A	Run 72 (drop Alb entirely as well as Big age-props) but **fix age-6 fishery selectivity instead of age-1**	Catch age props ofv again increased by 6; Catch RMSE decreased by 0.015 and Egg decreased by 0.02; Max F again decreased from approximately 3 to under 2.5; SSB trajectory remained ~ the same
	Summary to-date:	****** Across all model configurations, changing the fixed fishery selectivity age from age-1 to age-6 resulted in a more flat-topped selectivity and a decrease in the maximum F of ~ 0.5**
73	**Alb and Bigelow only (without egg index)** using wt/tow and original CVs	RMSE: Catch=1.31, Big = 2.18, Alb = 3.85
74	Alb and Big only (Run 73) but increase Big CV by 0.3 and Alb by 0.6 in each year	Catch RMSE = 0.65, Big = 1.3, Alb = 1.97; Age-comp. RMSE for Big = 2.44, Alb = 5.49; Funky Alb selectivity; SSB pattern hasn't changed

Run	Description	Diagnostics
75	Alb and Big only (Run 73) but increase Big CV by 0.3 and Alb by 0.75 in each year	Catch RMSE decreased from 0.65 to 0.62, Alb decreased from 1.97 to 1.8; Age-comp RMSE for catch = 1.86, Big = 2.44, Alb = 5.5; Funky Alb selectivity; SSB pattern hasn't notably changed
76	Run 75 but decrease ESS's (Big from 25 to 15 and Alb from 25 to 10)	Catch RMSE decreased from 0.62 to 0.6, Big increased from 1.3 to 1.44 and Alb stayed the same (1.8); Age-comp catch RMSE = 1.77, Big decreased to 2.03 and Alb decreased to 3.35; F decreased at end of time series but SSB pattern largely unchanged
77	Run 75 but decrease ESS's even more (Big from 15 to 10 and Alb from 10 to 5)	Age-comp catch RMSE decreased from 1.77 to 1.75; Magnitude of Big age-comp residuals increased but those of Alb decreased; Age-comp RMSE for Big decreased from 2.03 to 1.72 and that for Alb decreased from 3.35 to 2.22; F pattern largely the same as Run 76 but came down a little more at end of time series; SSB ~ the same;
78	Run 77 but add a stronger prior on Alb selectivity (decrease CV on Alb age 9-10 from 1 to 0.5)	Alb age-comps RMSE decreased from 2.22 to 2.15 but selectivity still a bit bowl shaped
79	Run 78 but even stronger prior on Alb selectivity (decrease CV on Alb age 9-10 from 0.5 to 0.2)	Age-comp Catch RMSE decreased from 1.75 to 1.74 and Alb decreased from 2.15 to 2.09; Alb selectivity less bowl shaped but still apparent; SSB ~ the same
80	Run 69 as a base but **use SSB instead of AEP**	Index ofv decreased from 86 to 74 and catch ofv decreased from -80 to -84; SSB RMSE high at 2.16; Age-comp RMSE for Alb high at 3.28; F now declines considerably at the end of the time series, though still reaches a very high peak in ~ 2010; **** Looked at difference between SSB and AEP – SSB showed a very slight uptick in the last couple of years that caused a decrease in F
81	Run 80 (SSB instead of AEP) but **fix age-6 fishery selectivity instead of age-1**	Catch age-comps ofv increased by 6 points; Catch RMSE decreased from 0.74 to 0.72; SSB RMSE decreased from 2.16 to 2.12 and Big increased by 0.01; Age-comp catch RMSE increased by 0.01 to 1.78, Big increased by 0.01 to 1.83 and Alb increased from 3.28 to 3.34; F again has a more flat-topped selectivity and max F again decreased by about 0.5, though pattern stayed the same; Bowl in Alb selectivity decreased a little
82	Run 81 (SSB, fix age-6 selectivity) but decrease Alb ESS from 10 to 5	Age-comp Alb RMSE decreased from 3.34 to 2.21, otherwise diagnostics effectively the same
83	Run 81 (SSB, fix age-6 fishery selectivity) but increase SSB CV by 0.15	SSB RMSE decreased from 2.12 to 1.38, Big decreased from 1.45 to 1.43, Alb decreased from 1.86 to 1.83 and catch decreased from 0.71 to 0.60; Age-comp RMSE for Big increased from 1.63 to 1.69, that for Alb increased from 2.21 to 3.38; F and SSB stayed the same
84	Run 83 but **remove Alb time series**	SSB RMSE decreased from 1.38 to 1.31, Big stayed the same; F and SSB stayed ~ the same, not surprisingly since the Alb did not have much weight in previous runs
85	Run 84 but decrease Big ESS from 10 to 5	Changes in diagnostics were minimal but Age-comp Big RMSE decreased from 1.87 to 1.2; Negligible changes in F and SSB
86	Run 83 but **remove Alb time series and Big age props** (so just Big agg..)	Big RMSE increased 0.02 to 1.47, otherwise RMSE's stayed the same; F and SSB stayed approximately the same
87	Run 86 but decrease catch ESS to 50	Catch RMSE decreased by 0.05 and index RMSE's changed by a max of 0.02; Age-comp catch RMSE decreased from 1.72 to 1.4; Changes in F and SSB negligible; **Changing Catch ESS had negligible impact**

Run	Description	Diagnostics
88	Run 84 **use ages 3+ for Big wt indices**	Big RMSE increased from 1.43 to 1.49; F had same temporal pattern, though terminal year F was lower in current run; SSB increased a little more at the end of the time series
88A	Run 88 but increase Big ESS from 10 to 25	Minimal changes to diagnostics and results
89	Assuming a flat-topped selectivity for the Bigelow	Increased the ofv by 6 points and Bigelow RMSE increased by 0.01 to 1.50; Age-comp Bigelow RMSE increased from 1.46 in Run 88 to 2.69; F ~ the same; obtained a bizarre Bigelow selectivity pattern; B ~ the same
90	Run 88A but AEP instead of SSB to make directly comparable to Run 71A; What is the impact of the Big 3+ wt when using AEP?	RMSE's very similar between Run 88A and Run 90 even though input data are different (AEP vs SSB); ***** With AEP over SSB, F is higher in recent years and SSB doesn't increase (though the increase is slight in the SSB run) in last couple of years**
	Summary to-date:	**Impact of Age-6 selectivity (Run 71 vs 71A);** Fishery age-comp ofv increased 6 points from 6177 to 6183; In Run 71 (fix age-1) age-10 selectivity up against bound and ==1, but in Run71a, age-9 and 10 selectivity up against bound and == 1; RMSE's only 0.01-0.0.2 different for catch and index, for fishery selectivity RMSE decreased from 0.432 (Run71) to 0.174 (Run 71a); From Run 71 to Run73a, Age-comp catch RMSE increased by only 0.02 to 1.73; Fishery selectivity became more flat-topped in Run71A from 6 onward; F pattern stayed the same but the max decreased; Other results were ~ the same; When moved from Run71 to Run71a, retro for F slightly decreased but that for SSB, recruitment, B and N increased **Impact of AEP vs SSB (Run 88A vs Run 90 – uses Big 3+ wt as the other index);** With AEP over SSB, the RETRO is in both directions not just one, though the magnitudes of the rhos are often bigger **Impact of Big age 3+ wt.tow vs wt.tow (Run 88 vs Run 84, Big ESS's are the same**); Big RMSE increased slightly from 1.43 to 1.49, Age-comp catch RMSE decreased from 1.73 to 1.71, Bigelow standardized residuals decreased in magnitude from -2:4 to -3:2; Age-comp Big RMSE decreased from 1.67 to 1.46 **Impact of wt/tow vs number/tow (Run 71a vs 63A)**: Differences in weights for the bigelow dataset; 63a (#) has CV at obs+0.45, 71a(#) has CV at obs+0.3; ESS for 63a is 15 where that for 71a is 10; Run71A has age-2 big selectivity against bounds and == 1; Run 71, Egg RMSE increased by 0.21 to 1.48 but otherwise RMSE's approximately the same; Big standardized residuals smaller in magnitude for Run 63a(#); Age-comp RMSE higher in Run 63a (1.93) than Run 71a (1.7); F higher in recent yers for Run 71a, otherwise trajectory approximately the same; B trajectory seems robust; ** Retro better for F in Run63a, but worse for SSB and rect.
91	Redo **Run88A** (**SSB**, **Big 3+ wt**) but with **modified selectivity and WAA for egg index** (that incorporates annual fecundity and maturity) as well as **corrected Bigelow selectivity**	Total ofv changed by only 1; Catch RMSE stayed the same; Index increased to 1.42; Fishery age-comp changes negligible and Age-comp catch RMSE the same (1.71); **Age-comp Big RMSE decreased from 1.91 to 1.62 by removing post age-7 parameters; Fishery selectivity, F and B ~ the same
92	Run 91 but assume flat-topped fishery selectivity for 6+ and turn off fishery selectivity penalties	ofv increased 2 points and fishery selectivity likelihood now 0; Catch RMSE did not change and fishery selectivity RMSE now 0; Negligible changes in fishery age-comps and Age-comp catch RMSE the same

Run	Description	Diagnostics
93	Run 92 but remove Big wt 3+ selectivity penalties	Bigelow age-7 selectivity parameter very uncertain (value = 0.08, CV=1.54); Index 1 RMSE increased by 0.01 (to 1.38), otherwise RMSE's the same; Magnitude of Bigelow age-comp residuals increased slightly and Age-comp Big RMSE decreased from 1.62 to 1.38; F & B ~ the same
94	Run 93 but reduce Big selectivity end age from 7 to 6	Index age ofv decreased by 3; Age-comp Big RMSE decreased from 1.38 to 1.34; All else ~ the same
95	Run 94 but remove first year abundance deviation penalty	Catch age-comps and aggregate ofv's each decreased by 3; Uncertainty greatly increased in N1 parameters and values for the older ages changed considerably; Catch RMSE decreased from 0.54 to 0.41 and index RMSE decreased 0.01 to 1.42; Age-comp catch RMSE increased 0.02 to 1.73; Small changes in B in beginning of time series, but overall trajectory the same
96	Run 95 but remove index penalties (Lambda3 tab)	Model did not converge
97	Run 95 but remove penalty for Total Catch in Weight (set lambda=0 on Lambda 3 tab);	Model did not converge
98	Run 95 but remove recruitment penalty	Small changes to catch & index ofv's; Catch RMSE decreased to 0.35 (from 0.42) and aggregate index RMSE increased by 0.01 to 1.43; Changes to fishery age-comp residuals negligible; Age-comp Big RMSE decreased from 1.34 to 1.31; Changes in F and B negligible
	Summary to-date	**To-date, patterns robust--- results of Run 98 ~ same to Run 88A**
99	Run 98 but **add back in Albatross 3+ wt index** (original CV's)	With original CV's, RMSE 3.79 so iteratively increased CV's to obs+0.6; At Alb CV=obs+0.6, Alb RMSE = 1.83 and the Egg RMSE increased fro, 1.37 to 1.42; Catch RMSE decreased by 0.01; Age-comp catch RMSE increased fro, 1.73 to 1.84; Age-comp Big RMSE increased by 0.01 (1.32) and Alb RMSE = 1.81; ***Model **effectively ignores Alb**; Trends in SSB and F the same
100	Run 99 but **add in Alb 3+ wt as a split index** (with original CV's, Alb RMSE's were 3.4 and 2.9) so added 0.45 to each year	Alb36 = 1.81, Alb 41 = 1.65; **Effectively ignores Alb** and not a ton of info in the Alb 40 Yankee series
101	Run 99 but create **fishery selectivity split** in 1998	Index age-comps ofv decreased by 4 and catch age-comps ofv decreased by 2; Catch RMSE stayed the same; Egg RMSE improved by 0.02, Big and Alb worsened by 0.02; Age-comp catch RMSE = 1.82; Age-comp Big RMSE stayed the same at 1.32 and Alb decreased from 1.81 to 1.63; **Selectivity at young ages actually decreased in the 2nd selectivity block – does not totally coincide with industry thoughts**; F pattern the same but max F increased; Trends in B the same
102	Run 101 (2nd selectivity block) but fix just age-6 instead of 6:10	ofv, Index and Catch RMSE's stayed the same; 1st selectivity block is effectively flat-topped. 2nd block is basically flat topped until the last age (where it drops), but the CV is very high and since this block represents the years of age-truncation, there likely isn't much information in the data; **Therefore, will keep flat-topped selectivity at 6+**
103	Run 101 but use **spring survey #/tow instead of wt/tow for ages 3+**	With original CV's, Big RMSE = 2.49 and Alb = 3.79; so increased Big CV to obs+0.3 and Alb to obs+0.6; Catch RMSE decreased by 0.01 to 0.33 and index increased by 0.02 to 1.71; Age-comp catch RMSE stayed the same (1.82), Big decreased from 1.32 to 1.26 and Alb decreased

Run	Description	Diagnostics
		from 1.63 to 1.61; **Otherwise results effectively the same and fishery selectivity trends counter-intuitive**
	Summary to-date	**Adding a second fishery selectivity block does not seem to improve diagnostics**
103A	Run 103 but return to one selectivity block	Minor changes; Age-comp RMSE a little high (1.75) and Alb selectivity pattern still bizarre
103B	Run 103 but 1 selectivity block, tightened Alb selectivity and decrease Alb ESS (#/tow for ages 3+ (big CV = obs+0.3, Alb = 0bs+0.6))	Age-comp catch RMSE decreased from 1.84 to 1.8 and Alb's decreased from 1.75 to 1.34; Alb selectivity still a little bizarre
103C	Run 103b but use **Canada's annual maturity ogives**	RMSE's stayed the same; Results~same
103D	Run103c but set ESS's = 0 for years where all survey age props = 0	Changes negligible
103E	Run 103d but increase Big ESS from 25 to 45	Big RMSE increased from 1.26 to 1.5
103F	Run 103d but increase Big ESS from 25 to 45 and Alb ESS from 15 to 25	As increase Alb ESS (Alb RMSE increased from 1.34 to 1.69, Catch RMSE gets worse (1.8 to 1.83)
103G	Run 103f but decrease catch ESS from 75 to 55	Age-comp RMSE for catch decreased from 1.83 to 1.6; Big decreased from 1.5 to 1.41 and Alb decreased from 1.69 to 1.62; Compared to Run 103d, increased number of parameters with relatively high CVs (more recruitment dev parameters I think); Otherwise results ~ the same
103H	Run 103g but scaled SSB index in 000's mt instead of mt	Results stayed the same (ofv, rmse's etc – only the q estimates changed
103I	Run 103h but put survey ESS's back to values in Run103d	Results effectively the same
104	Run 103 (still two selectivity blocks) but **use AEP instead of SSB**	Initial AEP CV's resulted in large RMSE's so increased AEP CV to obs+0.45; Catch RMSE decreased from 0.33 to 0.31, and total index RMSE increased by 0.01 to 1.72 (egg RMSE increased from 1.41 to 1.45, Big RMSE increased from 1.62 to 1.73 and Alb RMSE decreased from 1.87 to 1.85); Age-comp RMSE for catch increased 0.01 to 1.83, Big increased 0.02 to 1,28, and Alb increased 0.03 to 1.64; F in last year high (and very uncertain), and therefore B does not uptick at end
104A	Run 104 (AEP) but with **one selectivity block**	Catch RMSE stayed the same, total index RMSE decreased from 1.72 to 1.71 (due to slight decrease in egg and Alb); No notable changes to fishery selectivity; Age-comp catch RMSE increased by 0.02 to 1.85, Big stayed the same and Alb increased from 1.64 to 1.78; Maximum F decreased but F still high in last year; Trends in B the same
104B	Run 104a but tightened Alb selectivity and decrease Alb ESS	Catch RMSE decreased 0.01 to 0.29; Total index RMSE decreased 0.01 to 1.70; Age-comp RMSE for catch decreased from 1.85 to 1.81, Big stayed the same, and Alb decreased from 1.78 to 1.36; Standard deviation of Alb residuals decreased; Otherwise, results the same
104C	Run 104b but use **Canada's annual maturity ogives**	RMSE's stayed the same
104D	Run 104c but fix modified WAA matrix for AEP; ***Realized need to remove fecundity information	Made a slight difference in F in the last 3 years but nothing else; likely because fecundity has increased in the last 3 years

Run	Description	Diagnostics
	from the modified WAA matrix for the egg index if not using SSB	
105	Run 103/104 but **drop egg index** entirely	With CV's needed to get index RMSE's under 2, F trend did not change, B uptick a little greater at the end but not a drastic difference; Catch age-comps (in particular the age-truncation) likely driving the bus
106	Run 103c (SSB, Alb&Big 3+ #/tow) but **separate U.S. and Canadian catches into 2 fishing fleets**	Large pattern in U.S. fishery age-comps; Canadian age-comps looks much like those from 1 fleet; Age-comp U.S. and Canadian RMSE's huge
107	Run106 (**two fleets**) but have **3 selectivity blocks for U.S.** & for both fleets fix only age-6 selectivity	Still patterns in U.S. age-comps; Several selectivity parameters hitting upper bound of 1
108	Run107 (two fleets, 3 US selectivity blocks) But fix selectivity as flat-topped at age-6 for each selectivity block	Age-comp residual patterns and overall diagnostics still not ideal
109	Decrease US and Can ESS's from 75 to 25	Decrease in aggregate fishery catch RMSE's; 0.01 decrease in total aggregate index RMSE; Aggregate fishery catch residuals seemed to worsen in pattern; Magnitude of fishery age-comp residuals decreased; U.S. fishery age comp RMSE decreased from 3.13 to 1.82 and Canadian decreased from 2.78 to 1.59; Age comp Big RMSE decreased from 1.45 to 1.3; Alb decreased from 1.34 to 1.23; Spike in F occurs for Canadian fleet; Patterns in B and F ~ same
109A	Fix Alb ESS at 0 for years without any age props (1976, 1983)	Minimal differences
110	Run 103C but dropped trawl survey entirely: **Used only SSB index**	Slight improvement in fit to aggregate fishery catch (in terms of residual patterns); Fishery age-comp residuals ~ same; Trends in F, fishery selectivity and SSB approximately the same
111	Increase SSB CV from obs + 0.15 to obs + 0.3	Decrease in SSB RMSE from 1.37 to 1.04 and catch RMSE from 0.34 to 0.27; F, fishery selectivity, and B all effectively the same
112	Run 111 but decrease Catch ESS from 75 to 60	Patterns in fishery age comps ~ same; Fishery age comp RMSE decreased from 1.74 to 1.55; Trends in F, fishery selectivity and biomass ~ the same
113	Run 103C but **4 selectivity blocks**	Total index RMSE stayed the same (1.7) but small differences in the individual indices; Catch RMSE decreased from 0.31 to 0.30; No huge changes in fishery age comps; some decrease in magnitude of the age comps in the early years, but patterns effectively the same; Fishery age-comp RMSE decreased from 1.8 to 1.62;Age comp RMSE for the Big stayed the same and decreased by 0.03 for the Alb; Only noticeable difference in fishery selectivity was in the first time block (younger ages had higher selectivity); The patterns for the remaining 3 time blocks remarkably similar; Increase in maximum F but temporal pattern & terminal year estimate ~ the same; SSB ~ the same
114	Run 103C but with **censored catch**	Decrease in catch RMSE by 0.01; Total index RMSE the same though small changes in individual indices; Age-comp RMSE for fishery decreased by 0.02 while that for Alb and Big stayed the same; Maximum F decreased though temporal trends and F in last year ~ the same; SSB ~ the same
115	Run 103C but with **ages 2+ in trawl survey (#)**	Catch RMSE decreased 0.02 to 0.29; Total index RMSE decreased by only 0.03 but Big decreased from 1.61 to 1.15; Age comp RMSE for fishery decreased by 0.01, Magnitude of Big

Run	Description	Diagnostics
		standardized residuals decreased slightly; Increase in Alb residual pattern; Big and Alb age comp residuals seemed to show increased patterning; Age comp RMSE for Big increased from 1.26 to 1.62and Alb increased from 1.34 to 1.56; Patterns in F largely the same; Alb selectivity did not increase as much for ages 9-10; Trends in SSB ~ the same
116	Repeat of 103H	Repeat
117	Run 116 but with **U.S. maturity data** instead of Canadian maturity; Note that need to fix modified WAA matrix for egg index as well as maturity time series	Increase in catch RMSE by 0.01; Decrease in total index RMSE by 0.01 and very small changes to individual indices; Age comp RMSE for fishery, Alb and Big the same; Increase in magnitude of standardized residuals for SSB index; F, B and selectivity trends effectively the same, though less of an increase in SSB in the mid 1980's with U.S. maturity data
118	Run 116 but **fix modified WAA matrix used for SSB index (do NOT incorporate Fecundity)**; Accidentally incorporated fecundity when fitting to SSB instead of AEP; **New Base**	Index fit improved by 1 point; Catch RMSE stayed the same, but egg index RMSE decreased by 0.03 and Big decreased by 0.01; Age comp RMSE's for fishery and Alb stayed the same but Big decreased by 0.01; Take home points ~ the same though F appeared to decrease slightly in terminal year; Mohns rho's for retrospective analyses changed by a maximum of 0.01.
119	**Sensitivity** for Run 118: **egg index only**	Egg index RMSE decreased from 1.37 to 1.32 and catch RSE increased by 0.01; no major changes in fishery age props and fishery age prop RMSE decreased from 1.6 to 1.48; take home points effectively the same; Some retrospective iterations did not converge
120	Sensitivity for Run 118: Trawl survey incorporating ages 2^+ in number/tow	With original survey CVs Alb RMSE = 3.67, so set Big as obs+0.3 and Alb as obs+0.6 as did for 3+ indices in Run 118; Catch RMSE decreased by 0.02, total index RMSE decreased by 0.03 (increase in SSB RMSE be 0.5 but decrease in Big by 0.47 and increase in Alb by 0.02); no big changes in fishery age comps but RMSE increased by 0.05; Magnitude of Big standardized residuals decreased from a max of 4 to 3; Mag of Alb standardized residuals increased slightly from -4 to -5; Weird spike in Big ESS in last year; Age comp RMSE increased from 1.4 to 1.82 for Big and 1.62 to 2.31 for Alb
121	**Sensitivity** for Run 118: Run 120 (**Trawl survey incorporating ages 2^+** in number/tow) but decrease Alb ESS to 15 and decrease Big ESS to 35	Catch RMSE decreased by 0.01, Big RMSE decreased by 0.02 but total index RMSE stayed the same; Age comp RMSE for fishery decreased from 1.65 to 1.59, Big decreased from 1.82 to 1.67 and Alb decreased from 2.31 to 1.87; Time-series peak in F and last year a little higher but general trends the same; SSB effectively the same
122	Sensitivity for Run 118: AEP for egg index (so used modified WAA that incorporated fecundity)	Index RMSE's very high – need to increase AEP CV
123	Sensitivity for Run 118: AEP for egg index (so used modified WAA that incorporated fecundity) but increase CV to obs + 0.30	RMSE's still not ideal but Total Index RMSE = 1.77; Age comp RMSE for fishery increased by 0.01; magnitude of standardized residuals increased for egg index and Big; Age comp RMSE for Big increased by 0.05 to 1.45 and Alb increased by 0.03 to 1.65; F increased in terminal year to time-series high; SSB time series of SSB the same but did not increase at end
124	**Sensitivity** for Run 118: **AEP for egg index** (so used modified WAA that incorporated fecundity) but increase CV to obs + 0.45	Catch RMSE decreased 0.02; Egg RMSE decreased to 1.41 from 1.62; Big RMSE decreased from 1.84 t o1.79 and Alb increased by 0.01 to 1.83; Age comp RMSE did not change for fishery, decreased by 0.01 for Big and increased by 0.01 for Alb; F decreased less in last year; SSB ~ same

Run	Description	Diagnostics
125	Sensitivity for Run 118: AEP for egg index (so used modified WAA that incorporated fecundity) but increase CV to obs + 0.30 and increase Big CV to obs + 0.45	Increasing Big CV resulted in an increase in Egg RMSE (from 1.41 to 1.6) and a decrease in Big RMSE from 1.79 and 1.62; Tradeoff apparent between Big and AEP; Alb RMSE only changed by 0.01; Age comp RMSE stayed the same for fishery, decreased by 0.02 for Big and 0.01 for Alb; F skyrockets to 3.0+ in last year; SSB ~ same
126	**Sensitivity** for Run 118: Use **U.S. maturity ogives** (need to change maturity and modified WAA matrix)	Small changes (max of 0.02) to catch and index RMSE's; negligible differences to fishery age comps; Age comp RMSE same for fishery and Alb, Big increased 0.01; Negligible changes to F and SSB
127	**Sensitivity** for Run 118: **4 time blocks for fishery selectivity** (1968, 1978, 1992, 2000)	Increase in SSB RMSE by 0.06 to 1.43, increase in Big by 0.01, increase decrease in Alb by 0.03, Catch stayed the same; Some parameters must be near bounds because CV=0; Residual fishery age comps look a little better in early/mid years; Age comp RMSE decreased from 1.6 to 1.45 for fishery, increased by 0.01 for Big and decreased by 0.07 for Alb; So looks like increased flexibility in fishery selectivity helped the early/mid years; Fishery selectivity at age generally decreases as the time series progresses but most differences occur at ages 3-5; Time series maximum for F increased but general trends and terminal year ~ same; SSB ~ same
128	Sensitivity for Run 118: 2 fleets (U.S. and Canada)	Some pattern in age comp residuals for US Fleet; Age comp RMSE's for fishing fleets both large (2.85 and 2.37); Fleet-1 selectivity approaches full recruitment at age-3
129	**Sensitivity** for Run 118: **2 fleets (U.S. and Canada)**, Fishery ESS = 25 (reduced from 55), flat-topped fleet-1 selectivity at age-6,	Still some pattern in residuals for US Fleet; Age comp RMSE for US = 1.95 and 1.6 for Canada; Fleet-1 selectivity approaches full recruitment at age-3
130	**Sensitivity** for Run 118: **2 fleets (U.S. and Canada)**, Fishery ESS = 25, create flat-topped fleet-1 selectivity at age-4	Diagnostics still not ideal (some pattern in US age comps, RMSE's still a bit high)
131	**Sensitivity** for Run 118: Use **censored catch** estimates instead of reported catch	RMSE: Catch decreased by 0.01, Egg increased by 0.02, Big increased by 0.02 and Alb increased by 0.01; Age-comp RMSE decreased by 0.02 for fishery, 0.01 for both Big and Alb; Terminal year F ~ the same but time-series maximum decreased to well under 2.0; SSB ~ same
132	**Sensitivity** for Run 118: **Begin model in 1981**	Aggregate RMSE's look great; Fishery age-comp residuals look decent with RMSE = 1.48; Age-comp RMSE for Big = 1.4 and Alb = 1.59;
133	**Sensitivity** for Run 118: **Begin model in 1989**	Aggregate RMSE's look great; Fishery age-comp residuals look great, RMSE = 1.16 but ESS looks a little low according to McAllister and Ianelli plot; With shorter time series, residuals look much better for aggregate Egg, Big and Alb; Age-comp RMSE = 1.39 for Big, 1.54 for Alb
134	Sensitivity of Run 118: Begin model in 1989 (Run 133) and increase fishery ESS from 55 to 75	Results ~ same
135	**Run 127 (1 fleet, 4 selectivity time blocks), but fix age-6 selectivity** at 1 and estimate ages 1-5 and 7-10	Decline in Egg RMSE by 0.06 but increase in Alb by 0.02; Decrease in fishery age-comp RMSE by 0.03; Index age-comp RMSEs stayed the same; Selectivity flat-topped for 1992, Age-9 == 1 for 2000 and 1978 and only declines at age-10. Only true dome in is for 1968.

Run	Description	Diagnostics
136	**Run 130 (2 fleets)** but parameterize U.S. fleet with 4 selectivity time blocks and flat-topped selectivity at age-6 (Run 129)	Increase in Egg RMSE by 0.03; Decrease in Alb RMSE by 0.02; Increase in magnitude of fleet2 aggregate residuals; Decrease in magnitude of some fleet-1, age-1 residuals in early years; Decrease in age comp RMSE for fleet 1 from 1.95 to 1.81; Fleet 2 RMSE decreased by 0.01; Age comp RMSEs for Big and Alb decreased by 0.01; Somewhat bizarre selectivity patterns; SSB similar, some changes in F though temporal trends the same

Appendix A12:

A State-Space Stock Assessment Model (SAM) for Northwest Atlantic Mackerel

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November 28-30, 2017

Introduction

Fish stock assessments rely on observations (e.g., survey indices, catch, age composition) to inform fishing, survival, and reproduction processes (e.g., fishing mortality, selectivity). The observations and the processes are both subject to error. Observations are collected through sampling procedures that are subject to measurement error, while some processes like selectivity and survival are not directly observed and so are subject to process errors not reflected in the observed data.

Stock assessment approaches vary in the degree to which observation and process errors are acknowledged. Virtual population analyses do not allow any observation or process errors because data are assumed perfectly known. Statistical catch-at-age (SCAA) models permit observation errors and limited process error in recruitment, but the extent of the errors are user specified and the models estimate relatively many parameters (e.g., a fishing mortality rate and recruitment for each year). State-space models can separate observation and process errors using relatively few parameters (Nielsen and Berg 2014). This efficiency is achieved by estimating the variances of the assumed distributions for the observation and process errors, and the fishing mortality and abundance states are predictions from the assumed distributions, as opposed to free parameters as in SCAA models.

The objective of this working document was to apply a SAM model to NW Atlantic mackerel. I provide an overview of the model here, but details can be found in Nielsen and Berg (2014) and Berg and Nielsen (2016). Notation generally follows that of Nielsen and Berg (2014).

Methods

Observations

Catch and index observations are assumed to have lognormal errors, with separate variance parameters applied to different user selected age groups:

$$\log\left(C_{a,y}\right) = \log\left(\frac{F_{a,y}}{Z_{a,y}}(1 - e^{-Z_{a,y}})N_{a,y}\right) + e_{a,y}^{(o)} \; ;$$

$$e_{a,y}^{(o)} \sim N\left(0, \hat{\sigma}_{o,a}^2\right) \; ;$$

$$\log\left(I_{a,y}\right) = \log\left(\hat{q}N_{a,y}\right) + e_{a,y}^{(s)} \; ;$$

$$e_{a,y}^{(s)} \sim N\left(0, \hat{\sigma}_{s,a}^2\right) \; .$$

Age groups were defined to share variance parameters based on AIC and residual patterns.

Processes

SAM allows for process errors in recruitment, survival between sequential ages, and age specific fishing mortality rates. The recruitment and survival processes are assumed to follow lognormal distributions:

$$\log\left(R_{a=1,y}\right) = \log\left(f\left(SSB_{y-1} \; or \; R_{a=1,y-1}\right)\right) + \gamma_{a=1,y} \; ;$$

$$\gamma_{a=1,y} \sim N(0, \hat{\sigma}_R^2) \; ;$$

$$\log\left(N_{a,y}\right) = \log\left(N_{a-1,y-1}\right) - F_{a-1,y-1} - M_{a-1,y-1} + \gamma_{a>1,y} \; ;$$

$$\gamma_{a>1,y} \sim N(0, \hat{\sigma}_{a>1}^2) \; .$$

Recruitment in all model runs was assumed to follow a random walk. As with the observation variances, age groups were defined to share survival process variance parameters based on AIC and residual patterns.

Fishing mortality rates can be age-specific or groups of ages can be coupled to share fishing mortality rates, and these rates follow a random walk between years. The random walk fishing

mortality rates can be correlated among the age couplings, for example, with a correlation of 0.0 producing independent random walks among age couplings and a correlation of 1.0 producing parallel time trajectories in fishing mortality rates among age couplings (i.e., time invariant selectivity). This results in age- and year-specific random walk increments following a multivariate normal distribution:

$$\log\left(F_{a,y}\right) = \log\left(F_{a,y-1}\right) + \delta_y \; ;$$

$$\delta_y \sim \boldsymbol{N}\left(0, \widehat{\boldsymbol{E}}\right) .$$

The degree of correlation in the random walks can be fixed at 0.0 (i.e., independent) or estimated, and both were attempted. Age groups were defined to share fishing mortality states and process variances based on AIC and residual patterns.

Estimating Misreported Catch

SAM has the ability to estimate misreported catch as year- and age-specific multipliers of the observed catches. The misreported catches are distinct from the observation errors because they allow for bias in the observations and not just unbiased imprecision. Missing catches were suspected for Atlantic mackerel and misreported catch was estimated in some years, with the specific years chosen based on the models ability to converge, results from the censored population assessment model, and a priori knowledge about missing catches. A comparison of time series estimates between models with and without estimates of misreported catch was also conducted.

Input Data

The input data are identical to that used in the final ASAP model that was agreed to at the Model Meeting held in Woods Hole, MA, August 15-18, 2017. In summary, input data were:

- Catches-at-age for ages 1-10+, with age-10 as a plus group, for the years 1968-2016.
- The combined US/Canada egg survey in units of spawning stock biomass, in only those years with US and Canadian sampling.

- The NMFS spring bottom trawl survey for ages 3-10+ from years that predominately used the vessel Albatross, 1974-2008.
- The NMFS spring bottom trawl survey for ages 3-7 (no catches of mackerel older than age-7 have been observed in this case) from years that used the vessel Bigelow, 2009-2016.
- Natural mortality equaled 0.2 for all ages and years.
- Age- and year-specific maturity was based on the Canadian time series.

Results

More than 50 models were run in the development of the SAM model. Presenting the AIC values and diagnostic plots that led to the final model structure would be voluminous. Consequently, only the final model structure is described, along with diagnostics and some sensitivity run comparisons.

Observations

A single observation variance was estimated for fishery catches and shared among all ages. An attempt to estimate a separate observation variance for ages 1-7 and ages 8-10+ resulted in the observation variance for ages 1-7 hitting the bound of 0.0, and so age-specific fishery catch observation variances were not pursued further.

Age-3 in both bottom trawl survey time series was specified to have a different catchability than older ages. Each survey had a separate observation variance shared among all the ages covered by the given survey (i.e., one variance parameter for each survey).

Processes

Unique fishing mortality rates were specified for age-1, age-2, age-3, and ages 4-10+. An attempt was made to also specify unique fishing mortality rates for ages 9-10+, but the resulting fishing mortality rate estimates were unreasonably low, and so no additional fishing mortality rate couplings were pursued. An attempt to estimate the degree of correlation among the fishing mortality rates

resulted in some parameters hitting bounds and a correlation of 1.0 (i.e., time invariant selectivity), and so the fishing mortality rates were assumed independent (i.e., correlation of 0.0).

A single process variance was estimated for the fishing mortality rates. An attempt to estimate separate fishing process variances for ages 1-7 and 8-10+ resulted in non-convergence, and so no additional age-specific fishing process variance parameterizations were pursued.

Process variance in recruitment was estimated separately from a survival process variance shared among ages 2-10+. A run with a separate survival process variance for ages 8-10+ improved AIC by 40 units, but also caused a severe retrospective pattern and so this was abandoned.

Misreported Catch

Attempts to estimate year specific but age invariant misreported catch in all years failed due to non-convergence. The years 2006-2010 were believed to have accurate catch values (K. Curti personal communication), however, and so estimates of misreported catch were attempted in all years except 2006-2010. While this model converged, some parameters hit bounds and estimates were unrealistic, and so this model configuration was abandoned. The next course of action was to use the Canadian censored model as an indicator of which years did and did not have relatively accurate catch reporting. Years in which the Censored model had <15% estimated difference between observed and estimated catches were considered accurate, while misreported catch was estimated in the SAM model for all other years. Based on this approach, years in which SAM estimated misreported catch were: 1969, 1970, 1972, 1975, 1977, 1978, 1979, 1980, 1981, 1982, 1984, 1986, 1987, 1988, 1989, 1990, 1991, 1992, 1993, 1994, 1995, 1996, 1998, 1999, 2000, 2001, 2002, 2003, 2008, 2011, 2012, 2013, 2014, 2015, 2016. This model converged with no parameter bound problems. Based on visual inspection of the degree of misreported catches, some ranges of the listed years were forced to share a common level of estimated misreporting. Separate levels of misreporting were shared among the years within the ranges 1969-1972, 1975, 1977-1978, 1979-1991, 1992-1996, 1998-2003, and 2008-2016. This coupling improved AIC

by 2 units and had approximately half the parameters. Attempts at this stage to estimate separate levels of misreporting for ages 1-4 and ages 6-10 in each year led to worse AIC, and so age-specific misreporting was no longer considered. The misreported catch estimates for 1975 and 1979-1991 suggested over-reporting of catches, but this was not considered feasible (i.e., catches are generally thought to be under-reported). Consequently, misreported catches were no longer estimated for 1975 or 1979-1991.

Summary of Final SAM Model Structure

- One fishery catch observation variance common to all ages (1 parameter).
- One observation variance for each survey, common to all ages within each survey (3 parameters).
- One catchability for the egg index, a separate catchability for age-3 and ages 4-10 in the Albatross survey years, and a separate catchability for age-3 and ages 4-7 in the Bigelow survey years (5 parameters).
- Separate fishing mortality rates for age-1, age-2, age-3, and ages 4-10+, with a shared process variance (1 parameter).
- Process variance for recruitment and a survival process variance for ages 2-10+ (2 parameters).
- Misreported catch in 1969-1972, 1977-1978, 1992-1996, 1998-2003, and 2008-2016 (5 parameters).
- 17 total parameters.

Overview of Final SAM Model Estimates and Results ("Run 23")

Time series estimates of recruitment, fishing mortality rate, and biomass (abundance) were generally similar to the final ASAP run. This overview will consequently focus on the results uniquely provided by the SAM framework.

The time-varying fishing mortality rates suggested a generally flat-topped selectivity, with ages 4-10+ having the highest fishing mortality rates in most years. The fishing mortality rates and subsequent selectivity at age-2 and age-3, however, were relatively variable with a pattern of generally decreased selection during 1999-2011 and sharp increase in selection in recent years.

Recruitment had the largest of the process variances, followed by survival for ages 2-10+, and the fishing mortality process. Catch was estimated to have the lowest observation variance, followed by the egg index, Albatross survey years, and Bigelow survey years. The observation variances for the Albatross and Bigelow survey years were the largest of all the process and observation variance estimates.

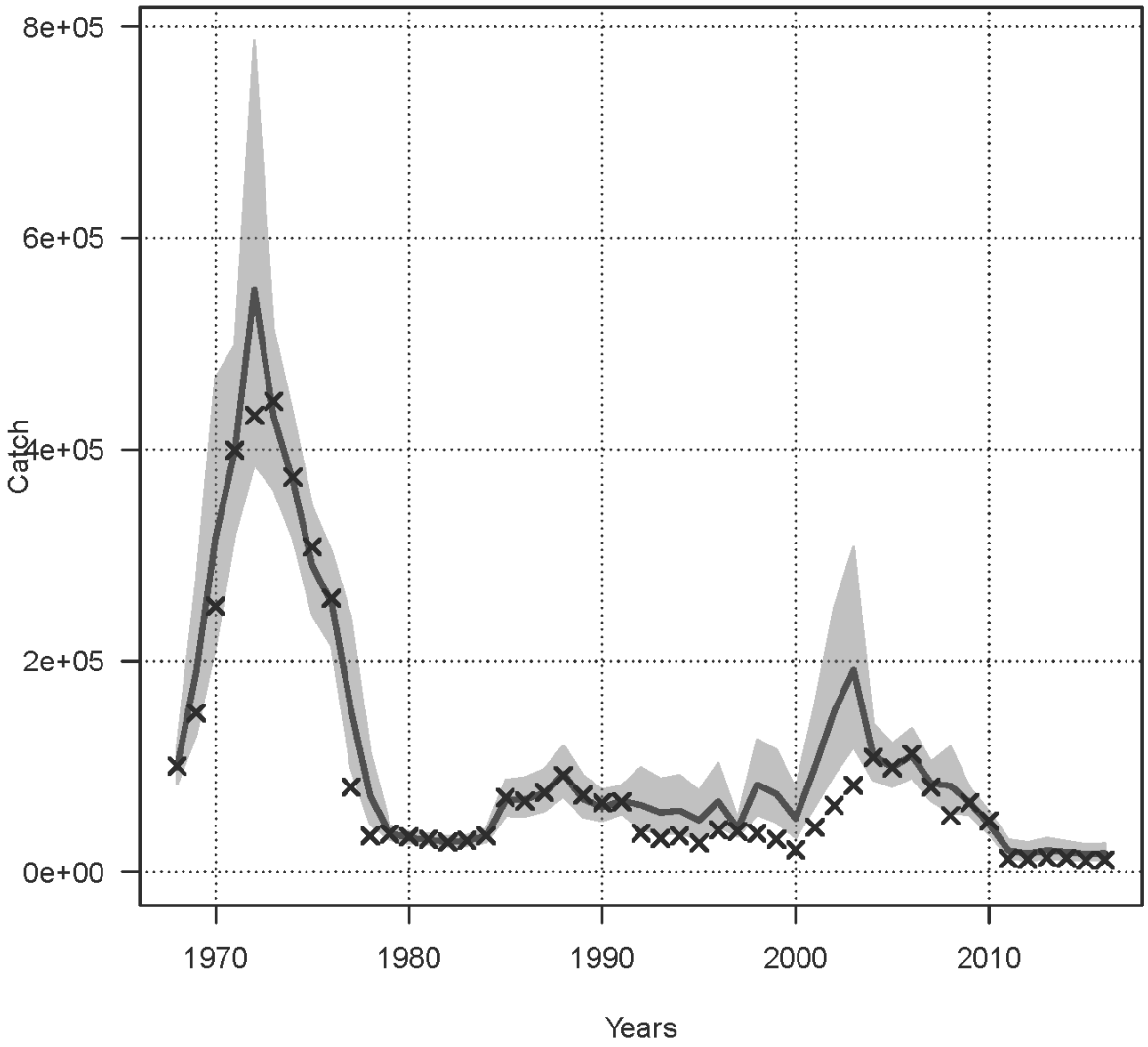
Misreported catch estimates as a proportion of reported catches were largest for the years 1977-1978 and 1998-2003, with estimated catch over twice that of reported catches. For other years, catches were estimated to be underreported by between 30% and 74% of the reported catches. A run without estimates of misreported catch ("Run 24") provided a fit that was 32 AIC units worse than the model with catch misreporting, but other than a relatively slight decrease in the scale of spawning stock biomass, provided generally similar estimates and diagnostics.

References

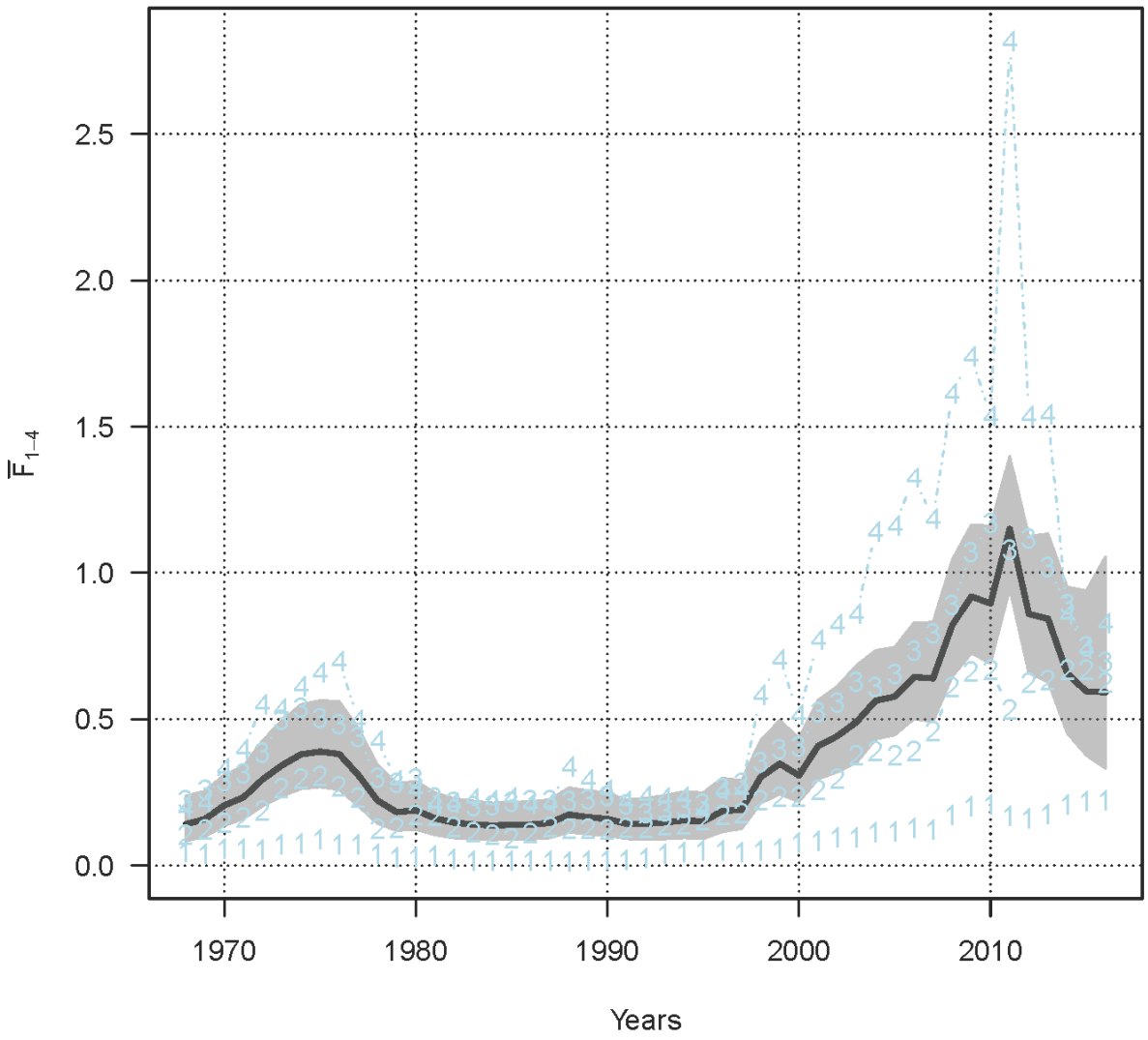
Berg, C.W., and Nielsen, A. 2016. Accounting for correlated observations in an age-based state-space stock assessment model. ICES Journal of Marine Science 73: 1788-1797.

Nielsen, A., and Berg, C.W. 2014. Estimation of time-varying selectivity in stock assessments using state-space models. Fisheries Research 158: 96-101.

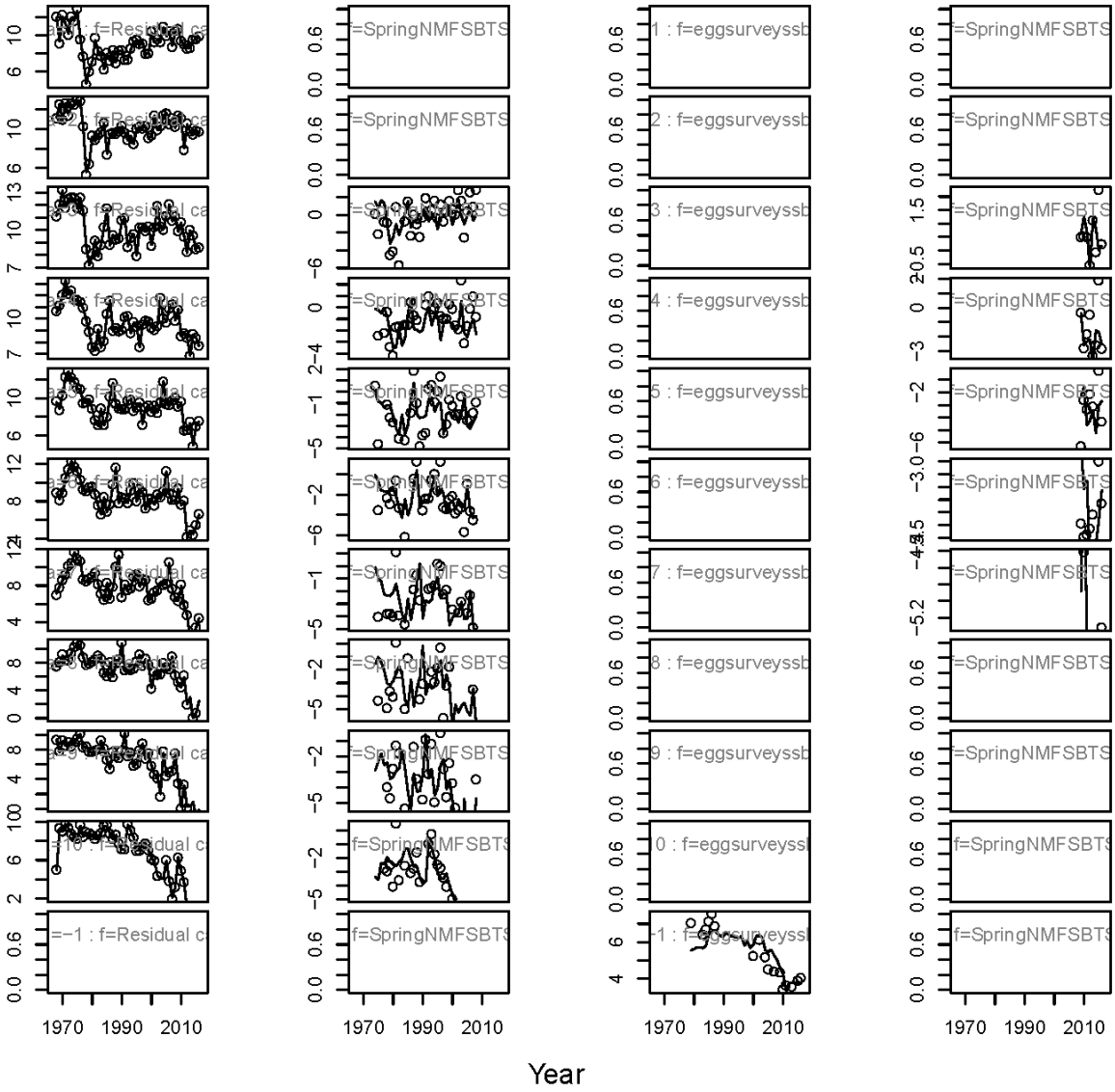
Observed (x) and predicted (line) catches with 95%CI (grey).



F states at age (numbers indicating age; 4 is age-4+) and average F among all ages (black line) with 95%CI (grey).

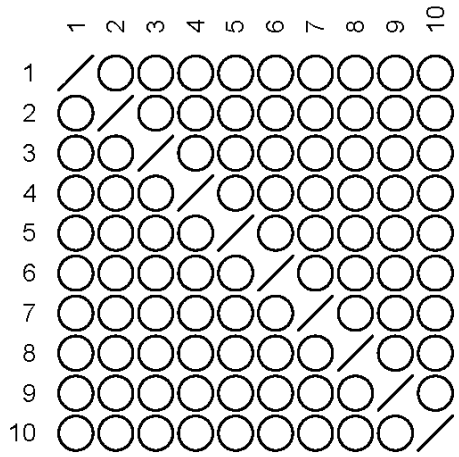


Log observed (circles) and predicted catches at age (first column), NMFS spring indices at age from *Albatross* years (second column), egg index (third column) and NMFS spring indices at age from *Bigelow* year (fourth column).

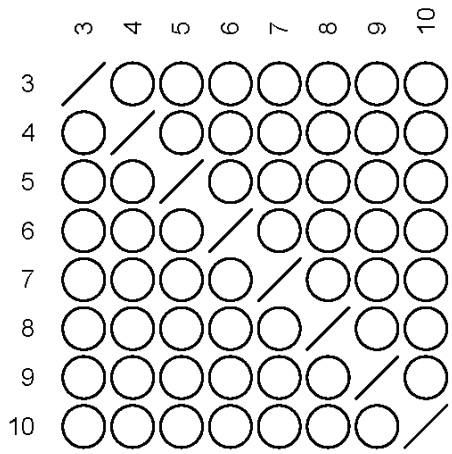


Graphical representation of the correlation among ages for each data source; all ages were assumed uncorrelated

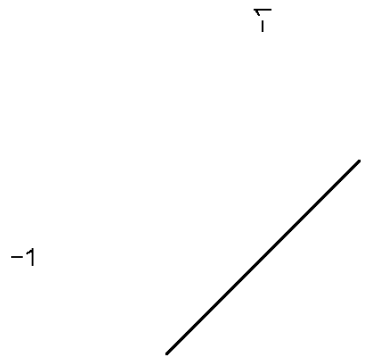
Residual catch



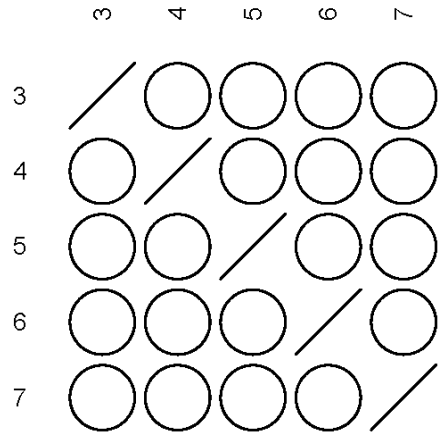
SpringNMFSBTSAlbYear



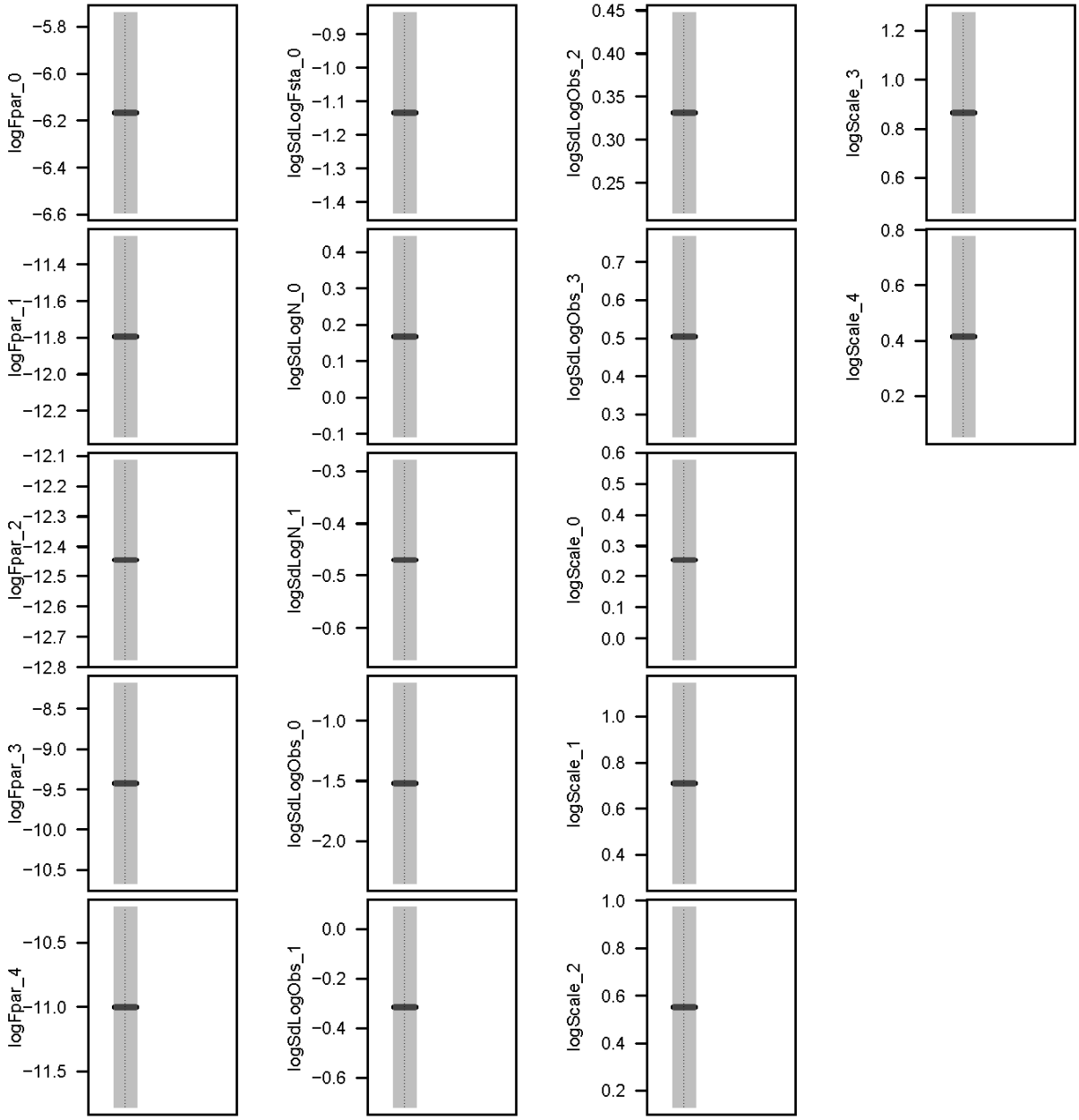
eggsurveyssbindex



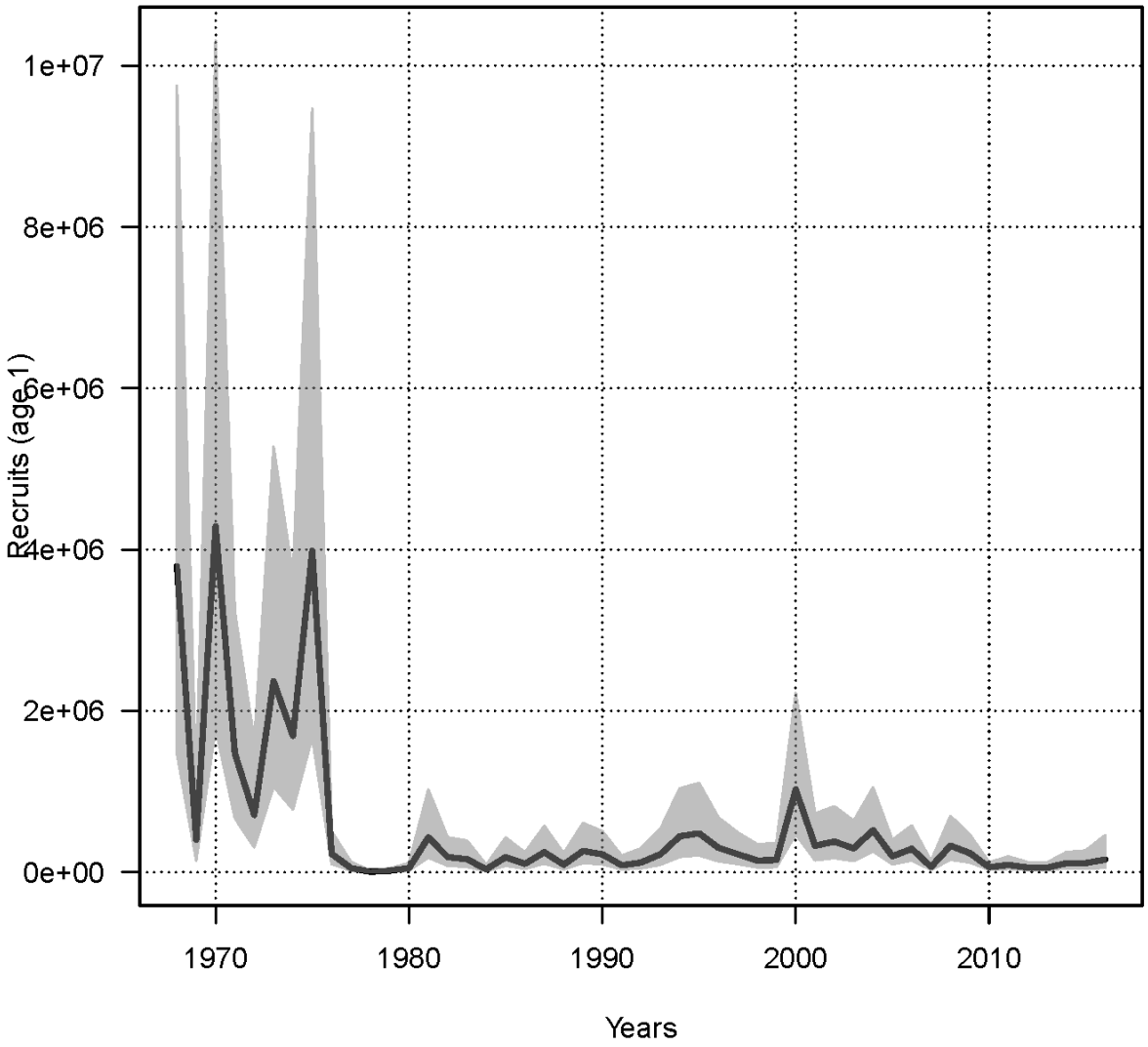
SpringNMFSBTSBigYear



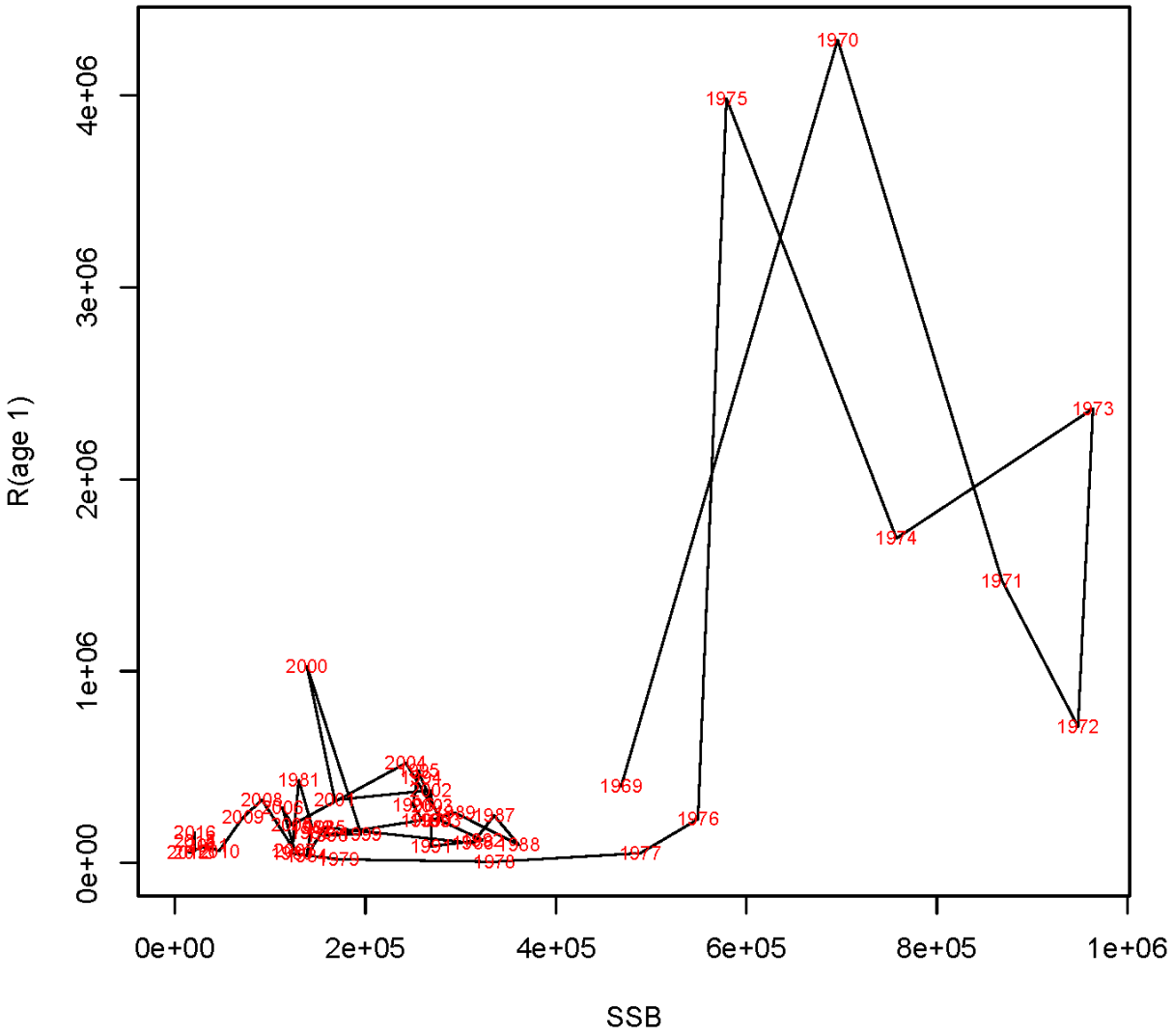
Log scale parameter estimates (black bar) and 95%CI (grey).



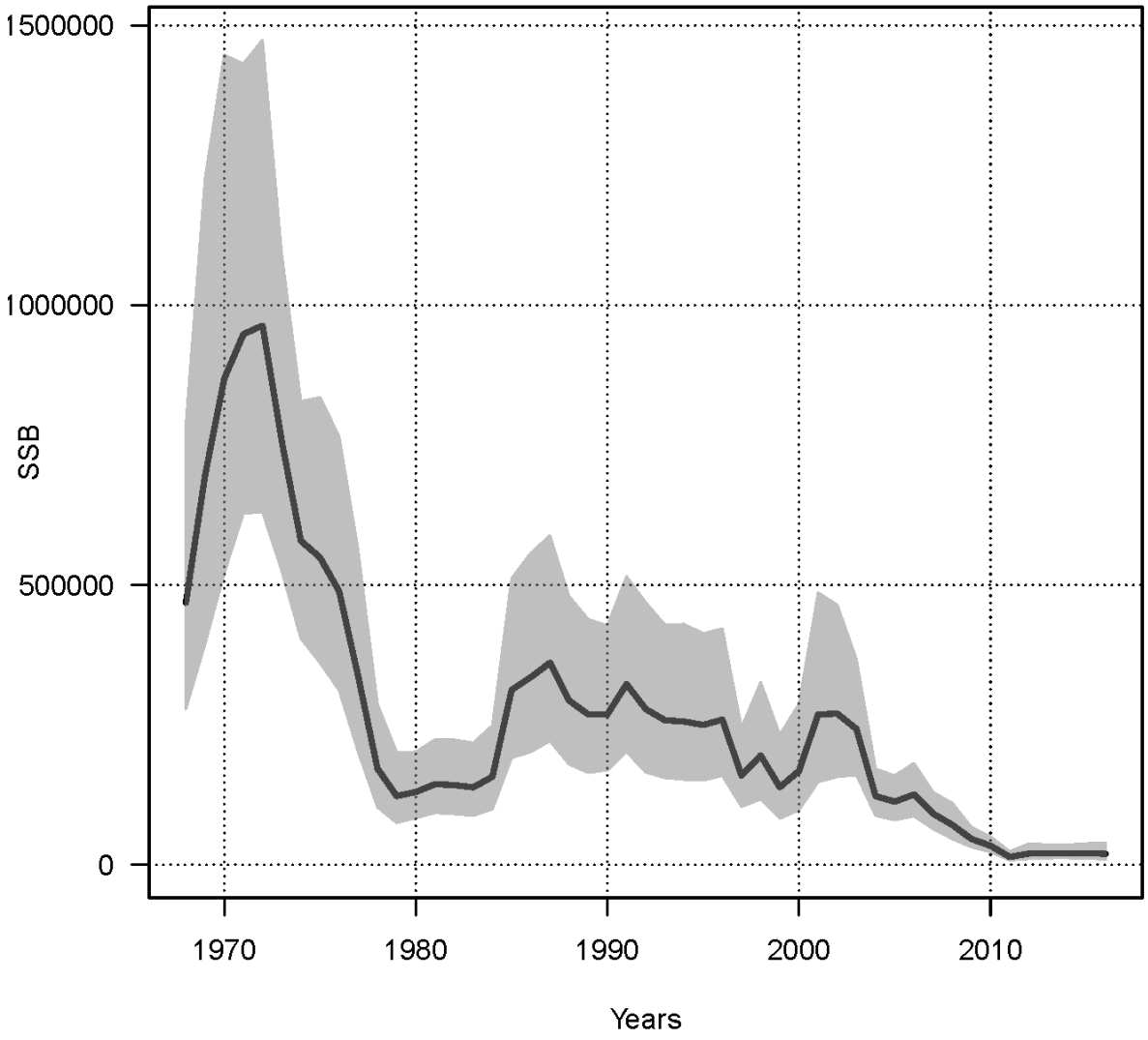
Time series of recruitment estimates and 95%CIs



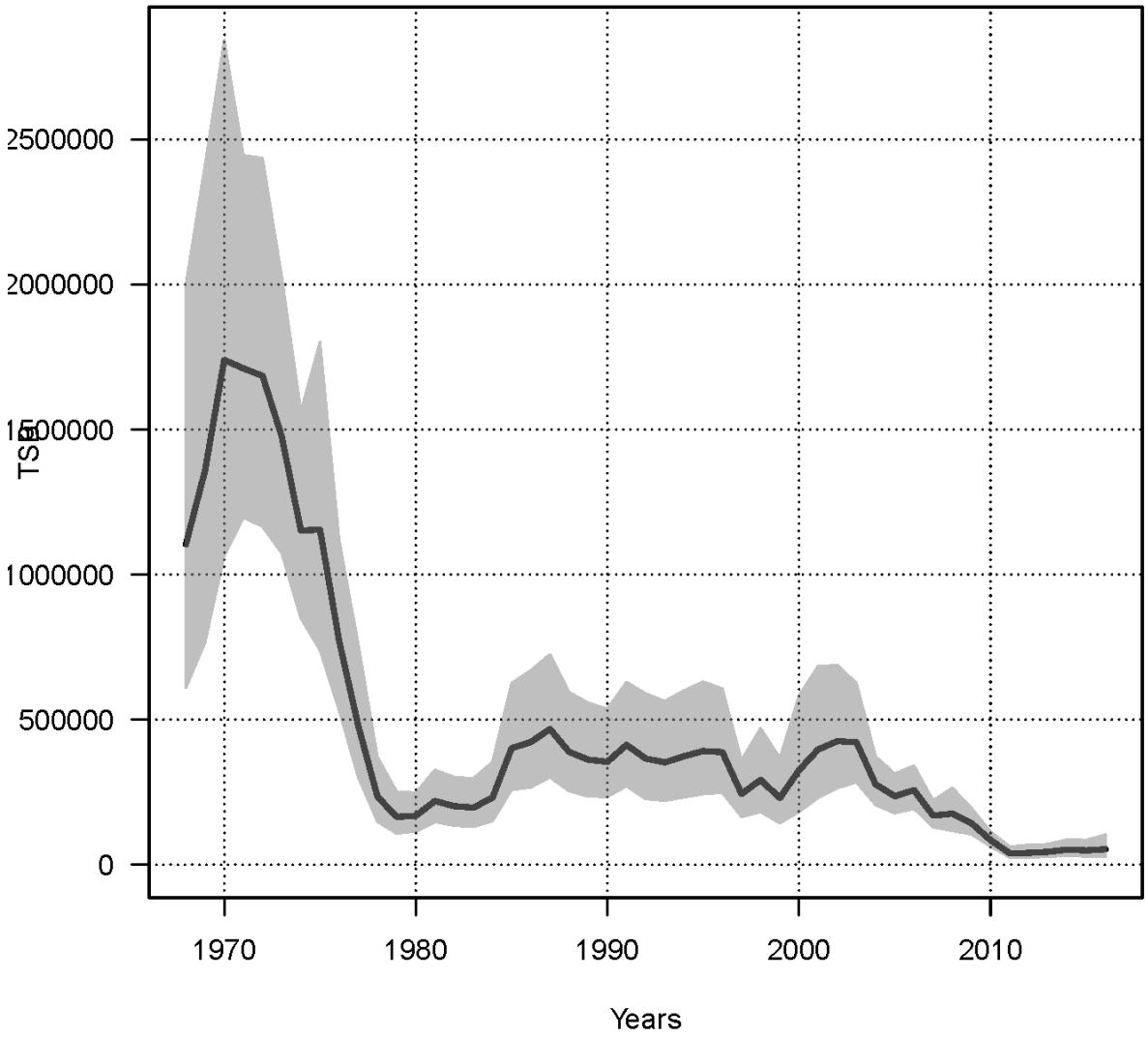
Stock-recruit plot



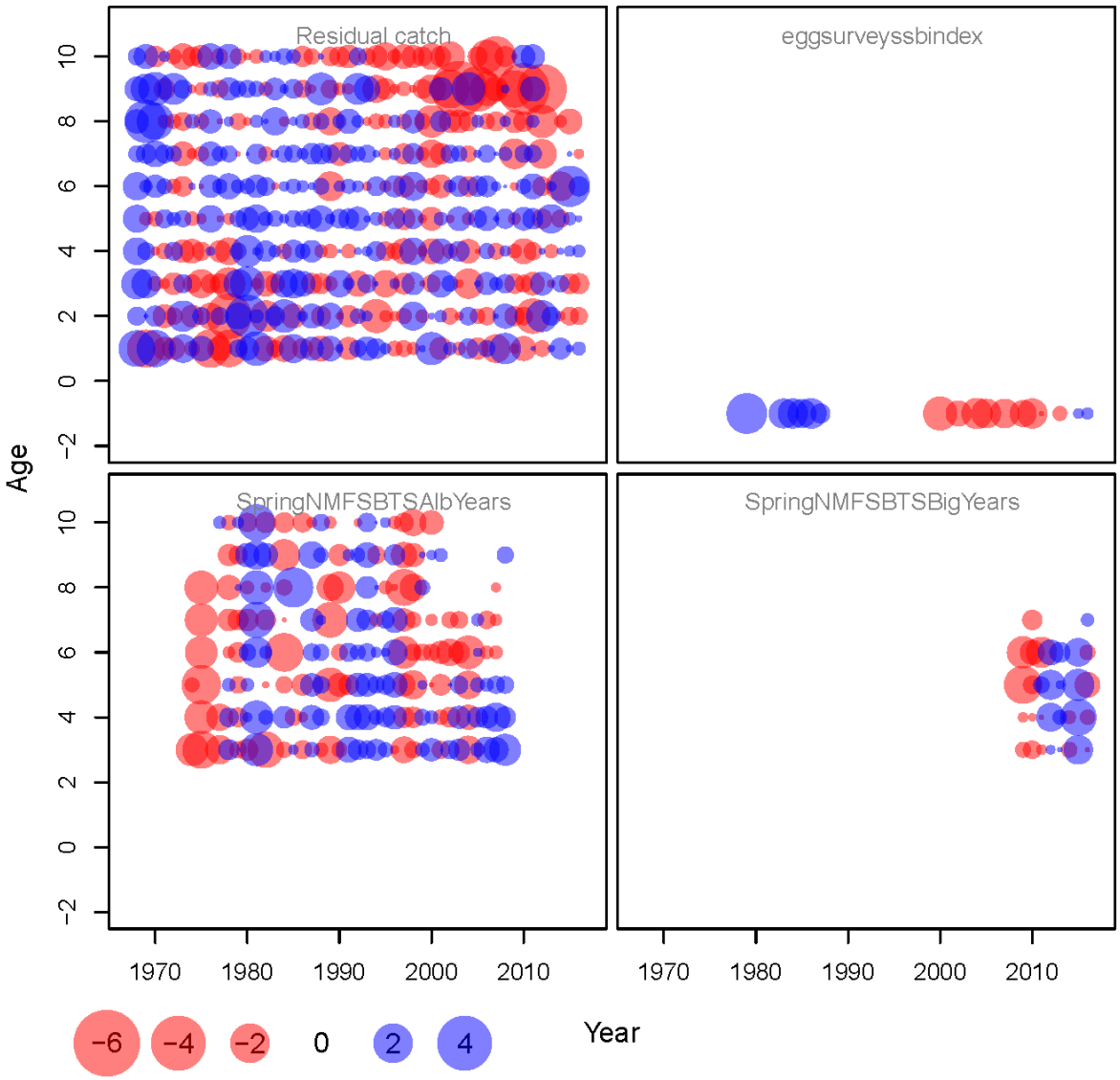
Time series of spawning stock biomass and 95%CIs



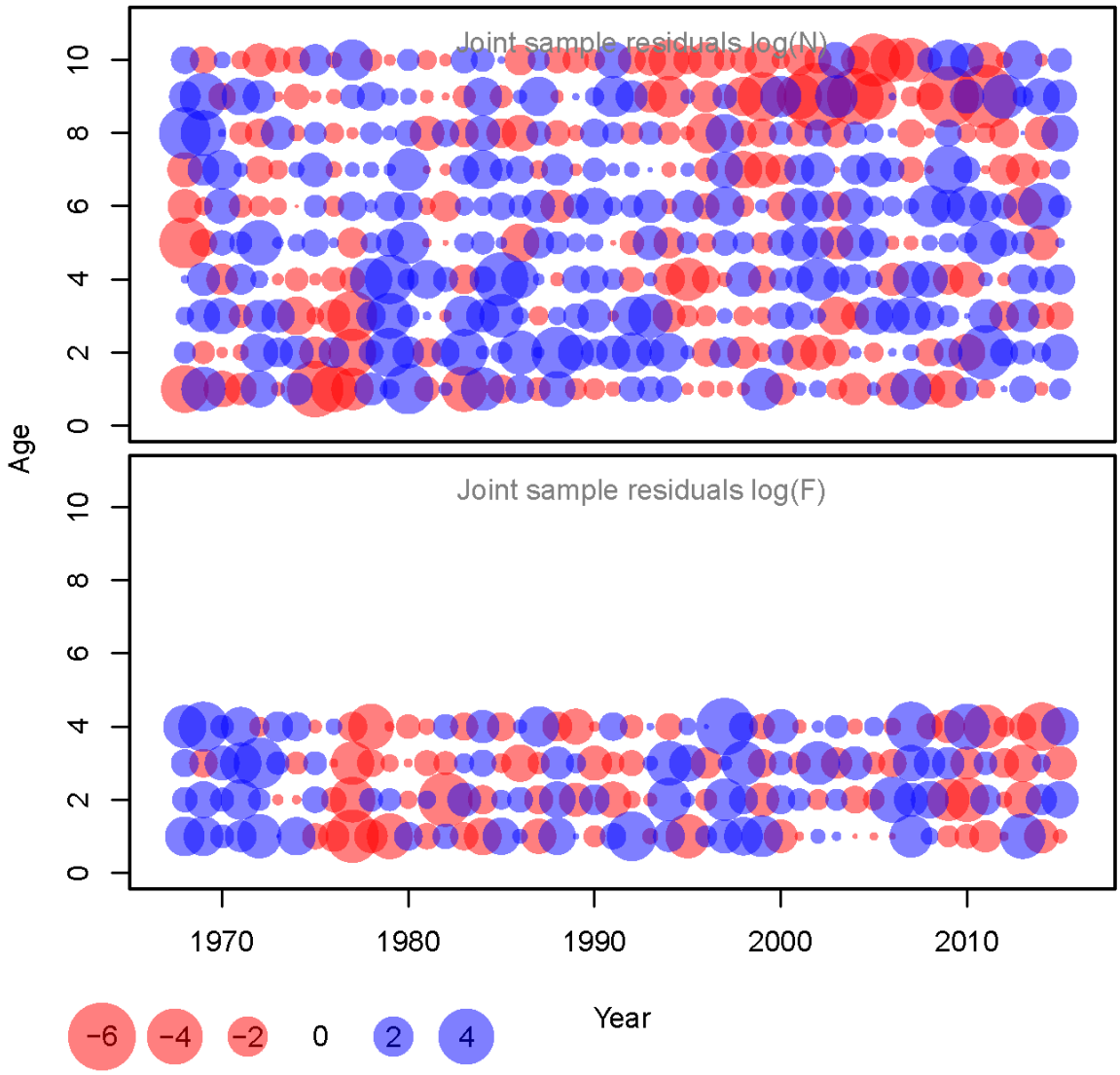
Total biomass time series and 95%CI.



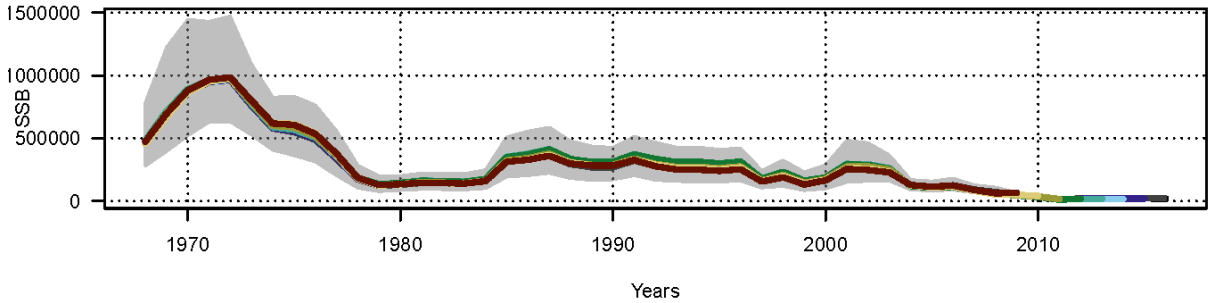
Standardized residual bubble plots for each data source

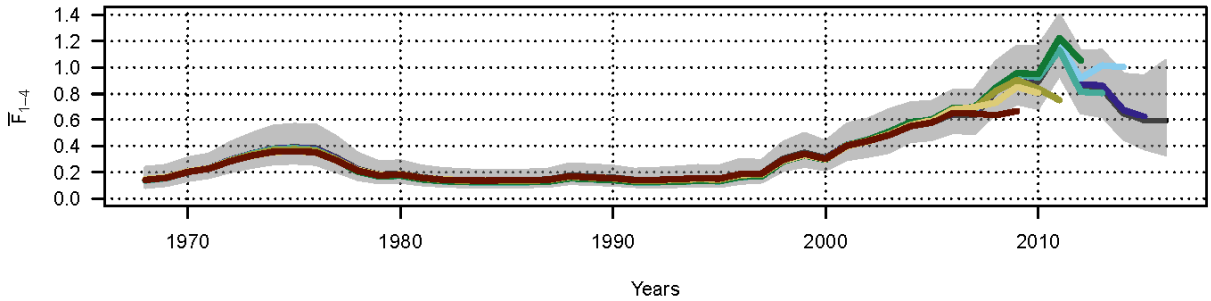


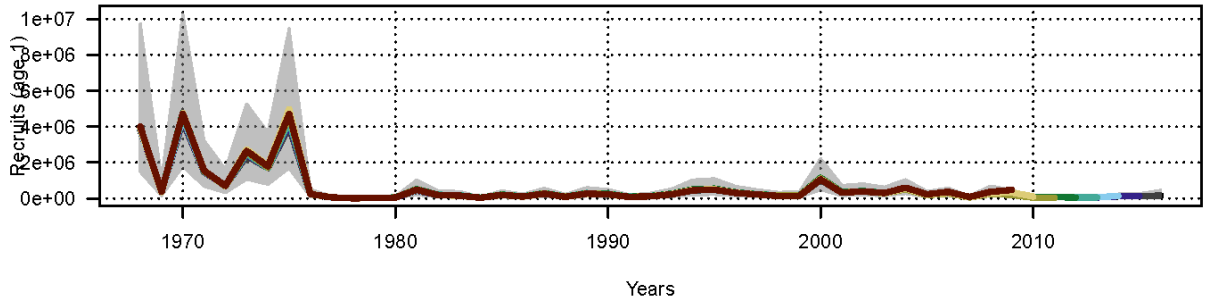
Standardized process errors (i.e., residuals) for the survival (top panel) and F processes (bottom panel)



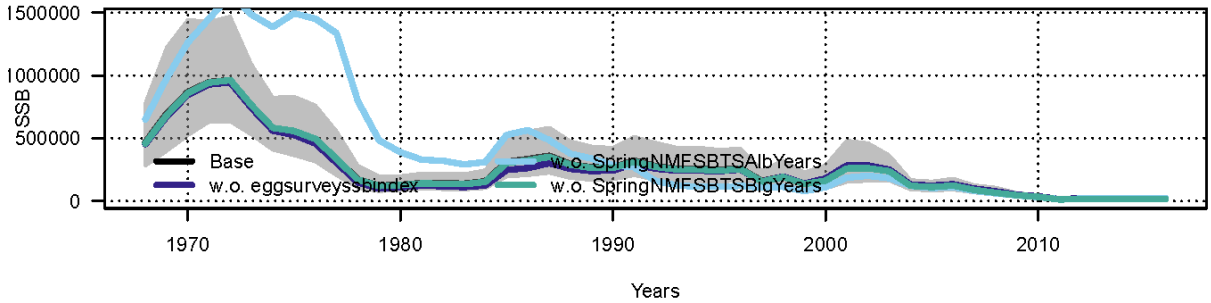
Retrospective patterns

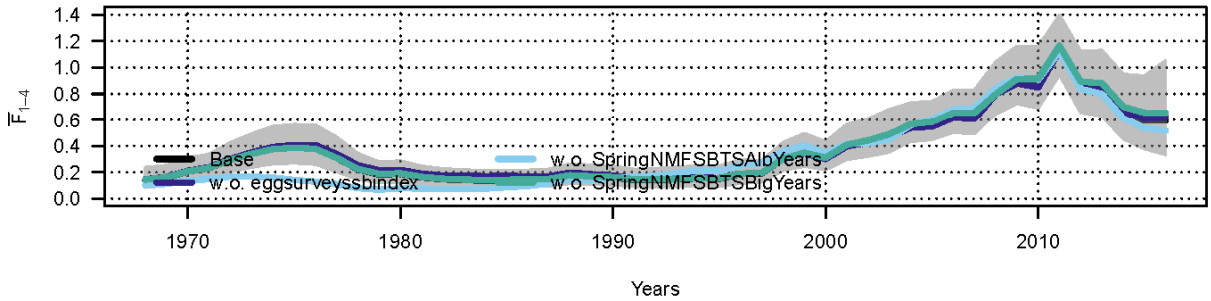


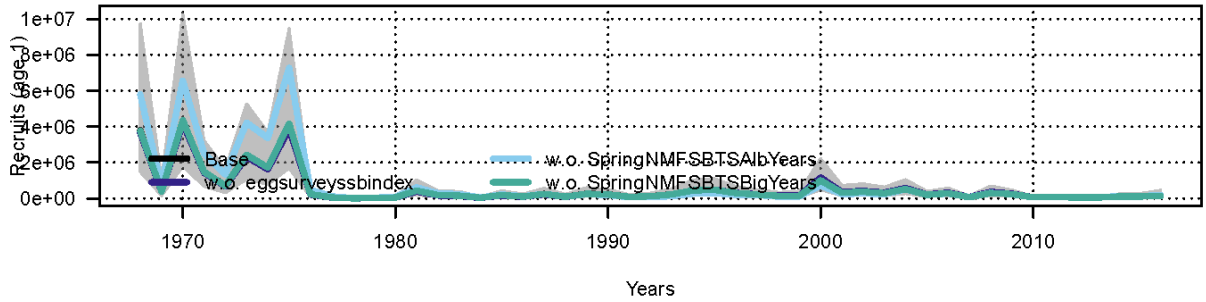




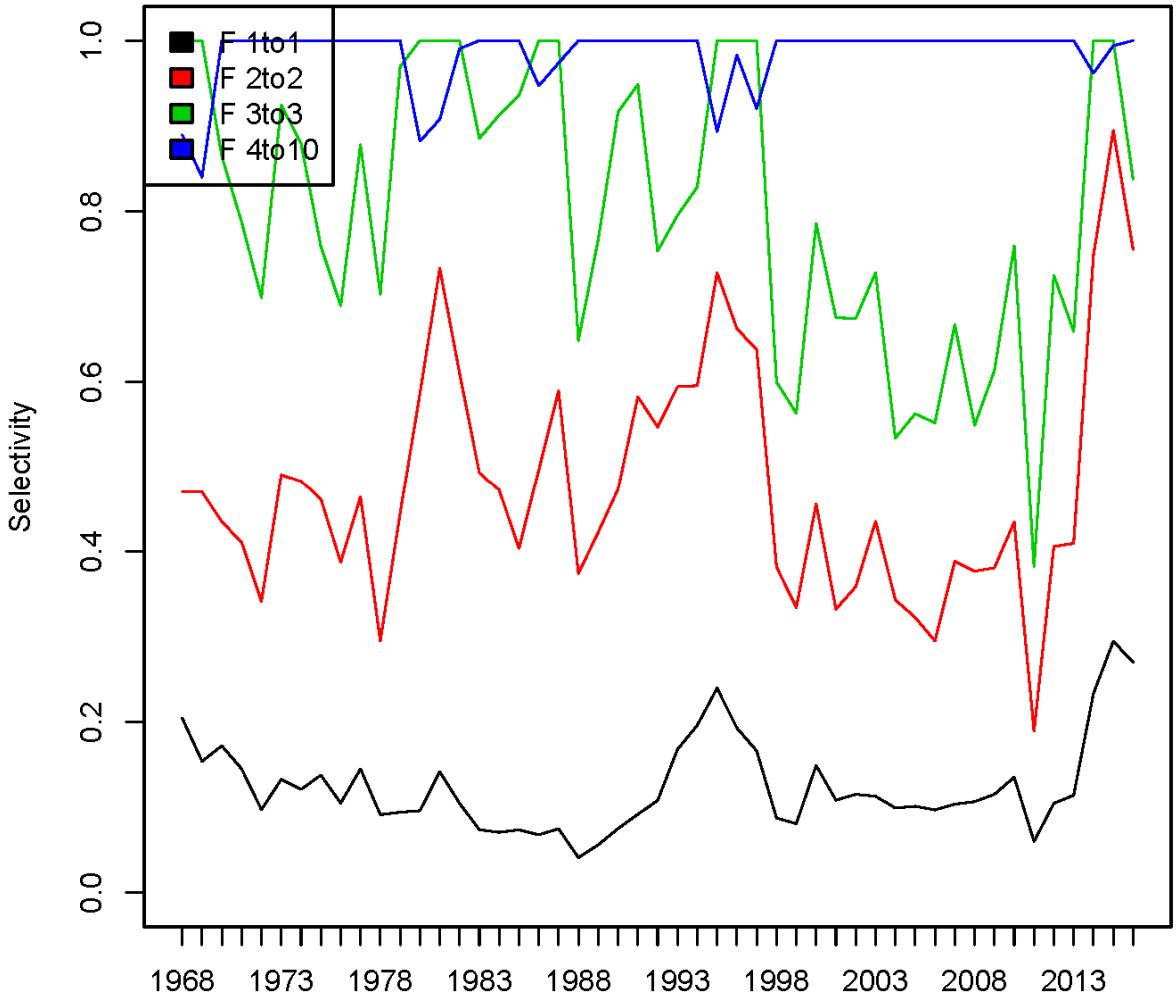
"Leave one out" analysis where one survey is absent from each fit



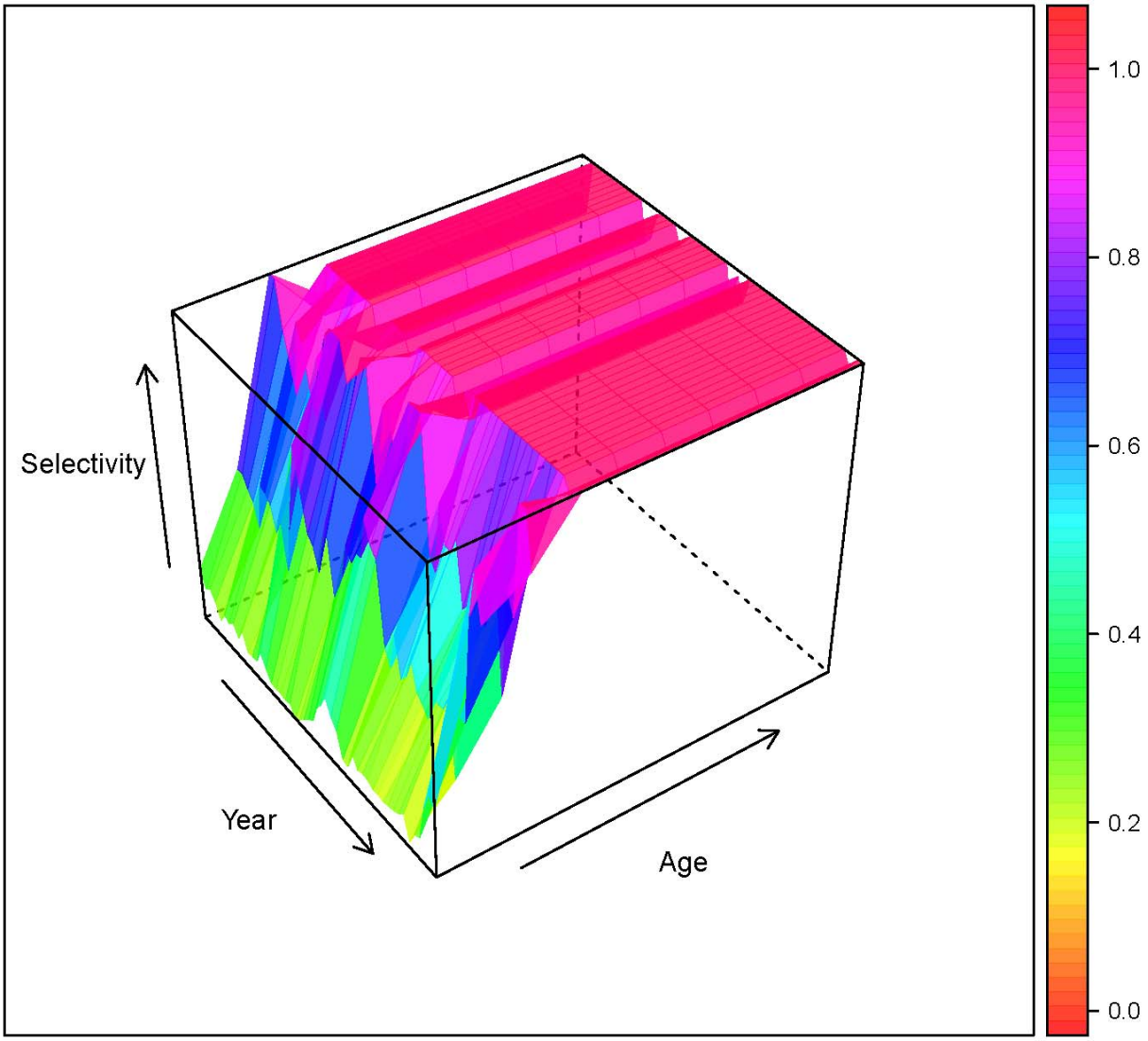




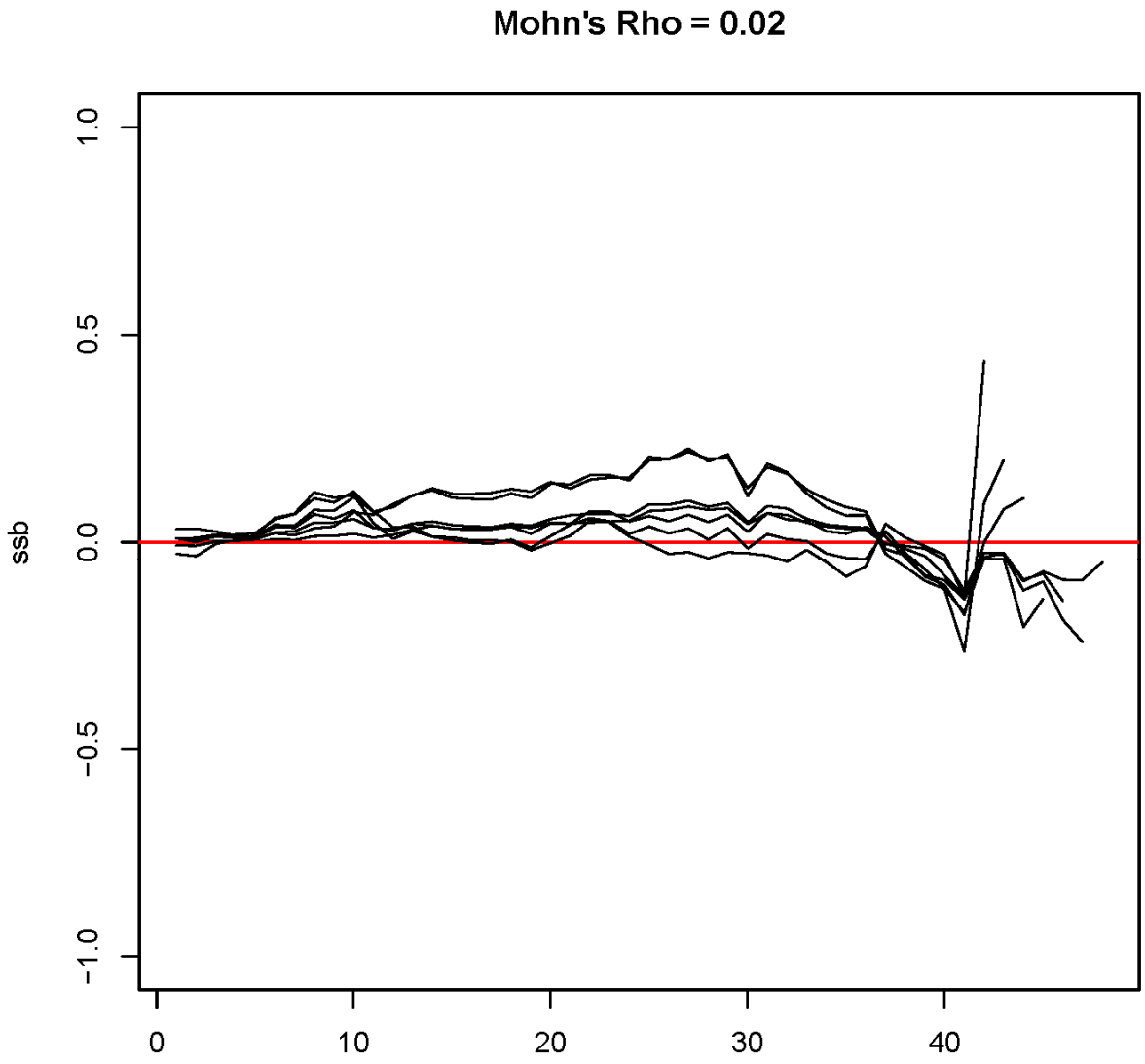
F-at-age states rescaled to a max of 1.0 in each year to represent a more traditional interpretation of selectivity.



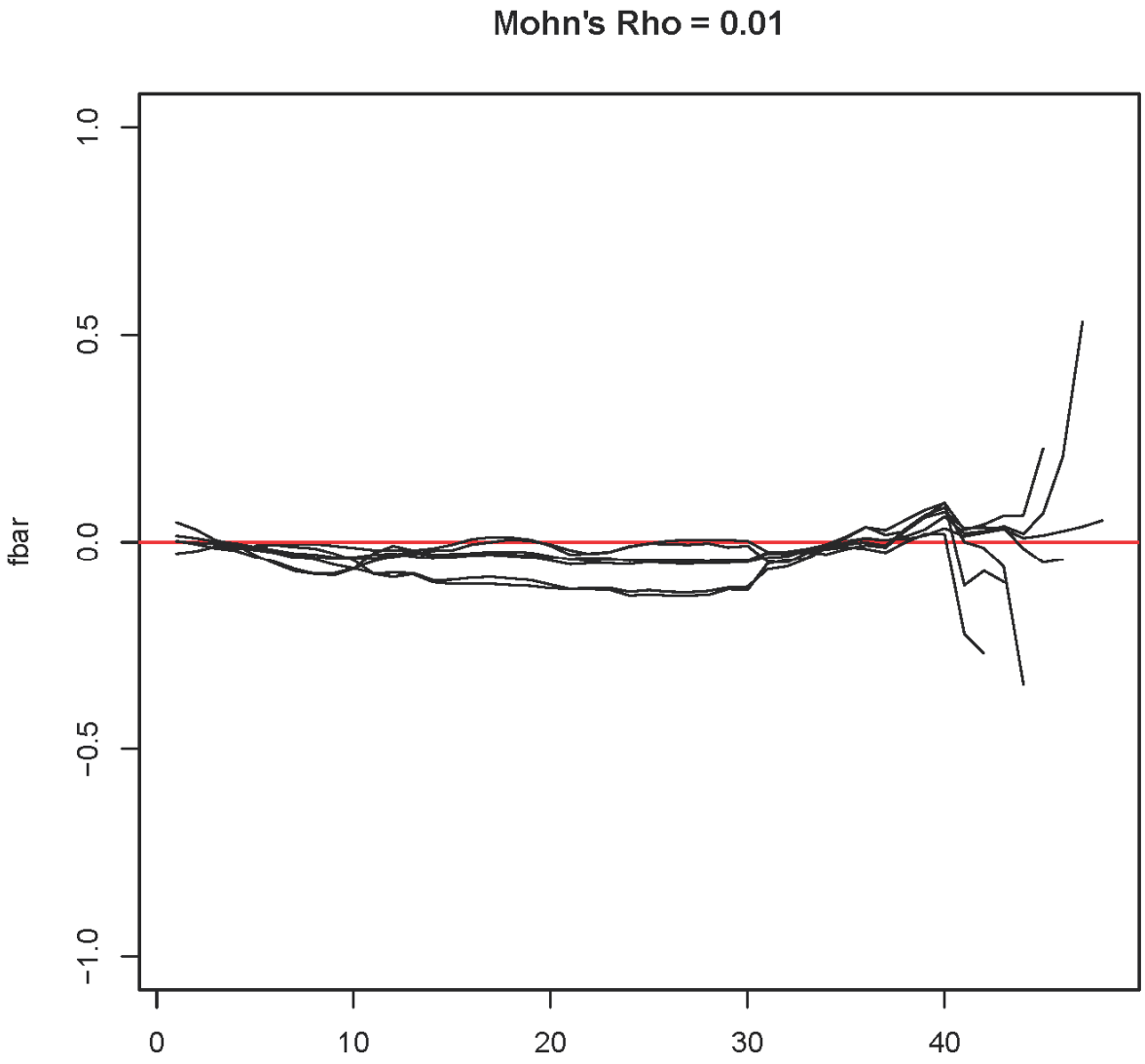
3-D representation of "selectivity" at age through years.



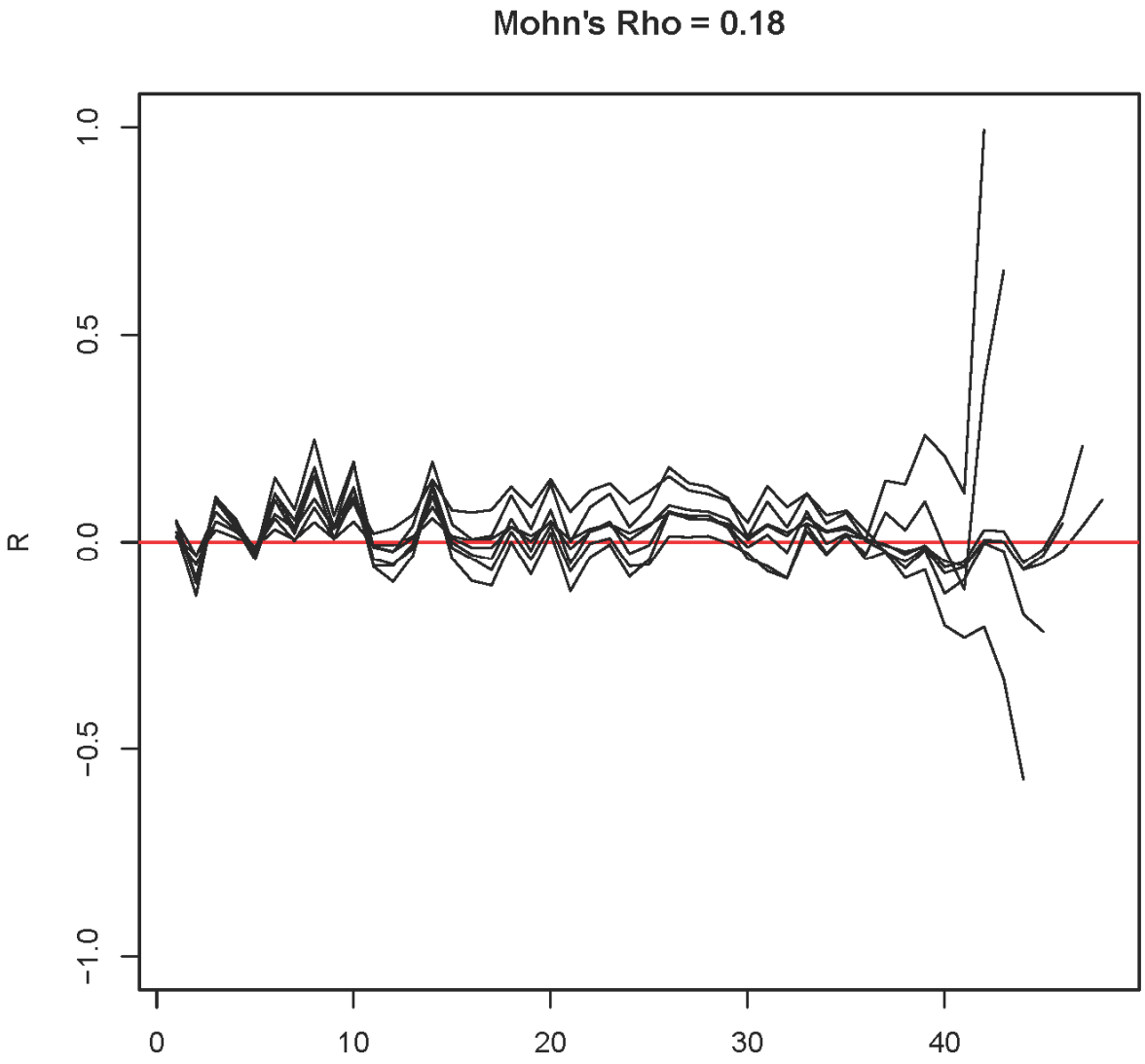
Relative retrospective patterns for spawning stock biomass with Mohn's Rho (7 year peel).



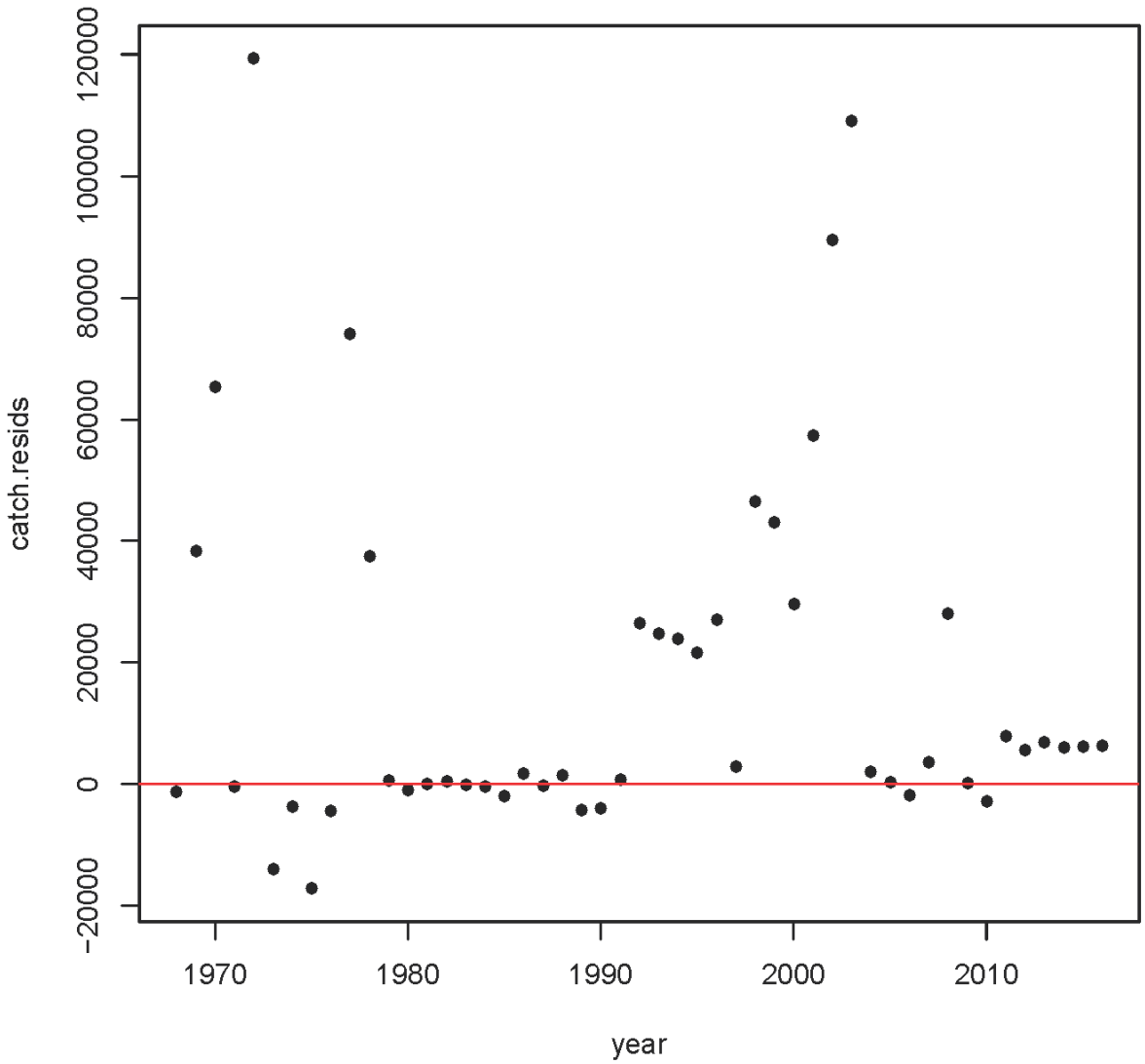
Relative retrospective patterns for fishing mortality with Mohn's Rho (7 year peel).



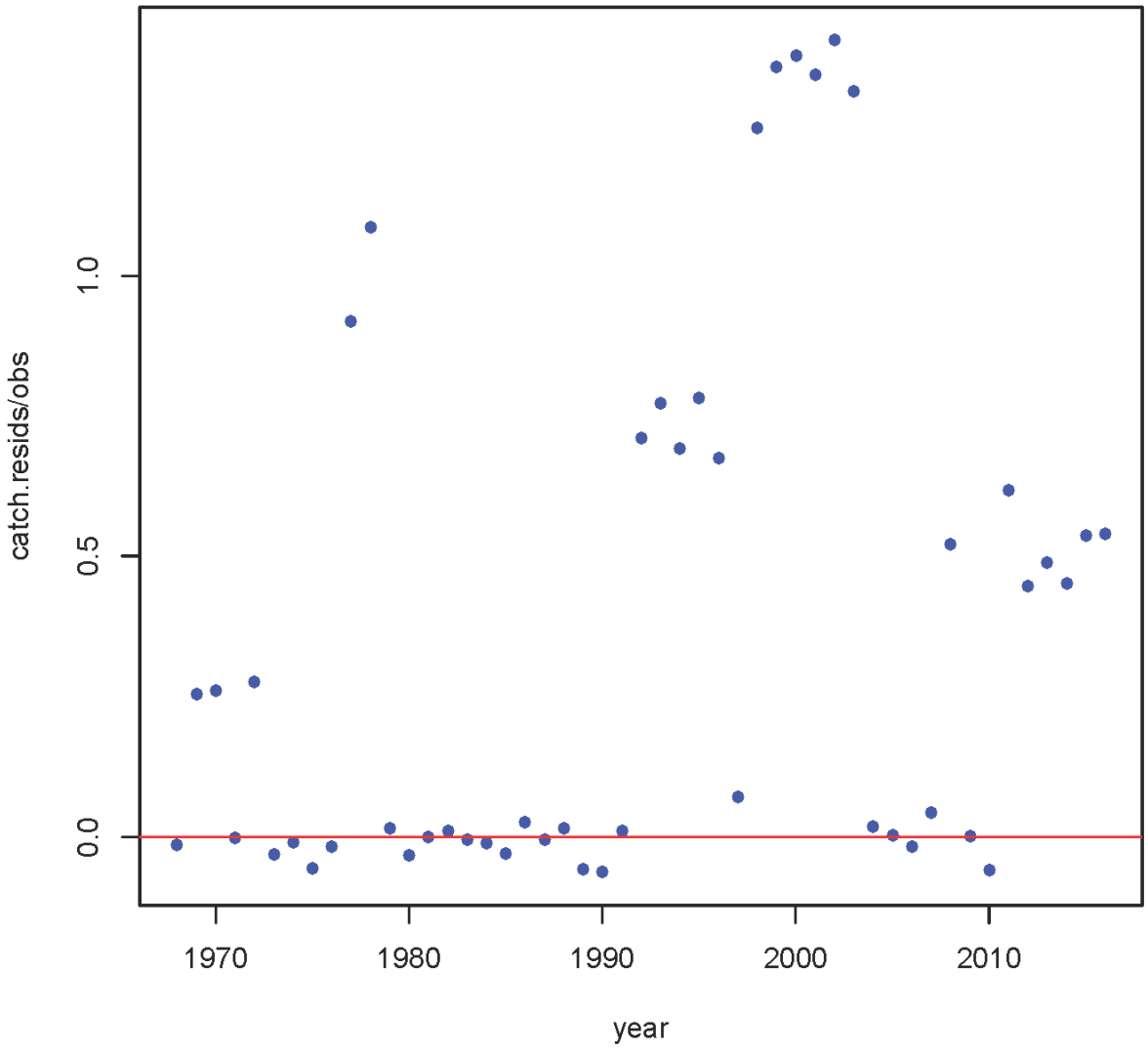
Relative retrospective patterns for recruitment with Mohn's Rho (7 year peel).



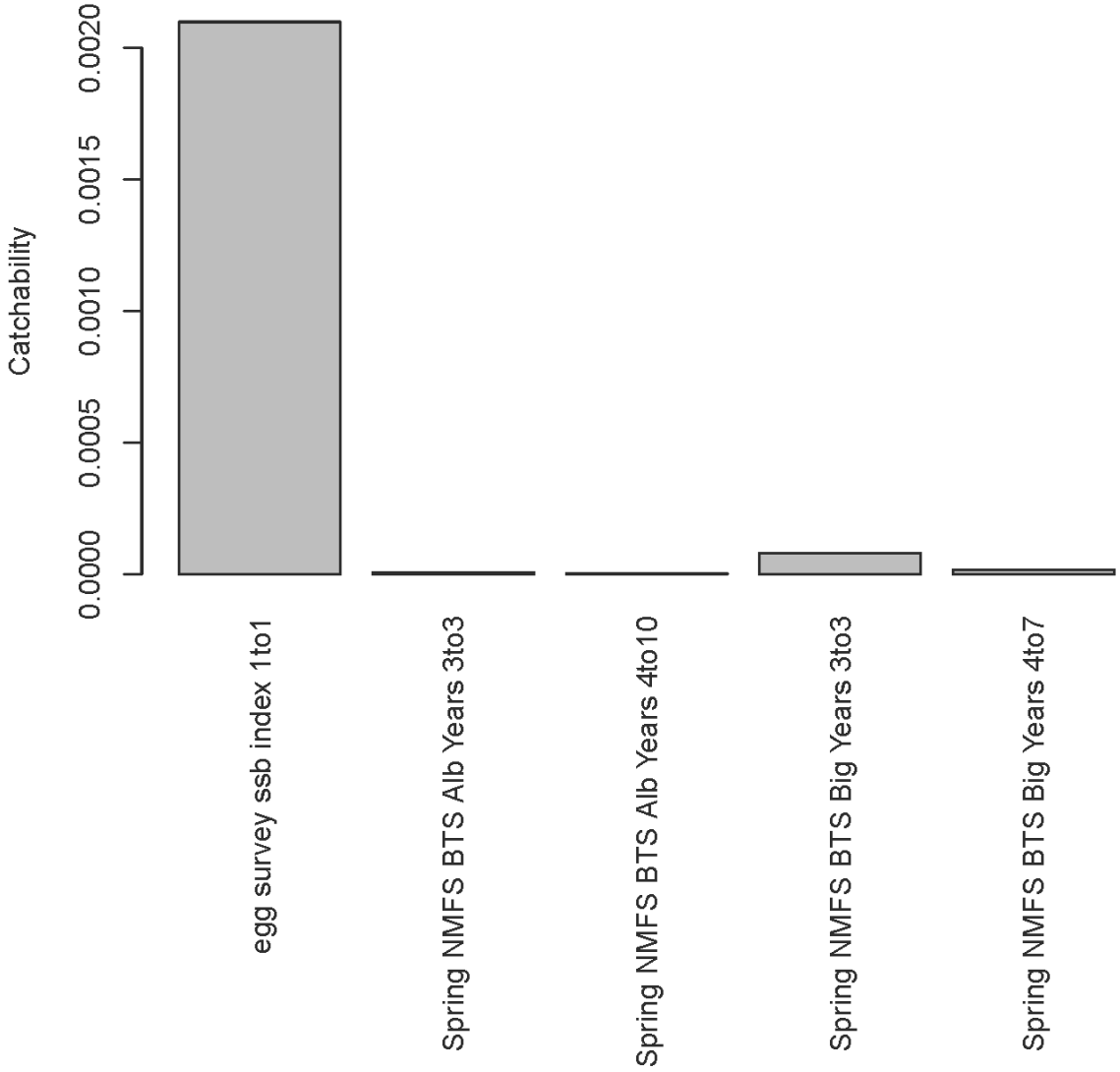
Catch residuals



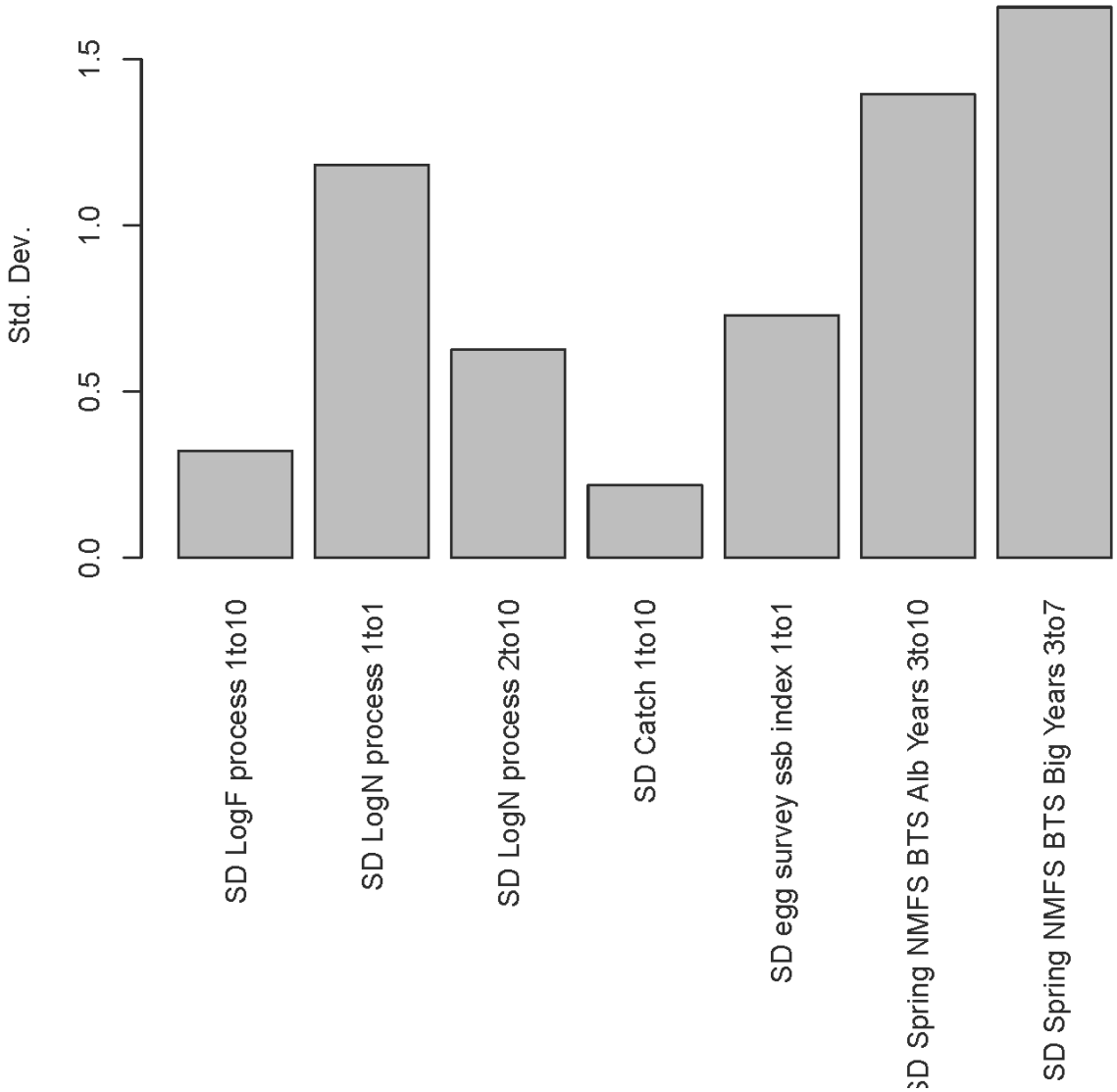
Standardized catch residuals



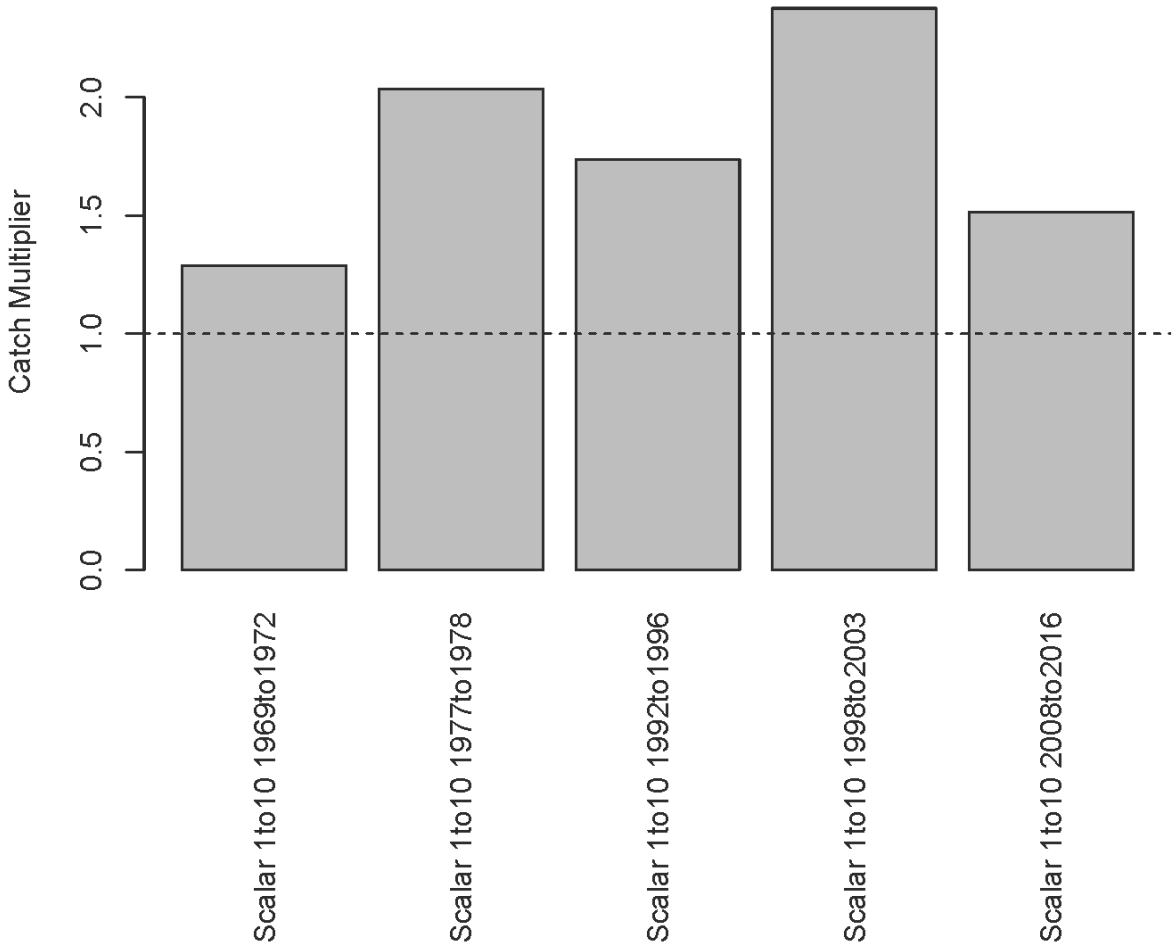
Catchability estimates for each survey and age range.



Standard deviation estimates for observation and process errors

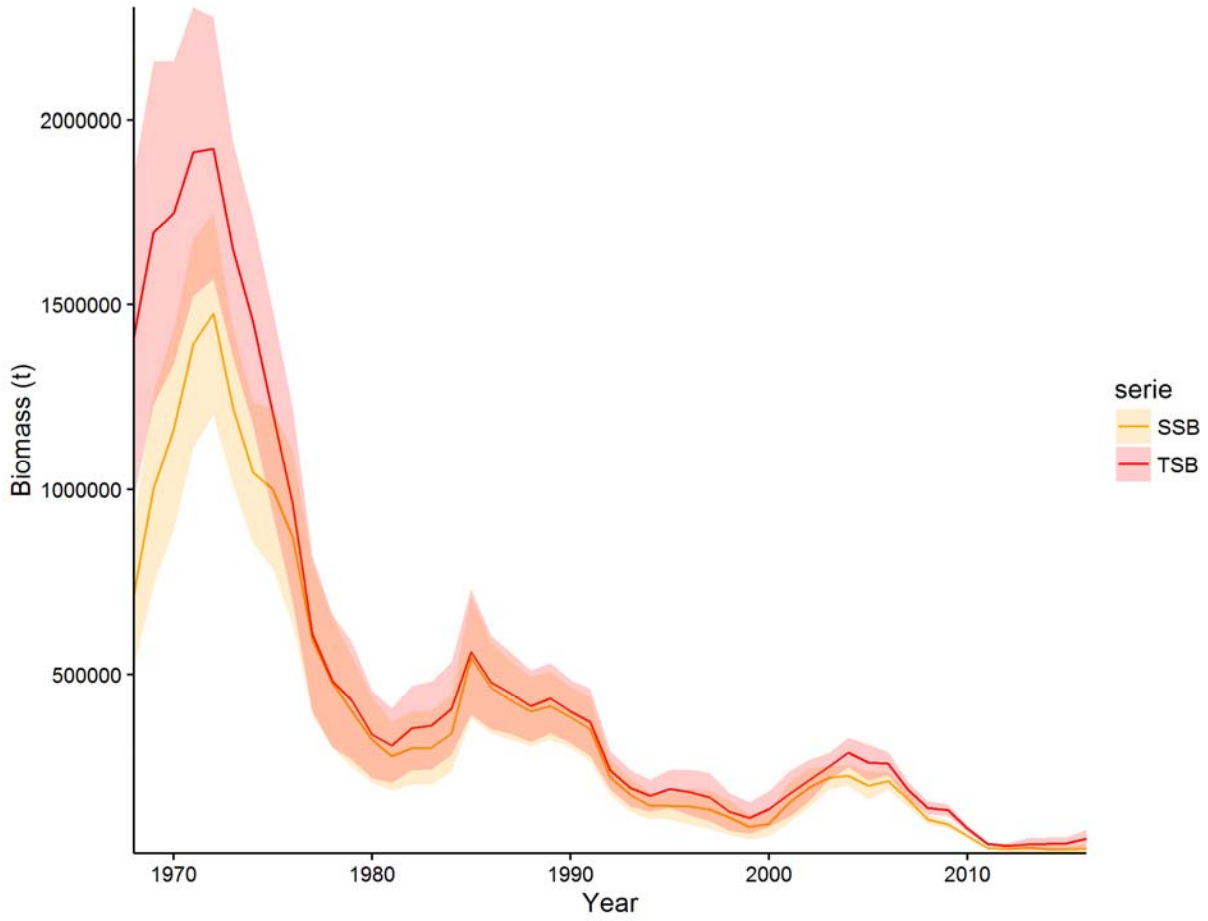


Catch multipliers (level of misreporting from observed catch) for specified ranges of ages and years.

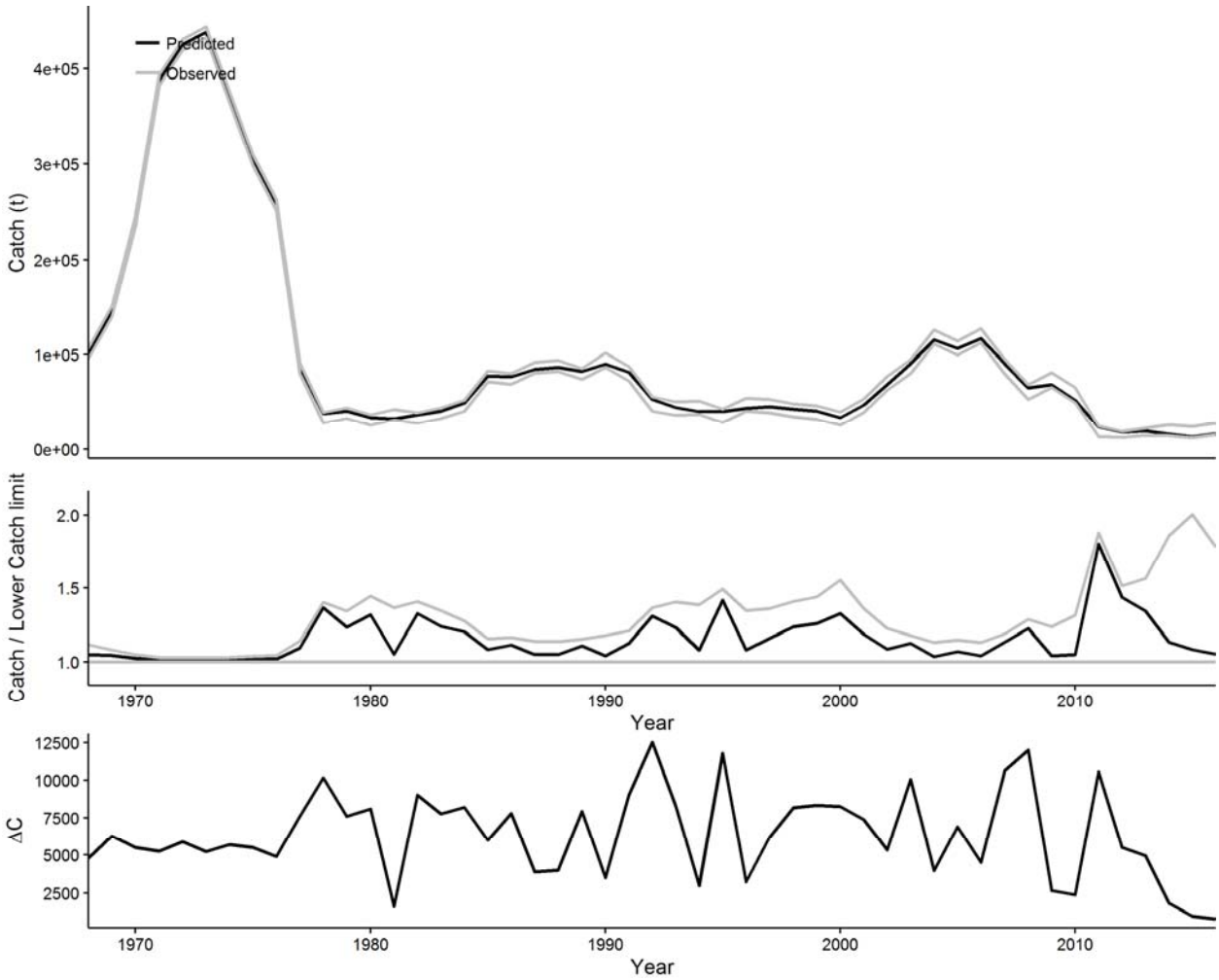


Appendix A13: Censored Catch Assessment Model (CCAM) figures

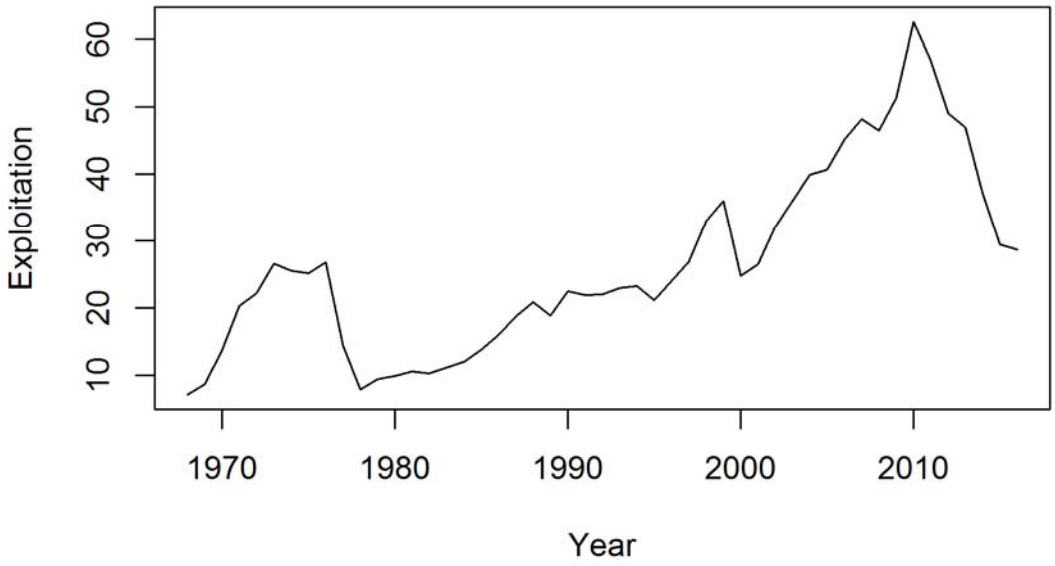
Biomass:



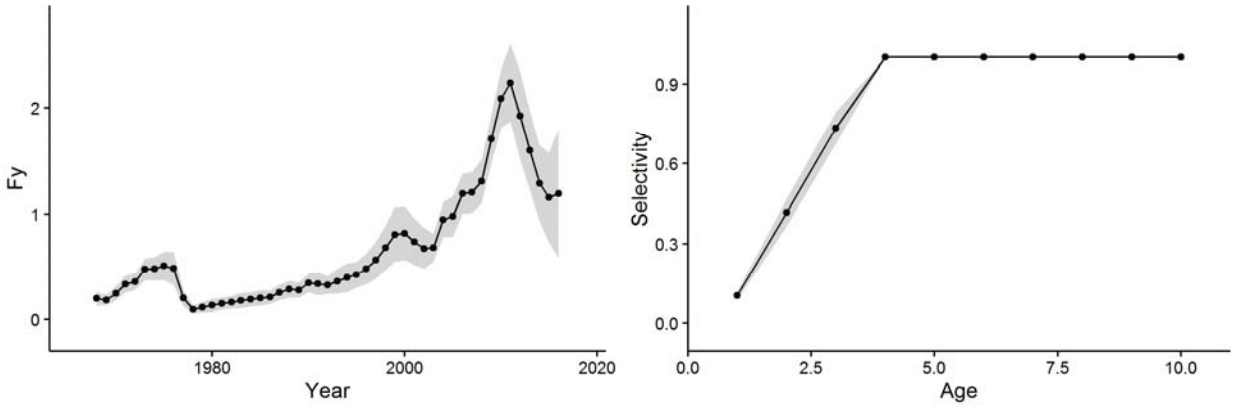
Catch:

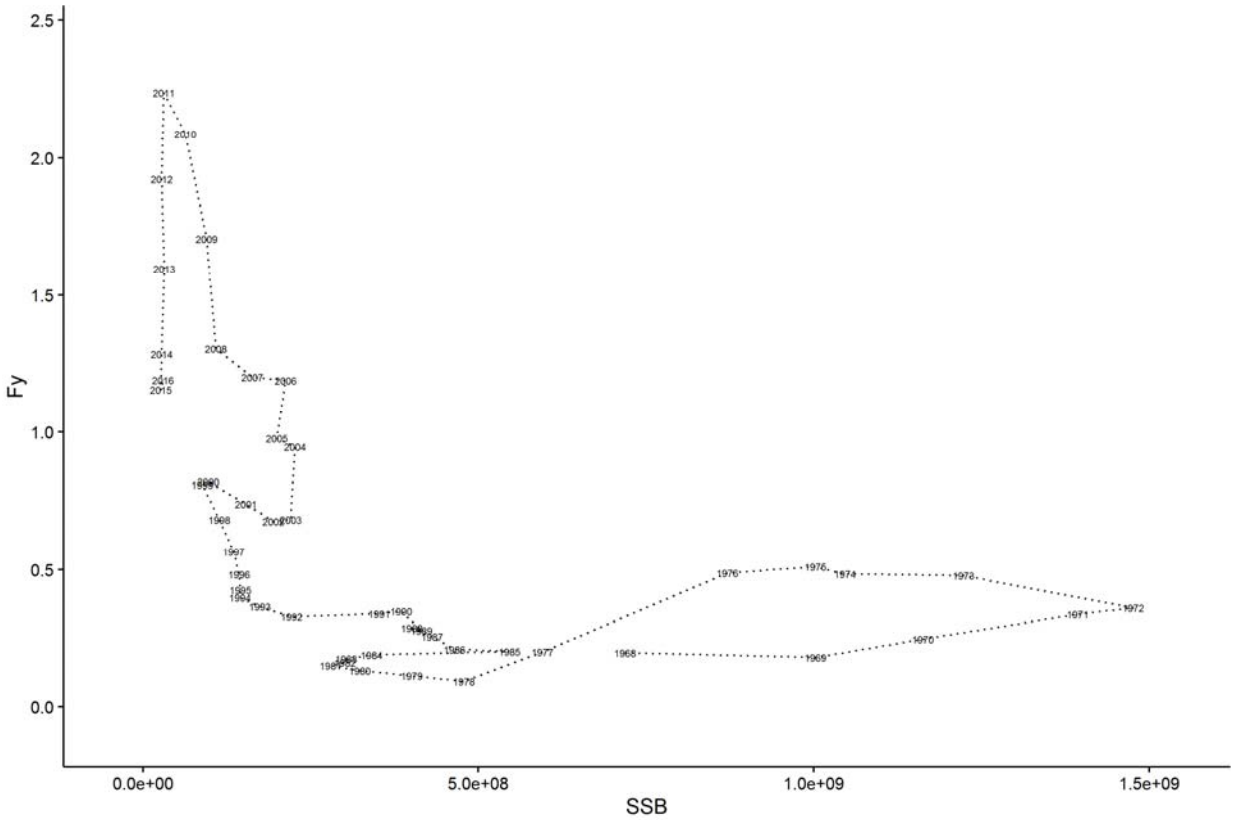

Predicted
Observed
Catch (t)
4e+05
3e+05
2e+05
1e+05
0e+00
Catch / Lower Catch limit
2.0
1.5
1.0
1970
1980
1990
2000
2010
Year
ΔC
12500
10000
7500
5000
2500
1970
1980
1990
2000
2010
Year

Exploitation:

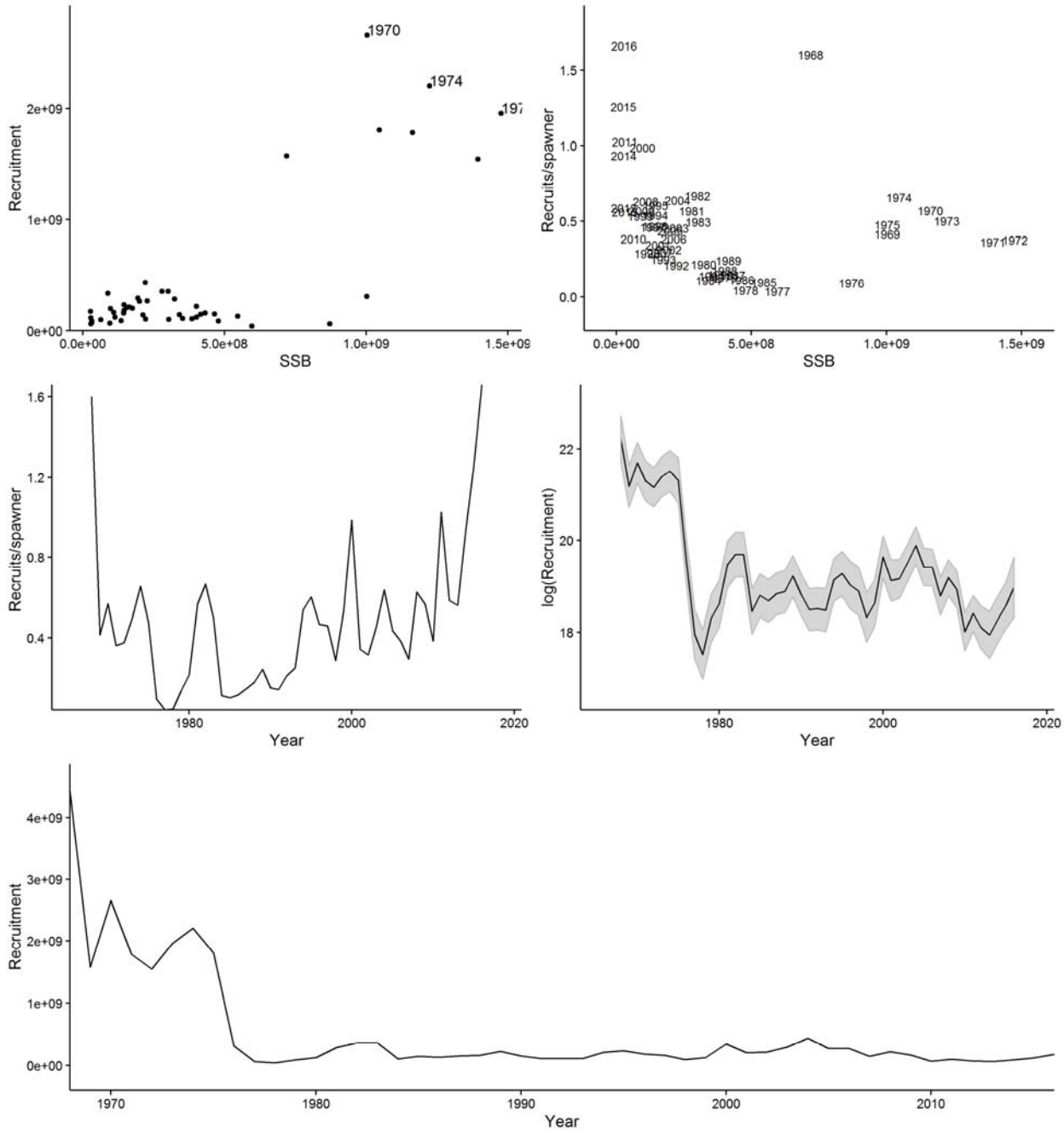


Fishing mortality:

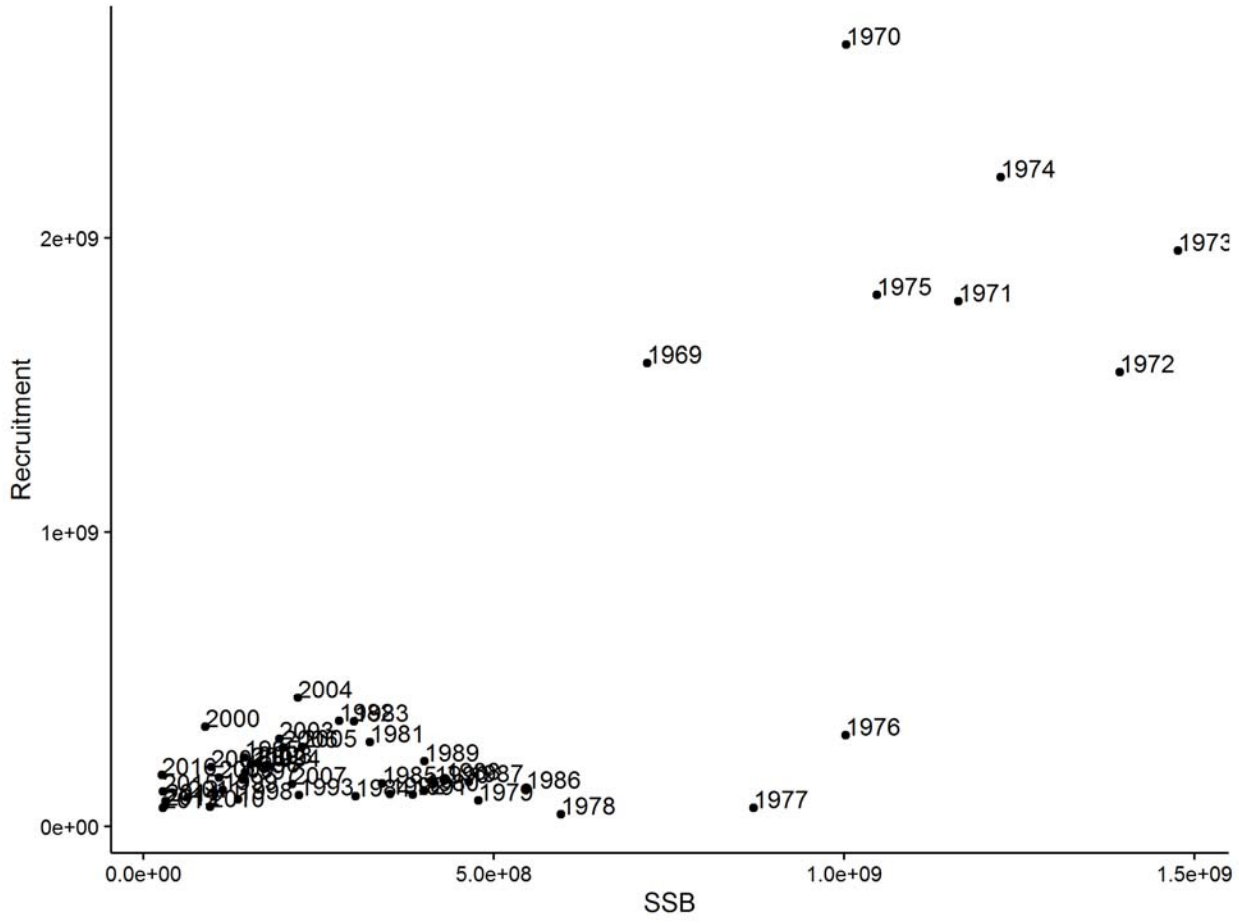




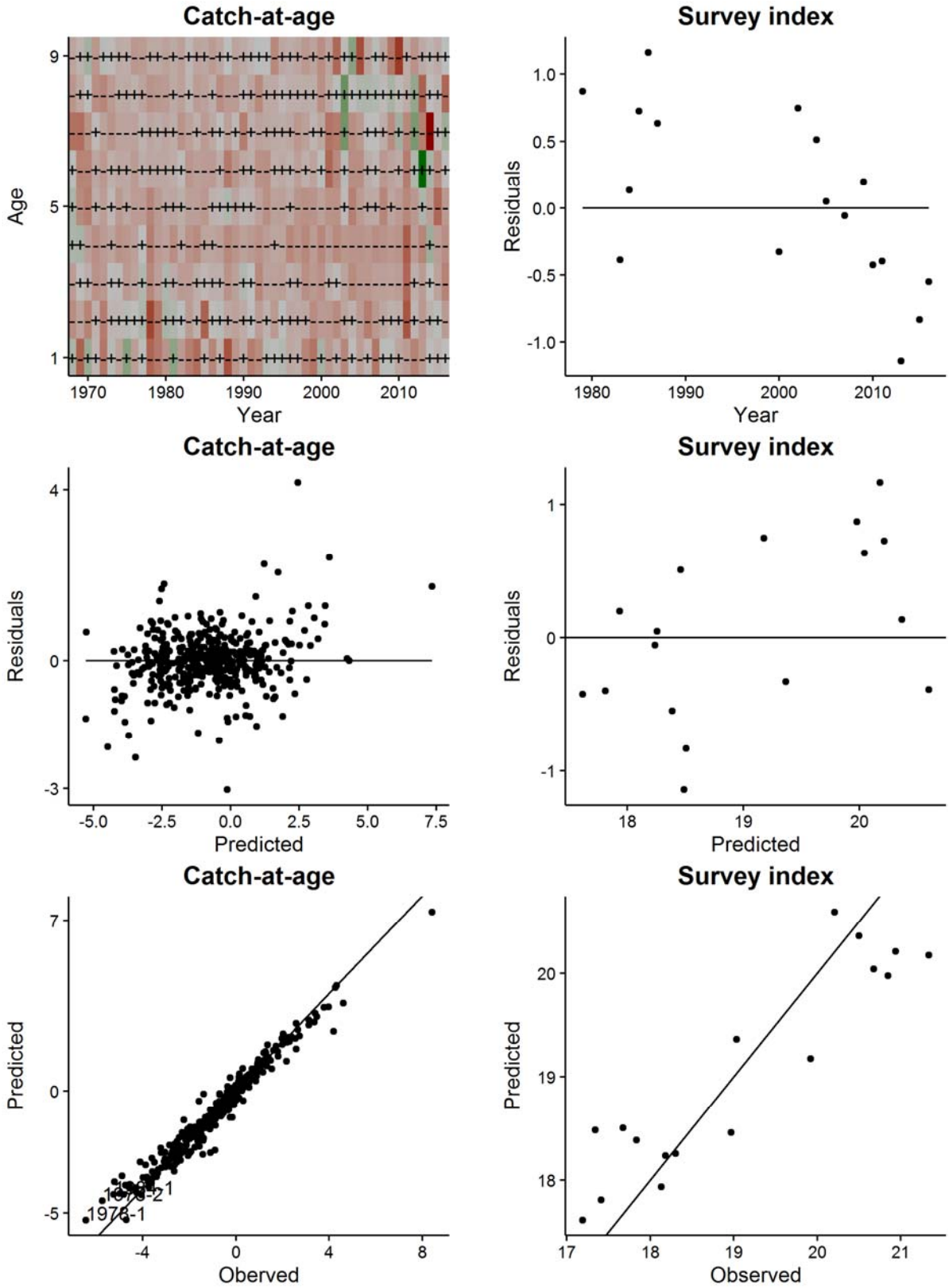
Recruitment:



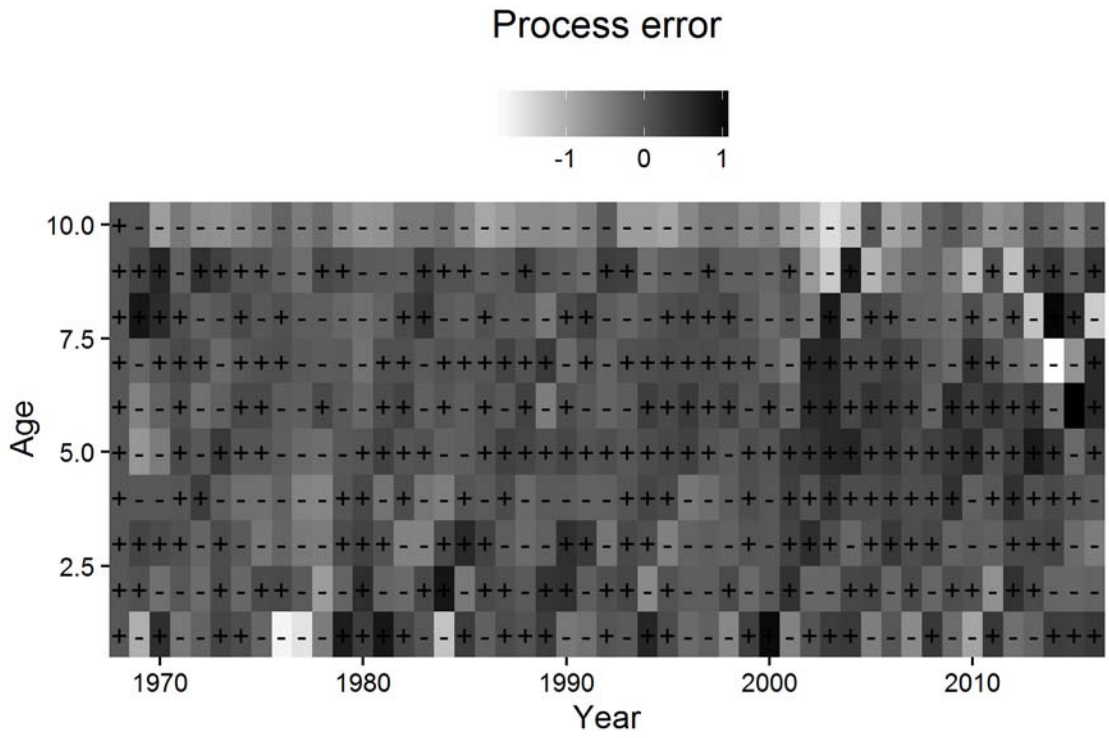
Spawning stock biomass and recruitment estimates:



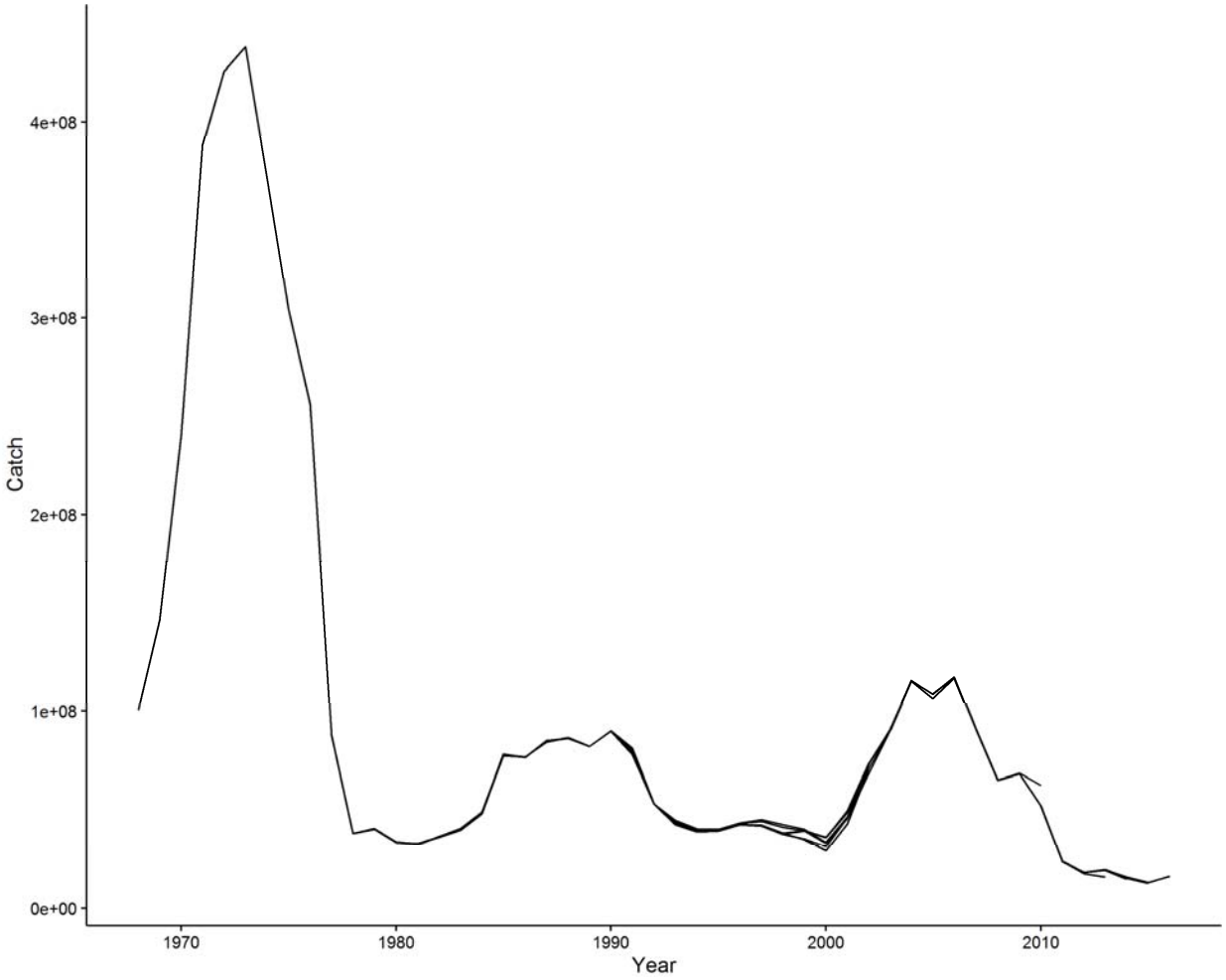
Residuals:

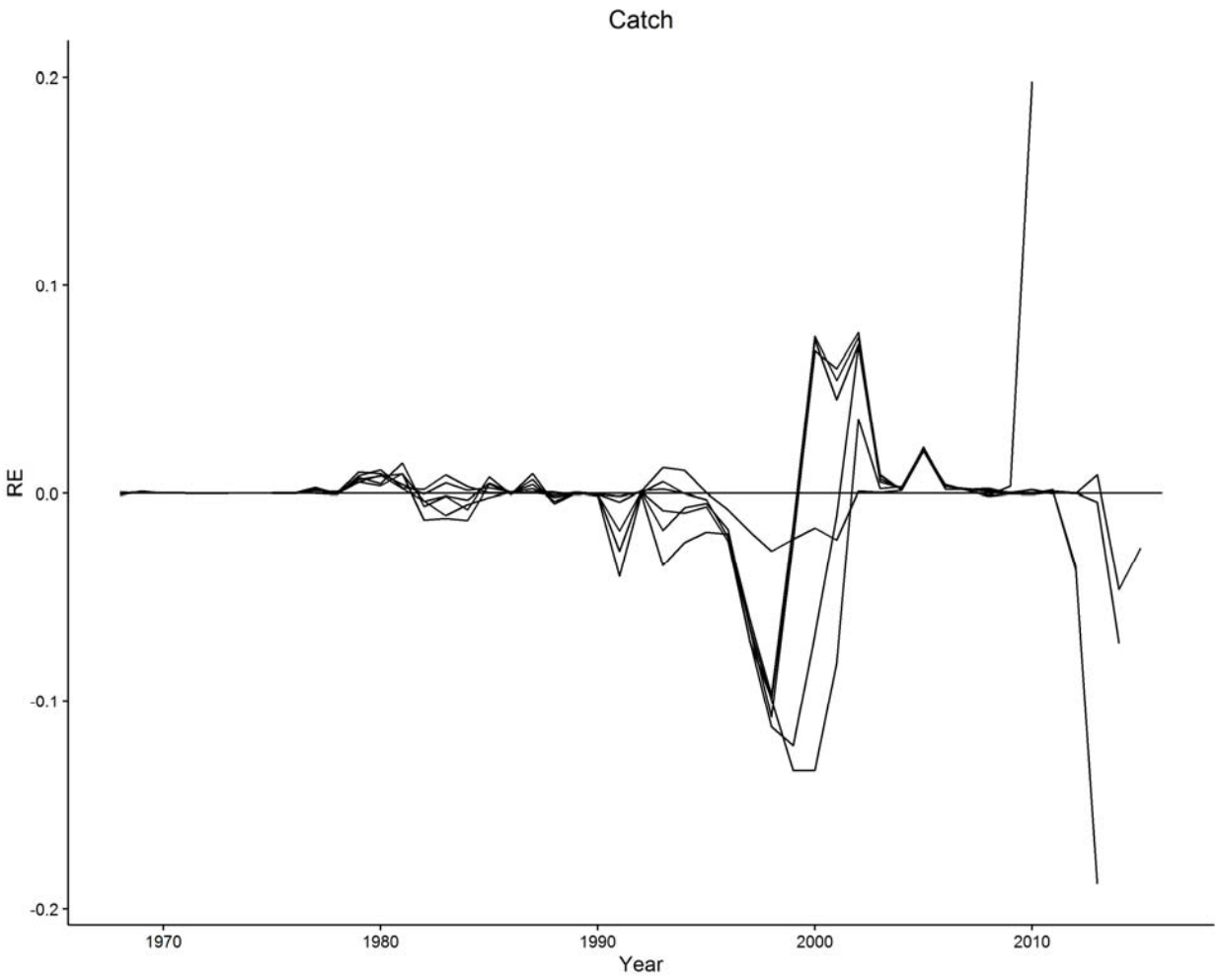

Catch-at-age
Age
Year
Survey index
Residuals
Year
Catch-at-age
Residuals
Predicted
Survey index
Residuals
Predicted
Catch-at-age
Predicted
Oberved
1978-1
Survey index
Predicted
Observed

Process error estimates:

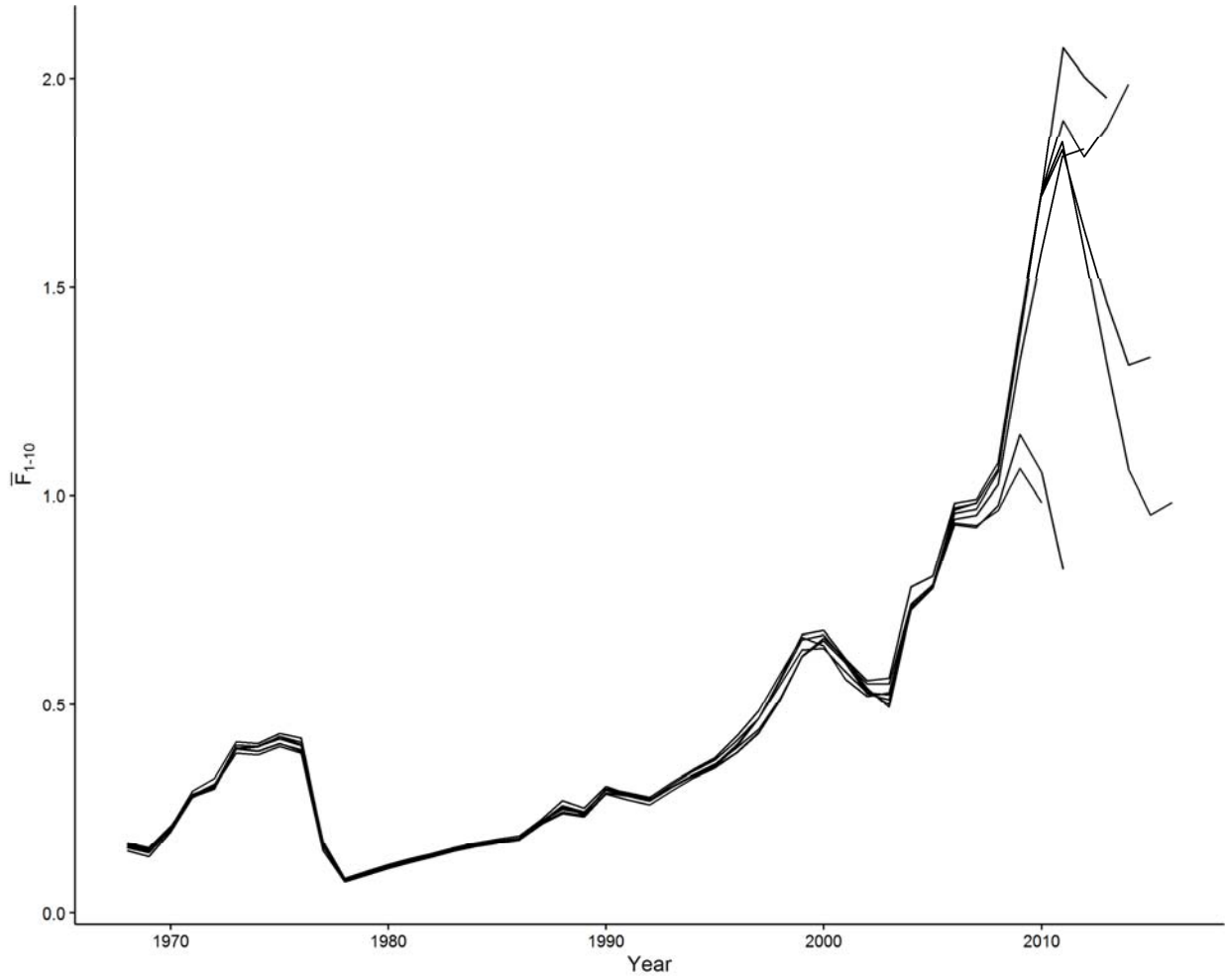


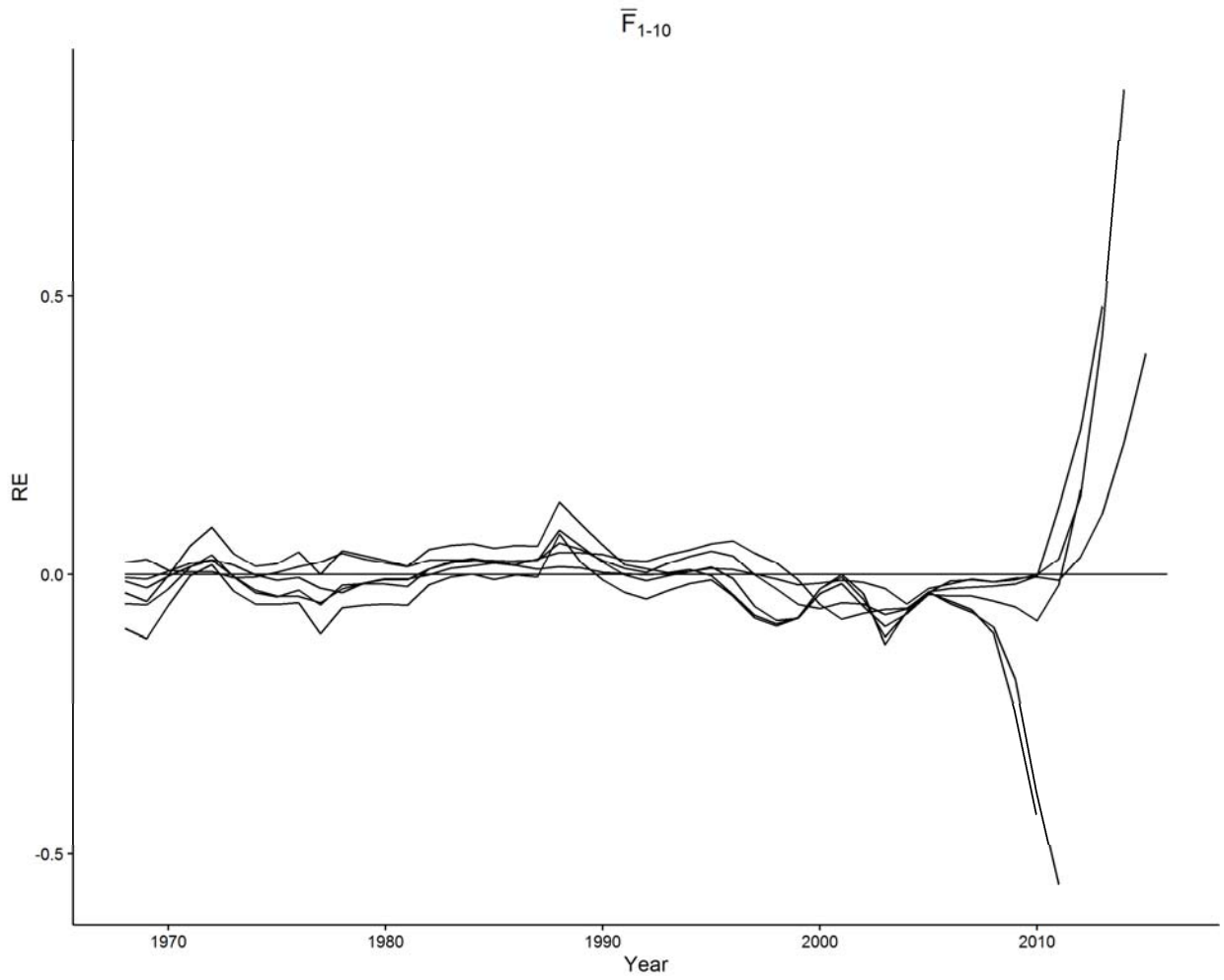
Retrospective analysis for catch:



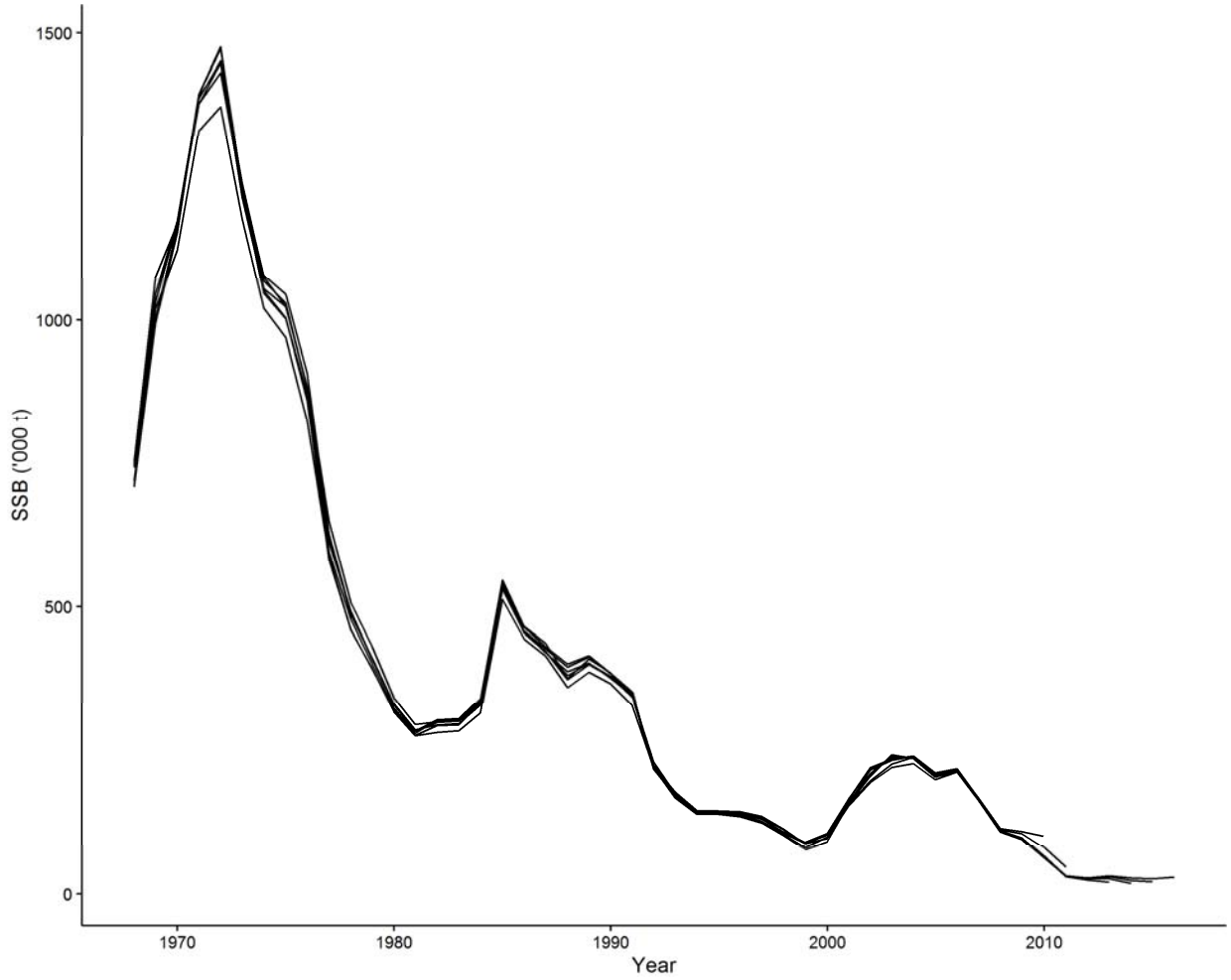

Catch
RE
0.2
0.1
0.0
-0.1
-0.2
1970
1980
1990
2000
2010
Year

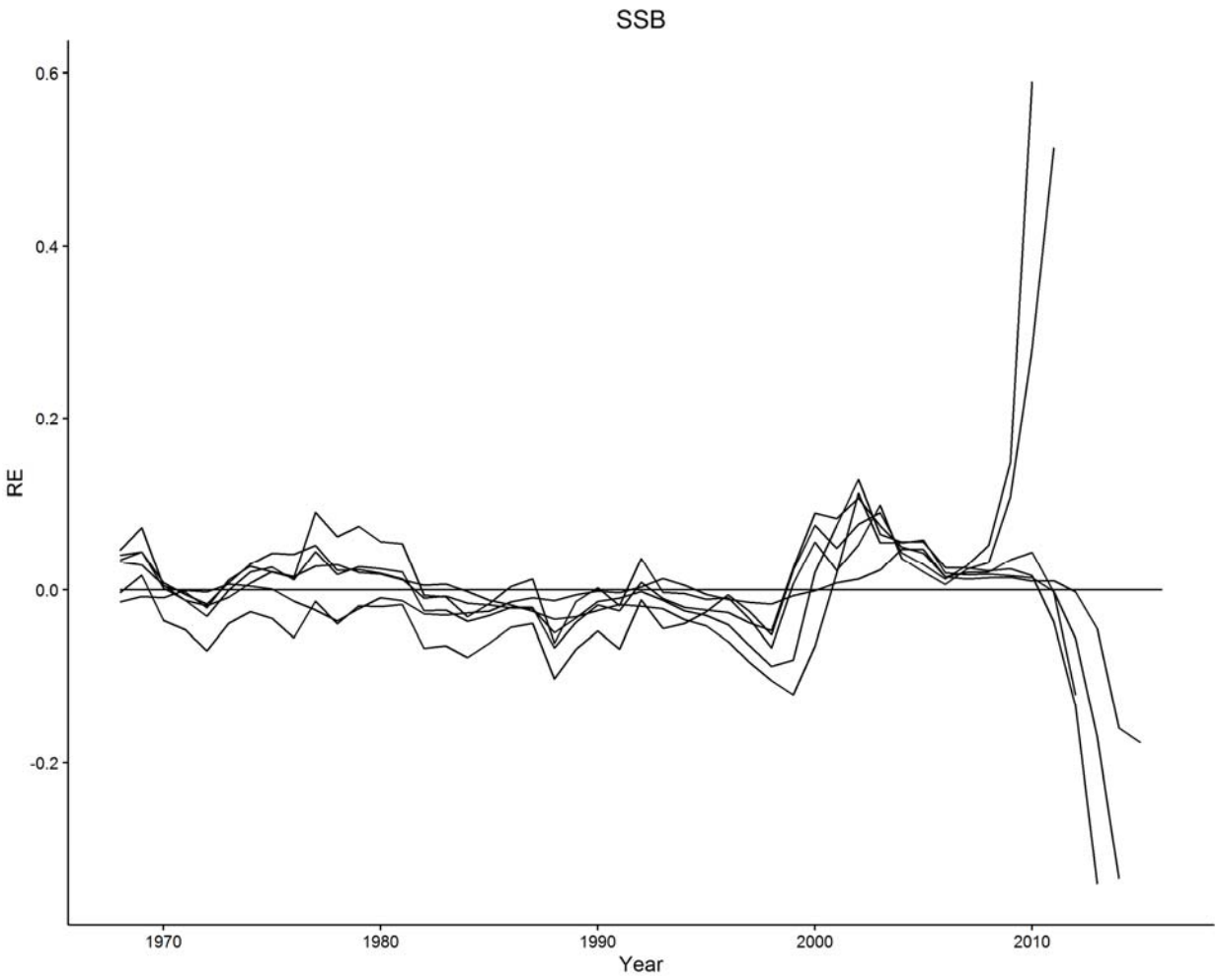
Retrospective analysis for F:




$\overline{F}_{1\text{-}10}$
0.5
0.0
-0.5
RE
1970
1980
1990
2000
2010
Year

Retrospective analysis for SSB:




SSB
RE
0.6
0.4
0.2
0.0
-0.2
1970
1980
1990
2000
2010
Year

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