Northeast Fisheries Science Center Reference Document 17-10

63rd Northeast Regional Stock Assessment Workshop (63rd SAW) Assessment Report

by the Northeast Fisheries Science Center

April 2017

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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 2017

Northeast Fisheries Science Center Reference Documents

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1 Ocean quahog Assessment

1.1 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 a 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. Both the SAW/SARC assessment reports and the CIE review reports are available online at http://www.nefsc.noaa.gov/saw/reports.html.

The 63rd SARC was convened in Woods Hole at the Northeast Fisheries Science Center (NEFSC), February 21-23, 2017 to review a benchmark stock assessment of ocean quahog (*Arctica islandica*). CIE reviews for SARC 63 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-63 Review Panel reports (available at http://www.nefsc.noaa.gov/saw/reports.html under the heading "SAW 63 Panelist Reports").

SARC 63 concluded that the ocean quahog stock is neither overfished nor did it experience overfishing in 2012-2016, the period since the last benchmark assessment. Outcomes based on the new SS3 model, the previous KLAMZ model, and empirical analyses all supported the conclusion. The Panel agreed that the focus on trends and ratios, especially for assessing stock status, was appropriate. The Panel also concluded that the SAW WG had reasonably and satisfactorily completed all tasks specified in the ToRs.

Fishery-independent survey results indicate that the northward shift in ocean quahog landings probably is a response of the fishery to declining

abundance in the southern subregions. These declines in the south were indicated by decreasing commercial effort and LPUE. The fishery is now concentrated off Long Island where 70-80% of landings were recorded during 2005-2015. Commercial LPUE indices were not used in the assessment, and the Panel agreed that this was appropriate because of the small proportion of the stock area fished. The Panel noted the mismatch between the broad spatial scale of the stock assessment for status determination vs the smaller spatial scales at which demographic differences likely occur, and encourages more research on this topic.

Table 1: 63rd Stock Assessment Review Committee Panel.

SARC Chairman (MAFMC SSC):

Dr. Ed Houde
Professor Emeritus
University of Maryland Center for Environmental Science
Chesapeake Biological Laboratory
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SARC Panelists (CIE):

Dr. Michael Bell
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Orkney, UK
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Science Manager, Aquatic Environment
Ministry for Primary Industries
Wellington, NZ
Email: martin.cryer@mpi.govt.nz

Dr. Anthony Hart
Principal Research Scientist
Western Australia Fisheries Research Division
North Beach, Australia
Email: anthony.hart@fish.wa.gov.au

Table 2: Agenda, 63rd Stock Assessment Review Committee Meeting.

February 21-23, 2017

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

AGENDA[1] (version: 2/15/2017)

TIME	TOPIC	PRESENTER(S)	RAPPORTEUR
Tuesday, Feb. 21			
10 - 10:30 AM			
	Welcome	**James Weinberg**, SAW Chair	
	Introduction	**Edward Houde**, SARC Chair	
	Agenda Conduct of Meeting		
10:30 - 12:30 PM	Assessment Presentation (A. Ocean quahog)	**Dan Hennen**	**Toni Chute**
12:30 - 1:30 PM	Lunch		
1:30 - 3:30 PM	Assessment Presentation (A. Ocean quahog)	**Dan Hennen**	**Toni Chute**
3:30 - 3:45 PM	Break		
3:45 - 5:45 PM	SARC Discussion w/ Presenters (A. Ocean quahog)	**Ed Houde**, SARC Chair	**Michele Traver**
5:45 - 6 PM	Public Comments		
7 PM	(Social Gathering)		

Table 2 cont.

TIME	TOPIC	PRESENTER(S)	RAPPORTEUR
Wednesday, Feb. 22			
9:00 - 10:45	Revisit with Presenters (A. Ocean quahog)	**Ed Houde**, SARC Chair	**Alicia Miller**
10:45 - 11	Break		
11 - 11:45	Revisit with Presenters (A. Ocean quahog)	**Ed Houde**, SARC Chair	**Alicia Miller**
11:45 - Noon	Public Comments		
12 - 1:15 PM	Lunch		
1:15 - 4 PM	Review/Edit Assessment Summary Report (A. Ocean quahog)	**Ed Houde**, SARC Chair	**Alicia Miller**
4 - 4:15 PM	Break		
4:15 - 5:00 PM	SARC Report writing		
Thursday, Feb. 23			
9:00 AM - 5:00 PM	SARC Report writing		

Table 3: 63rd SAW/SARC, List of Attendees.

NAME	AFFILIATION	EMAIL
Ed Houde	U Maryland Center for Environmental Science	ehoude@umces.edu
Anthony Hart	Western Australian Fisheries	Anthony.Hart@fish.wa.gov.au
Mike Bell	Heriot-Watt University - Intl Centre for Island Tech	M.C.Bell@hw.ac.uk
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Jim Weinberg	NEFSC	james.weinberg@noaa.gov
Larry Jacobson	NEFSC	larry.jacobson@noaa.gov
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Toni Chute	NEFSC	toni.chute@noaa.gov
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D.H. Wallace	Wallace & Associates	DHWallace@aol.com
Doug Potts	NMFS/GARFO	douglas.potts@noaa.gov
Gary Shepherd	NEFSC	gary.shepherd@noaa.gov

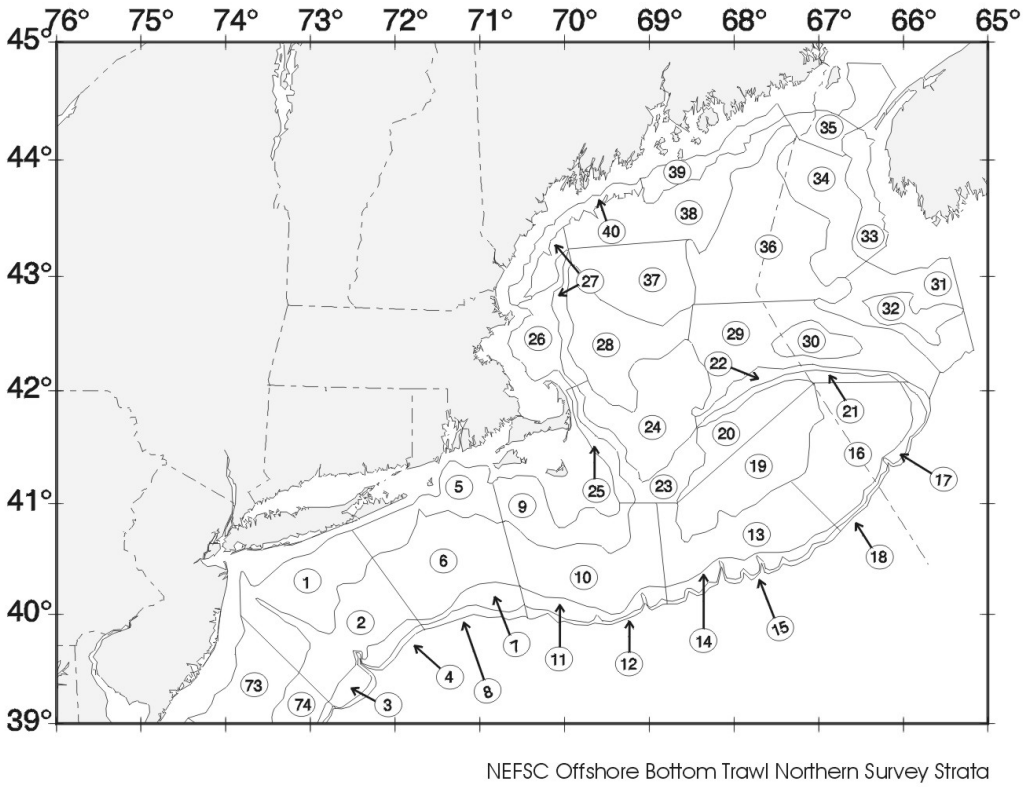


Figure 1: Offshore depth strata that have been sampled during Northeast Fisheries Science Center bottom trawl research surveys. Some of these may not be sampled presently.

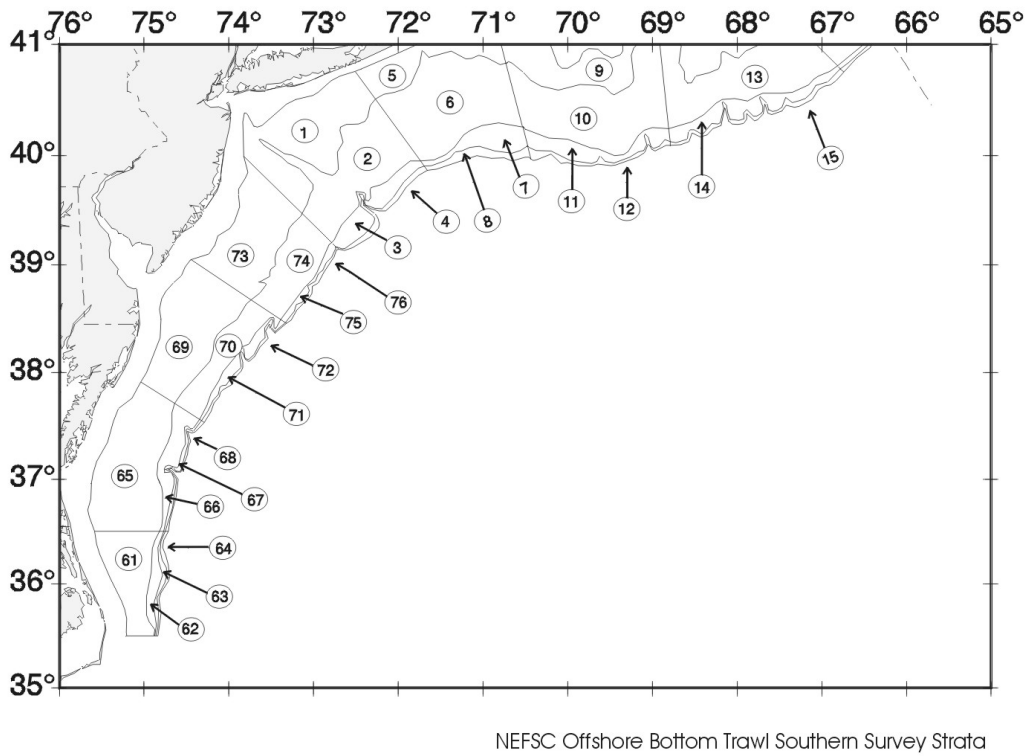


Figure 1 cont.

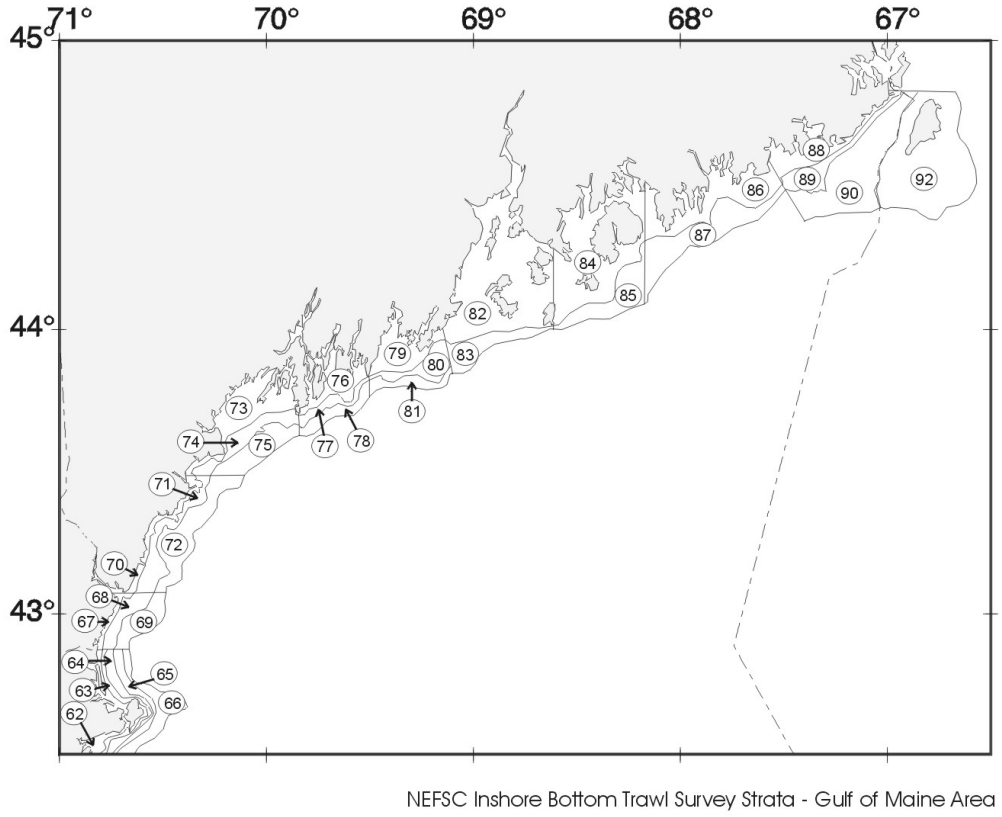


Figure 2: Inshore depth strata that have been sampled during Northeast Fisheries Science Center bottom trawl research surveys. Some of these may not be sampled presently.

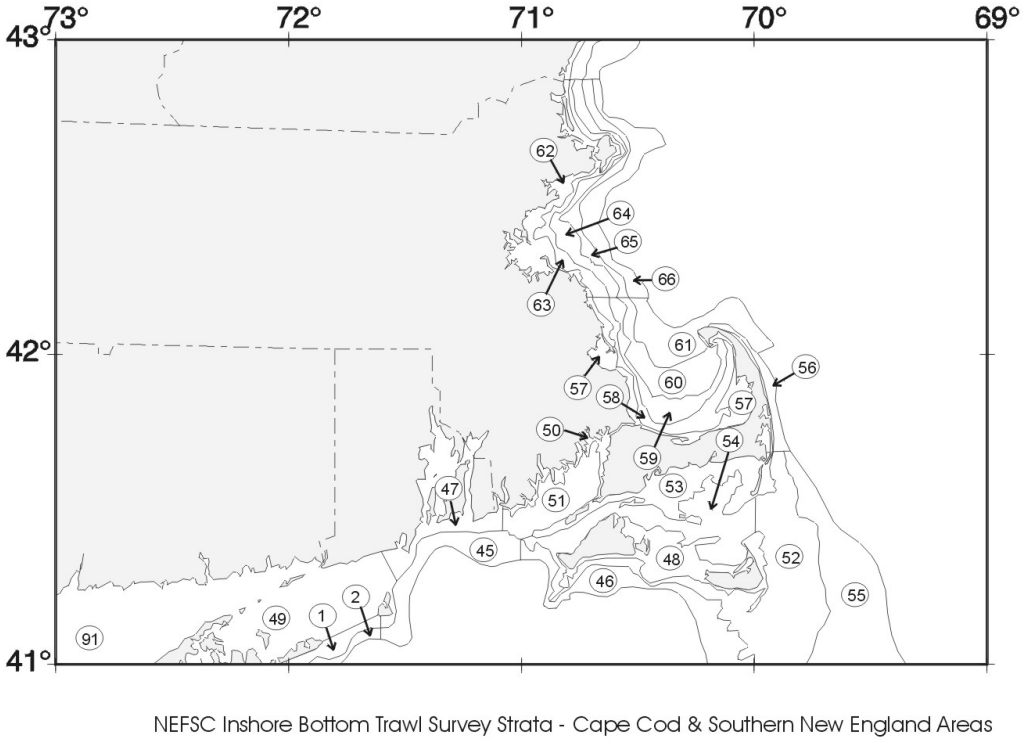


Figure 2 cont.

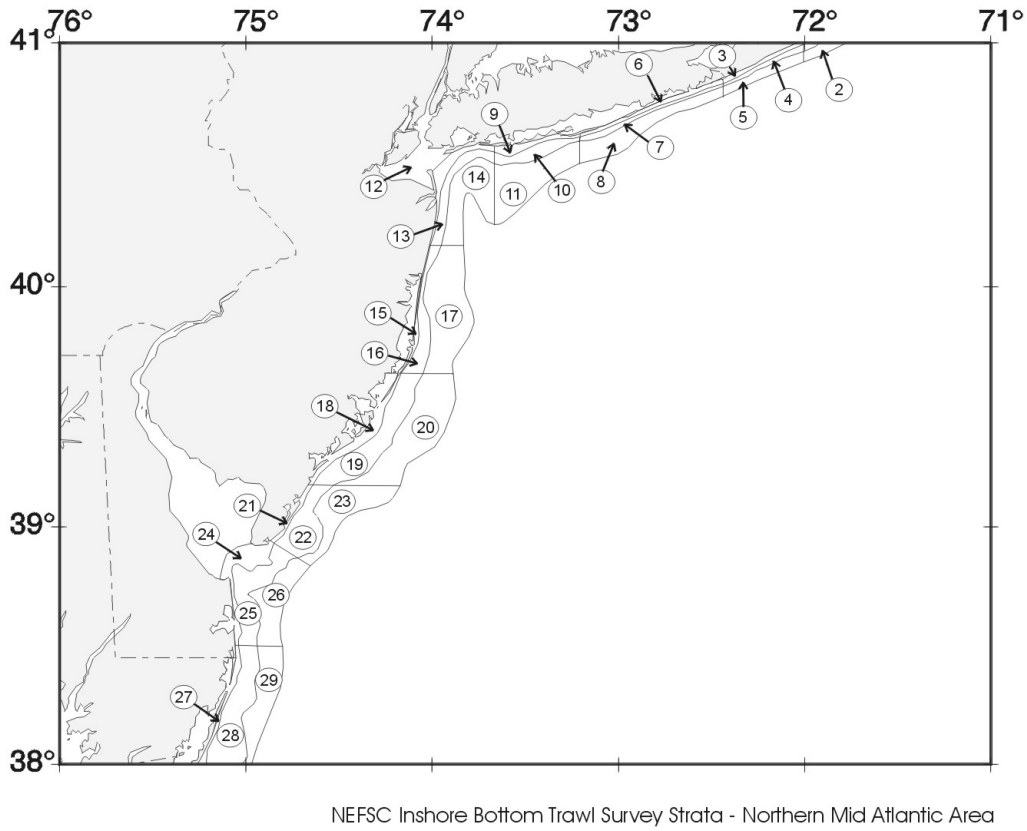
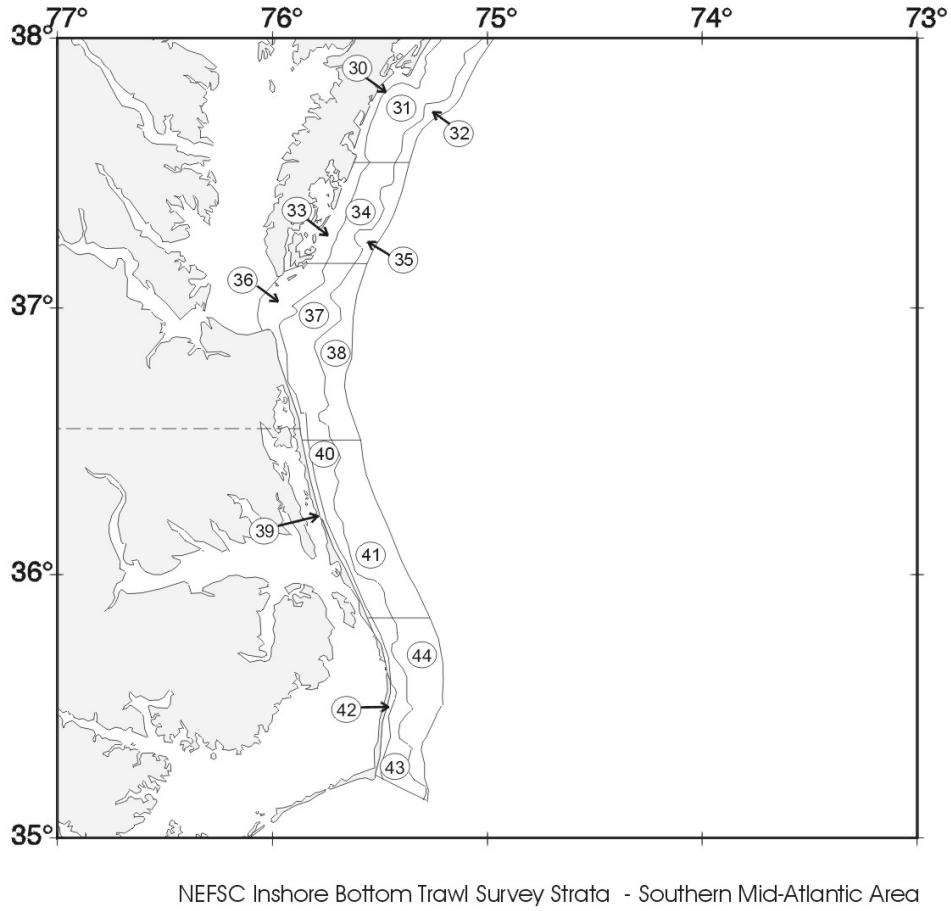


Figure 2 cont.



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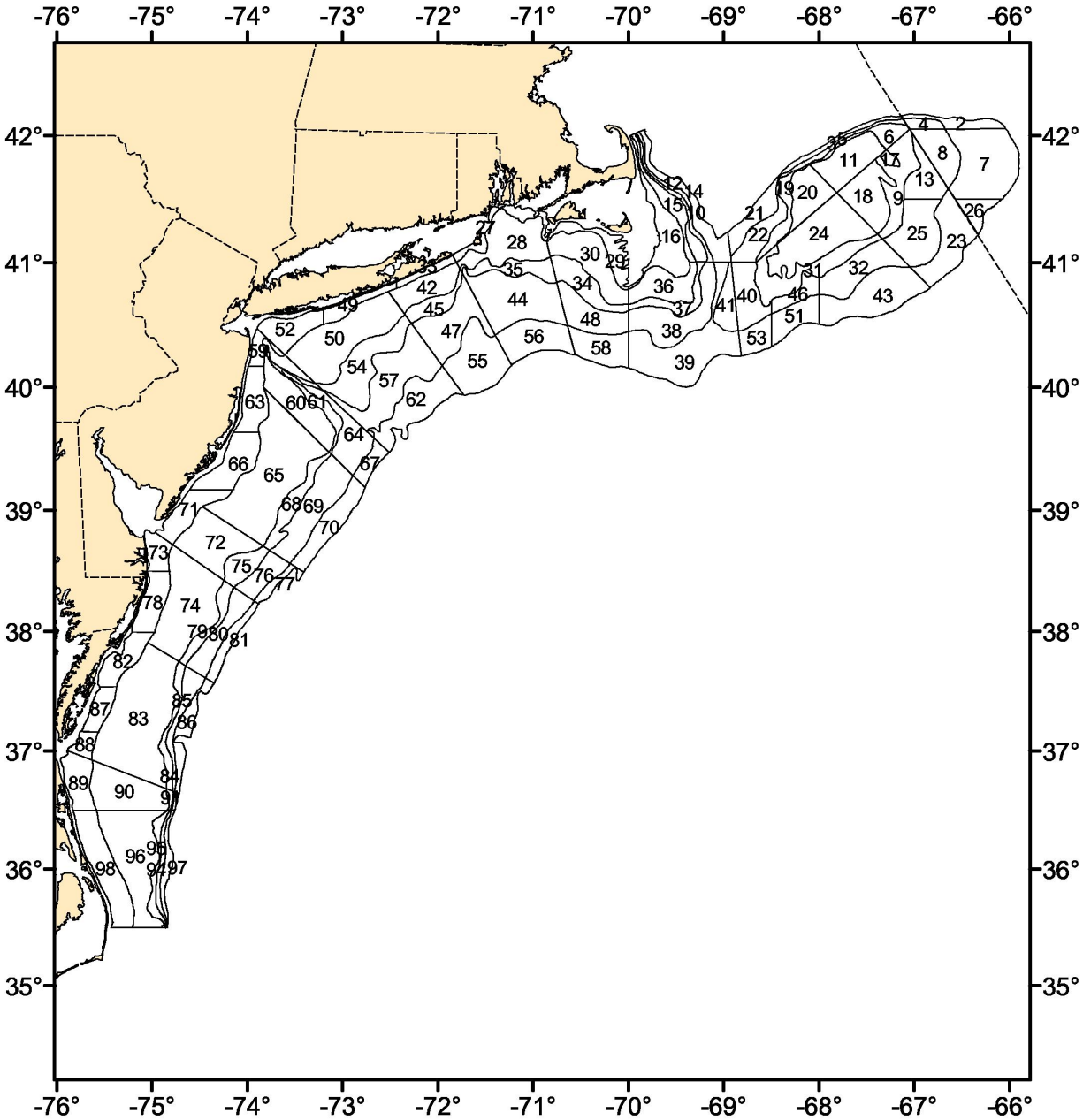

Figure 3: Depth strata sampled during Northeast Fisheries Science Center clam dredge research surveys.

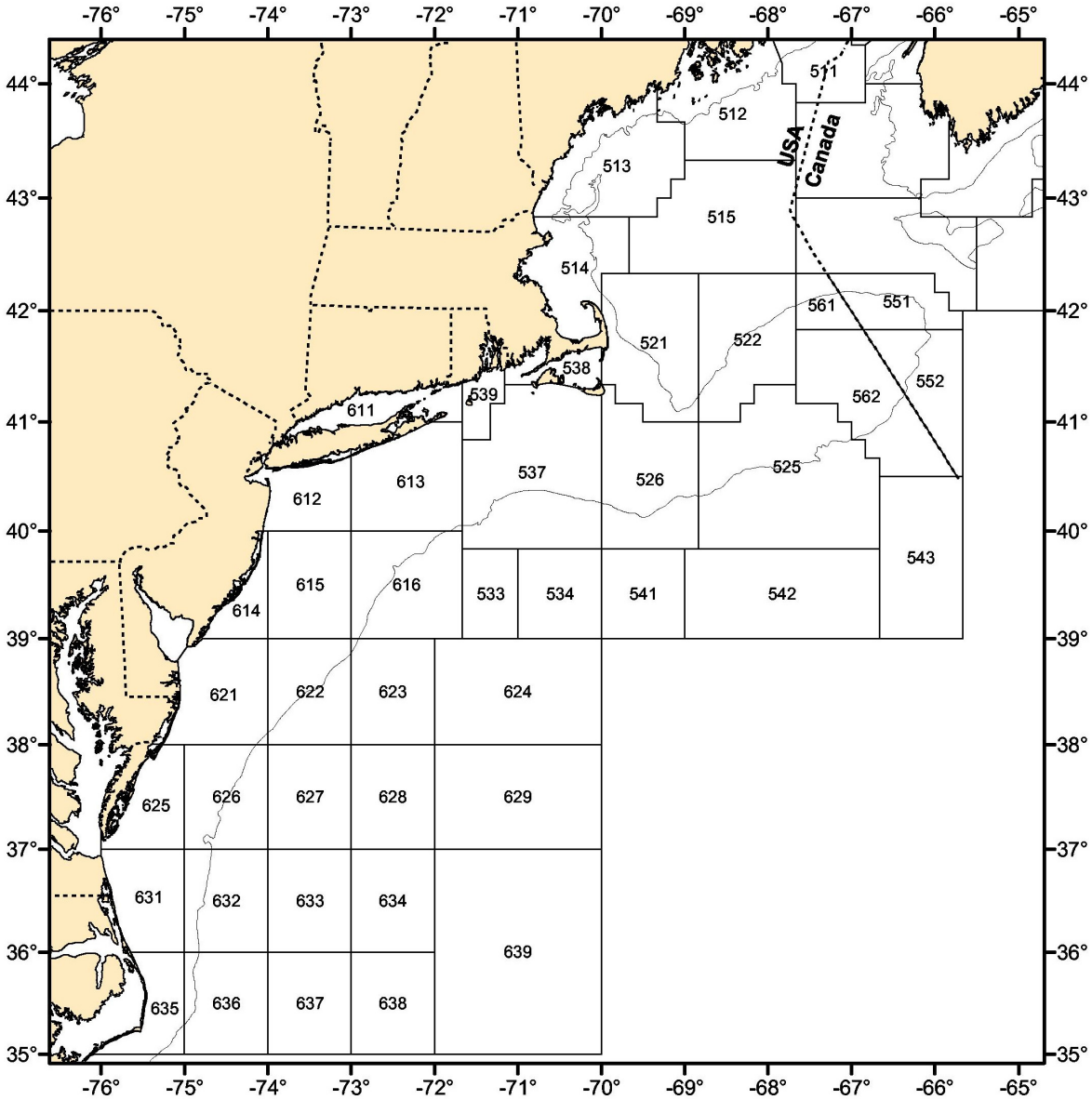

Figure 4: Statistical areas used for reporting commercial catches.

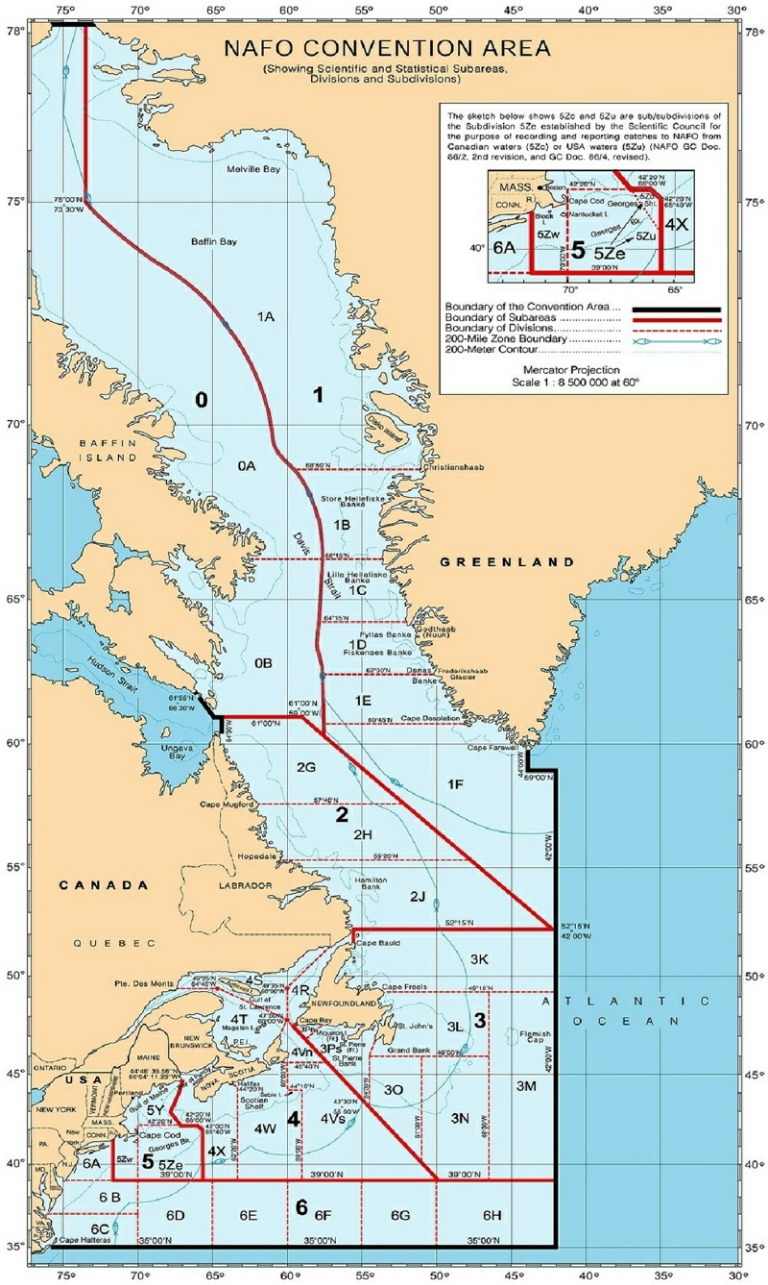

Figure 5: Catch reporting areas of the Northwest Atlantic Fisheries Organization (NAFO).

1.2 Executive Summary

This assessment is for ocean quahog in the US exclusive economic zone (EEZ, federal waters, 3-200 nm from shore) individual transferable quota (ITQ) fishery. The assessment divides the US stock into a northern (Georges Bank or GBK) and a southern (south of GBK to Cape Hatteras) area for modelling purposes (Figures 6 - 7). However, the resource is managed as a single stock so estimates for the north and south are combined for status determination.

ToR 1. Estimate catch from all sources including landings and discards. Map the spatial and temporal distribution of landings, discards, fishing effort, and gross revenue, as appropriate. Characterize the uncertainty in these sources of data.

Commercial landings and fishing effort data are reported both by processors and by vessels, in logbooks by ten-minute square (TNMS) and are considered reliable. Catch includes a 5% allowance for incidental mortality. A small amount of ocean quahog discards occur on Atlantic surfclam trips, but ocean quahog are not vulnerable to other types of fishing gear.

Landings, fishing effort and location, and landings per unit effort (LPUE, bu per hour fished), have shifted north over time as fishery productivity in the south declined (Figures 13-18). Total landings have declined from about 21 thousand mt meats between 1985 and 1995 to around 13 thousand mt meats recently (Tables 4-5 and Figures 8-9). The decline appears linked to a decrease in demand. Effort has also decreased over the same period. The fishery is now concentrated off Long Island (Table 6 and Figure 10). There is little indication of change over time in the length composition of ocean quahog except in the south (Figures 22-26).

ToR 2. Present the survey data being used in the assessment (e.g., indices of relative or absolute abundance, recruitment, state surveys, age-length data, etc.). Use logbook data to investigate regional changes in LPUE, catch and effort. Characterize the uncertainty and any bias in these sources of data. Evaluate the spatial coverage, precision, and accuracy of the new clam survey.

The NEFSC clam survey used the *RV Delaware II* and a small 5 ft research dredge (RD) prior to 2012 and a commercial fishing vessel and modified commercial dredge (MCD) since. The entire resource was surveyed with the RD in 2011 (Tables 10-11). The MCD was used in 2012 and 2015 in the south and on GBK in 2013 and 2016. Data from the two periods are not comparable although capture efficiency and size selectivity estimates can be used to calculate relatively consistent swept-area stock sizes for 1997-2016. Based on swept-area estimates, biomass declined slightly in the south and was stable on GBK (Appendix 9).

ToR 3. Describe the relationship between habitat characteristics (e.g., benthic, pelagic, and climate), survey data, and ocean quahog distribution, and report on any changes in this relationship.

Changes ocean quahog distribution are likely to be slow (geologic time scales) and difficult to detect using survey data because of the life history traits of ocean quahog. Environmental variables appeared to be good predictors of ocean quahog locations in the survey. More work is required to determine the spatial precision of model based predictions, and how these predictions might be used in assessments.

ToR 4. Evaluate age determination methods and available data for ocean quahog to potentially estimate growth, productivity, and recruitment. Review changes over time in biological parameters such as length, width, and condition.

Preliminary data indicated ocean quahog growth may not follow the Von Bertalanffy pattern assumed in this assessment, but additional work is required to test the hypothesis. Shell length-meat weight parameters were updated and demonstrated region and depth related differences.

ToR 5. Estimate annual fishing mortality, recruitment and stock biomass (both total and spawning stock) for the time series (integrating results from ToR 4, as appropriate) and estimate their uncertainty. Include a historical retrospective analysis to allow a comparison with previous assessment results and previous projections.

The primary assessment was a statistical catch at age model implemented in Stock Synthesis (SS), which replaced the KLAMZ biomass dynamic model used previously. The assessment model was spatial, which allowed separate estimates of recruitment, selectivity, and catchability (as well as growth in sensitivity runs) for each area. The model was relatively stable and without serious diagnostic problems. SS, KLAMZ (Appendix 6) and empirical calculations (Appendix 9) all indicate spawning stock biomass (SSB) is high and fishing mortality (F) is low. Terminal estimates from the base model were SSB_{2016} =3,287,300 (mt) and F_{2016} =0.005.

ToR 6. 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, particularly as they relate to stock assumptions.

The current and recommended stock status definitions are listed in Table 4 (Part 1.9). The current stock status definitions were revised based on a management strategy evaluation (Part 8) and assessment model improvements. Recommended reference points were $SSB_{Threshold}$ =1,610,868 (mt) and $F_{Threshold}$ =0.019.

ToR 7. Evaluate stock status with respect to the existing model (from previous peer reviewed accepted assessment) and with respect to any new model or models developed for this peer review.

A. When working with the existing model, update it with new data and evaluate stock status (overfished and overfishing) with respect to the existing BRP estimates.

B. Then use the newly proposed model and evaluate stock status with respect to "new" BRPs and their estimates (from ToR-5).

The ocean quahog population is not overfished and overfishing is not occurring under either the current or recommended reference point definitions and using either the previous or newly developed models (Part 1.10; Appendix 6; Tables 27, 29-30). The ocean quahog stock is currently 2.04 times the recommended biomass threshold and 0.246 of $F_{MSYproxy}$.

ToR 8. Develop approaches and apply them to conduct stock projections.

A. Provide numerical annual projections (5-50 years) and the statistical distribution (e.g., probability density function) of the OFL (overfishing level), including model estimated and other uncertainties. Consider cases using nominal as well as potential levels of uncertainty in the model. 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.

C. Describe this stock's vulnerability (see 10) to becoming overfished, and how this could affect the choice of ABC.

Projections indicate that the population is unlikely to be overfished and that overfishing is unlikely to occur by 2067 using a range of possible biomass scales, recruitment scenarios, and assumed catches (Part 1.11; Tables 31 - 33).

ToR 9. Review, evaluate and report on the status of the SARC and Working Group research recommendations listed in most recent SARC reviewed assessment and review panel reports. Identify new research recommendations.

Progress on research recommendations from the last assessment includes: implementation of new, more efficient survey gear, improved prior distributions for capture efficiency and development of a new age/length based assessment model. Important new research recommendations include refinement of growth estimates (Part 1.12).

Terms of Reference

A. Ocean quahog

1. Estimate catch from all sources including landings and discards. Map the spatial and temporal distribution of landings, discards, fishing effort, and gross revenue, as appropriate. Characterize the uncertainty in these sources of data.

2. Present the survey data being used in the assessment (e.g., indices of relative or absolute abundance, recruitment, state surveys, age-length data, etc.). Use logbook data to investigate regional changes in LPUE, catch and effort. Characterize the uncertainty and any bias in these sources of data. Evaluate the spatial coverage, precision, and accuracy of the new clam survey.

3. Describe the relationship between habitat characteristics (e.g., benthic, pelagic, and climate), survey data, and ocean quahog distribution, and report on any changes in this relationship.

4. Evaluate age determination methods and available data for ocean quahog to potentially estimate growth, productivity, and recruitment. Review changes over time in biological parameters such as length, width, and condition.

5. Estimate annual fishing mortality, recruitment and stock biomass (both total and spawning stock) for the time series (integrating results from TOR 4, as appropriate) and estimate their uncertainty. Include a historical retrospective analysis to allow a comparison with previous assessment results and previous projections.

6. 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, particularly as they relate to stock assumptions.

7. Evaluate stock status with respect to the existing model (from previous peer reviewed accepted assessment) and with respect to any new model or models developed for this peer review.

   (a) When working with the existing model, update it with new data and evaluate stock status (overfished and overfishing) with respect to the existing BRP estimates.

   (b) Then use the newly proposed model and evaluate stock status with respect to "new" BRPs and their estimates (from TOR-5).

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

(a) Provide numerical annual projections (5-50 years) and the statistical distribution (e.g., probability density function) of the OFL (overfishing level), including model estimated and other uncertainties. Consider cases using nominal as well as potential levels of uncertainty in the model. 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.

(c) Describe this stock's vulnerability (see Appendix 10) to becoming overfished, and how this could affect the choice of ABC.

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

1.4 ToR1: Commercial data

In this assessment for ocean quahog the northern area was in federal waters (3-200 nm from shore) on Georges Bank (GBK) and the southern area was federal waters from south and west of GBK to Cape Hatteras (Figure 6). A number of smaller regions were important for ocean quahog (Figure 6 and below).

Abbreviation	Region
GBK	Georges Bank
SNE	Southern New England
LI	Long Island
NJ	New Jersey
DMV	Del Marva

Commercial landings were provided in meat weights for ease of comparison to survey data and in analyses, but were originally reported in units of industry cages. Landings per unit of fishing effort (LPUE) data were reported in this assessment as landings in bushels per hour fished, based on mandatory clam vessel logbook reports. The spatial resolution of the clam logbook reports was usually one ten-minute square.

Unit	Equivalent
Industry or Mid-Atlantic bushel (bu)	1.88 ft^3
Maine (US standard) bushel (Maine bu)	1.2448 ft^3
Maine bu	0.662 bu
1 cage	32 bu
1 bu	10 lbs. meats
1 bu	4.5359 kg meats

The estimates of biomass and fishing mortality for the EEZ stock in this assessment do not include the Maine mahogany ocean quahog fishery, which started in inshore Maine but now takes place almost entirely in federal waters. The Maine stock biomass is small (<1% relative to the rest of the EEZ) and fishing effort is concentrated in a small area. The EEZ and Maine ocean quahog populations have different biological characteristics, support fisheries that are managed separately, use different vessels and gear, and provide different products. Updated information for the Maine fishery is presented in Appendix 7. Landings from Maine are excluded included when total EEZ landings are calculated in this report. Annually, 100,000 Maine bushels from the EEZ quota are allocated to the Maine fishery.

As in previous stock assessments (Chute et al. 2013), "catch" was defined as the sum of landings, plus 5% of landings, plus discards. Based on Murawski and Serchuk (1989), ocean quahog catch in previous assessments was assumed to be 5% larger than landings to account for incidental mortality of clams in the path of the dredge.

Ocean quahog are not taken recreationally, as they are mostly found offshore in deep water, require expensive gear and vessels to harvest, and because they provide a less desirable product than inshore quahogs (*Mercenaria mercenaria*), which can be harvested with less effort. Landings of ocean quahog from state waters (inshore of three miles) are effectively zero.

Discard data

A small amount of bycatch of ocean quahog occurs in the Atlantic surfclam fishery although there is strong incentive not to fish in areas where both species occur, as mixed loads of surfclams and ocean quahog are not allowed under current regulations, and it is not practical to sort catches at sea. Fisheries Observers aboard 16 surfclam trips between 2004 and 2006 reported discarded ocean quahog averaged about 100 pounds per surfclam trip. No clam trips were observed between 2007 and 2014, but observers began accompanying clam trips again in 2015. In 19 observed surfclam trips in 2015 and 2016, about 1500 lbs. of ocean quahog were discarded per 100,000 lbs. of surfclam landed. Off DMV and SVA in the southern end of the ocean quahogs range, survey catches including both surfclam and ocean quahog have become more common in recent years as surfclams have shifted towards deeper water in response to warm water conditions (Weinberg 2005; Appendix 5). This may change discard patterns in the future.

Bycatch and discard of ocean quahog in other fisheries is zero. Ocean quahog are not vulnerable to bottom trawls, scallop dredges (because they are too deep in the sediment), gillnets or hook and line gear.

Landings, fishing effort and prices

Landings and fishing effort data for 1982-2016 (incomplete at the time of this writing) were from mandatory logbook reports (similar but more detailed than standard Vessel Trip Reports used in most other Northeast fisheries) with information on the location, duration, and landings of each trip. Data for earlier years were from Northeast Fisheries Science Center (2003) and Mid-Atlantic Fishery Management Council (2006).

Landings data from ocean quahog logbooks are considered accurate in comparison to other fisheries because of the Individual Transferable Quota (ITQ) and cage tag systems.

Ocean quahog landings were mostly from the US Exclusive Economic Zone (EEZ) during 1965 to 2011 (Table 4 and Figure 8). Landings have not reached the quota of 26,218 mt since it was set in 1990 because of limited markets. Approximate Maine landings are shown in Table 5 and discussed in detail in Appendix 7.

The bulk of EEZ landings were from the NJ region during 1980-1991 (Figure 9). After 1991, the bulk of landings were from the LI region (Table 5 and Figure 9). Landings from SNE peaked in 1997 and have declined since then. Small amounts of landings were taken from GBK starting in 2009.

Total fishing effort increased after 1990 and has been relatively high, but declining since then in all regions other than LI. Effort in DMV and NJ has declined substantially (Table 6 and Figure 10). The bulk of the fishing effort was in areas where the majority of landings come from, other than MNE where effort has been high in proportion to landings.

Real (adjusted) ex-vessel prices for the inshore and EEZ fisheries have been stable, since the mid-1990s (Table 8 and Figure 11). Nominal revenues for ocean quahog during 2015 were about $24 million.

Landings per unit effort (LPUE)

Nominal landings per unit effort (LPUE) based on logbook data were computed as total landings divided by total fishing effort for all vessels and all trips (Table 7 and Figure 12). Standardized LPUE was not estimated for this assessment because the data are not used analytically and because Northeast Fisheries Science Center (2007) showed that nominal and standardized trends were almost identical when standardized trends were estimated in separate general linear models for each region with vessel and year effects.

LPUE is not an ideal measure of fishable biomass trends for sessile and patchy stocks like ocean quahog because fishermen target high density beds and change their operations to maintain relatively high catch rates as stock biomass declines (Hilborn et al. 1992).

Spatial patterns in fishery data

Mean landings, fishing effort, and LPUE were calculated by ten-minute square (TNMS) from 1979-2016 in 5 year blocks (Figures 13 – 18). Only TNMS where more than 5 kilo bushels (kb) of ocean quahog were caught over the time period were included in maps. TNMS with reported landings less than 5 kb were probably in error, or from just a few exploratory tows. Inclusion of TNMS, with less than 5 kb distorted the graphical presentations because the area fished appeared unrealistically large.

Figures 13 – 18 show the spatial patterns of the ocean quahog fishery over most of its history. In most blocks, the greatest concentration of fishing effort and landings occurred in the same thirty or so TNMS in the NJ region, with intermittent fishing activity in other regions and recent emphasis on SNE and GBK.

TNMS with the highest LPUE levels over time have been mostly in the NJ and DMV regions with irregular contributions from GBK and the Nantucket Shoals region of SNE.

Important TNMS

TNMS "important" to the fishery were identified by choosing the 10 TNMS with the highest mean landings during each 5 year time block. For example, a TNMS important during 1991-1995 could be selected regardless of its importance during earlier or later time periods. The list contains a subset of the total TNMS, because of overlap between the time periods and because the same TNMS tend to remain important. These plots are complicated by the "rule of three", which states that fine scale fishing location data cannot be shown for areas fished by three or fewer vessels due to confidentiality concerns. Trends in landings, effort, and LPUE were plotted for the important TNMS to show changes in conditions over time within individual TNMS (Figures 19 – 21).

With the exception of SNE and LI, where catch rates have been largely steady, there are very few important TNMS still being fished in which the LPUE has trended upwards in recent years.

Age and size at recruitment to the fishery

Age at recruitment to the ocean quahog fishery depends on growth rates, which probably vary both spatially and temporally (see 1.7), but are largely unknown due to a lack of age data for ocean quahog. Size at recruitment depends on the fishery selectivity estimated in the model. This issue is discussed in detail in Section 1.8.

Fishery length composition

Since 1982, port samplers have routinely collected shell length measurements from approximately 30 random landed ocean quahog from selected fishing trips each year (Table 9).

Port sample length frequency data from the four regions show modest variation in size of landed ocean quahog over time with declines in modal size in DMV and NJ since 2000 (Figures 22 – 27). Care should be taken in interpreting these due to small sample sizes in some cases, but in general the data indicate that most landed ocean quahog have been larger than 80mm shell length (SL). Commercial size distributions are discussed in detail in section (1.8).

Fishery management

Ocean quahog are managed by the Mid-Atlantic Fishery Management Council (Council). The Council is one of eight regional fishery management councils created when the United States (U.S.) Congress passed Public Law 94-265, the Magnuson-Stevens Fishery Conservation And Management Act of 1976 (also known as Magnuson-Stevens Act or MSA). The law created a system of regional fisheries management designed to allow for regional, participatory governance. The Council develops fishery management plans and recommend management measures to the Secretary of Commerce through the National Marine Fisheries Service (NMFS) for its federal fisheries in the EEZ of the U.S.

Ocean quahog is managed with Atlantic surfclam (*Spisula solidissima*) under a single fishery management plan, that was first developed by the Council in 1977. The ocean quahog fishery was initially managed using quotas, which were not fully utilized annually. An individual transferrable quota (ITQ) system was established in 1990 which initially allocated shares to vessel owners based on a formula including historical catch and vessel size. This system also established a small allocation for the state of Maine ocean quahog (mahoghany quahog) fishery. Economic efficiency improved as a result of initial ITQ implementation, but it also led to consolidation and displacement of labor (particularly non-vessel owning captains and crew). ITQ shares can be traded or leased to any non-foreign person or entity, with no pre-conditions of vessel ownership. Market consolidation and existing vertical integration have increased over time. From 1992 to 2016, the ocean quahog fleet size decreased by about 65% from 128 vessels to 44.

Under the current management system, managers set an annual catch limit for ocean quahog and allocate landings to the ITQ fishery, and to the small Maine fishery. The Council's annual catch limit recommendations for the upcoming fishing year(s) cannot exceed the acceptable biological catch (ABC) recommendation of its Scientific and Statistical Committee (SSC). The SSC serves

as the Councils primary scientific/technical advisory body, and provides ongoing scientific advice for fishery management decisions, including recommendations for ABCs, preventing overfishing, maximum sustainable yield, and achieving rebuilding targets.

In order to participate in the ocean quahog fishery, fishermen must have a permit to commercially harvest and sell ocean quahogs, and there are mandatory reporting and vessel-monitoring requirements, as well as clam cage-tagging requirements in the ITQ fishery. Fishing areas can be closed due to environmental degradation or due to the toxins that cause paralytic shellfish poisoning (PSP). PSP is caused by saxitoxins produced by the alga *Alexandrium fundyense* (red tide) that accumulate in shellfish, and has resulted in fishery closures in the Georges Bank Area of the EEZ. NMFS recently (2013) reopened portions of the closed areas to harvest of ocean quahog for those vessels using a protocol for onboard screening and dockside testing to verify that quahogs harvested from these areas are safe.

1.5 ToR2: Survey data

NEFSC clam surveys

Survey data used in this assessment were from 2 different sampling platforms. The first was the NEFSC clam survey conducted during 1982–2011 by the *RV Delaware II* during summer (June–July) using a standard NEFSC survey hydraulic dredge with a submersible pump. The survey dredge had a 152 cm (60 in) blade and 5.08 cm (2 in) mesh liner to retain small individuals of the two target species (ocean quahog and Atlantic surfclams). The survey dredge differed from commercial dredges because it was smaller (5 ft instead of 8-12.5 ft blade), had the small mesh liner, and the pump was mounted on the dredge instead of the deck of the vessel. The survey dredge retained ocean quahog as small as 50 mm SL (size selectivity described below). The second survey platform was the *ESS Pursuit*, a commercial vessel that was contracted to conduct the NEFSC clam survey starting in 2012, when the *RV Delaware II* was retired. The *ESS Pursuit* used a modified commercial dredge described in detail in Hennen et al. (2016). Surveys conducted from the *ESS Pursuit* were carried out in August each year since 2012.

Surveys prior to 1982 were not used in this assessment because they were carried out during different seasons, used other sampling equipment or, in the case of 1981, have not been integrated into the clam survey database (Table A7 in Northeast Fisheries Science Center (2003)).

NEFSC clam surveys were organized around NEFSC shellfish strata and stock assessment regions (Figure 6). Most ocean quahog landings originate from areas covered by the survey. The survey did not cover GBK during 2005 and provided marginal coverage there in 1982, 1983, and 1984. Individual strata in other areas were sometimes missed. Strata and regions not sampled during a particular survey were "filled" for assessment purposes by borrowing data from the same stratum in the previous and/or next survey if these data were available (Table 10). Survey data were never borrowed from surveys before the previous, or beyond the next survey.

Surveys followed a stratified random sampling design, allocating a pre-determined number of tows to each stratum and data were presented as numbers caught per square meter, accounting for tow distance and dredge width. A standard tow prior to 2012 was nominally 0.125 nm (232 m) in length (i.e. 5 minutes long at a speed of 1.5 knots) although sensor data used on surveys since 1997 show that tow distance increases with depth, varies between surveys and was typically longer than 0.125 nm (Weinberg et al. 2002). These problems were eliminated in 2012 when the survey was switched to the *ESS Pursuit*. For trend analysis using data from before 2012, changes in tow distance with depth were ignored and tow distance was based on ship's speed and start and stop times recorded on the bridge. After 2012 and for some analyses starting in 1997, tow distance were measured directly using sensors (see below). Stations used to measure trends in ocean quahog abundance were either random or "nearly" random. A few, nearly random tows were added in some previous surveys in a quasi–random fashion to ensure that important areas were sampled. Other non-random stations were occupied for a variety of purposes (e.g. selectivity experiments) but not used to estimate trends in abundance. GBK and the southern area were surveyed in sequential years starting in 2012, with a third year reserved for gear testing. Locations and catches of all stations in the survey have been mapped (Figures 28–34).

Occasionally, randomly selected stations were found to be too rocky or rough to tow, particularly on GBK. The proportion of random stations that could not be fished was an estimate of the proportion of habitat in an area that was not suitable habitat for ocean quahog (see Appendix 1.6).

Following most survey tows, all ocean quahog in the survey dredge were counted and shell length was measured to the nearest mm. Large catches were subsampled. Mean meat weight (kg) per tow was computed with shell length-meat weight (SLMW) equations (updated in this assessment) based on fresh meat weight samples obtained during the 1997–2016 surveys (see below).

Survey tow distance and gear performance based on sensor data

Beginning with the 1997 survey, sensors were used to monitor depth (ambient pressure), differential pressure (the difference in pressure between the interior of the pump manifold and the ambient environment at fishing depth), x-tilt (port-starboard angle, or roll), y-tilt (fore-aft angle, or pitch) and ambient temperature during survey fishing operations. At the same time, sensors on board the ship monitored GPS position, vessel bearing and vessel speed. Most of the sensor data were averaged and recorded at 1 second intervals. These metrics of tow performance can be used to accurately gauge the true distance fished by the dredge.

Determination of time fishing

The determination of time fishing, the "fishing seconds" for each tow (after 1997), was based on a measurement of the pitch of the dredge during each second of the tow. Pitch data were smoothed using a 7 second moving average and then compared to a "critical angle" to determine when the dredge was fishing effectively (see Appendix 11).

It is important to find a critical angle for tow distance that is neither too small, nor too large. When the dredge is bouncing over rough terrain it is unlikely to be fishing effectively and those seconds should be excluded. There is however, a certain amount of pitch that is within fishing tolerance and a certain amount of noise in the data. If the critical angle is too small, many seconds when the dredge was actually fishing would be excluded, which would tend to bias estimates of tow distance down. Further discussion of the determination of critical angle as well as summaries of dredge performance by year are in Northeast Fisheries Science Center (2017) and Appendix (11).

NEFSC clam survey trends and length composition data

NEFSC clam survey data for ocean quahog, including the number and weight caught per tow were tabulated by year, region and for the entire stock (Table 11). Mean numbers per tow were used in the plots of trends because trends in mean kg per tow were similar. Approximate asymmetric 95% confidence intervals were based on the CV for stratified means and assume that the means were log normally distributed.

Survey trends for small ocean quahog (Figures 33 and 35) provide some evidence for recruitment trends over time. Recent trends are difficult to interpret because of gear changes, but recruitment

appears to be increasing or stable in DMV, NJ, and GBK, and decreasing in SNE since 2011. Survey trends for fishable (70+mm)(Figures 34 and 36) and composite (>50 mm, Figure 37) ocean quahog are noisy, but generally show stability, or gradual depletion, over time. Based on survey data for the entire southern area, recruitment and fishable abundance have been increasing since the last assessment in 2011 (Figures 38 – 40).

Ocean quahog are not aged by NEFSC, but are capable of living for hundreds of years (Butler et al. 2013).

Shell length composition data (Figures 41 – 45) can be helpful in visually identifying shifts in population demography. For example, there is evidence of recent recruitment in the DMV region.

Dredge efficiency

Changes to the NEFSC survey involved changes to the survey gear. In particular, shifting the survey dredge from the research dredge (RD) used on the *RV Delaware II* to the modified commercial dredge (MCD) used on the *ESS Pursuit* was an important modification that necessitated a re-evaluation of capture efficiency (as well as selectivity). These estimates are discussed in detail in Appendix 3.

Estimates of survey dredge efficiency were used to generate prior distributions for capture efficiency for each survey in the assessment model (see 1.8). This process is described in detail in Appendix 4. A comparison of the prior distribution for the RD to the prior distribution for the MCD shows that the MCD has higher and more precisely estimated efficiency (Figure 46).

Size selectivity

Selectivity data were collected on industry vessels during selectivity experiments in 2008-2016. Data from the experiments were used to estimate size selectivity for the MCD. The MCD was configured for survey operations, using closer bar spacing generating higher selectivity for small ocean quahog, rather than commercial fishing operations. Thus, the size selectivity estimates for the commercial dredge used by the *ESS Pursuit* during cooperative survey work are not directly applicable to commercial catch data. Selectivity experiments are described in Hennen et al. (2016).

The data available for each selectivity study site included shell length data from one MCD tow, and one tow with a commercial dredge lined with wire mesh or a specially designed selectivity dredge (SD) engineered to capture small ocean quahog efficiently. Gear testing work done in 2014 showed that the SD and the lined commercial dredge should be interchangeable in selectivity studies (Hennen et al. 2016).

Shell length data from selectivity experiments conducted since the last assessment (Chute et al. 2013) were tabulated using 1 mm shell length size groups (Tables 12 – 13). Survey size selectivity was estimated using data from 20 total sites.

Selectivity was modelled as a generalized additive mixed model (GAMM), where the shell length bin was a covariate, predicting the binomial proportion of the survey catch over the total catch (SD + MCD). The fully saturated model was

$$P_L = e^{(\alpha + s(L) + s[YrSta,L] + offset)} \tag{1}$$

Where P_L is the binomial proportion (logit link) estimated for shell length L with intercept α. The $s()$ terms indicate a spline over shell length (L) with a random effect (indicated with braces) due to station and year. The final term is an offset (Pinheiro and Bates 2006) based on the tow distance at each station. Tow distance is a potential source of bias without the offset catch accumulates as tow distance increases. The nominal time fished for the lined dredge is 45 s compared to 5 min. for a nominal survey tow, while the SD was towed for 2 min.

Approximate confidence intervals were estimated using

$$CI_L = elogit^{(\rho_L \pm 1.96\sigma_L)} \tag{2}$$

Where CI_L is the approximate confidence interval for selectivity at length L, ρ_L is the corresponding logit scale model estimate, σ_L is the standard error and elogit is the inverse of the logit function.

Selectivity estimates (Tables 14 – 15; Figure 48) were used to generate swept area and survey index plots (Figures 35 – 40) and are useful for comparison to assessment model results.

Shell length, meat weight relationships

The shell length-meat weight (SLMW) relationships are important because they are used to convert numbers of ocean quahog in survey catches to meat weight equivalents. Meat weights for ocean quahog include all of the soft tissues within the shell. All meat weights greater than 0.5 kg were assumed to be data entry error, and were removed from the analysis.

Generalized linear mixed models (GLMM; Venables and Dichmont (2004)) were used to predict ocean quahog meat weight, using equations of the form:

$$MW = e^{(\alpha + \beta_0 ln(L) + \beta_1 c_1 + \beta_2 c_2 + \cdots + \beta_n c_n)} \tag{3}$$

where MW was meat weight, L was shell length, $c_1, \cdots, c_n$ were covariate predictors (e.g., region or depth), and α and β_i were the estimated parameters. Examination of the variance of the weights as a function of shell length indicated that weight increased approximately linearly with shell height, implying that the Poisson family was reasonable for the distributions of meat weights (McCullagh and Nelder 1989). The GLMM in all analyses used the quasi-Poisson family with a log link. Quasi-Poisson is a Poisson distribution with a variance inflation parameter that relaxes the Poisson requirement that the mean must equal the variance. Because shell length to meat weight relationships for ocean quahog at the same station are likely to be more similar than those at other stations, we considered the sampling station as a grouping factor ("random effect") in the analysis.

We fit models with fixed effects for year and region (Table 16). The best model by AIC and BIC was a model with fixed effects for shell length, depth, and region and random effects for shell length slope and the intercept, using both the year and the station as the grouping variables.

Regional differences in meat weight are meaningful, particularly for the largest animals (Figure 49), though some of the differences between regions can be explained by the different depths found there (Figure 50).

1.6 ToR3: Habitat

The distribution of ocean quahog shifted in response to environmental conditions over the last 10 thousand years (Weinberg et al. 2002). However, it would probably be difficult to detect habitat shifts over shorter time periods using survey data because ocean quahog are long lived, recruit slowly, can aestivate in response to unfavorable environmental conditions and are found in relatively deep water where they may be somewhat insulated from environmental changes. Their current distribution likely reflects oceanographic conditions over the last several centuries.

Surfclams and ocean quahog partition marine habitats along the northeast coast between the intertidal zone out to about 80 m depth with the transition to ocean quahog starting at about 40 m, depending on location (Figures 206-211). Northeast Fisheries Science Center (2017) used co-occurrence in survey tows along the deep water boundary for surfclams and shallow water boundary for ocean quahog to measure climate effects on surfclam distributions and habitat. Presence-absence models showed that the probability of co-occurrence decreased almost linearly during 1982-2011 in the SNE region while increasing almost linearly in the LI and NJ regions (Appendix XXII in Northeast Fisheries Science Center (2017)). However, these trends were due to shifts in the distribution of surfclams with no apparent change in the distribution of ocean quahog. Results in this assessment show a statistically significant ($p < 0.05$) but modest shift in median depth (8 cm per year) for ocean quahog only off NJ (Figure 211).

The SAW/SARC-62 witch flounder assessment working group examined random forest regression trees and annual environmental data to predict changes in habitat and distribution with the eventual goal of modeling survey catchability and predicting recruitment (Northeast Fisheries Science Center 2017). Regression trees are currently being used to identify survey stratification schemes for surfclam and ocean quahog. The catchability and recruitment topics seem less applicable to sessile, long lived ocean quahog in deep water habitat. In this assessment, we use random forest regression trees and longer term environmental data to predict ocean quahog distributions and to identify which environmental variables are important. In summary, the analysis showed that random forest models and long term environmental data were useful for predicting survey catches and ocean quahog distributions and that the relative importance of predictor variables was consistent in two different regions.

The clam survey data used in random tree regression analyses were tow-by-tow catches (number per square meter swept by the dredge) from the GBK and SNE+LI regions during 1997-2011. The same survey dredge was used during this period and swept area estimates were accurate because sensors were used to measure tow distance. The period 1997-2011 seemed long enough to provide sufficient data and recent enough to reflect current conditions. The dependent variable was the cube root of the number of the ocean quahog catch per square meter swept by the dredge. The predictor variables were depth, average fall and spring bottom temperatures, benthic indices derived from multi-beam sonar data and three sets of climatology data derived from satellite measurements (Table 17).

Depths used in modeling were measured at each survey station. Bottom temperatures were 1997-2011 averages of predictions at each clam station based on interpolated temperature fields derived from fall and spring NEFSC survey bottom trawl survey data. The interpolations were a type of optimal interpolation based on a Kriging annual data with additional information provided by

mean anomaly fields from the full survey bottom temperature time series. The fall (fallBT) and spring (springBT) bottom temperature data were collected approximately during the warmest and coolest times of the year when temperature is most likely to affect ocean quahog distributions. The benthic indices included a vector ruggedness measure (namera vrm), bathymetric position index (namera bpi), rugosity and a sediment type index (soft sed). The climatology data were for sea surface temperature (SST) fronts (sst9kmfronts), chlorophyll density (chl9km) and chlorophyll fronts (chl9kmfronts) during July-August of 2000-2015 calculated at 9 km resolution. Latitude and longitude are useful for predicting ocean quahog catches but were excluded because they alias the environmental variables which were of particular interest. Benthic data were selected from a larger set of available variables to minimize collinearity but there were substantial correlations, particularly involving depth, bottom temperature and climatologies (Table 18). Although random forest predictions are robust to correlated predictors, such correlations make identification of causation more difficult in any model.

Both regression tree models were stable after 500 iterations (Table 19). The cross validated percent deviance explained based on predictions to data not used in fitting the models ranged from 44% (SNE+LI) to 67% (GBK) indicating that both models are useful (conventional R2 89%-94%). The five most useful predictors based on rank importance were chl9km, depth, soft sed, fallBT and sst9kmfronts for GBK and chl9km, nameravrm, depth, sst9kmfronts and springBT for SNE+LI (Figure 51). Importance ranks were relatively consistent in the two regions except that softsed and fallBT were more important for GBK and namera vrm was more important for SNE+LI (Figure 52). The distributions for residuals were somewhat right skewed and both models under-predicted at high catches levels (Figures 53-54). Other transformations (log, square root, fourth root, or inverse) did not improve residual diagnostics or model fit. The spatial pattern of the original survey and model predictions match reasonably well (Figures 55-56). The models predict fine-scale variability not evident in the original data. Future work might be oriented towards determining reliability of the predictions at fine spatial scales which may be useful in finding fishable ocean quahog beds.

1.7 ToR4: Growth

Ocean quahog older than several decades are relatively difficult to age because they grow slowly, live hundreds of years and have compressed annual rings. Relatively little growth information was available for use in this assessment. The von Bertalanffy curve used in KLAMZ models for ocean quahog on Georges Bank is based on ring counts from only 144 specimens collected at a single survey station during 1994 (Lewis et al. 2001). The von Bertalanffy curve used in KLAMZ models for the Mid-Atlantic Bight is based on a mark-recapture data for 267 specimens collected at one site during 1978-1979, ring counts for 134 specimens collected at one station during 1978 and modal increment analysis using a large number of specimens collected during 1970 and 1980 (Murawski et al. 1982). Kilada et al. (2006) supply growth curves for ocean quahog in Canadian waters that were used as a starting point for modeling growth in SS3 models for the whole stock.

The pace of research on ocean quahog age and growth intensified during the last two decades because of interest in ocean quahog longevity, which may exceed 500 y and use of growth ring increments in long term environmental research (Butler et al. 2013). These new data have not yet been compiled and used to estimate growth curves suitable for stock assessment.

The SAW Working Group reviewed preliminary data (Roger Mann, Virginia Institute of Marine Science, pers. comm.) collected using a high resolution digital camera and specialized software which suggests ocean quahog growth is substantially different from the von Bertalanffy pattern assumed in previous US and Canadian ocean quahog stock assessments (Northeast Fisheries Science Center 2009; Roddick, D. 2012). In particular, the new growth pattern was slower at young ages, faster at old ages and non-asymptotic. Tanaka (a.k.a. ALOG) growth equations matched the preliminary data reasonably well (Figure 57, Tanaka (1982); Karkach (2006)). Moreover, preliminary age composition information did not seem to decline over older ages in the manner expected with relatively constant mortality and recruitment over time as assumed in catch-curve analysis (Eric Powell, University of Southern Mississippi, pers. comm.).

The digital images and presumed annual marks seemed clear to the Working Group and no technical problems with the ageing study were identified based on the information presented although some ideas for improving age composition estimates were discussed. The Working Group agreed that the new growth information was potentially important because fishing mortality rate estimates from stock assessment models, forecasts and biological reference points depend strongly on growth. In addition, the pattern in age composition data for old ocean quahog may have been due to unusual long term recruitment trends, very low natural mortality rates or other important factors. One very interesting result indicates substantial changes in growth of ocean quahog south of Georges Bank over the last 250 years (Figure 58).

The stock assessment models for ocean quahog in this assessment (SS and KLAMZ) are not flexible enough to accommodate Tanaka growth but it is possible to approximate non-asymptotic growth to a limited extent in SS. The Working Group was not able to resolve questions about individual, temporal and spatial patterns in growth based on the preliminary results. In particular, the new growth pattern was not compared to results from the many recent and few older growth studies (Figure 57), the physiological basis for non-asymptotic growth after maturity remains unexplained, and there was no direct validation of the age data using radioisotopes or other means (Kilada et al. 2006).

Based on these considerations and the preliminary nature of the information, the Working Group based management advice on von Bertalanffy results while using the Tanaka pattern for sensitivity analysis. Both von Bertalanffy and Tanaka patterns were used in management strategy evaluations (MSE). Prior distributions used to help estimate von Bertalanffy growth parameters in stock assessment models were broad enough to accommodate non-asymptotic (Tanaka-like) patterns to the degree possible. This is an important area of future research that will require considerable attention prior to the next assessment after the new data are reviewed and published.

1.8 ToR5: Model

The primary ocean quahog assessment model was implemented in SS[2] (Methot and Wetzel 2013). SS allows for spatially separable model estimates, which in this case allowed for a division of the stock into two areas, the north and the south. Differences in availability of survey data and divergent population dynamics including different biomass and mortality trends, changes in proportion of total biomass in the two areas over time, and very limited fishing in the north drove the decision to use a spatial model.

SS replaced the biomass dynamics KLAMZ models used in the previous assessment, but KLAMZ models were rerun for comparative purposes and to build a bridge (Appendix 6). Empirical assessment calculations that did not involve assessment models were also included for comparison (Appendix 9). Together the three approaches form a complementary set that lead to the same conclusions for the ocean quahog stock.

Configuration

Fishery and survey selectivity were functions of size rather than age in SS models. Logistic selectivity curves were estimated for each survey in each area (Figure 60), and for the fishery in each area. Field estimates (e.g. Figure 48) were used to inform prior distributions for selectivity parameters.

Survey trend data were split into three series for each area. The first is the RDtrend series which covers the entire RD time series and is based on numbers per m^2 using vessel speed and start/stop times as explained in Section 1.5. The second series is RDscale, which was based on numbers per tow using the more precise sensor tow distances. RDscale was used to fit the catchability parameter for RDtrend, but did not inform trend (it was turned off in the likelihood). RDscale was available from 1997 till the end of the RD time series. The third series was MCD which used sensor distances and informed both scale (its own catchability parameter) and trend, but was available only for the period of the MCD survey (2 years for each area, see Figure 59).

The number of trips sampled by port agents was used as initial effective sample sizes for fishery length data in each year. The number of survey tows that caught ocean quahog was used as initial effective sample size for survey size composition data in each year. Initial log scale standard deviations for survey abundance trend data were derived from the CV for mean numbers per tow in each year (and assumed that errors were lognormal). The initial sample size assumptions for length data were "tuned" (adjusted up or down) based on preliminary model fits by multiplying the values for each type of data by a constant based on Francis (2011). The initial standard deviations for survey trend data were tuned, if necessary, based on preliminary model fits by adding a constant to the standard deviation for each observation in the time series (Francis 2011).

The proportion of total recruitment (estimated as annual deviations from the stock recruitment relationship) that ended up in each each area was allowed to vary over time by linking recruitment to a random walk process in the proportion recruited to each area with annual time steps. Including autocorrelation in the function was useful because the limited information value of the length composition data did not allow for very much flexibility in recruitment modelling. Preliminary attempts

[2]Stock Synthesis Model version SS-V3.24Y compiled for 64-bit linux.

to estimate annual deviations in the proportion of total recruitment that went to each area resulted in models that did not converge. Animals were not allowed to move from one area to the other in the model. Variance in recruitment was constrained such that annual deviations in recruitment were not excessive. Without this constraint, the model tended to produce one unreasonably large year class in order to closely fit the sharply peaked commercial length composition data.

Growth parameters, other than variance in size at age, were fixed at a solution from an earlier run where parameters were constrained by relatively weak prior distributions with means set to approximate preliminary estimates from recent field work and published von Bertalanffy curves (see 1.7). In the basecase, growth was fixed because constraining recruitment variance, as described above, tended to push growth into an unreasonable state, where animals grew much faster than field estimates.

The fixed biological parameters used in the assessment model were natural mortality (constant at $M = 0.02$), maturity (Figure 62) and weight at length (Figure 63), which were set to current best estimates. Other configuration details are shown in (Tables 20 – 21).

In general, parameters were given prior distributions when field experiments or other sources of prior information were available. Prior distributions were given the central tendency of the field based estimates as means and were initially diffuse, but were potentially tightened to bring the model closer to field estimates in some cases (Table 20).

Priors for survey dredge capture efficiency

The prior distributions for survey dredge capture efficiencies were important because the models are not otherwise strongly informed regarding scale. Appendices 3 and 4 detail the work that was done to estimate priors for the distribution of capture efficiency for the research dredge (RD) and the modified commercial dredge (MCD) used since 2011. These prior distributions were used for both the northern and southern areas, though a separate catchability parameter was estimated for each area.

Issues

The dynamics of ocean quahog cannot account for the survey trends, which indicates that the variance in survey data is likely to be primarily noise. The survey trends are variable, but there is no credible driver for that volatility. Total mortality is likely to be low (see Appendix 9), which means there is no ready explanation for the rapid reduction in abundance between 1994 and 2000 in the southern area, or between 1986 and 1989 in the northern area (Figure 40). With no available explanation for the rapid reduction in abundance it is unreasonable to add large year classes of recruits to explain the rapid increases in abundance that proceed them, leaving no ready explanation for the rapid increases either.

Length composition data provide some information about selectivity, but are probably providing limited information about growth and recruitment. The reason for this is that preliminary field estimates appear to indicate that variation in size at age is relatively high, such that there can be

approximately 100 different age classes present in a single 1 cm length bin (Figure 58). Length composition data are probably the best source of information available to explain recruitment since there are no age data available and the survey trends are noisy. In general the model fit the length composition data well at the expense of the survey trend data.

Iterations of the basecase model produced various recruitment solutions that fit the length composition data reasonably well, through adjustments to growth and selectivity. Because the data do not push the model into a particular recruitment pattern solution, there are various solutions that work about equally well, but produce somewhat different trends at the end of the time series. This tends to make trend relatively poorly determined although there is little doubt that the population is near its unfished size.

One factor mitigating the relative paucity of information is the abundance of field estimates for quantities of interest. Catchability (Appendices 3 and 4), and selectivity (1.5) of the survey sampling gear have been well studied and ocean quahog growth has been investigated to some extent (see 1.7). The field estimates constitute a body of prior knowledge for many of the model parameters, which was helpful in generating models that converged on relatively stable solutions.

Fit and estimates from basecase models

Fishery selectivity estimates were plausible based on prior information (Figure 60). The fit to the surveys was acceptable and the residuals did not show trends or high variance (Figures 66 – 70). The fit to the length composition data was tight (Figures 71 - 89). Data weighting decisions are shown in Figure 90. Model time series results are shown in Figure 92 and parameter estimates are shown in Table 21.

Likelihood profile analysis

Likelihood profile analysis of the model consisted of fixing the unfished recruitment parameter (R_0) at successive values that bracketed the R_0 solution (from the base case model) and estimating all of the other parameters in the model.

Likelihood profile results for the south indicate general agreement across each of the important contributors to the total likelihood (Table 22 and Figure 93). The RD survey trend and commercial length composition data support a slightly lower R_0 (lower biomass) solution than the parameter priors, but the difference is small in both relative biomass and likelihood units.

Sensitivities

Experimental model runs testing the effects of model manipulations (for example with either extra parameters or fewer sources of data) were informative. Some sensitivity runs were made using an earlier version of the basecase model.

Early runs of the ocean quahog model showed a tendency to rapidly increase biomass at the end of the time series. This produced a poor fit to the survey indices and seemed unlikely given the typical

dynamics of long lived species near theoretical unfished equilibrium biomass (low productivity and mortality). In an effort to isolate the source of the tendency to rapidly increase, different data were sequentially excluded from the model by setting the λ value (a constant applied to the likelihood component) equal to 0. When the length composition data were removed entirely, or the commercial length composition data were removed, the biomass increased after 2013 and 2005, respectively (Figure 94). The biomass increased earlier, in 1994, when the MCD trend data were removed. It appears that the commercial length compositions and the MCD survey provide enough information to counter the increase that the other data in the model support. Removing other pieces of data tend to produce changes in scale, but not in trend (Figure 94).

The priors for catchability (Figure 91) are influential in setting scale in this assessment because F is low and the survey indices do not respond to it. Therefore, the model has no way to fix scale once it has added enough ocean quahog to account for the fact that fishing does not affect trend. That is, there is little reason for the model to prefer one biomass scale to another, so long as both are sufficiently large to make fishing removals unimportant. A sensitivity run exploring the affect of the prior distributions on catchability demonstrated the affect of these priors on scale (Figure 95).

The magnitude of the large recruitment event in 1996 in the basecase model appears unlikely, in that the time series shows only two very large recruitment events over about 100 years (Figure 64) and preliminary age data indicate some recruitment in each year (Figure 58). There is little information in the data to support recruitment estimation, but what information exists tends to point to a large recruitment event occurring around 1996. For example, there is evidence of a proportional increase in small animals in 2005 and 2008 in the survey length composition data for the southern area (Figure 77). A sensitivity run constraining the variance of recruitment attempted to reduce the magnitude of this recruitment event. This run showed a relatively steady recruitment, without large departures from the mean (Figure 96), but was not able to fit the length compositions well without producing an unlikely growth curve (Figure 97). The trend in biomass produced by this run was somewhat flatter than the base run (Figure 98).

The fit to the RD survey in the south was poor in some years (Figure 66). In order to fit this survey better, the model needs to have some mechanism for rapidly removing biomass from the system. Biomass cannot be removed quickly in the basecase, because both natural and fishing mortality are low. A sensitivity run in which the model was allowed to estimate a Lorenzen type mortality at age function was implemented in order to better fit the survey trend data. This run resulted in a tighter fit to the survey data (Figure 99), but the model estimated a natural mortality that was approximately 0.1 on average (Figure 100). A natural mortality that high would imply a maximum age of approximately 31, which is unreasonable given that ages over 100 are commonly observed.

The survey catchability (q) estimated for the south were high relative to the medians of the prior distributions for them (Figure 91). A sensitivity run in which the cv for the prior distributions on survey q (for both dredges) was reduced to hold the estimated survey q closer to the median (Figure 101). This restriction resulted in a worse fit to the length composition data for the surveys in the southern area (Figure 102), but no substantial change in biomass trend (Figure 103).

The two areas may experience differential growth rates (Murawski et al. 1982; Lewis et al. 2001). Sensitivity runs in which growth was allowed to vary by area produced runs with only slightly different growth curves when K was fixed (Figure 104). When the K parameter was estimated

separately for each area, the growth curve for the southern area was improbable (Figure 105). Biomass trends were similar in each case and did not differ substantially from the base case (Figure 106).

Internal retrospective

The internal retrospective analysis of the ocean quahog assessment basecase model shows no important retrospective pattern in estimated trend, but does show a minor shift in scale and an increase in uncertainty as years of data are sequentially removed (Figure 107).

Historical retrospective

The estimated whole stock biomass in this assessment is similar in trend and scale to recent assessments (Figure 108).

Projections from the previous assessment were based on a bootstrap sample of terminal biomass estimates (Chute et al. 2013). The median projected SSB from the previous assessment was below the current estimate of SSB, though within the confidence envelope implied by the bootstrap uncertainty bounds (Figure 109).

Results

Fishing mortality has been low for the entire time series (Table 23, Figure 110). Spawning stock biomass has been near unfished levels for the entire time series (Table 24, Figure 111). While the biomass scale of this assessment model appears relatively stable, scale is frequently difficult to determine accurately in low F fisheries. Therefore, it is probably better to discuss the results, particularly relative to biological reference points, in a scale free context to the extent this is possible. The results relative to reference points are presented as ratios in TOR (1.10).

True recruitment was difficult to estimate in the ocean quahog assessment because there was no age composition data and growth was highly variable. These factors coupled with the extreme longevity of ocean quahog, imply that there can be more than 100 year classes present in a single one cm length bin. Initial aging studies (see 1.7) showed a broad range of ages present in several length bins. Therefore length composition data were unlikely to provide sufficient resolution to accurately estimate annual recruitment and recruitment estimates from this assessment should not be used to make inference on the timing or magnitude of pulses in true annual recruitment. The recruitment estimates from the assessment indicate a largely steady recruitment with a few years of low recruitment followed by a short period strong recruitment late in the time series (Table 25, Figure 112).

1.9 ToR6: Reference points

Current reference points

According to the biological reference points (BRP) in the FMP for ocean quahog, overfishing occurred whenever the annual fishing mortality rate on the whole stock was larger than the overfishing threshold, which was defined as a proxy for F_{MSY} ($F_{Threshold} = F_{MSYproxy} = F_{45\%} = 0.022\,y^{-1}$). The value of $F_{45\%}$, which was defined as the fishing rate that would reduce egg production to 45% of its potential, was considered a proxy because it was based on the life history traits associated with a long lived rockfish (*Sebastes sp.*). B_{Target} was defined as half of the fishable fraction of the whole stock biomass during 1978 ($B_{Target} = \frac{1}{2}B_{1978}$), where B_{1978} was considered unfished biomass and a reasonable approximation of B_{MSY}. The stock was overfished if total biomass fell below $B_{Threshold}$, which was $\frac{2}{5}B_{1978}$.

Current and recommended BRP for ocean quahog are proxies because spawner-recruit relationships required to determine F_{MSY} and B_{MSY} directly have not been estimated (low stock size has never been observed).

Reference points may be selected based on fishery performance and/or policy (risk aversion). Recommendations in this assessment are based on fishery performance criteria leaving the council to consider policy and risk involved in setting acceptable catch levels, with the advice of its Scientific and Statistical Committee (SSC).

The recommended biomass reference point is the unfished spawning stock biomass, SSB_0 estimated in the assessment model. It is the same in principle as the current reference point, B_{1978}, which simply assumed that the biomass in 1978 was similar to an unfished biomass. The current reference point uses the fishable biomass to make a status determination, while the recommended reference point uses spawning biomass. This should make scant difference in the determination of status, but is preferred because there is a clear long term benefit to the resource of maintaining spawning biomass, while the benefit of maintaining fishable biomass is less clear, particularly if selectivity changes over time.

F_{MSY} and proxies depend on spawner-recruit, and yield/spawning biomass per-recruit relationships. Proxies for F_{MSY} are often set at some fraction of M ($F_{MSY} = cM$, $c < 1$ such that M is an upper bound for F_{MSY}) or at the fishing mortality rate corresponding to some fraction of maximum average reproductive output per recruit ($F_{SPR\%}$, Zhou et al. 2012). Existing $F_{SPR\%}$ proxies are not applicable to ocean quahog because the analyses on which they are based generally assume that individuals mature and recruit to the fishery at about the same time. In addition, F_{MSY} cannot be computed directly because we have never observed a low stock size and thus have no way to characterize the stock recruit relationship.

Simulation analyses can be used to identify robust reference points that work well across a range of potential spawner-recruit curves and life-history patterns. This assessment includes management strategy evaluation (MSE) simulations which were tailored to ocean quahog and the uncertainties about their life history and dynamics (8). The MSE analysis included two scenarios, one using a preliminary Tanaka growth equation discussed in 1.7 and the other using a Beverton-Holt growth equation based on parameter estimates from Kilada et al. (2006).

MSE

MSE simulations were used to evaluate how MAFMC control rule parameters (a simplified version) affect average biomass relative to virgin biomass $\frac{SSB}{SSB_0}$, average relative yield measured as $\frac{Y}{SSB_0}$, interannual variation in yield cv(Y) and the proportion of years with no fishing ($t_{F=0}$). Simulations included a relatively wide and realistic range of random inputs for recruitment parameters, natural mortality, steepness, growth patterns, and other important, but uncertain parameters (Appendix 8).

MSE results assuming both Beverton-Holt and Tanaka growth curves showed that F and biomass reference points were important for maintaining ocean quahog biomass and yield over the long term (Appendix 8). However, a wide range of different combinations of these parameters performed well based on MSE results.

The control rule used in ocean quahog involves a "biological reference point" that has not been defined previously and requires some explanation.

The current process for setting catch and associated landings limits (i.e., quotas) for the ocean quahog fishery is complicated. For Council managed stocks, acceptable biological catch limits (ABC) are set at a level less than the catch associated with the maximum fishing mortality threshold rate using a control rule that is a combination of the predetermined Council's risk policy (i.e., maximum tolerance for overfishing under specific conditions) and SSC decisions on the degree of uncertainty associated with the stock assessment. Because setting these catch limits involves a committee decision on the degree of uncertainty in the assessment, and is not a purely formulaic control rule, it is difficult to apply directly and requires some simplification for simulation in this MSE.

The Council's risk policy, which is used in the derivation of the ocean quahog ABC, is described on page 51 of Amendment 16 to the fishery management plan (MAFMC 2011). The risk policy is conditioned on the ratio of current stock biomass relative to the control rule (stock replenishment) threshold, and whether the life history is considered to be typical or atypical[3]. The policy includes a stock replenishment threshold defined as the ratio of $\frac{B}{BMSY} = 0.10$, to ensure the stock does not reach low levels from which it cannot recover. The probability of overfishing is 0 percent at $\frac{B}{BMSY} = 0.10$ and increases linearly until the inflection point of $\frac{B}{BMSY} = 1.0$, where a 40 percent probability of overfishing is utilized for stocks defined as typical, and a 35 percent probability for those defined as atypical. In addition, the risk policy has associated regulations that govern setting ABC for stocks under rebuilding plans and in instances where no maximum fishing mortality rate threshold has been identified. Neither of these cases apply to ocean quahog. The stock replenishment threshold will be termed SSB_{Cease} to avoid confusion with the biomass threshold used to determine overfished status. Thus, $SSB_{Cease} = 0.1 * B_{MSY} = 0.1 * SSB_{Target} = 0.05 * SSB_0$.

Although the true ocean quahog control rule is based on the probability of overfishing, rather than the fraction of SSB_0 remaining, and acts on the ABC, rather than the F_{target}, the functional response of the stock to management is similar. In both cases, the catch will be reduced in proportion to biomass, when biomass drops below a target value (the probability of overfishing depends on

[3] An atypical stock has a life history strategy that results in greater vulnerability to exploitation, and whose life history has not been fully addressed through the stock assessment and biological reference point development process.

F_{target} and biomass; when biomass is low, F_{target} must be reduced proportionately to reduce the probability of overfishing). In both cases, fishing will no longer be allowed when the biomass drops below a threshold value ($SSB < 0.05 * SSB_0$).

Process for recommending reference points

To further clarify terminology we will use SSB_{Cease} to refer to the biomass at which F is set to 0 under the control rule described above and SSB_{Target} as the biomass below which F is reduced from its target rate (see Figure 243). To simplify analysis we base recommendations on results for council control rule values of $SSB_{Cease} = 0.1 * SSB_{MSY} = 0.05 * SSB_0$, $SSB_{Target} = SSB_{MSY} = \frac{1}{2} SSB_0$. This does not directly apply to the ocean quahog control rule, but does reflect the likely functional outcome of ocean quahog management. That is, a reduction in quota when the stock is determined to be overfished.

Using Tables 39 - 54, and concentrating on the columns for $SSB_{Cease} = 0.05 * SSB_0$ and $SSB_{Target} = \frac{1}{2} SSB_0$, it is possible to isolate values of F_{Target} that could serve as $F_{Threshold}$. For example, the yield tables indicate F_{Target} values that produce the maximum average yield over either 100 or 1000 years based on the MSE. These F_{Target} values, which we will call $\hat{F}_{MSY}$ should probably form an upper bound on $F_{Threshold}$, because maximizing average yield is not desirable in the market limited ocean quahog fishery. A lower bound on $F_{Threshold}$ might be based on finding the F_{Target} values that result in an average biomass close to theoretical SSB_{MSY} ($\frac{1}{2} SSB_0$), as there is no practical reason to restrict F_{Target} further than that. Table 26 has the values for this bounding exercise based on the MSE results.

Because ocean quahog are very long lived, 100 years is less than 2 generations. Therefore it may be wise to base the decisions on $F_{Threshold}$ on the 1000 year simulations. Based on Table 26, this would give an approximate $0.011 < F_{Threshold} < 0.023$.

Reference points should reflect any uncertainty in their value. In order to approximate the uncertainty in $F_{Threshold}$, the 1000 year simulation results for average yield and average biomass were fit with a GAM over F_{Target}. The F_{Target} that resulted in maximum average yield could be considered $F_{MSYproxy}$. These values along with a range of 5% quantiles to either side of $F_{MSYproxy}$ were calculated for each growth pattern under consideration (Figure 113). A lognormal distribution based on $F_{MSYproxy}$ for each growth pattern is shown in Figure 114.

Similarly, a proxy for F stability ($F_{Stab.}$) might be the F_{Target} values that resulted in average biomasss between SSB_{Target} and $SSB_{Threshold}$ (See Figures 115 - 116). Falling below $SSB_{Threshold}$ would trigger a rebuilding plan that would result in a reduced quota and having a biomass that is above SSB_{Target} would theoretically reduce sustainable yield. Therefore a point of relative stability should fall between SSB_{Target} and $SSB_{Threshold}$. Combining information from each of these distributions, that is, the F_{Target} that corresponds to $F_{MSYproxy}$ with uncertainty in the form of 5% quantiles above and below, *or* $F_{Stab.}$, with uncertainty in the form of the range from SSB_{Target} to $SSB_{Threshold}$ results in an estimate of $F_{Threshold}$ that carries uncertainty from the MSE (Figure 117). The MSE incorporated a broad range of uncertainty around life history traits, including growth, and the preferred $F_{Threshold}$ should work well over varied potential and currently unknown ocean quahog biological characteristics.

Recommendations

The preferred $F_{Threshold} = 0.019$ was chosen because it should maintain relatively high average yield with low interannual variation in yield and infrequent years with no fishing (Tables 39 - 54; Figures 247 - 249). The recommended $F_{Threshold}$ was superior to the current $F_{Threshold} = M = 0.022$ because it was based on an MSE, rather than a proxy from an unrelated long-lived species, and because it included a meaningful estimate of its uncertainty.

The preferred B_{Target} and B_{MSY} values were based on Council policy rather than catch maximization and risk minimization in the MSE. However, the recommended values should perform well for ocean quahog based on MSE results.

Table 4: Biological reference points used in the last assessment and those recommended in this assessment for ocean quahog. The recommended F reference point is based on an MSE analysis (Hennen 2015) adapted to include new information on growth (Appendix 8).

Reference point	Previous assessment	Revised
$F_{MSY} = F_{Theshold}$	$F_{MSYproxy} = F_{45\%} = 0.022$	$F_{Threshold} = 0.019$
B_0	B_{1978}	SSB_0
$B_{MSY} = B_{Target}$	$\frac{B_{1978}}{2}$	$\frac{SSB_0}{2}$
$B_{Threshold} = \frac{B_{MSY}}{2}$	$\frac{2}{5}B_{1978}$	$\frac{2}{5}SSB_0$
MSY		$\frac{F_{MSY}}{F_{MSY}+M}SSB_0\left(1 - e^{(-(F_{MSY}+M))}\right)$

1.10 ToR7: Stock status

It was not possible to add the new survey data to the previous assessment model because it was not configured to accept data from a different survey. Therefore, the previous assessment model cannot be directly compared to the model used in the current assessment, though a reasonable effort has been made to do so in Appendix 6. It is, however, possible to compare the new assessment estimates of biomass and fishing mortality to the current and recommended biological reference points.

Current reference points

Comparing the terminal spawning biomass (SSB_{2016}) and fishing mortality estimates (F_{2016}) to the current reference points (Table 4) shows a low probability of either overfishing or overfished status for the ocean quahog stock in the US EEZ (Table 27) with slight changes in the point estimates of the reference points (Table 28). The current $F_{threshold}$ was a point estimate with no associated uncertainty. Therefore the probability of overfishing was equal to the probability of overlap between the distribution of F_{2016} and the point estimate of $F_{threshold}$.

Recommended reference points

According to the recommended reference point definitions, the ocean quahog stock is not overfished and overfishing is not occurring. There is a near zero probability that the ocean quahog stock in the US EEZ is experiencing overfishing ($F_{2016} < F_{Threshold}$; Table 29; Figure 118–119), and there is a near zero probability that the ocean quahog stock in the US EEZ is overfished ($SSB_{2016} < SSB_{Threshold}$; Table 30; Figure 118 and 120).

1.11 ToR8: Projections

Basecase models were used to project biomass of ocean quahog, catch (mt), and fully recruited fishing mortality during 2017-2066 (Tables 31 - 32 and Figure 123). Three harvest policies were assumed: 1) $F = F_{Threshold}$ (OFL catch), 2) status quo catch (15341 mt) and 3) the maximum allowed catch under the current FMP or "quota level" catch (25400 mt) in the combined areas. Results indicate that biomass will remain higher than the biomass threshold and projected fishing mortality levels will be lower than the fishing mortality threshold for the entire resource.

Projections for each year assumed time series average recruitment with uncertainty in starting stock size equal to the uncertainty in the final (non-forecast) model year (Figure 124). Proportional recruitment to each area was assumed equal to the proportional recruitment in each area in the terminal year (except in some sensitivity runs, see below). Catch was equal to the sum of the catch from the northern and southern areas. Because most of the catch is currently taken from the southern area, projections assumed that 90% of the forecast catch came from the southern area (except in some sensitivity runs, see below).

It is unlikely that the stock will be overfished within the next 50 years. The maximum probability of overfished status coincides with the minimum biomass estimate over the forecast time horizon. The distributions of SSB_y and $SSB_{Threshold}$ were assumed lognormal with means equal to their respective point estimates and variances equal to their delta method variances. One million draws from possible threshold values were taken from correlated distributions with means and variances as described above, where the correlation between them was equal to the correlation between SSB_y and $SSB_{Threshold}$ estimated in the model. Each pair of draws was compared. Overfished status occurred when the threshold draw was greater than the biomass draw. Probabilities were equal to the number of overfished occurrences divided by the number of comparisons made (Shertzer et al. 2008). The probability of the whole stock being overfished was low for all projection scenarios considered (Figure 125).

The most likely fishing scenario is probably status quo catch, because the fishery is market limited and has caught less than the quota level every year except 1996 - 1998 (Table 4). The quota scenario with higher catches was therefore a reasonable upper bound on likely fishing pressure over the next 50 years. Using the quota scenario, the maximum probability of being overfished in any one year in next five (P^*) was low (Figure 125) and the cumulative probability of being overfished at any time during the next ten years ($1 - \prod_y \{1 - p_y^*\}$) (Table 33), where p_y^* is the P^* value for each year was also low (see Shertzer et al. (2008)).

Projected fishing mortality levels were lower than the fishing mortality threshold for the entire resource under all scenarios except $F = F_{Threshold}$ for each of the stock areas (Figure 126; Table 32). The cumulative probability of experiencing overfishing using the status quo catch or quota scenarios in any of the projection years was also low (Table 33).

In order to test the sensitivity of the projections to uncertainty in biomass scale, as well as model specification, quota scenario projections were conducted where all of the removal occurred in either the southern or northern area. Additional sensitivity runs were status quo projections in which natural mortality was either 0.01 (low M) or 0.03 (high M) and where recruitment was relatively high or low (Figure 127). Projecting forward using these sensitivity runs showed that probabilities of overfishing and overfished status were similar over a wide range of biomass scales (Table 34). The

projection sensitivity results indicate that the status of the stock over the forecast time horizon is robust to uncertainty in biomass scale, when recruitment remains near time series average values.

Probability distributions of the catch at the OFL were generated by repeated draws from a lognormal distribution of catch in each year, with a mean equal to the point estimate of the catch and a cv equal to the model estimated cv for each catch value (Figure 128; Table 35).

1.12 TOR 9: Research recommendations

The following are research recommendations from the previous assessment (**?**), (in rough order of priority):

1. The next survey should be conducted by a commercial vessel that is more efficient in sampling ocean quahog compared to the *RV Delaware II*. The pilot program and analysis of existing cooperative survey data suggest that the data collected by a commercial vessel will be more precise and easier to interpret compared to data collected by the existing clam survey. The survey should commence immediately in 2010 on a 15 days at sea per year schedule. *Completed. As of 2012 the clam survey has been conducted using a commercial vessel deploying a modified commercial dredge. Instead of surveying the whole stock area every three years, survey activity takes place annually, with the goal of covering the MAB region in year one, the GBK region in year two, and with research activities in year three. Further survey improvements are anticipated.*

2. The 2011 survey should be of sufficient length, including anticipated down time, to cover all of the regions from Delmarva through Georges Bank. *Completed.*

3. Carry out simulations to determine optimum proxies for F_{MSY} and B_{MSY} in ocean quahog, given their unusual biological characteristics. *Completed. (Hennen 2015).*

4. The survey sensor package (SSP) should be modified so that y-tilt sensors are situated to better measure y-tilt at shallow angles; it is not important to measure y-tilt accurately at steep angles. Consider using a sensor not prone to vibration and resonance effects. *With the new survey platform, this is no longer needed.*

5. The SSP equipment should be redesigned and battery life extended for greater reliability and use on commercial dredges. Backup sensors should be improved as well and used routinely. *Completed. SSP no longer used.*

6. Estimate relationships between size and number of eggs produced. Determine spawning frequency if possible. *No progress.*

7. Additional age and growth studies are required to determine if extreme longevity (e.g. 400 y) is typical or unusual and to refine estimates of natural mortality. Similarly, additional age and growth studies over proper geographic scales could be used to investigate temporal and spatial recruitment patterns. *Some progress has been made. Animals from four sites have been aged, and age frequencies constructed for these sites. This effort needs to be expanded to other sites.*

8. Better information about maturity at length is required. *Some progress has been made. There have been clams of every size collected for ageing and sex determination, and we plan to include maturity in this process in the future.*

9. There has been progress in improving port sampling for ocean quahog since the last assessment and efforts in this direction should continue, particularly as the distribution of the fishery shifts and if a fishery develops on Georges Bank. *Completed.*

10. Commercial dredge selectivity estimates should be obtained for the next assessment. *Completed.*

11. Improve estimates of biological parameters for age, growth (particularly of small individuals), and maturity for ocean quahog in both the EEZ and in Maine waters. *Some progress has been made - see above.*

12. Additional estimates of survey dredge efficiency from cooperative depletion studies are required. *Completed.*

13. Develop a length (and possibly age) structured stock assessment model for ocean quahog that makes better use of survey and fishery length composition data which may provide better estimates of recruitment trends. *Completed. Stock Synthesis model incorporates length composition data and is now used for the assessment.*

14. Conduct further analyses to determine the relationship between dredge efficiency, depth, substrate, and clam density. *No progress.*

15. Changes in length composition during a depletion experiment might be incorporated into efficiency estimation by, for example, including selectivity parameters in the Patch model. Efficiency estimates (and commercial selectivity) might be more precise because more size groups would be included in catch data. *No progress.*

16. It would be useful to analyze efficiency estimates in terms of season because ocean quahog are believed to change their depth in sediments on a seasonal basis. *No progress.*

17. Investigate model formulations that accommodate spatial heterogeneity. *Progress has been made. The current assessment model is spatial and includes area specific recruitment, catchability, and selectivity, while sensitivity runs include area specific growth.*

18. Examine existing underwater photographs of ocean quahog to evaluate the potential use of HABCAM or other optical surveys for surveying ocean quahog and for measuring their habitat. *Progress has been made. Preliminary studies of the visibility of clam siphons in the optical surveys and the ability to identify species have been conducted, but results are not yet published.*

19. Regions used in future cooperative surveys should be spatially distinct (non-overlapping) and sensible with respect to fishery patterns, management requirements and the biological distribution of the animals. It is important that the spatial resolution of the catch and port sampling data are adequate for use with the new survey regions. The survey should cover the entire habitat area. It may be advisable to break SNE into two portions, one associated with biological patterns on GBK and the other associated with LI. *Progress has been made. The current assessment model is spatial (see above) and the survey reflects the assessment regions.*

20. It may be advantageous to use survey strata that are appropriate for ocean quahog and surfclams per se, rather than for all shellfish including scallops and other shellfish. *Progress has been made. The distributions of surfclams and ocean quahog and their overlap have been analyzed and survey redesign studies are underway.*

21. Presentation of results for SVA complicates the assessment and this area should be dropped or combined with DMV in the next assessment. *Completed.*

New research recommendations (major groups and items within major groups in rough priority order)

Age data

1. Verify and publish new age determination methods.
2. Publish growth curves and evidence for indeterminate growth. Consider mixed-effects growth models that account for correlated increment measurements from the same specimen and correlated growth/maturity parameters among specimens from the same site.
3. Expand and refine age sampling to obtain representative data across larger regions used in stock assessment modeling. Modify the stock assessment model if necessary to accommodate non-asymptotic growth patterns and use age data in the next stock assessment if available.
4. Use the large number of age groups in ocean quahog age composition data to characterize spatial and temporal patterns in recruitment and growth over the last several centuries. Try to relate changes to historical environmental conditions and potential future changes in ocean quahog distribution and productivity due to climate.
5. Age small ocean quahog to refine maturity at length, estimate maturity at age and investigate sexually dimorphic growth hypotheses.
6. Determine if evidence of a strong year-class in survey length data born in the mid-1990s is supported by age data.

Survey

8. Improve precision of the clam survey by targeting one species at a time to increase sample density and so that stations can be allocated optimally for the target species. Consider other changes to stratification scheme and survey frequency as appropriate. Use an MSE style analysis to determine if proposed changes will improve stock assessment results particularly if changes with reduce the frequency of stock assessments.
9. The scale of ocean quahog stock assessment estimates depends almost entirely on parameters used to convert survey catches to density and abundance. Improve area swept and stock area estimates considering habitat outside the survey area, rocky parts of the survey area that may be poor habitat and procedures at-sea for handling rocky ground. Improve capture efficiency estimates considering ocean quahog that may be aestivating deep in the sediments and hard to capture during depletion experiments and extrapolation to areas where depletion experiments are not carried out. At minimum, determine if swept area biomass estimates are likely to be over- or underestimated using current procedures.
10. Assemble or collect information that could be used to estimate the proportion of ocean quahog that are too deep in sediments to be sampled effectively. Is it possible to predict the proportion based on bottom temperatures? How much bias is likely due to burrowing behavior?
11. Current borrowing procedures used to fill unsampled strata may not be needed in future due to survey improvements but are still required for historical data.

Fishery-related

12. Refine estimates for parameters that convert landings from reported volumes (cages) to meat weight equivalents. Estimate inaccuracy due to changes in size composition and seasonal recruitment patterns. Evaluate effects of inaccuracy on stock assessment results.

13. Increase and refine presentation of survey and fishery information about ocean quahog dynamics at small spatial scales (e.g. 10 minutes squares) for presentation in the assessment focusing on dense aggregations that are important to the fishery and possibly important for recruitment.

14. Use new vessel monitoring system (VMS) data with logbook data more fully in the assessment, particularly for analyses at small spatial scales.

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2 Tables

Table 4: Annual ocean quahog landings (excluding Maine) and quotas in metric tons of meats.

Year	EEZ	Quota	Proportion
1980	12134	15880	0.76
1981	12121	18140	0.67
1982	13205	18140	0.73
1983	14586	18140	0.8
1984	17975	18140	0.99
1985	20726	22230	0.93
1986	18902	27220	0.69
1987	21514	27220	0.79
1988	20273	27220	0.74
1989	22359	23590	0.95
1990	20965	24040	0.87
1991	22064	24040	0.92
1992	22477	24040	0.93
1993	21876	24490	0.89
1994	20985	24490	0.86
1995	21108	22230	0.95
1996	20061	20180	0.99
1997	19628	19580	1
1998	17897	18140	0.99
1999	17381	20410	0.85
2000	14723	20410	0.72
2001	17069	20410	0.84
2002	17947	20410	0.88
2003	18815	20410	0.92
2004	17655	22680	0.78
2005	13635	24190	0.56
2006	14273	24190	0.59
2007	15564	24190	0.64
2008	15727	24190	0.65
2009	15710	24190	0.65
2010	16289	24190	0.67
2011	14332	24190	0.59
2012	15864	24190	0.66
2013	14721	24190	0.61
2014	14498	24190	0.6
2015	13639	24190	0.56
2016	9542	24190	0.39
min	9542	15880	0.39
max	22477	27220	1
mean	17250	22491	1

Table 5: Annual ocean quahog landings and quotas in metric tons of meats. Landings from unknown areas in each year were prorated to known areas based on logbook proportions of landings in known areas. Totals are for the EEZ area and do not include Maine (MNE). Summary statisitics ignore years without landings.

Year	SVA	DMV	NJ	LI	SNE	GBK	MNE	Total
1980	0	4284	7844	6	0	0		12134
1981	56	3644	8418	3	0	0		12121
1982	6	4627	8572	0	0	0		13205
1983	0	5506	8417	21	642	0		14586
1984	6	7650	9442	0	877	0		17975
1985	177	7951	11789	44	765	0		20726
1986	0	8529	9381	410	582	0		18902
1987	0	10554	9082	1182	697	0		21514
1988	42	11727	7022	641	842	0		20273
1989	0	6444	14112	606	1197	0		22359
1990	14	3686	15592	739	934	0	3	20965
1991	0	4863	14649	1682	869	0	110	22064
1992	0	2386	6965	11979	1147	0	75	22477
1993	0	1958	10231	8664	1023	0	56	21876
1994	0	996	6967	12064	958	0	65	20985
1995	0	703	5386	9578	5441	0	114	21108
1996	0	742	4905	5993	8421	0	142	20061
1997	0	1084	4276	5199	9069	0	218	19628
1998	0	1385	2723	6955	6834	0	218	17897
1999	0	1109	3093	6442	6736	0	279	17381
2000	0	1083	3430	4905	5254	51	357	14723
2001	0	963	4910	6129	5054	14	326	17069
2002	0	1775	2850	9340	3981	0	387	17947
2003	0	917	3770	11900	2228	0	359	18815
2004	0	635	2810	10879	3331	0	307	17655
2005	0	932	685	9948	2070	0	301	13635
2006	0	507	479	11392	1895	0	365	14273
2007	0	102	1597	11507	2357	0	306	15564
2008	0	267	1738	11437	2284	0	201	15727
2009	0	213	2442	8687	4350	17	167	15710
2010	0	432	2339	9996	3508	13	169	16289
2011	0	294	1894	10380	1764	0	196	14332
2012	0	167	1427	11848	2315	106	226	15864
2013	0	0	363	10035	4157	166	176	14721
2014	0	14	541	10448	2814	681	137	14498
2015	0	0	683	10667	2208	81	125	13639
2016	0	62	843	6723	1821	92	69	9542

Table 5 continued.

min	0	0	363	0	0	0	3	9542
max	177	11727	15592	12064	9069	681	387	22477
mean	8	2598	5352	6338	2610	32	147	17250

Table 6: EEZ fishing effort (hours fished by all vessels) for ocean quahog, by stock assessment area and year based on logbook data. The fraction of logbook effort from unknown areas in each year was prorated to known areas based on effort in known areas. Effort data prior to 1981 are less reliable due to restrictions on hours fished per day. Summary statistics ignore years without effort.

Year	SVA	DMV	NJ	LI	SNE	GBK	MNE	Total
1982	7	7137	14603					21747
1983		7149	13971	50	1538			22708
1984	16	11575	16131		2630			30352
1985	224	11039	19634	95	2267			33260
1986		12701	14877	374	1179			29131
1987		15841	14720	807	1342			32710
1988	64	19137	11620	616	1641			33079
1989		12139	24293	798	2330			39560
1990	25	8166	29327	1282	1838		286	40924
1991		12048	30397	1844	1433		17110	62832
1992		5513	15998	13148	1964		13424	50047
1993		4622	25457	12883	1783		5720	50465
1994		2263	20566	19187	2084		5062	49162
1995		1621	13598	16015	8561		5731	45526
1996		1523	9352	10252	11881		8415	41424
1997		2742	9382	8295	13515		11734	45668
1998		3231	6996	10528	10659		11652	43066
1999		2601	7639	9151	12284		10844	42519
2000		2555	8087	7178	10702	64	12400	40986
2001		2240	11192	8063	11770	23	13533	46820
2002		4298	6695	11626	7811		16809	47239
2003		2622	10772	16147	4611		17869	52021
2004		2495	7905	14608	6642		19000	50650
2005		3448	1974	12533	4048		16920	38923
2006		1811	1386	14511	3314		14641	35663
2007		346	3719	15607	4286		13821	37779
2008		934	4710	15243	4182		10749	35818
2009		790	5335	10868	7045	30	9634	33703
2010		1709	6416	12827	5141	20	9423	35536
2011		970	4776	14163	3712		9058	32679
2012		581	3480	16583	4648	154	7580	33027
2013			848	16168	7643	190	6306	31155
2014		85	1424	17422	5372	511	5032	29846
2015			2025	17268	4546	92	5704	29636
2016		220	1659	11969	3844	61	3158	20910
min	7	85	848	50	1179	20	286	20910
max	224	19137	30397	19187	13515	511	19000	62832
mean	10	4768	11011	9108	4785	31	7586	38473

Table 7: Nominal landings per unit effort (LPUE, bushels h^{-1}) for ocean quahog fishing (all vessels) in the US EEZ from logbooks. LPUE is total landings in bushels divided by total hours fished. Landings and fishing effort from unknown areas were prorated to area before LPUE was calculated. Summary statistics ignore years without fishing.

Year	SVA	DMV	NJ	LI	SNE	GBK	MNE	Total
1982	85.7	64.8	58.7					60.7
1983		77	60.2	42	41.7			64.2
1984	37.5	66.1	58.5		33.3			59.2
1985	79	72	60	46.3	33.7			62.3
1986		67.2	63.1	109.6	49.4			64.9
1987		66.6	61.7	146.5	51.9			65.8
1988	65.6	61.3	60.4	104.1	51.3			61.3
1989		53.1	58.1	75.9	51.4			56.5
1990	56	45.1	53.2	57.6	50.8		1	51.2
1991		40.4	48.2	91.2	60.6		0.6	35.1
1992		43.3	43.5	91.1	58.4		0.6	44.9
1993		42.4	40.2	67.3	57.4		1	43.3
1994		44	33.9	62.9	46		1.3	42.7
1995		43.4	39.6	59.8	63.6		2	46.4
1996		48.7	52.4	58.5	70.9		1.7	48.4
1997		39.5	45.6	62.7	67.1		1.9	43
1998		42.9	38.9	66.1	64.1		1.9	41.6
1999		42.6	40.5	70.4	54.8		2.6	40.9
2000		42.4	42.4	68.3	49.1	79.7	2.9	35.9
2001		43	43.9	76	42.9	60.9	2.4	36.5
2002		41.3	42.6	80.3	51		2.3	38
2003		35	35	73.7	48.3		2	36.2
2004		25.5	35.5	74.5	50.2		1.6	34.9
2005		27	34.7	79.4	51.1		1.8	35
2006		28	34.6	78.5	57.2		2.5	40
2007		29.5	42.9	73.7	55		2.2	41.2
2008		28.6	36.9	75	54.6		1.9	43.9
2009		27	45.8	79.9	61.7	56.7	1.7	46.6
2010		25.3	36.5	77.9	68.2	65	1.8	45.8
2011		30.3	39.7	73.3	47.5		2.2	43.9
2012		28.7	41	71.4	49.8	68.8	3	48
2013			42.8	62.1	54.4	87.4	2.8	47.3
2014		16.5	38	60	52.4	133.3	2.7	48.6
2015			33.7	61.8	48.6	88	2.2	46
2016		28.2	50.8	56.2	47.4	150.8	2.2	45.6
min	37.5	16.5	33.7	42	33.3	56.7	0.6	34.9
max	85.7	77	63.1	146.5	70.9	150.8	3	65.8
mean	64.8	42.9	45.5	73.8	52.8	87.8	2	47

Table 8: Real and nominal exvessel prices and revenues (millions of dollars) for ocean quahog based on dealer data. Average price (dollar per bu) was computed as total revenues divided by total landed meat weight during each year, rather than as annual averages of prices for individual trips, to reduce effects of small deliveries at relatively high prices. The consumer price index (CPI) used to convert nominal dollars to 2009 equivalent dollars is for unprocessed and packaged fish, which includes shellfish and finfish (Eric Thunberg, NEFSC, pers. comm.).

Year	CPI	Nominal_Prices	Real_Prices	Nominal_Revenue	Real_Revenue
1982	0.45	3.06	6.80	11.12	24.72
1983	0.46	3.06	6.58	10.91	23.50
1984	0.48	3.06	6.31	12.10	24.97
1985	0.50	3.07	6.12	14.91	29.73
1986	0.51	3.46	6.78	15.72	30.76
1987	0.53	3.30	6.23	16.51	31.17
1988	0.55	3.22	5.84	14.92	27.05
1989	0.58	3.21	5.56	16.39	28.35
1990	0.61	3.47	5.70	16.25	26.68
1991	0.63	3.67	5.78	17.89	28.17
1992	0.65	3.83	5.85	19.30	29.51
1993	0.67	4.15	6.16	22.71	33.72
1994	0.69	4.02	5.83	18.77	27.17
1995	0.71	4.31	6.07	22.10	31.11
1996	0.73	4.51	6.16	20.98	28.68
1997	0.75	4.54	6.06	19.93	26.63
1998	0.76	4.60	6.05	18.36	24.16
1999	0.78	4.79	6.17	18.54	23.86
2000	0.80	5.17	6.44	16.98	21.15
2001	0.83	6.28	7.61	23.87	28.91
2002	0.84	6.37	7.60	25.49	30.39
2003	0.86	6.22	7.25	26.03	30.34
2004	0.88	6.02	6.84	23.65	26.85
2005	0.91	6.10	6.70	18.56	20.38
2006	0.94	6.09	6.48	19.42	20.66
2007	0.97	5.94	6.15	20.61	21.32
2008	1.00	5.92	5.90	20.35	20.28
2009	1.00	6.28	6.28	21.92	21.92
2010	1.02	6.43	6.32	23.18	22.80
2011	1.05	6.95	6.63	22.09	21.07
2012	1.07	7.37	6.88	25.87	24.17
2013	1.09	7.33	6.75	23.65	21.78
2014	1.10	7.59	6.88	23.84	21.60
2015	1.10	7.89	7.15	23.67	21.46

Table 9: Numbers of commercial trips sampled and numbers of ocean quahog measured in port samples from landings during 1982-2016, by region.

	DMV		NJ		LI		SNE		GBK	
Year	Lengths	Trips	Lengths	Trips	Lengths	Trips	Lengths	Trips	Lengths	Trips
1982										
1983										
1984										
1985										
1986										
1987										
1988							30	1		
1989							310	10		
1990							796	25		
1991							634	21		
1992					240	13	822	27		
1993							761	25		
1994	180	6	30	1	1845	100				
1995	570	19								
1996	390	13	420	14	1496	77	540	31		
1997	960	32	420	14	1145	64	839	46		
1998	690	23	600	20	1713	100	582	33		
1999	660	22	780	26	3003	156	820	47		
2000	120	4	510	17	2167	109	1584	84		
2001	390	13	390	13	1862	97	1813	96		
2002	360	21	15	1	1705	92	2021	110		
2003	368	20	77	4	2074	113	1177	66		
2004			53	3	1276	73	781	43		
2005	75	4	188	10			812	46		
2006	40	2	181	10			595	33	33	2
2007	164	9	384	21	30	1	541	30		
2008	107	6	477	26	1012	32	705	40		
2009	144	7	394	20	480	16				
2010	23	1	411	20	1440	48			10	1
2011			117	6	390	13			41	2
2012			162	9	180	6				
2013			168	9	150	5			33	2
2014			65	4	990	33			161	8
2015					240	13	30	1	17	1
2016					1166	64	310	10	19	1
min	23	1	15	1	30	1	30	1	10	1
max	960	32	780	26	3003	156	2021	110	161	8
mean	328	13	292	12	1172	58	786	39	45	2

Table 10: Number of successful random tows in NEFSC clam surveys used for survey trends and efficiency corrected swept area biomass. 'Holes' (unsampled survey strata in some years) were filled by borrowing from adjacent surveys where possible (borrowed totals are negative numbers in gray shaded boxes). Holes that could not be filled are shown by black boxes. Survey strata are grouped by region. Starting in 2012 not all regions were sampled in each survey year. Instead the survey was conducted more often, but over less of the stock area. Areas intentionally not sampled are left blank in those years. For example, 2014 was not intended to be a survey year, but some strata were sampled in order to fill holes left over from 2013. SNE was surveyed in 2013 (except stratum 96, which was surveyed in 2014), but the survey results were borowed to 2012 and not used in 2013. Survey strata not used for ocean quahogs are not shown.

Strata	1982	1983	1984	1986	1989	1992	1994	1997	1999	2002	2005	2008	2011	2012	2013	2014	2015	2016
									SVA									
5	4	9	13	8	8	8	7	8	-16	8	8	-17	9	8			6	
6	1	1	1	1	1	1	1	1	-3	2	1	-1	0	0			0	
									DMV									
9	30	26	35	29	37	37	39	39	38	39	36	26	15	9			9	
10	2	2	3	3	3	3	3	3	3	3	3	1	4	3			4	
11	2	2	-4	2	2	2	2	2	2	2	2	-6	4	4			2	
13	19	18	25	20	20	20	21	22	19	20	18	14	6	5			4	
14	2	2	2	3	3	3	5	3	3	3	3	-25	22	6			8	
15	4	4	-8	4	4	4	5	4	5	4	4	-9	5	5			3	
									NJ									
17	11	11	17	12	12	12	12	14	12	12	12	11	5	5			4	
18	3	3	-6	3	3	3	3	3	3	3	3	3	5	4			3	
19	3	3	-6	3	2	3	3	3	3	3	3	0	4	5			3	
21	16	18	21	19	20	20	23	26	38	29	20	26	15	9			8	
22	3	3	-6	3	3	3	5	3	3	3	3	2	5	4			3	
23	7	6	-11	5	4	5	5	5	5	5	5	1	4	5			-5	
25	9	9	13	8	9	9	9	12	8	9	8	13	8	4			24	
26	2	2	-5	3	3	3	3	3	3	3	3	3	2	3			3	
27	4	4	-8	4	4	4	4	4	4	4	3	2	4	5			2	
87	8	7	10	9	9	9	9	9	8	16	7	8	5	10			3	
88	15	15	24	17	20	20	19	21	23	20	15	17	6	7			4	
89	14	15	21	15	18	17	17	19	18	18	8	14	4	5			11	
90	2	2	3	2	2	2	2	2	2	2	2	1	4	3			12	
									LI									
29	10	10	-20	10	10	10	10	10	11	10	10	15	9	5			2	
30	6	8	-14	6	6	6	6	6	7	6	7	10	4	5			3	

Table 10 Continued

31	9	7	-12	5	7	8	8	8	9	8	10	5	8	4			3	
33	4	4	-8	4	4	4	5	4	4	4	4	10	4	4			3	
34	2	2	-4	2	2	2	5	2	2	2	2	8	6	6			3	
35	4	2	-4	2	5	6	6	6	6	6	6	6	5	4			-4	
91	2	2	4	4	3	3	3	3	3	3	2	4	11	4			13	
92	2	2	3	2	2	2	2	2	2	2	2	5	11	7			5	
93	1	1	2	1	1	1	1	1	1	2	1	4	6	4			7	
SNE																		
37	7	4	-7	3	-6	3	5	4	4	3	-3	-2	2	-2	2		2	
38	3	2	-5	3	3	3	5	3	3	3	2	3	6	-6	6		2	
39	6	4	-6	2	5	5	5	5	5	5	5	5	8	-4	4		0	
41	6	5	7	5	6	6	6	6	5	6	6	6	4	-3	3		3	
45	3	7	9	4	4	4	4	4	4	3	3	4	7	-4	4		3	
46	2	5	5	3	2	3	5	3	3	2	3	3	6	-4	4		-3	3
47	4	3	4	2	2	4	5	4	3	1	7	4	8	-10	10		-3	3
94	1	2	-2	0	-1	1	2	2	-4	2	-2	-3	3	0	0		0	
95	4	14	11	4	4	4	4	4	4	4	-7	3	5	-6	6		2	
96	-12	12	-13	1	1	3	2	4	-4	0	-1	1	-1	-2	0	2	-5	5
GBK																		
54	0	-3	3	3	-6	3	3	3	-3	0	-1	1	2		-5	5		8
55	3	-3	-3	3	1	3	3	3	2	2	-4	2	3		7			9
56	0	0	0	0	0	0	0	-4	4	-4	0	0	0		3			2
57	0	0	-2	2	1	2	5	2	2	2	-4	2	8		11			7
58	0	0	0	0	0	0	0	-5	5	-5	0	0	0		6			2
59	1	3	-4	1	2	6	5	5	4	5	-9	4	15		9			14
60	0	0	-2	2	2	-4	2	5	5	5	-9	4	5		3			2
61	8	1	-6	5	-12	7	6	6	6	6	-11	5	5		5			17
62	0	0	-1	1	-1	-4	4	4	4	4	-7	3	4		3			3
65	0	0	-2	2	-4	2	4	3	-4	1	-1	-3	3		4			8
67	0	-5	5	5	7	7	7	7	-7	0	0	0	1		-9	9		7
68	1	-8	7	3	6	6	5	5	-5	0	-6	6	-6		-5	5		13
69	2	5	-11	6	6	6	7	6	7	-7	-2	2	1		3			13
70	1	2	-6	4	-8	4	4	4	3	2	-6	4	19		9			14
71	0	-1	1	3	1	2	3	3	1	2	-3	1	3		3			5

Table 10 Continued

72	2	-10	8	1	8	7	8	8	6	-6	-3	3	4	3	11
73	1	1	-4	3	6	6	6	6	5	6	-8	2	4	6	9
74	3	-4	1	3	-7	4	4	4	3	3	-6	3	10	4	11

Table 11: Trends in abundance and biomass for ocean quahogs > 50 mm SL during 1982-2016 based on NEFSC clam survey data. Survey values are the quahogs caught in the survey dredge. Stock values are the survey values adjusted to account for the selectivity and efficiency of the survey dredge. Fishable values are the stock values adjusted to account for the selectivity of a commercial dredge. Figures include original plus borrowed tows. 'N strata surveyed' includes strata sampled by tows borrowed from the previous and subsequent surveys if needed. Surveys after 2011 were conducted from a commercial platform using a more efficiency dredge and have been italicized to reflect the change in survey gear.

	Survey				**Stock**				**Fishable**						
Year	$\frac{N}{tow}$	CV	$\frac{kg}{tow}$	CV	$\frac{N}{tow}$	CV	$\frac{kg}{tow}$	CV	$\frac{N}{tow}$	CV	$\frac{kg}{tow}$	CV	N tows	Pos. tows	N strata
								SVA							
1982	0	0	0	0	0	0	0	0	0	0	0	0	5	1	2
1983	0	0.58	0	0.58	0	0.58	0	0.58	0	0.58	0	0.58	10	3	2
1984	0	0.85	0	0.87	0	0.84	0	0.87	0	0.85	0	0.87	14	2	2
1986	0	0	0	0	0	0	0	0	0	0	0	0	9	1	2
1989	0	0	0	0	0	0	0	0	0	0	0	0	9	1	2
1992	0		0		0	0	0	0	0	0	0	0	9	0	2
1994	0.01	0.79	0	0.81	0.01	0.78	0	0.8	0.01	0.79	0	0.81	8	2	2
1997	0	0	0	0	0	0	0	0	0	0	0	0	9	1	2
1999	0	0.55	0	0.61	0	0.5	0	0.54	0	0.56	0	0.61	19	2	2
2002	0	1	0	1	0	1	0	1	0	1	0	1	10	1	2
2005	0		0		0	0	0	0	0	0	0	0	9	0	2
2008	0		0		0	0	0	0	0	0	0	0	18	0	2
2011	0		0		0	0	0	0	0	0	0	0	9	0	1
2012	*0*	*0.752*	*0*	*0.752*	*0*	*0.753*	*0*	*0.753*	*0*	*0.751*	*0*	*0.753*	*8*	*2*	*1*
2015	*0*		*0*		*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*6*	*0*	*1*
								DMV							
1982	0.19	0.32	0.01	0.34	0.2	0.31	0.01	0.33	0.18	0.32	0.01	0.34	59	24	6
1983	0.2	0.49	0.01	0.42	0.25	0.52	0.01	0.45	0.2	0.49	0.01	0.42	54	28	6
1984	0.13	0.38	0	0.32	0.16	0.4	0	0.34	0.13	0.37	0	0.32	77	33	6
1986	0.18	0.23	0.01	0.22	0.2	0.24	0.01	0.22	0.17	0.23	0.01	0.22	61	28	6
1989	0.15	0.58	0	0.46	0.2	0.62	0	0.51	0.14	0.56	0	0.45	69	31	6
1992	0.17	0.36	0	0.31	0.2	0.4	0.01	0.33	0.16	0.36	0	0.3	69	25	6
1994	0.09	0.25	0	0.23	0.11	0.27	0	0.24	0.09	0.25	0	0.23	75	28	6
1997	0.11	0.21	0	0.21	0.13	0.22	0	0.21	0.11	0.21	0	0.21	73	28	6
1999	0.07	0.29	0	0.27	0.08	0.29	0	0.27	0.06	0.29	0	0.26	70	23	6

Table 11 Continued

2002	0.08	0.25	0	0.23	0.09	0.26	0	0.23	0.07	0.25	0	0.22	71	19	6
2005	0.05	0.49	0	0.53	0.06	0.45	0	0.5	0.04	0.5	0	0.53	66	21	6
2008	0.04	0.3	0	0.34	0.05	0.26	0	0.32	0.04	0.31	0	0.35	81	43	6
2011	0.04	0.33	0	0.38	0.06	0.29	0	0.35	0.04	0.34	0	0.39	56	36	6
2012	*0.1*	*0.36*	*0*	*0.38*	*0.1*	*0.35*	*0*	*0.37*	*0.1*	*0.37*	*0*	*0.38*	*32*	*22*	*6*
2015	*0.1*	*0.32*	*0*	*0.31*	*0.1*	*0.32*	*0*	*0.31*	*0.1*	*0.32*	*0*	*0.31*	*30*	*21*	*6*
NJ															
1982	0.27	0.2	0.01	0.2	0.31	0.2	0.01	0.2	0.26	0.2	0.01	0.2	97	49	13
1983	0.2	0.21	0.01	0.21	0.23	0.21	0.01	0.21	0.2	0.21	0.01	0.21	98	55	13
1984	0.35	0.24	0.01	0.24	0.4	0.24	0.01	0.24	0.34	0.24	0.01	0.24	151	79	13
1986	0.34	0.23	0.01	0.22	0.38	0.24	0.01	0.22	0.33	0.23	0.01	0.22	103	52	13
1989	0.17	0.22	0	0.22	0.21	0.22	0.01	0.21	0.16	0.22	0	0.22	109	52	13
1992	0.21	0.18	0.01	0.17	0.23	0.18	0.01	0.17	0.2	0.18	0.01	0.17	110	52	13
1994	0.56	0.22	0.02	0.2	0.64	0.22	0.02	0.21	0.54	0.22	0.02	0.2	114	59	13
1997	0.29	0.16	0.01	0.15	0.32	0.16	0.01	0.15	0.28	0.16	0.01	0.15	124	59	13
1999	0.14	0.15	0	0.14	0.17	0.16	0	0.14	0.14	0.15	0	0.14	130	60	13
2002	0.21	0.24	0.01	0.24	0.24	0.22	0.01	0.23	0.21	0.24	0.01	0.24	127	60	13
2005	0.11	0.15	0	0.14	0.15	0.15	0	0.14	0.11	0.15	0	0.14	92	53	13
2008	0.1	0.26	0	0.23	0.14	0.26	0	0.23	0.1	0.26	0	0.23	101	53	12
2011	0.18	0.15	0	0.14	0.24	0.16	0.01	0.14	0.17	0.15	0	0.14	71	51	13
2012	*0.3*	*0.2*	*0*	*0.19*	*0.3*	*0.2*	*0*	*0.19*	*0.3*	*0.19*	*0*	*0.19*	*69*	*41*	*13*
2015	*0.3*	*0.17*	*0*	*0.16*	*0.3*	*0.17*	*0*	*0.16*	*0.3*	*0.17*	*0*	*0.15*	*85*	*60*	*13*
LI															
1982	0.66	0.16	0.02	0.16	1.03	0.16	0.02	0.16	0.61	0.16	0.02	0.16	40	34	9
1983	0.44	0.21	0.01	0.21	0.6	0.22	0.02	0.21	0.42	0.21	0.01	0.21	38	36	9
1984	0.56	0.17	0.02	0.16	0.76	0.18	0.02	0.16	0.53	0.17	0.02	0.16	71	63	9
1986	0.76	0.22	0.02	0.2	1.01	0.22	0.02	0.21	0.71	0.21	0.02	0.2	36	31	9
1989	0.53	0.34	0.01	0.29	0.87	0.38	0.02	0.33	0.49	0.33	0.01	0.28	40	36	9
1992	0.76	0.18	0.02	0.16	1.1	0.2	0.02	0.17	0.71	0.18	0.02	0.16	42	36	9
1994	1.4	0.16	0.04	0.16	1.96	0.18	0.05	0.16	1.31	0.16	0.04	0.16	46	44	9
1997	0.95	0.16	0.03	0.16	1.23	0.17	0.03	0.16	0.9	0.16	0.02	0.16	42	35	9
1999	0.55	0.17	0.02	0.15	0.73	0.19	0.02	0.16	0.52	0.17	0.01	0.14	45	41	9
2002	0.6	0.21	0.02	0.2	0.78	0.21	0.02	0.2	0.57	0.21	0.02	0.2	43	40	9
2005	0.35	0.18	0.01	0.19	0.51	0.19	0.01	0.18	0.33	0.19	0.01	0.2	44	39	9

Table 11 Continued

2008	0.36	0.19	0.01	0.18	0.48	0.21	0.01	0.18	0.35	0.19	0.01	0.18	67	60	9
2011	0.47	0.19	0.01	0.2	0.7	0.2	0.02	0.2	0.44	0.19	0.01	0.2	64	53	9
2012	*1.2*	*0.26*	*0*	*0.24*	*1.3*	*0.27*	*0*	*0.24*	*1*	*0.25*	*0*	*0.22*	*43*	*38*	*9*
2015	*1.2*	*0.27*	*0*	*0.26*	*1.4*	*0.27*	*0*	*0.26*	*1.1*	*0.26*	*0*	*0.25*	*43*	*36*	*9*
SNE															
1982	0.66	0.27	0.02	0.25	0.82	0.28	0.02	0.26	0.63	0.27	0.02	0.25	48	30	10
1983	0.41	0.29	0.01	0.3	0.56	0.31	0.01	0.29	0.39	0.29	0.01	0.3	58	37	10
1984	0.44	0.27	0.01	0.29	0.55	0.26	0.01	0.28	0.43	0.27	0.01	0.29	69	38	10
1986	0.68	0.31	0.02	0.3	0.93	0.35	0.02	0.32	0.65	0.3	0.02	0.3	27	23	9
1989	0.65	0.19	0.02	0.18	0.83	0.2	0.02	0.19	0.62	0.19	0.02	0.18	34	29	10
1992	0.79	0.19	0.02	0.2	0.94	0.19	0.02	0.19	0.76	0.19	0.02	0.2	36	31	10
1994	1.25	0.22	0.03	0.2	1.58	0.25	0.04	0.21	1.19	0.22	0.03	0.2	43	32	10
1997	0.69	0.54	0.01	0.45	1.06	0.61	0.02	0.52	0.64	0.53	0.01	0.43	39	27	10
1999	0.6	0.54	0.02	0.48	0.74	0.56	0.02	0.51	0.57	0.53	0.01	0.48	39	30	10
2002	0.43	0.22	0.01	0.22	0.49	0.22	0.01	0.22	0.42	0.22	0.01	0.22	29	28	9
2005	0.37	0.26	0.01	0.23	0.79	0.42	0.01	0.27	0.34	0.25	0.01	0.22	39	33	10
2008	0.58	0.34	0.01	0.3	1.67	0.64	0.02	0.39	0.51	0.31	0.01	0.3	34	29	10
2011	0.33	0.28	0.01	0.24	0.54	0.32	0.01	0.27	0.31	0.28	0.01	0.23	50	39	10
2012	*0.6*	*0.36*	*0*	*0.31*	*0.7*	*0.38*	*0*	*0.32*	*0.5*	*0.33*	*0*	*0.29*	*41*	*36*	*9*
2015	*0.3*	*0.39*	*0*	*0.39*	*0.3*	*0.39*	*0*	*0.39*	*0.3*	*0.39*	*0*	*0.39*	*23*	*12*	*8*
GBK															
1982	0.62	0.12	0.02	0.11	0.77	0.13	0.02	0.12	0.59	0.12	0.02	0.11	22	16	9
1983	1.07	0.2	0.03	0.2	1.35	0.2	0.03	0.2	1.02	0.2	0.03	0.2	46	18	12
1984	0.61	0.28	0.01	0.26	0.92	0.31	0.02	0.28	0.57	0.27	0.01	0.26	66	29	16
1986	0.66	0.19	0.02	0.18	1.02	0.23	0.02	0.2	0.6	0.18	0.01	0.18	47	21	16
1989	0.22	0.26	0.01	0.25	0.3	0.24	0.01	0.25	0.21	0.26	0	0.26	78	38	16
1992	0.82	0.21	0.02	0.21	1.15	0.19	0.03	0.2	0.77	0.21	0.02	0.21	73	41	16
1994	0.96	0.2	0.03	0.2	1.37	0.19	0.03	0.19	0.91	0.2	0.02	0.2	76	40	16
1997	0.64	0.19	0.02	0.18	0.92	0.19	0.02	0.18	0.6	0.19	0.02	0.19	83	44	18
1999	0.65	0.17	0.02	0.19	0.86	0.16	0.02	0.18	0.61	0.17	0.02	0.19	76	47	18
2002	0.78	0.18	0.02	0.19	1.13	0.15	0.03	0.18	0.73	0.18	0.02	0.19	60	38	15
2005	0.78	0.2	0.02	0.19	1.42	0.22	0.03	0.2	0.71	0.2	0.02	0.19	80	55	15
2008	0.77	0.3	0.02	0.28	1.64	0.31	0.03	0.29	0.68	0.29	0.01	0.27	45	30	15
2011	0.72	0.23	0.02	0.22	1.39	0.22	0.02	0.22	0.65	0.23	0.01	0.22	93	66	16

Table 11 Continued

2013	*0.9*	*0.17*	*0*	*0.18*	*1.1*	*0.17*	*0*	*0.18*	*0.8*	*0.18*	*0*	*0.18*	*98*	*64*	*18*
2016	*1.5*	*0.14*	*0*	*0.12*	*1.8*	*0.15*	*0*	*0.12*	*1.2*	*0.13*	*0*	*0.1*	*155*	*100*	*18*
SVAtoSNE															
1982	0.42	0.12	0.01	0.12	0.56	0.12	0.01	0.12	0.4	0.12	0.01	0.12	249	138	40
1983	0.3	0.14	0.01	0.14	0.39	0.15	0.01	0.14	0.28	0.14	0.01	0.14	258	159	40
1984	0.36	0.12	0.01	0.13	0.46	0.12	0.01	0.12	0.35	0.12	0.01	0.13	382	215	40
1986	0.47	0.14	0.01	0.13	0.6	0.16	0.02	0.14	0.44	0.14	0.01	0.13	236	135	39
1989	0.35	0.15	0.01	0.13	0.49	0.18	0.01	0.14	0.33	0.15	0.01	0.13	261	149	40
1992	0.45	0.11	0.01	0.1	0.57	0.12	0.02	0.11	0.43	0.11	0.01	0.1	266	144	40
1994	0.79	0.12	0.02	0.11	1.02	0.13	0.03	0.11	0.76	0.11	0.02	0.11	286	165	40
1997	0.48	0.2	0.01	0.15	0.64	0.25	0.02	0.18	0.46	0.19	0.01	0.14	287	150	40
1999	0.32	0.25	0.01	0.21	0.4	0.26	0.01	0.22	0.3	0.25	0.01	0.21	303	156	40
2002	0.31	0.12	0.01	0.12	0.38	0.13	0.01	0.12	0.3	0.12	0.01	0.12	280	148	39
2005	0.21	0.13	0.01	0.12	0.36	0.23	0.01	0.14	0.2	0.13	0.01	0.12	250	146	40
2008	0.26	0.19	0.01	0.15	0.56	0.46	0.01	0.22	0.24	0.18	0.01	0.15	301	185	39
2011	0.25	0.13	0.01	0.11	0.37	0.14	0.01	0.12	0.23	0.12	0.01	0.11	250	179	39
2012	*0.5*	*0.17*	*0*	*0.14*	*0.6*	*0.18*	*0*	*0.15*	*0.4*	*0.16*	*0*	*0.14*	*193*	*139*	*38*
2013	*0.6*	*0.36*	*0*	*0.31*	*0.7*	*0.38*	*0*	*0.32*	*0.6*	*0.33*	*0*	*0.29*	*39*	*36*	*8*
2015	*0.4*	*0.18*	*0*	*0.16*	*0.5*	*0.18*	*0*	*0.16*	*0.4*	*0.17*	*0*	*0.16*	*187*	*129*	*37*
2016	*0.2*	*0.77*	*0*	*0.81*	*0.3*	*0.76*	*0*	*0.8*	*0.2*	*0.78*	*0*	*0.82*	*11*	*3*	*3*

Table 12: Shell length composition data used to estimate dredge selectivity for ocean quahog between 2012 and 2016. Number of animals caught (no.) and positive stations (pos.) for the modified commercial dredge used for the NEFSC survey and a lined dredge presumed to catch all animals available.

SL group	Lined no.	Survey no.	Lined pos.	Survey pos.
0-10	4	0	2	0
10-20	24	0	5	0
20-30	119	0	9	0
30-40	342	4	12	1
40-50	541	51	16	3
50-60	1805	265	18	9
60-70	7772	2822	20	19
70-80	4287	6153	20	20
80-90	3985	11465	20	20
90-100	2556	9638	20	20
100-110	916	3354	18	20
110-120	205	685	14	15

Table 13: Numbers of ocean quahogs in survey dredge selectivity experiments by length bin and station between 2012 and 2016. For example, 3:8 in the row corresponding to SL bin 40−50, 3 ocean quahogs between 40 and 50 mm were caught in the survey dredge and 8 ocean quahogs were caught in the selectivity dredge at that station. Column labels identify the selectivity experiment.

SL bin	2012108	2012117	2012127	2012136	2012150	2012162
0-10	0:0	0:0	0:0	0:0	0:0	0:0
10-20	0:0	1:0	6:0	0:0	0:0	0:0
20-30	0:0	1:0	5:0	0:0	0:0	0:0
30-40	0:0	5:0	15:0	0:0	3:0	0:0
40-50	0:5	5:0	39:14	4:0	12:0	1:0
50-60	1:0	1:5	15:56	12:0	4:0	3:0
60-70	13:50	13:20	19:126	92:42	23:16	19:1
70-80	41:525	10:105	35:644	144:372	18:28	186:113
80-90	224:655	34:240	125:1820	62:102	83:192	300:170
90-100	342:780	89:580	104:1778	162:333	102:576	121:87
100-110	98:560	19:305	24:294	152:381	28:324	31:17
110-120	4:115	0:20	2:42	40:162	2:88	9:2

SL bin	2012170	2012178	2012182	2012184	2013013	2013046	2013059
0-10	0:0	0:0	1:0	0:0	0:0	0:0	0:0
10-20	0:0	0:0	9:0	0:0	0:0	0:0	0:0
20-30	2:0	2:0	33:0	0:0	0:0	0:0	0:0
30-40	7:0	1:0	88:0	2:0	0:0	2:0	27:0
40-50	3:0	1:0	43:0	12:0	0:0	3:0	56:0
50-60	1:0	0:0	15:6	11:4	4:0	5:0	66:0
60-70	2:20	5:16	11:91	43:40	4:28	32:72	195:15
70-80	58:240	48:206	63:139	148:328	8:42	49:296	353:370
80-90	157:460	76:302	209:452	234:624	66:427	174:732	731:1205
90-100	139:615	48:166	172:364	134:340	146:1176	86:276	287:380
100-110	65:245	14:86	57:246	32:80	46:287	13:32	20:35
110-120	5:15	0:10	3:31	1:4	3:21	1:0	4:20

SL bin	2013067	2015059	2015113	2016077	2016116	2016117	2016175
0-10	0:0	3:0	0:0	0:0	0:0	0:0	0:0
10-20	0:0	6:0	0:0	0:0	0:0	0:0	2:0
20-30	1:0	10:0	0:0	0:0	1:0	0:0	64:0
30-40	8:0	32:0	0:0	0:0	0:0	0:0	152:4
40-50	25:0	86:0	0:0	0:0	28:0	134:0	89:32
50-60	21:0	87:10	0:0	15:6	195:12	1116:160	233:6
60-70	36:33	55:30	1:0	303:138	660:188	5112:1880	1134:16
70-80	126:270	84:150	6:2	840:666	363:364	960:1180	747:113
80-90	361:924	102:195	33:20	168:810	204:572	525:1360	117:203
90-100	111:421	305:590	44:55	54:588	68:296	24:180	18:57

Table 13 Continued

100-110	9:28	132:265	122:67	6:78	0:12	48:10	0:2
110-120	3:0	27:25	101:118	0:12	0:0	0:0	0:0

Table 14: Results from generalized additive model fits to selectivity data. The response variable is number of ocean quahogs caught in the survey dredge (a modified commercial dredge) compared to the number of ocean quahogs caught in a lined dredge. The predictors are length bin (L), and year−station (YrSta). Some models included an offset based on the tow distance at each station. The s indicates a smooth function and RE indicates random effects. The best model by AIC included random effects for each year−station combination in both intercept and length.

Model	AIC	BIC
s(L)+s(YrSta,RE)+s(YrSta,L,RE)	2173	2318
s(L)+s(YrSta,RE)	2913	2999
s(L)+s(YrSta,RE)+offset	2913	2999
s(L)	7766	7792
s(L)+offset	9545	9570

Table 15: The selectivity coefficients estimated using the best (by AIC) selectivity model.

Length	Selx	se	uci	lci
5	0.000	1.000	0.036	0.000
11	0.000	0.999	0.024	0.000
16	0.000	0.992	0.018	0.000
22	0.001	0.967	0.016	0.000
27	0.002	0.908	0.021	0.000
33	0.010	0.839	0.051	0.002
38	0.044	0.791	0.148	0.012
44	0.139	0.755	0.332	0.050
49	0.273	0.719	0.489	0.128
55	0.397	0.678	0.581	0.239
61	0.523	0.639	0.660	0.382
66	0.653	0.609	0.746	0.548
72	0.767	0.596	0.829	0.691
77	0.835	0.607	0.886	0.766
83	0.863	0.636	0.916	0.783
88	0.871	0.672	0.933	0.767
94	0.875	0.710	0.945	0.741
99	0.888	0.747	0.959	0.727
105	0.909	0.782	0.973	0.735
111	0.932	0.814	0.984	0.759

Table 16: Results from model fits to predict meat weight. Predictors are ln(shell length) (L), ln(depth) (D), density (ρ) and region (R). Random effects are enclosed in parentheses. Regional coefficients are shown. DMV is assumed to have coefficient equal to 0.

Formula	int	L	D	ρ	R	AIC	BIC
L+D+Density+R+(L+St)+(L+Year)	-7.68 (0.041)	2.57 (0.07)	0.01 (0.024)	-0.009 (0.004)	X	24600	24686
L+R+(L+St)+(L+Year)	-7.68 (0.041)	2.57 (0.069)			X	24602	24676
L+D+R+(L+St)+(L+Year)	-7.61 (0.041)	2.57 (0.069)	-0.02 (0.022)		X	24604	24684
L+R+(L+St)	-7.67 (0.029)	2.58 (0.034)			X	24684	24739
L+D+R+(L+St)	-7.6 (0.029)	2.58 (0.034)	-0.02 (0.024)		X	24685	24747
L+D+(L+St)+(L+Year)	-7.59 (0.036)	2.58 (0.077)	-0.05 (0.018)			29739	29796
L+(L+St)+(L+Year)	-7.83 (0.038)	2.59 (0.076)				29746	29797
L+Density+(L+St)	-7.7 (0.007)	2.59 (0.031)		-0.02 (0.003)		29933	29972
L+D+(L+St)	-7.77 (0.008)	2.57 (0.031)	-0.12 (0.019)			29949	29987
L+(L+St)	-7.83 (0.008)	2.59 (0.031)				29984	30016
L+D+(St)	-7.2 (0.007)	2.55 (0.017)	-0.12 (0.021)			30721	30747
L+(St)	-7.72 (0.007)	2.56 (0.017)				30753	30772

Formula	NJ	LI	SNE	GBK
L+D+Density+R+(L+St)+(L+Year)	-0.02 (0.029)	-0.05 (0.031)	-0.04 (0.032)	-0.09 (0.035)
L+R+(L+St)+(L+Year)	-0.02 (0.029)	-0.06 (0.031)	-0.05 (0.032)	-0.11 (0.034)
L+D+R+(L+St)+(L+Year)	-0.02 (0.029)	-0.06 (0.031)	-0.05 (0.032)	-0.1 (0.035)
L+R+(L+St)	-0.05 (0.031)	-0.09 (0.032)	-0.1 (0.032)	-0.2 (0.031)
L+D+R+(L+St)	-0.05 (0.031)	-0.09 (0.032)	-0.1 (0.032)	-0.2 (0.032)
L+D+(L+St)+(L+Year)				
L+(L+St)+(L+Year)				
L+Density+(L+St)				
L+D+(L+St)				
L+(L+St)				
L+D+(St)				
L+(St)				

Table 17: Predictor variables used in random forest regression trees for ocean quahog. NAMERA is the Northwest Atlantic Marine Ecoregional Assessment project.

Variable name	Full name	Description
depth	Depth at station or lat/lon position	Measured at station for model fitting, raster derived for predictions
fallBT	Fall bottom temperatures	Interpolated from bottom trawl survey data
springBT	Spring bottom temperatures	Interpolated from bottom trawl survey data
rugosity	Rugosity	Ratio of real to geometric area (Friedman et al. 2012)
namera vrm	Vector ruggedness measure	Variation around plane fit to bathymetry (NAMERA , Sappington et al. (2007))
namera bpi	Bathmetric position index	Ratio elevation of inner 5 m circular area to surrounding 50 m circular area (NAMERA , Lundblad et al. (2006))
soft sed	Soft sediments	Classify soft sediments (< 2 mm) by grain size (500 m resolution)
seabedforms	Topography	Seabed position and slope (NAMERA)
sst9kmfronts	SST fronts	Mean gradient magnitude sea surface temperature based on MODIS-terra 9km monthly data
chl9km	Chlorophyl concentration	Mean chlorophyll concentration based on MODIS-aqua 9km monthly data
chl9kmfronts	Chlorophyl fronts	Mean gradient magnitude chlorophyll concentration based on MODIS-aqua 9km monthly data

Table 18: Correlations among predictor variables in tree models for ocean quahog survey catches in the GBK (top) and SNE+LI (bottom) regions during 1997-2011. Correlations with absolute value > 0.3 are highlighted.

Variable	lat	lon	depth	namera vrm	namera bpi	rugosity	mab sed	soft sed	fallBT	
					GBK					
fallBT	-0.70									
springBT	0.27	-0.27								
rugosity	0.03	-0.07	0.18							
namera vrm	-0.36	0.30	0.04	0.06						
namera bpi	-0.06	-0.35	0.31	0.17	0.09					
soft sed	-0.44	0.28	0.09	-0.03	0.30	-0.02				
seabedforms	-0.08	-0.09	0.09	-0.04	0.28	0.53	-0.01			
sst9kmfronts	0.34	-0.23	0.23	0.13	-0.24	0.21	-0.23	-0.02		
chl9km	-0.81	0.61	-0.04	-0.01	0.47	-0.02	0.50	0.00	-0.56	
chl9kmfronts	-0.58	0.37	0.05	0.08	0.05	0.20	0.19	-0.04	0.11	0.48
					SNE+LI					
fallBT	-0.85									
springBT	0.82	-0.80								
rugosity	-0.25	0.27	-0.16							
namera vrm	-0.11	0.06	-0.04	0.13						
namera bpi	-0.04	-0.09	0.18	0.17	0.12					
soft sed	-0.13	0.12	-0.12	0.10	0.16	-0.04				
seabedforms	0.15	-0.21	0.23	0.04	0.31	0.55	0.05			
sst9kmfronts	-0.19	0.31	-0.23	0.28	0.23	0.00	0.12	0.08		
chl9km	-0.63	0.65	-0.45	0.22	0.06	-0.03	0.02	-0.17	0.11	
chl9kmfronts	-0.63	0.69	-0.48	0.24	0.02	-0.04	-0.01	-0.20	0.12	0.94

Table 19: Random forest regression tree results for models fit to ocean quahog survey data from the GBK and SNE+LI regions during 1997-2011.

Statistic	GBK	SNE+LI
N	381	669
Number trees	500	500
Cross validated %Deviance explained	67%	44%
R^2	94%	89%
Predictor variable	Importance	
depth	2	3
fallBT	4	7
springBT	7	5
rugosity	9	8
namera vrm	8	2
namera bpi	10	10
soft sed	3	9
seabedforms	11	11
sst9kmfronts	5	4
chl9km	1	1
chl9kmfronts	6	6

Table 20: Structure of SS3 models used for ocean quahog.

Model aspect	Value	Note
M	0.02	Constant for all ages and years
Age bins	0–300	
Length bins	1–12 cm	
Time	1982–2016	
Seasons/morphs/areas	1/1/2	
Recruitment allocation to areas	Proportion followed a random walk	
Growth	Von Bert.	Priors from field estimates, publications
Commercial fleets	1 per area	
Fishery selectivity	Logistic	Priors from field estimates
Surveys (trend)	3	RD (trend), RD (scale), MCD (scale and trend)
Survey selectivity (RD)	Logistic	Priors from field estimates
Survey selectivity (MCD)	Logistic	Priors from field estimates
Survey catchability (RD-SWAN)	Estimated	Priors from field estimates
Survey catchability (MCD)	Estimated	Priors from field estimates
Recruitment model	Beverton-Holt	Fixed steepness, estimated R_0 and variance
Recruit dev years	1900–2016	
Bias adjustment parameters	1900,1990,2011,2015,0.0001	Not used due to lack of data
F method	Hybrid	6 iterations (exact F)

Table 21: Selected parameters estimated internally and externally in SS3 base model for ocean quahog. S and N refer to southern and northern areas. Numbers of parameters are summarized in the last rows.

Parameter	Value	Note
M	0.02	Fixed
Length at age 10	5.268	Fixed at prelim. solution
Length at age 300	8.651	Estimated with prior
Von Bertalanffy K	0.083	Fixed at prelim. solution
CV of size at age 10 y	0.106	Estimated with prior
CV of size at age 300 y	0.201	Estimated with prior
Shell length to meat weight multiplier	0.00011	Fixed
Shell length to meat weight exponent	2.733	Fixed
Age at 50% maturity	6	Fixed
Slope of maturity curve	-1.5	Fixed
Spawner recruit R_0	14.975	Estimated
Spawner recruit steepness	0.95	Fixed
Spawner recruit sd	0.907	Estimated with prior
Catchability (RD) S	0.36	Estimated with prior
Catchability (MCD) S	0.906	Estimated with prior
Catchability (RD) N	0.213	Estimated with prior
Catchability (MCD) N	0.642	Estimated with prior
Fishery selectivity inflection S	8	Estimated with prior
Fishery selectivity width S	1.913	Estimated with prior
Fishery selectivity inflection N	8	Estimated with prior
Fishery selectivity width N	1.47	Estimated with prior
Survey (RD) selectivity inflection S	7.982	Estimated with prior
Survey (RD) selectivity width S	3.555	Estimated with prior
Survey (RD) selectivity inflection N	6.103	Estimated with prior
Survey (RD) selectivity width N	2.229	Estimated with prior
Survey (MCD) selectivity inflection S	7.642	Estimated with prior
Survey (MCD) selectivity width S	1.787	Estimated with prior
Survey (MCD) selectivity inflection N	6.843	Estimated with prior
Survey (MCD) selectivity width N	1.176	Estimated with prior
Initial F S	0.01	Fixed (0.0 in N)
Total estimated (-recruit deviations)	57	
Recruit deviations	35	
Total estimated	92	

Table 22: Likelihood profile over unfished recruitment parameter (R0). The values in the table are the differences, in likelihood units, between each profile run and the minimum likelihood for that row (likelihood component). Conflicts within the data are apparent when the minimum likelihood values (gray cells) occur in different columns for each row. That is, different likelihood components within the model were minimized at different values of R0. Because R0 is important for setting the scale of estimated biomass in the model (Relative B; last row), data conflicts around R0 tend to increase uncertainty in scale. The coloumn corresponding to the minimum total likelihood is shown in italics.

ln(R0)	14.5	14.75	*15.1*	15.25	15.50	16.00
Total	178.9	33.3	*0*	1.2	5.0	10.8
Parm priors	29.5	16.3	*0*	1.1	4.5	5.6
ComLen	41	1.7	*0*	0.2	0.8	1.6
Relative B	1	1.2	*3.9*	5.5	9.4	22.4

Table 23: Fishing mortality estimates from the ocean quahog assessment base model, including lower and upper 95% confidence bounds.

Year	F	CV	Lower	Upper
1982	0.004	0.147	0.003	0.005
1983	0.004	0.147	0.003	0.005
1984	0.005	0.146	0.003	0.006
1985	0.005	0.146	0.004	0.007
1986	0.005	0.146	0.004	0.006
1987	0.006	0.146	0.004	0.007
1988	0.005	0.146	0.004	0.007
1989	0.006	0.146	0.004	0.008
1990	0.006	0.145	0.004	0.007
1991	0.006	0.145	0.004	0.008
1992	0.006	0.145	0.004	0.008
1993	0.006	0.145	0.004	0.008
1994	0.006	0.145	0.004	0.007
1995	0.006	0.145	0.004	0.007
1996	0.006	0.145	0.004	0.007
1997	0.005	0.144	0.004	0.007
1998	0.005	0.144	0.004	0.006
1999	0.005	0.144	0.004	0.006
2000	0.004	0.144	0.003	0.005
2001	0.005	0.144	0.004	0.006
2002	0.005	0.143	0.004	0.007
2003	0.006	0.143	0.004	0.007
2004	0.005	0.143	0.004	0.007
2005	0.004	0.143	0.003	0.005
2006	0.004	0.143	0.003	0.005
2007	0.005	0.143	0.003	0.006
2008	0.005	0.143	0.003	0.006
2009	0.005	0.143	0.003	0.006
2010	0.005	0.143	0.004	0.006
2011	0.004	0.144	0.003	0.006
2012	0.005	0.144	0.004	0.006
2013	0.005	0.144	0.003	0.006
2014	0.005	0.145	0.003	0.006
2015	0.004	0.147	0.003	0.005
2016	0.005	0.148	0.003	0.006

Table 24: Spawning stock biomass estimates from the ocean quahog assessment base model in mt, including lower and upper 95% confidence bounds.

Year	SSB	CV	Lower	Upper
1982	3525900	0.131	2624026	4427774
1983	3516750	0.130	2619127	4414373
1984	3506110	0.130	2612948	4399272
1985	3491540	0.130	2602999	4380081
1986	3473650	0.130	2589884	4357416
1987	3456320	0.130	2577517	4335123
1988	3435970	0.130	2562241	4309699
1989	3415900	0.130	2547375	4284425
1990	3393490	0.130	2530226	4256754
1991	3371730	0.130	2513783	4229677
1992	3348660	0.130	2496015	4201305
1993	3324960	0.130	2477560	4172360
1994	3301580	0.130	2459333	4143827
1995	3278840	0.130	2441606	4116074
1996	3256000	0.130	2423592	4088408
1997	3234190	0.131	2406384	4061996
1998	3213090	0.131	2389610	4036570
1999	3194050	0.131	2374578	4013522
2000	3176370	0.131	2360520	3992220
2001	3162170	0.131	2349505	3974835
2002	3147930	0.131	2337838	3958022
2003	3135610	0.132	2327331	3943889
2004	3126270	0.132	2318775	3933765
2005	3122830	0.132	2314681	3930979
2006	3128620	0.132	2317950	3939290
2007	3139720	0.132	2324382	3955058
2008	3154130	0.133	2332698	3975562
2009	3170180	0.133	2341923	3998437
2010	3187620	0.134	2351592	4023648
2011	3205130	0.134	2360646	4049614
2012	3224030	0.135	2370715	4077345
2013	3240820	0.136	2378508	4103132
2014	3257400	0.136	2386172	4128628
2015	3272450	0.137	2392555	4152345
2016	3287300	0.138	2399158	4175502

Table 25: Recruitment estimates (000's) from the ocean quahog assessment base model, including lower and upper 95% confidence bounds.

Year	Recruits	CV	Lower	Upper
1980	3187600	0.110	2571852	3950769
1981	3187600	0.110	2571852	3950769
1982	2198530	0.765	581291	8315178
1983	2224500	0.771	583537	8480018
1984	2242940	0.773	586058	8584104
1985	2254470	0.777	586469	8666507
1986	2242700	0.779	581538	8648969
1987	2254460	0.781	582571	8724408
1988	2311800	0.790	590376	9052572
1989	2447260	0.803	613988	9754399
1990	2631030	0.823	642294	10777484
1991	2801130	0.847	662579	11842109
1992	3017060	0.872	690640	13180032
1993	3325120	0.914	722231	15308698
1994	3847200	0.984	766897	19299784
1995	4708490	1.110	813371	27256782
1996	6313770	1.454	781996	50976822
1997	7711710	2.539	479758	123959345
1998	8693030	2.525	544270	138844393
1999	5079540	1.239	767324	33625581
2000	3692050	0.972	746818	18252409
2001	3199810	0.903	704053	14542632
2002	2989080	0.882	676118	13214559
2003	2926690	0.873	669063	12802256
2004	2970910	0.880	673632	13102559
2005	3015440	0.889	676078	13449448
2006	3060550	0.893	682178	13730965
2007	3080050	0.897	683063	13888485
2008	3115900	0.903	685629	14160478
2009	3156150	0.910	688842	14460917
2010	3164900	0.912	689194	14533772
2011	3167950	0.912	689471	14555959
2012	3176470	0.913	690229	14618278
2013	3177350	0.913	690348	14623864
2014	3177580	0.913	690409	14624691
2015	3178000	0.913	690479	14627065
2016	3178140	0.913	690523	14627433

Table 26: Potential $F_{Threshold}$ bounding values derived from MSE, where $SSB_{Cease} = 0.1$, and $SSB_{Target} = 0.4$. The columns are: the number of years of simulated fishing (Years), the growth curve used (Growth), F_{MSY} the F_{Target} that resulted in maximum average yield, and F_{LB} the F_{Target} that resulted in average biomasses closest to the theoretical $SSB_{MSY} = \frac{1}{2}SSB_0$.

	Years	Growth	F_{MSY}	F_{LB}
3	1000	VB	0.019	0.010
4	1000	Tanaka	0.023	0.012

Table 27: Summary stock biomass (mt) and fishing mortality status estimates with cv and approximate 95% confidence intervals, using the current reference points from the previous assessment. The current F reference point was a point estimate with no uncertainty. The current F reference reflected only the exploited stock, which was the southern area only. The northern area has been fished since 2012 and is considered part of the exploited stock here.

	Estimate	CV	LCI	UCI
SSB_{2016}	3287300	0.138	2512199	4301546
SSB Threshold	1410360	0.131	1093237	1819473
F_{2016}	0.005	0.148	0.003	0.006
F Threshold	0.022			

Table 28: Comparison of reference points estimated in an earlier assessment and from the current assessment update. The recommended F reference point is based on an MSE analysis (Hennen 2015) adapted to include new information on growth. MSY values are not based on per recruit modeling, but rather applying F_{MSY} to the unfished biomass, while accounting for natural mortality. Note that biomass values between the two assessments are not directly comparable as the previous assessment used a summary biomass, while the 2017 assessment used spawning biomass (See Figure 122).

	2013	2017
F_{MSY} *proxy*	0.022	0.019 (0.011 - 0.032)
SSB_0 (mt)	3460000	4027170 (3276220 - 4778120)
SSB_{MSY} (mt)	1730000	2013585 (1638110 - 2389060)
$SSB_{Threshold}$ (mt)	1384000	1610868 (1310488 - 1911248)
MSY (mt)		73298
Overfishing	No	No
Overfished	No	No

Table 29: Spawning stock ocean quahog fishing mortality status estimates (based on recommended reference points) with cv and approximate 95% confidence intervals.

	Ratio	CV	LCI	UCI
$\frac{F_{2016}}{F_{Threshold}}$	0.246	0.315	0.134	0.449

Table 30: Spawning stock ocean quahog biomass status estimates (based on recommended reference points) with cv and approximate 95% confidence intervals.

	Ratio	CV	LCI	UCI
$\frac{SSB_{2016}}{SSB_{Threshold}}$	2.04	0.089	1.72	2.43

Table 31: Projected spawning stock biomass (mt) and biomass status ($\frac{SSB}{SSB_{Threshold}}$, where $SSB_{Threshold} = 0.4 * SSB_0$) during 2017-2066 for ocean quahog.

Year	Status Quo	Quota	OFL
	SSB (mt)		
2017	3299930	3299930	3299930
2018	3310860	3302630	3270880
2019	3320590	3304210	3241460
2020	3329230	3304800	3211770
2021	3336870	3304480	3181920
2022	3343620	3303360	3152030
2023	3349560	3301530	3122190
2024	3354780	3299070	3092500
2025	3359330	3296060	3063050
2026	3363300	3292570	3033920
2027	3366730	3288660	3005160
2028	3369690	3284380	2976850
2029	3372210	3279790	2949030
2030	3374350	3274920	2921730
2031	3376150	3269820	2895010
2032	3377630	3264530	2868870
2033	3378840	3259070	2843350
2034	3379790	3253480	2818470
2035	3380530	3247780	2794230
2036	3381060	3242000	2770640
2037	3381430	3236160	2747710
2038	3381630	3230270	2725440
2039	3381700	3224360	2703830
2040	3381650	3218430	2682860
2041	3381490	3212500	2662550
2042	3381230	3206580	2642870
2043	3380890	3200690	2623820
2044	3380480	3194820	2605390
2045	3380010	3188990	2587560
2046	3379480	3183210	2570320
2047	3378900	3177470	2553670
2048	3378280	3171780	2537580
2049	3377620	3166160	2522040
2050	3376940	3160590	2507040
2051	3376230	3155090	2492560
2052	3375500	3149660	2478580
2053	3374750	3144290	2465100
2054	3373990	3138990	2452090
2055	3373210	3133760	2439550
2056	3372430	3128600	2427450
2057	3371640	3123520	2415790

Table 31 Continued

2058	3370850	3118500	2404550
2059	3370050	3113560	2393710
2060	3369260	3108690	2383260
2061	3368460	3103890	2373200
2062	3367660	3099160	2363500
2063	3366870	3094490	2354150
2064	3366080	3089900	2345140
2065	3365290	3085380	2336460
2066	3364510	3080920	2328100
	$\frac{SSB}{SSB_{Threshold}}$		
2017	2.05	2.05	2.05
2018	2.06	2.05	2.03
2019	2.06	2.05	2.01
2020	2.07	2.05	1.99
2021	2.07	2.05	1.98
2022	2.08	2.05	1.96
2023	2.08	2.05	1.94
2024	2.08	2.05	1.92
2025	2.09	2.05	1.90
2026	2.09	2.04	1.88
2027	2.09	2.04	1.87
2028	2.09	2.04	1.85
2029	2.09	2.04	1.83
2030	2.09	2.03	1.81
2031	2.10	2.03	1.80
2032	2.10	2.03	1.78
2033	2.10	2.02	1.77
2034	2.10	2.02	1.75
2035	2.10	2.02	1.73
2036	2.10	2.01	1.72
2037	2.10	2.01	1.71
2038	2.10	2.01	1.69
2039	2.10	2.00	1.68
2040	2.10	2.00	1.67
2041	2.10	1.99	1.65
2042	2.10	1.99	1.64
2043	2.10	1.99	1.63
2044	2.10	1.98	1.62
2045	2.10	1.98	1.61
2046	2.10	1.98	1.60
2047	2.10	1.97	1.59
2048	2.10	1.97	1.58
2049	2.10	1.97	1.57
2050	2.10	1.96	1.56

Table 31 Continued

2051	2.10	1.96	1.55
2052	2.10	1.96	1.54
2053	2.09	1.95	1.53
2054	2.09	1.95	1.52
2055	2.09	1.95	1.51
2056	2.09	1.94	1.51
2057	2.09	1.94	1.50
2058	2.09	1.94	1.49
2059	2.09	1.93	1.49
2060	2.09	1.93	1.48
2061	2.09	1.93	1.47
2062	2.09	1.92	1.47
2063	2.09	1.92	1.46
2064	2.09	1.92	1.46
2065	2.09	1.92	1.45
2066	2.09	1.91	1.45

Table 32: Projected catch (landings + incidental mortality; mt) and fishing mortality status ratio $\frac{F}{F_{Threshold}}$ during 2017-2066 for ocean quahog.

Year	Status Quo	Quota	OFL
	Catch (mt)		
2017	15341	25400	64708
2018	15341	25400	64167
2019	15341	25400	63636
2020	15341	25400	63107
2021	15341	25400	62576
2022	15341	25400	62042
2023	15341	25400	61502
2024	15341	25400	60958
2025	15341	25400	60410
2026	15341	25400	59859
2027	15341	25400	59307
2028	15341	25400	58756
2029	15341	25400	58206
2030	15341	25400	57661
2031	15341	25400	57121
2032	15341	25400	56587
2033	15341	25400	56061
2034	15341	25400	55544
2035	15341	25400	55036
2036	15341	25400	54539
2037	15341	25400	54052
2038	15341	25400	53576
2039	15341	25400	53112
2040	15341	25400	52660
2041	15341	25400	52220
2042	15341	25400	51792
2043	15341	25400	51376
2044	15341	25400	50973
2045	15341	25400	50581
2046	15341	25400	50201
2047	15341	25400	49834
2048	15341	25400	49478
2049	15341	25400	49133
2050	15341	25400	48800
2051	15341	25400	48477
2052	15341	25400	48166
2053	15341	25400	47864
2054	15341	25400	47574
2055	15341	25400	47293
2056	15341	25400	47022
2057	15341	25400	46760

Table 32 Continued

2058	15341	25400	46507
2059	15341	25400	46264
2060	15341	25400	46029
2061	15341	25400	45802
2062	15341	25400	45583
2063	15341	25400	45373
2064	15341	25400	45169
2065	15341	25400	44973
2066	15341	25400	44784
	$\frac{F}{F_{Threshold}}$		
2017	0.251	0.416	1.027
2018	0.249	0.415	1.027
2019	0.248	0.413	1.026
2020	0.246	0.412	1.025
2021	0.245	0.410	1.024
2022	0.243	0.409	1.023
2023	0.242	0.407	1.021
2024	0.240	0.406	1.019
2025	0.239	0.404	1.016
2026	0.237	0.402	1.010
2027	0.235	0.400	1.004
2028	0.233	0.398	0.997
2029	0.233	0.398	0.997
2030	0.233	0.400	0.998
2031	0.234	0.401	1.000
2032	0.234	0.403	1.002
2033	0.234	0.404	1.004
2034	0.234	0.405	1.006
2035	0.234	0.406	1.007
2036	0.234	0.406	1.008
2037	0.234	0.407	1.009
2038	0.234	0.407	1.010
2039	0.234	0.408	1.010
2040	0.234	0.408	1.011
2041	0.233	0.408	1.011
2042	0.233	0.409	1.011
2043	0.233	0.409	1.011
2044	0.233	0.409	1.011
2045	0.233	0.410	1.011
2046	0.233	0.410	1.011
2047	0.232	0.410	1.011
2048	0.232	0.411	1.011
2049	0.232	0.411	1.011
2050	0.232	0.411	1.011

Table 32 Continued

2051	0.232	0.411	1.011
2052	0.232	0.412	1.011
2053	0.232	0.412	1.010
2054	0.231	0.412	1.010
2055	0.231	0.412	1.010
2056	0.231	0.412	1.010
2057	0.231	0.413	1.010
2058	0.231	0.413	1.010
2059	0.231	0.413	1.009
2060	0.231	0.413	1.009
2061	0.230	0.413	1.009
2062	0.230	0.413	1.009
2063	0.230	0.413	1.009
2064	0.230	0.413	1.008
2065	0.230	0.413	1.008
2066	0.230	0.413	1.008

Table 33: Cumulative probability of being in overfished status in any of the years from 2017-2066 under a variety of catch scenarios for ocean quahog.

Catch scenario	$P[Overfished]$	$P[Overfishing]$
Status Quo	0.000	0.000
Quota	0.000	0.000
OFL	0.009	0.680

Table 34: Projected stock status ($\frac{SSB}{SSB_{Threshold}}$ and $\frac{F}{F_{Threshold}}$) during 2017-2066 for ocean quahog from projections based on the entire quota being caught in the southern or northern area, high and low natural mortality, and high and low recruitment scenarios with status quo catch. The results indicate that projected stock status is robust to biomass scale uncertainty.

Year	Quota N	Quota S	High M	Low M	High R	Low R
2017	2.049	2.049	2.194	1.785	2.051	2.051
2018	2.051	2.050	2.202	1.791	2.058	2.058
2019	2.052	2.051	2.210	1.796	2.065	2.065
2020	2.052	2.051	2.216	1.801	2.070	2.070
2021	2.052	2.051	2.221	1.806	2.075	2.075
2022	2.052	2.051	2.226	1.810	2.080	2.080
2023	2.051	2.049	2.230	1.814	2.084	2.084
2024	2.050	2.048	2.233	1.817	2.087	2.087
2025	2.048	2.046	2.236	1.820	2.091	2.089
2026	2.046	2.044	2.238	1.823	2.095	2.091
2027	2.043	2.041	2.240	1.825	2.099	2.092
2028	2.041	2.039	2.241	1.827	2.103	2.092
2029	2.038	2.036	2.242	1.829	2.109	2.091
2030	2.035	2.033	2.243	1.831	2.115	2.089
2031	2.032	2.030	2.243	1.832	2.121	2.086
2032	2.028	2.026	2.243	1.833	2.128	2.083
2033	2.025	2.023	2.243	1.834	2.136	2.078
2034	2.021	2.020	2.243	1.835	2.144	2.073
2035	2.018	2.016	2.243	1.836	2.153	2.068
2036	2.014	2.012	2.243	1.836	2.162	2.061
2037	2.010	2.009	2.242	1.837	2.172	2.055
2038	2.006	2.005	2.242	1.837	2.181	2.048
2039	2.002	2.001	2.241	1.837	2.192	2.040
2040	1.999	1.998	2.240	1.838	2.202	2.032
2041	1.995	1.994	2.239	1.838	2.213	2.024
2042	1.991	1.990	2.239	1.838	2.223	2.016
2043	1.987	1.987	2.238	1.838	2.234	2.008
2044	1.983	1.983	2.237	1.838	2.245	1.999
2045	1.979	1.980	2.236	1.837	2.256	1.990
2046	1.975	1.976	2.235	1.837	2.267	1.982
2047	1.972	1.972	2.234	1.837	2.278	1.973
2048	1.968	1.969	2.233	1.837	2.289	1.964
2049	1.964	1.965	2.232	1.836	2.300	1.955
2050	1.960	1.962	2.231	1.836	2.311	1.946
2051	1.957	1.959	2.230	1.835	2.322	1.937
2052	1.953	1.955	2.229	1.835	2.332	1.928
2053	1.950	1.952	2.228	1.835	2.343	1.920
2054	1.946	1.949	2.227	1.834	2.354	1.911
2055	1.943	1.945	2.226	1.834	2.364	1.902
2056	1.939	1.942	2.225	1.833	2.374	1.894

Table 34 Continued

2057	1.936	1.939	2.225	1.833	2.385	1.885
2058	1.932	1.936	2.224	1.832	2.395	1.877
2059	1.929	1.933	2.223	1.832	2.405	1.868
2060	1.926	1.930	2.222	1.831	2.415	1.860
2061	1.923	1.927	2.221	1.830	2.424	1.852
2062	1.920	1.924	2.220	1.830	2.434	1.844
2063	1.916	1.921	2.219	1.829	2.443	1.836
2064	1.913	1.918	2.219	1.829	2.453	1.828
2065	1.910	1.915	2.218	1.828	2.462	1.821
2066	1.908	1.912	2.217	1.828	2.471	1.813
			$\frac{F}{F_{Threshold}}$			
2017	0.313	0.355	0.222	0.198	0.211	0.211
2018	0.312	0.354	0.221	0.197	0.210	0.210
2019	0.311	0.353	0.219	0.196	0.209	0.209
2020	0.311	0.351	0.217	0.195	0.207	0.207
2021	0.311	0.350	0.216	0.194	0.206	0.206
2022	0.310	0.348	0.214	0.193	0.205	0.205
2023	0.310	0.346	0.213	0.193	0.203	0.203
2024	0.309	0.345	0.211	0.192	0.202	0.202
2025	0.308	0.343	0.210	0.191	0.201	0.201
2026	0.306	0.342	0.208	0.190	0.199	0.199
2027	0.304	0.340	0.207	0.184	0.197	0.198
2028	0.302	0.338	0.205	0.184	0.195	0.195
2029	0.302	0.338	0.205	0.184	0.195	0.195
2030	0.301	0.340	0.205	0.184	0.195	0.196
2031	0.301	0.341	0.206	0.184	0.195	0.196
2032	0.302	0.342	0.206	0.184	0.196	0.196
2033	0.302	0.343	0.206	0.184	0.196	0.197
2034	0.303	0.344	0.206	0.184	0.195	0.197
2035	0.304	0.344	0.206	0.184	0.195	0.197
2036	0.305	0.345	0.206	0.184	0.195	0.198
2037	0.306	0.345	0.206	0.184	0.194	0.198
2038	0.307	0.345	0.206	0.184	0.194	0.198
2039	0.308	0.345	0.206	0.184	0.193	0.198
2040	0.309	0.345	0.205	0.184	0.192	0.199
2041	0.310	0.345	0.205	0.184	0.191	0.199
2042	0.311	0.346	0.205	0.184	0.191	0.199
2043	0.312	0.346	0.205	0.184	0.190	0.200
2044	0.313	0.346	0.204	0.184	0.189	0.200
2045	0.314	0.346	0.204	0.184	0.188	0.201
2046	0.314	0.346	0.204	0.184	0.187	0.201
2047	0.315	0.346	0.204	0.184	0.186	0.202
2048	0.316	0.346	0.203	0.184	0.184	0.203
2049	0.317	0.346	0.203	0.184	0.183	0.204

Table 34 Continued

2050	0.318	0.346	0.203	0.184	0.182	0.205
2051	0.319	0.346	0.203	0.184	0.180	0.206
2052	0.320	0.346	0.203	0.184	0.179	0.207
2053	0.321	0.346	0.202	0.184	0.178	0.208
2054	0.321	0.346	0.202	0.184	0.177	0.209
2055	0.322	0.346	0.202	0.184	0.176	0.210
2056	0.323	0.346	0.202	0.184	0.175	0.211
2057	0.324	0.346	0.201	0.184	0.174	0.212
2058	0.324	0.346	0.201	0.184	0.173	0.213
2059	0.325	0.345	0.201	0.184	0.172	0.214
2060	0.326	0.345	0.201	0.184	0.171	0.215
2061	0.327	0.345	0.201	0.184	0.170	0.215
2062	0.327	0.345	0.200	0.184	0.169	0.216
2063	0.328	0.345	0.200	0.184	0.168	0.217
2064	0.329	0.345	0.200	0.184	0.167	0.218
2065	0.329	0.344	0.200	0.184	0.166	0.219
2066	0.330	0.344	0.200	0.184	0.165	0.220

Table 35: Estimated catch (landings + incidental mortality; mt) at the Overfishing Limit (OFL) from selected years between 2017-2066 for ocean quahog.

Year	Mean	Median	CV	LCI	UCI
2017	65293	64702	0.14	50173	84969
2018	64755	64167	0.14	49760	84269
2019	64225	63642	0.14	49352	83580
2020	63693	63116	0.14	48849	83048
2021	63138	62573	0.14	48423	82324
2026	60410	59846	0.14	46152	79072
2041	52689	52202	0.14	40410	68700
2066	45066	44785	0.11	36138	56199

3 Figures

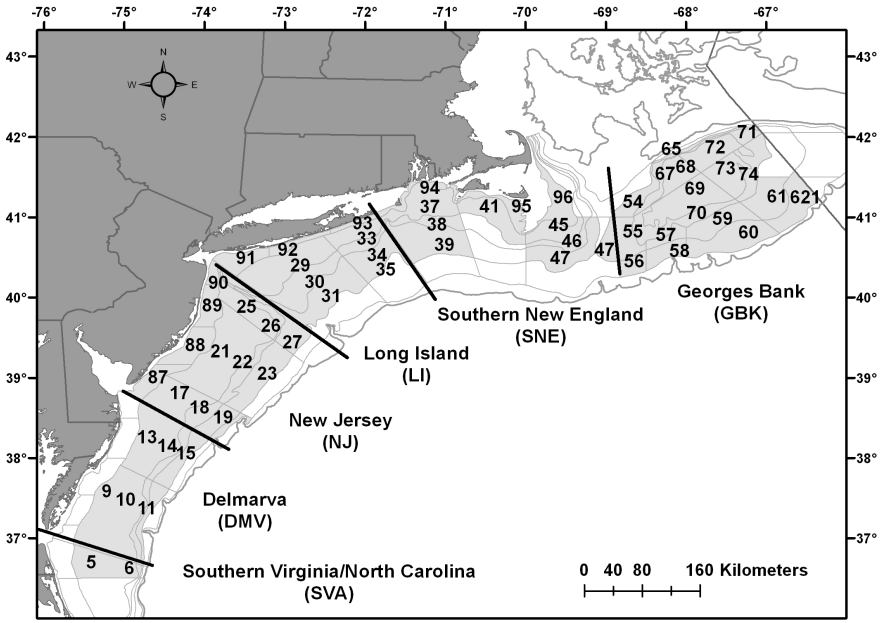

Figure 6: Ocean quahog stock assessment regions and NEFSC shellfish survey strata. The shaded strata are where ocean quahogs have been found and are used to estimate stock abundance in this assessment.

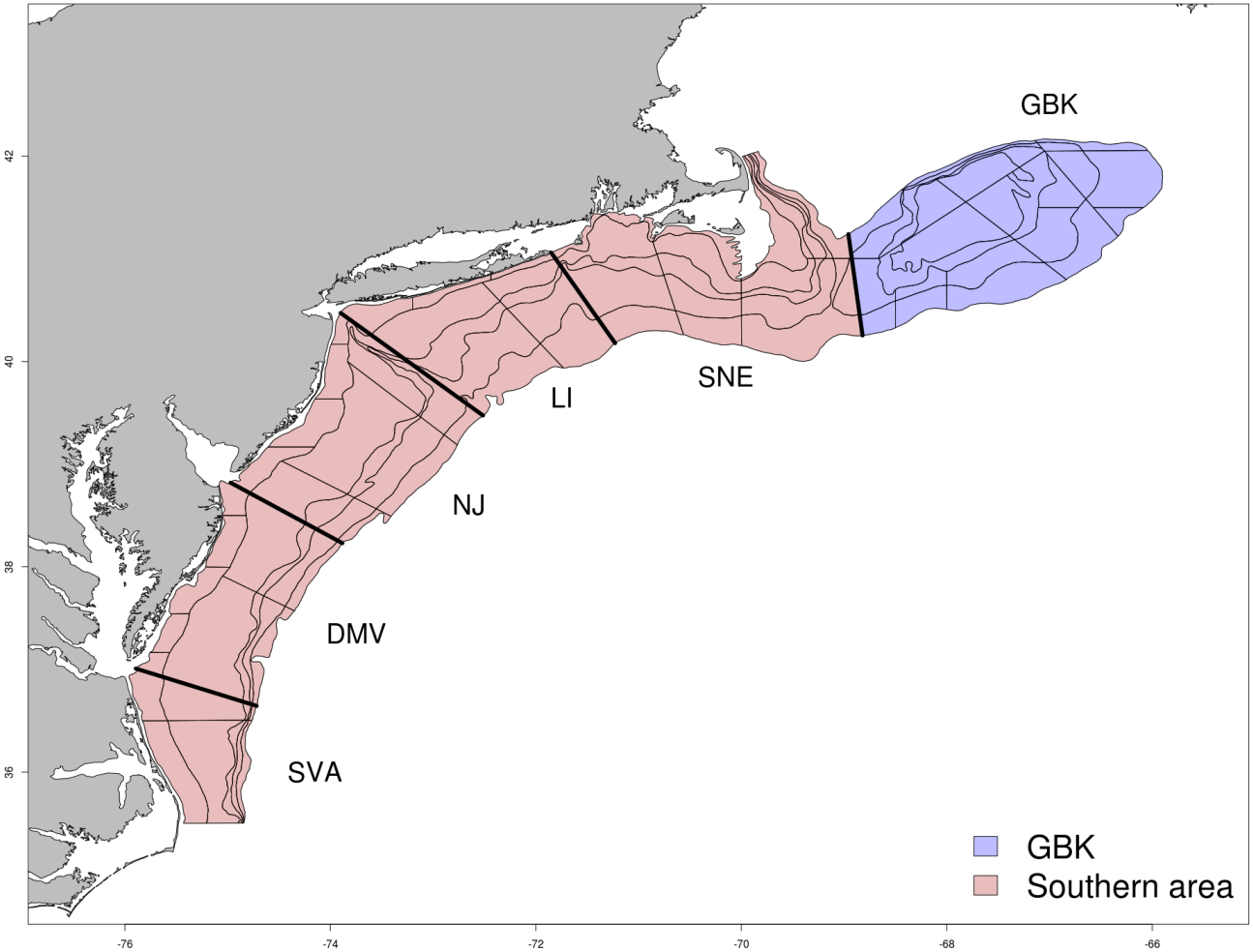

Figure 7: Ocean quahog regions divided into two areas.

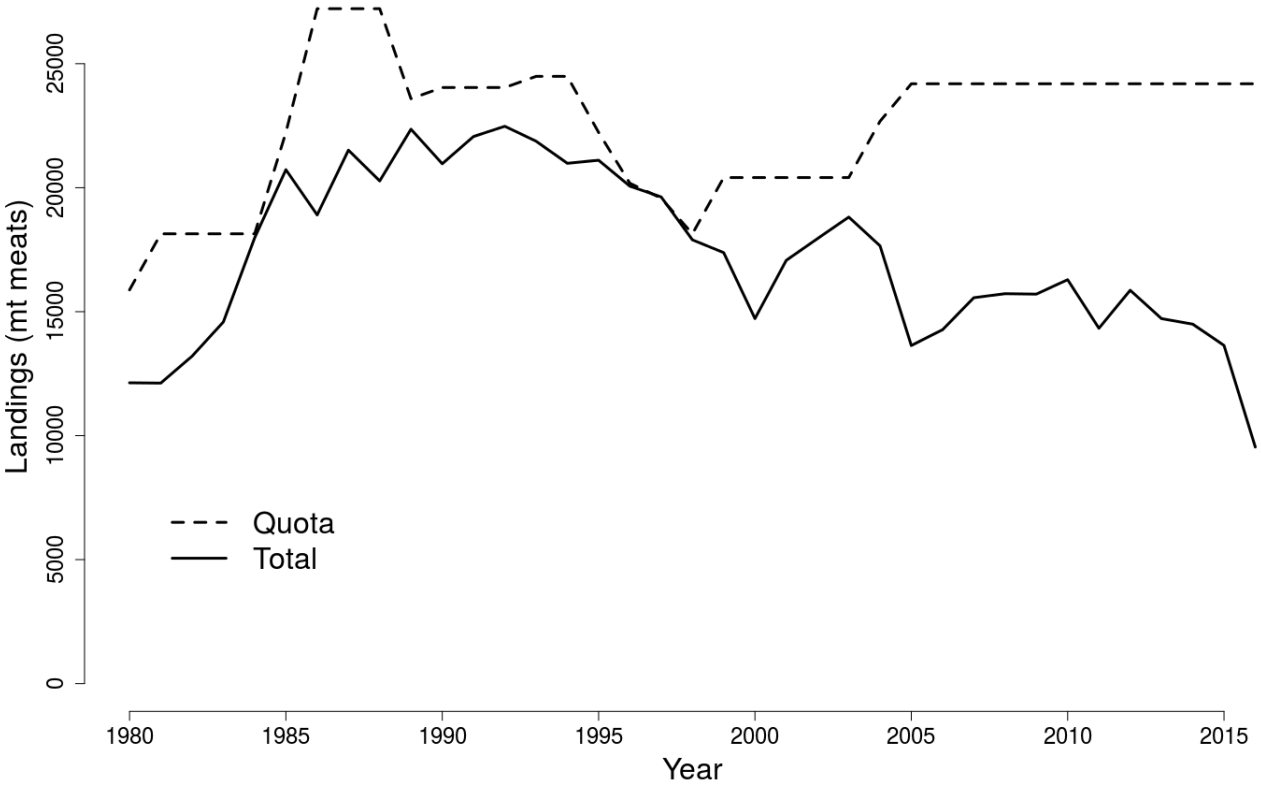

Figure 8: Total ocean quahog landings and quotas during 1980-2016.

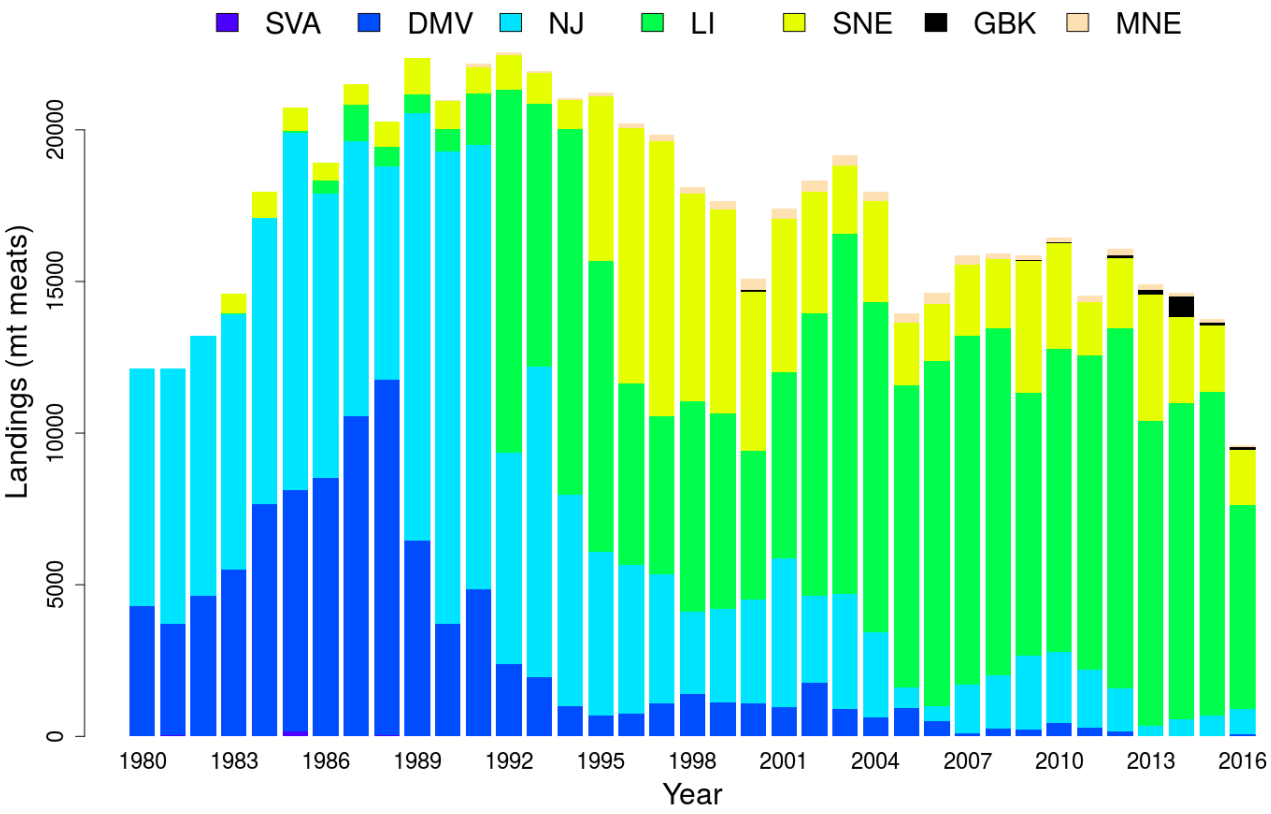

Figure 9: Ocean quahog landings from the US EEZ during 1980-2016, by stock assessment region.

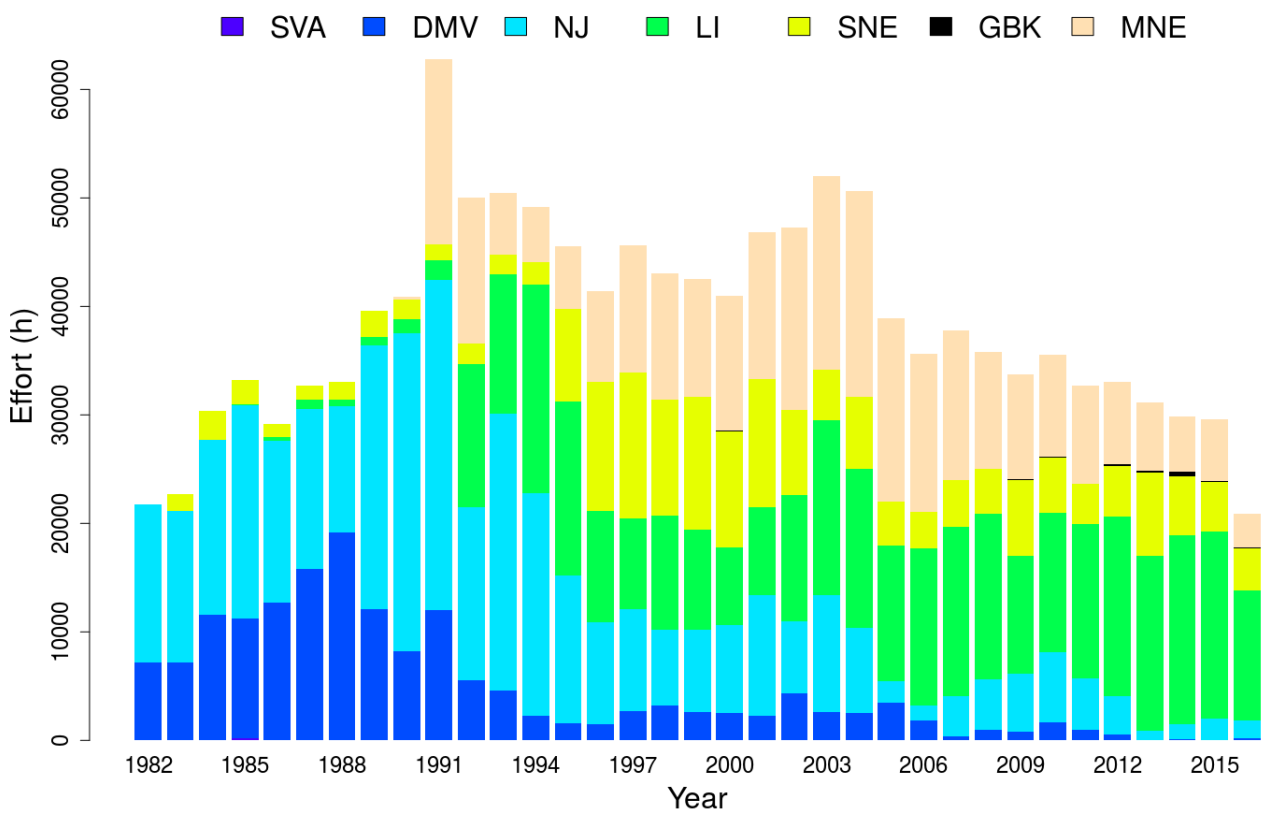

Figure 10: Ocean quahog hours fished from the US EEZ during 1982-2016, by stock assessment region.

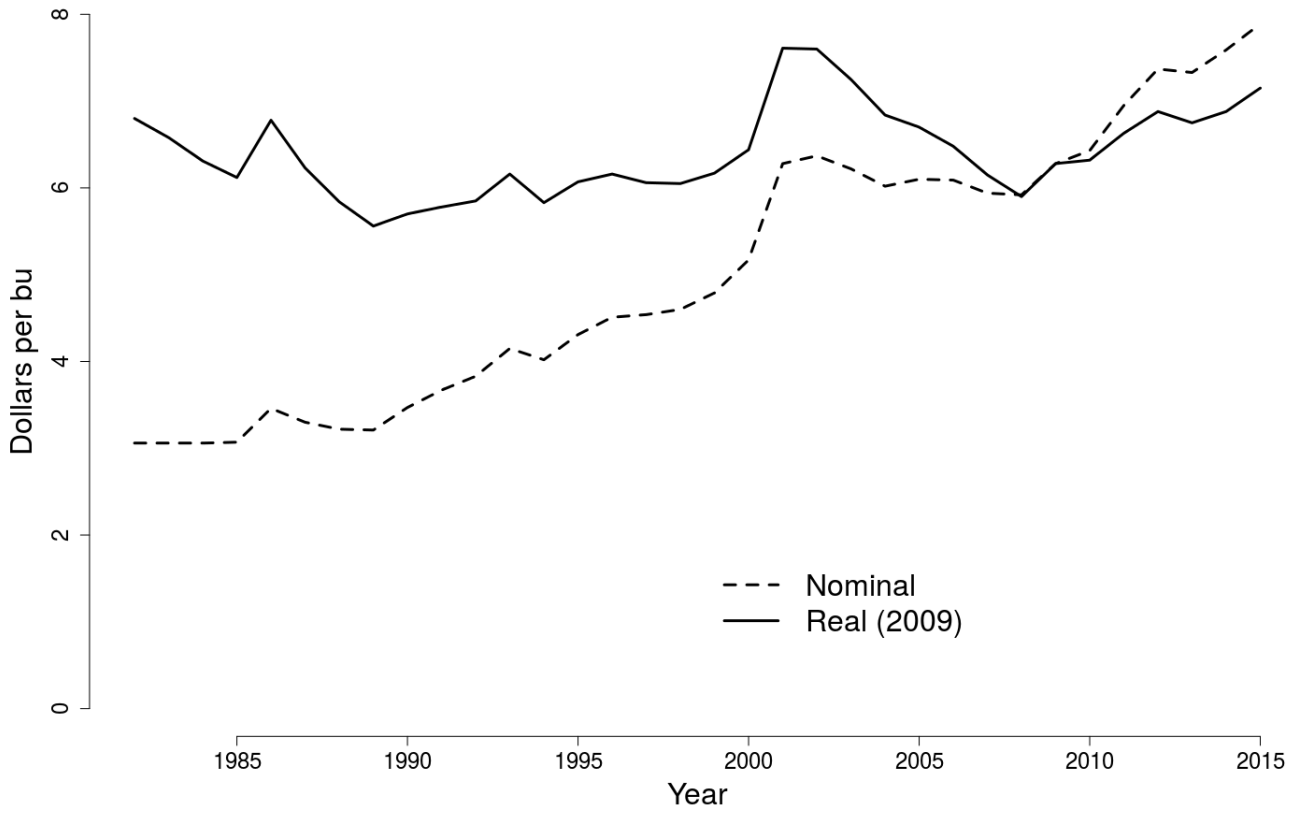

Figure 11: Nominal and real dollar equivalent prices for ocean quahog 1981-2016.

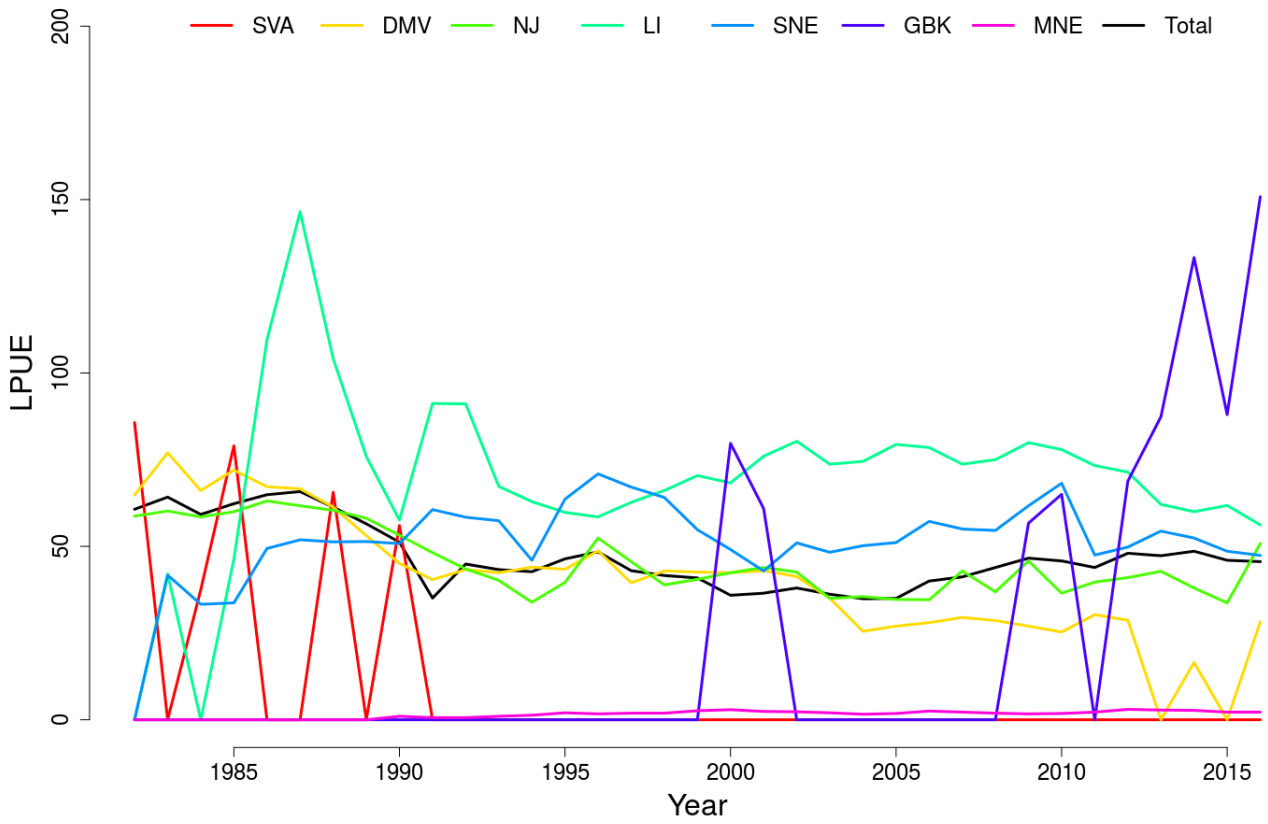

Figure 12: Nominal landings per unit effort (LPUE in bushels landed per hour fished) for ocean quahog, by region, 1981-2016. LPUE is total landings in bushels divided by total fishing effort.

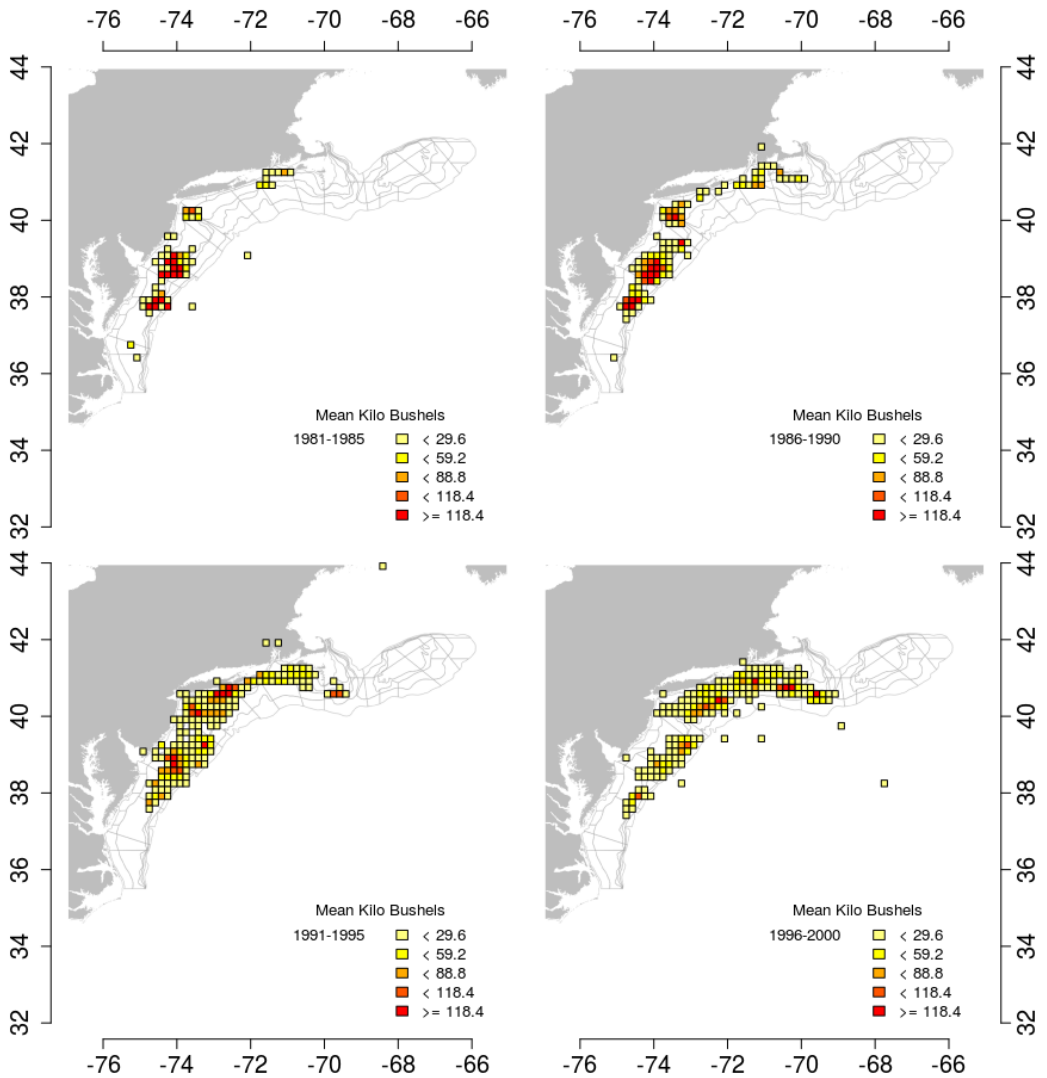

Figure 13: Average ocean quahog landings by ten-minute squares over time. Only squares where more the 5 kilo bushels were caught are shown.

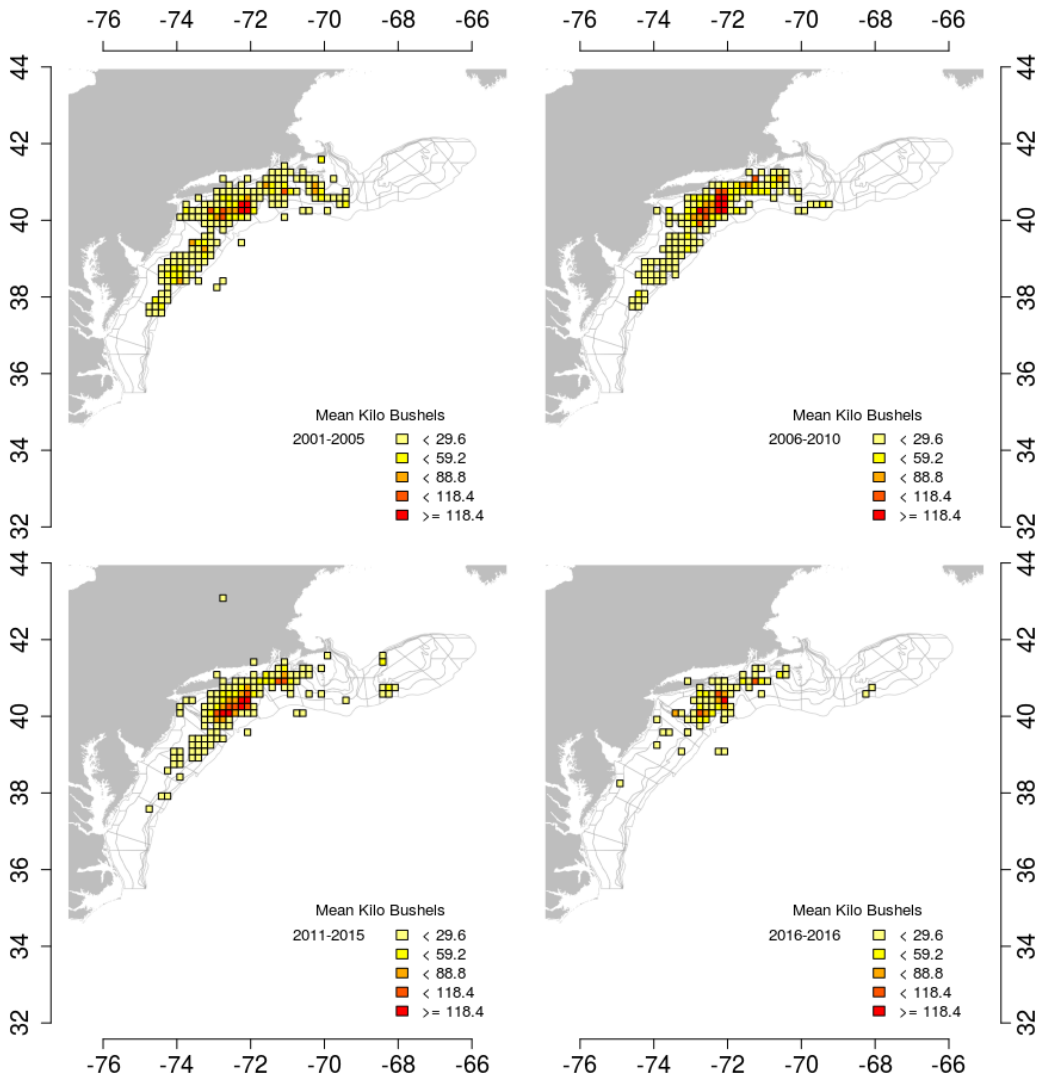

Figure 14: Average ocean quahog landings by ten-minute squares over time. Only squares where more the 5 kilo bushels were caught are shown.

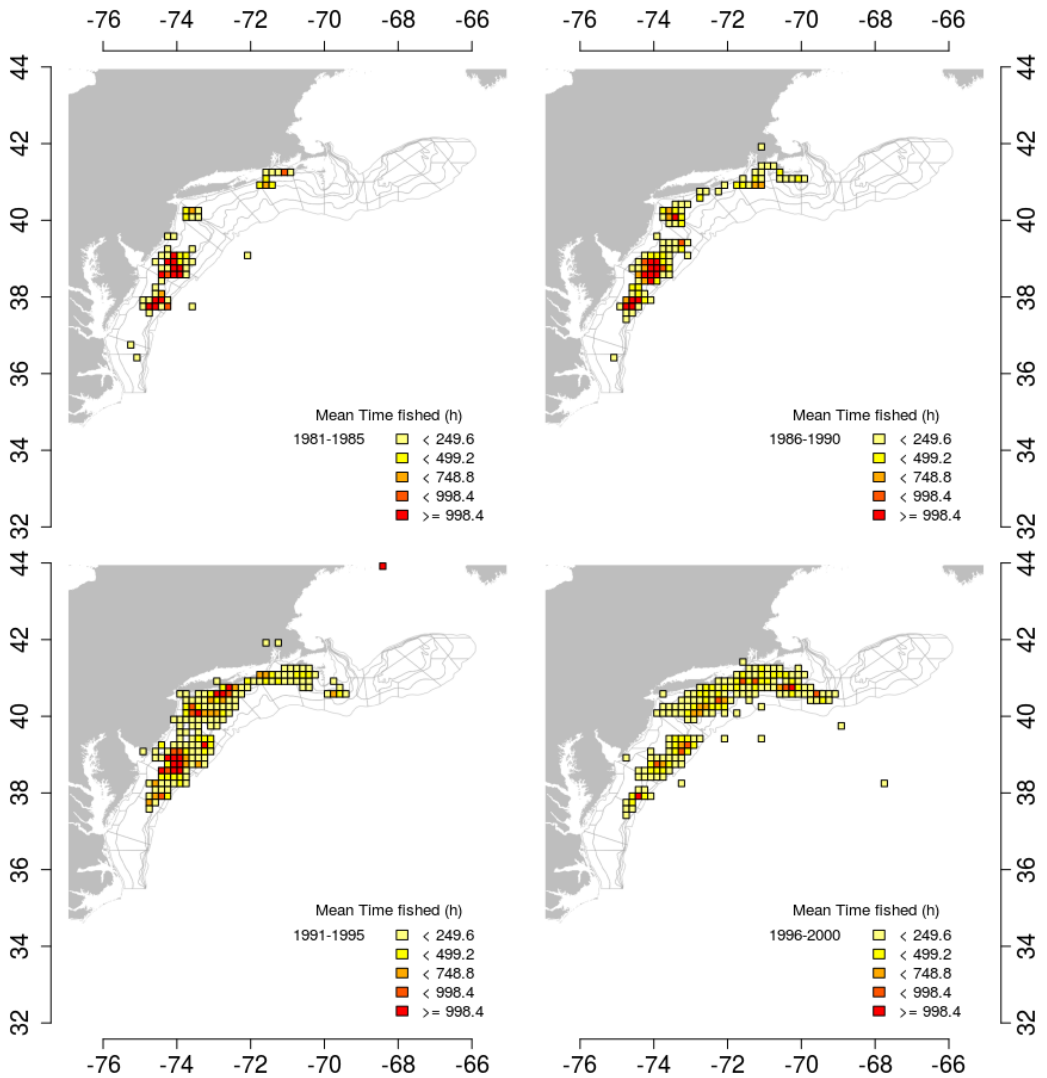

Figure 15: Average ocean quahog effort by ten-minute squares over time. Only squares where more the 5 kilo bushels were caught are shown.

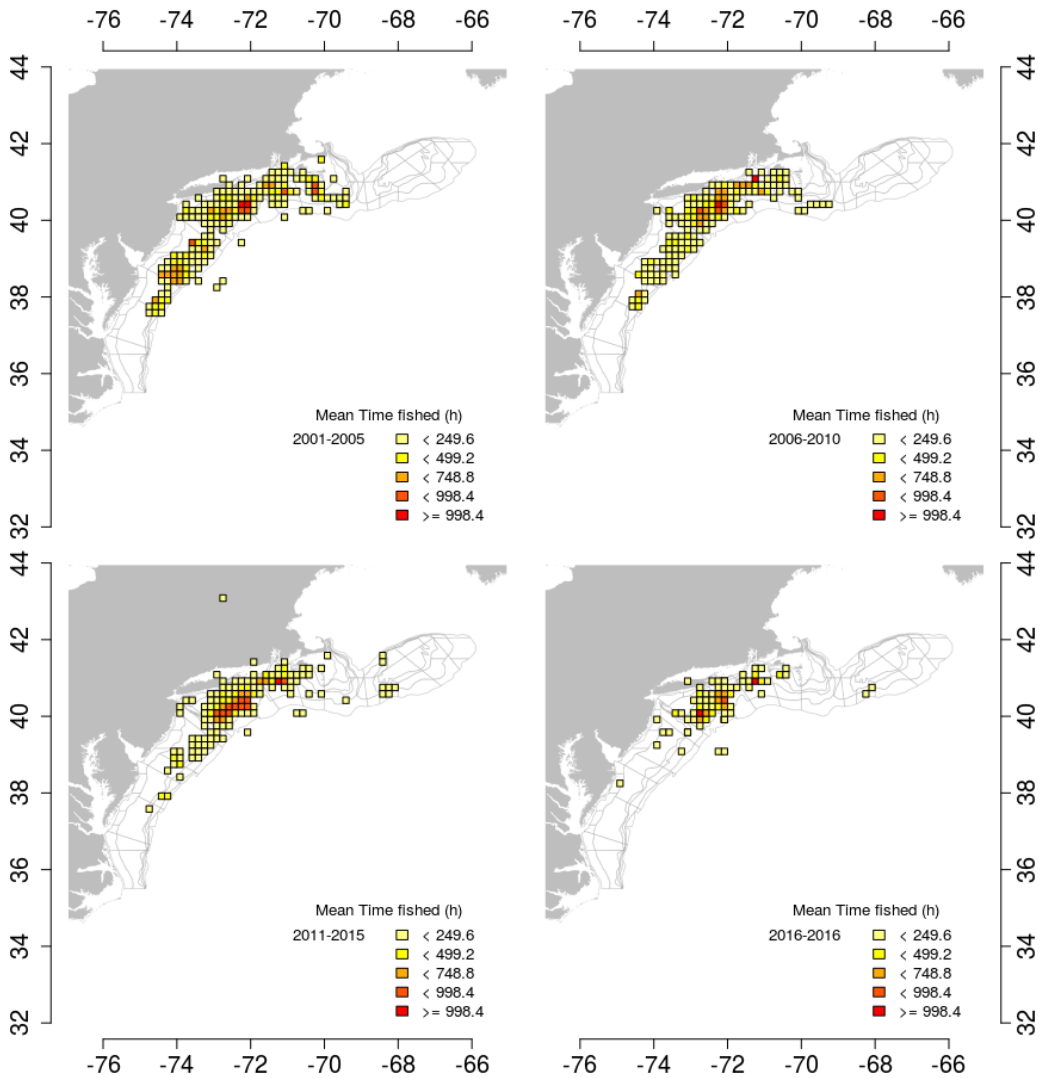

Figure 16: Average ocean quahog effort by ten-minute squares over time. Only squares where more the 5 kilo bushels were caught are shown.

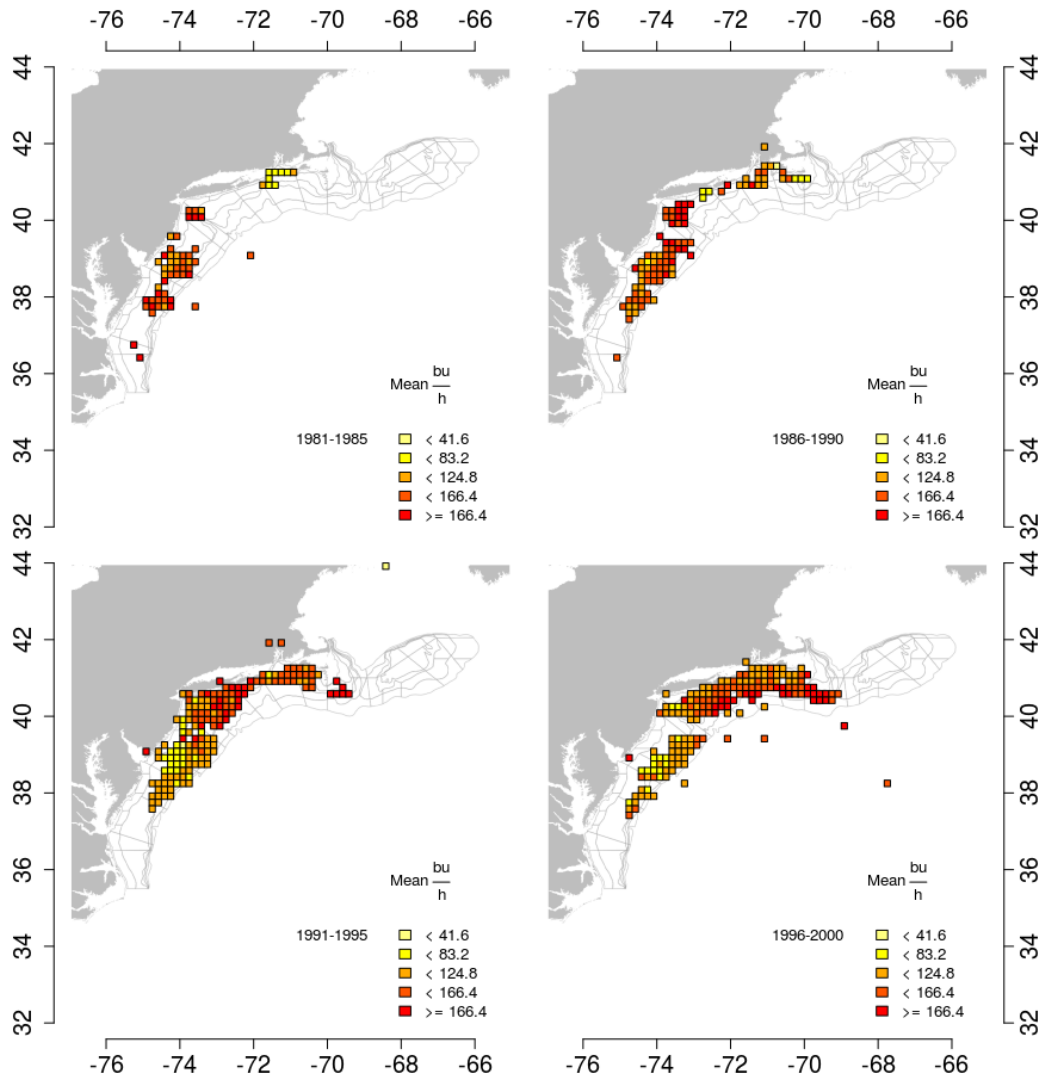

Figure 17: Average ocean quahog LPUE (bu. h^{-1}) by ten-minute squares over time. Only squares where more the 5 kilo bushels were caught are shown.

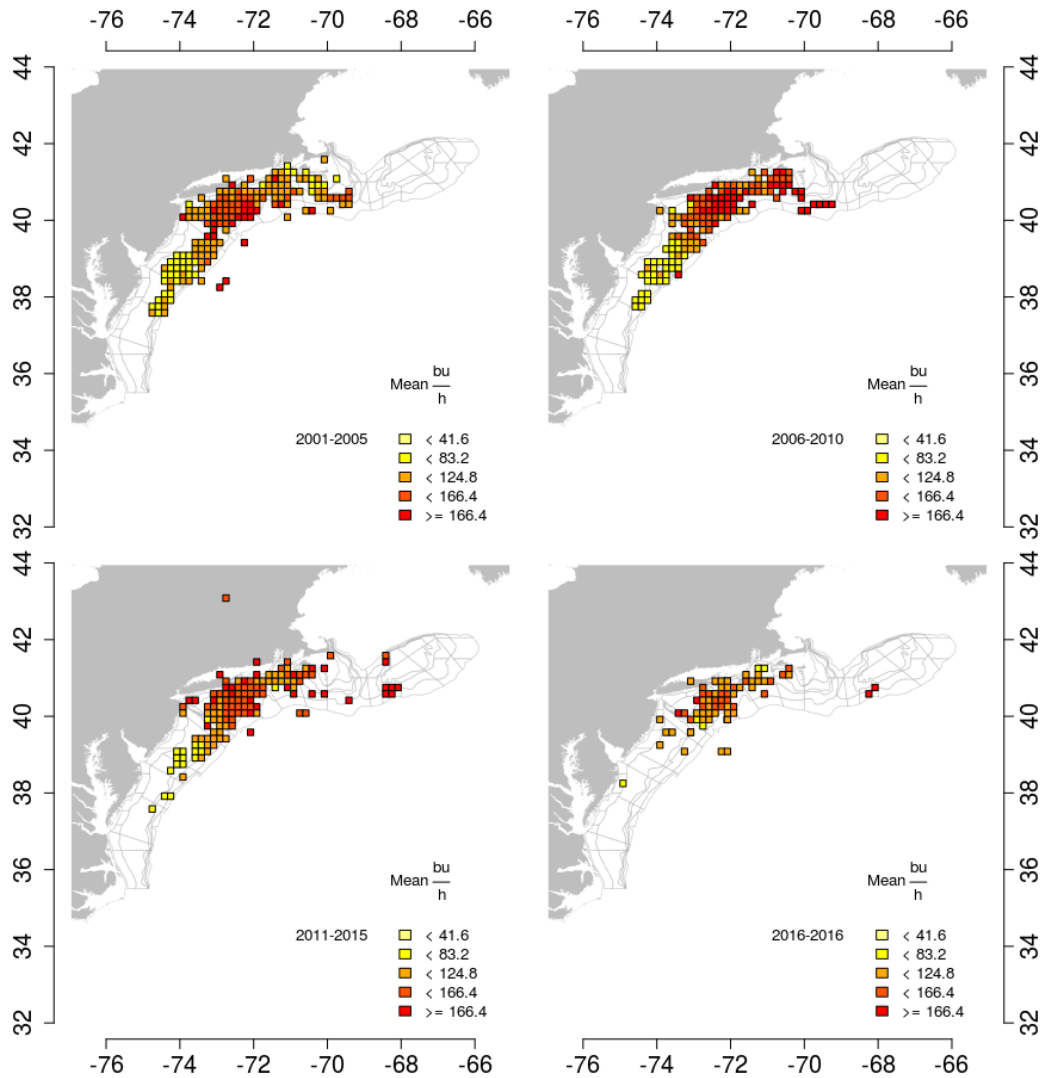

Figure 18: Average ocean quahog LPUE (bu. h^{-1}) by ten-minute squares over time. Only squares where more the 5 kilo bushels were caught are shown.

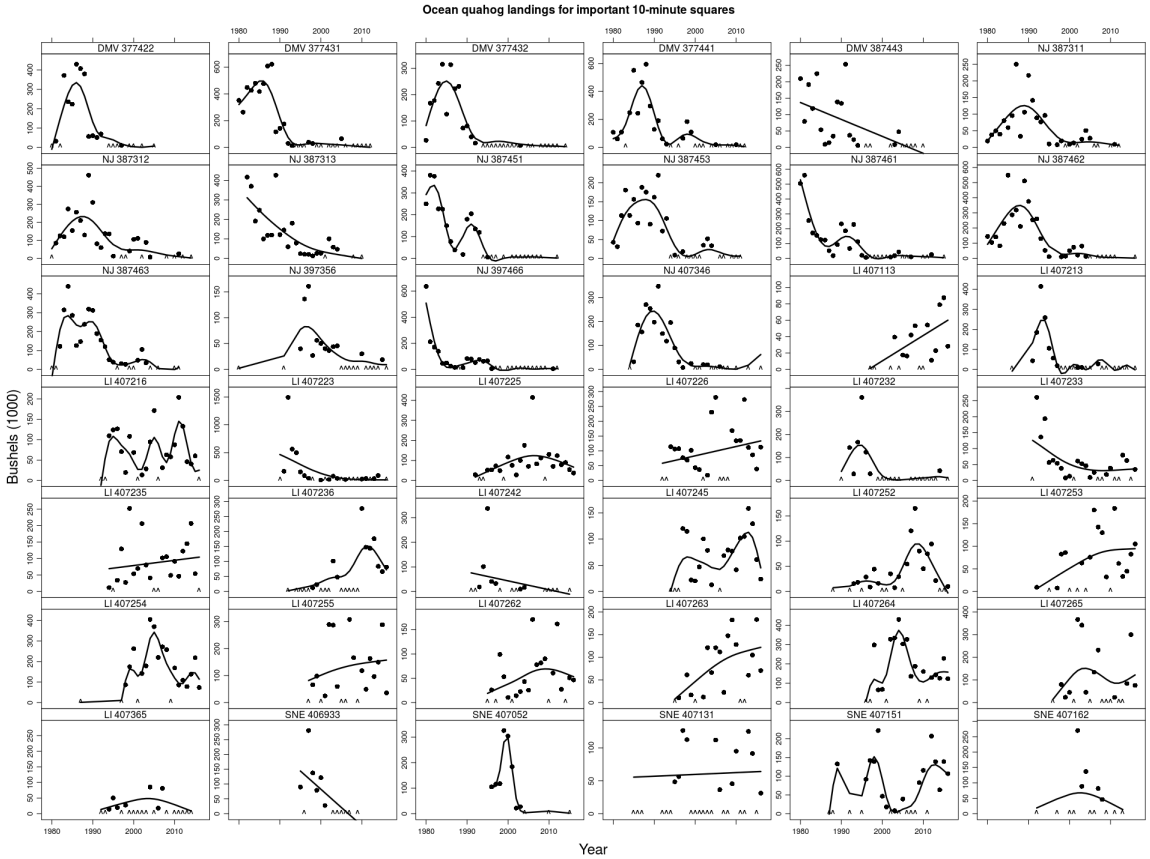

Figure 19: Annual ocean quahog landings in "important" ten minute squares (TNMS) during 1980-2016 based on logbook data. Important means that a square ranked in the top 10 TNMS for total landings during any five-year period (1980-1984, 1985-1989, ...). Data for 2016 are incomplete and preliminary. To protect the privacy of individual firms, data are not plotted if the number of vessels is less than 3. Instead, a "$\wedge$" is shown on the x-axis to indicate where data are missing. The solid dark line is a spline intended to show trends. The spline was fit to all available data, including data not plotted.

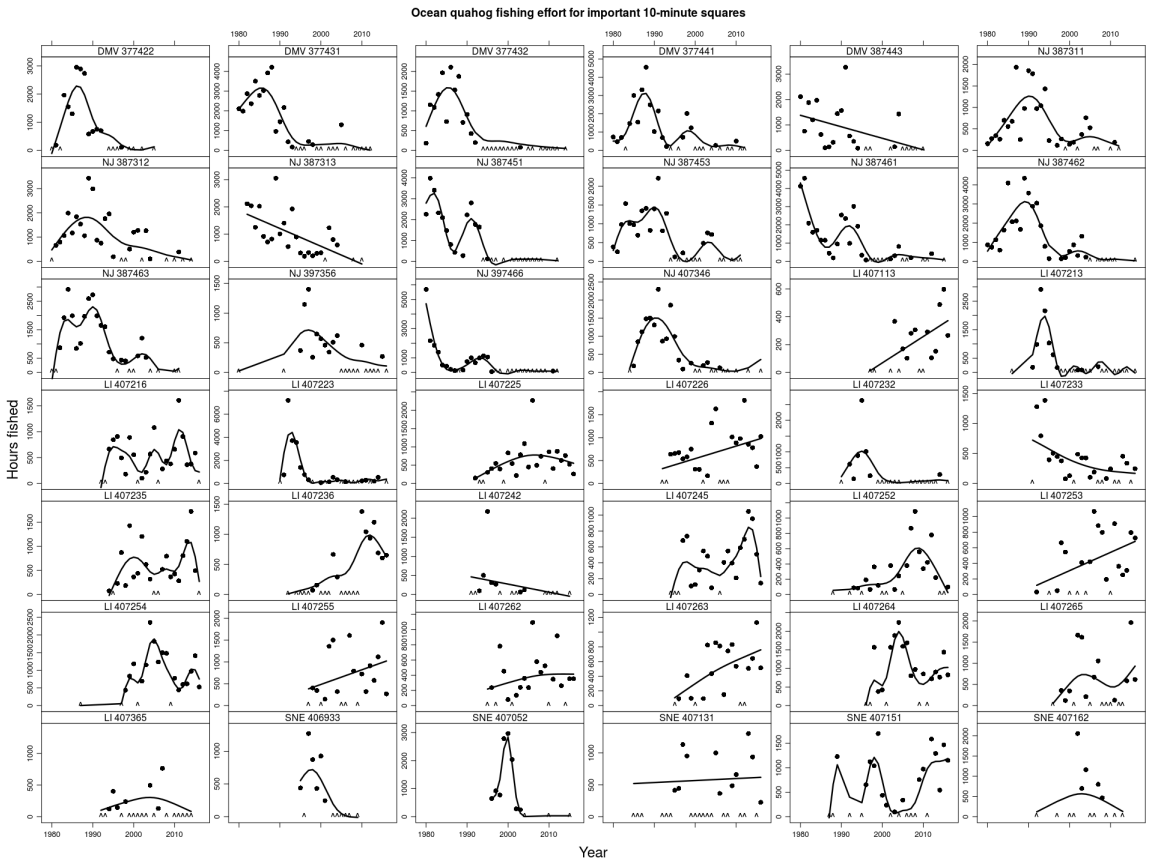

Figure 20: Annual ocean quahog effort (hours y^{-1}) in "important" ten minute squares (TNMS) during 1980-2016 based on logbook data. Important means that a square ranked in the top 10 TNMS for total landings during any five-year period. Data for 2016 are incomplete and preliminary. To protect the privacy of individual firms, data are not plotted if the number of vessels is less than 3. Instead, a "$\wedge$" is shown on the x-axis to indicate where data are missing. The solid dark line is a spline intended to show trends. The spline was fit to all available data, including data not plotted.

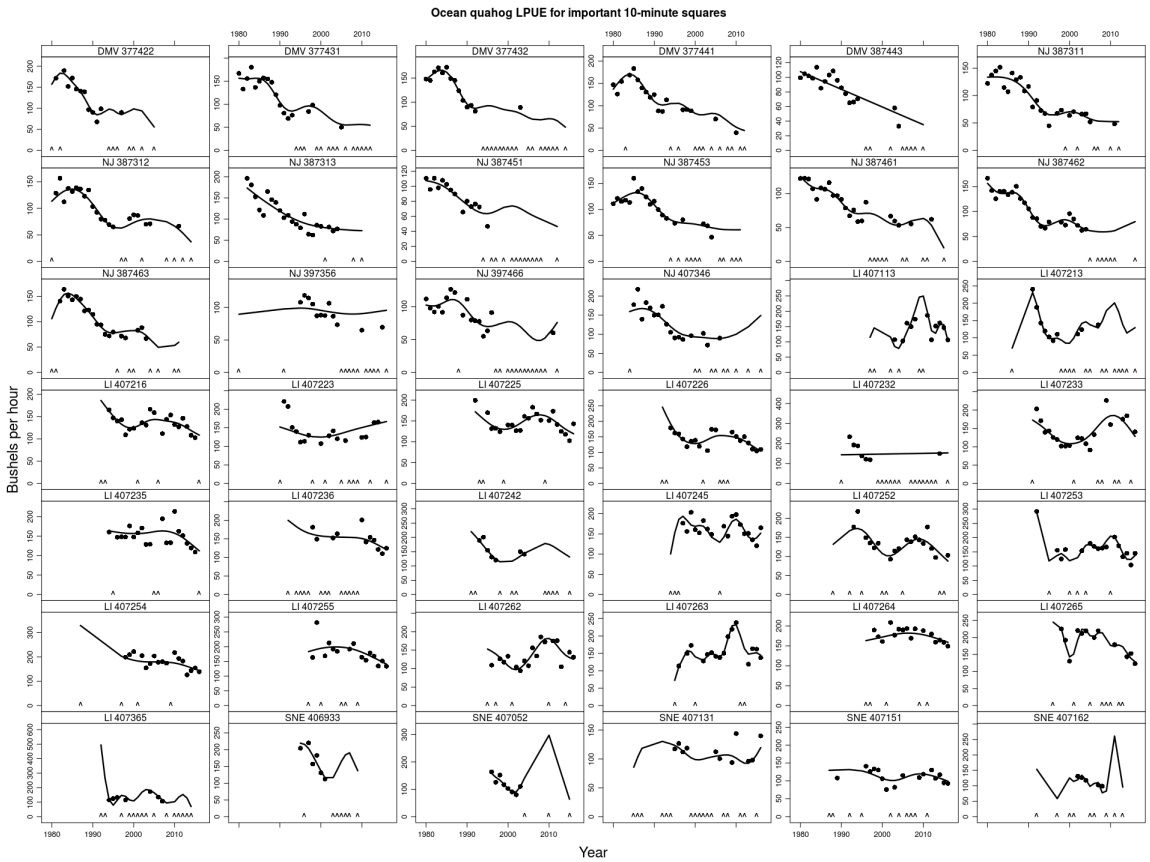

Figure 21: Annual ocean quahog LPUE (bu h^{-1}) in "important" ten minute squares (TNMS) during 1980-2016 based on logbook data. Important means that a square ranked in the top 10 TNMS for total landings during any five-year period . Data for 2016 are incomplete and preliminary. To protect the privacy of individual firms, data are not plotted if the number of vessels is less than 3. Instead, a "$\wedge$" is shown on the x-axis to indicate where data are missing. The solid dark line is a spline intended to show trends. The spline was fit to all available data, including data not plotted.

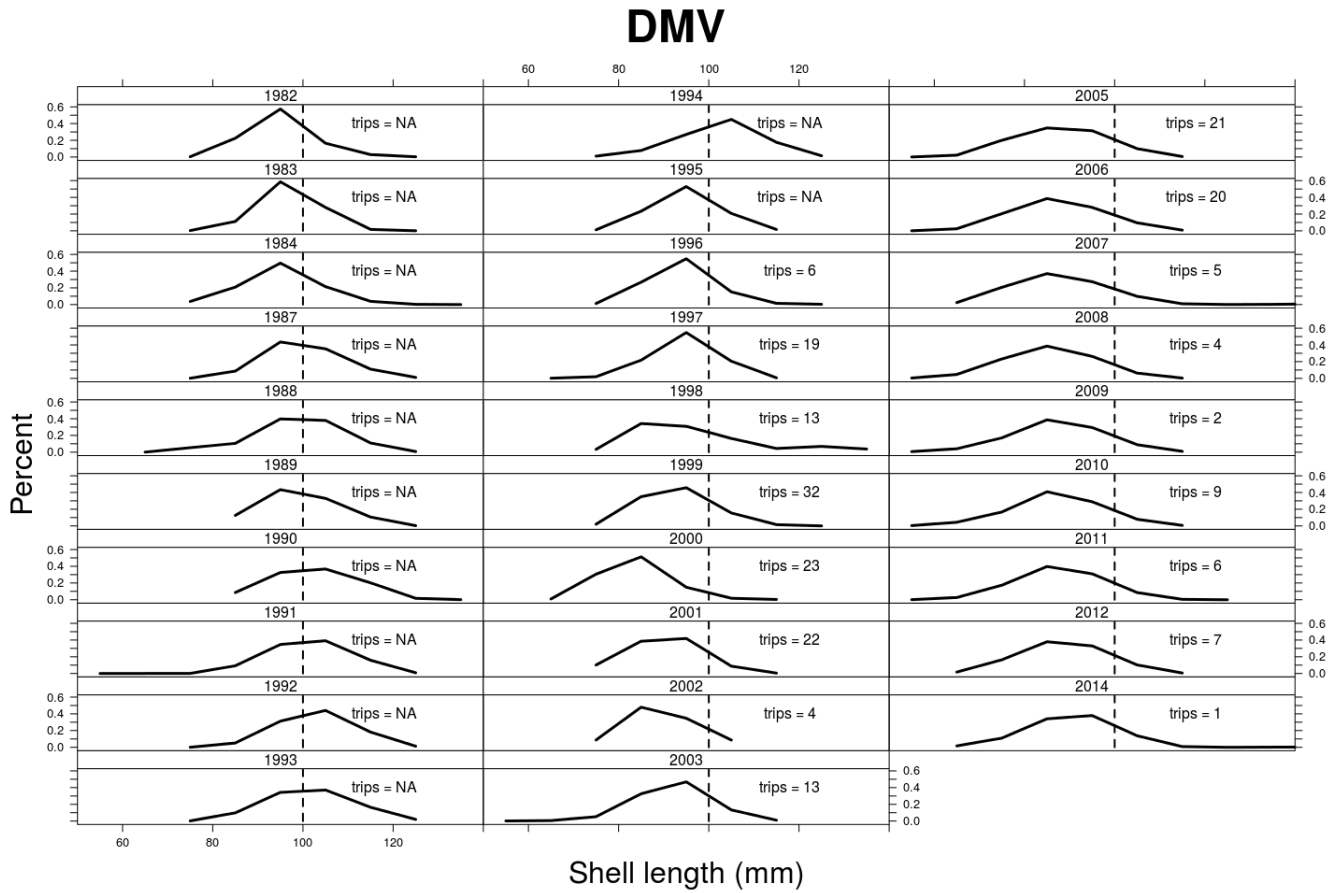

Figure 22: Length compositions of port-sampled landed ocean quahogs from the DMV region. Sample sizes are the number of trips sampled in each year. Number of trips sampled before 1996 are unknown.

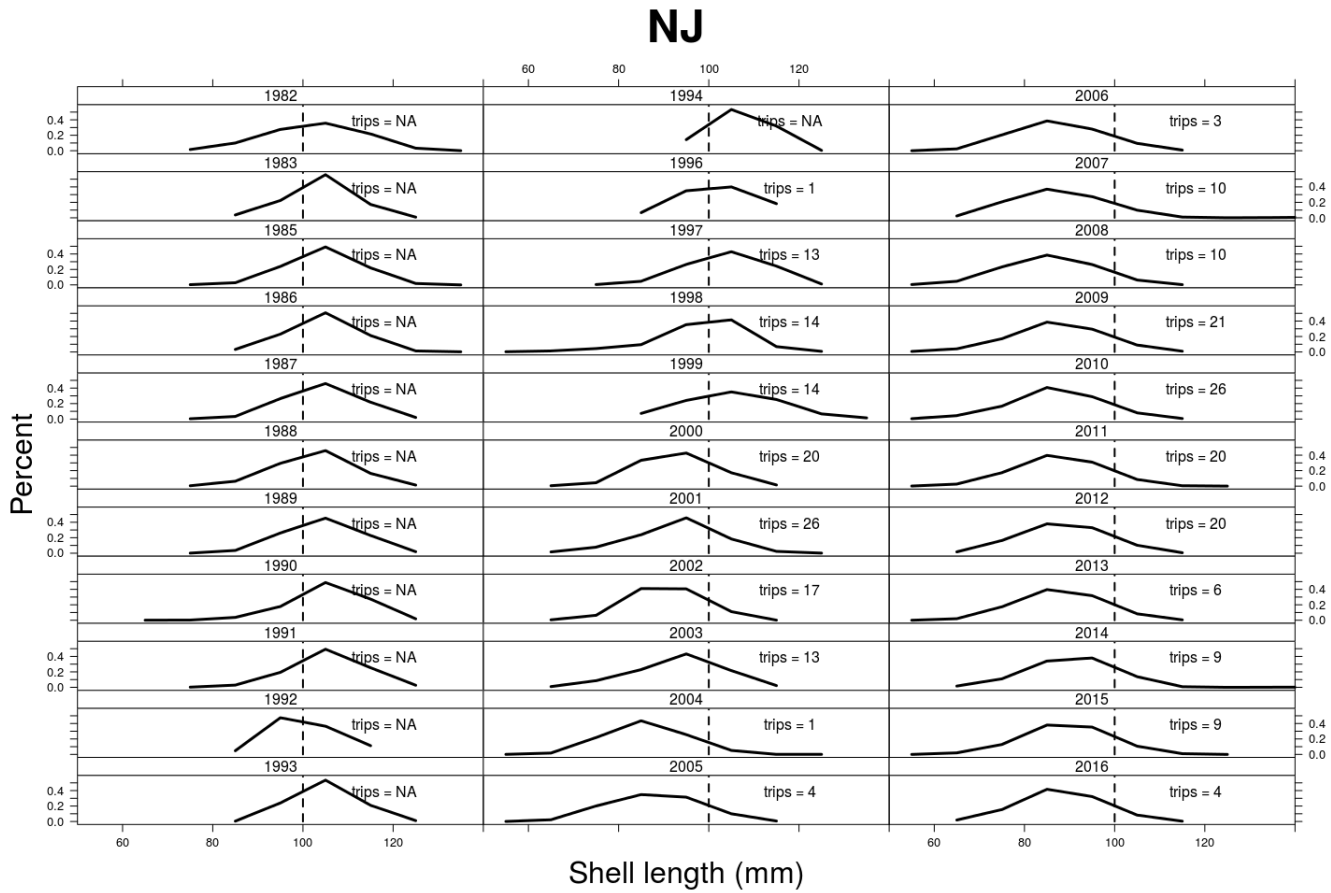

Figure 23: Length compositions of port-sampled landed ocean quahogs from the NJ region. Sample sizes are the number of trips sampled in each year. Number of trips sampled before 1996 are unknown.

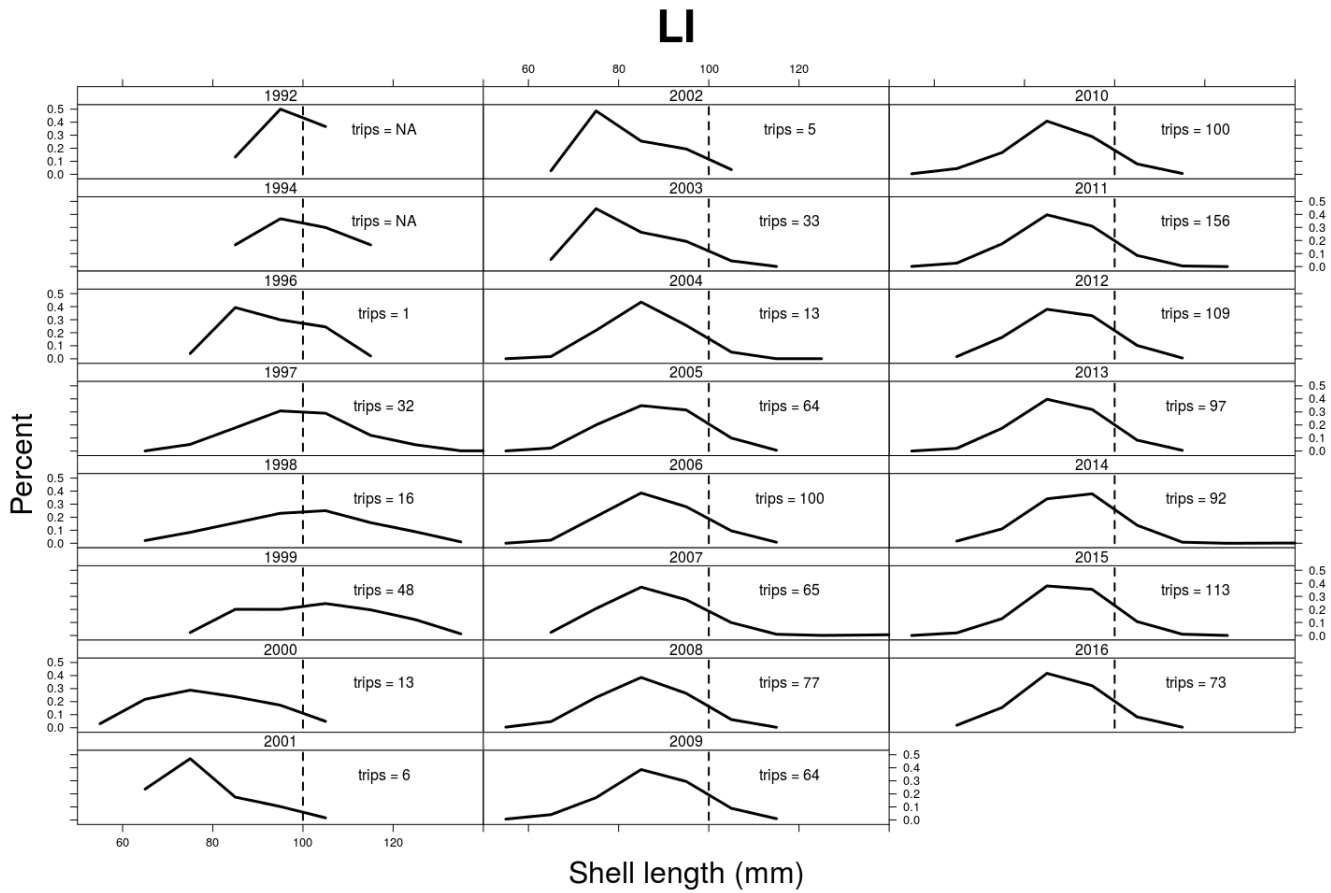

Figure 24: Length compositions of port-sampled landed ocean quahogs from the LI region. Sample sizes are the number of trips sampled in each year. Number of trips sampled before 1996 are unknown.

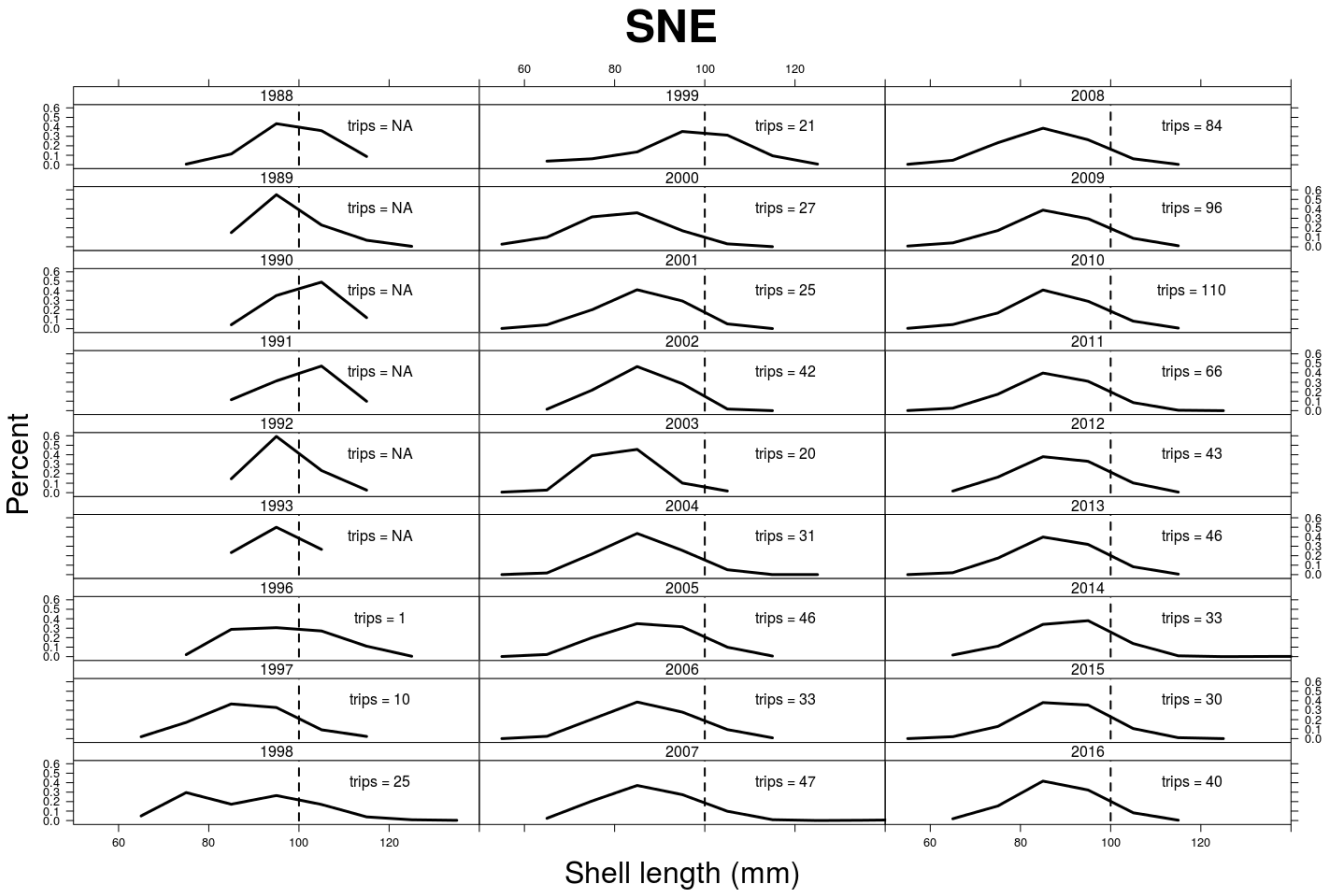

Figure 25: Length compositions of port-sampled landed ocean quahogs from the SNE region. Sample sizes are the number of trips sampled in each year. Number of trips sampled before 1996 are unknown.

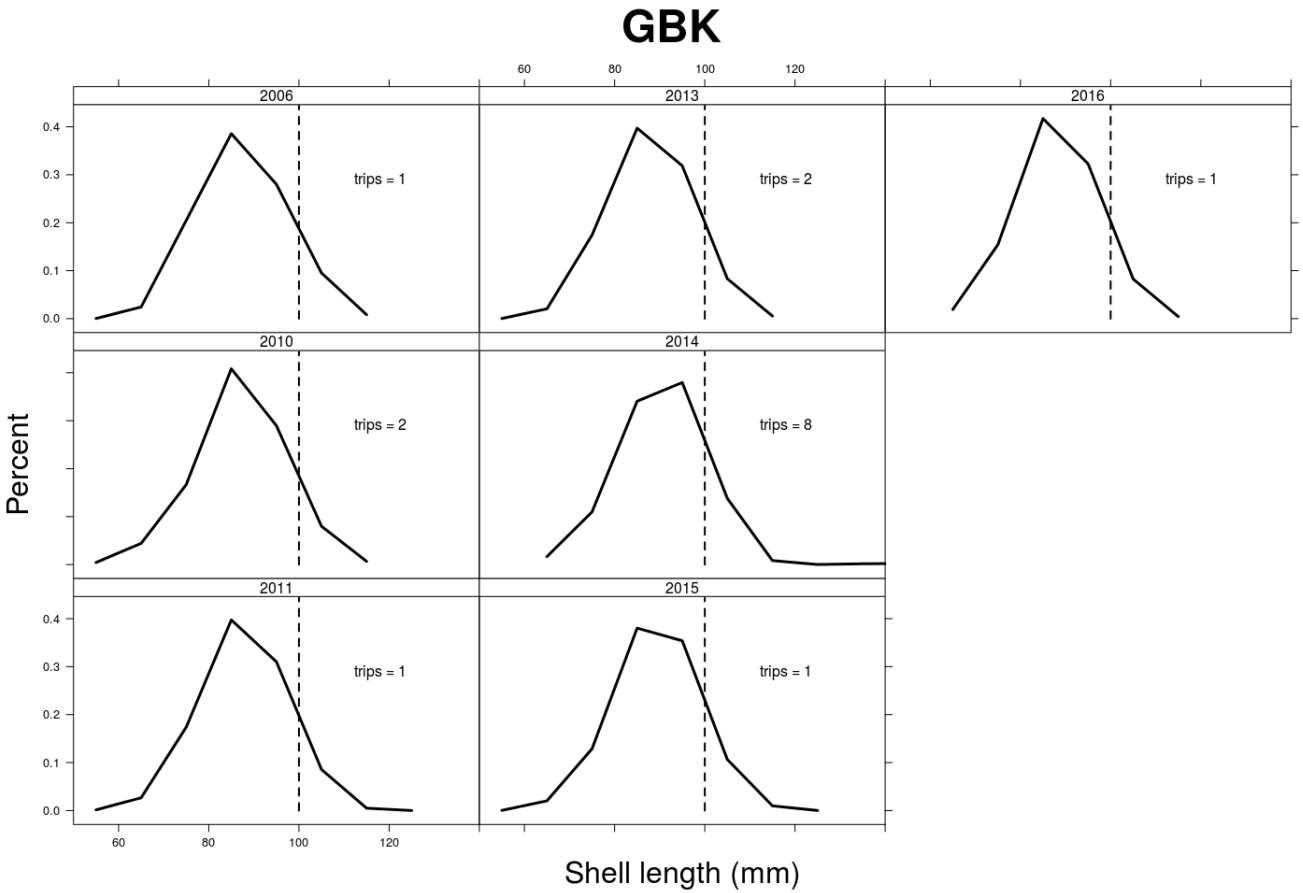

Figure 26: Length compositions of port-sampled landed ocean quahogs from the GBK region. Sample sizes are the number of trips sampled in each year. Number of trips sampled before 1996 are unknown.

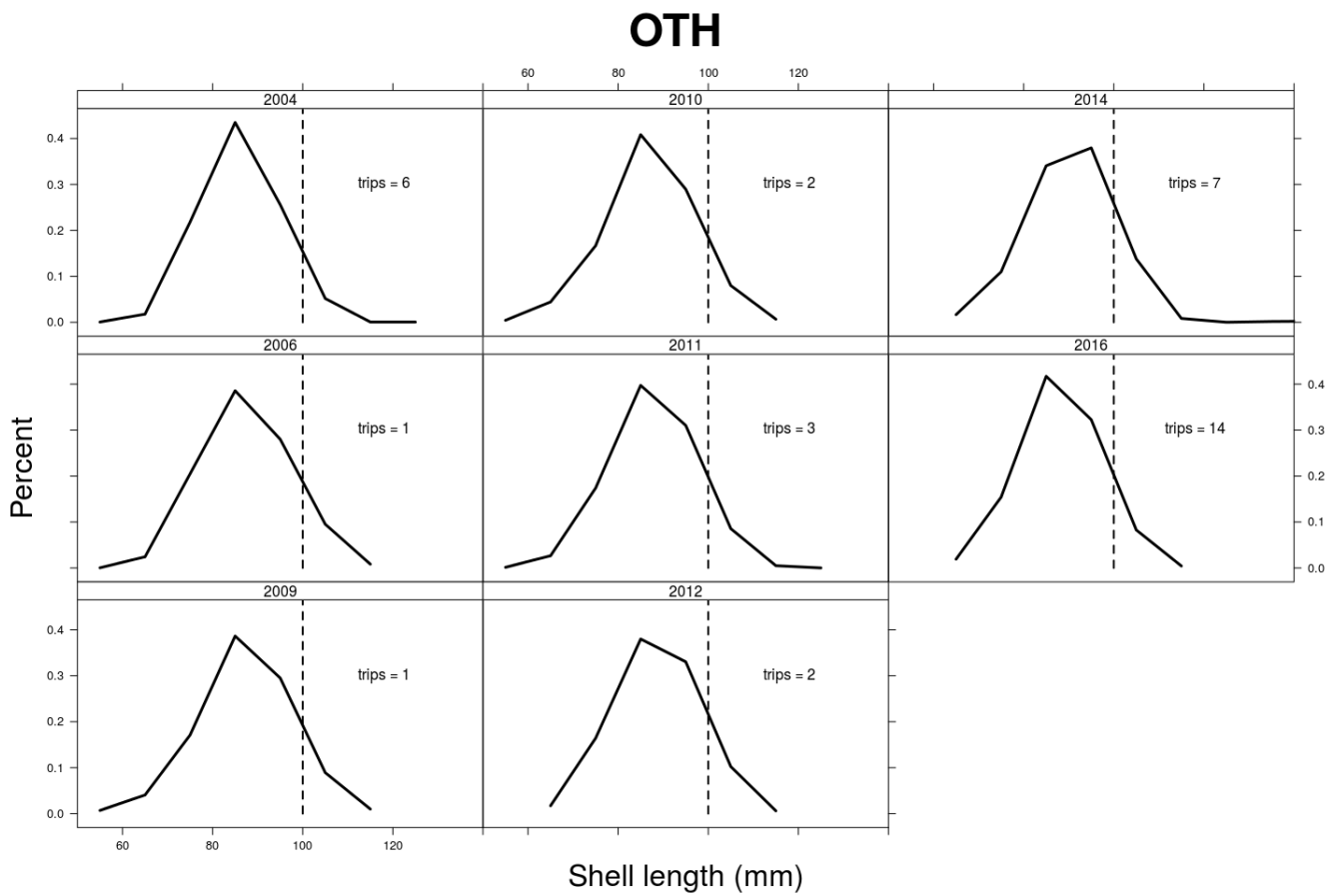

Figure 27: Length compositions of port-sampled landed ocean quahogs for which no area was recorded. Sample sizes are the number of trips sampled in each year. Number of trips sampled before 1996 are unknown.

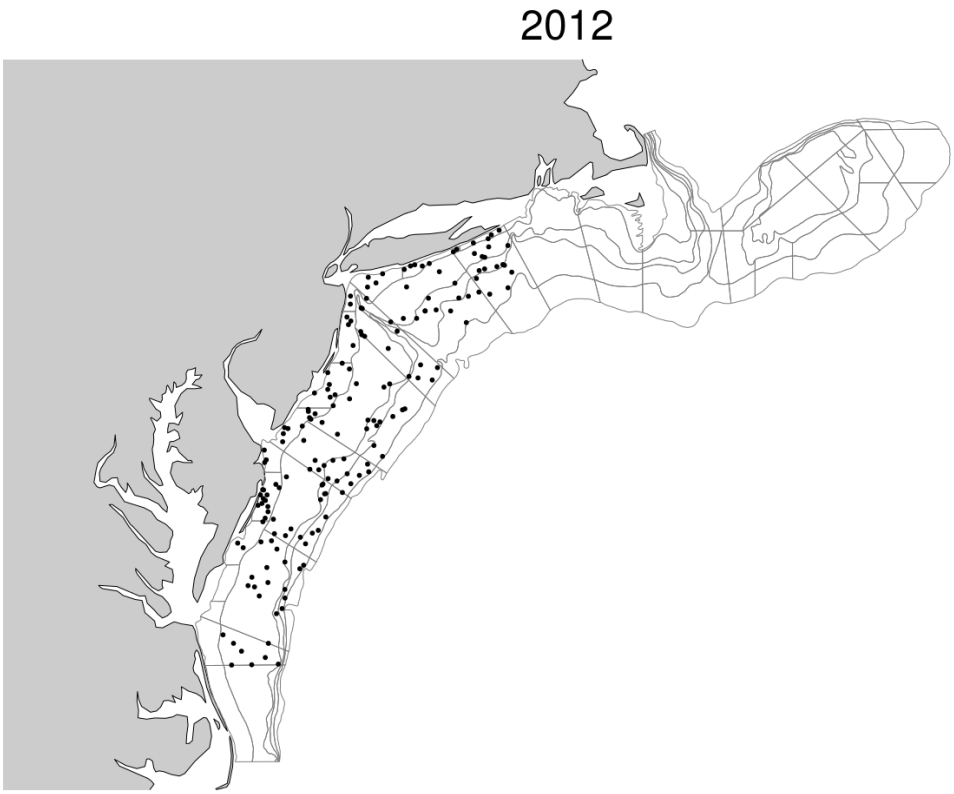

Figure 28: Station locations from the 2012 survey.

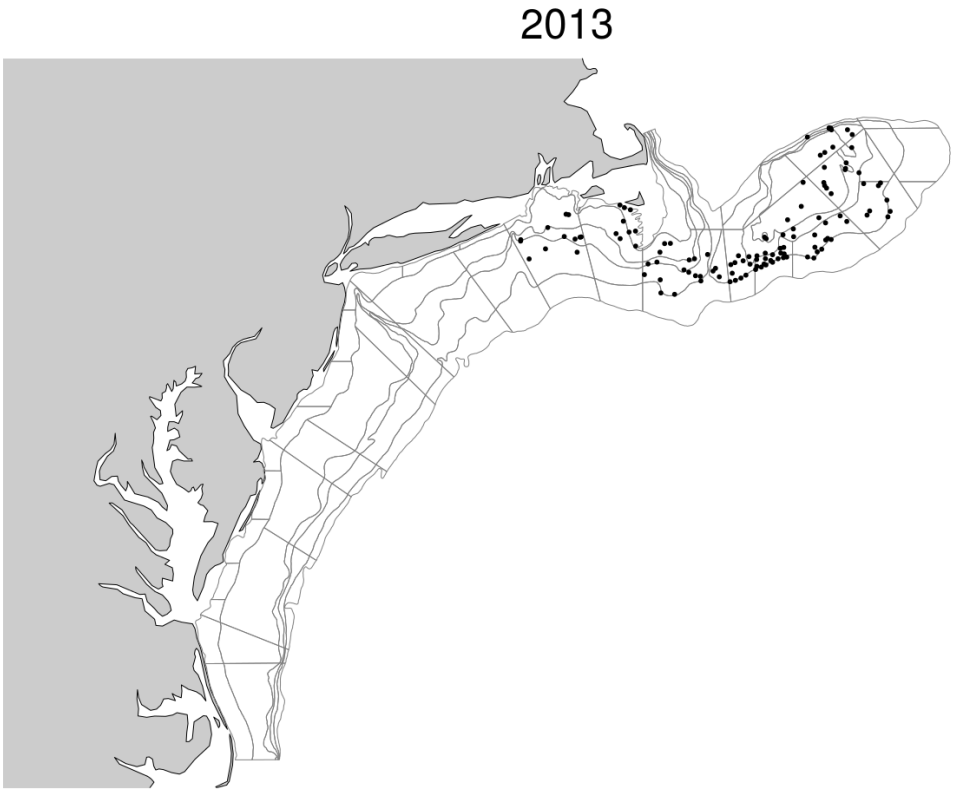

Figure 29: Station locations from the 2013 survey.

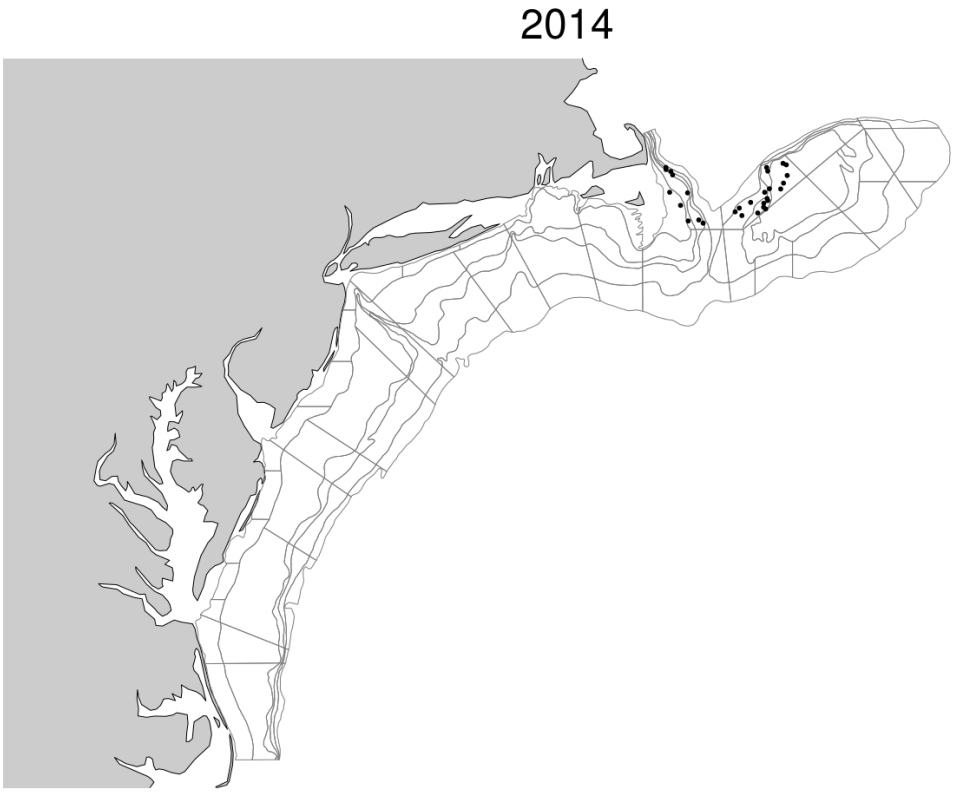

Figure 30: Station locations from the 2014 survey.

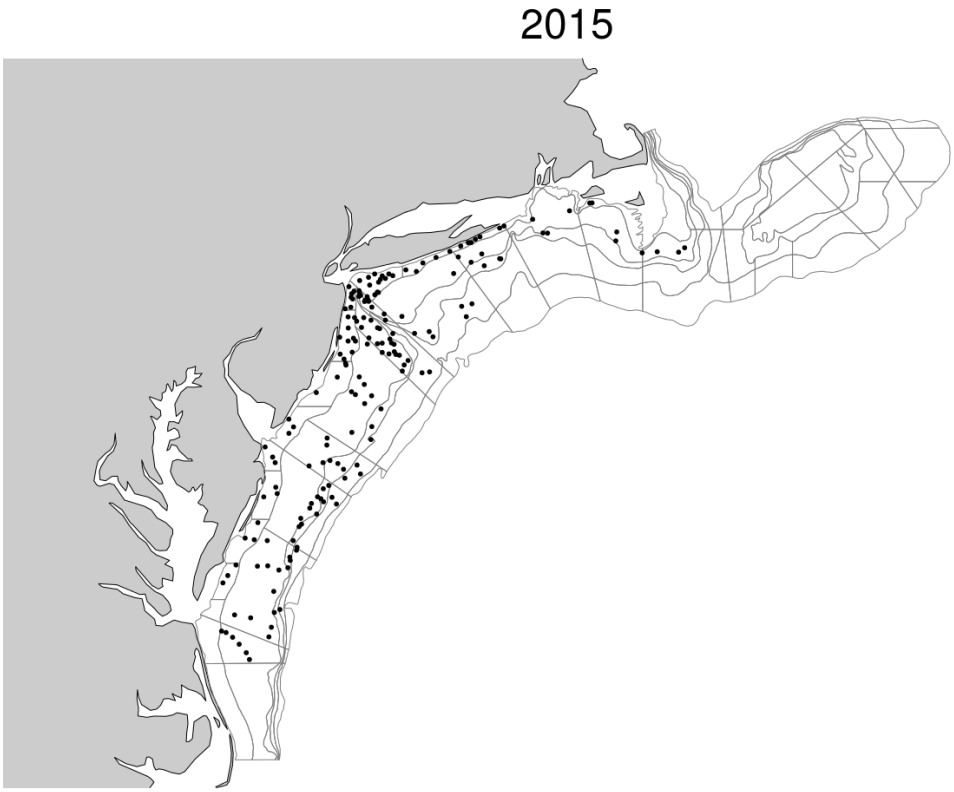

Figure 31: Station locations from the 2015 survey.

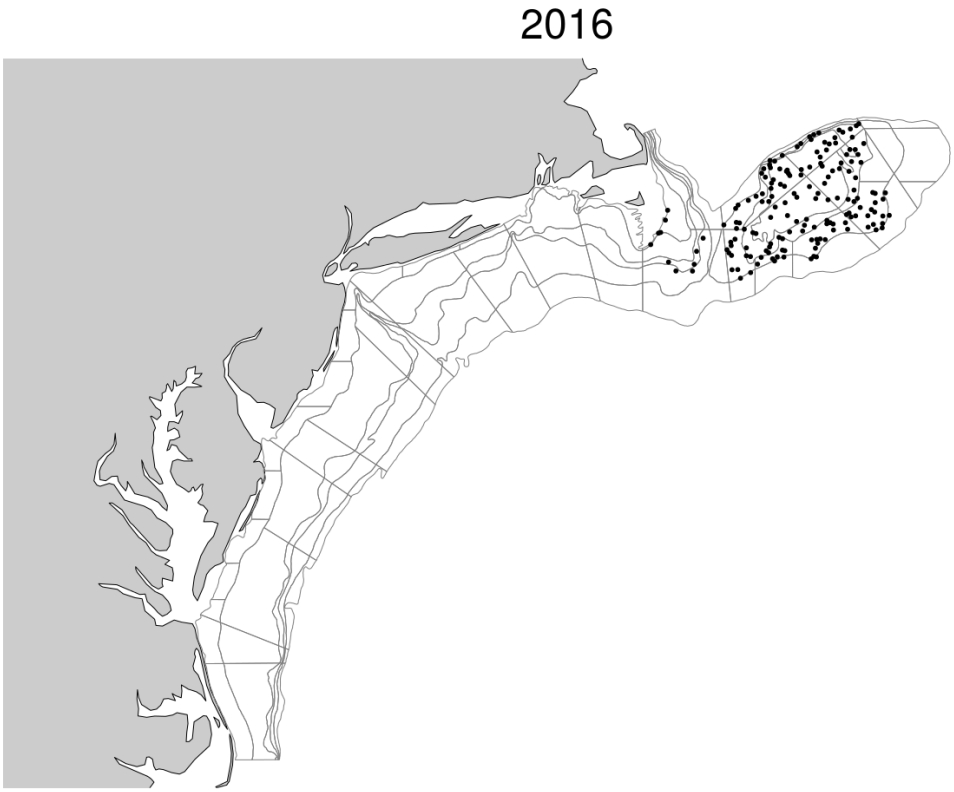

Figure 32: Station locations from the 2016 survey.

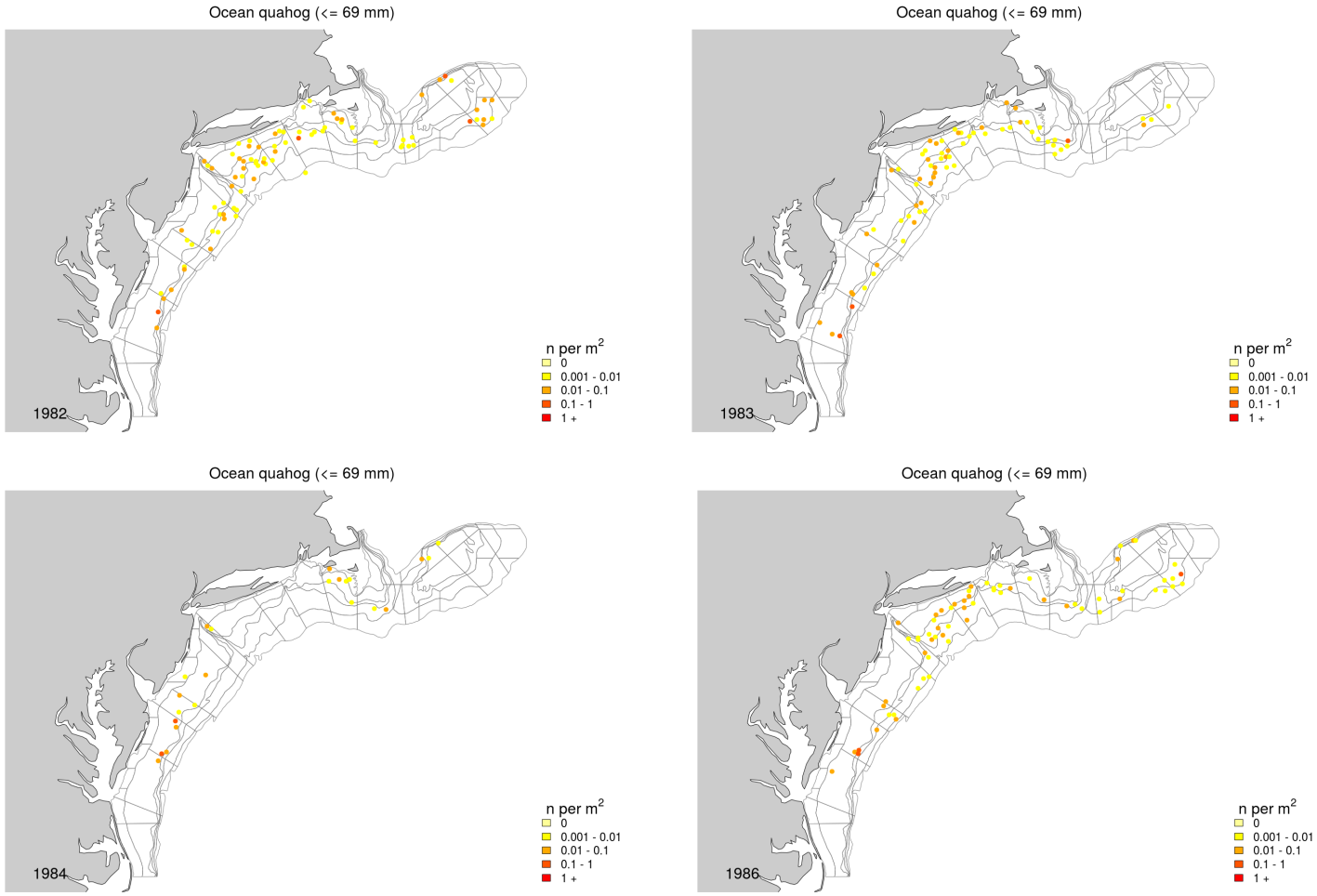

Figure 33: Survey stations where small ($<= 69\ mm$) ocean quahog were caught, by year.

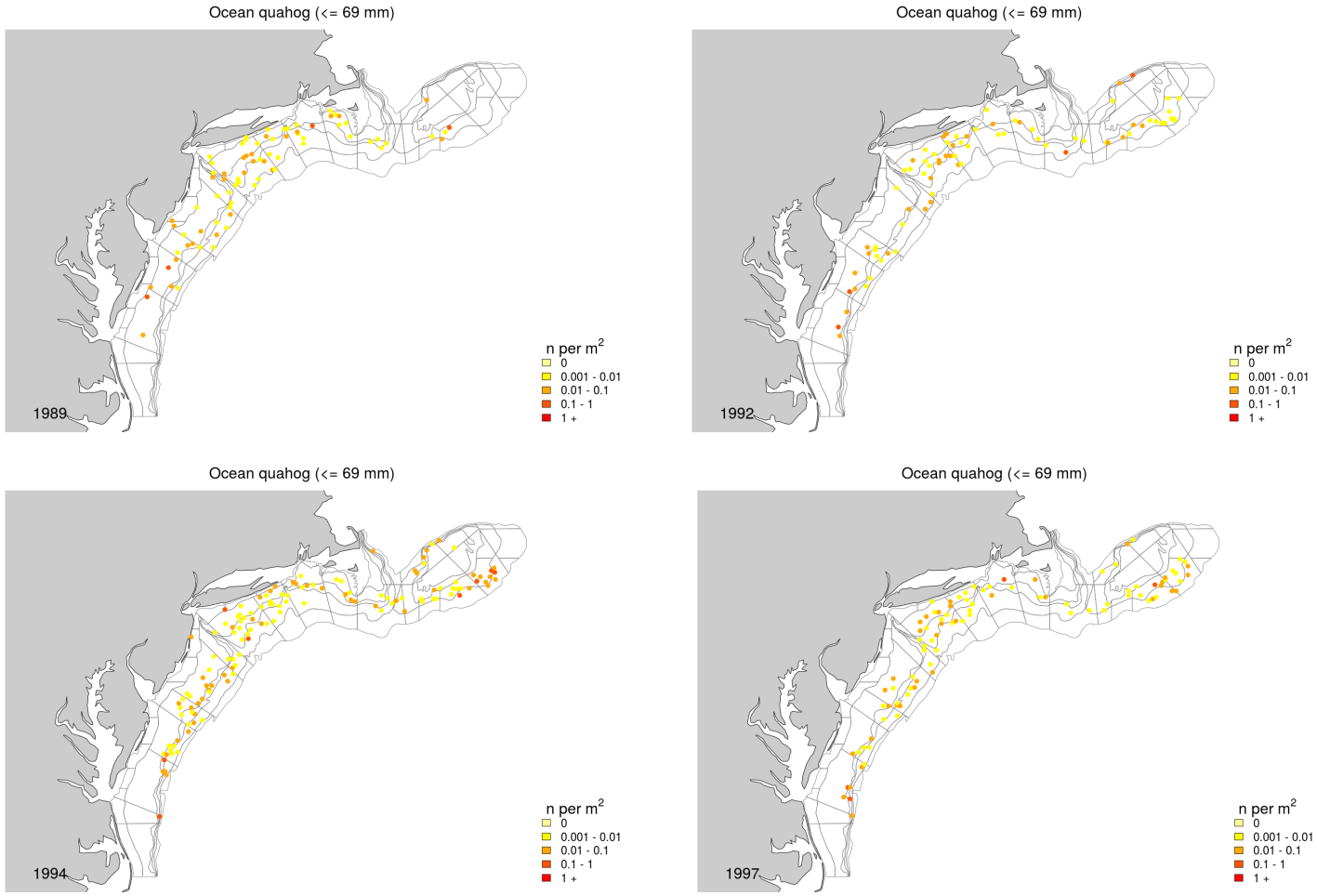

Figure 33 cont.

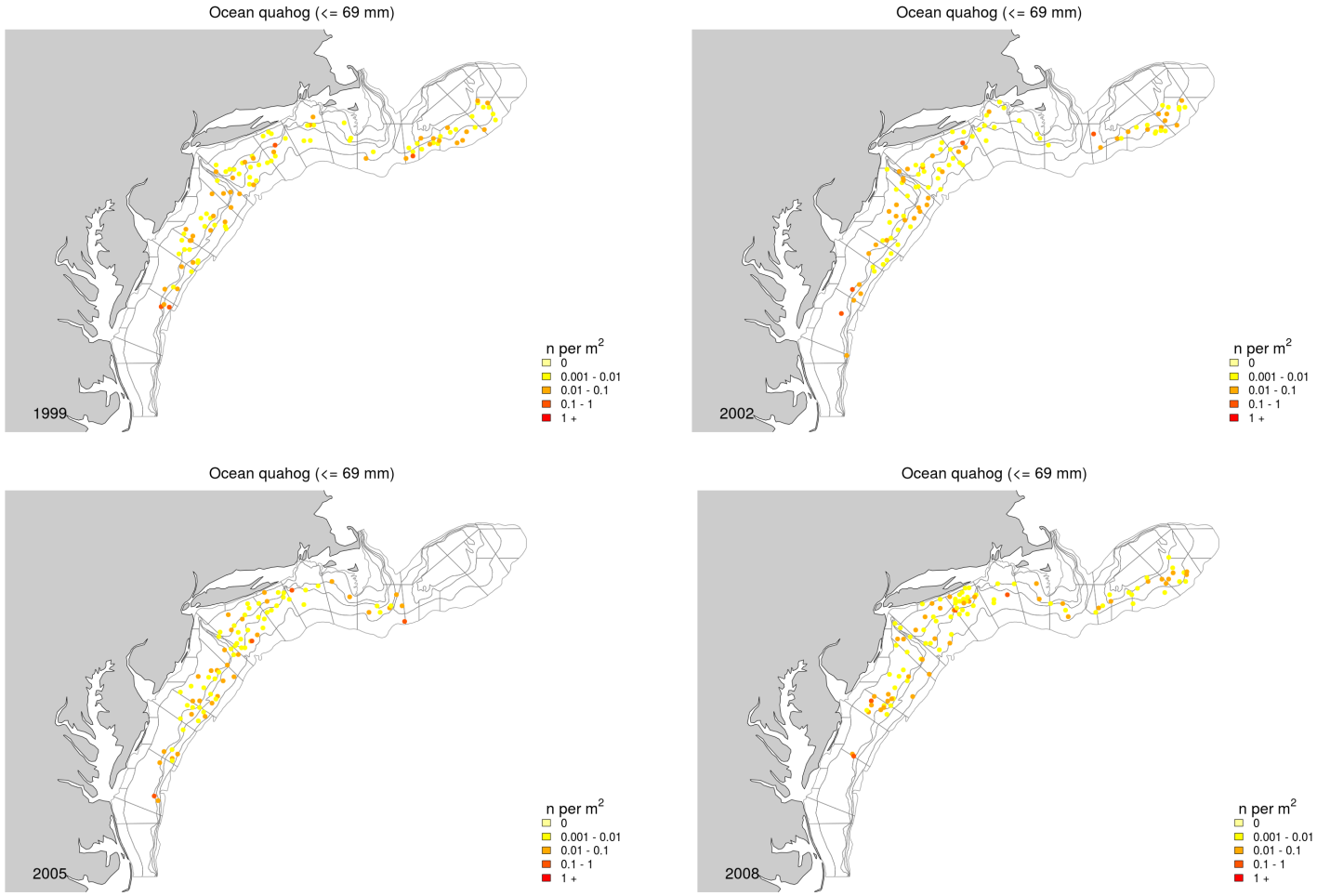

Figure 33 cont.

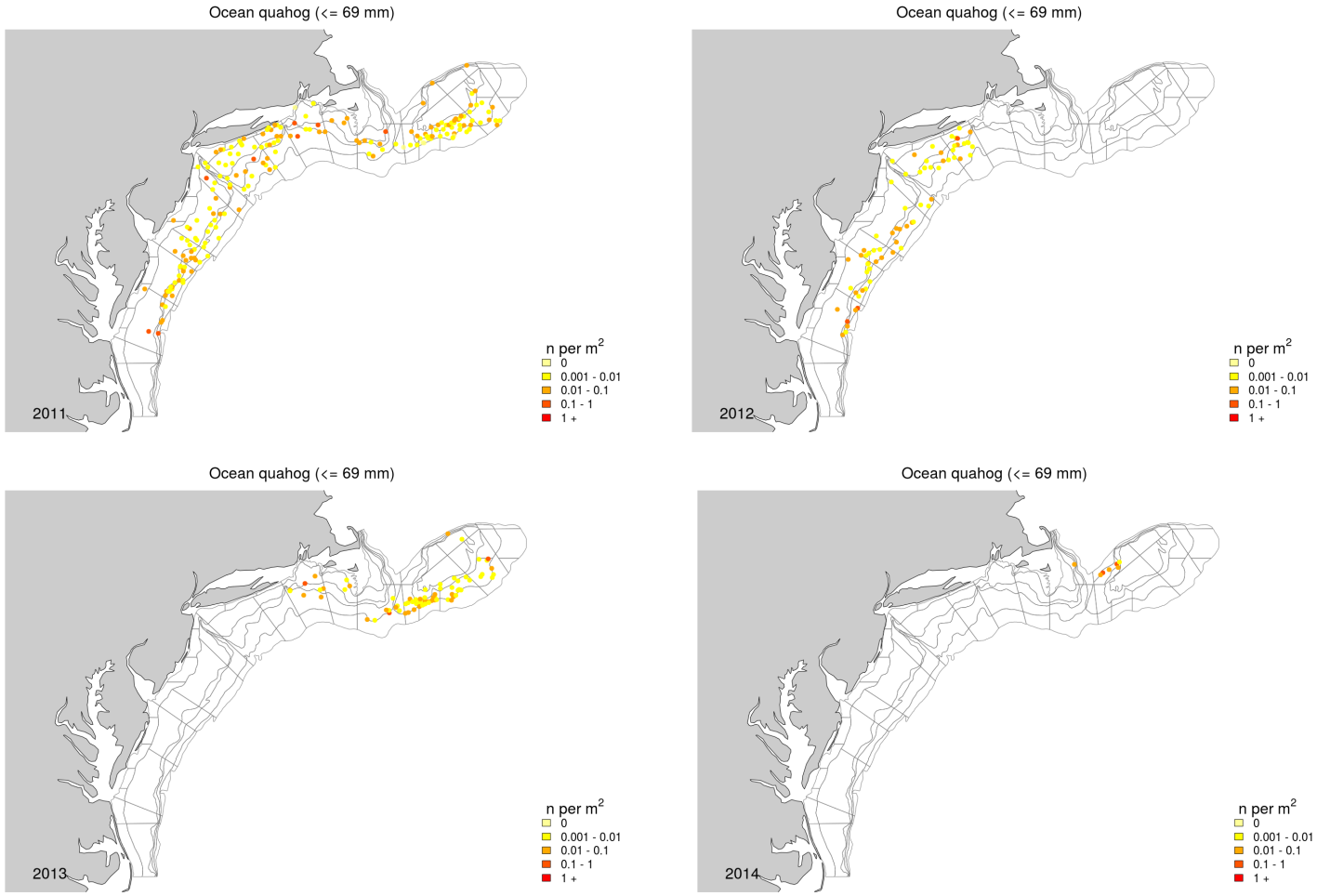

Figure 33 cont.

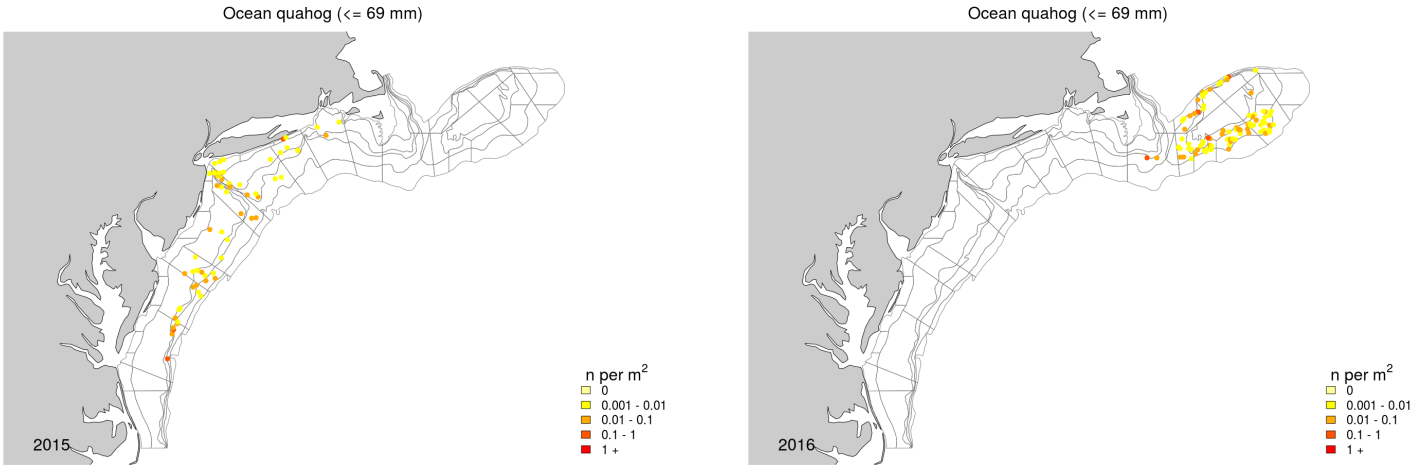

Figure 33 cont.

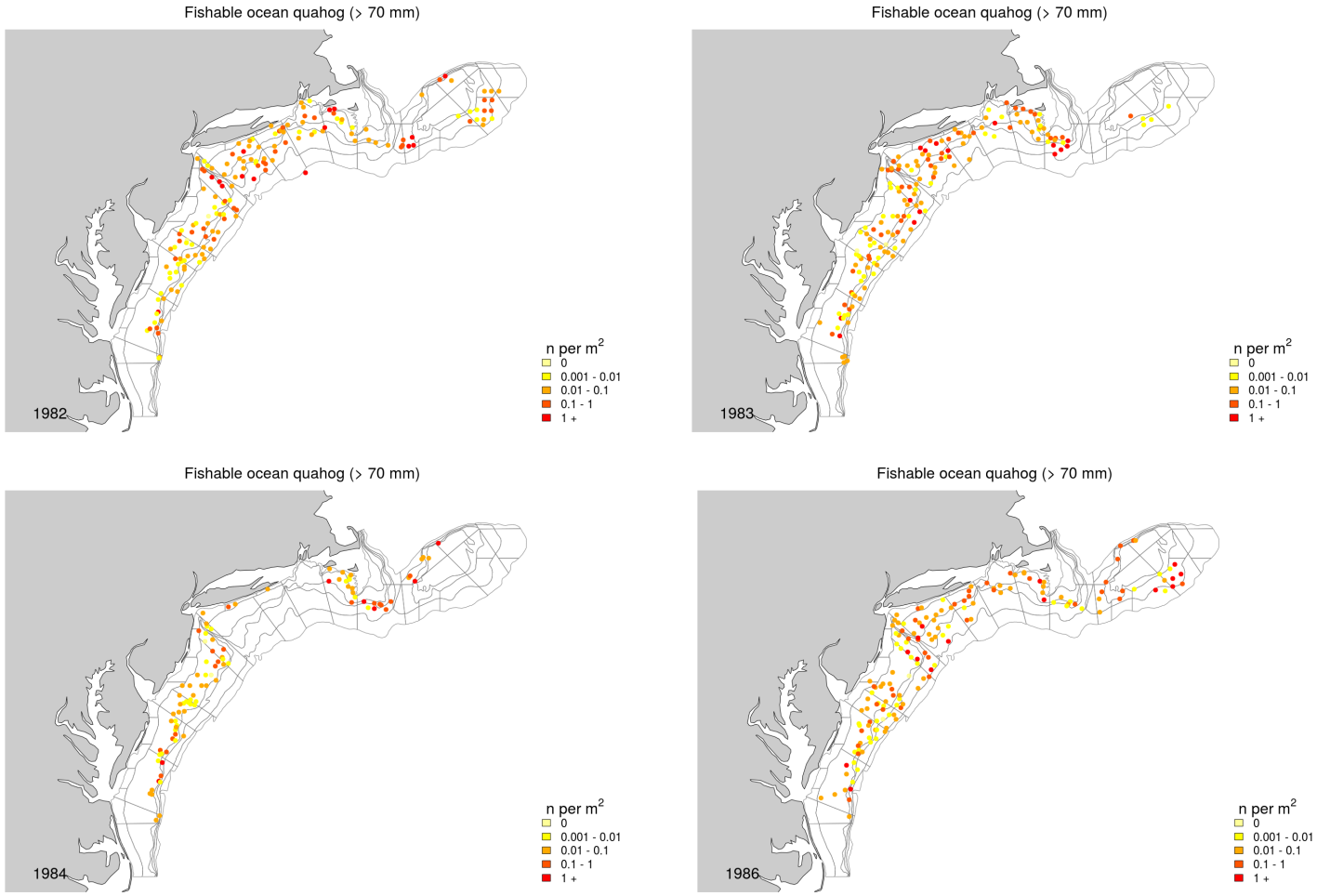

Figure 34: Survey stations where large ($>= 70\ mm$) ocean quahog were caught, by year.

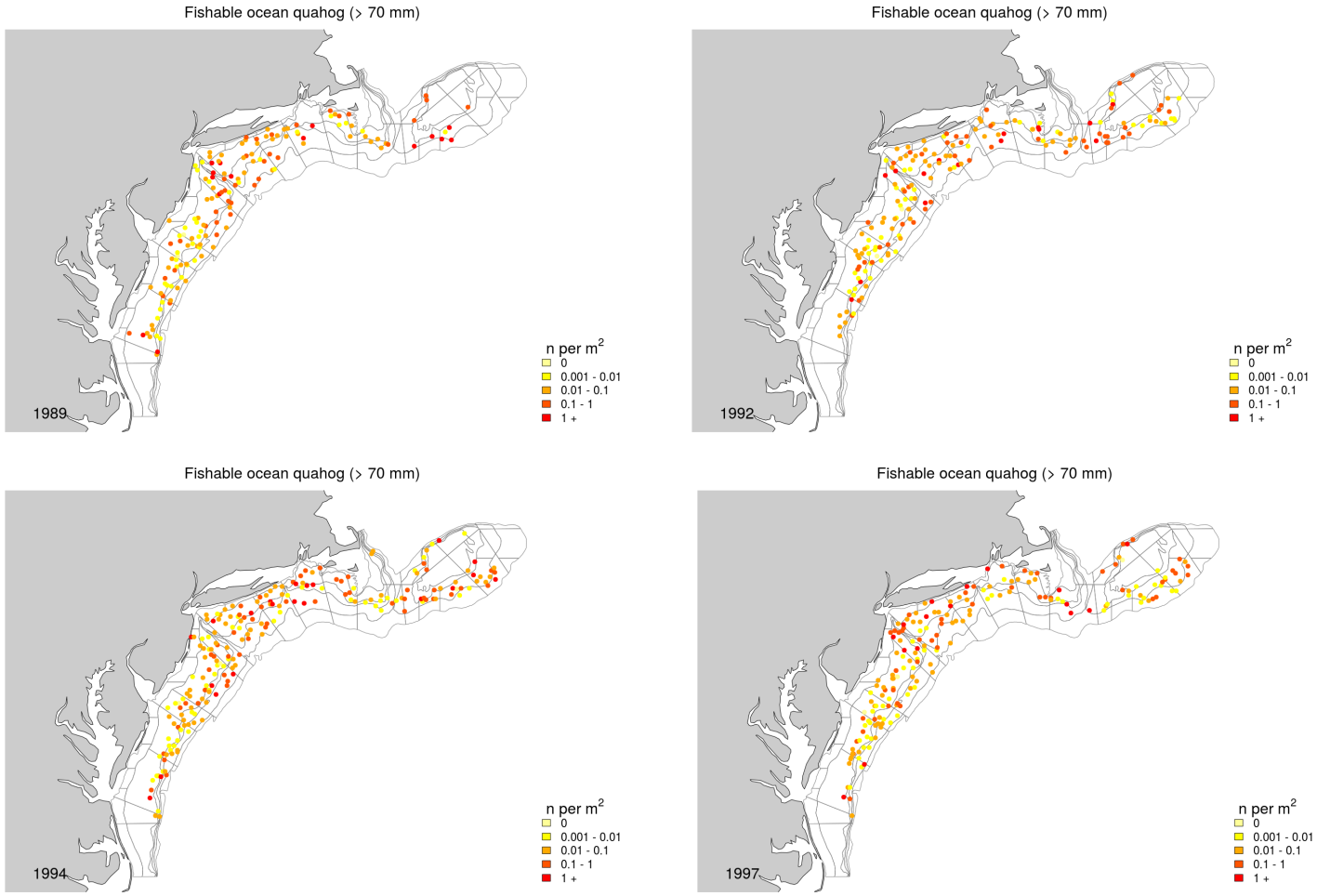

Figure 34 cont.

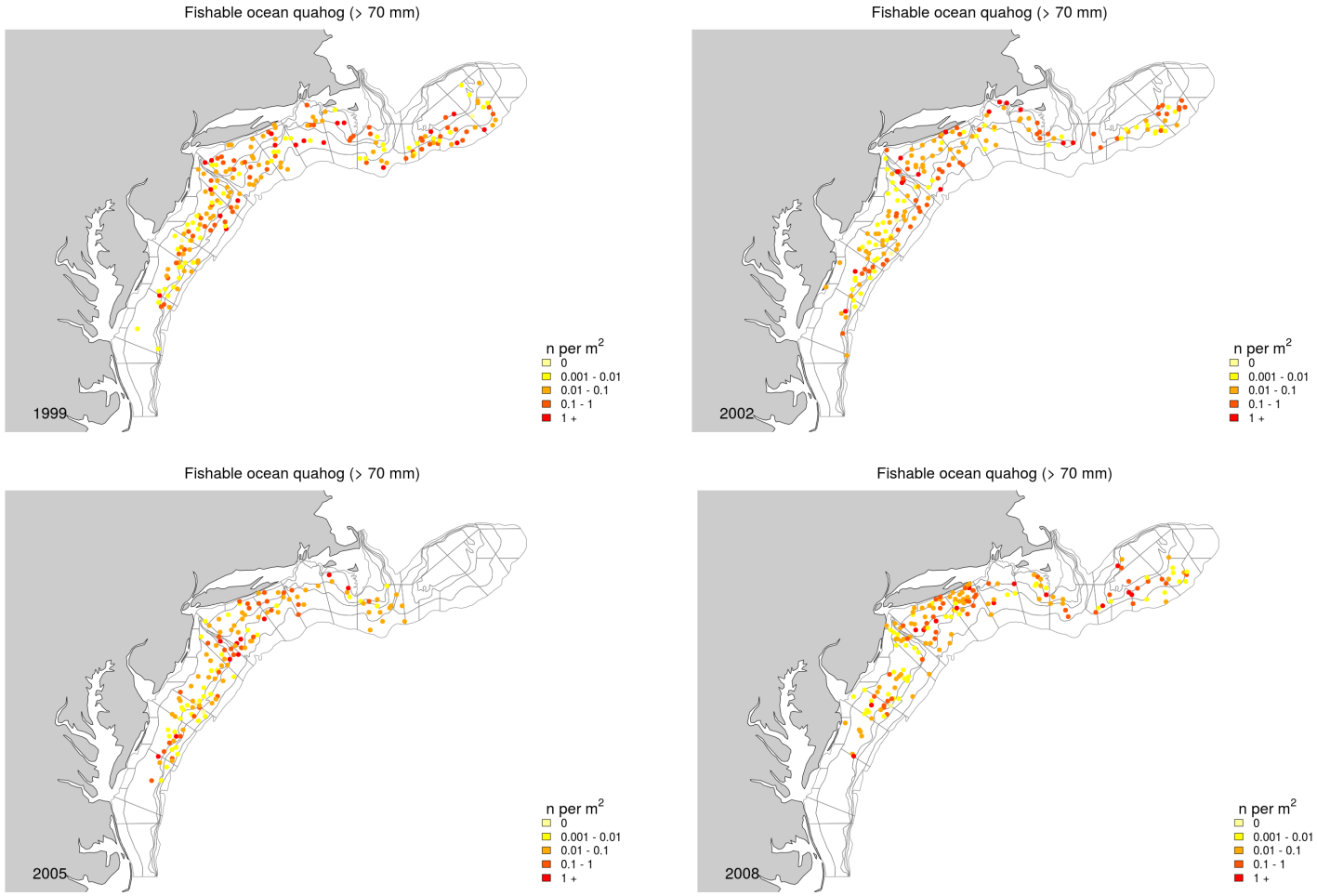

Figure 34 cont.

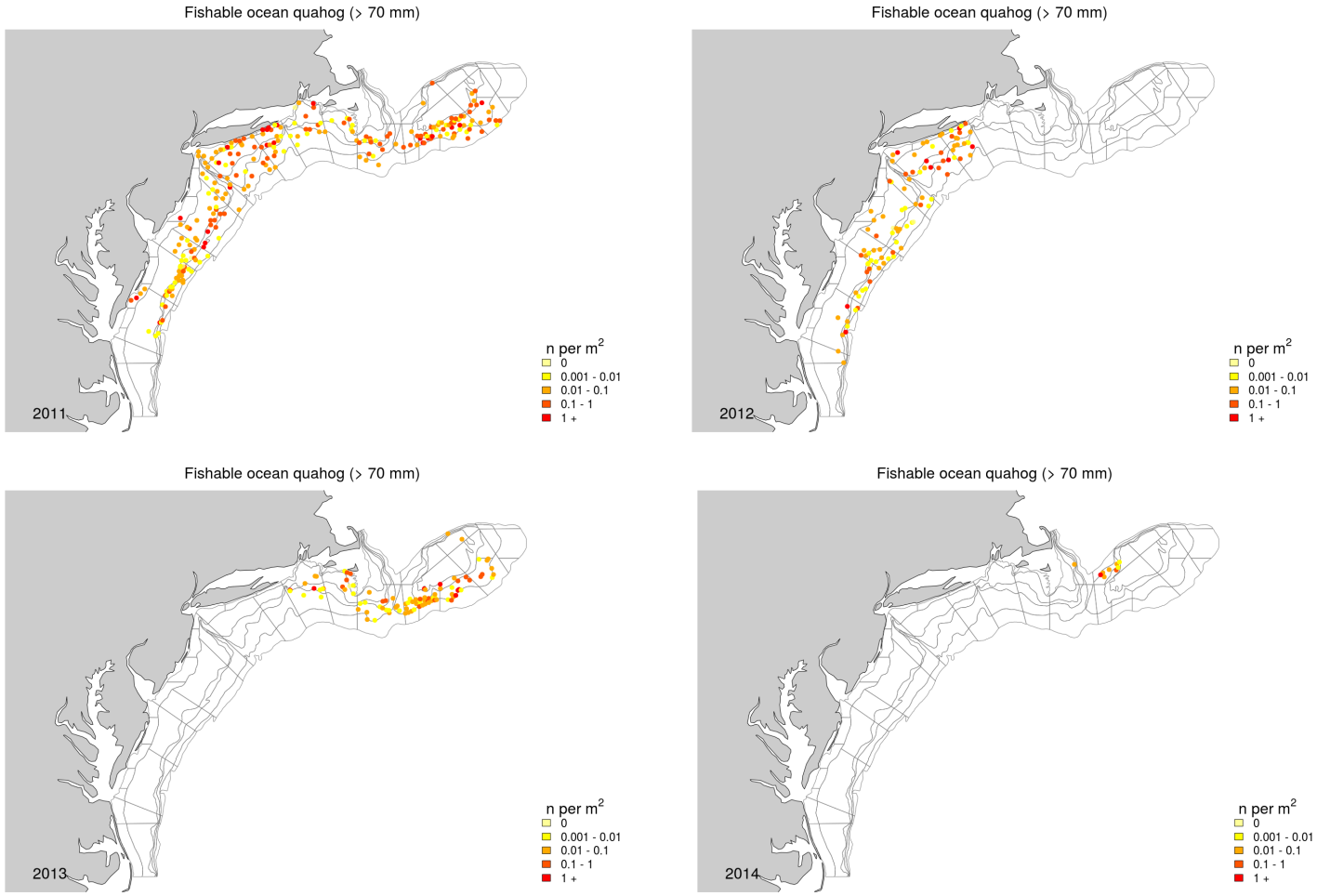

Figure 34 cont.

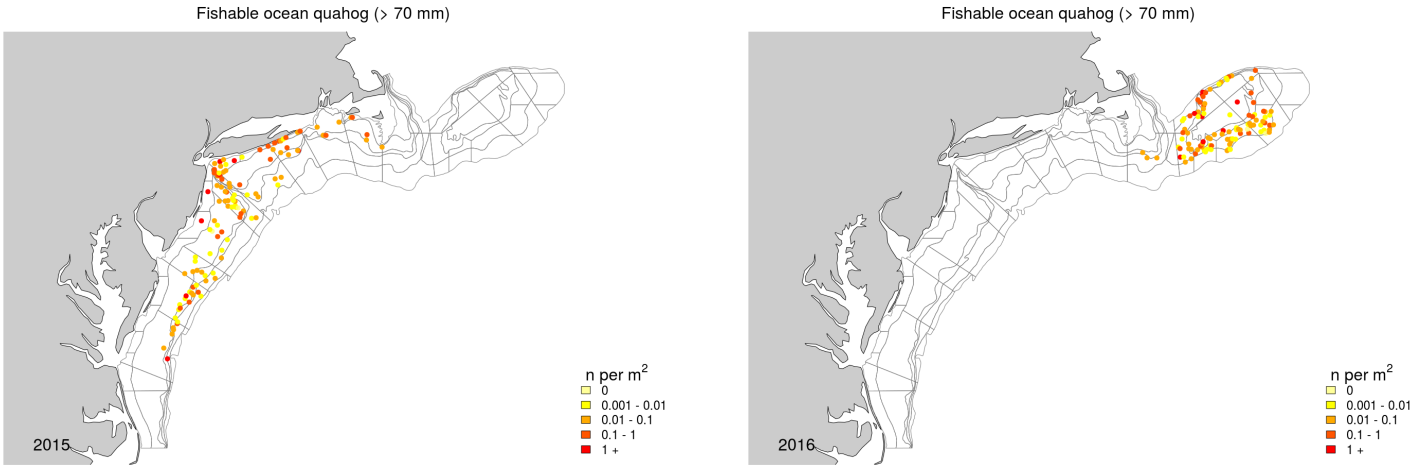

Figure 34 cont.

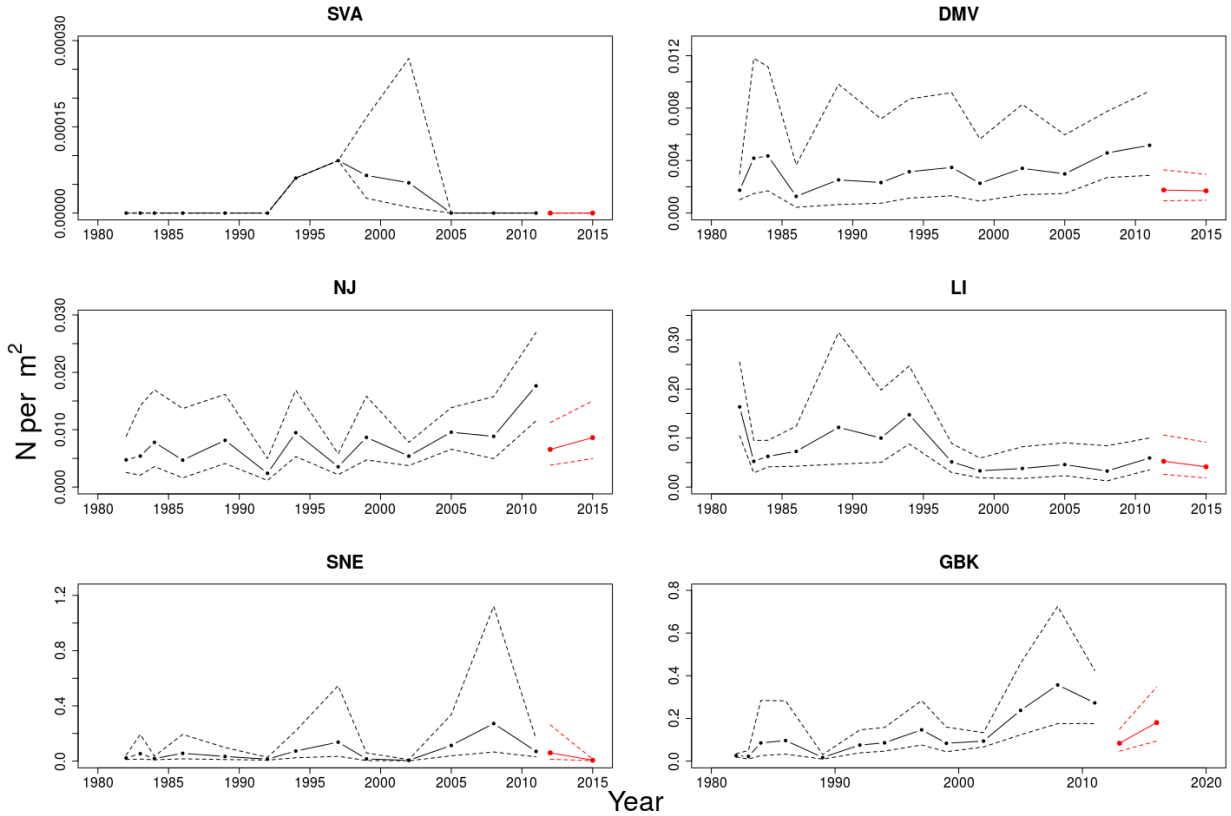

Figure 35: Trends in small ocean quahog abundance < 70 mm SL from NEFSC surveys adjusted for selectivity, but not efficiency changes in 2012, with approximate 95% asymmetric confidence intervals. Beginning in 2012, the survey was conducted from a commercial platform using a dredge with higher capture efficiency. Results from the new survey platform are shown as a separate series in red. GBK and SNE were not sampled in 2012 and SVA, DMV, NJ and LI were not sampled in 2013 or 2014.

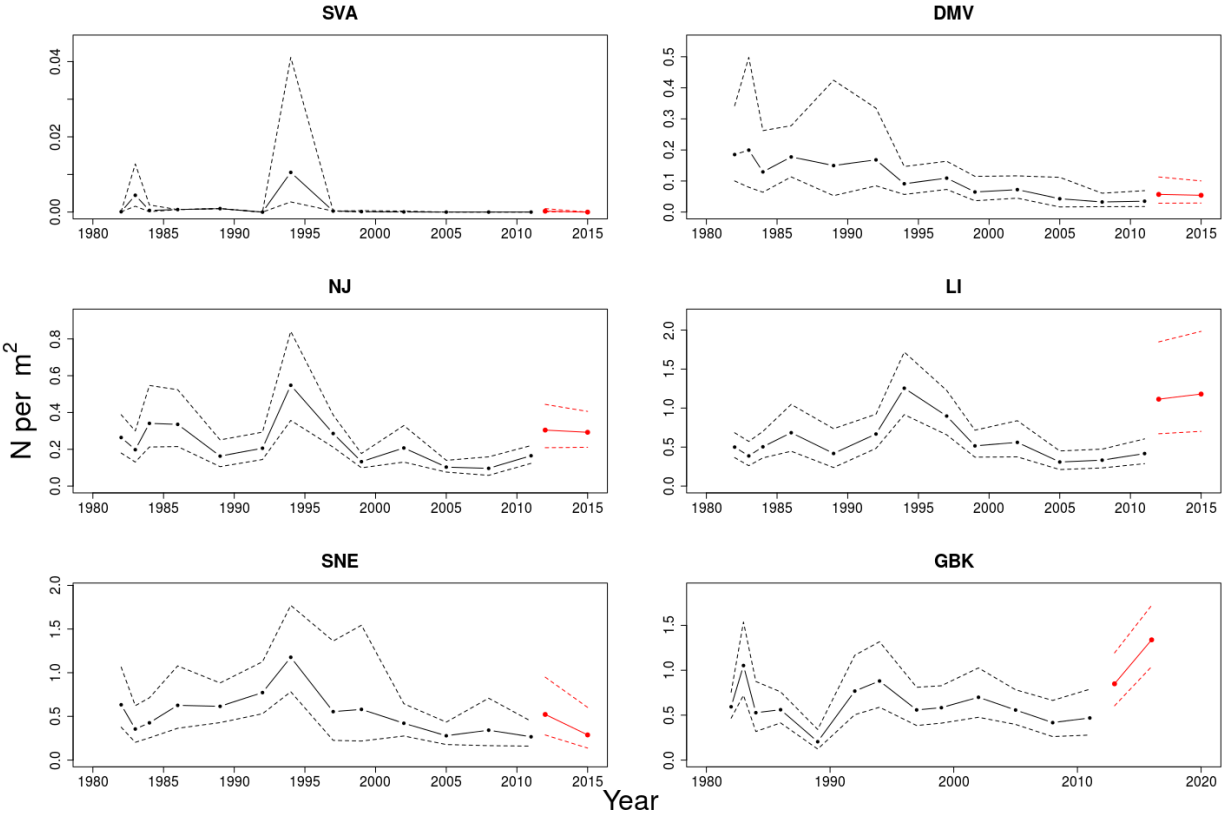

Figure 36: Trends in large ocean quahog abundance > 69 mm SL from NEFSC surveys adjusted for selectivity, but not efficiency changes in 2012, with approximate 95% asymmetric confidence intervals. Beginning in 2012, the survey was conducted from a commercial platform using a dredge with higher capture efficiency. Results from the new survey platform are shown as a separate series in red. GBK and SNE were not sampled in 2012 and SVA, DMV, NJ and LI were not sampled in 2013 or 2014.

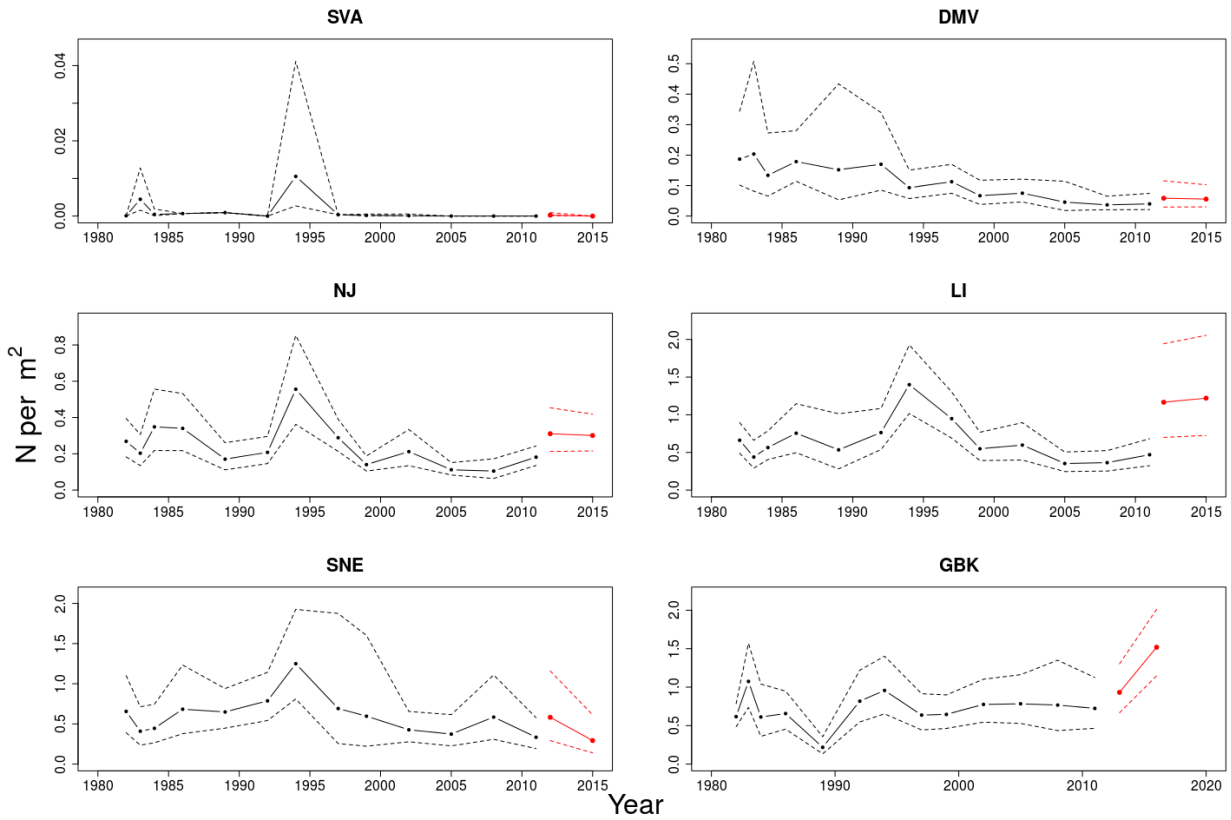

Figure 37: Trends in total ocean quahog abundance > 50 mm SL from NEFSC surveys adjusted for selectivity, but not efficiency changes in 2012, with approximate 95% asymmetric confidence intervals. Beginning in 2012, the survey was conducted from a commercial platform using a dredge with higher capture efficiency. Results from the new survey platform are shown as a separate series in red. GBK and SNE were not sampled in 2012 and SVA, DMV, NJ and LI were not sampled in 2013 or 2014.

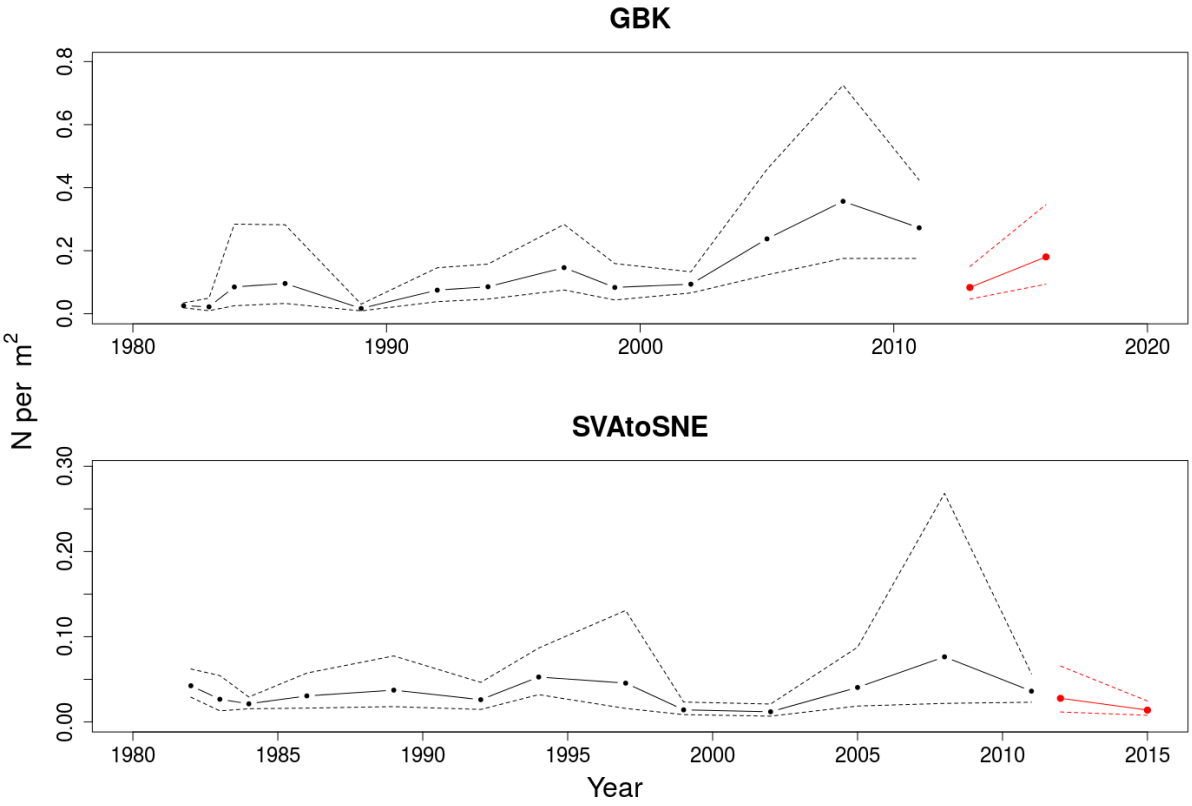

Figure 38: Trends in small ocean quahog abundance < 70 mm SL from NEFSC surveys adjusted for selectivity, but not efficiency changes in 2012, with approximate 95% asymmetric confidence intervals. Beginning in 2012, the survey was conducted from a commercial platform using a dredge with higher capture efficiency. Results from the new survey platform are shown as a separate series in red. GBK and SNE were not sampled in 2012 and SVA, DMV, NJ and LI were not sampled in 2013 or 2014.

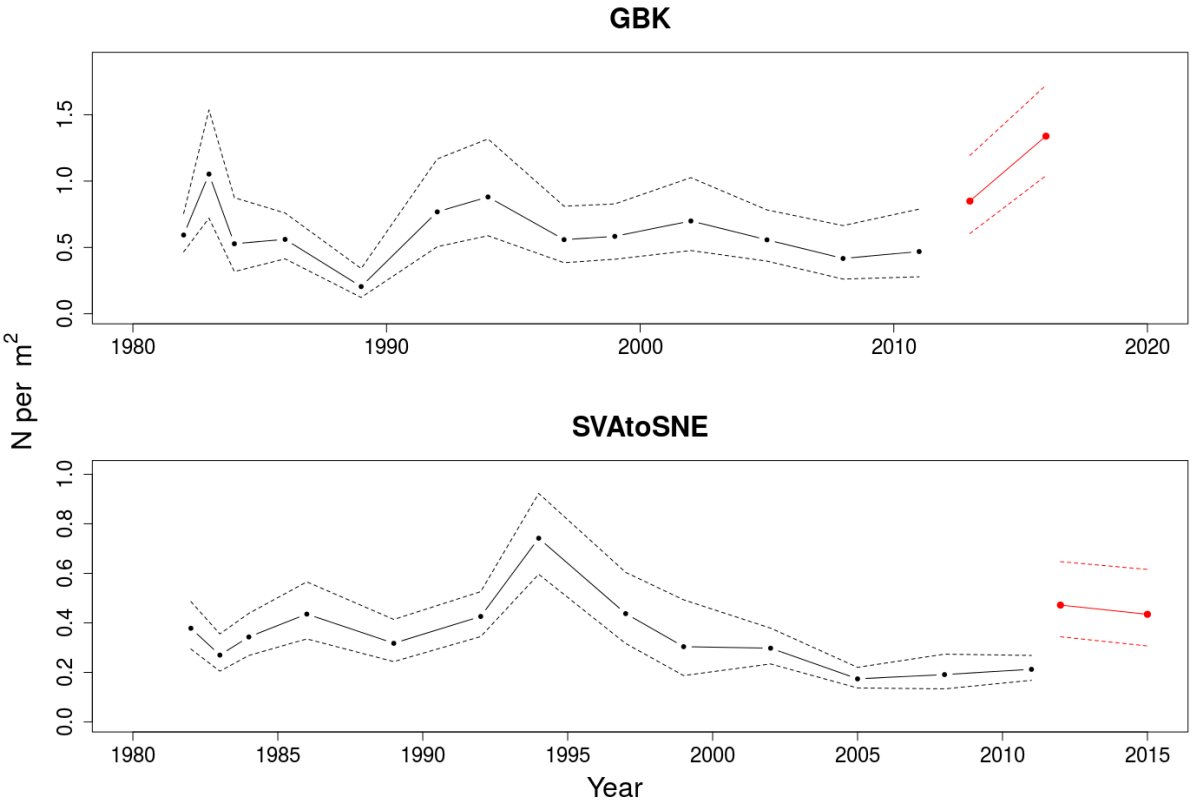

Figure 39: Trends in large Ocean quahog abundance > 69 mm SL from NEFSC surveys adjusted for selectivity, but not efficiency changes in 2012, with approximate 95% asymmetric confidence intervals. Beginning in 2012, the survey was conducted from a commercial platform using a dredge with higher capture efficiency. Results from the new survey platform are shown as a separate series in red. GBK and SNE were not sampled in 2012 and SVA, DMV, NJ and LI were not sampled in 2013 or 2014.

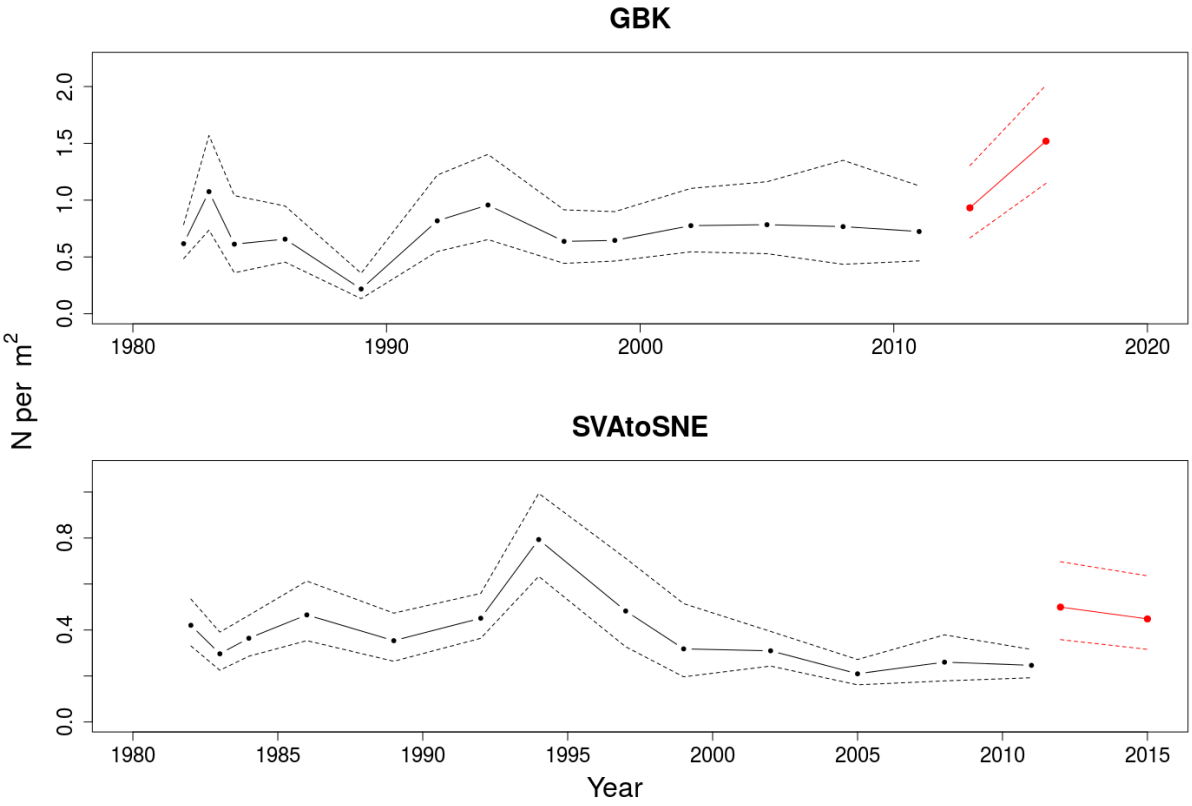

Figure 40: Trends in total Ocean quahog abundance > 50 mm SL from NEFSC surveys adjusted for selectivity, but not efficiency changes in 2012, with approximate 95% asymmetric confidence intervals. Beginning in 2012, the survey was conducted from a commercial platform using a dredge with higher capture efficiency. Results from the new survey platform are shown as a separate series in red. GBK and SNE were not sampled in 2012 and SVA, DMV, NJ and LI were not sampled in 2013 or 2014.

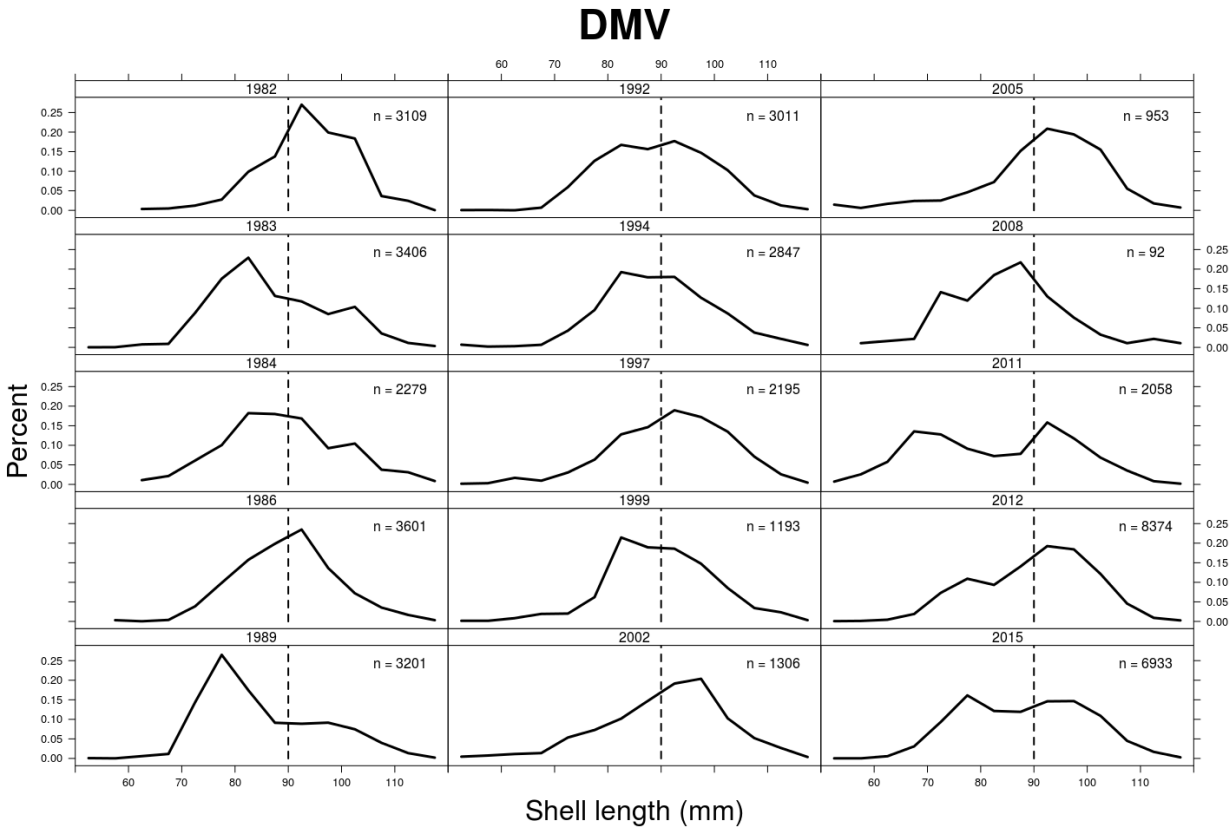

Figure 41: Length composition of NEFSC surveys in DMV. The sample sizes shown in each plot are the total number of clams caught in each survey year, not the number actually measured because a subsample of the total catch is taken when the total catch is larger than approximately 400 ocean quahog.

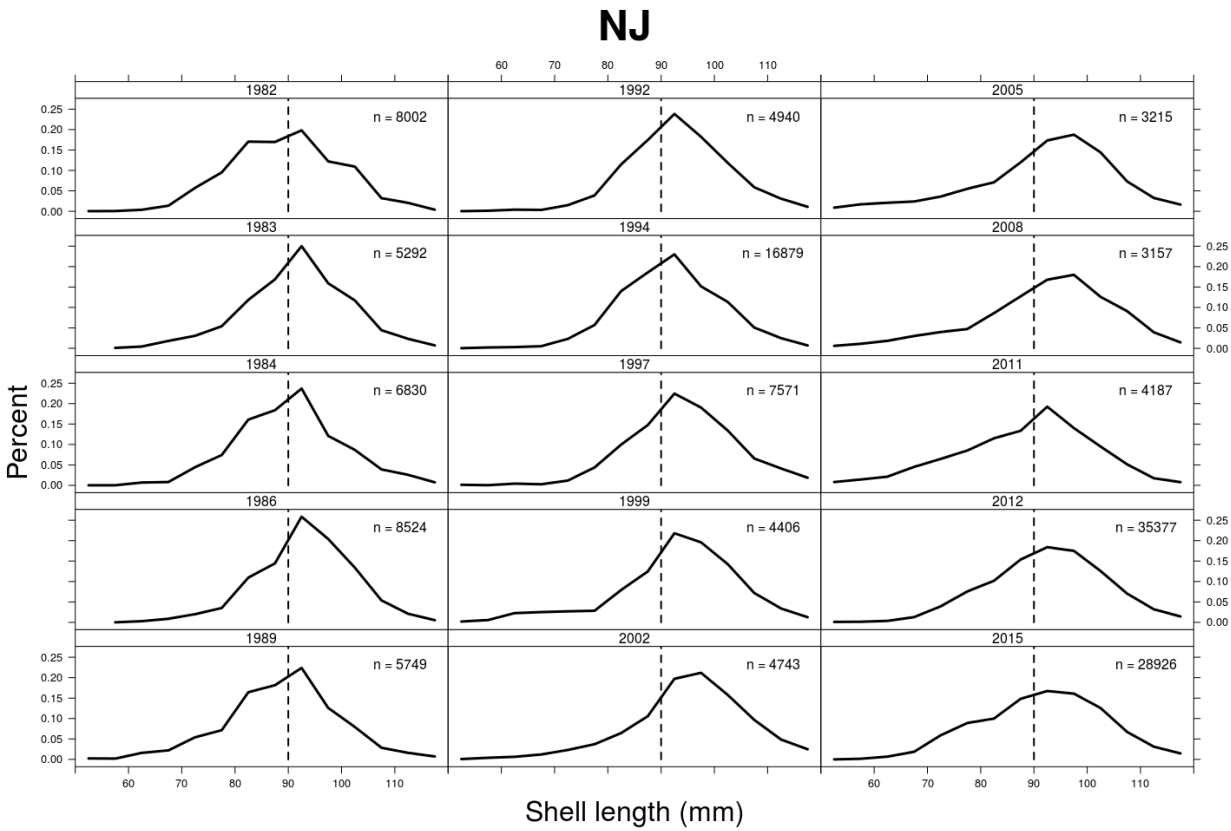

Figure 42: Length composition of NEFSC surveys in NJ. The sample sizes shown in each plot are the total number of clams caught in each survey year, not the number actually measured because a subsample of the total catch is taken when the total catch is larger than approximately 400 ocean quahog.

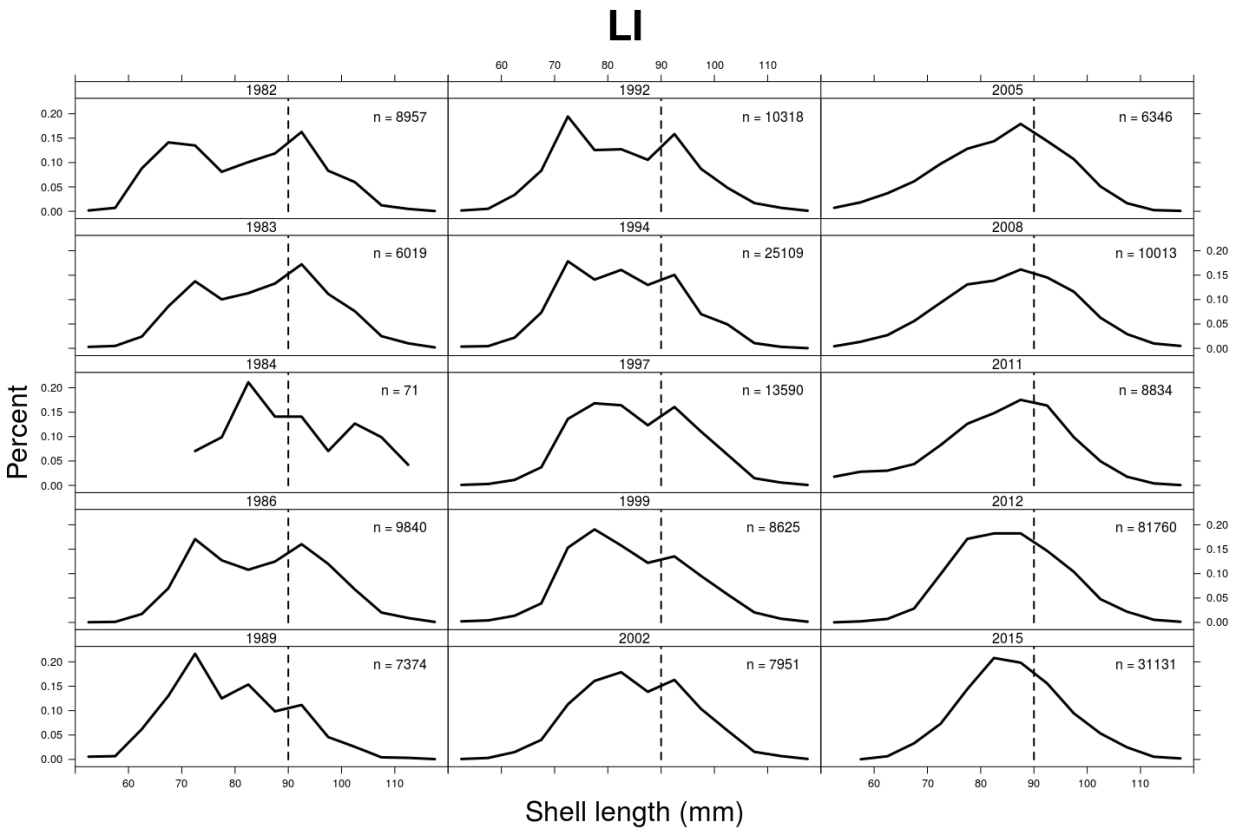

Figure 43: Length composition of NEFSC surveys in LI. The sample sizes shown in each plot are the total number of clams caught in each survey year, not the number actually measured because a subsample of the total catch is taken when the total catch is larger than approximately 400 ocean quahog.

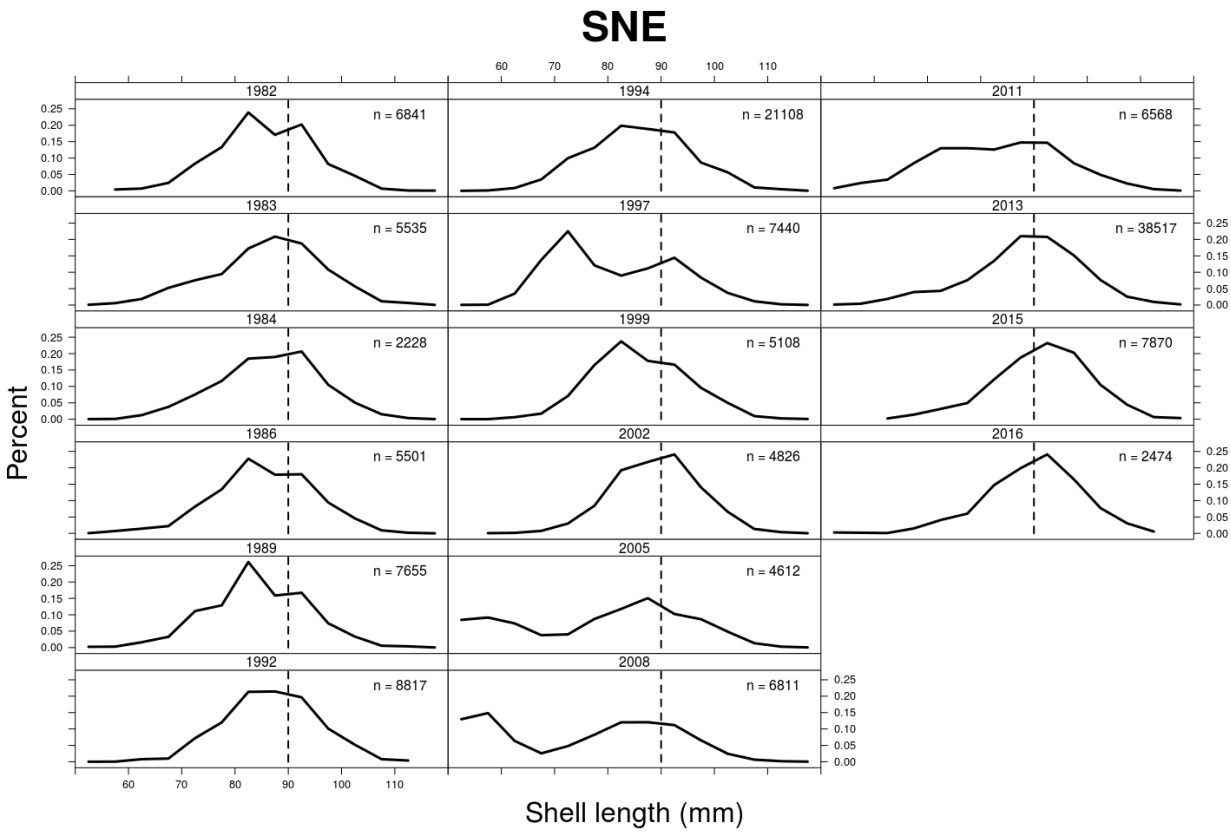

Figure 44: Length composition of NEFSC surveys in SNE. The sample sizes shown in each plot are the total number of clams caught in each survey year, not the number actually measured because a subsample of the total catch is taken when the total catch is larger than approximately 400 ocean quahog.

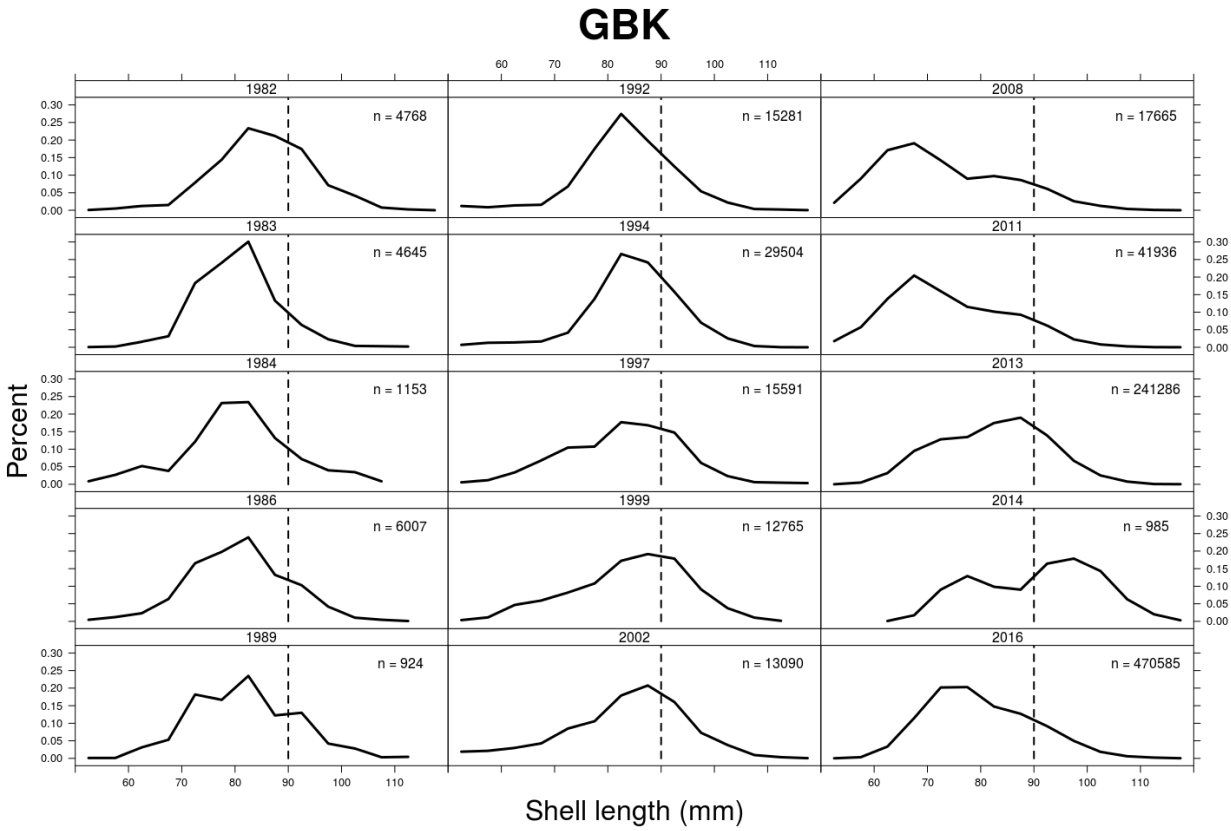

Figure 45: Length composition of NEFSC surveys in GBK. The sample sizes shown in each plot are the total number of clams caught in each survey year, not the number actually measured because a subsample of the total catch is taken when the total catch is larger than approximately 400 ocean quahog.

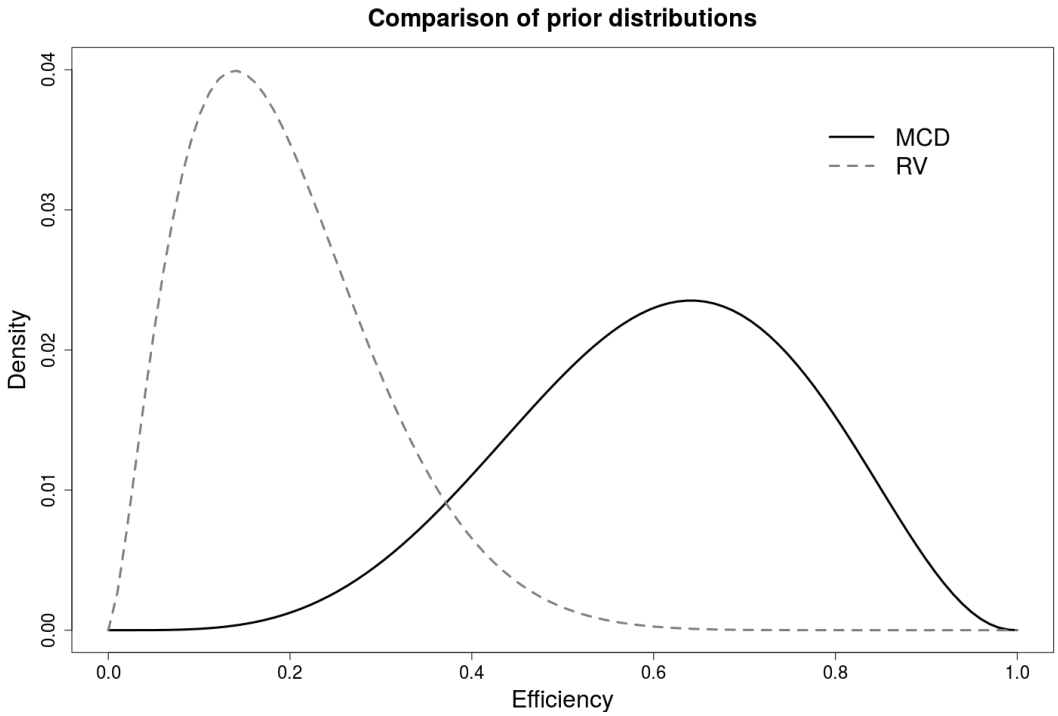

Figure 46: A comparison of the prior probability distributions for survey catchability for ocean quahog in the research dredge (RD) used prior to 2012 and the modified commercial dredge (MCD) used after 2011 based on depletion experiments. The MCD has a higher and more precisely determined estimated capture efficiency.

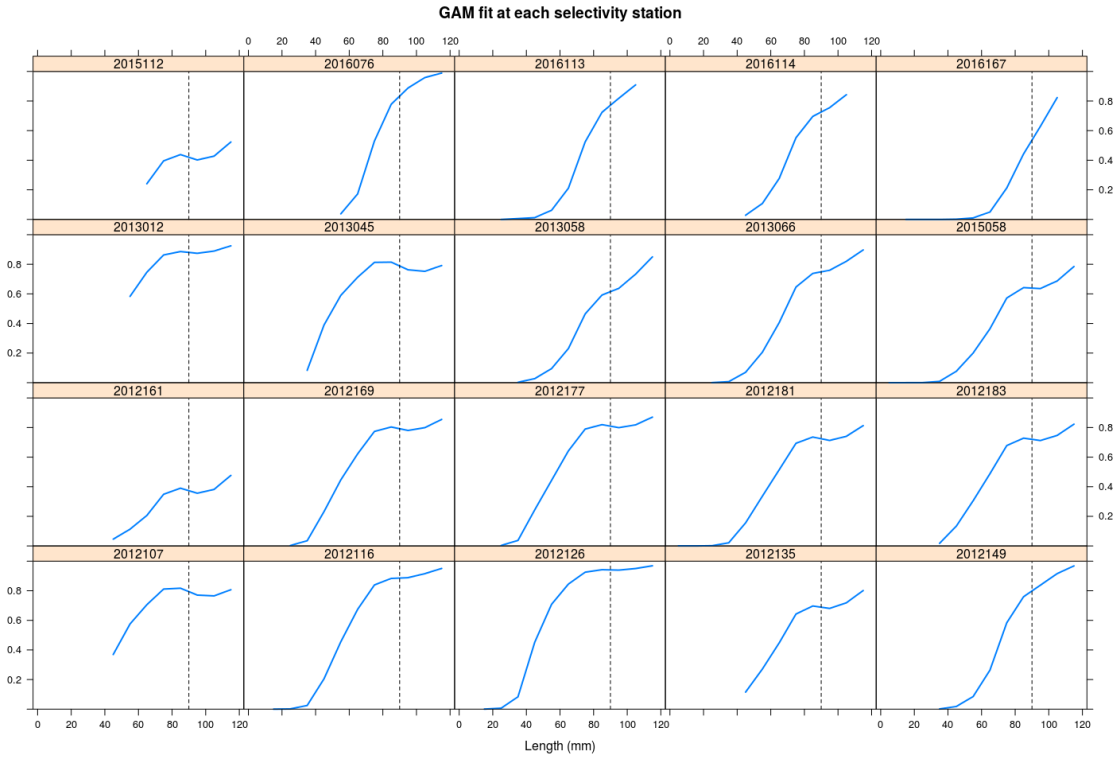

Figure 47: GAM fits to the selectivity data (modified commercial dredge compared to lined dredge) at each year and station combination. The plots generally indicate flat topped selectivity curves.

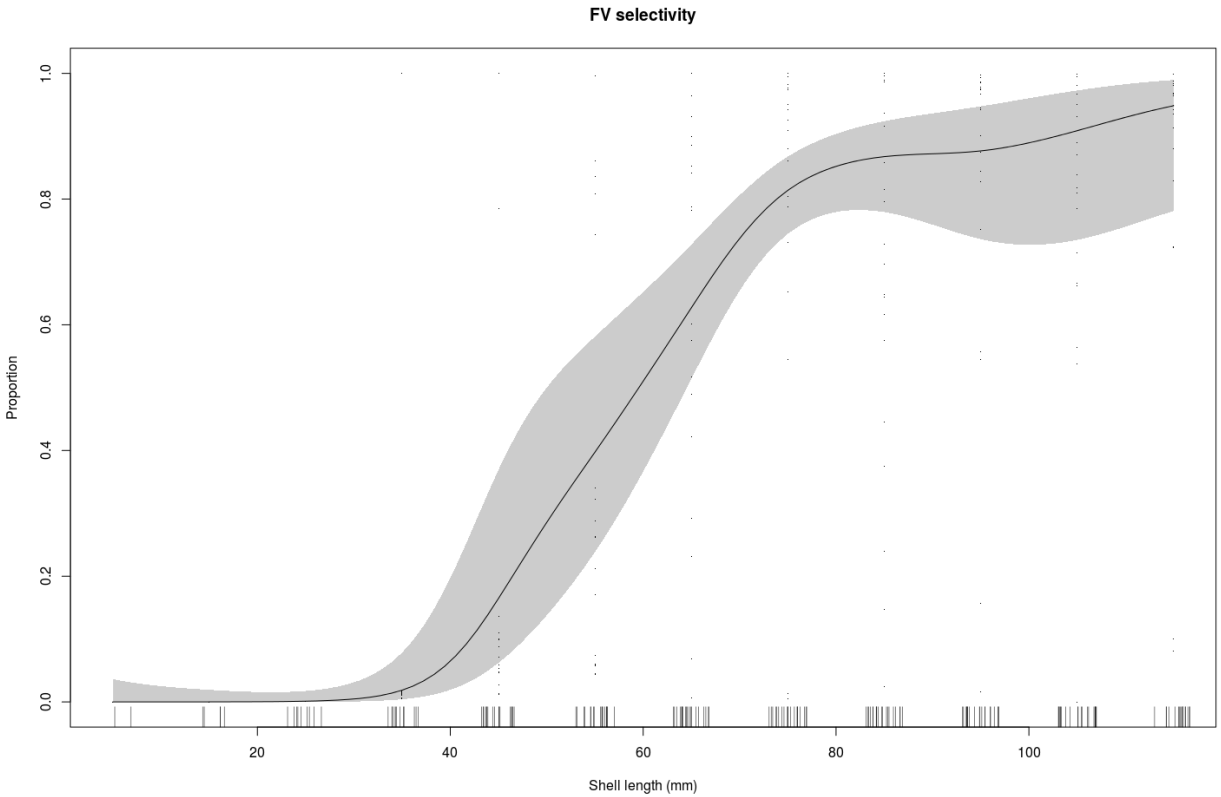

Figure 48: The GAM fit to all the selectivity data in all years. The best (by AIC) model included random effects in both the intercept and spline over length. The data density is shown in the rug plot along the horizontal axis and relative confidence is represented by the shaded region.

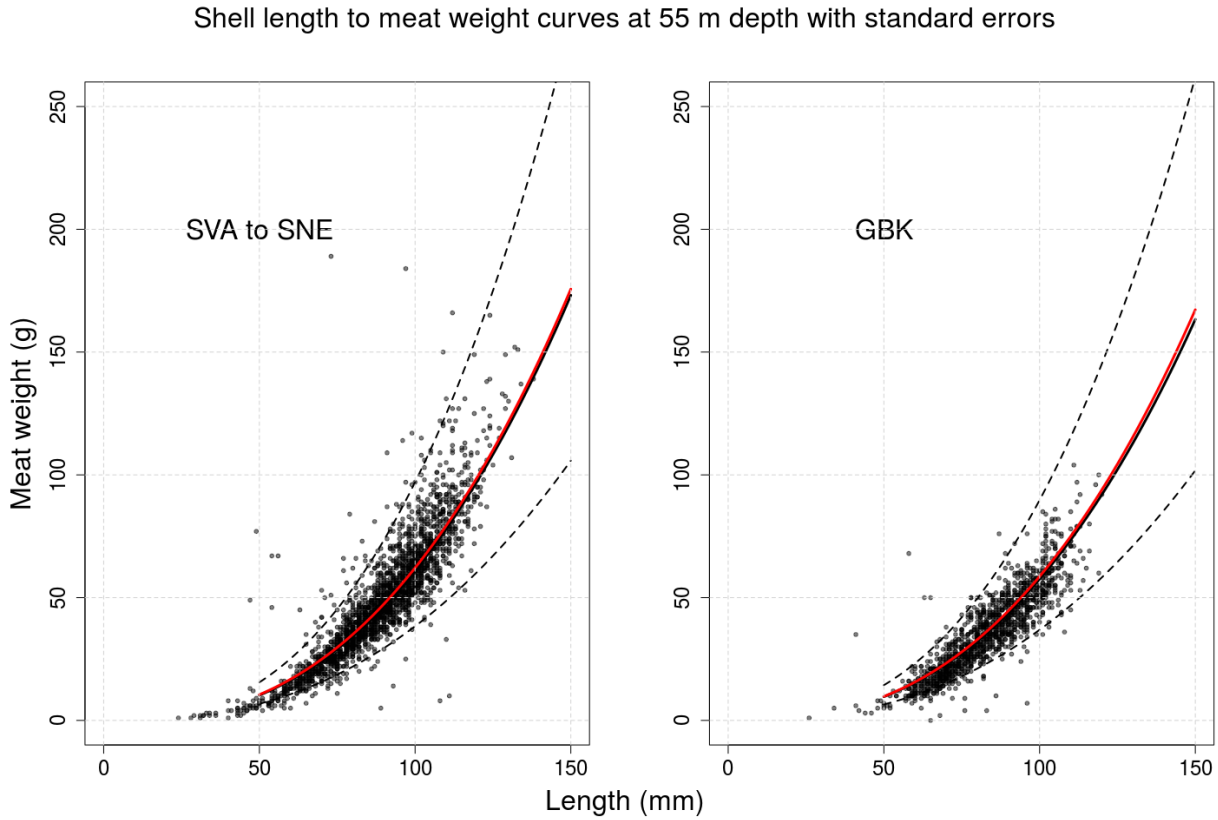

Figure 49: Broad scale area differences in allometric relationships for ocean quahog. The same depth (55 m) was used to generate the curves for each area. The 95% confidence regions are represented by the dotted line.

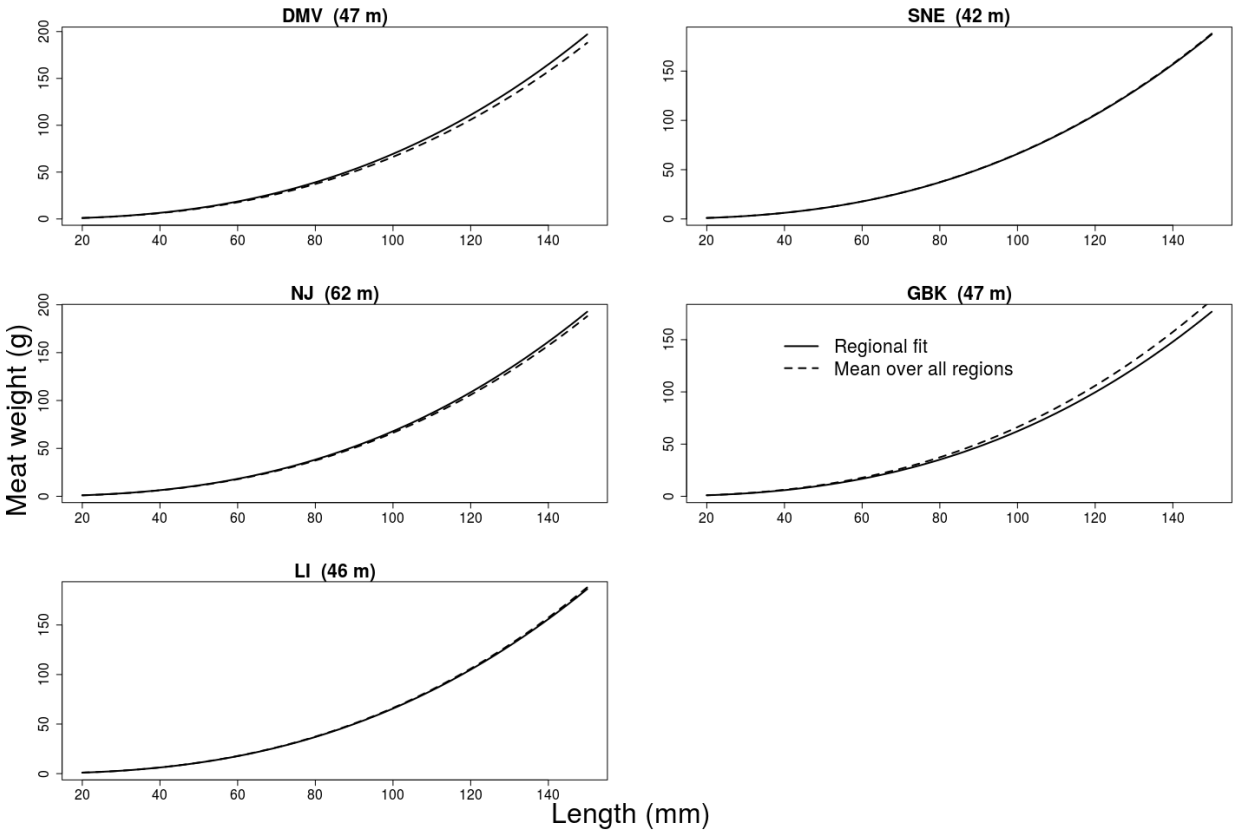

Figure 50: Regional differences in allometric relationships for ocean quahog. The median depth in each region was used to generate the curves. The global mean is represented by the dashed line.

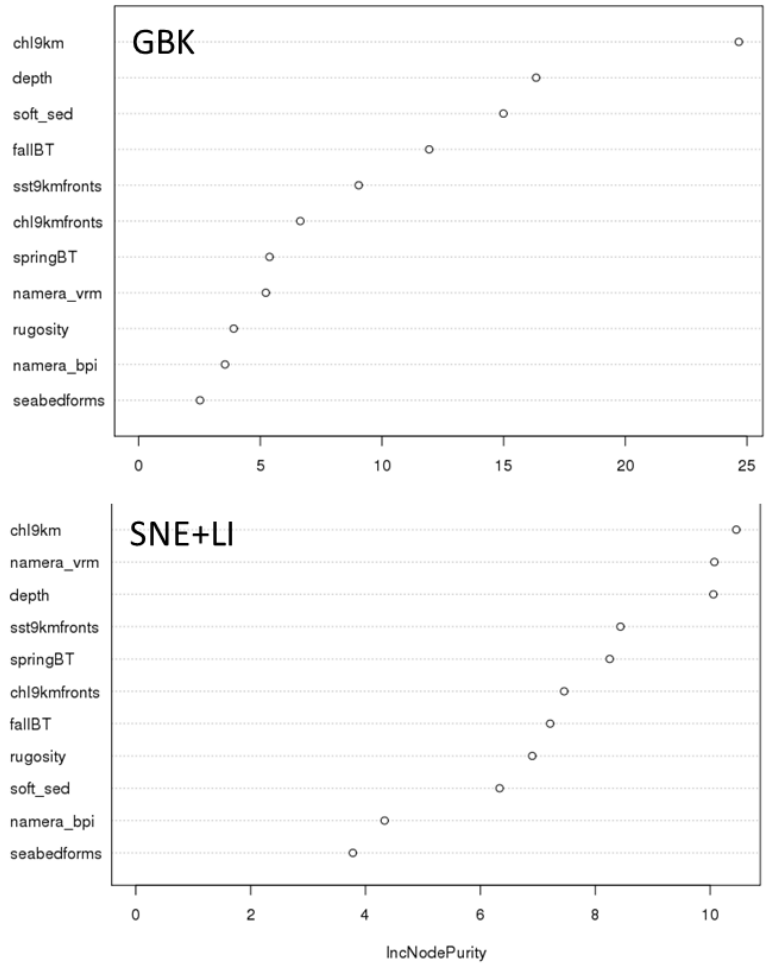

Figure 51: Variable importance plots for random forest models fit to NEFSC clam survey catches of ocean quahog in the GBK (top) and SNE+LI regions (bottom) during 1997-2011. The increase in node purity (IncNodePurity) is the average reduction in mean squared error when a variable is removed (permuted randomly) over all splits in all trees. The most important variable is at the top and other variables are listed in order of decreasing importance.

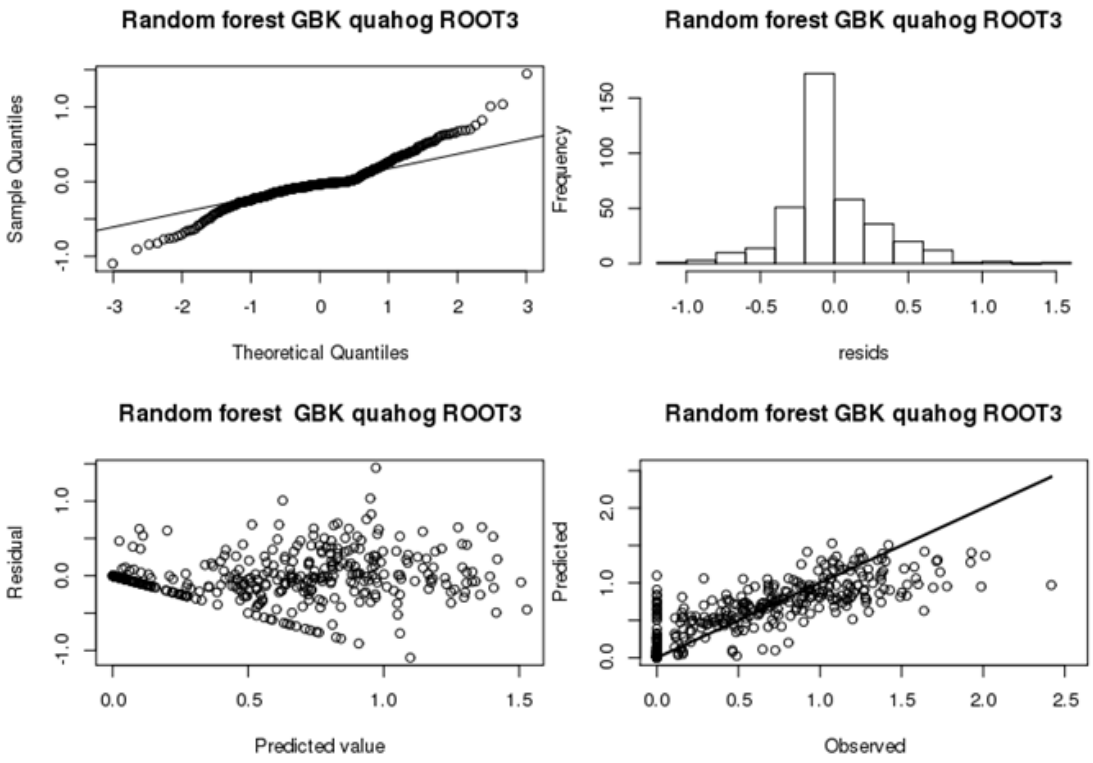

Figure 52: Ranked importance of predictor variables in random forest regression tree models for the GBK and SNE+LI regions. Rank 1 is the highest importance levels and rank 11 is the lowest.

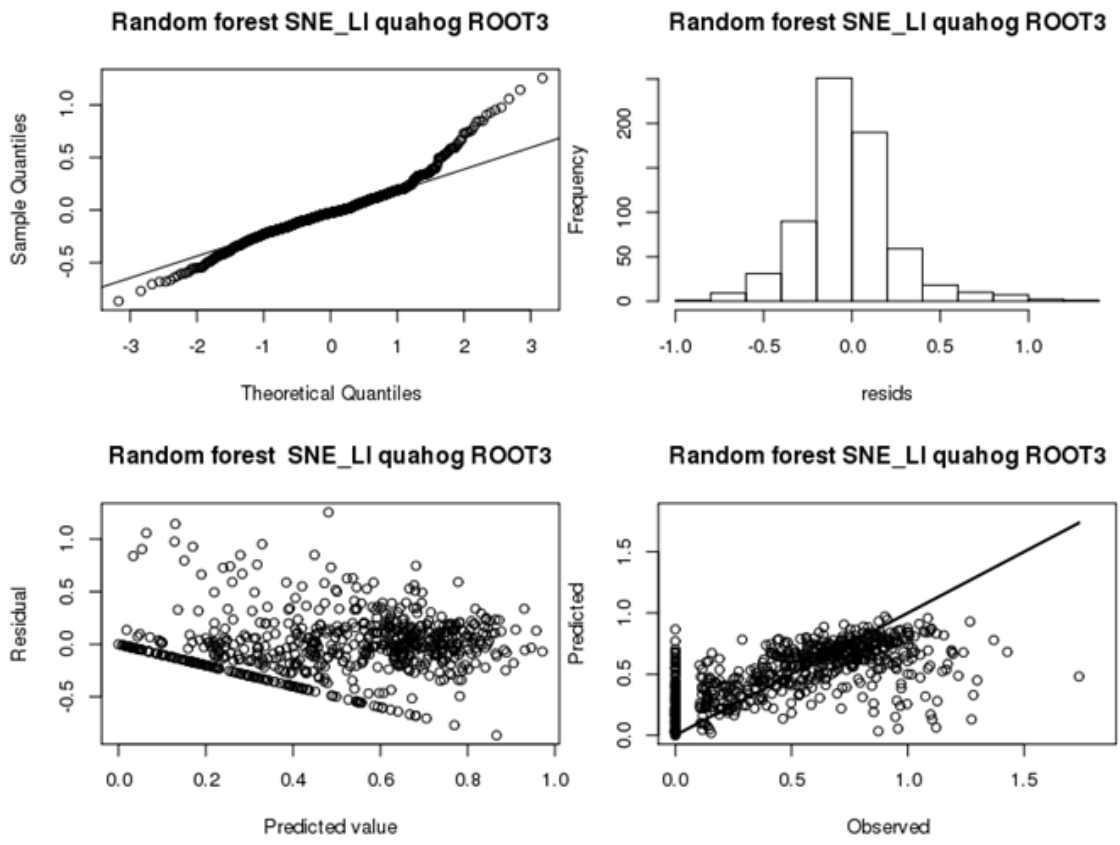

Figure 53: Residual plots for a random forest model fit to NEFSC clam survey catches of ocean quahog in the GBK region during 1997-2011. The residuals are sqrt(observed) - sqrt(predicted).

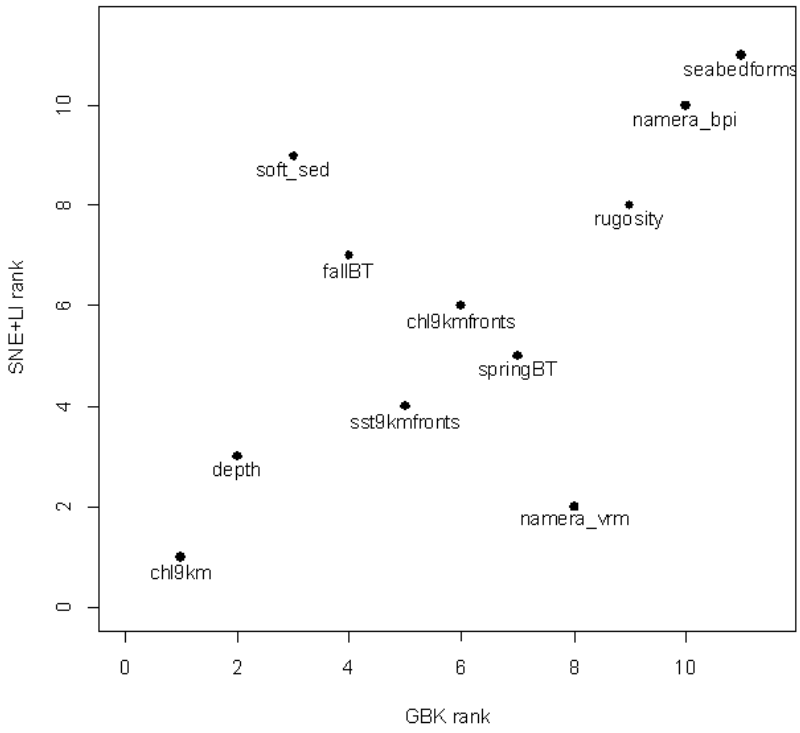

Figure 54: Residual plots for a random forest model fit for NEFSC clam survey catches of ocean quahog in the SNE+LI region during 1997-2011. The residuals are in cube root transformed units.

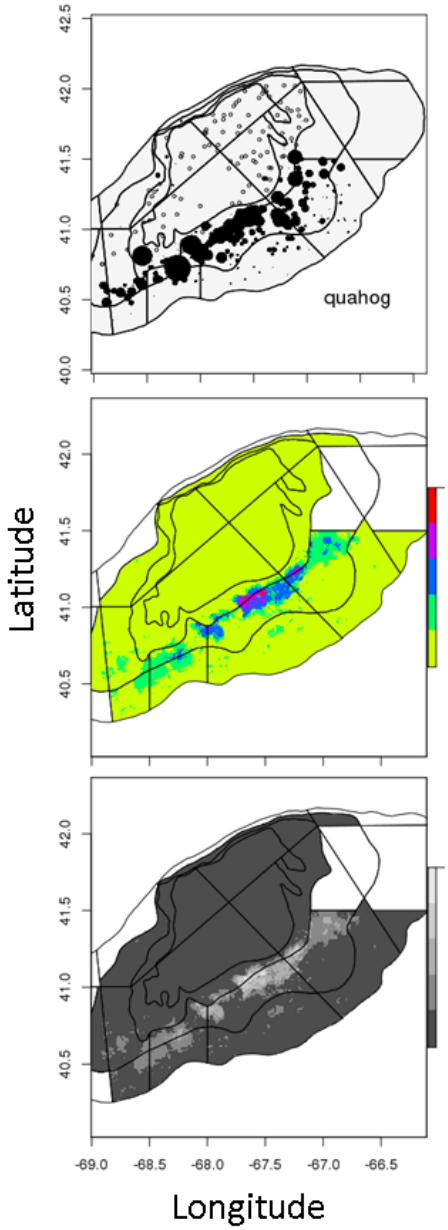

Figure 55: Survey catch data for GBK ocean quahog during 1997-2011 (top) and predicted values from a random forest regression tree (middle in color and bottom in shades of grey). Predicted values ranged from 0 to 1.4 ocean quahog m^2.

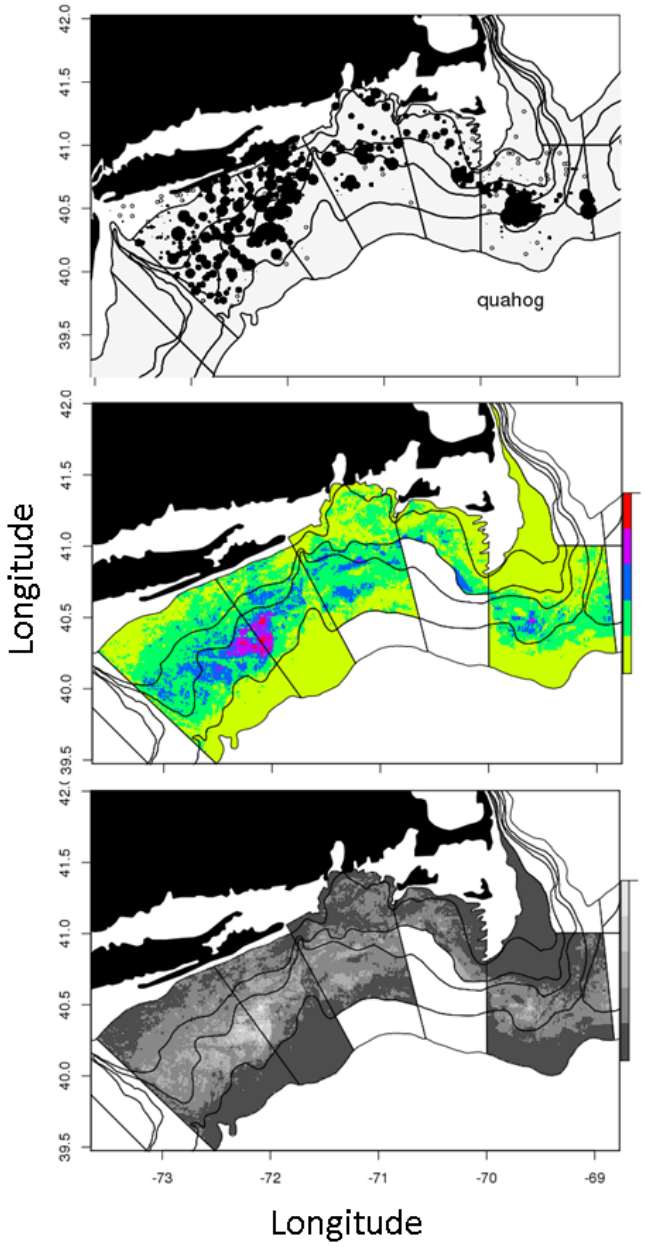

Figure 56: Survey catch data for LI+SNE ocean quahog during 1997-2011 (top) and predicted values from a random forest regression tree (middle in color and bottom in shades of grey). Predicted values ranged from 0 to 0.37 ocean quahog m^2.

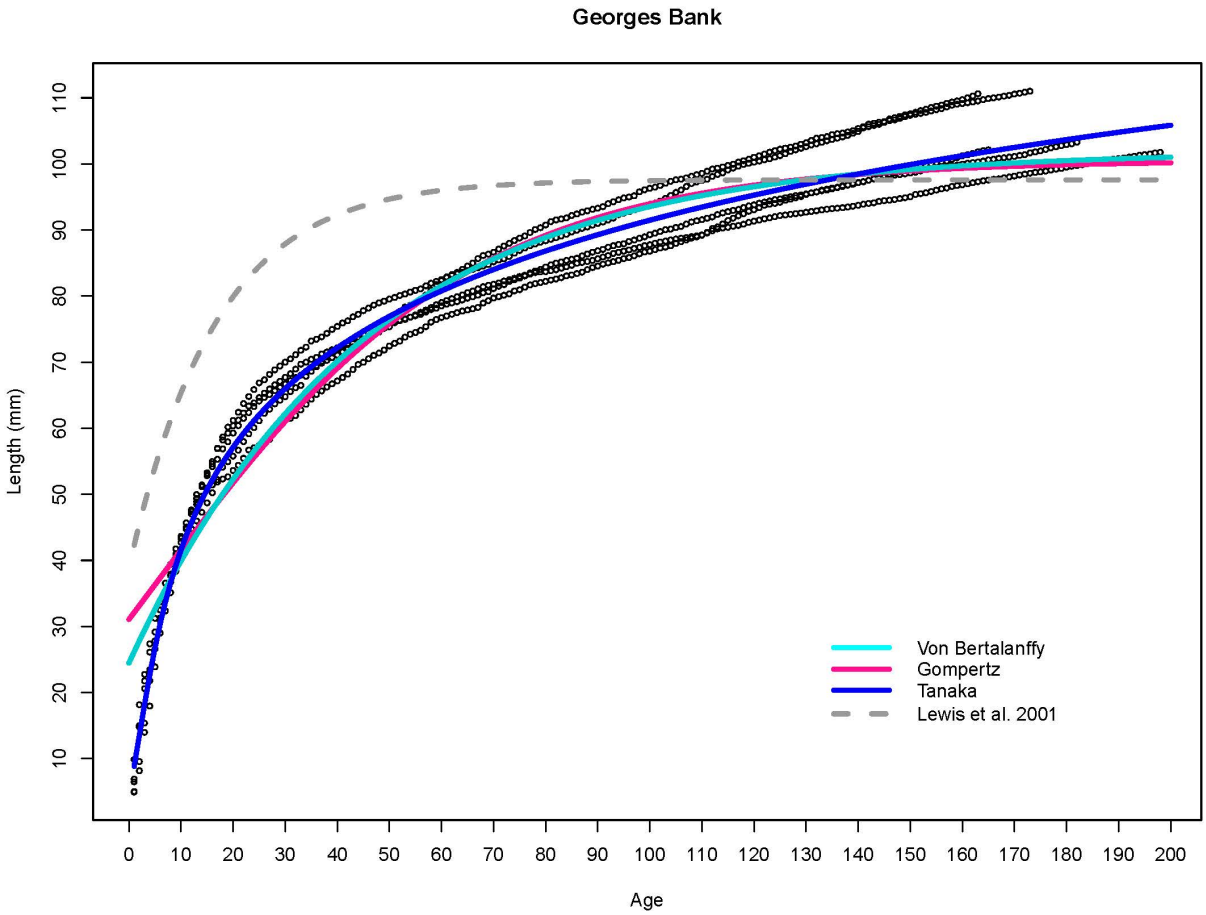

Figure 57: Top: Growth models for ocean quahog on GBK including Tanaka, Gompertz and von Bertalanffy curves fit to back calculated growth data for five ocean quahog collected at one station and a growth curve from 144 ocean quahog collected at a single survey station during 1994 (Lewis et al. 2001). This information was compiled after discussions by the Working Group.

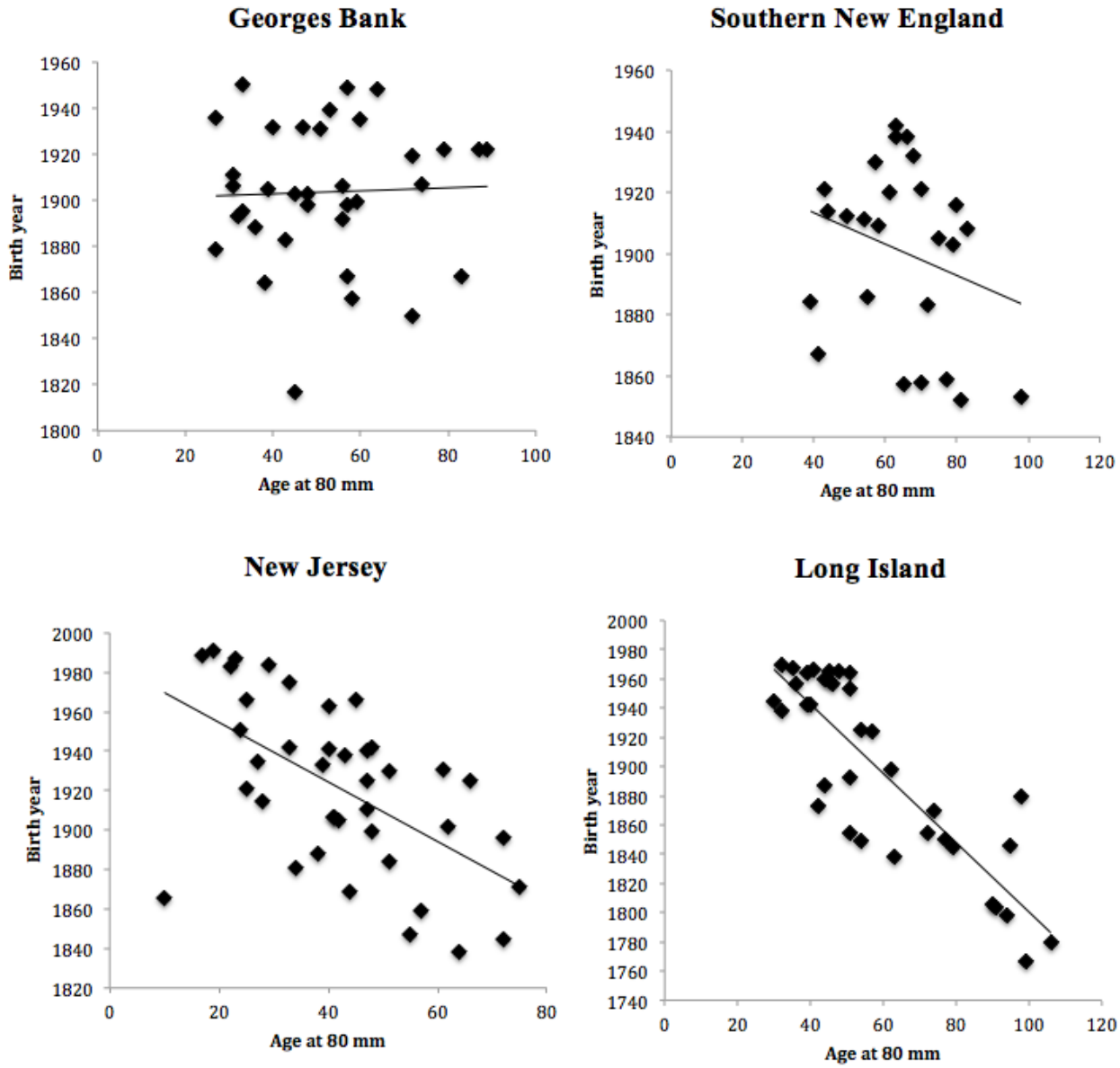

Figure 58: Birth year (age = 2015 - birth year) at 80 mm SL for ocean quahog collected at one station in each of four regions.

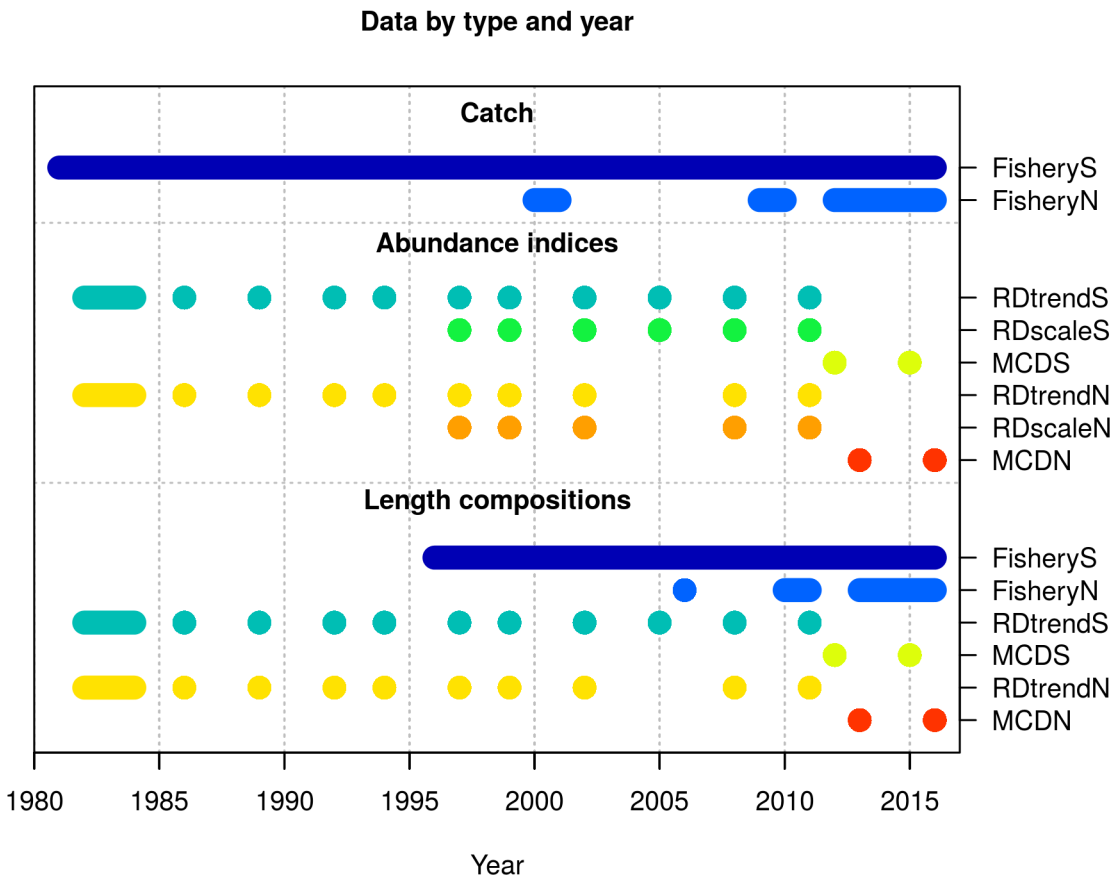

Figure 59: Data included in the ocean quahog assessment model. RD scale was not included in the likelihood.

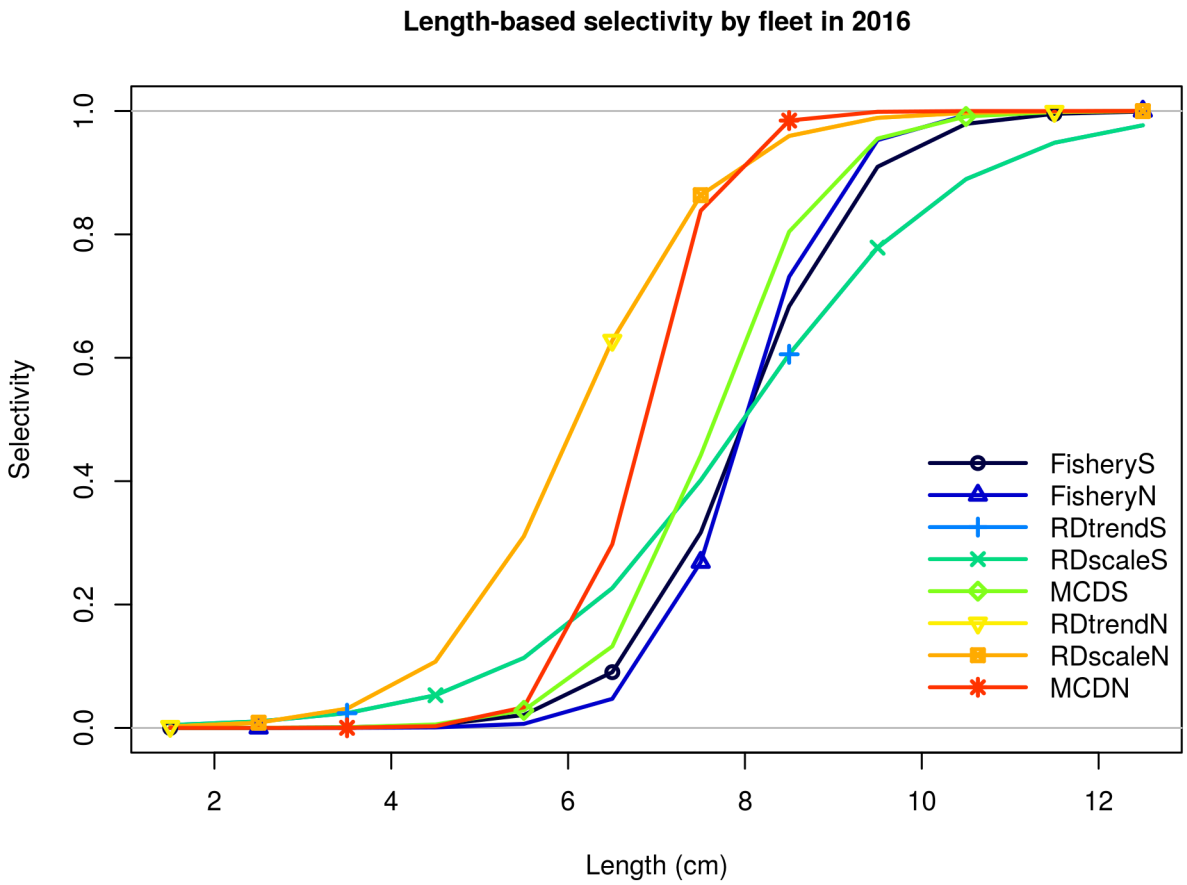

Figure 60: Comparison of selectivity curves for each fleet included in the assessment model for ocean quahog. RD trend and RD scale have identical selectivities because they are from the same survey (RD scale was not included in the likelihood).

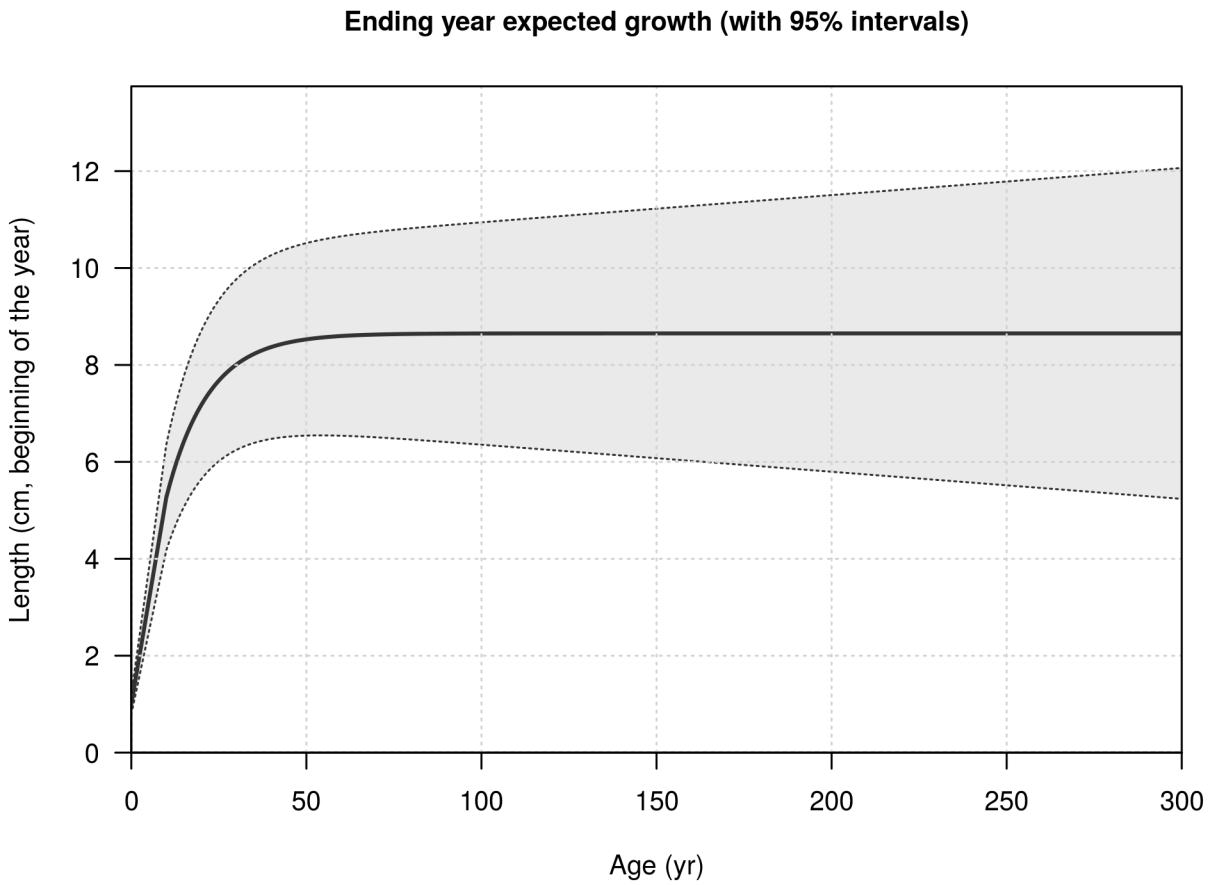

Figure 61: Length at age relationship from the assessment model for ocean quahog.

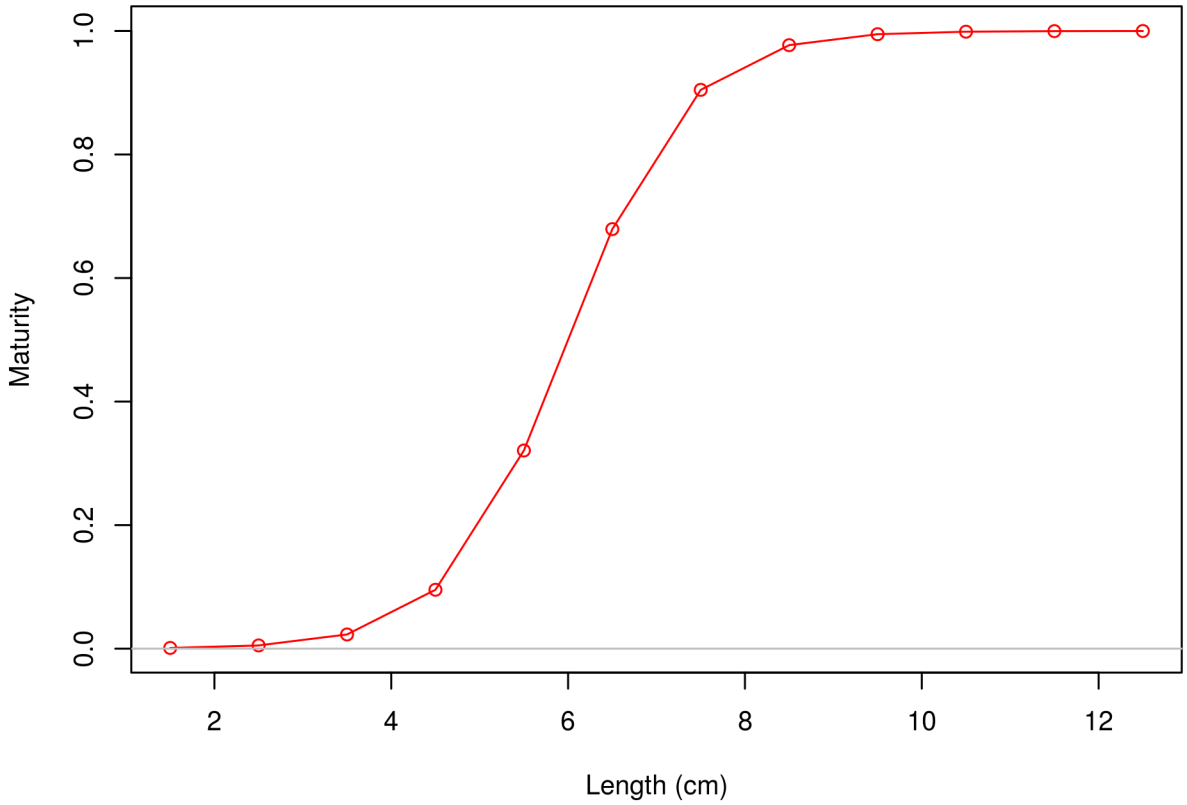

Figure 62: Maturity at age relationship in the assessment model for ocean quahog.

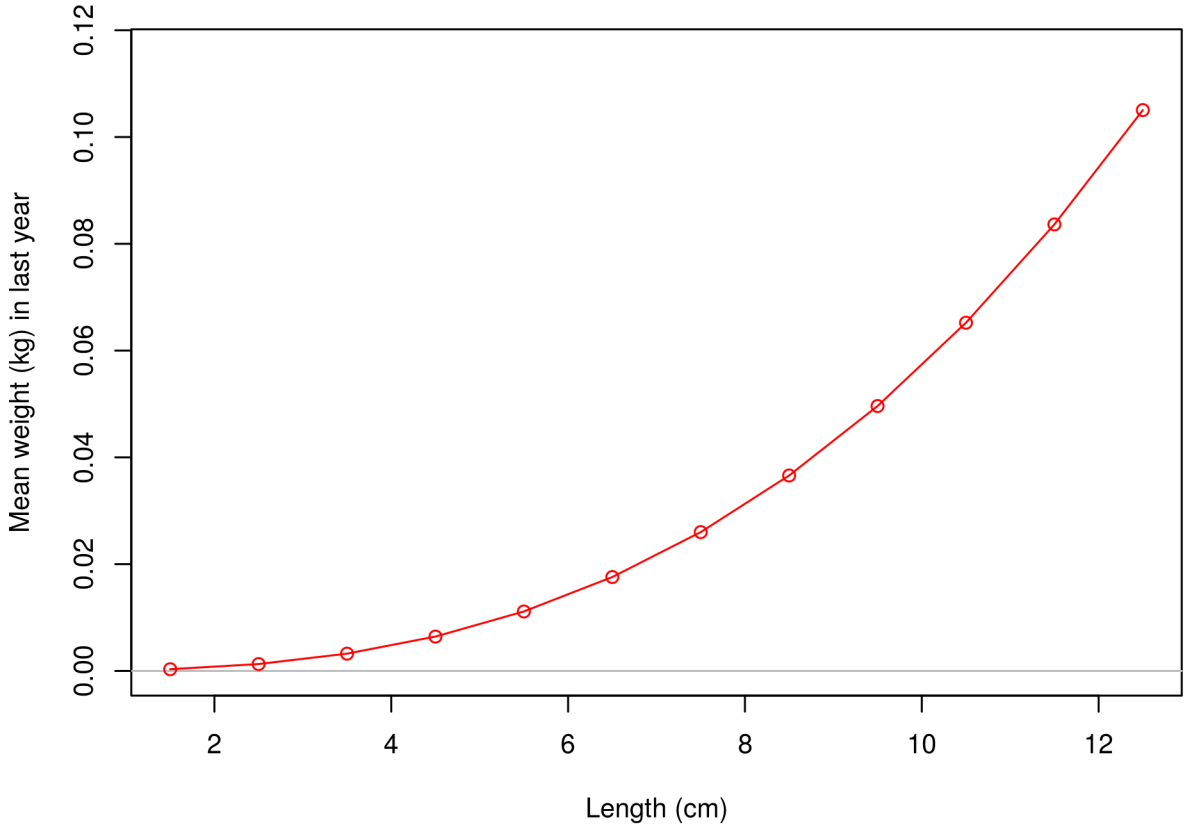

Figure 63: Weight at length relationship in the assessment model for ocean quahog.

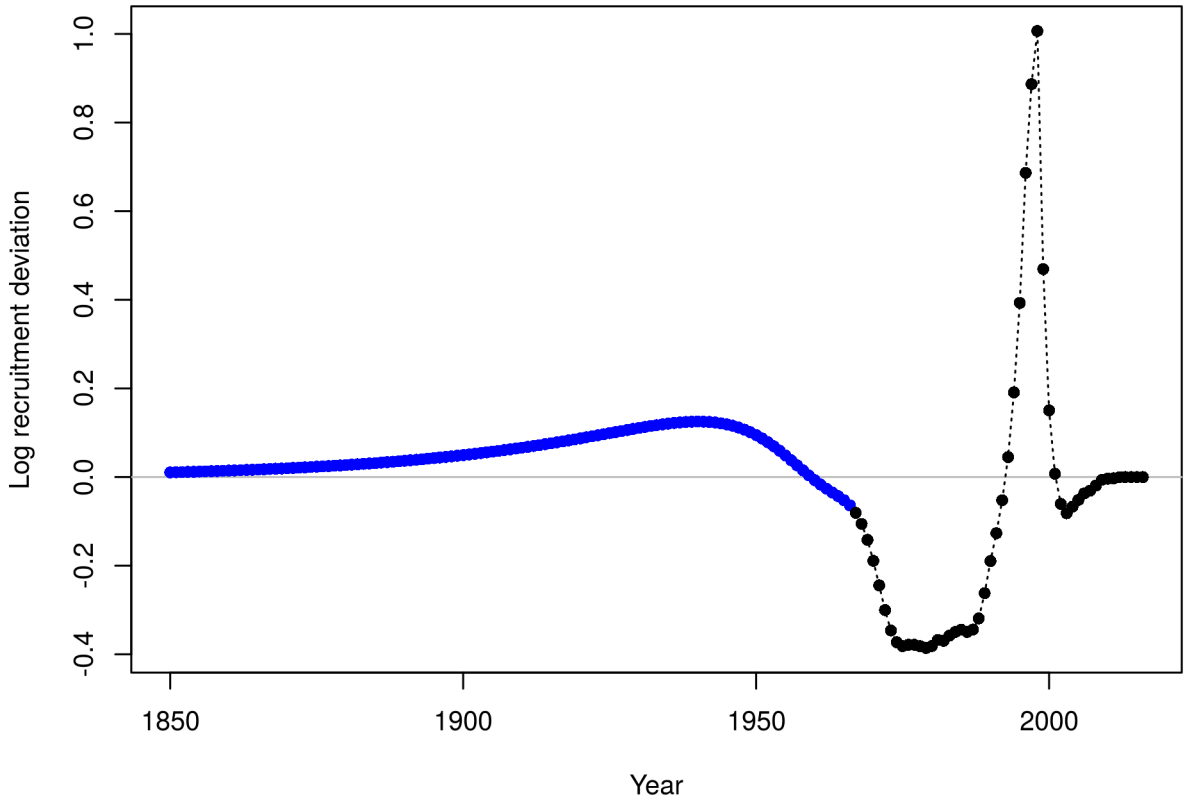

Figure 64: Recruitment deviations estimated in the basecase assessment model for ocean quahog.

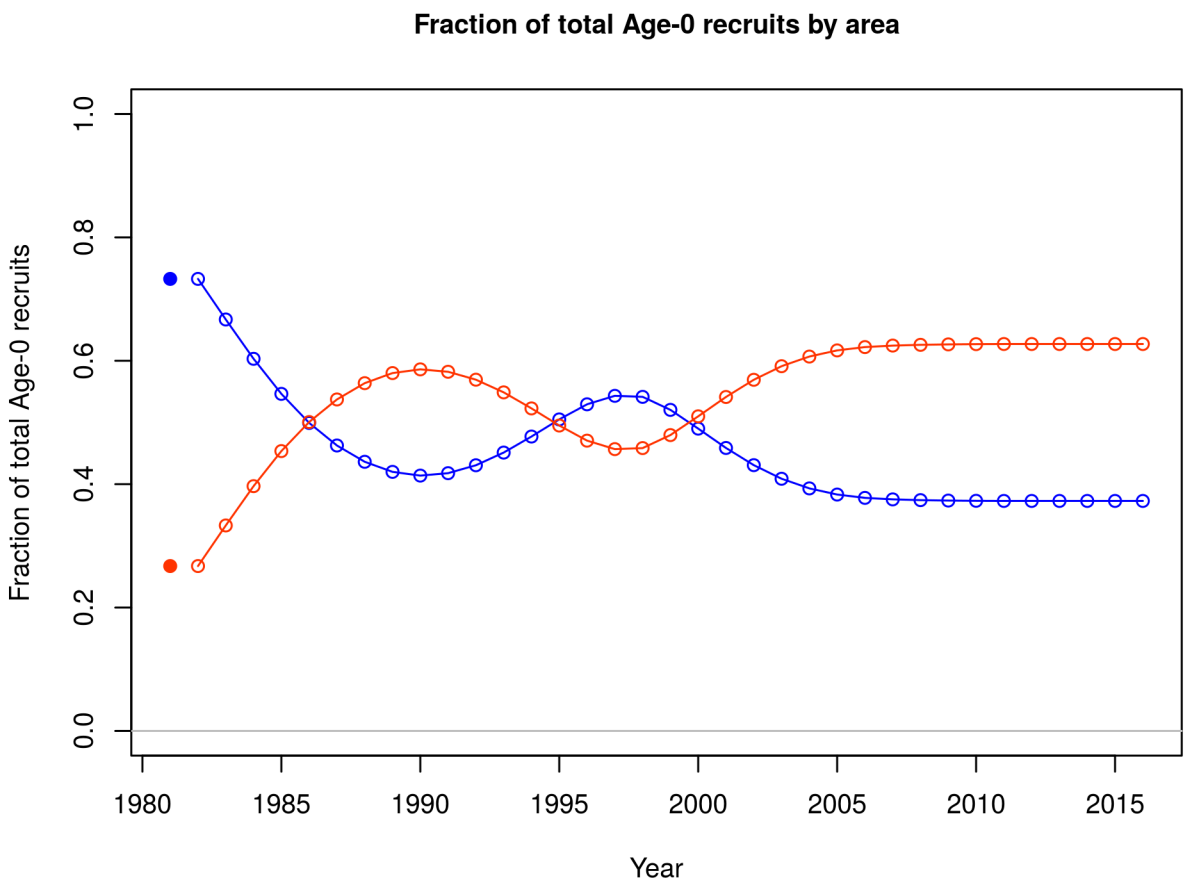

Figure 65: Proportion of total recruitment assigned to each area in the assessment model for ocean quahog. The southern area is blue and the northern area is red.

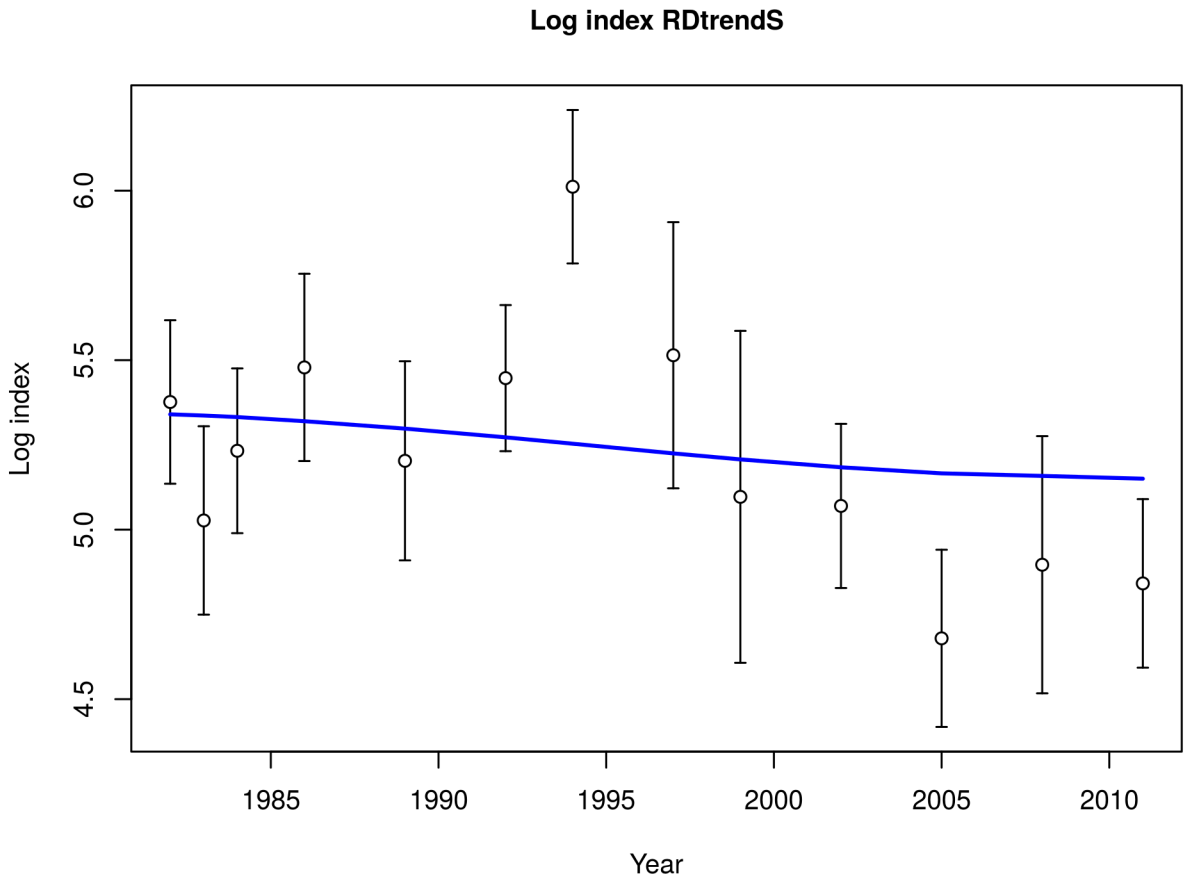

Figure 66: Fit to log RDtrend survey for ocean quahog in the southern area. Vertical lines are 95% confidence intervals.

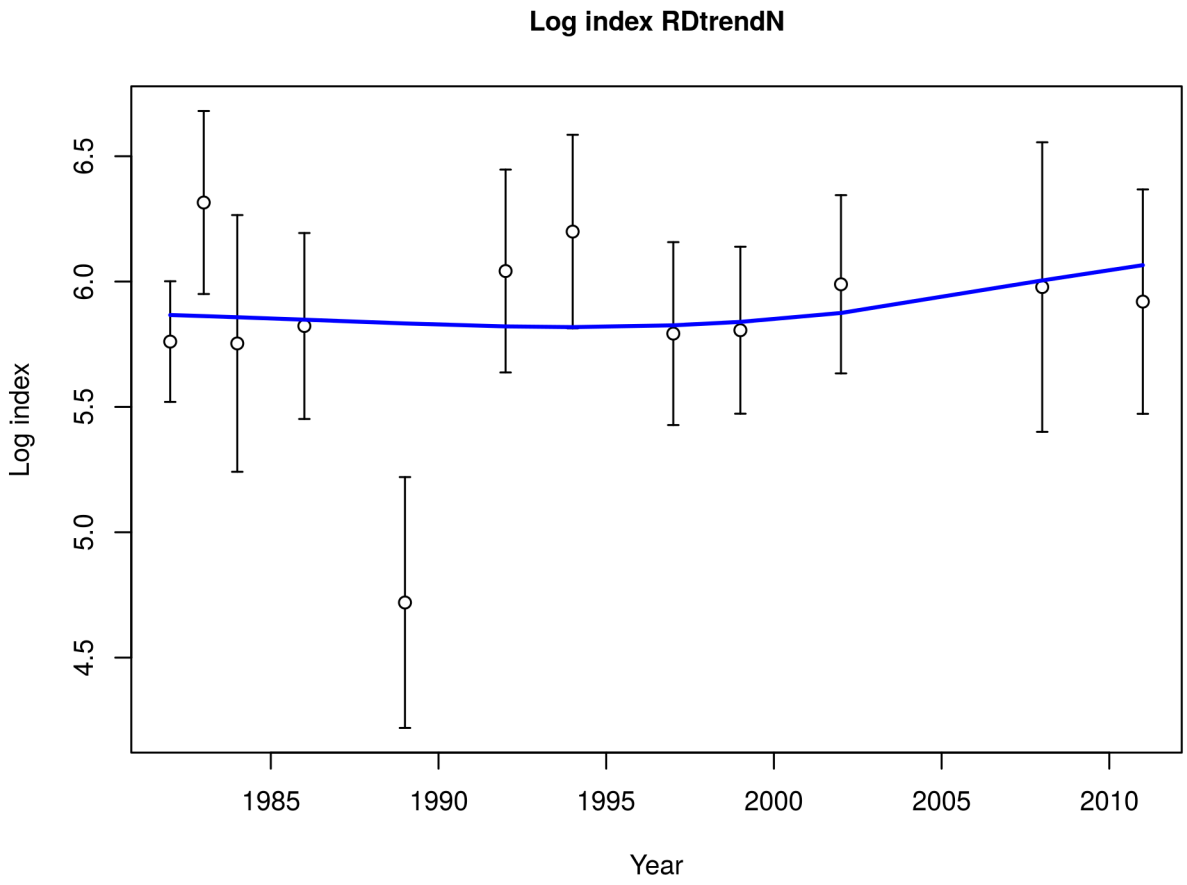

Figure 67: Fit to log RDtrend survey for ocean quahog in the northern area. Vertical lines are 95% confidence intervals.

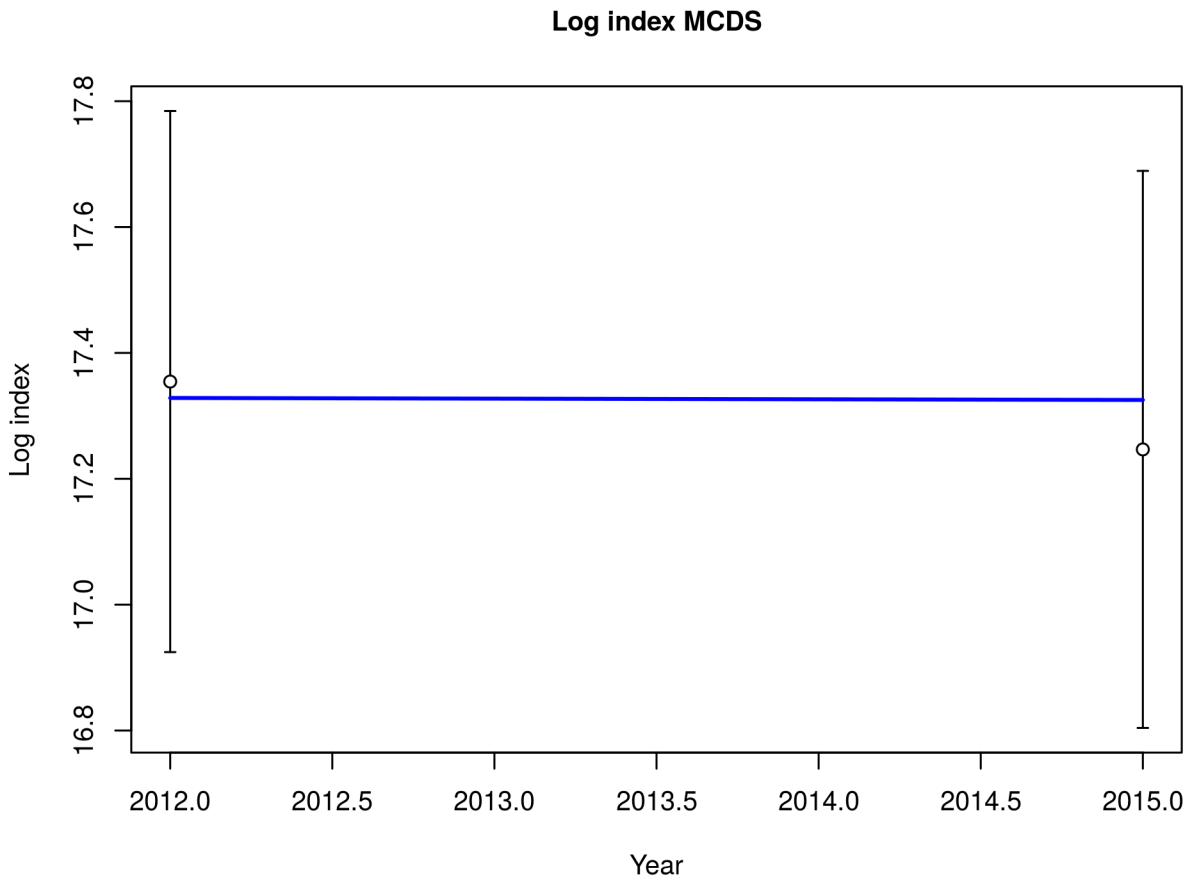

Figure 68: Fit to log MCD survey for ocean quahog for the southern area. Vertical lines are 95% confidence intervals.

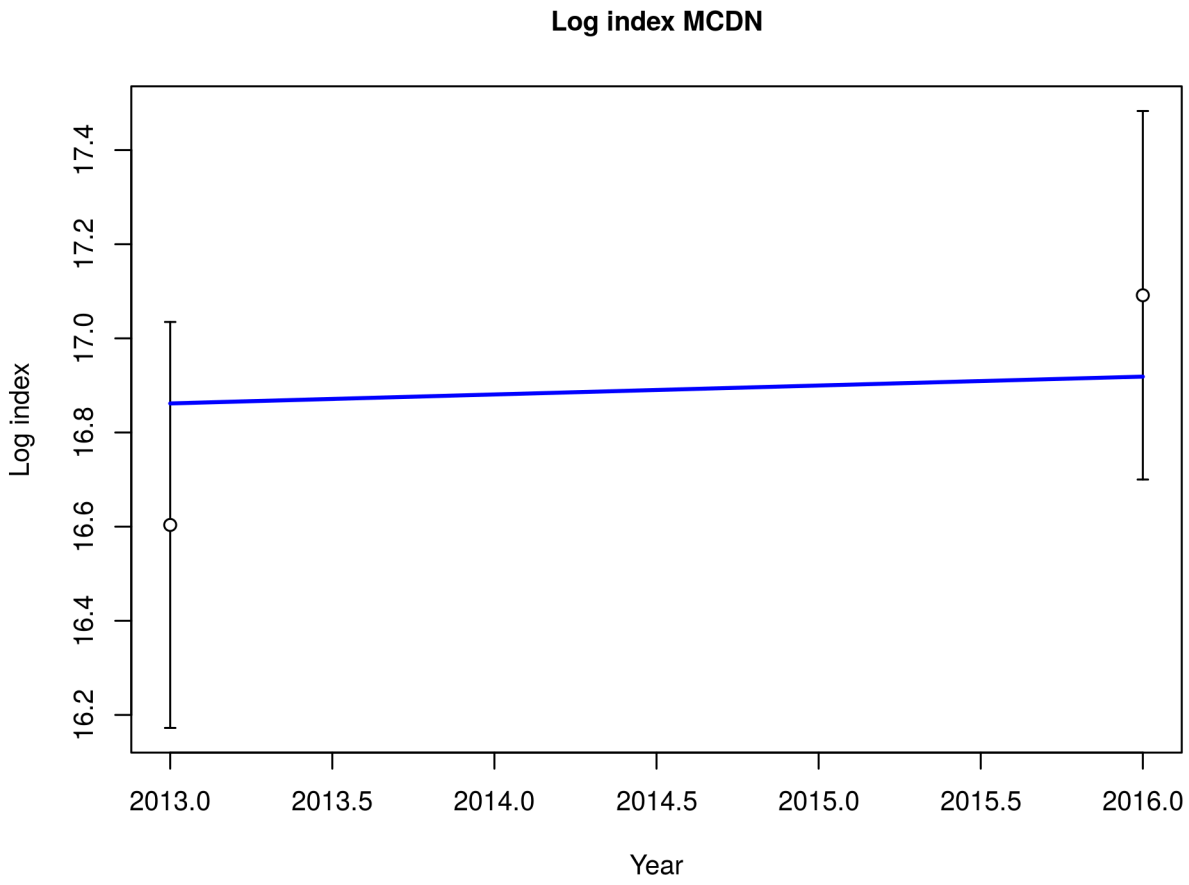

Figure 69: Fit to log MCD survey for ocean quahog for the northern area. Vertical lines are 95% confidence intervals.

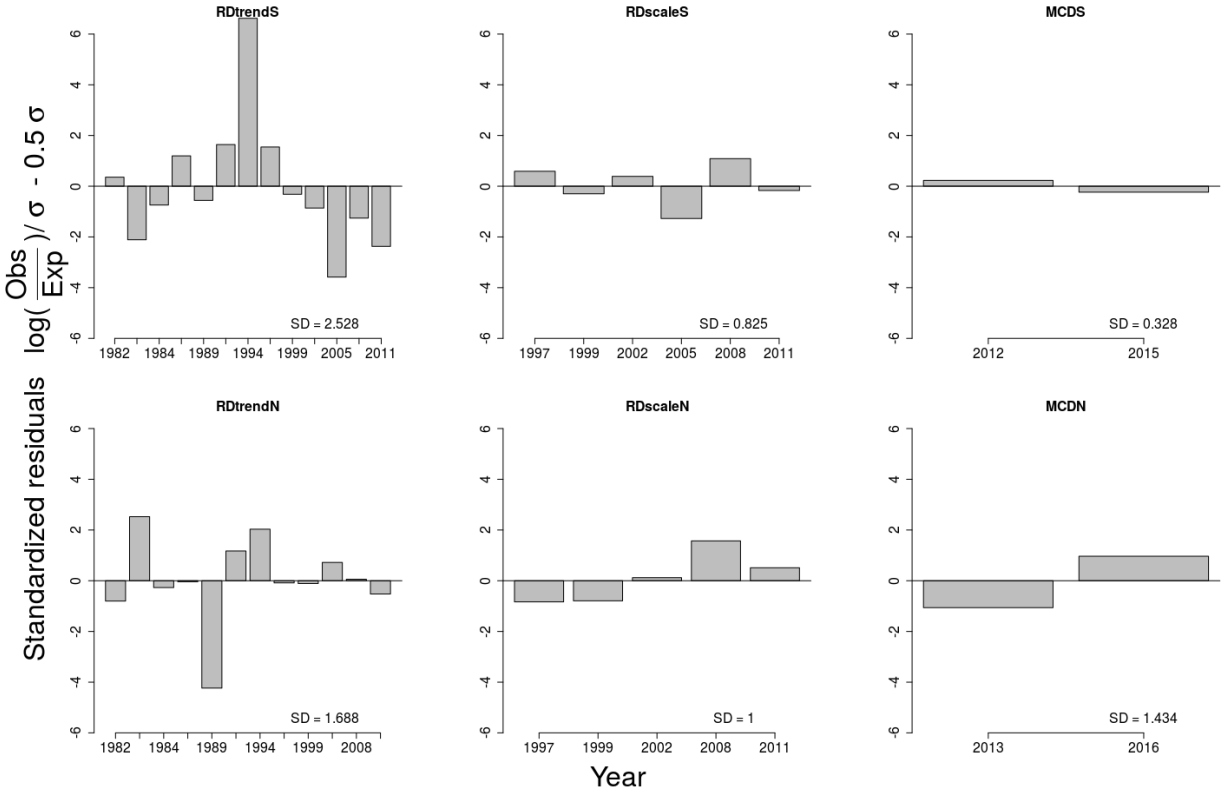

Figure 70: Residuals from the model fits to each survey index in the assessment model for ocean quahog by year. The standard deviation of the residuals over the time series is indicated above the horizontal axis.

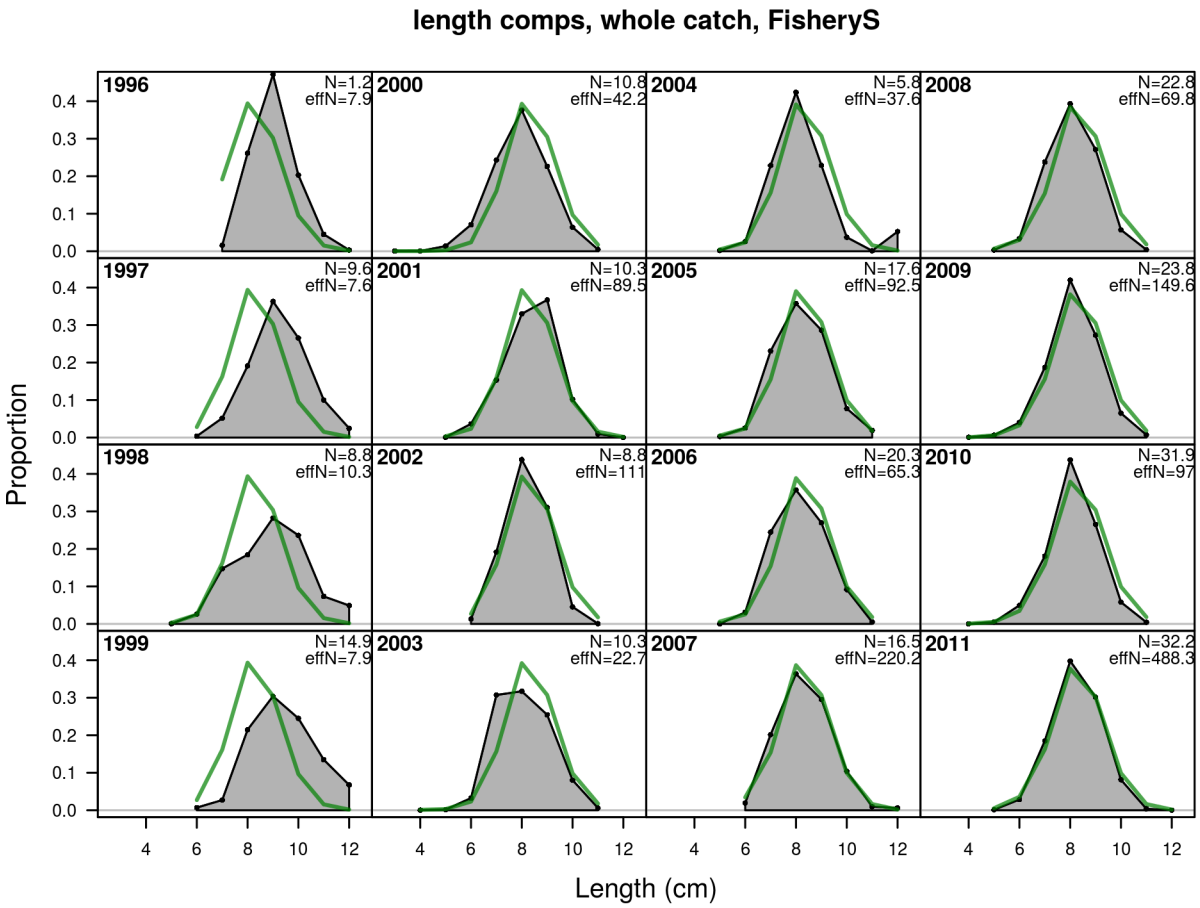

Figure 71: Model fit to length composition data from the commercial fishery in the southern area in the assessment model for ocean quahog.

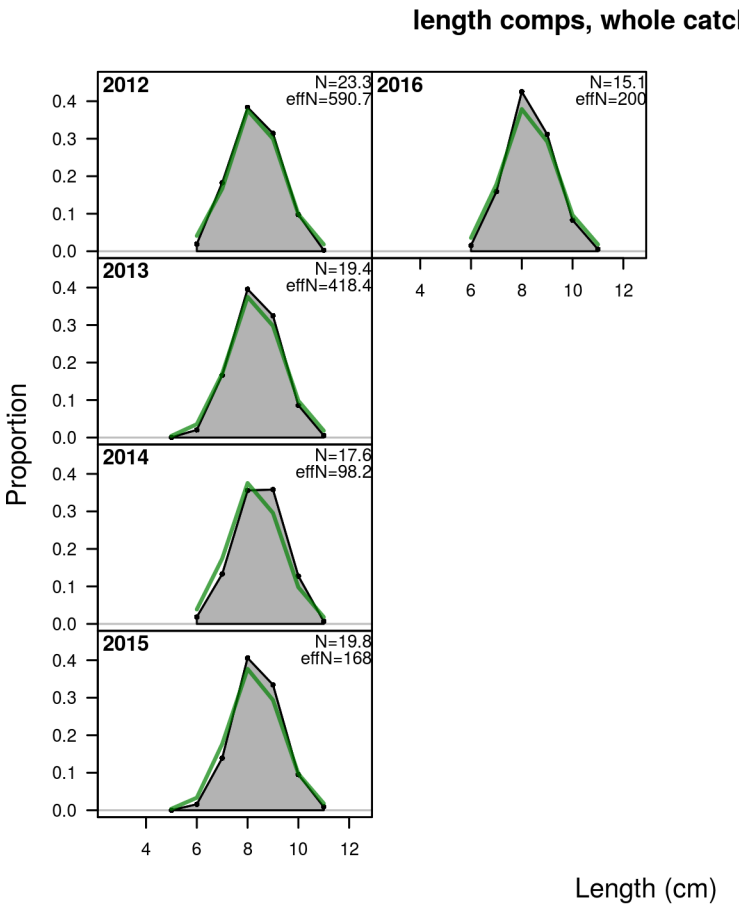

Figure 71 cont.

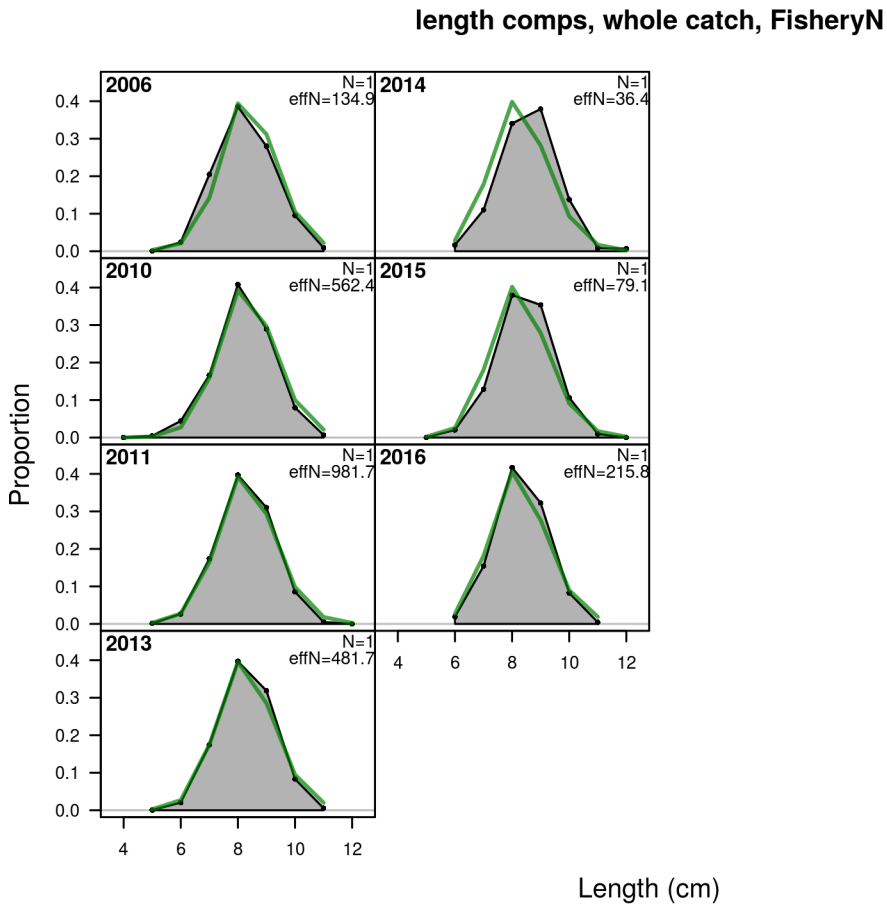

Figure 72: Model fit to length composition data from the commercial fishery in the northern area in the assessment model for ocean quahog.

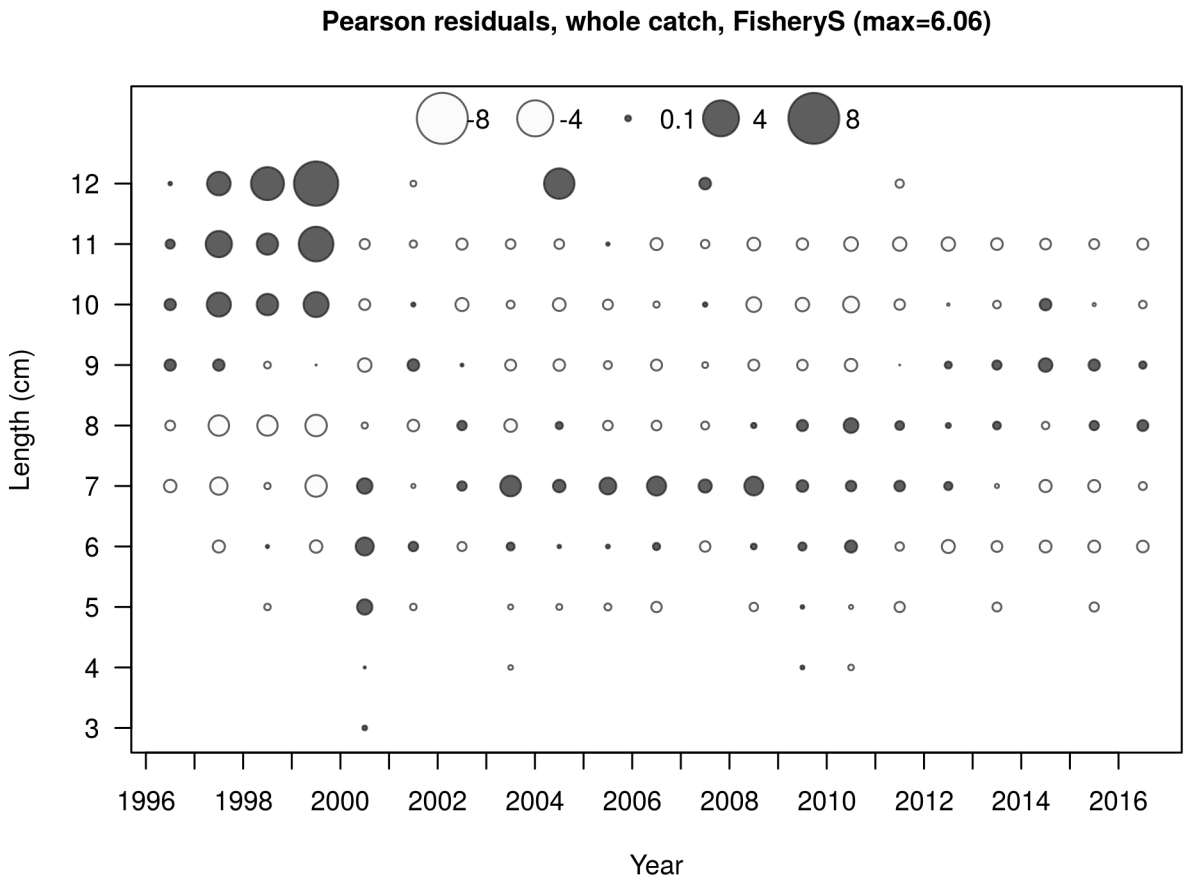

Figure 73: Pearson residuals from the fit to commercial length composition data in the assessment model for ocean quahog in the southern area. Closed bubbles are positive residuals (observed > expected) and open bubbles are negative residuals (observed < expected).

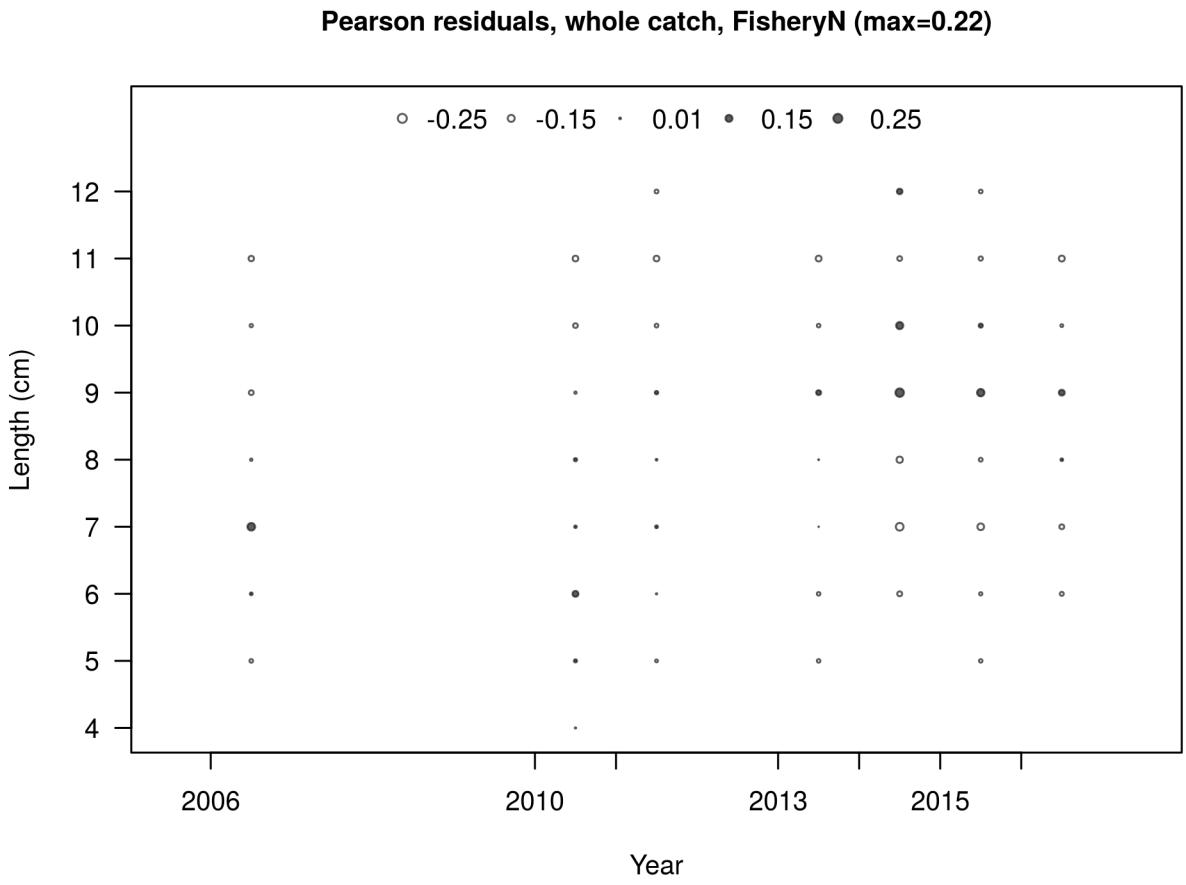

Figure 74: Pearson residuals from the fit to commercial length composition data in the assessment model for ocean quahog in the northern area. Closed bubbles are positive residuals (observed > expected) and open bubbles are negative residuals (observed < expected).

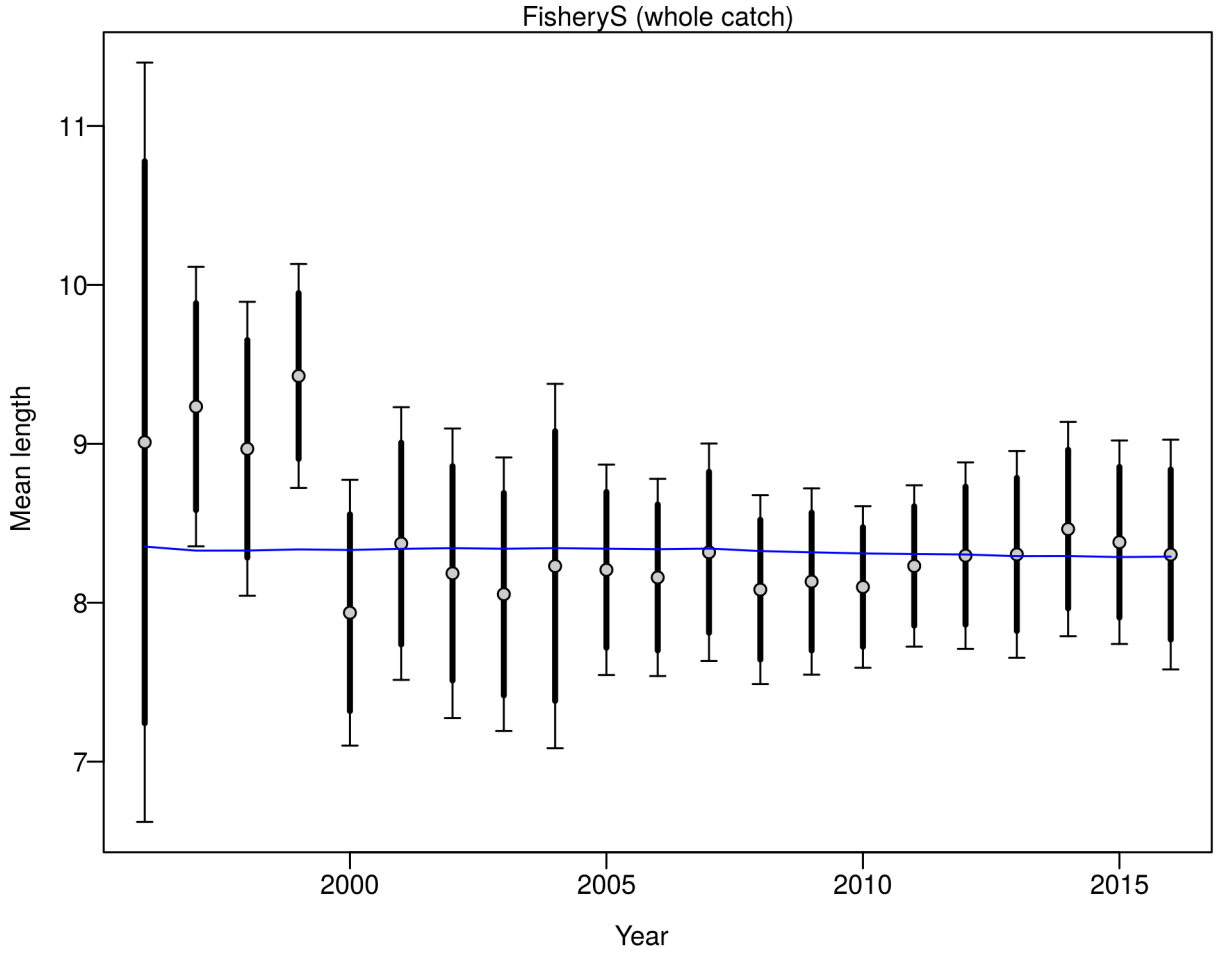

Figure 75: Observed mean length (cm) vs. the mean length predicted by the model based on fits to commercial length composition data in the assessment model for ocean quahog in the southern area.

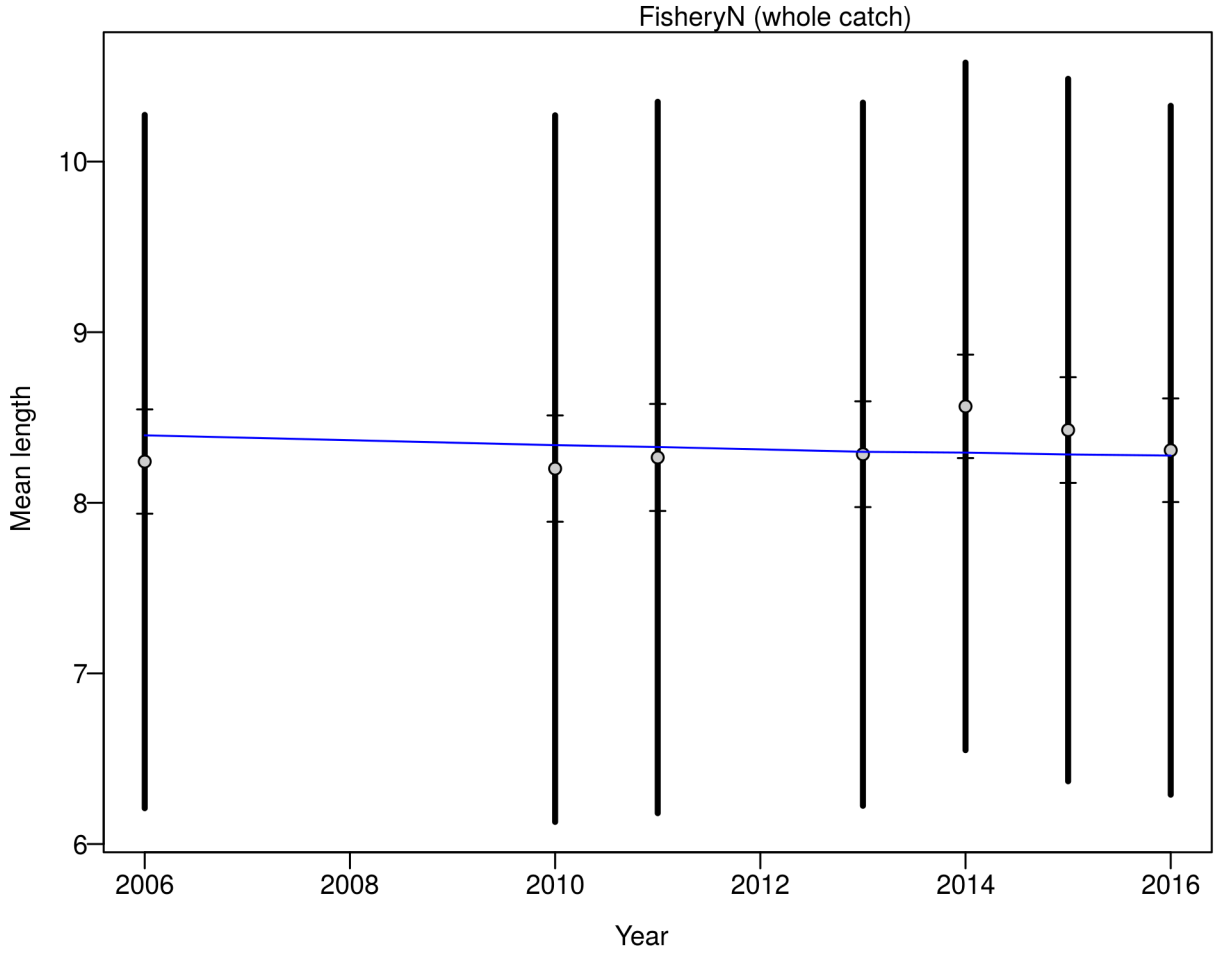

Figure 76: Observed mean length (cm) vs. the mean length predicted by the model based on fits to commercial length composition data in the assessment model for ocean quahog in the northern area.

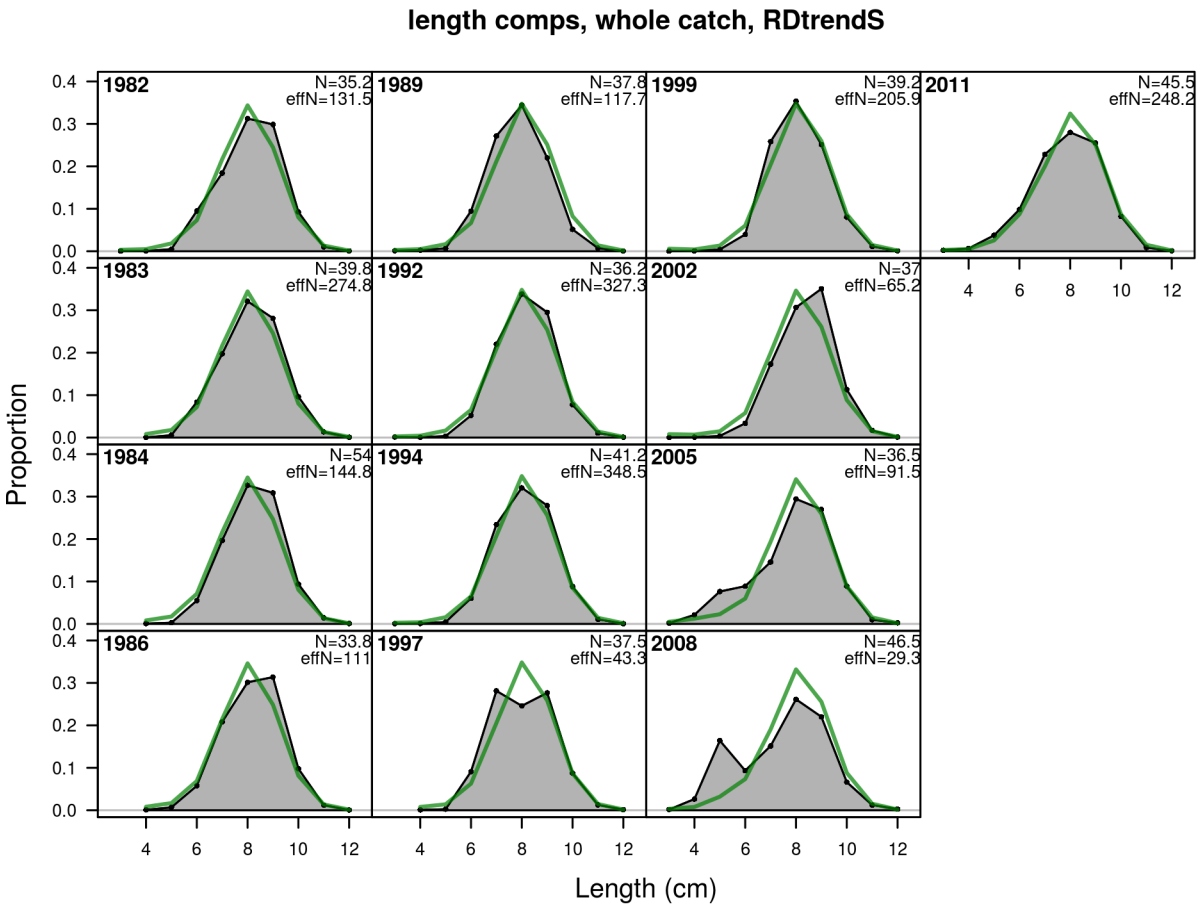

Figure 77: Model fit to length composition data from the NEFSC survey (RD) in the assessment model for ocean quahog in the southern area.

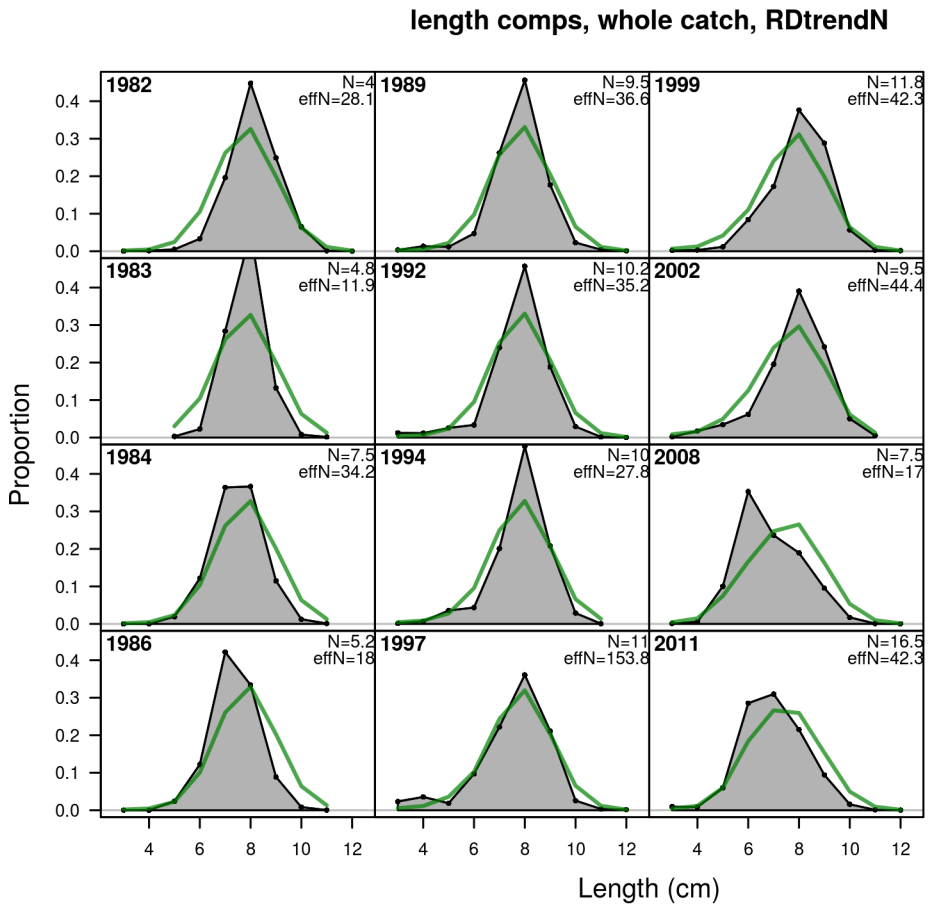

Figure 78: Model fit to length composition data from the NEFSC survey (RD) in the assessment model for ocean quahog in the northern area.

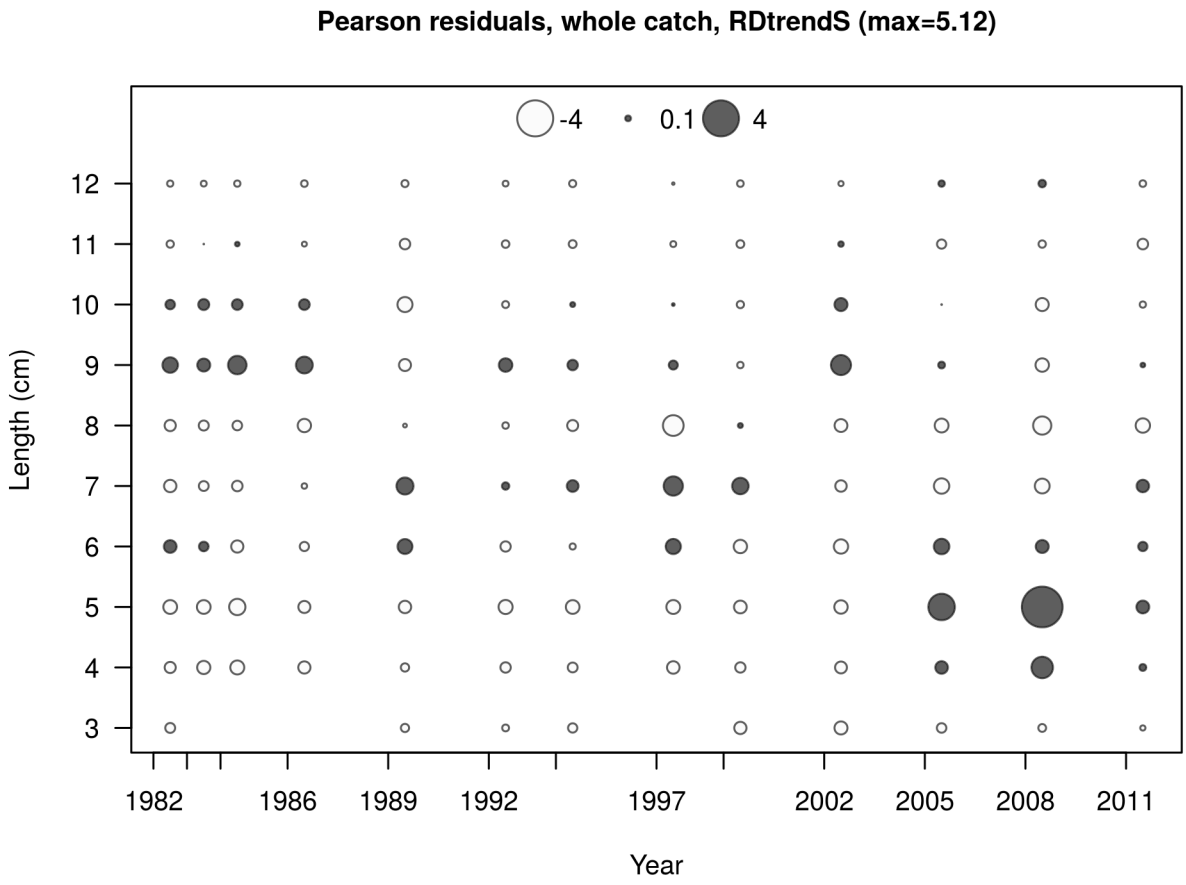

Figure 79: Pearson residuals from the fit to NEFSC survey (RD) length composition data in the assessment model for ocean quahog in the southern area. Closed bubbles are positive residuals (observed > expected) and open bubbles are negative residuals (observed < expected).

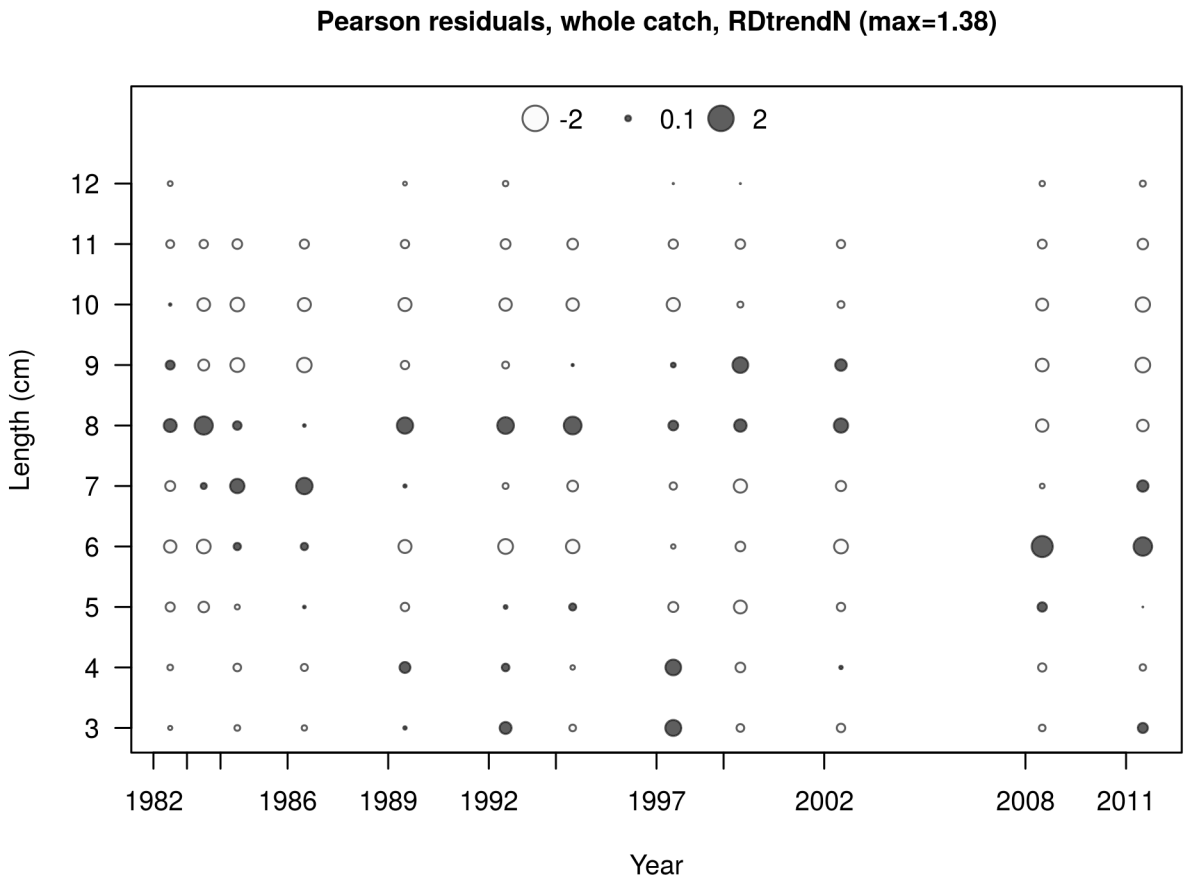

Figure 80: Pearson residuals from the fit to NEFSC survey (RD) length composition data in the assessment model for ocean quahog in the northern area. Closed bubbles are positive residuals (observed > expected) and open bubbles are negative residuals (observed < expected).

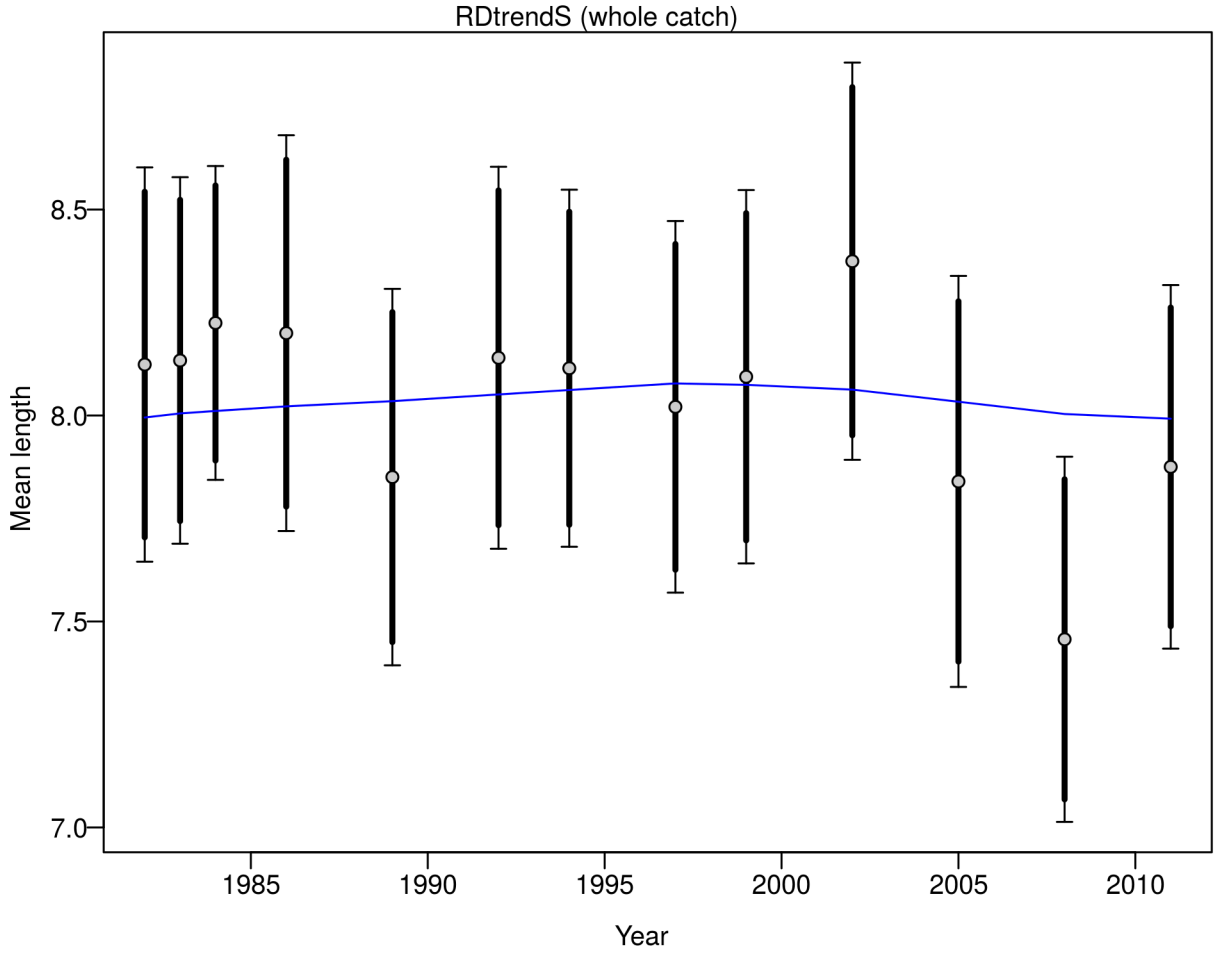

Figure 81: Observed mean length (cm) vs. the mean length predicted by the model based on fits to NEFSC survey (RD) length composition data in the assessment model for ocean quahog in the southern area.

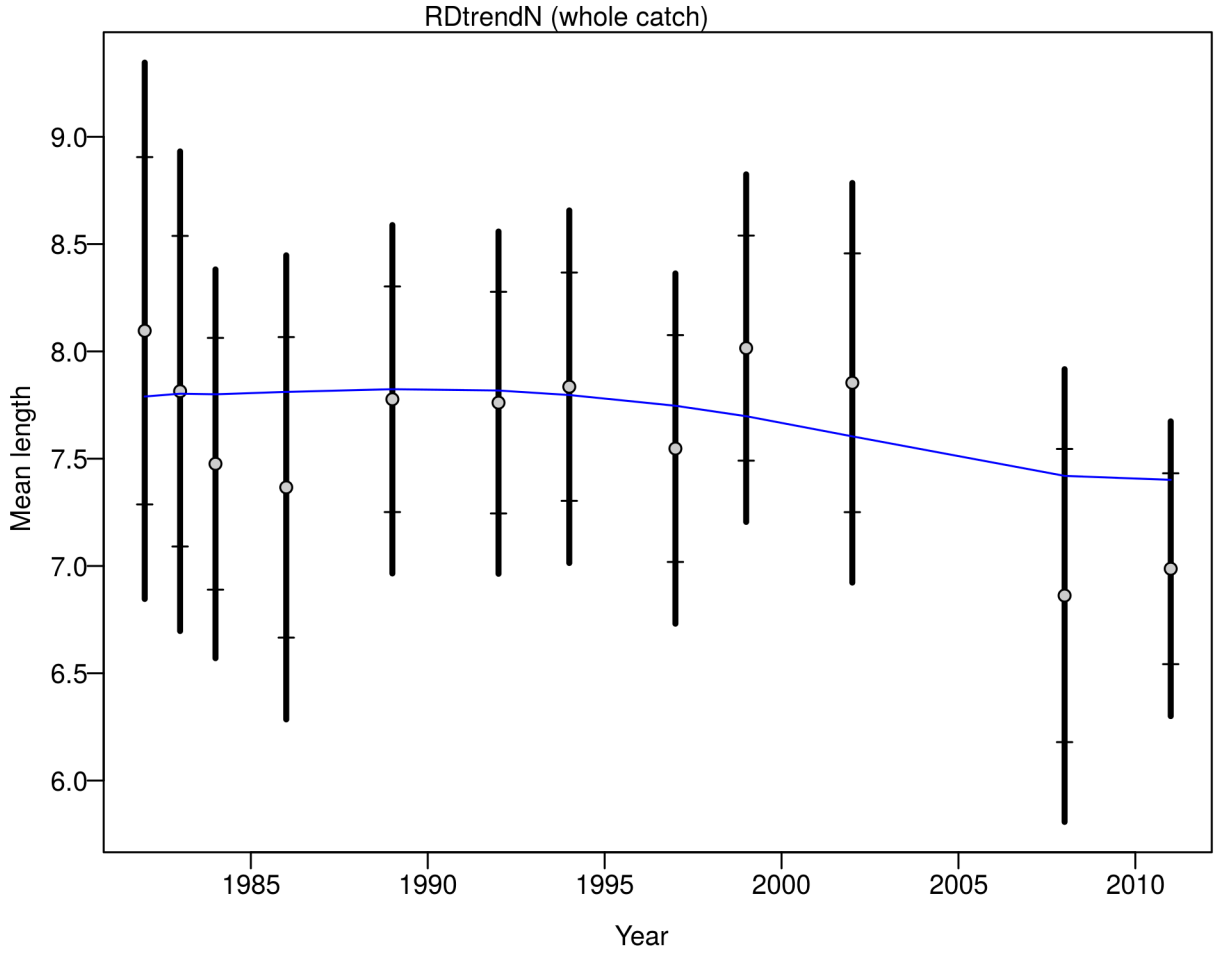

Figure 82: Observed mean length (cm) vs. the mean length predicted by the model based on fits to NEFSC survey (RD) length composition data in the assessment model for ocean quahog in the northern area.

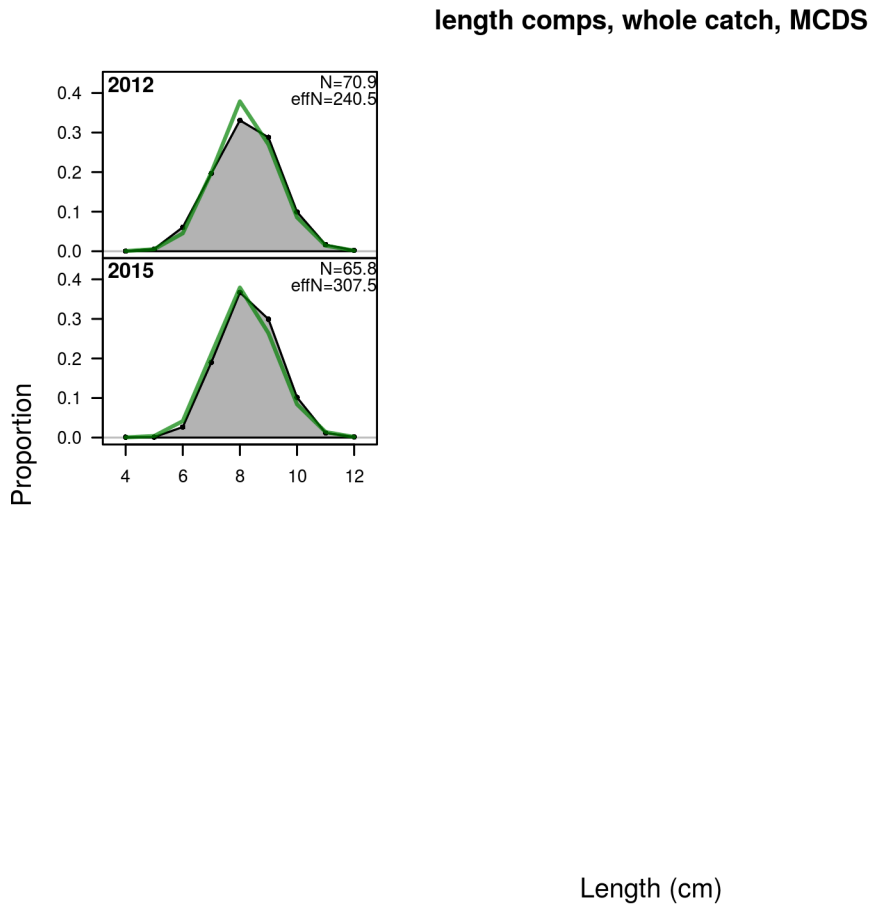

Figure 83: Model fit to length composition data from the NEFSC survey (MCD) in the assessment model for ocean quahog in the southern area.

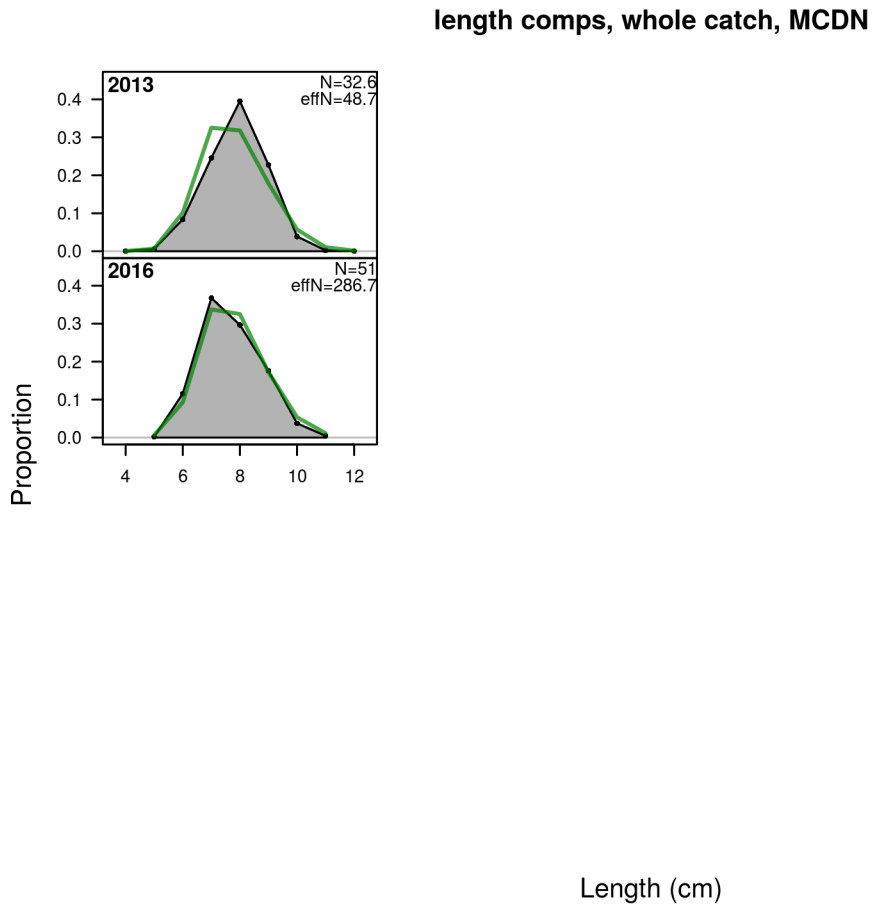

Figure 84: Model fit to length composition data from the NEFSC survey (MCD) in the assessment model for ocean quahog in the northern area.

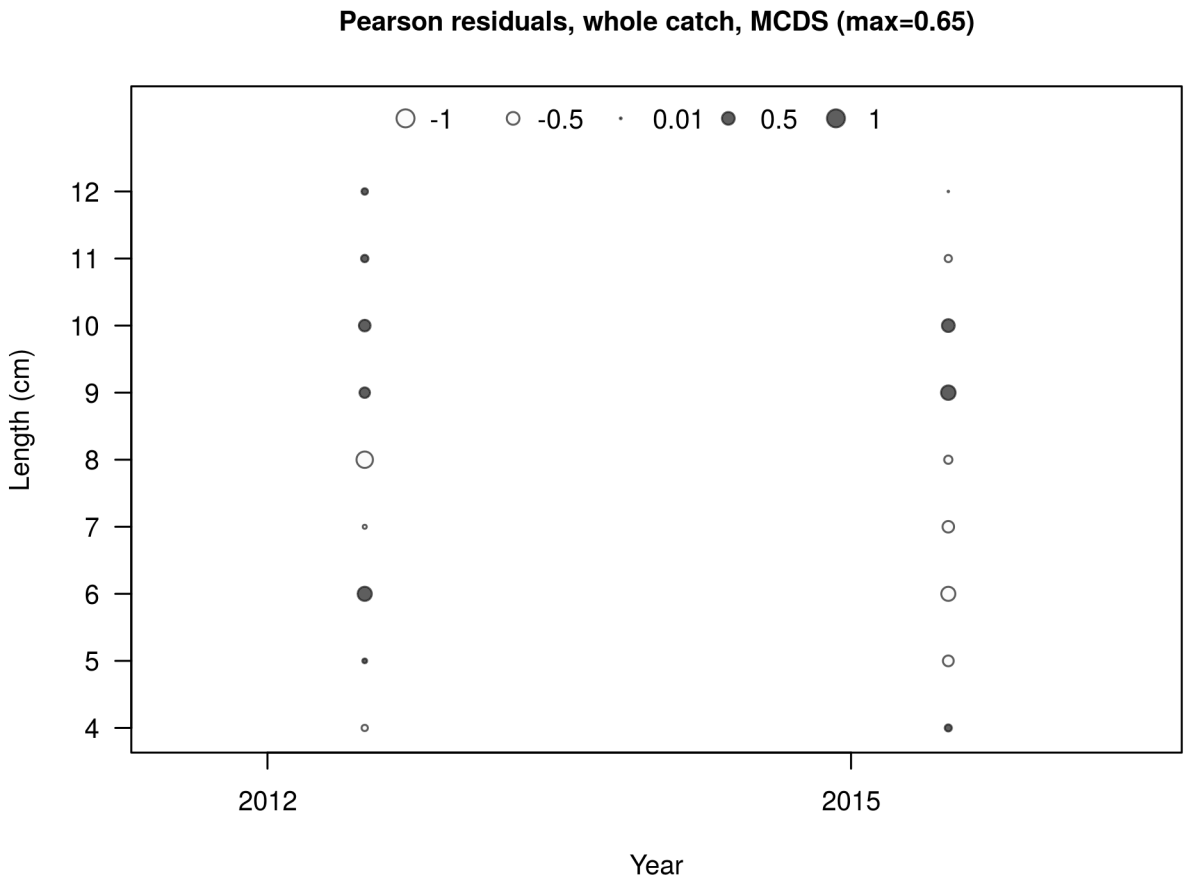

Figure 85: Pearson residuals from the fit to NEFSC survey (MCD) length composition data in the assessment model for ocean quahog in the southern area. Closed bubbles are positive residuals (observed > expected) and open bubbles are negative residuals (observed < expected).

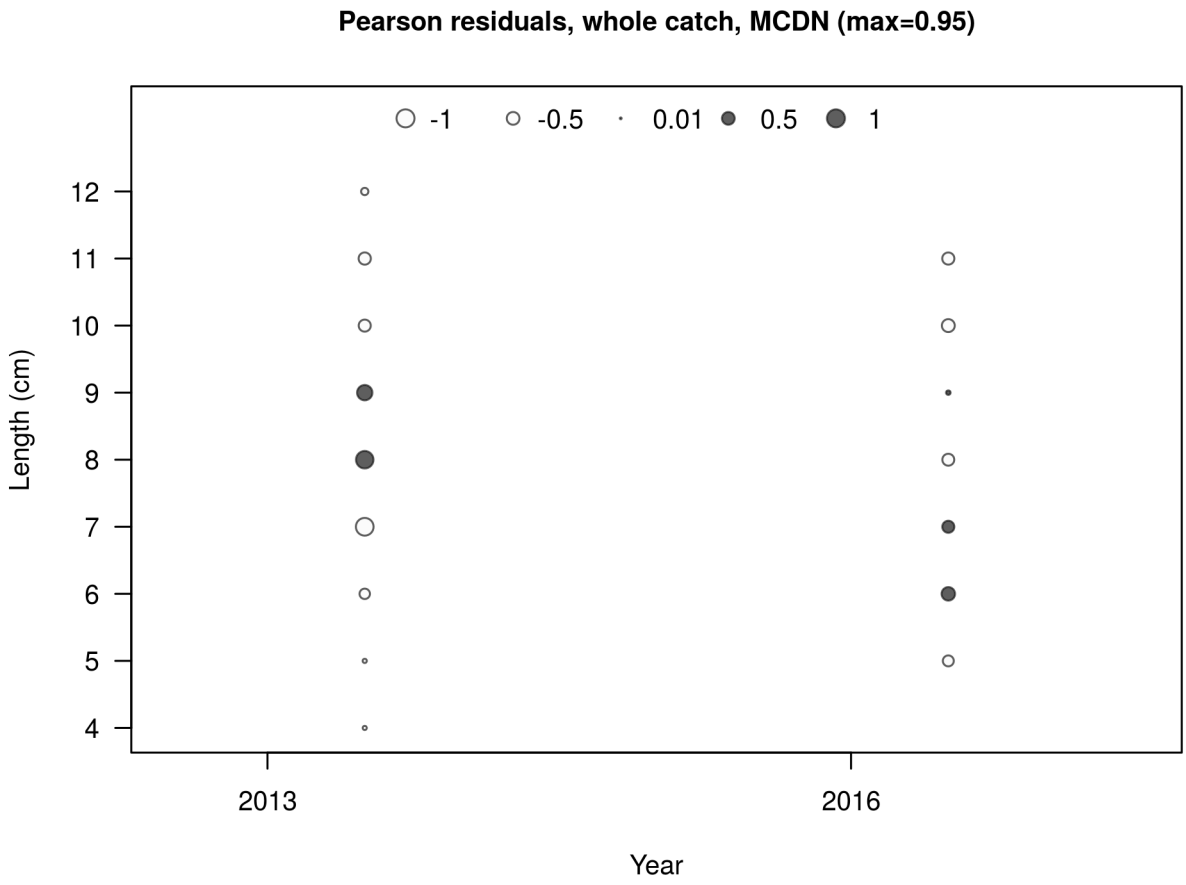

Figure 86: Pearson residuals from the fit to NEFSC survey (MCD) length composition data in the assessment model for ocean quahog in the northern area. Closed bubbles are positive residuals (observed > expected) and open bubbles are negative residuals (observed < expected).

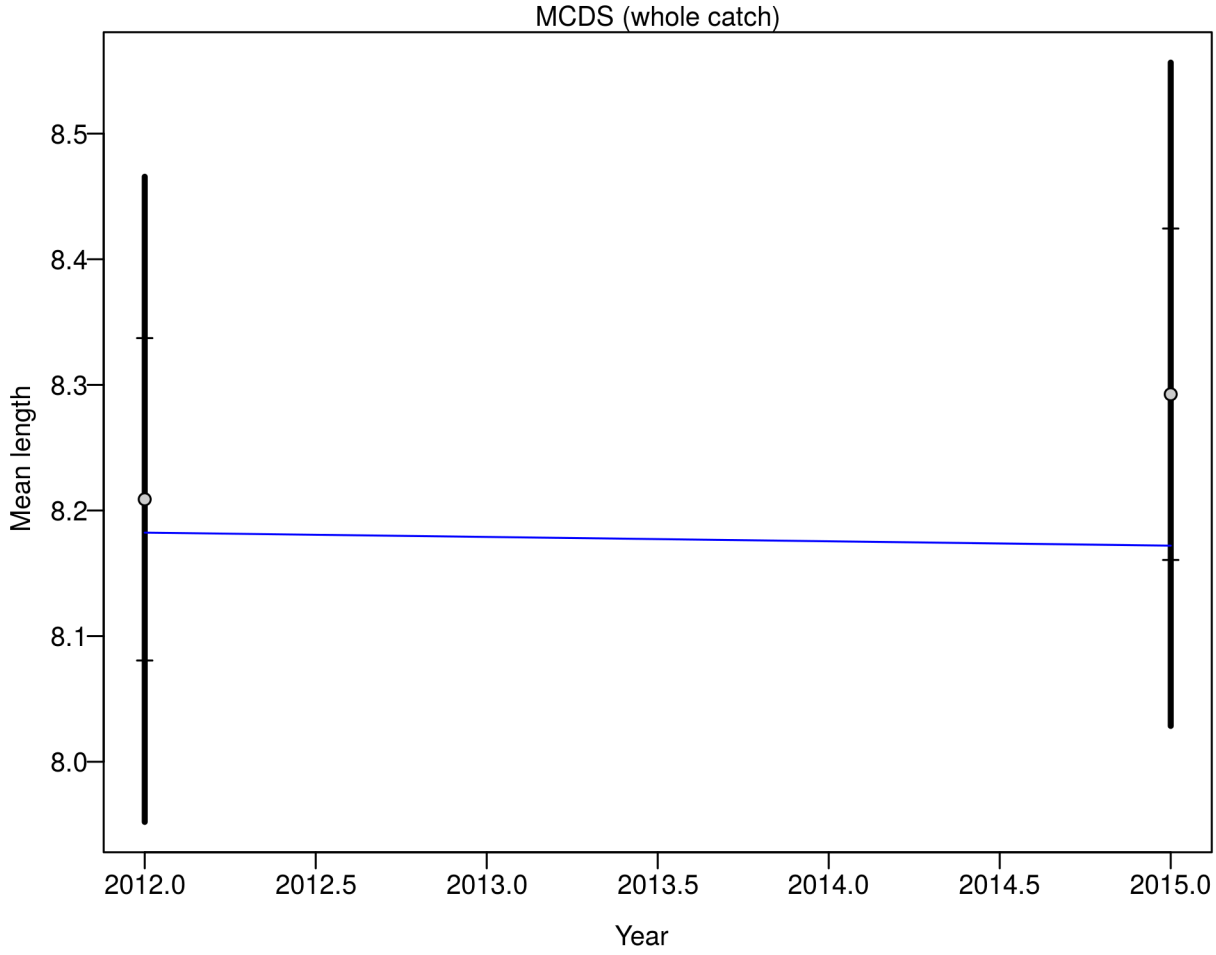

Figure 87: Observed mean length (cm) vs. the mean length predicted by the model based on fits to NEFSC survey (MCD) length composition data in the assessment model for ocean quahog in the southern area.

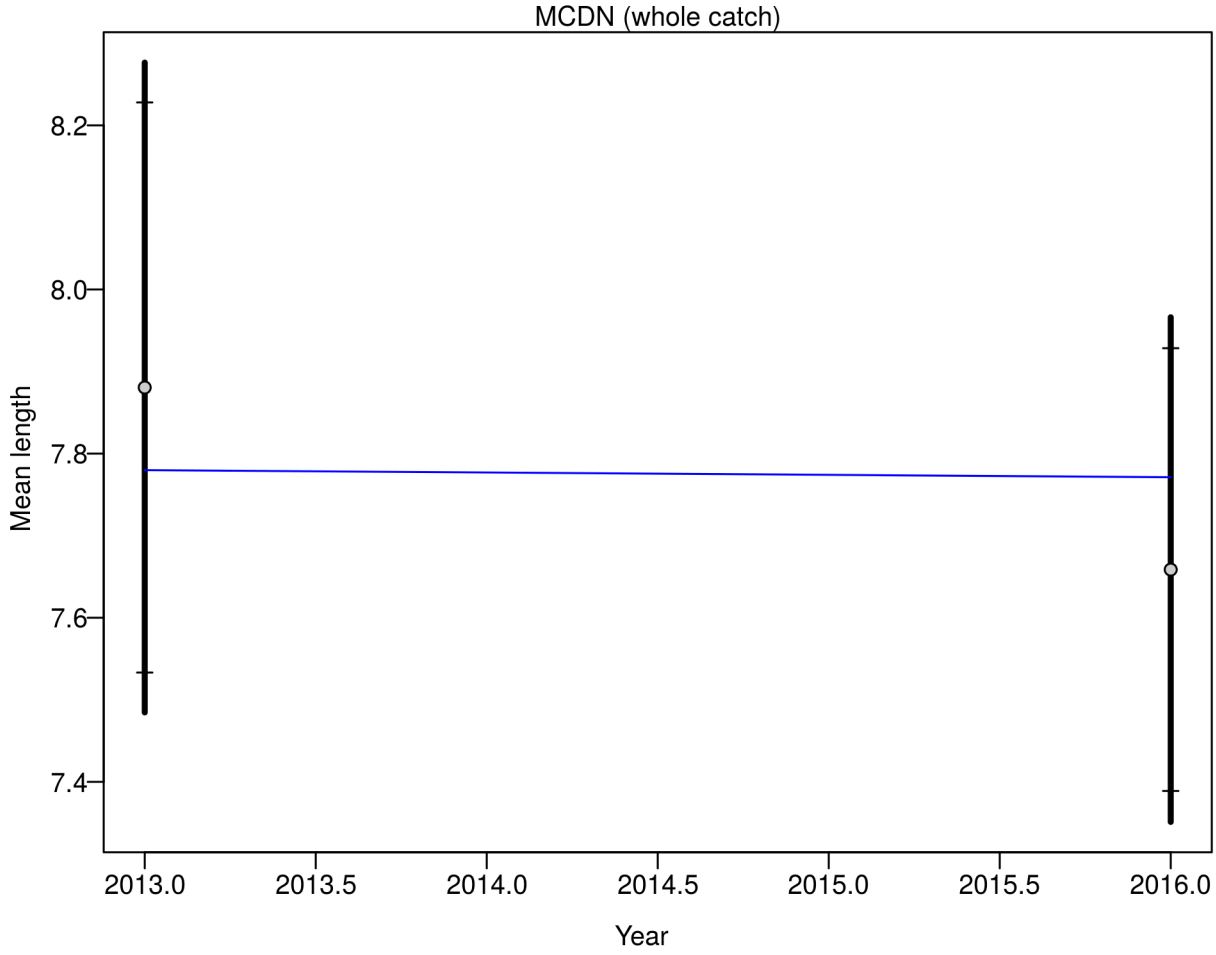

Figure 88: Observed mean length (cm) vs. the mean length predicted by the model based on fits to NEFSC survey (MCD) length composition data in the assessment model for ocean quahog in the northern area.

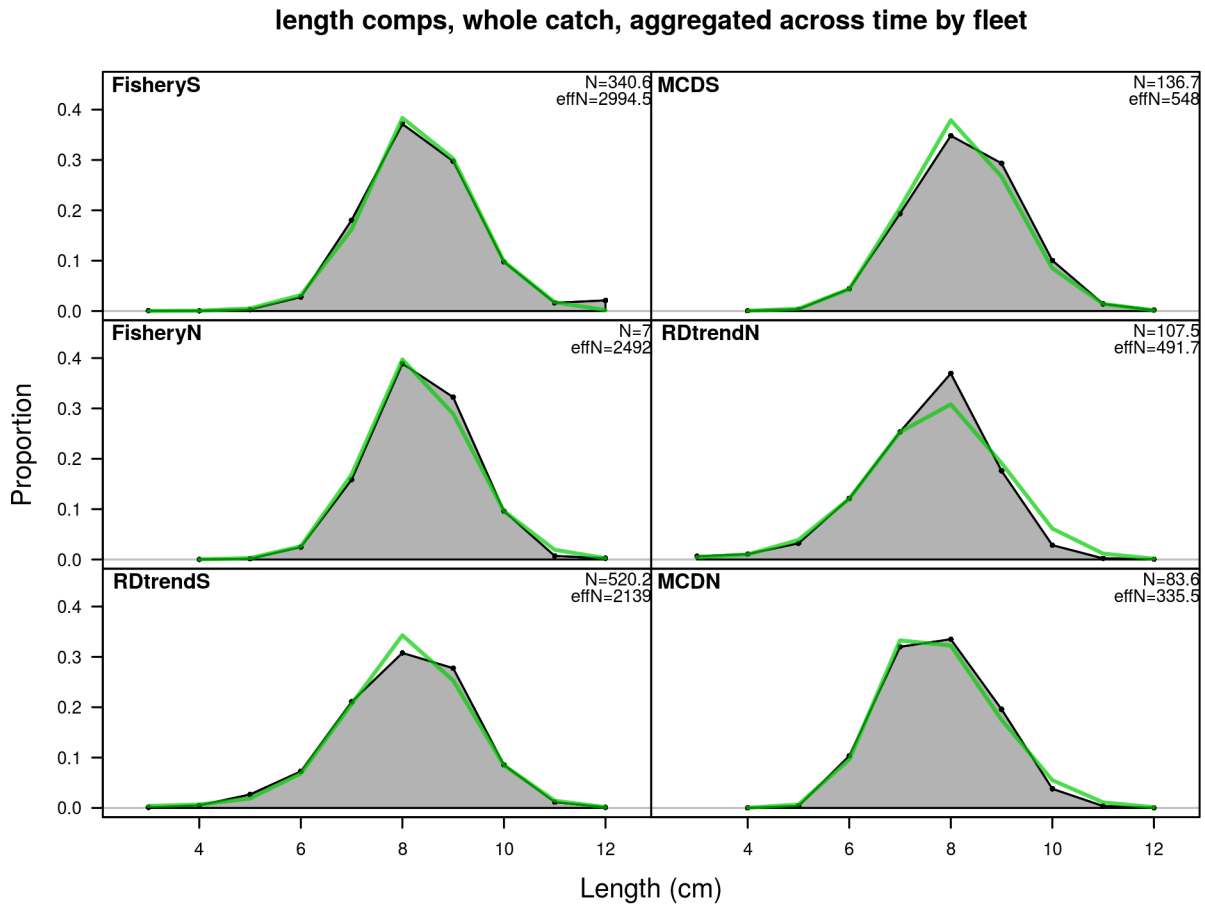

Figure 89: Model fit to length composition data from all sources aggregated across time, in the assessment model for ocean quahog.

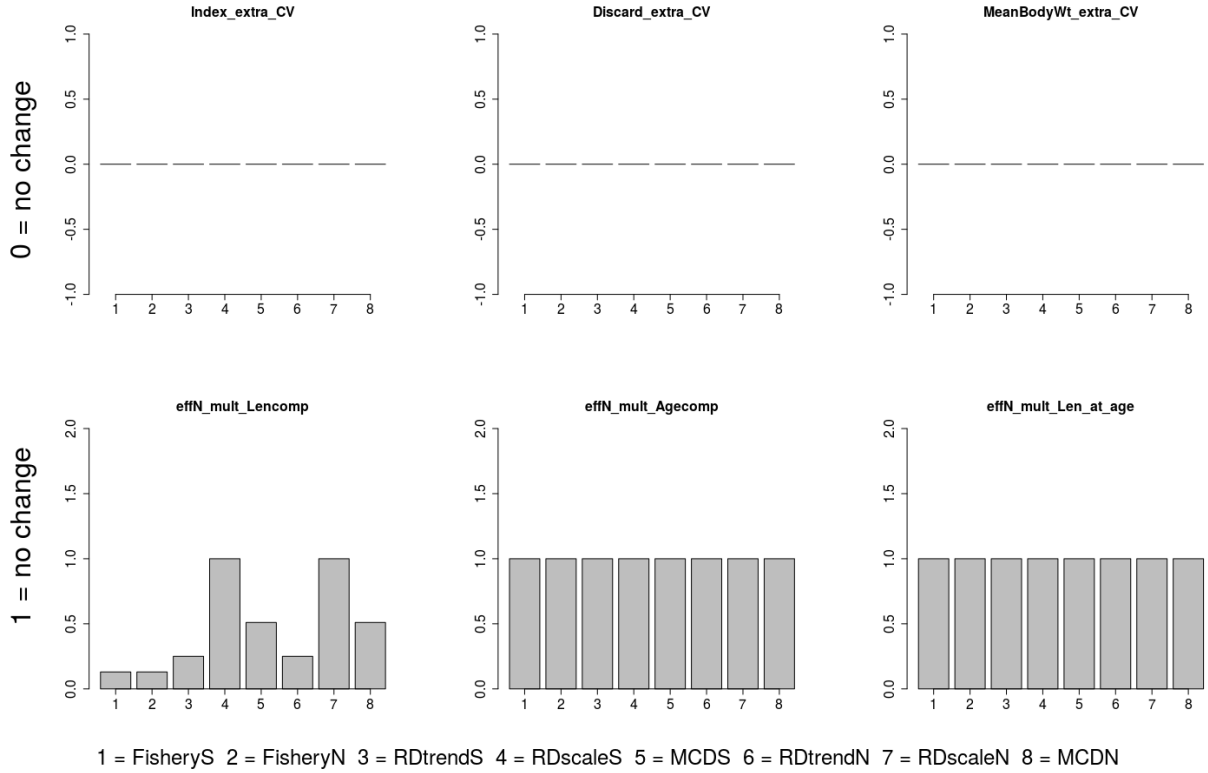

Figure 90: Adjustments made to variance components of model parameters in the assessment model for ocean quahog. The bar plots reflect data weighting decisions. In the top row deviations from 0 are the amount added to the standard deviation used initially. In the bottom row, the value shown in the bar plot is multiplied by the initial effective sample size associated with each composition component. Thus, a value of less than 1 represents a reduction in the relative weight of a component.

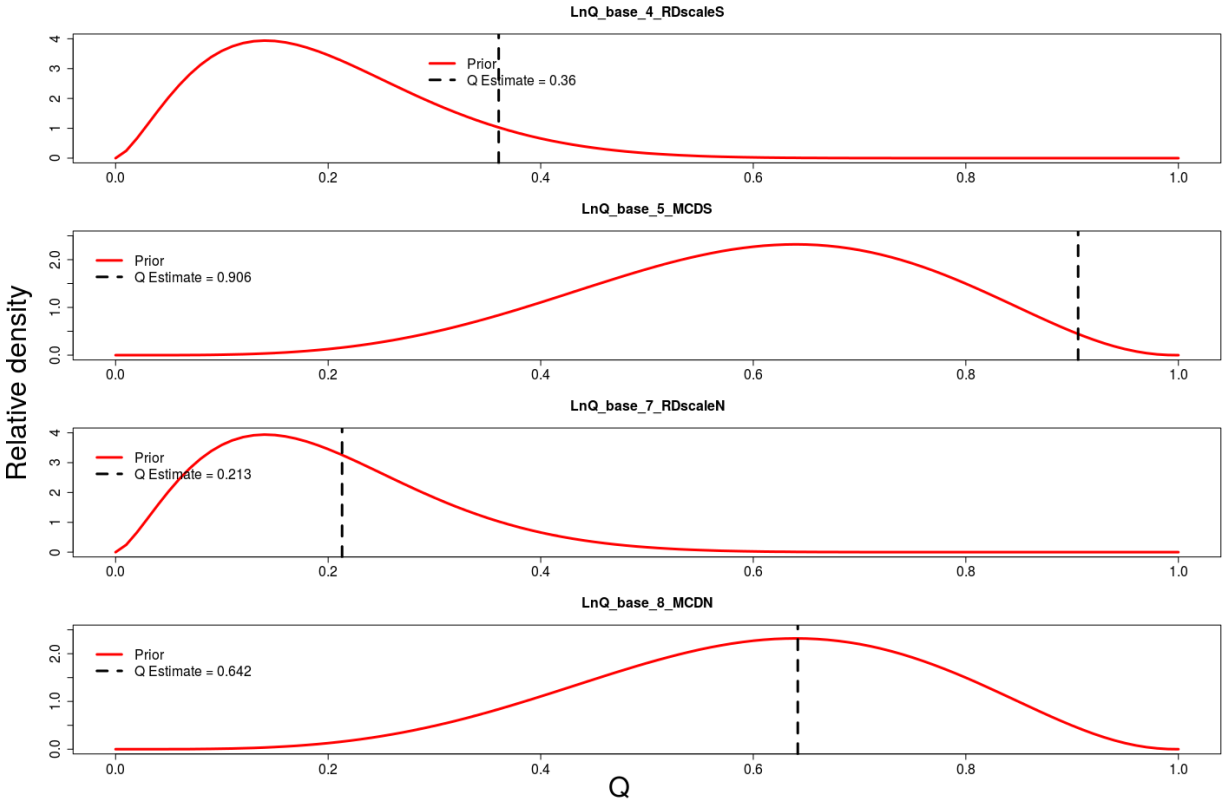

Figure 91: The prior distributions for catchability for each survey index and the model estimates that resulted from the basecase model for ocean quahog.

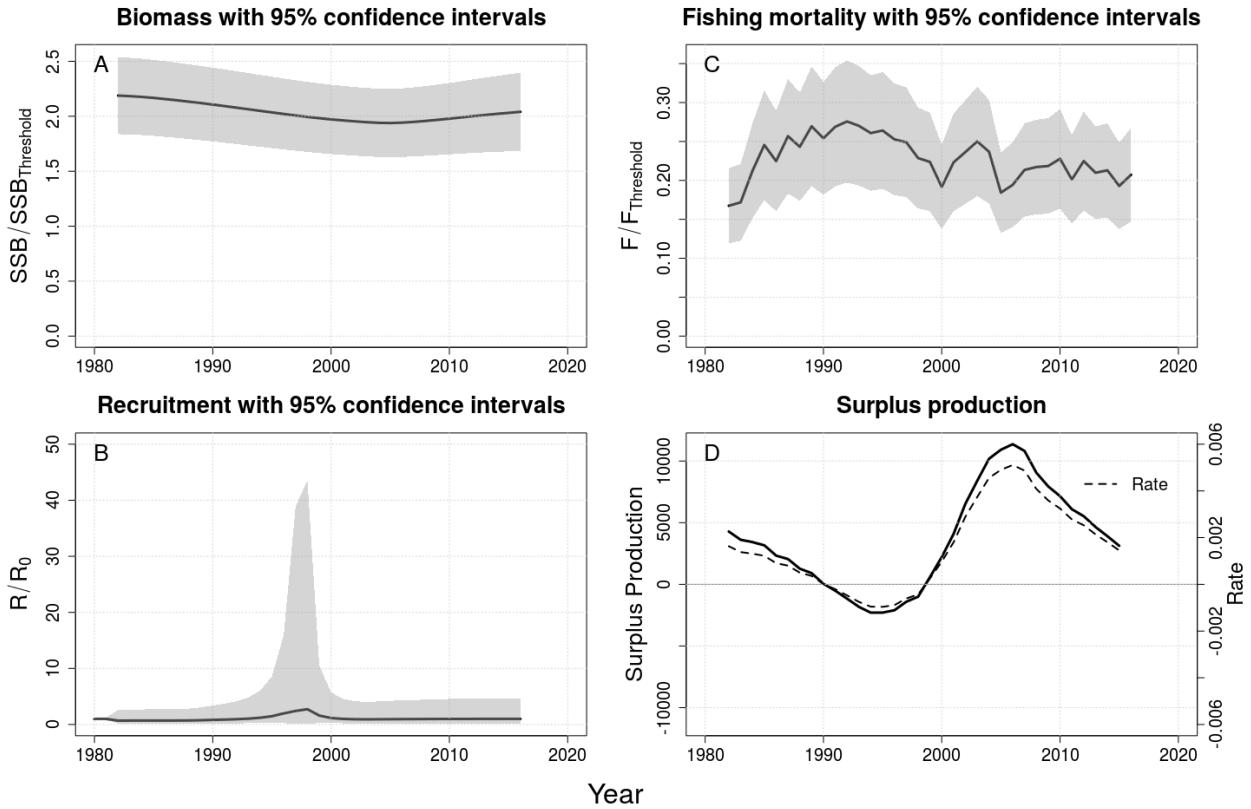

Figure 92: Trends and approximate 95% asymmetric confidence intervals for, (A) estimated SSB, (B) estimated recruitment, (C) estimated fully selected fishing mortality, and (D) surplus production with surplus production rate.

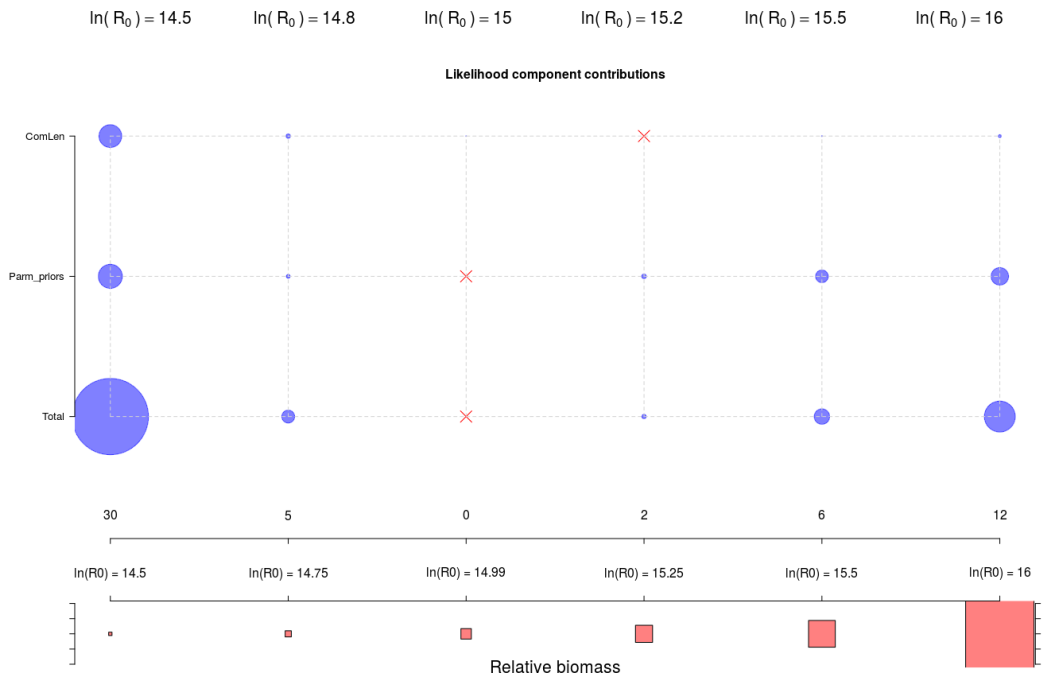

Figure 93: Likelihood profile over the virgin recruitment parameter (R0). A total of 5 model runs are depicted here. In each case, the R0 parameter was fixed at a different value. The columns of the large plot show how the component and total likelihoods change as the R0 parameter is varied. Each column of the large bubble plot represents one model run and the non-zero likelihood components in each run are shown in rows. For each row, the minimum likelihood component value was subtracted from each individual value, such that the minimum value in each row is represented by a red x. Bubbles are proportional to the values of each likelihood component in each run. The base value for R0 is the value at the model solution (middle column). The difference (in likelihood units) between each column and the minimum total likelihood is shown just above the x axis. Conflicts within the data are apparent when the minimum likelihood values (red x's) occur in different columns for each row. The red boxes show the relative difference in estimated terminal year biomass between runs.

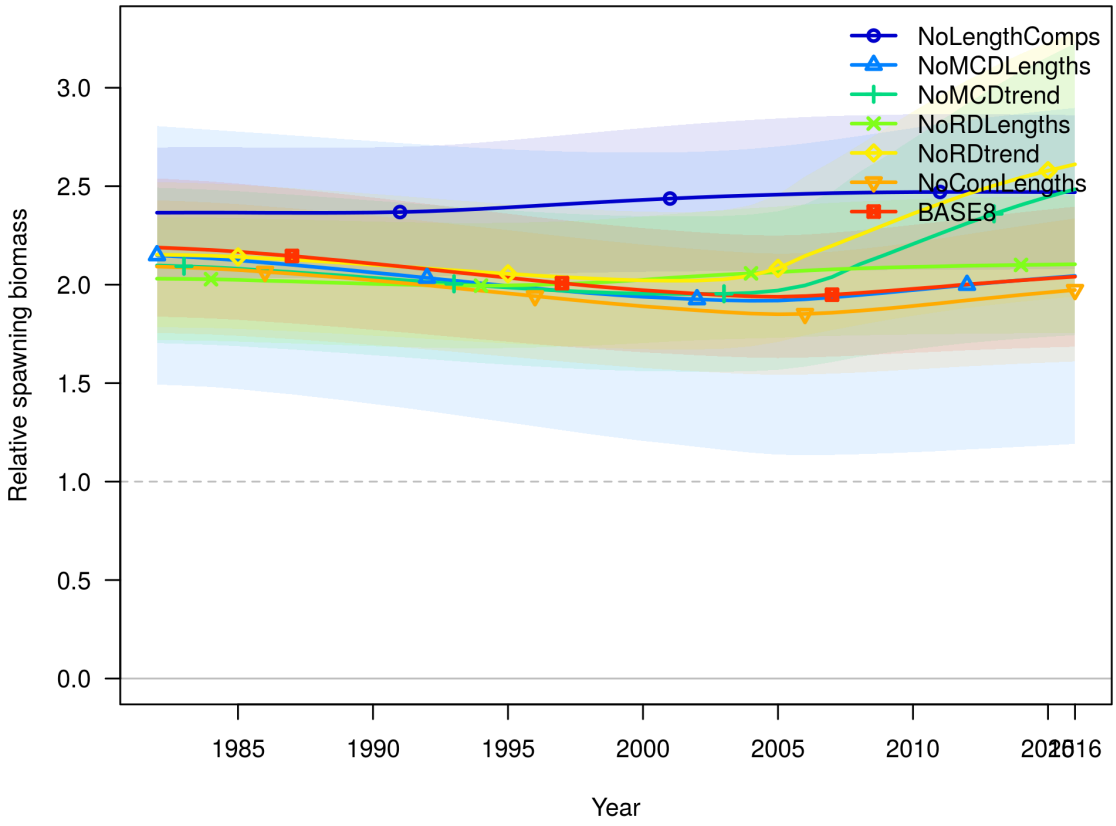

Figure 94: A comparison of the estimated biomass between the base run for ocean quahog (BASE8) and sensitivity runs in which different data were removed from the likelihood calculation (λ set to 0 for each component). The data removed were: all length composition data (NoLengthComps), lengths from the commercial fisheries (NoComLengths), lengths from the the MCD survey (NoMCDLengths), lengths from the RD survey (NoRDLengths), survey trend data from the MCD survey (NoMCDtrend), and survey trend data from the MCD survey (NoRDtrend).

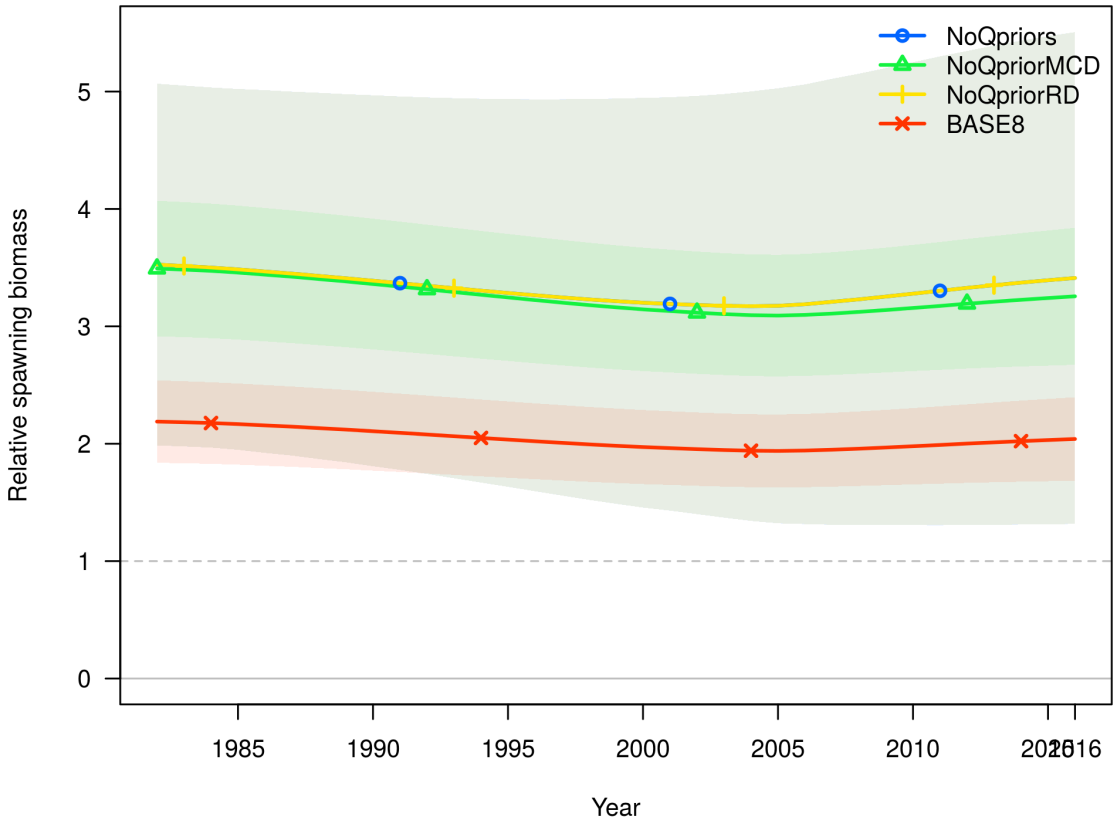

Figure 95: Biomass in model sensitivity runs for ocean quahog in which the priors for catchability from the surveys were not used compared to the base model (BASE8).

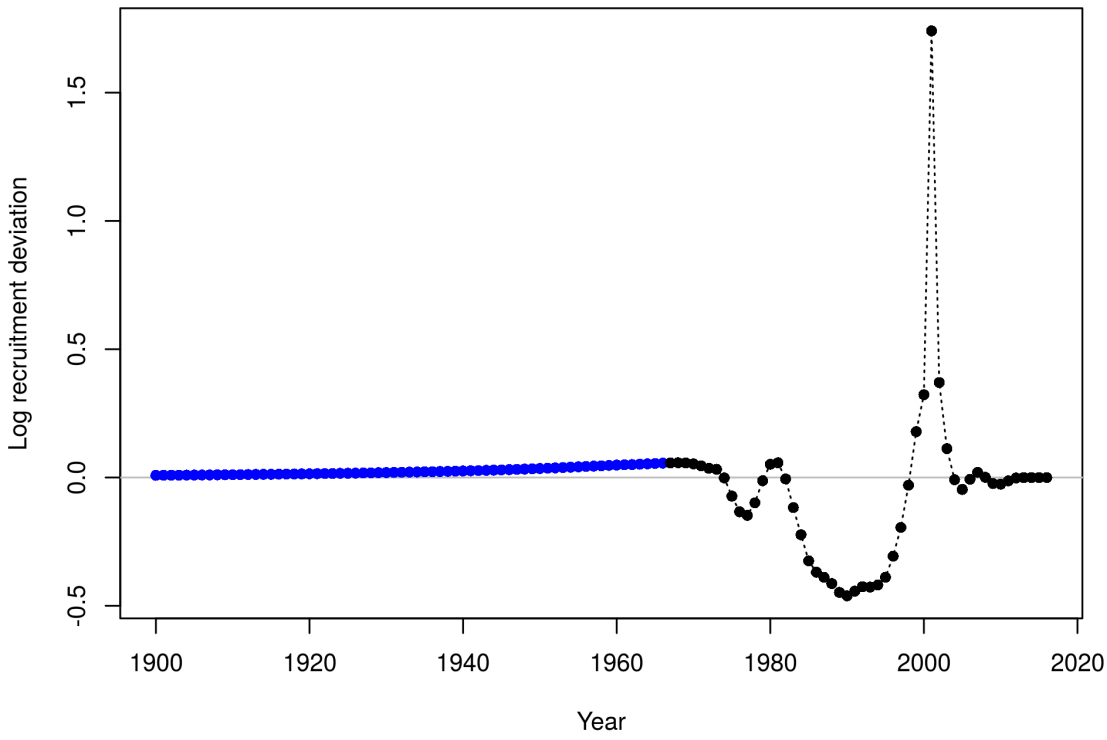

Figure 96: Recruitment deviations from a sensitivity run in which the recruitment variance was constrained relative to the base model.

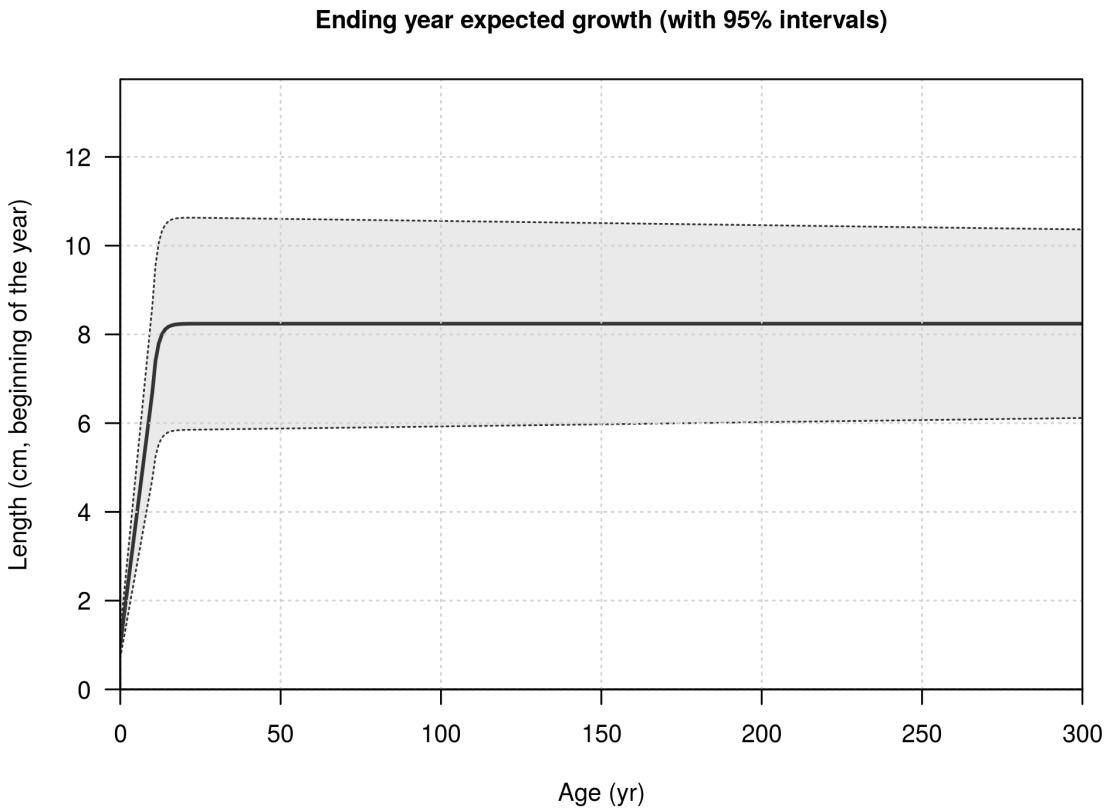

Figure 97: Growth curve from a sensitivity run in which the recruitment variance was constrained relative to the base model.

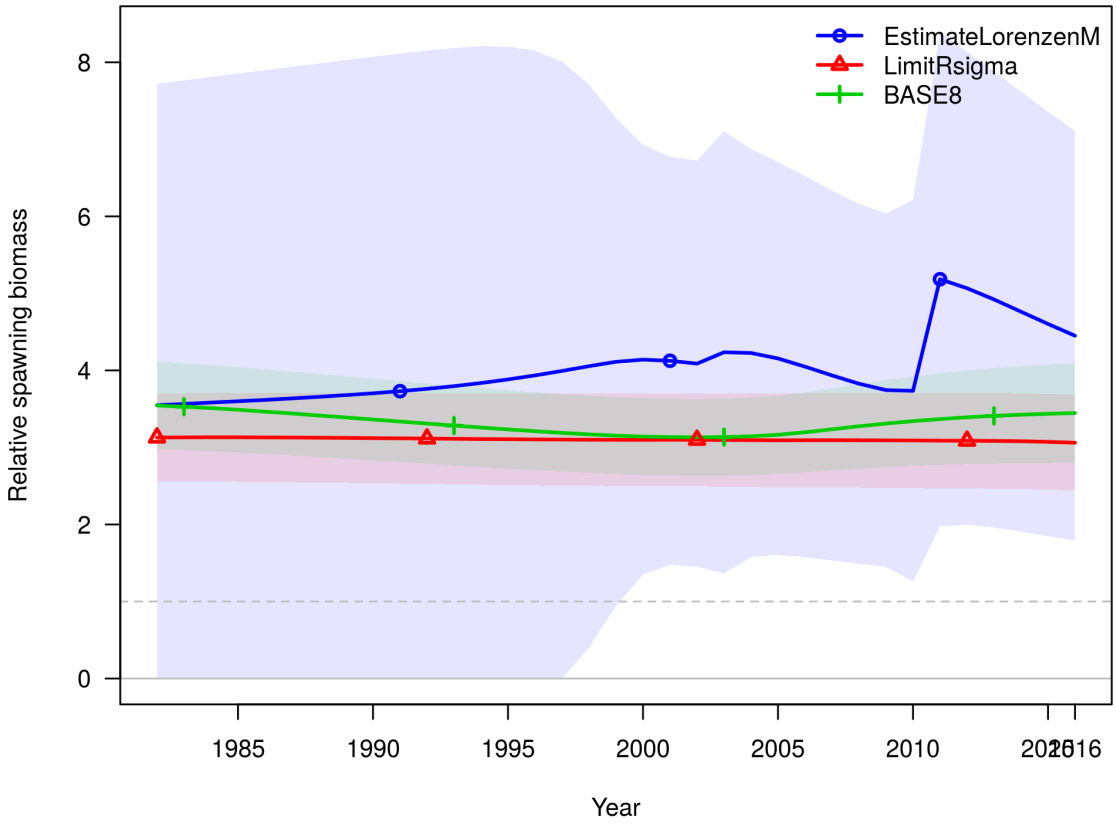

Figure 98: Biomass trends in model sensitivity runs for ocean quahog in which a Lorenzen M was estimated, and recruitment variance was tightly constrained, compared to the base model (BASE8).

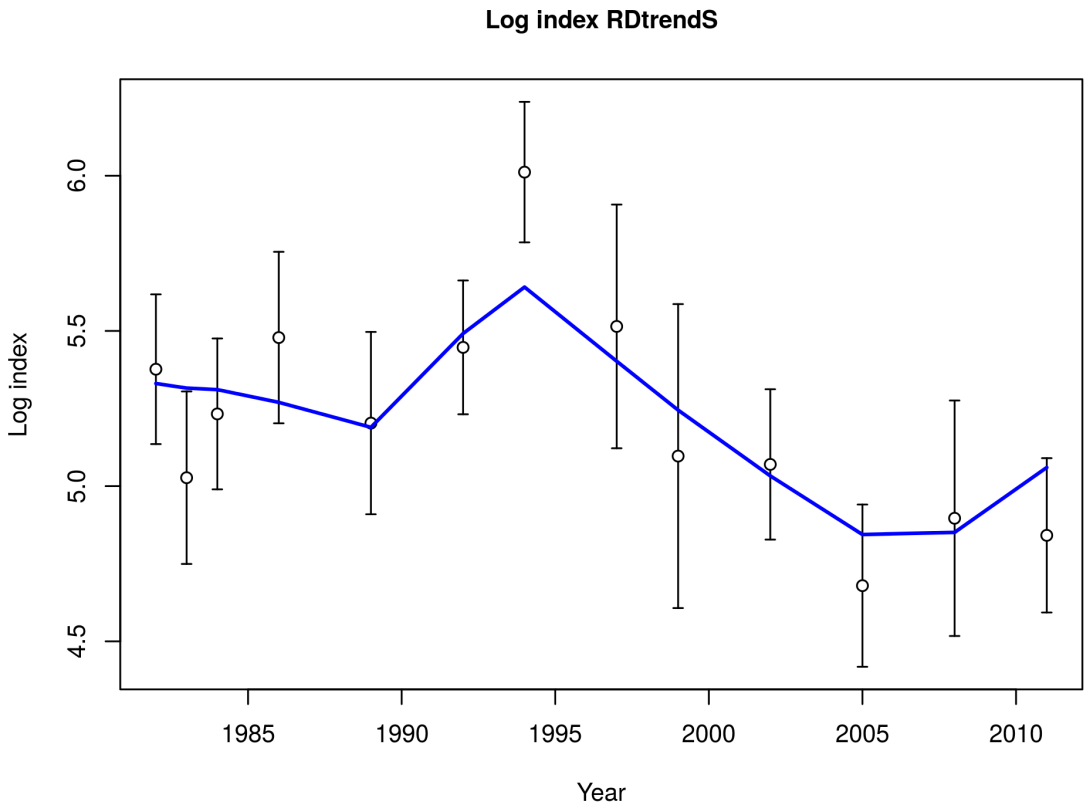

Figure 99: Fit to log index data on log scale for RDtrend survey for ocean quahog in the southern area from a sensitivity run in which a Lorenzen type natural mortality curve at age was estimated. Vertical lines are 95% confidence intervals.

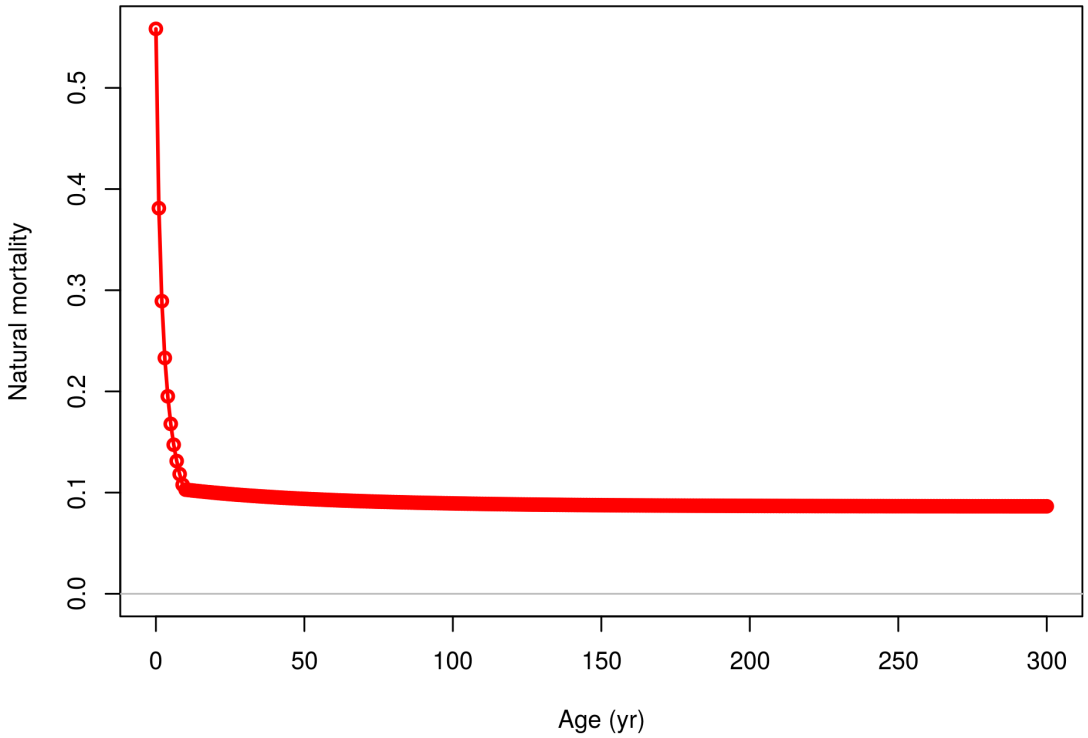

Figure 100: Natural mortality at age for ocean quahog from a sensitivity run in which a Lorenzen type natural mortality curve at age was estimated.

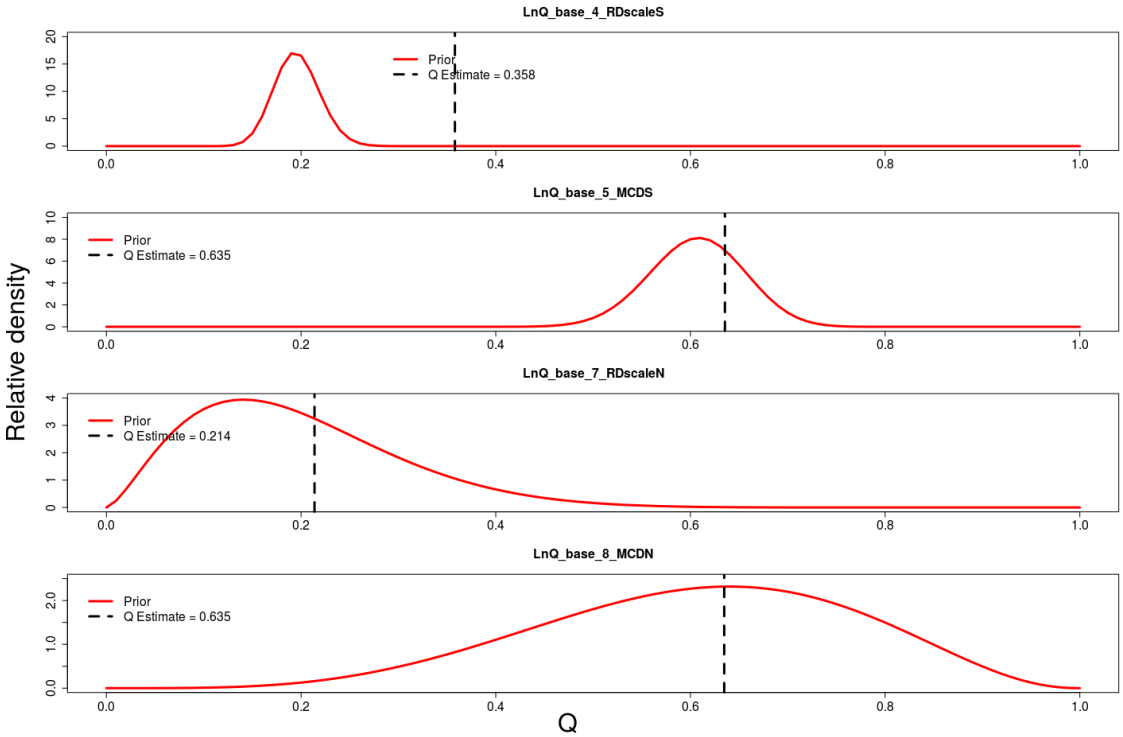

Figure 101: Estimated survey q with prior distributions for ocean quahog from a sensitivity run in which the variance of the prior distributions for survey q in the southern area was reduced, and the variance adjustments to the composition data for the southern area were reduced.

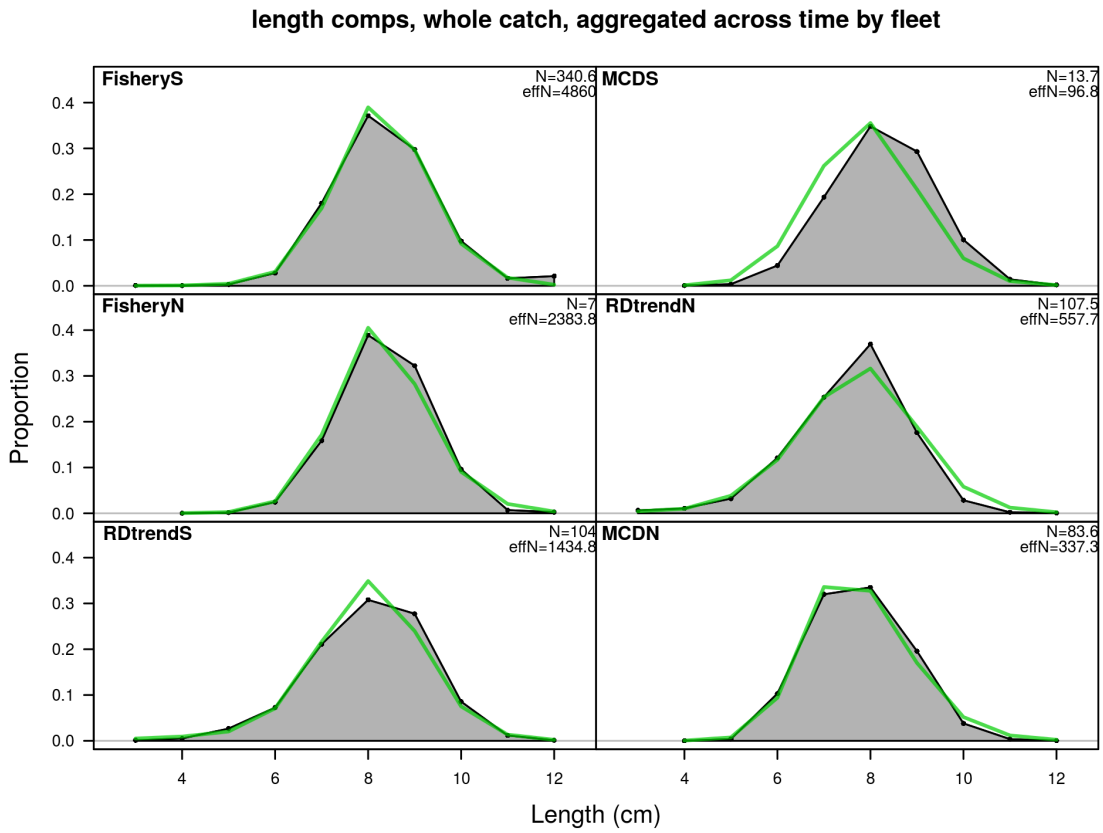

Figure 102: Model fit to length composition data from all sources aggregated across time for ocean quahog from a sensitivity run in which the variance of the prior distributions for survey q in the southern area was reduced, and the variance adjustments to the composition data for the southern area were reduced.

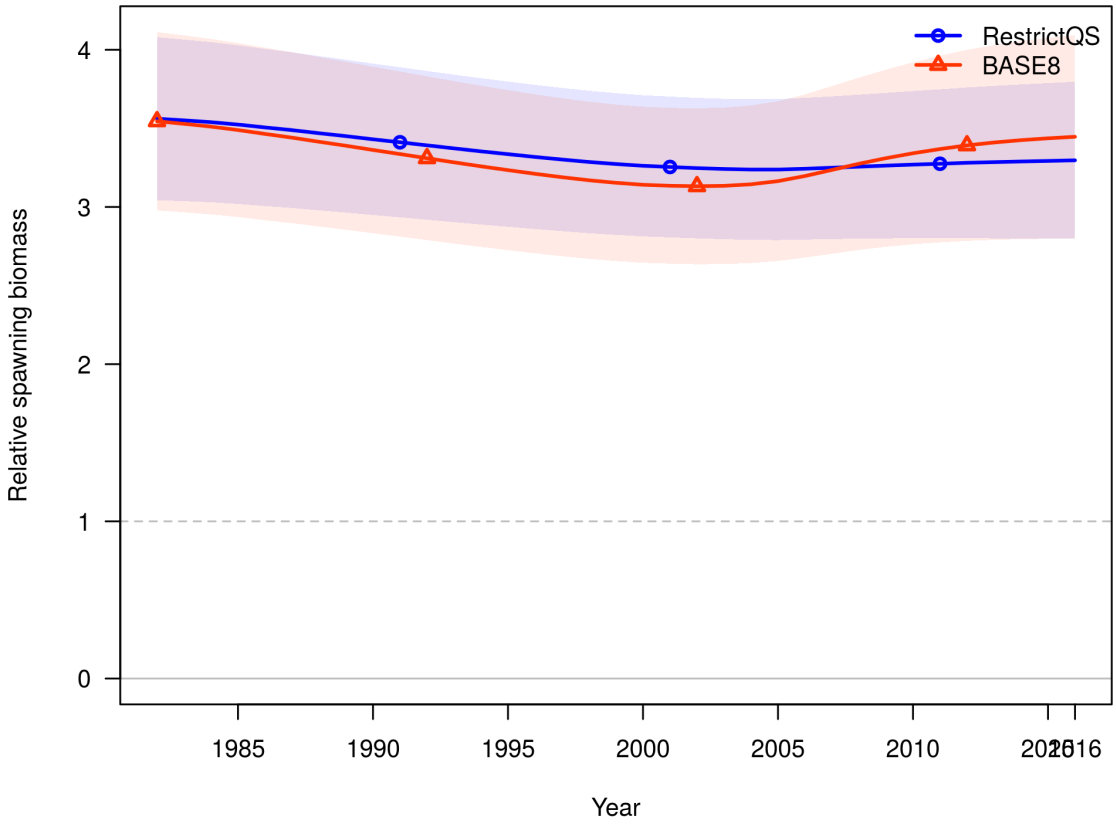

Figure 103: Biomass trends in model sensitivity runs for ocean quahog in which the variance of the prior distributions for survey q in the southern area was reduced, and the variance adjustments to the composition data for the southern area were reduced, compared to the base model (BASE8).

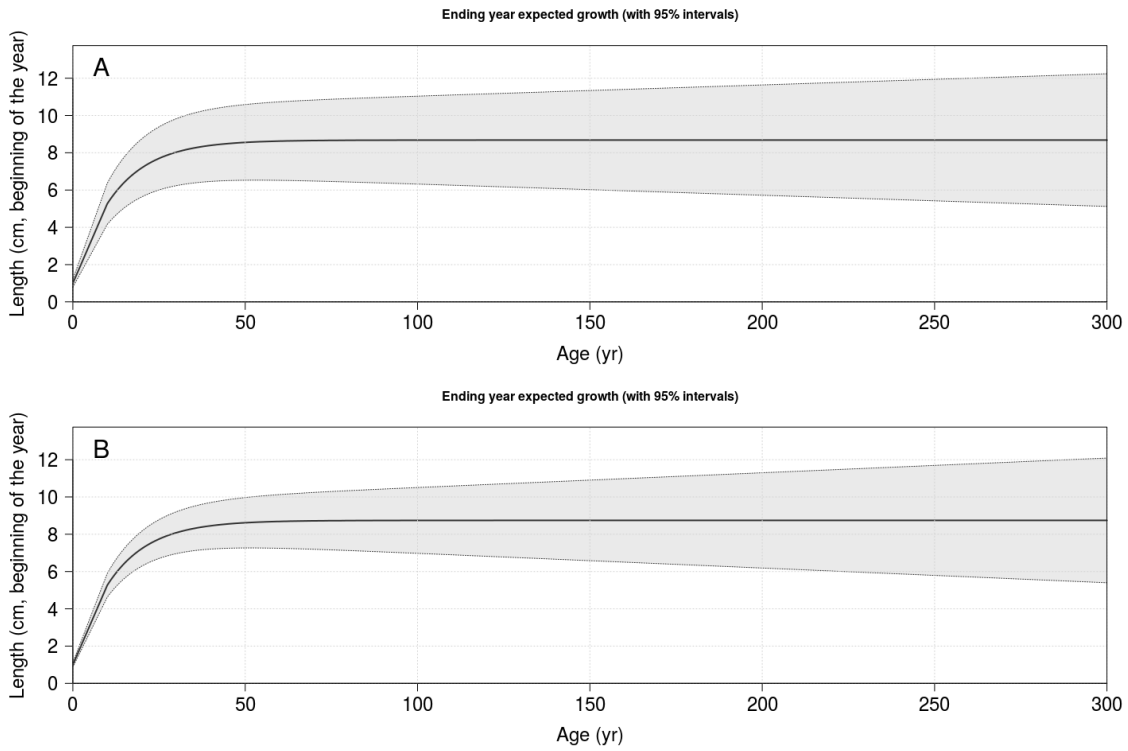

Figure 104: Length at age relationship by area from a sensitivity run for ocean quahog in which growth was allowed to vary by area, although the K parameter was fixed at the same value for each area.

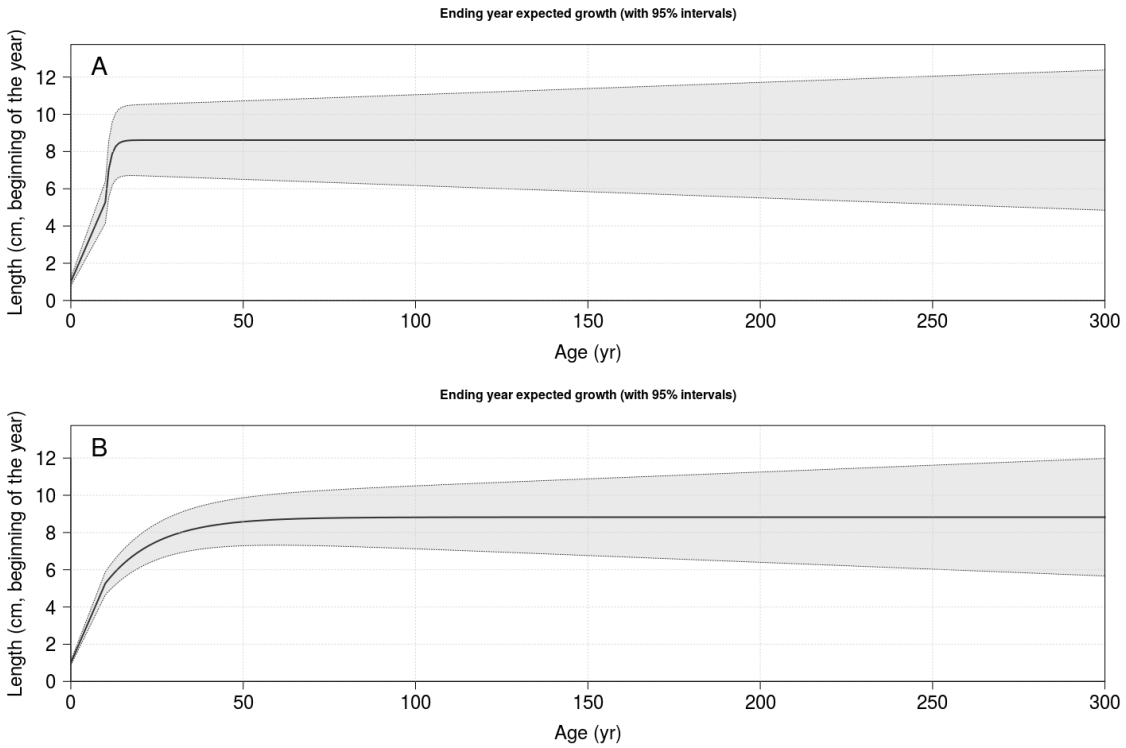

Figure 105: Length at age relationship by area from a sensitivity run for ocean quahog in which growth was allowed to vary freely by area.

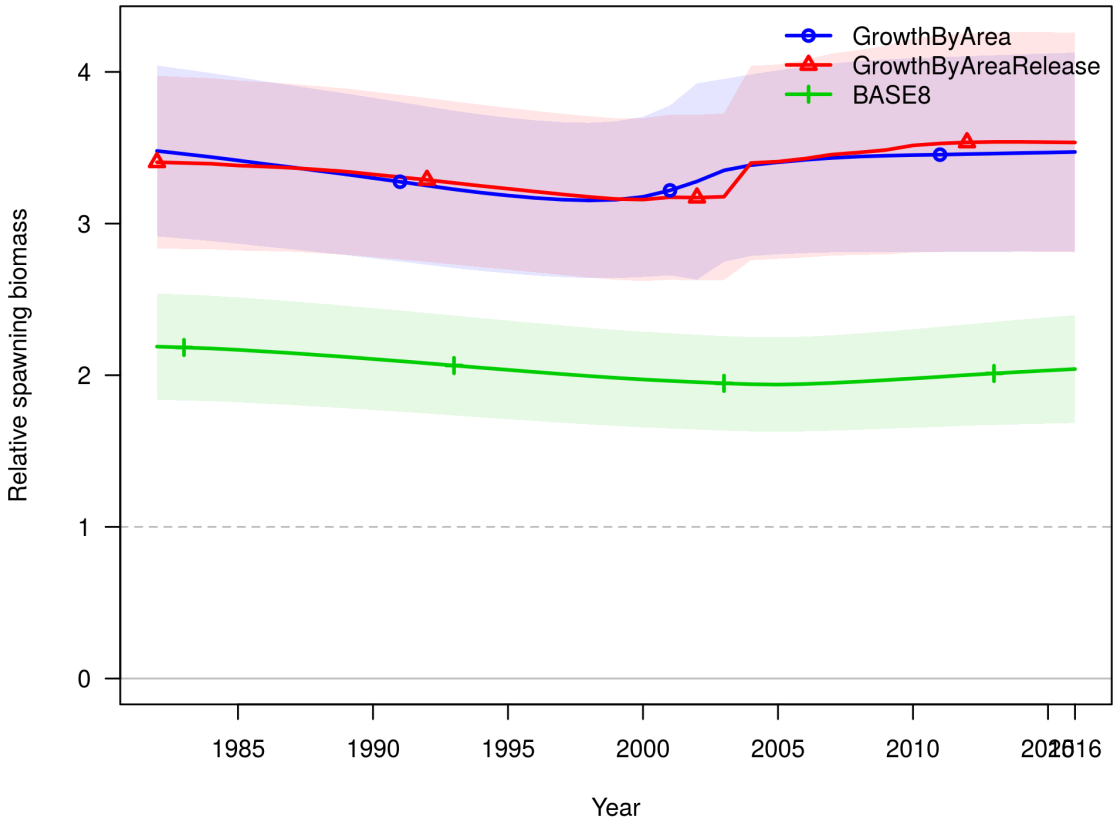

Figure 106: Biomass trends in model sensitivity runs for ocean quahog in which growth was allowed to vary by area with the K parameter fixed at the same value for each area (GrowthByArea), and where growth was allowed to vary freely by area (GrowthByAreaRelease), compared to the base model (BASE8).

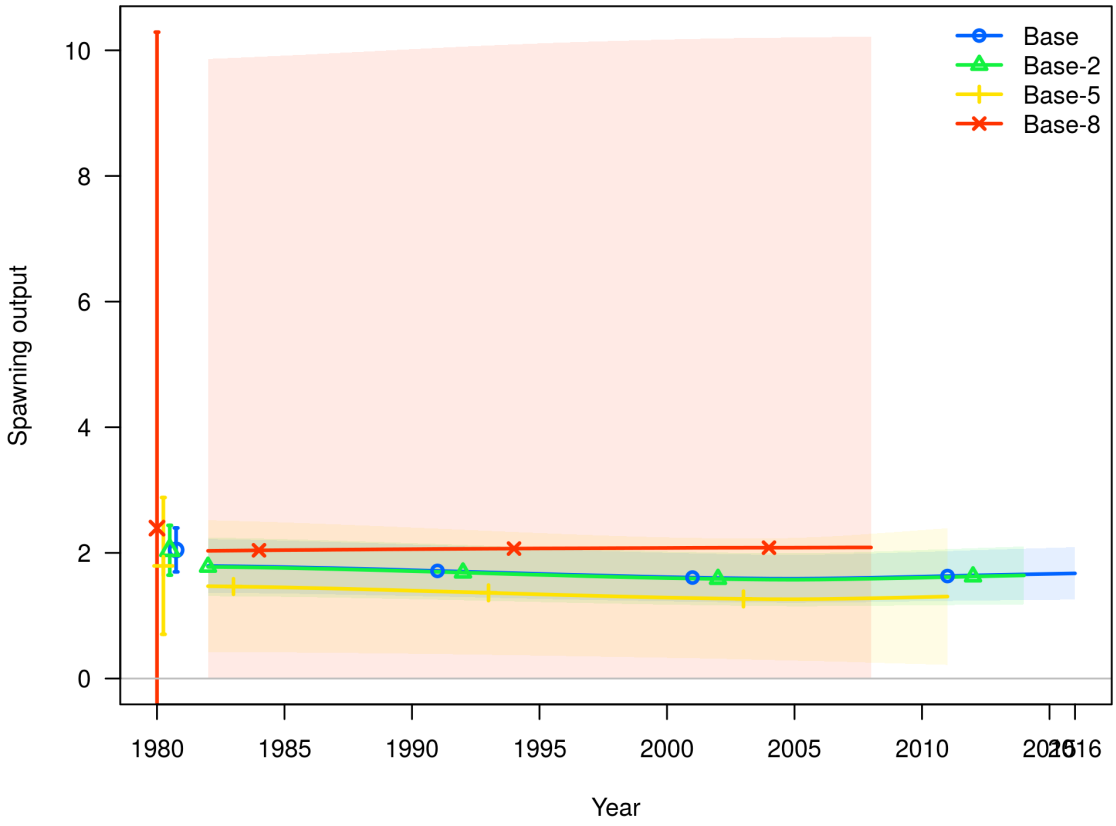

Figure 107: Biomass scale and uncertainty from 4 retrospective runs of the model for ocean quahog. The y axis is the proportional number of spawning clams in all areas. The biomass scale changes slightly, and uncertainty increases substantially, as survey data are removed.

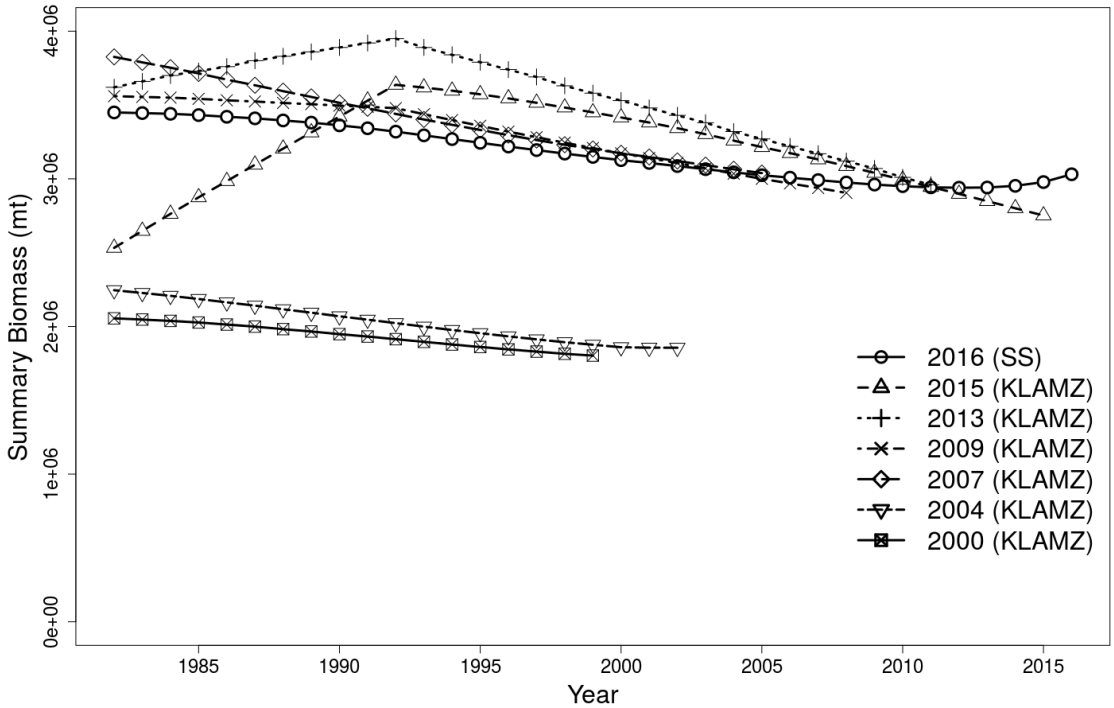

Figure 108: Historical retrospective plot showing the biomass trajectory from each of the previous ocean quahog assessments as well as the KLAMZ model run from Appendix 6 (2015) and the current SS base model (2016). All biomasses shown are "summary", which corresponds to all animals older than 20 years in SS and all animals longer than 50 mm in all other models.

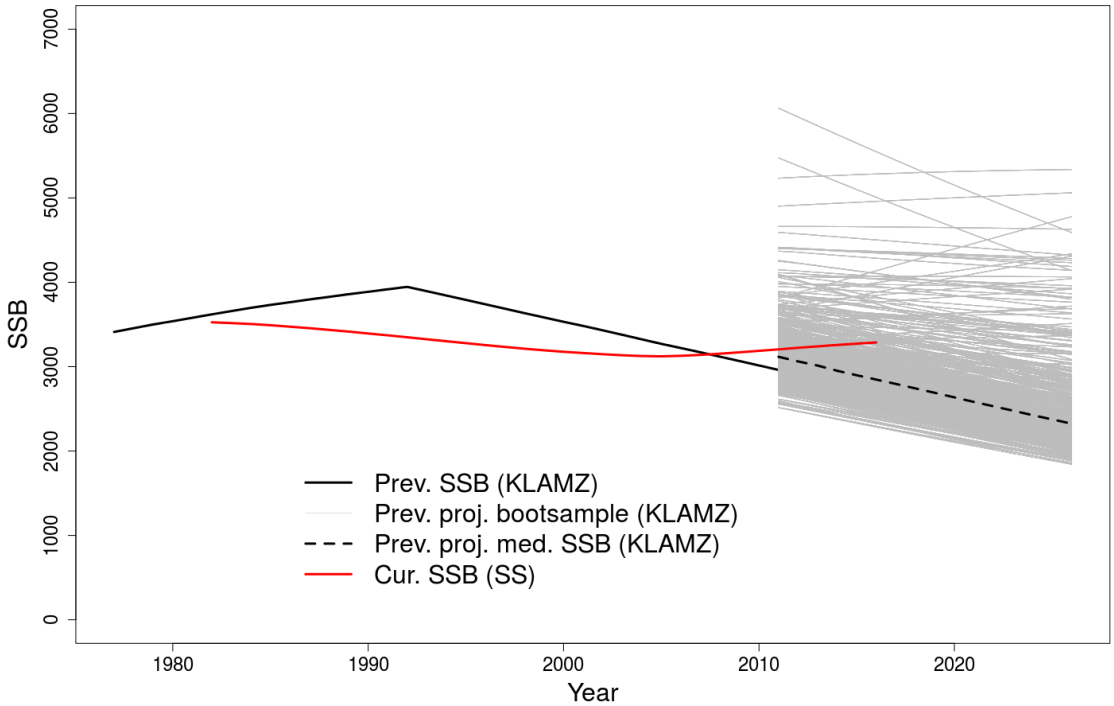

Figure 109: Point estimates of SSB, bootstrap projections, and median projected SSB from the previous assessment, compared to the current point estimates of SSB.

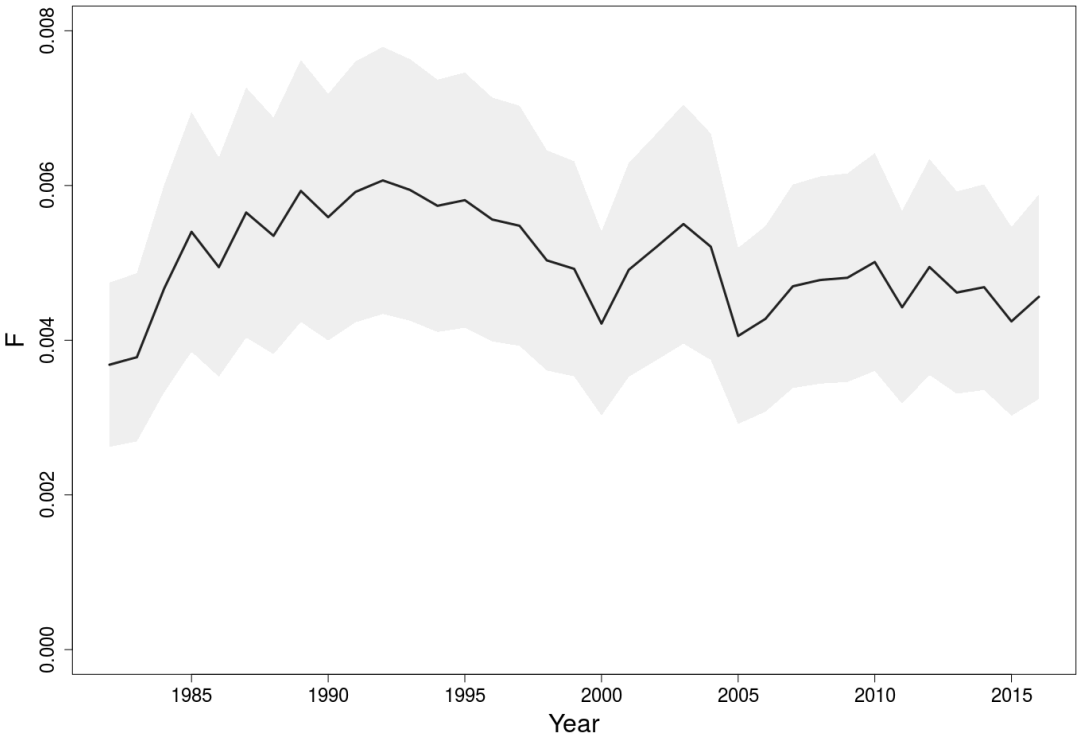

Figure 110: Fishing mortality estimates from the ocean quahog assessment base model, including lower and upper 95% confidence bounds.

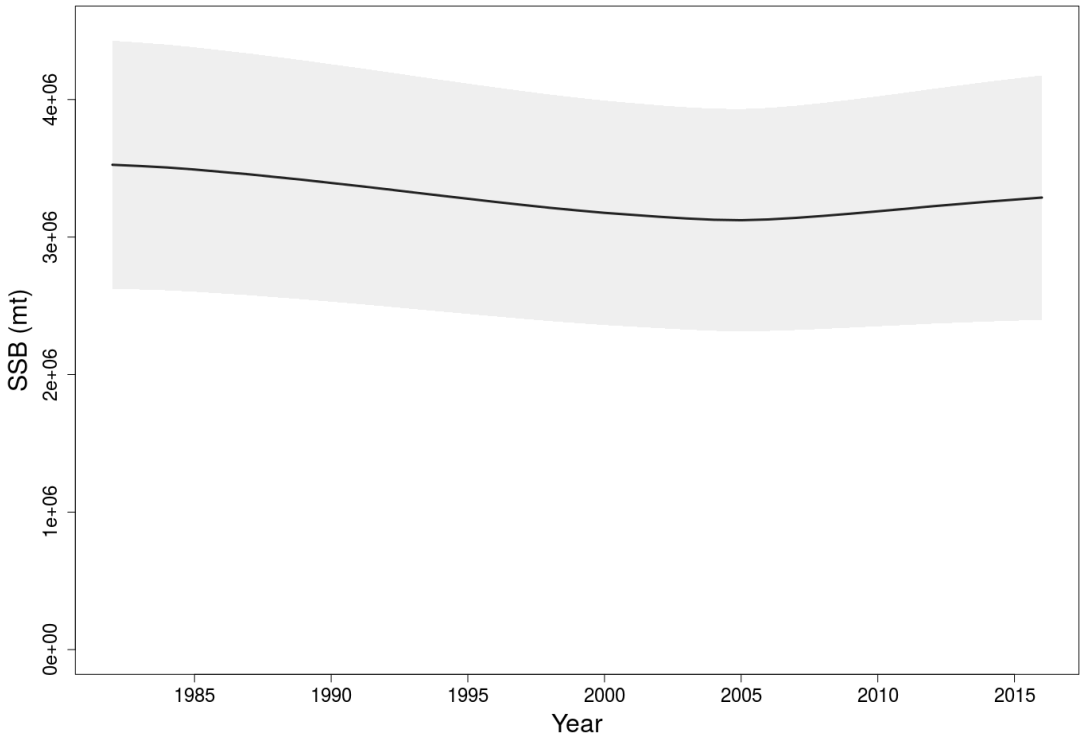

Figure 111: Spawning stock biomass estimates from the ocean quahog assessment base model in '000 mt, including lower and upper 95% confidence bounds.

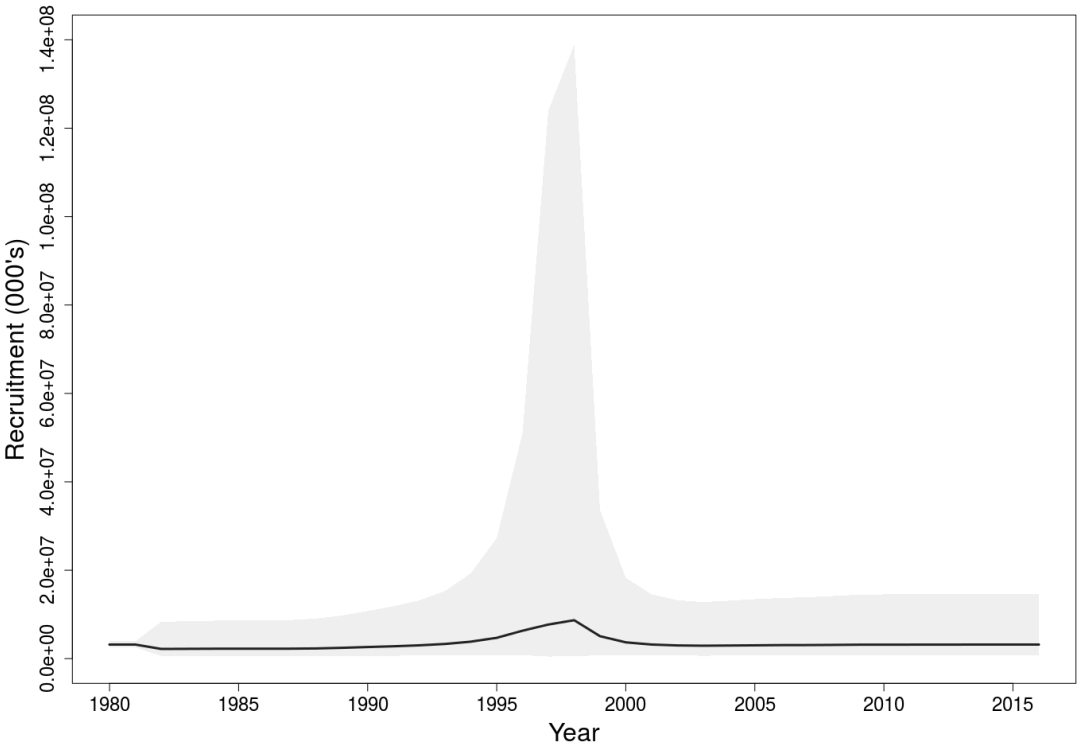

Figure 112: Recruitment estimates from the ocean quahog assessment base model, including lower and upper 95% confidence bounds.

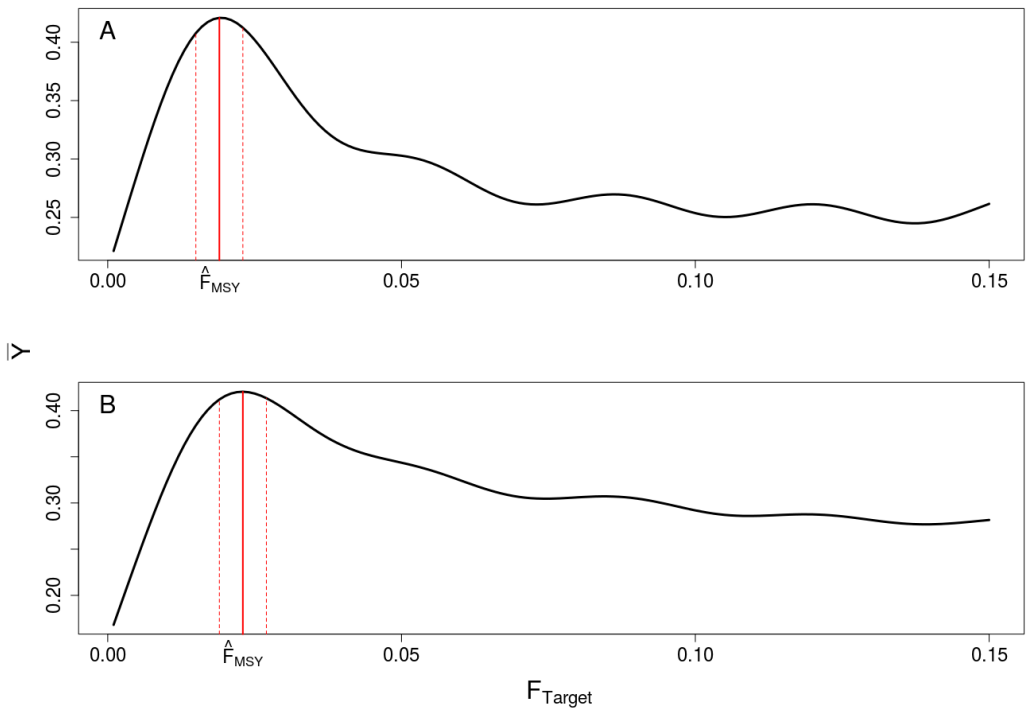

Figure 113: $F_{MSYproxy}$ from the MSE. The average yield over 1000 years fit to a GAM over the F_{Target} from each simulation run. Maximum average yield was achieved at the F_{Target} that is designated as $\hat{F}_{MSY}$ and a solid red vertical line. The dashed red vertical lines show the F_{Target} closest to the 95% quantiles of average yield to either side of $\hat{F}_{MSY}$. Panel A shows the results for simulations where growth was Von Bertalanffy and panel B shows the results from simulations using Tanaka growth.

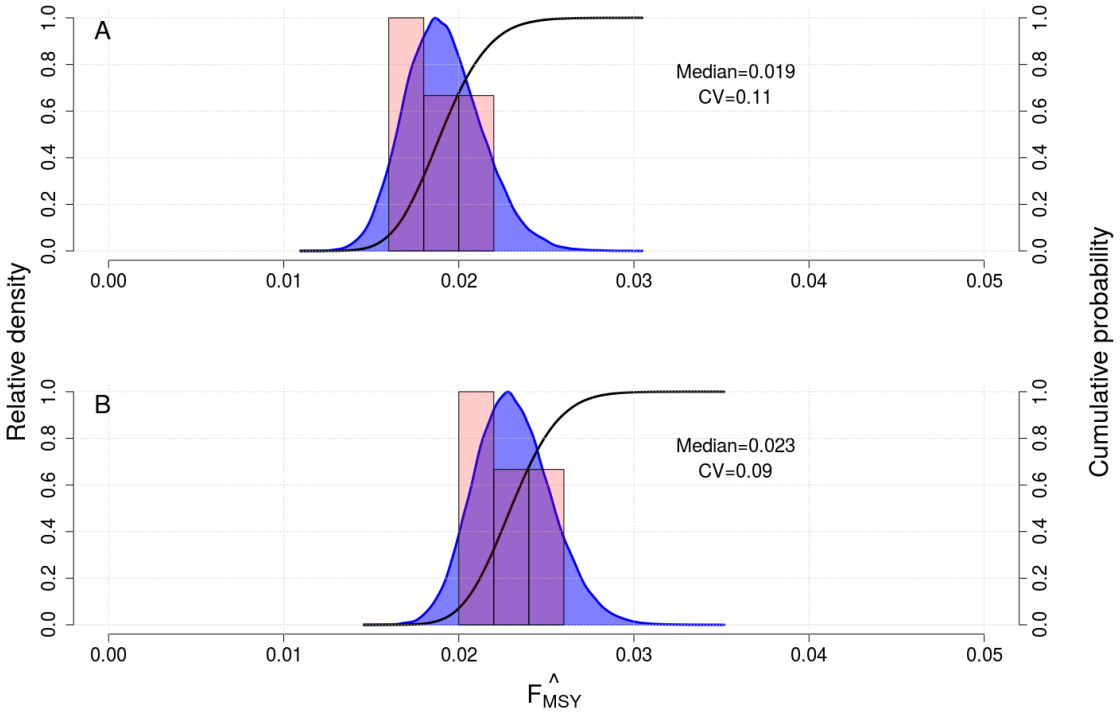

Figure 114: A lognormal distribution with mean, $\hat{F}_{MSY}$ and variance based on all of the F_{Target} that resulted in average yield between the bounds formed by the 95% quantiles to either side of $\hat{F}_{MSY}$ (see Figure 113) in the MSE. A frequency histogram of the F_{Target} values used to produce each distribution is superimposed over each plot. Panel A shows the results for simulations where growth was Von Bertalanffy and panel B shows the results from simulations using Tanaka growth.

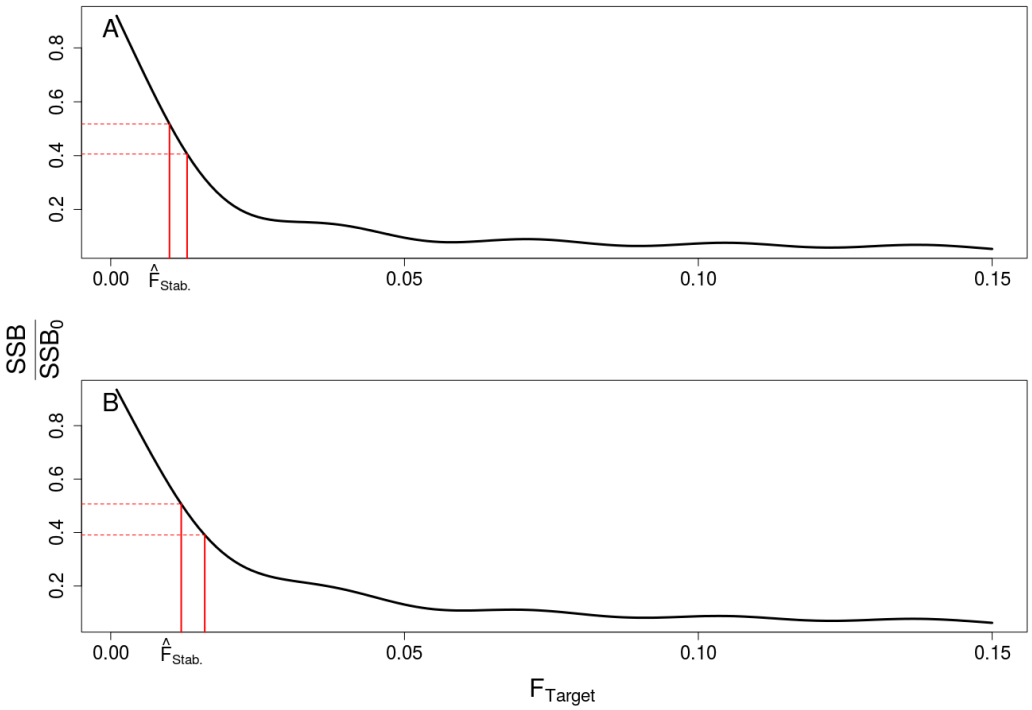

Figure 115: $F_{Stab.proxy}$ from the MSE. The average biomass over 1000 years fit to a GAM over the F_{Target} from each simulation run. Average biomass closest to $SSB_{Target} = \frac{1}{2}SSB_0$ was achieved at the F_{Target} that is designated as $\hat{F}_{Stab.}$ and a solid red vertical line. The second solid red vertical lines show the F_{Target} closest to the $SSB_{Theshold} = \frac{2}{5}SSB_0$. Panel A shows the results for simulations where growth was Von Bertalanffy and panel B shows the results from simulations using Tanaka growth.

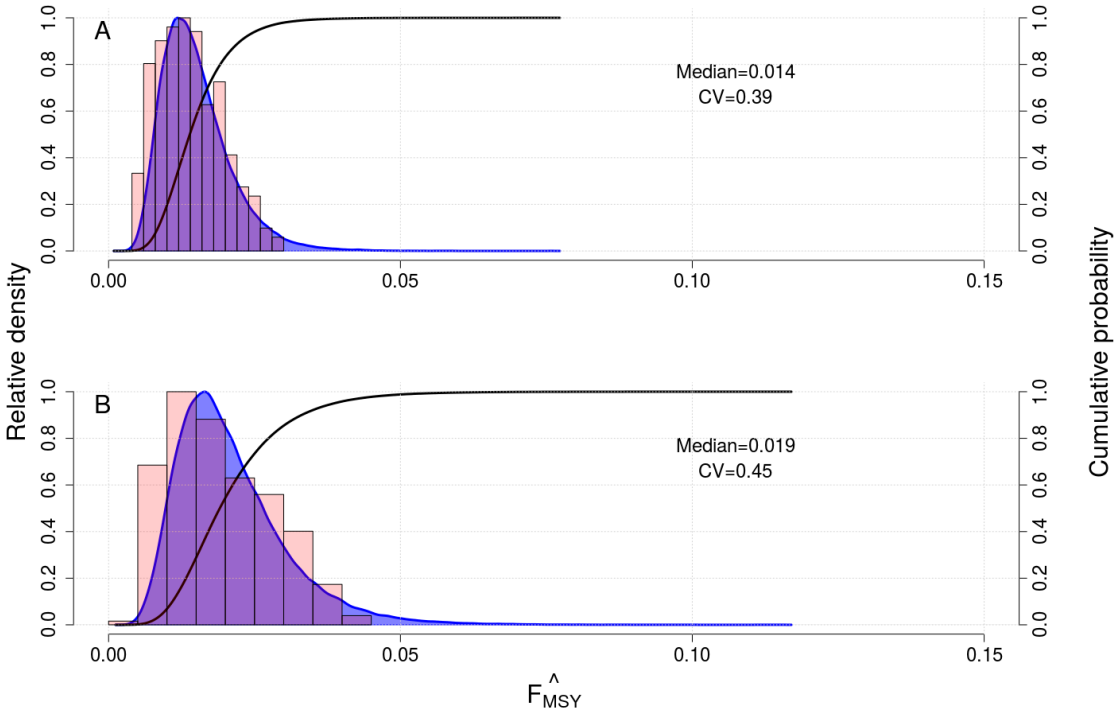

Figure 116: A lognormal distribution with mean, $\hat{F}_{Stab.}$ and variance based on all of the F_{Target} that resulted in average biomass between the bounds formed by $\frac{2}{5}SSB_0$ and $\frac{1}{2}SSB_0$ (see Figure 115) in the MSE. A frequency histogram of the F_{Target} values used to produce each distribution is superimposed over each plot. Panel A shows the results for simulations where growth was Von Bertalanffy and panel B shows the results from simulations using Tanaka growth.

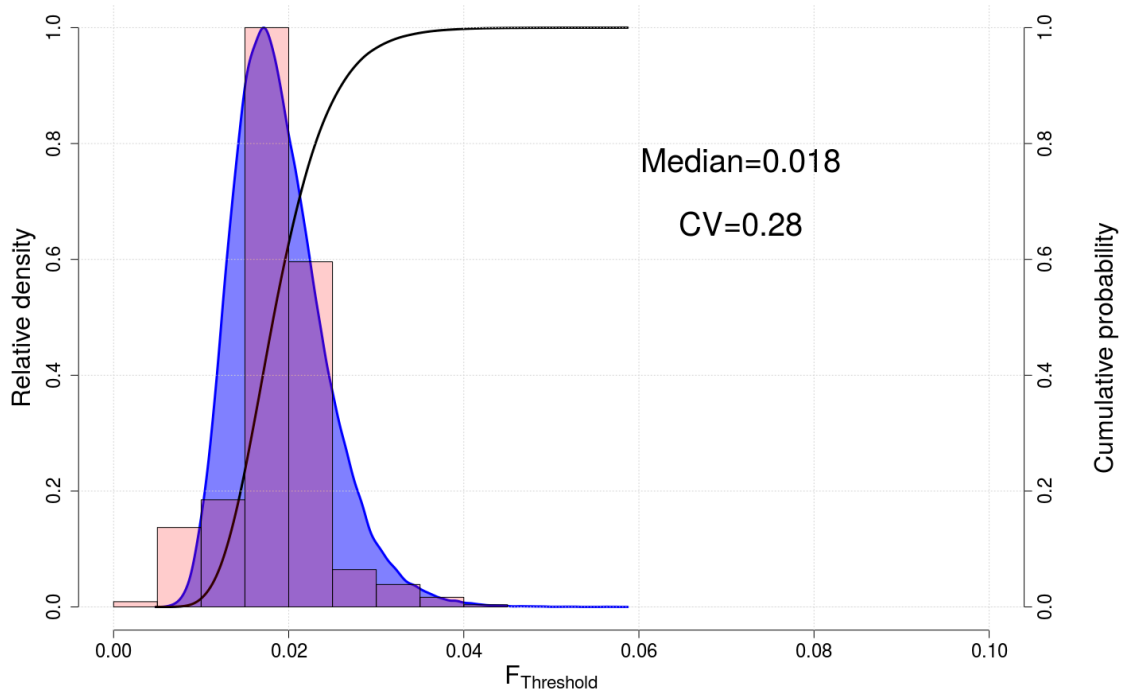

Figure 117: A lognormal distribution with mean and variance based on all of the F_{Target} that resulted in average biomass between the bounds formed by $\frac{2}{5}SSB_0$ and $\frac{1}{2}SSB_0$, or average yield between the bounds formed by the 95% quantiles to either side of $\hat{F}_{MSY}$ (see Figures 113 - 115). A frequency histogram of the F_{Target} values used to produce the distribution is superimposed over the plot. This is the preferred $F_{Threshold}$ used to determine stock status for ocean quahog.

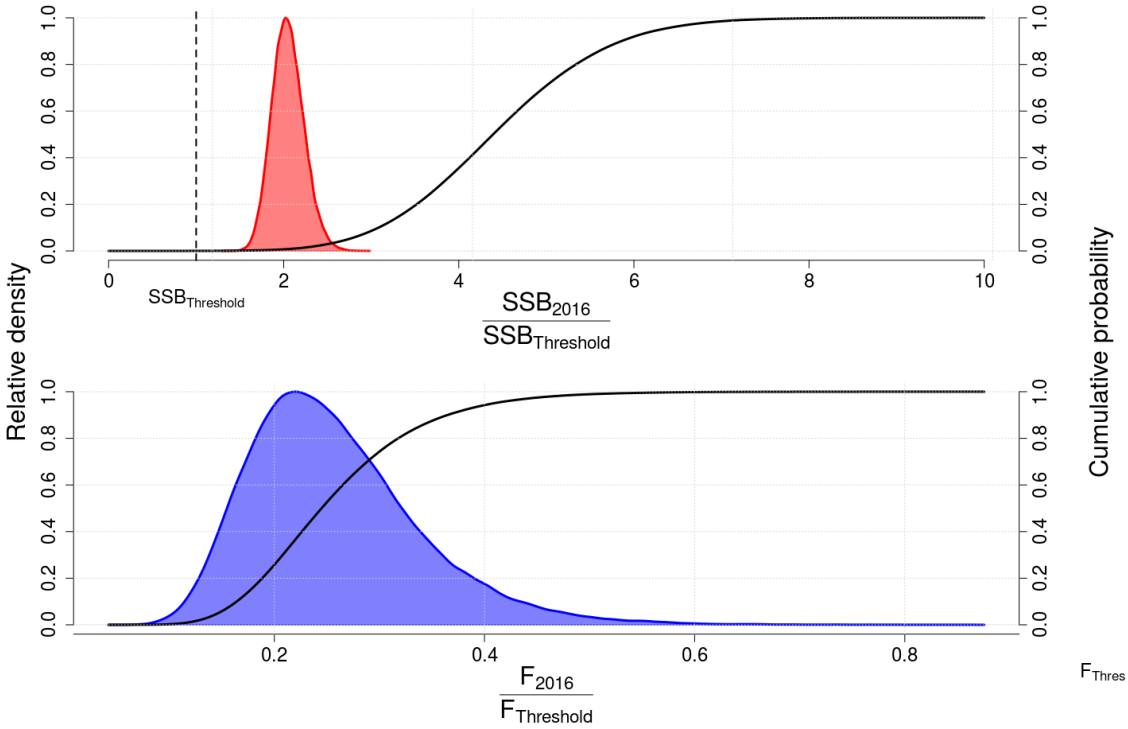

Figure 118: Probability distributions of $\frac{SSB_{2016}}{SSB_{Threshold}}$ and $\frac{F_{2016}}{F_{Threshold}}$, using the recommended reference points. The probability of overfished status during 2016 is equal to the area of the red, upper curve that is less than $SSB_{Threshold}$. The probability of overfishing status during 2016 is equal to the area of the blue, lower curve that is greater than $F_{Threshold}$. The probability of overfished and overfishing status can be approximated by the elevation (y axis scale) at which the solid line representing the cumulative probability distribution crosses the dashed vertical line representing the reference point in each plot. The probability distributions presented in this figure account for the positive correlation between the reference points ($SSB_{Threshold} = 0.4 * SSB_0$ and $F_{Threshold} = F^* \frac{F_{MSY}}{F^*_{Max}}$) and the fishing mortality and spawning biomass estimates in 2016, as well as the uncertainty in the estimation of both the point estimates and their respective reference points.

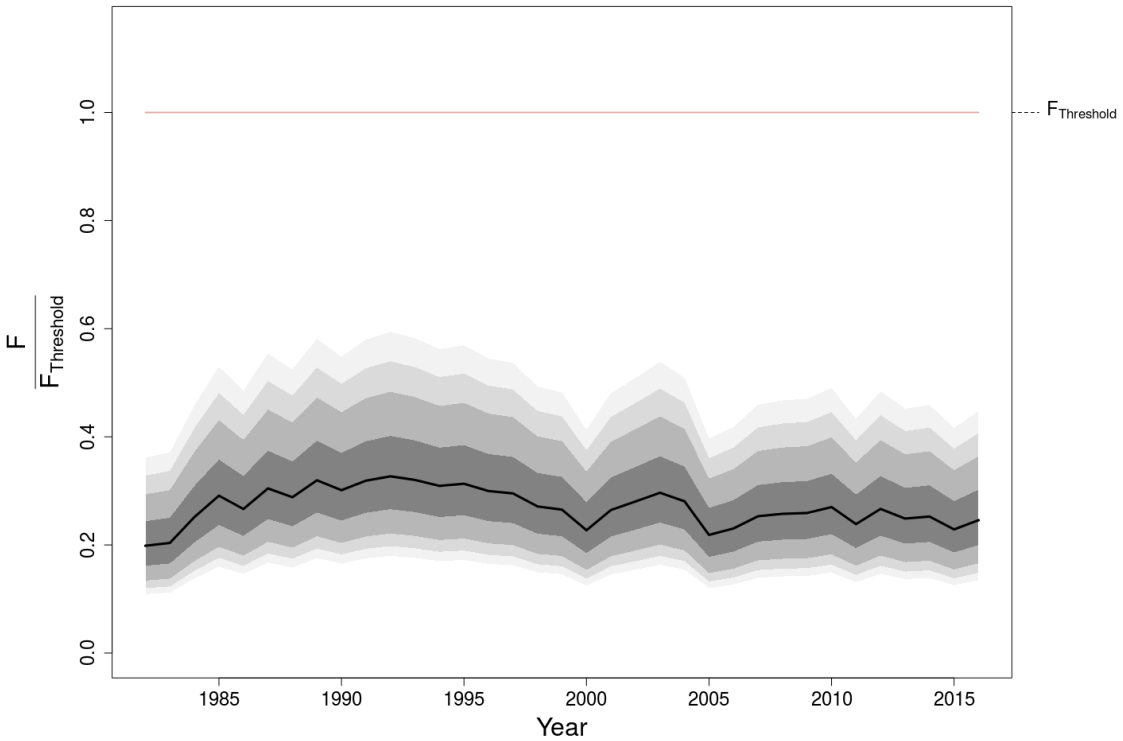

Figure 119: The time series of the ratio of fishing mortality estimates to the recommended F threshold, with the 95% confidence interval. The confidence interval accounts for the correlation between F and $F_{Threshold}$. Overfishing would occur if the ratio exceed 1.0.

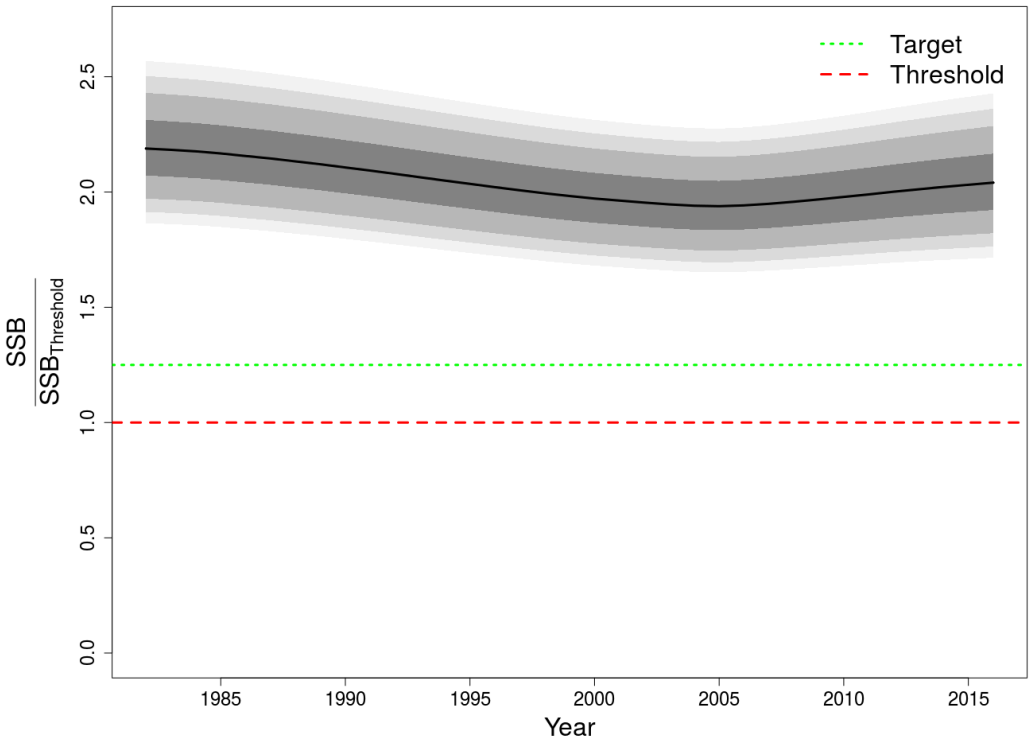

Figure 120: The time series of the ratio of spawning biomass estimates to the unfished spawning biomass (SSB_0), with the 95, 90, 80 and 50% confidence intervals. The confidence interval accounts for the correlation between SSB and SSB_0. Overfished status would occur if the ratio went below 1.0.

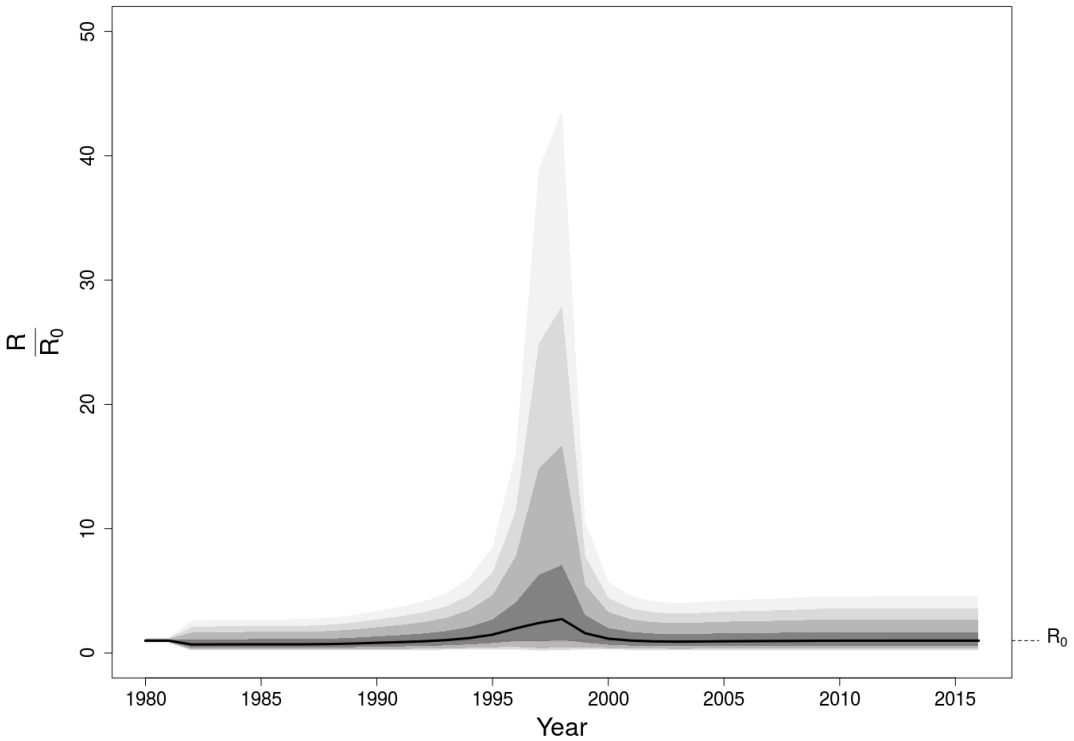

Figure 121: The time series of the ratio of recruitment estimates to the equilibrium recruitment (R_0), with the 95, 90, 80 and 50% confidence intervals.

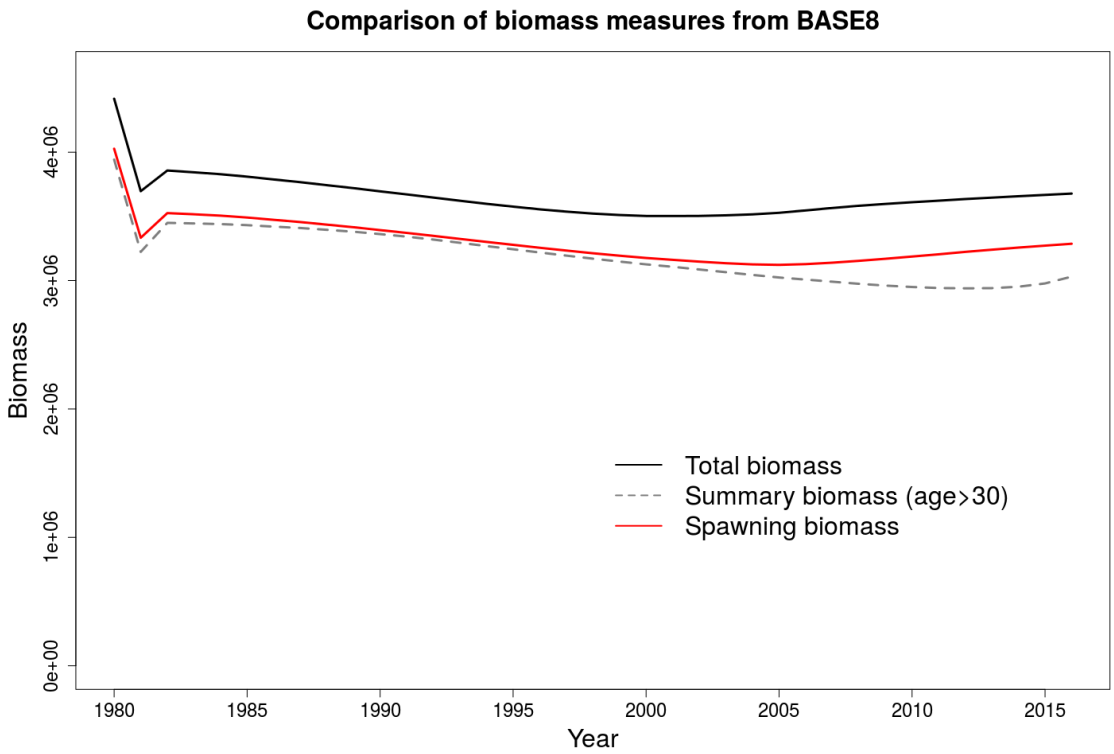

Figure 122: A comparison of different measures of biomass.

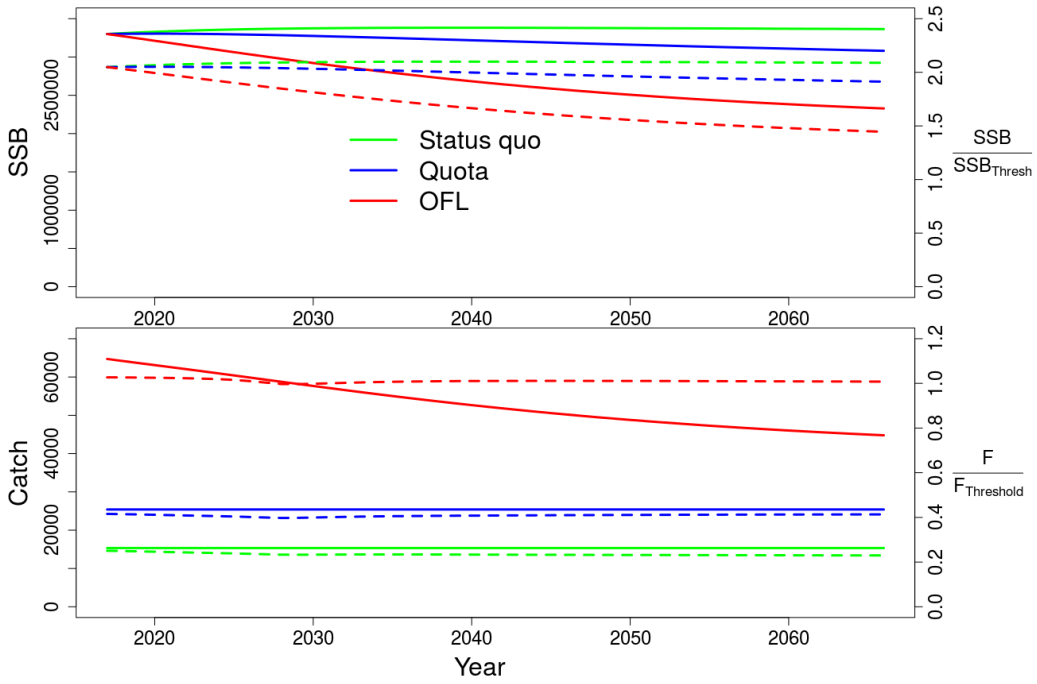

Figure 123: Projections using three different catch scenarios. The upper plot shows the biomass trends over time (solid lines) and the ratio of biomass to biomass threshold (dashed lines). The lower plot shows the landings (solid lines) and the ratio of F to $F_{Threshold}$. In all plots the status quo catch scenario is green, the quota catch scenario is blue and the OFL scenario is red.

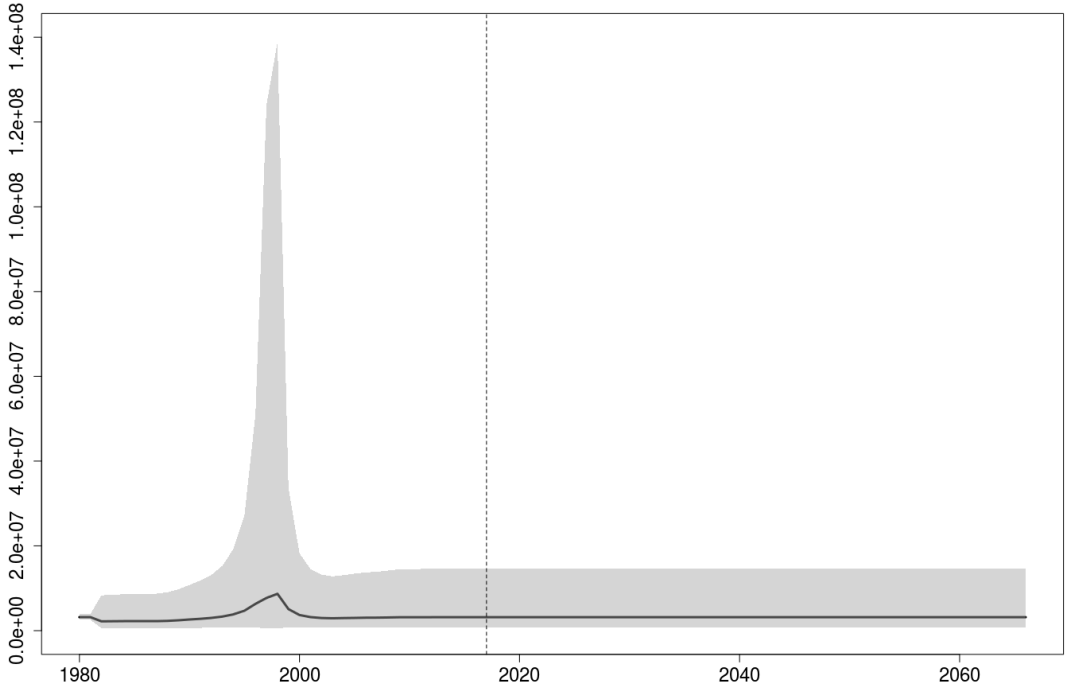

Figure 124: Forecast and time series recruitment estimates. Projections begin at the vertical dashed line.

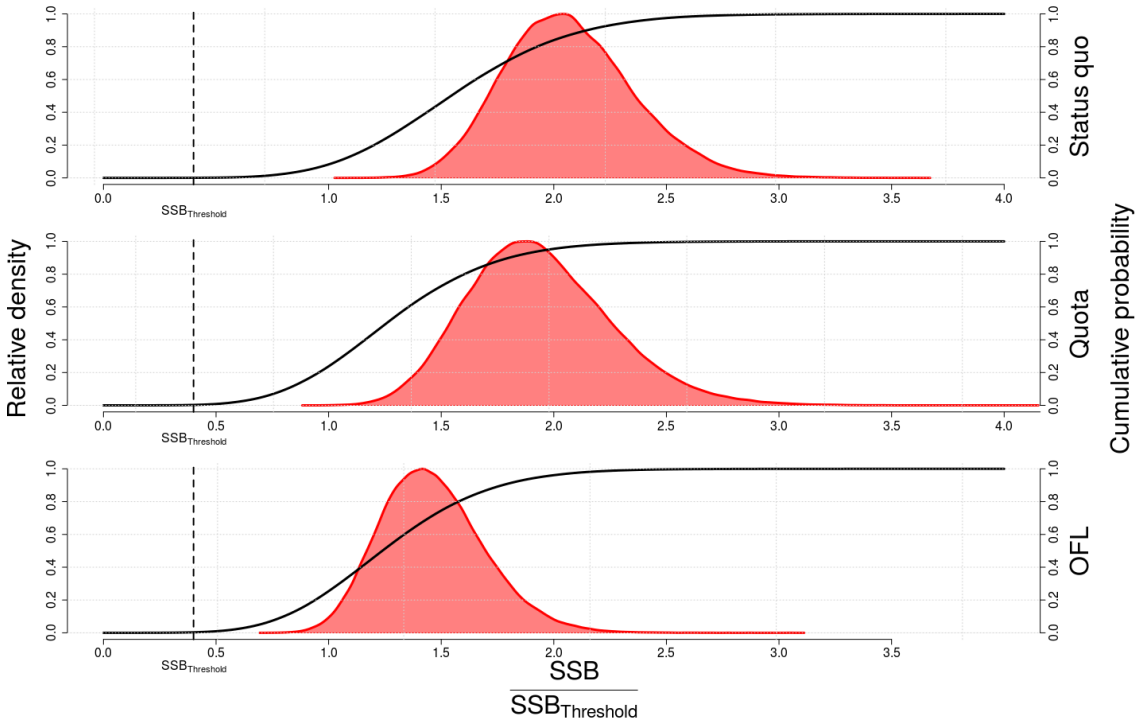

Figure 125: Probability of overfished status for ocean quahog during the projection year with the lowest biomass from 2017-2066. The different catch scenarios are in rows.

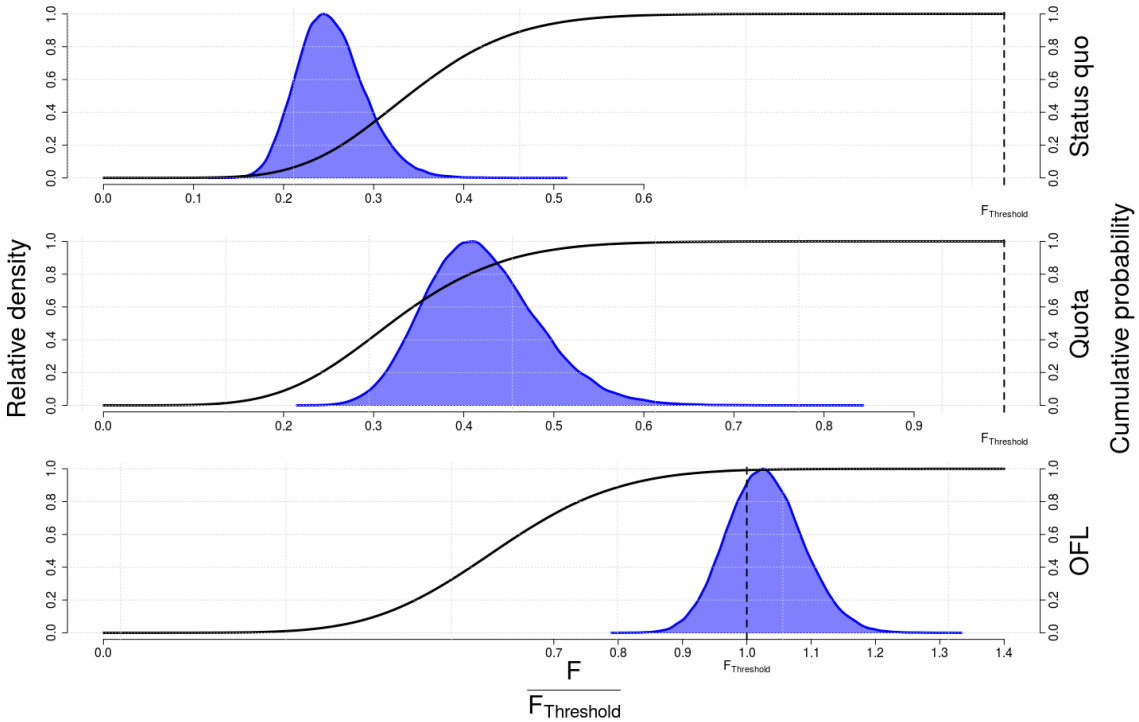

Figure 126: Probability of overfishing status for ocean quahog during the projection year with the highest F from 2017-2066. The different catch scenarios are in rows.

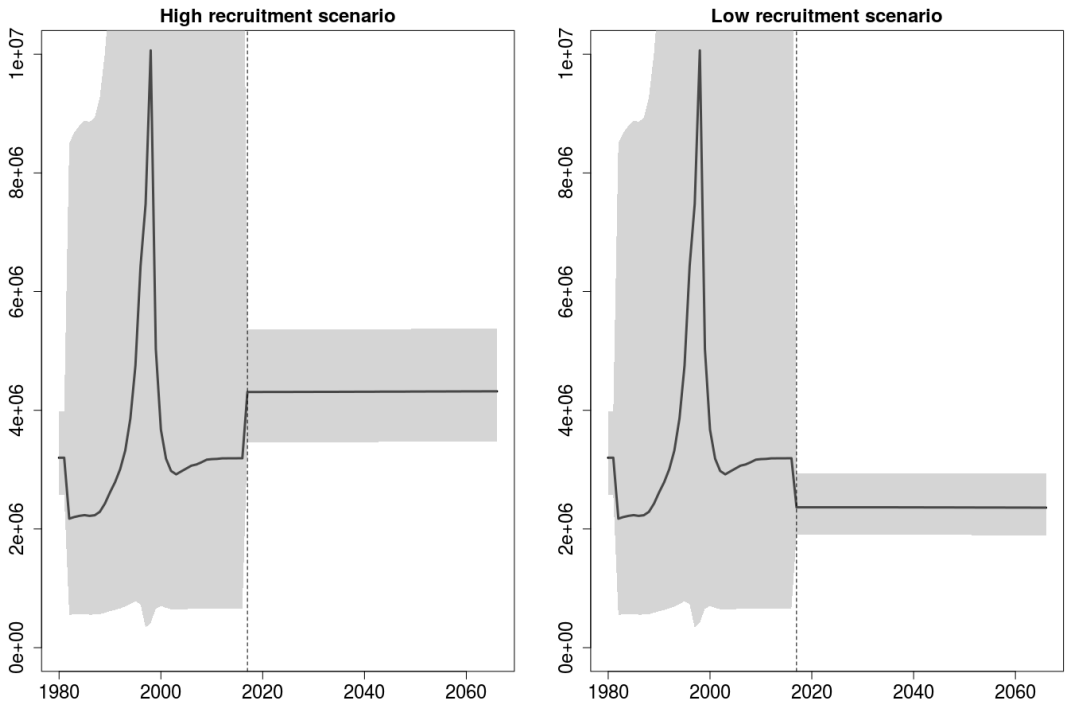

Figure 127: Forecast recruitments for the high and low recruitment scenarios in sensitivity projection runs for ocean quahog.

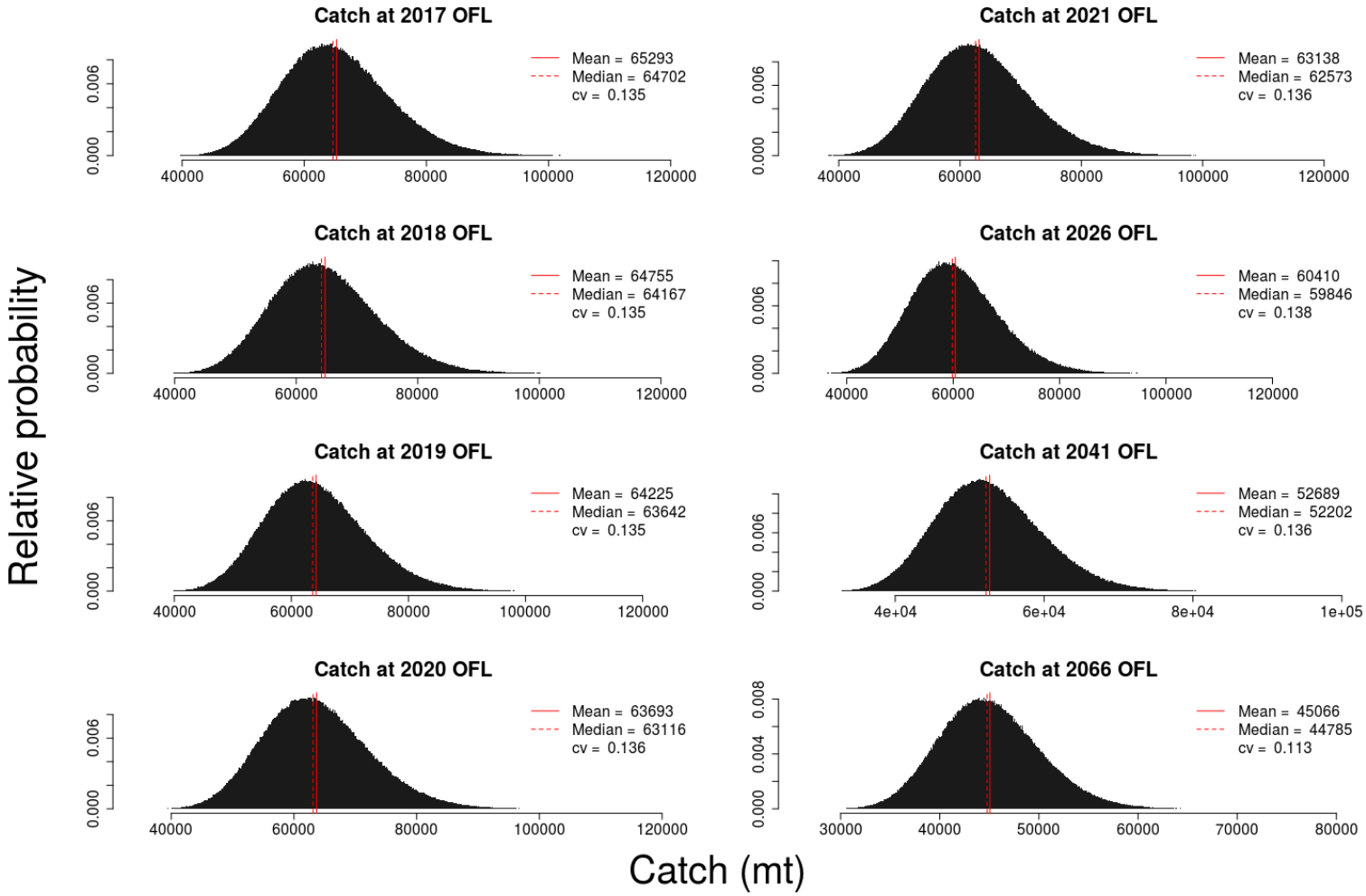

Figure 128: Distribution of catch (landings + incidental mortality) at the Overfishing Limit (OFL) from 2017-2066 for ocean quahog in four example years.

Appendix 1 Ocean quahog assessment working group members

The working group met October 17-20 and December 19-22 at the NEFSC in Woods Hole, MA to work on the ocean quahog stock assessment. Members, contributors and attendees are listed alphabetically below.

Working group:

Jessica Coakley (MAFMC)
Bob Glenn (Mass. DMR)
Dan Hennen (NEFSC, Assessment Lead)
Tom Hoff (Wallace and Associates)
Larry Jacobson (NEFSC, Subcommittee Chair)
Daphne Munroe (Rutgers)
Eric Powell (University of Southern Mississippi)

Contributors/attendees:

Tom Alspach (SeaWatch International)
Nicole Charriere (NEFSC)
Toni Chute (NEFSC)
Wendy Gabriel (MAFMC SSC, NEFSC)
Scott Gallagher (WHOI)
Jon Hare (NEFSC)
Deborah Hart (NEFSC)
Robert Johnston (NEFSC)
Chris Legault (NEFSC)
Roger Mann (VIMS)
Michael Martin (NEFSC)
Vic Nordahl (NEFSC)
Jeff Normant (NJ DFW)
Loretta O'Brien (NEFSC)
Jennifer O'Dwyer (NY DEC)
Doug Potts (GARFO)
Robert RUssell (ME DMR) Mark Terceiro (NEFSC)
Dave Wallace (Wallace and Associates)
Jim Weinberg (NEFSC)

Appendix 2 VMS

A Vessel Monitoring System (VMS) is used to monitor the location and movement of commercial fishing vessels in the EEZ for certain fisheries. The system uses satellite-based communications from on-board transceiver units that report location at prescribed intervals. The VMS system reports vessel location at least once an hour in the clam fishery.

VMS data can be used to determine the approximate location of vessels during fishing operations. This is done by counting all returns (pings) from the system where the boat was moving at <5 knots (i.e. where the positions recorded one hour apart are less than 5 nm apart). The assumption being that any vessels moving between 0 and 5 knots are likely to be fishing rather than docked or transiting. VMS can approximate effort, and identify fishing locations, but not landings data.

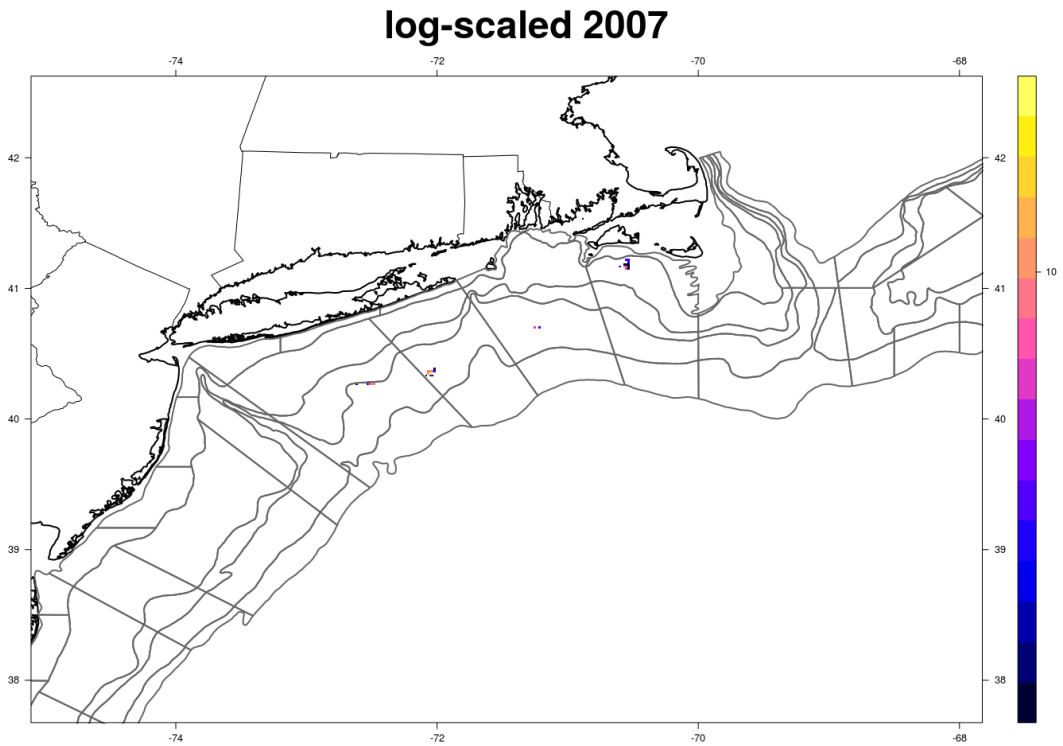

Figure 129: Locations of VMS compliant vessels fishing for ocean quahog in 2007. Locations reflect probable fishing effort based on vessel speed. Locations (1 nm square) where less than 4 boats operated within 2007 are not shown.

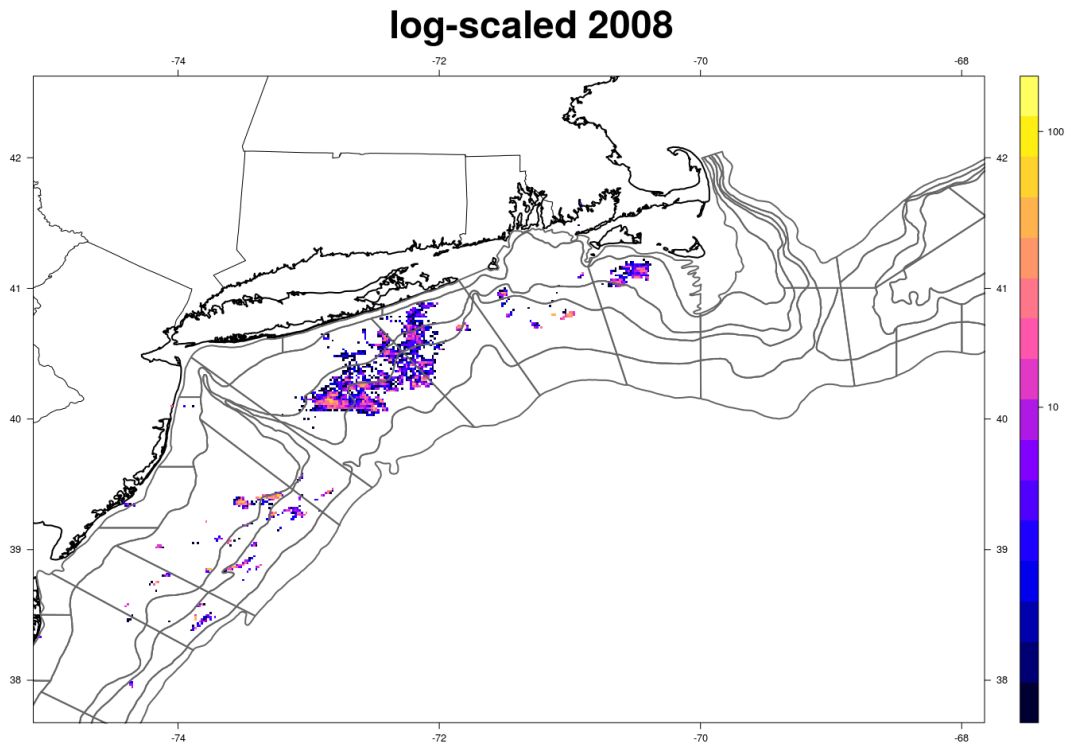

Figure 130: Locations of VMS compliant vessels fishing for ocean quahog in 2008. Locations reflect probable fishing effort based on vessel speed. Locations (1 nm square) where less than 4 boats operated within 2008 are not shown.

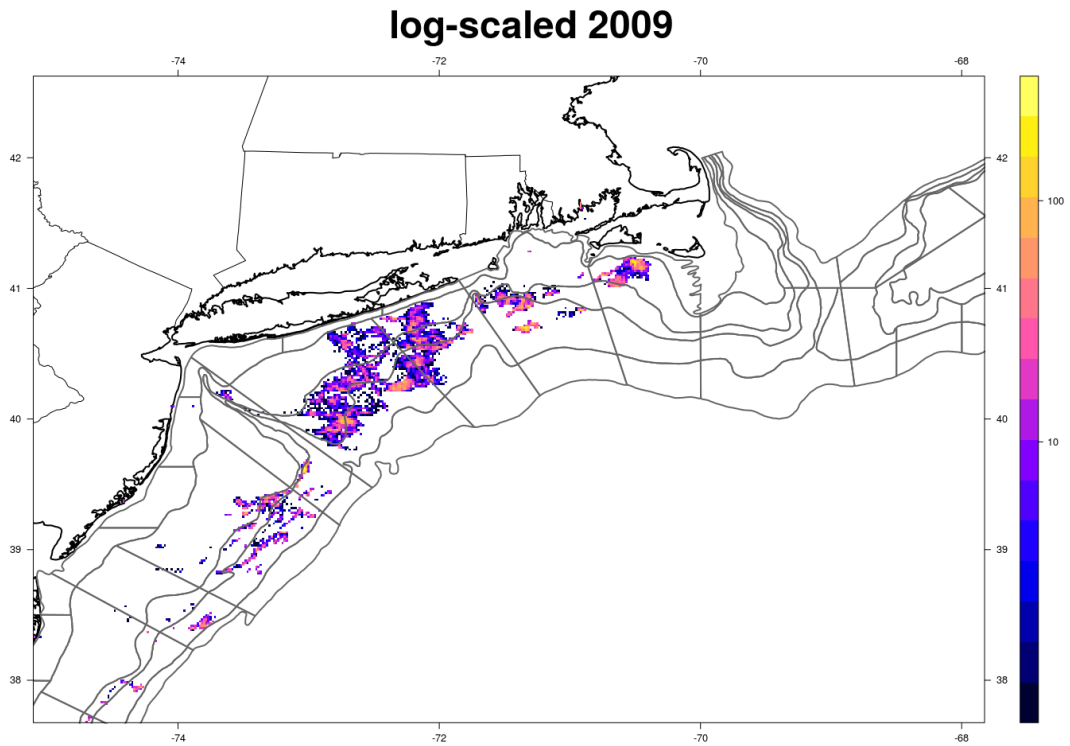

Figure 131: Locations of VMS compliant vessels fishing for ocean quahog in 2009. Locations reflect probable fishing effort based on vessel speed. Locations (1 nm square) where less than 4 boats operated within 2009 are not shown.

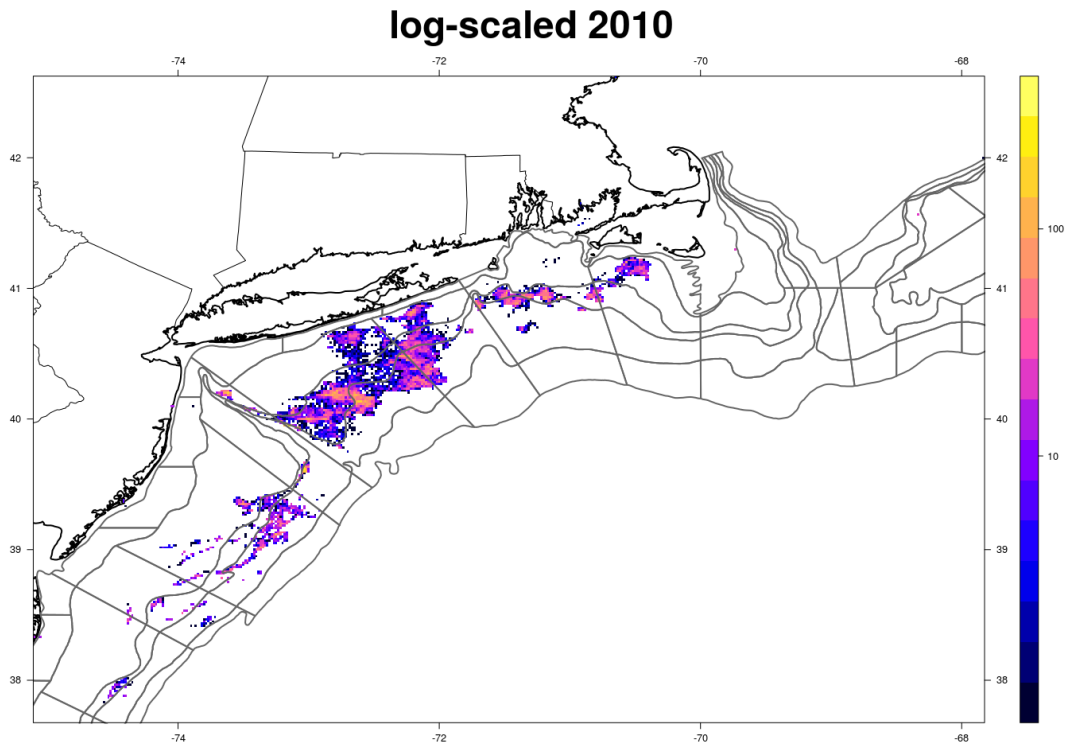

Figure 132: Locations of VMS compliant vessels fishing for ocean quahog in 2010. Locations reflect probable fishing effort based on vessel speed. Locations (1 nm square) where less than 4 boats operated within 2010 are not shown.

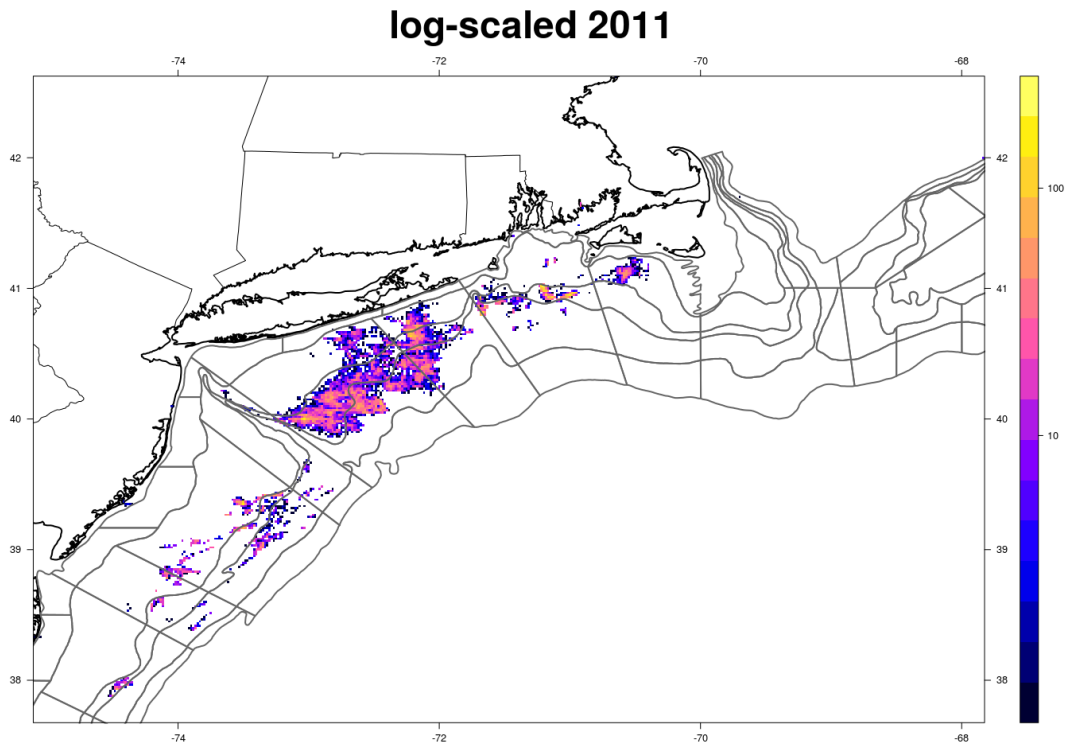

Figure 133: Locations of VMS compliant vessels fishing for ocean quahog in 2011. Locations reflect probable fishing effort based on vessel speed. Locations (1 nm square) where less than 4 boats operated within 2011 are not shown.

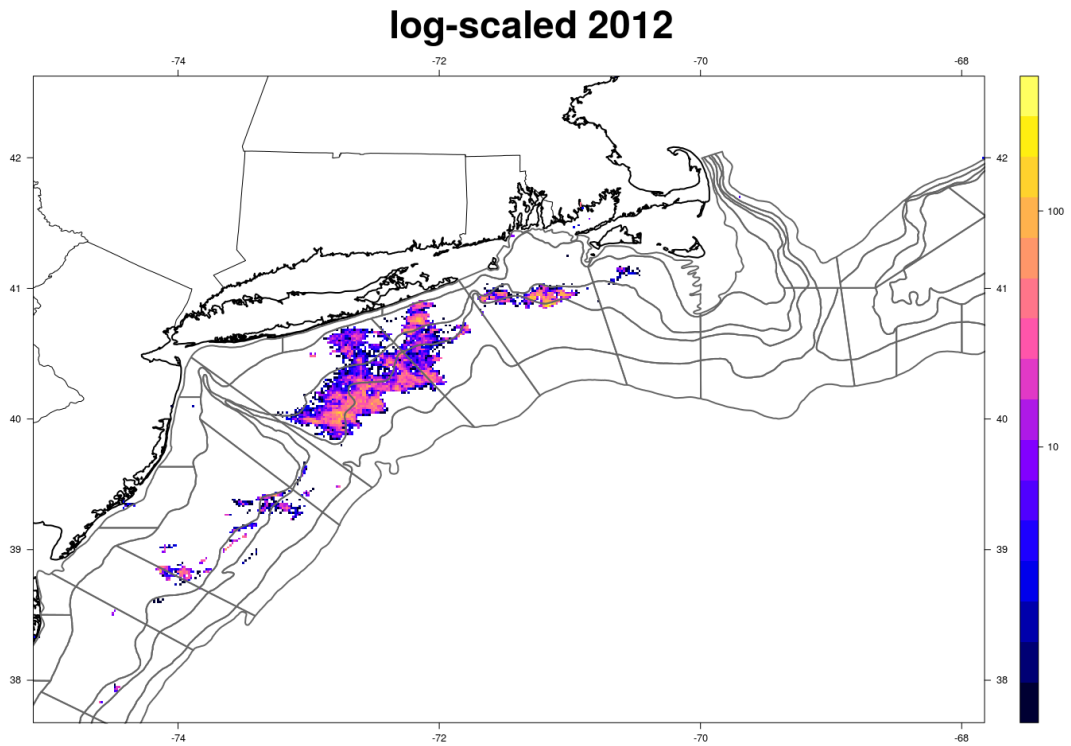

Figure 134: Locations of VMS compliant vessels fishing for ocean quahog in 2012. Locations reflect probable fishing effort based on vessel speed. Locations (1 nm square) where less than 4 boats operated within 2012 are not shown.

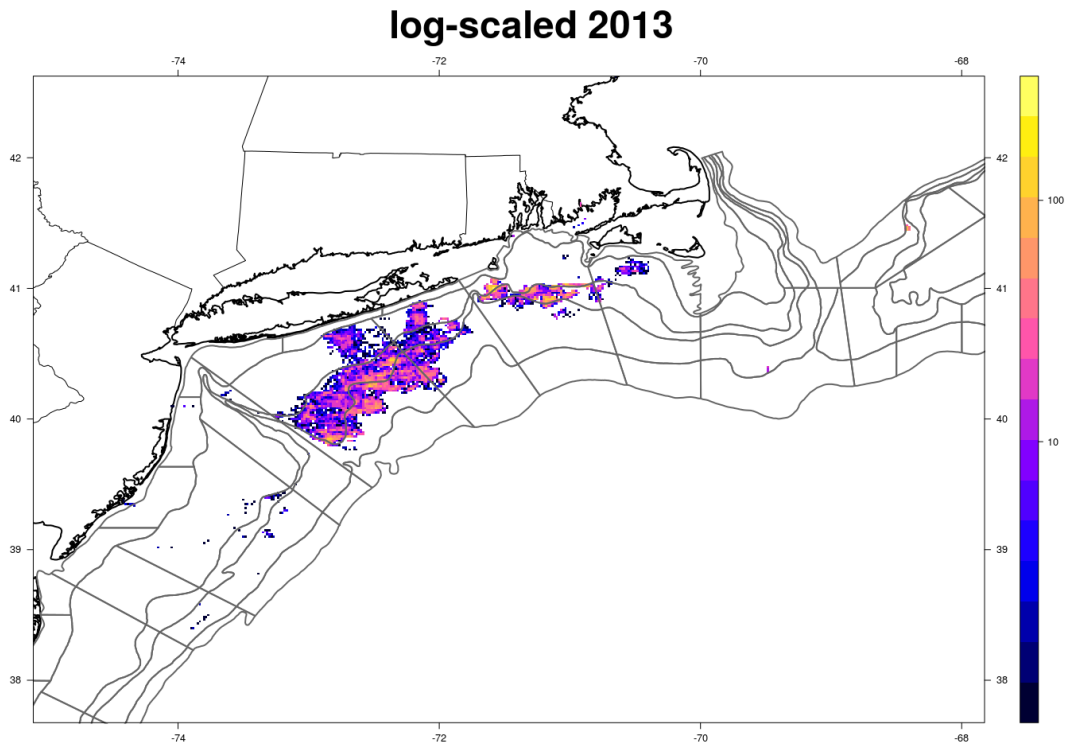

Figure 135: Locations of VMS compliant vessels fishing for ocean quahog in 2013. Locations reflect probable fishing effort based on vessel speed. Locations (1 nm square) where less than 4 boats operated within 2013 are not shown.

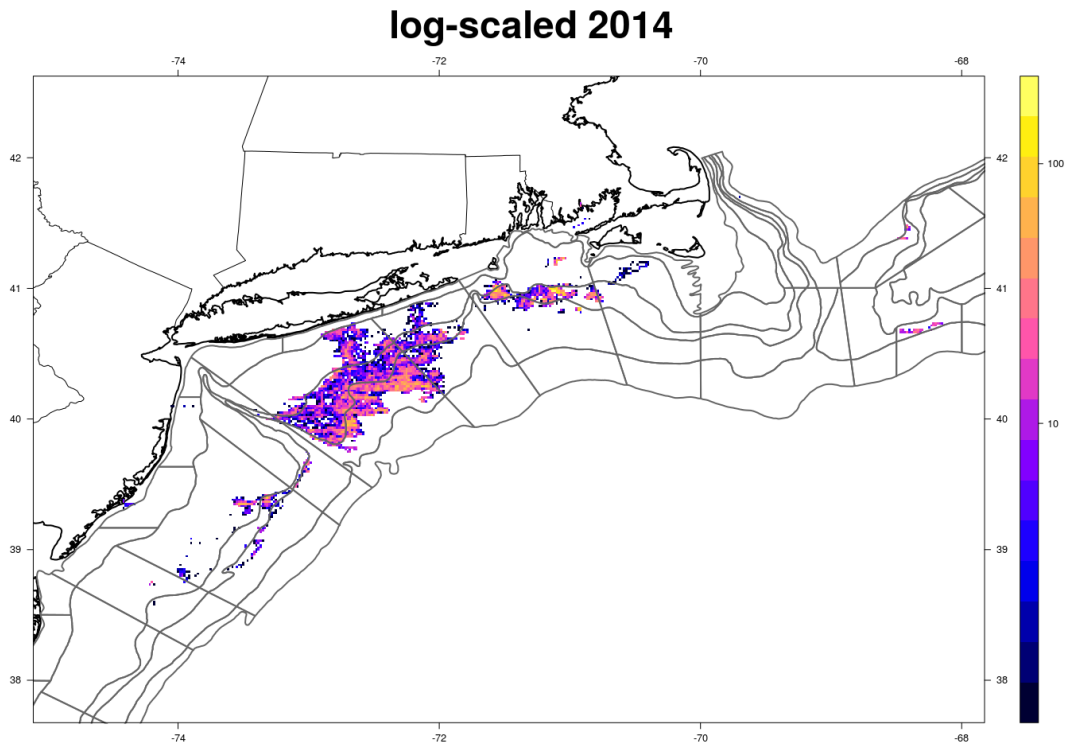

Figure 136: Locations of VMS compliant vessels fishing for ocean quahog in 2014. Locations reflect probable fishing effort based on vessel speed. Locations (1 nm square) where less than 4 boats operated within 2014 are not shown.

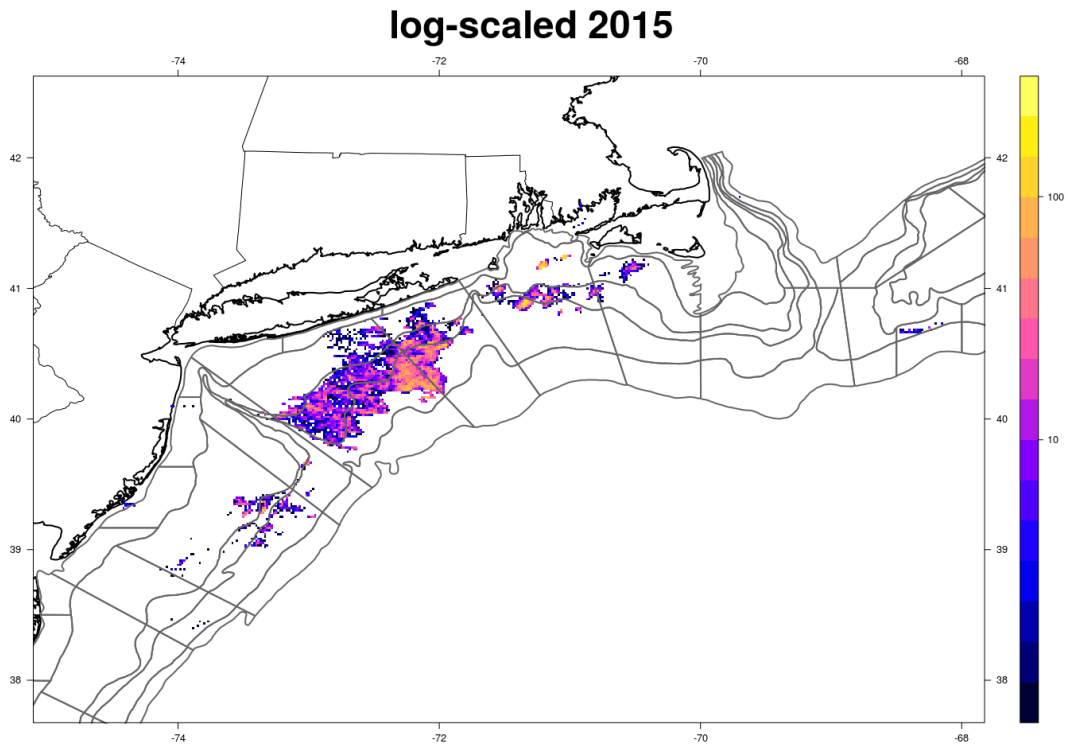

Figure 137: Locations of VMS compliant vessels fishing for ocean quahog in 2015. Locations reflect probable fishing effort based on vessel speed. Locations (1 nm square) where less than 4 boats operated within 2015 are not shown.

Appendix 3 Depletion analysis

Ocean quahog depletion experiments aboard commercial fishing vessels (Figure 139) were analyzed using standard Patch methodology (Rago et al. 2006) except that NEFSC employed a new method for calculating the hit matrix (Hennen et al. 2012). Sixteen of the nineteen ocean quahog depletion experiments worked well (estimated efficiency$<$ 1.0 and cv$<$ 2.0). Estimated densities ranged from 0.015 - 0.385 clams per ft^2 (Table 36). Estimated efficiencies for commercial dredges ranged from 0.164 - 0.878 for ocean quahog. These values are similar to values from previous assessments (Figure 138).

Capture efficiency estimates for the RD depend on the commercial efficiency estimates and setup tows (Northeast Fisheries Science Center 2013). Maps of the tow sequences from the depletion plots (Figures 140 - 157) generally show thorough coverage of study sites with high degrees of overlap between tows (Hennen et al. 2012). Overlap between the setup tows and the depletion sequence was variable, but in general improved over time (Figures 140 - 157). The hit matrices generated for patch model analysis were resolved to approximately 1 cm spatial resolution (Figures 158 - 176 - for illustration, not shown to full resolution). In general the current estimates of MCD efficiency are lower and density higher, resulting in higher estimates of RD efficiency.

It is usually possible to diagnose the cause of poor efficiency estimates using the diagnostic plots. Patch model diagnostics include examining the catch vs. expected catch and, trends in catch per unit of effective area, and likelihood residuals (Figures 192 - 195). For example, one depletion study that did not produce reasonable estimates (Figure 192) had its highest catch on the 8th tow of the depletion sequence, which had a very low effective area swept (a measure of the area swept that deprecates areas already covered). Altering this value toward the expected catch changes the Patch model results to estimated values that closely agree with results from the other three OQ depletion experiments. Inclinometer and pressure sensors did not indicate any mechanical problems during this tow and the tow was of normal length. In short there was no apriori reason to exclude this tow from the depletion sequence. However, the results from this experiment were not well estimated (cv$>$ 2.0) so it was excluded from the assessment.

Table 36: Estimates of FV efficiency, density, RV efficiency and set up density from 19 depletion experiments for ocean quahog.

Site	Tows	Efficiency	CVe	Density	CVd	RVefficiency	CVRVe	SetupD	CVsuD
OQ00 01	22	0.878	0.279	0.084	0.191	0.003	0.933	0.000	0.913
OQ00 02	16	0.682	0.308	0.051	0.246	0.145	0.853	0.007	0.816
OQ00 03	27	0.541	0.597	0.090	0.501	0.082	0.788	0.007	0.608
OQ02 01	24	0.381	0.205	0.354	0.148	0.082	0.180	0.029	0.103
OQ02 02	22	0.652	0.167	0.185	0.107	0.132	0.218	0.024	0.191
OQ02 03	20	0.652	0.136	0.089	0.103	0.268	0.236	0.024	0.212
OQ02 04	24	0.229	0.535	0.076	0.440	0.049	0.997	0.004	0.894
OQ05 01	20	0.164	0.630	0.081	0.480	0.148	0.497	0.012	0.129
OQ05 02	21	0.360	0.139	0.053	0.080	0.150	0.237	0.008	0.223
OQ05 03	20	0.561	0.089	0.101	0.080	0.100	0.296	0.010	0.285
OQ05 04	17	0.714	0.103	0.030	0.082	0.141	0.131	0.004	0.102
OQ05 06	20	0.498	0.227	0.165	0.161	0.000	49.449	0.000	60.558
OQ08 01	17	1.000	0.000	0.069	0.090	0.449	0.481	0.031	0.472
OQ08 02	17	0.795	0.094	0.085	0.061	0.206	0.061	0.018	0.000
OQ08 03	17	1.000	0.000	0.117	0.098	0.290	0.103	0.034	0.031
OQ11 01	10	0.071	2.735	0.300	2.636	0.080	2.651	0.024	0.281
OQ11 02	20	0.779	0.153	0.015	0.113	0.406	0.245	0.006	0.217
OQ11 02S	18	0.555	0.168	0.025	0.120	0.240	0.248	0.006	0.217
OQ11 05	22	0.629	0.222	0.385	0.124	0.049	0.300	0.019	0.274
Mean	20	0.586	0.357	0.124	0.309	0.159	3.100	0.014	3.501
Median	20	0.629	0.168	0.085	0.120	0.141	0.296	0.010	0.223

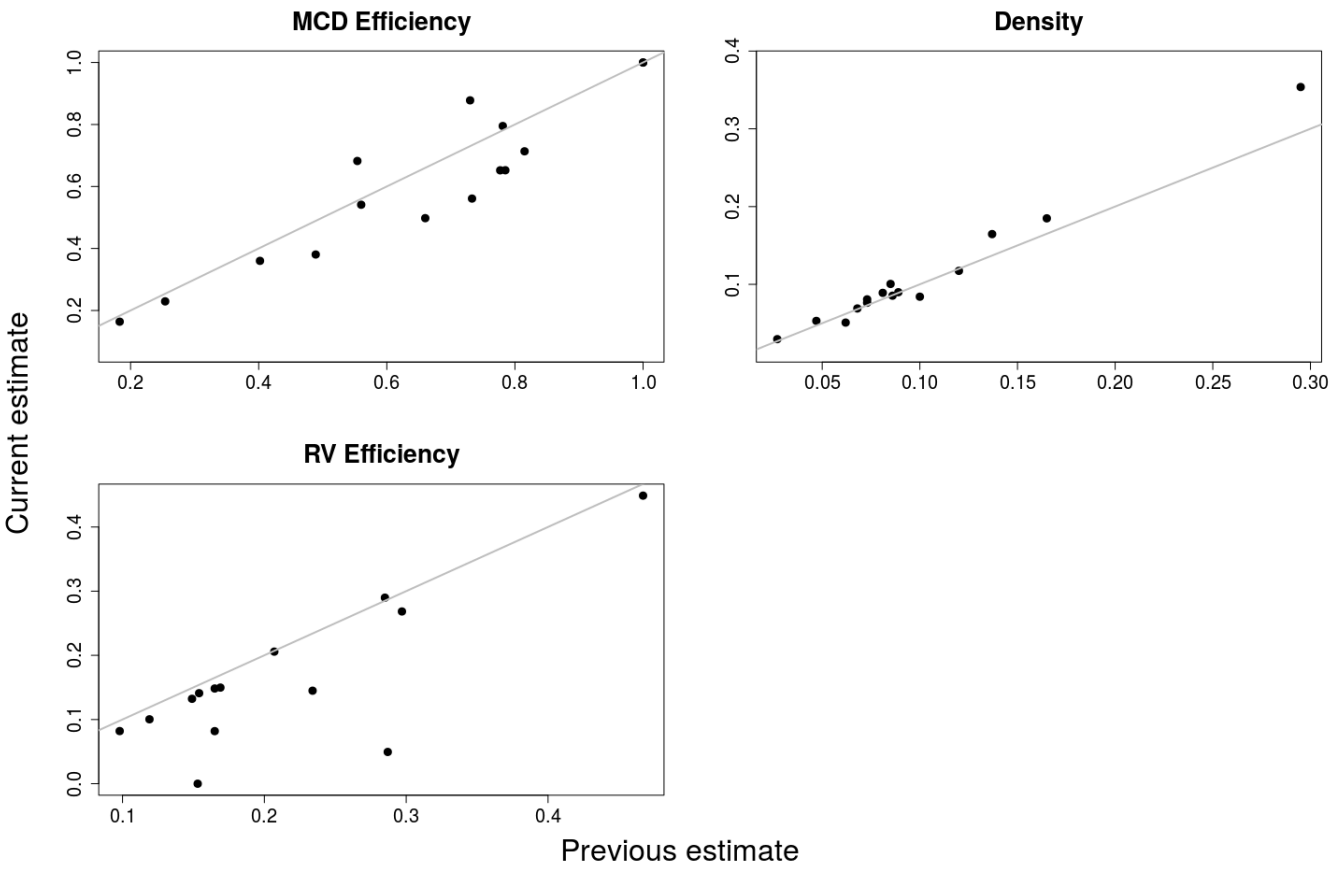

Figure 138: A comparison of patch model estimates made previously by Northeast Fisheries Science Center (2009) and in this assessment. In general the current estimates are lower in MCD efficiency and higher in density, resulting in higher estimates of RV efficiency. The gray lines in each plot represent perfect agreement.

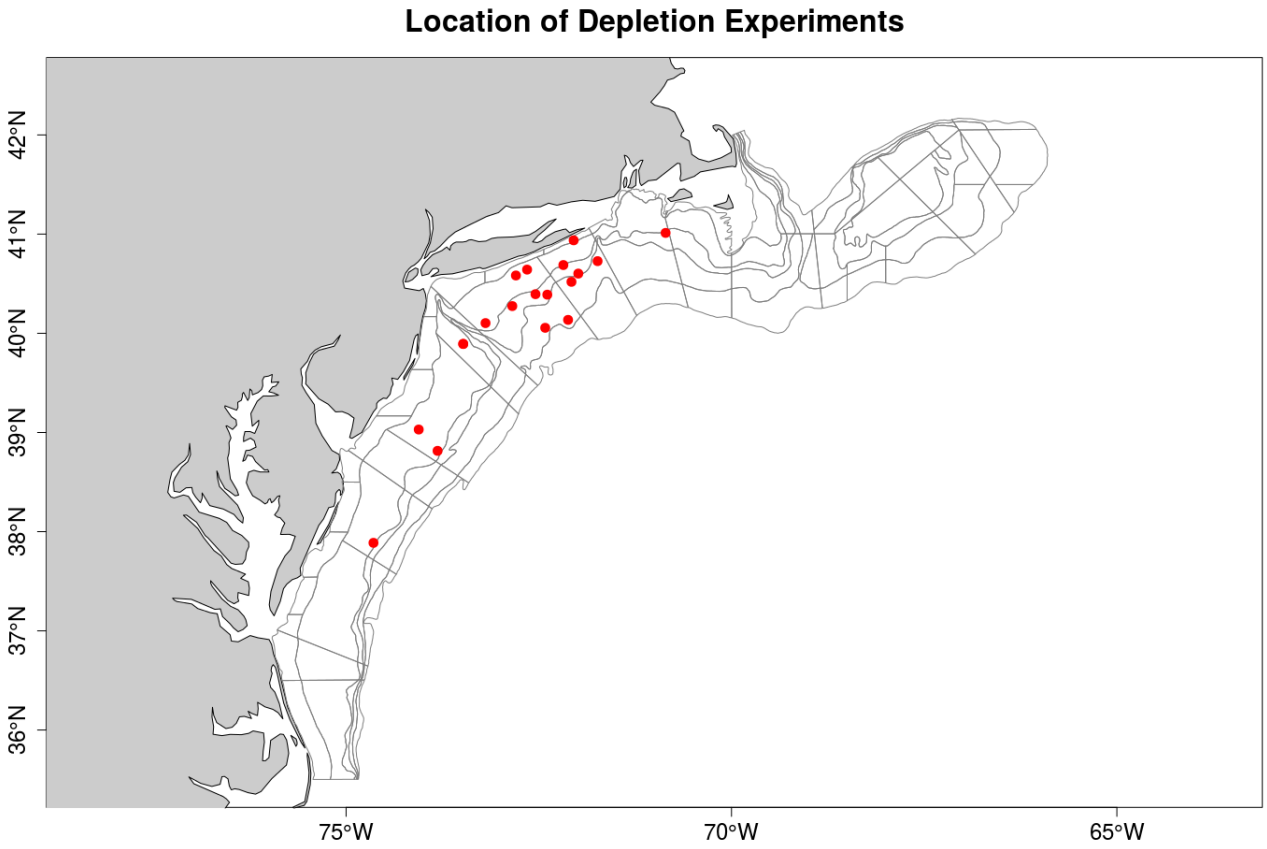

Figure 139: Location of all ocean quahog depletion experiments since 1999.

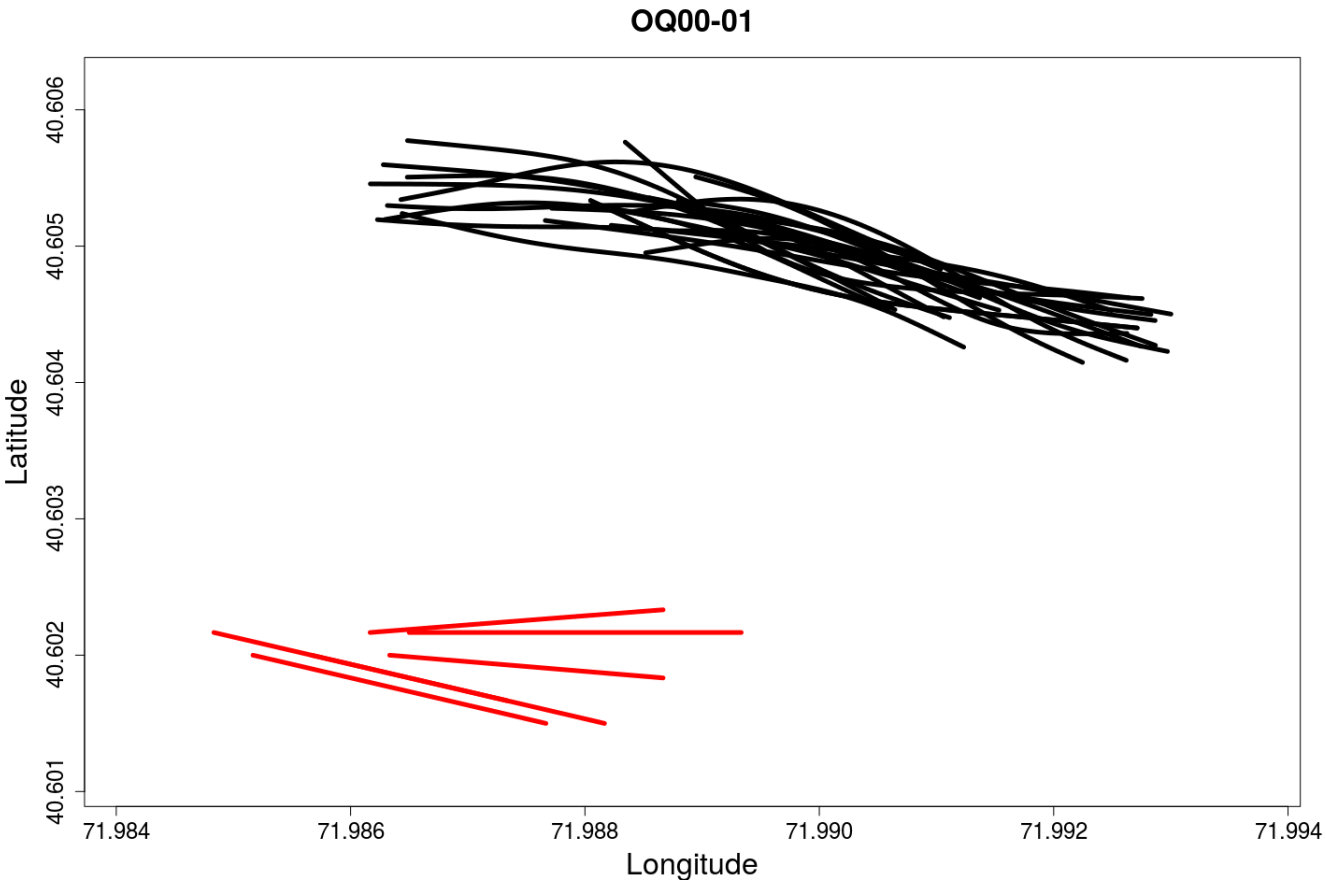

Figure 140: Relative positions of each tow in the set up (red lines) and depletion sequences (black) for depletion experiment OQ00-01.

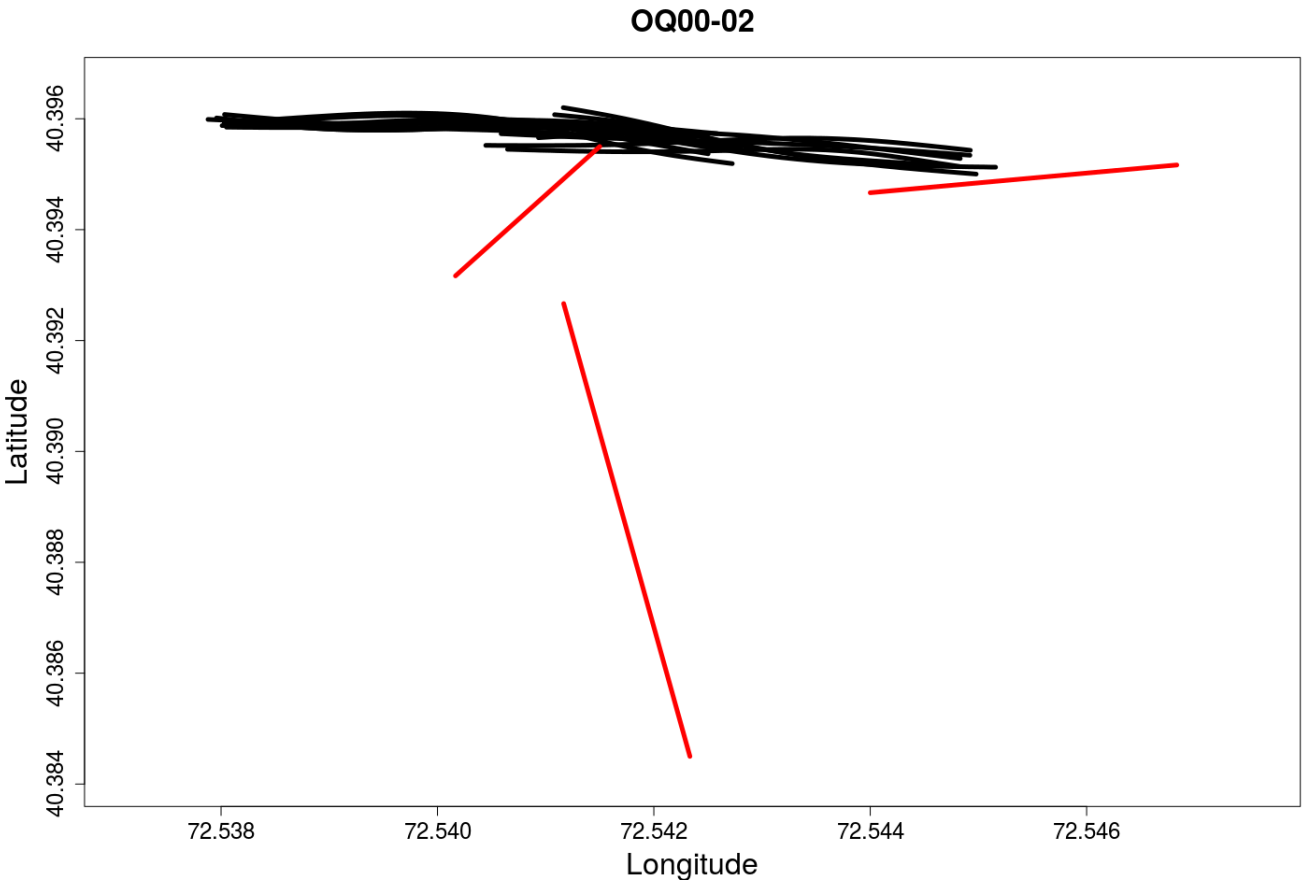

Figure 141: Relative positions of each tow in the set up (red lines) and depletion sequences (black) for depletion experiment OQ00-02.

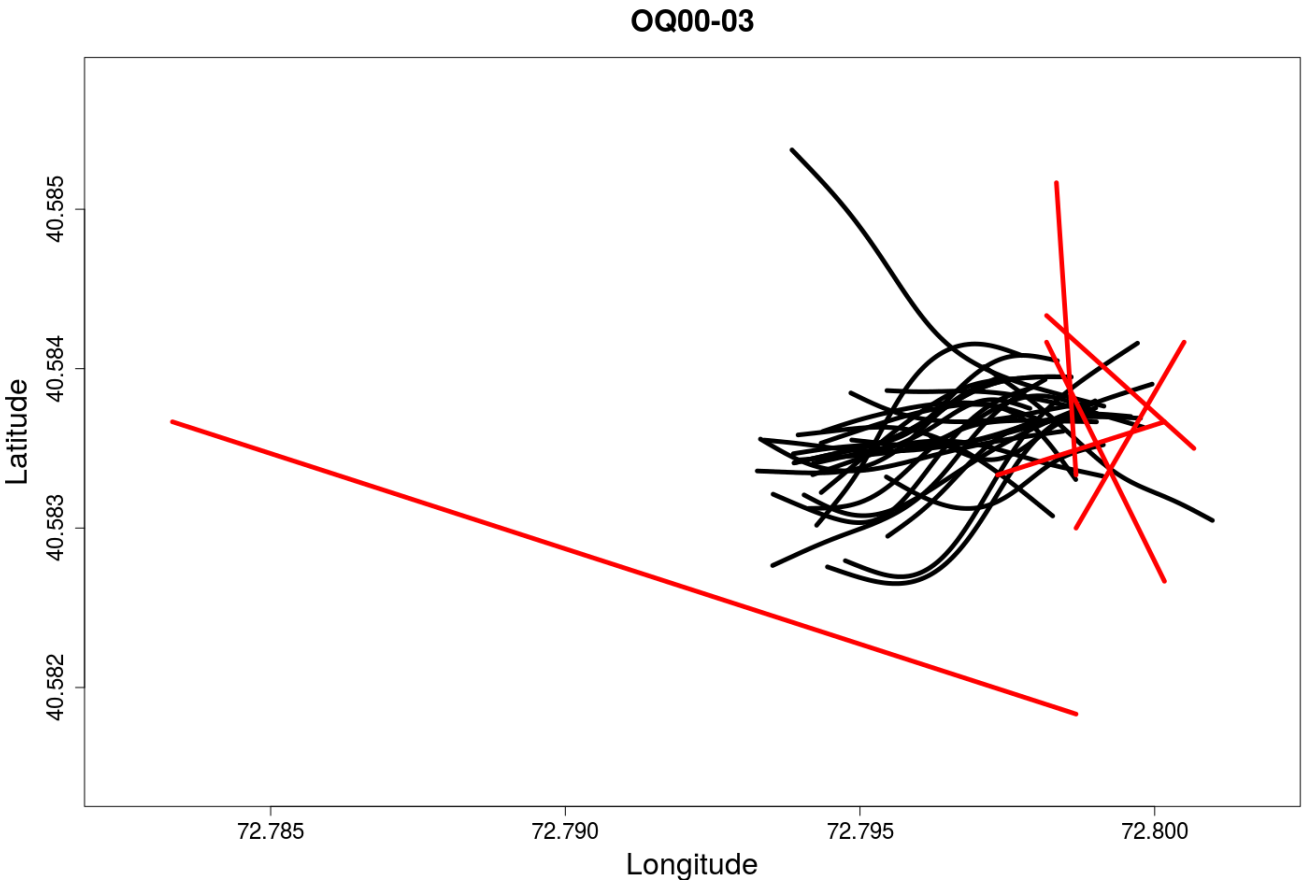

Figure 142: Relative positions of each tow in the set up (red lines) and depletion sequences (black) for depletion experiment OQ00-03.

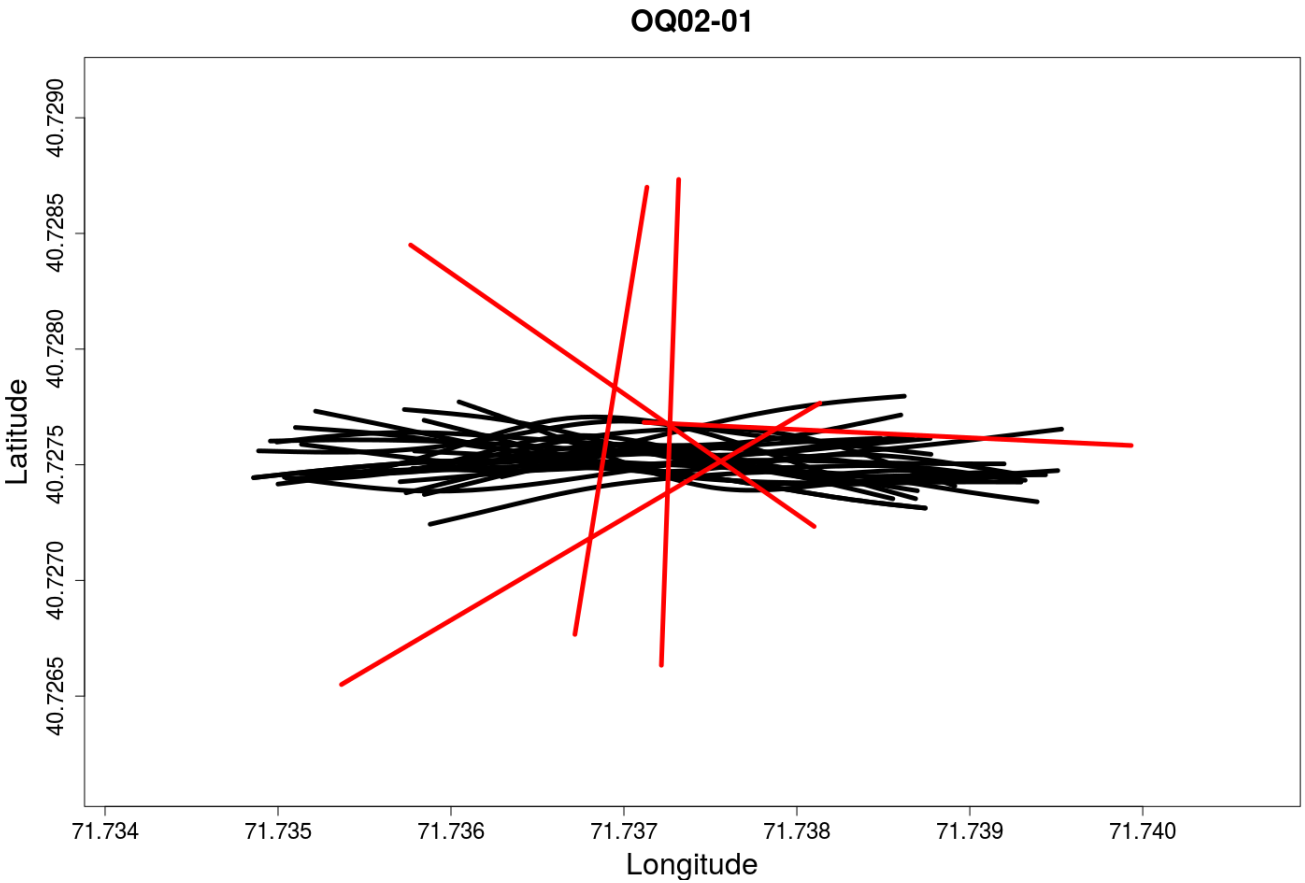

Figure 143: Relative positions of each tow in the set up (red lines) and depletion sequences (black) for depletion experiment OQ02-01.

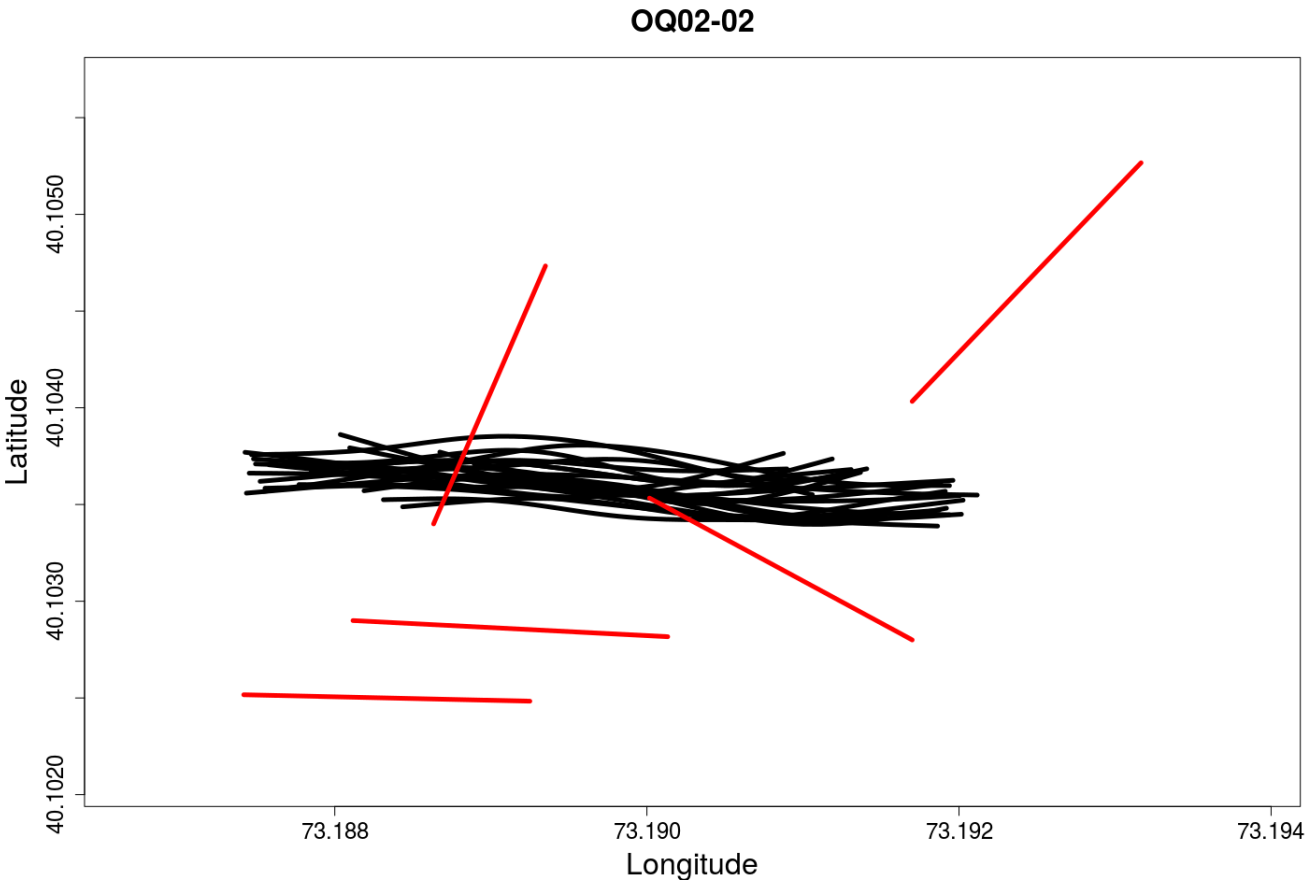

Figure 144: Relative positions of each tow in the set up (red lines) and depletion sequences (black) for depletion experiment OQ02-02.

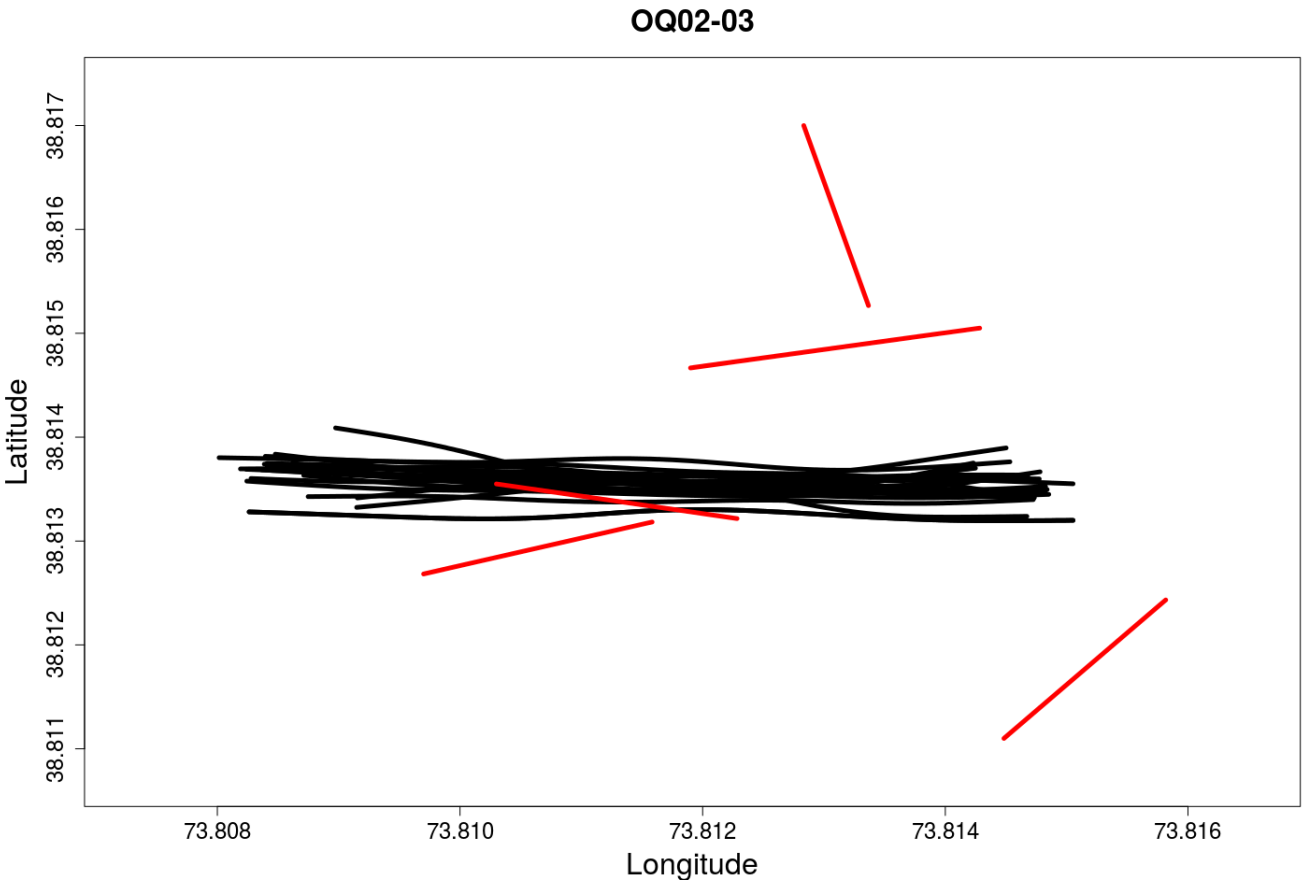

Figure 145: Relative positions of each tow in the set up (red lines) and depletion sequences (black) for depletion experiment OQ02-03.

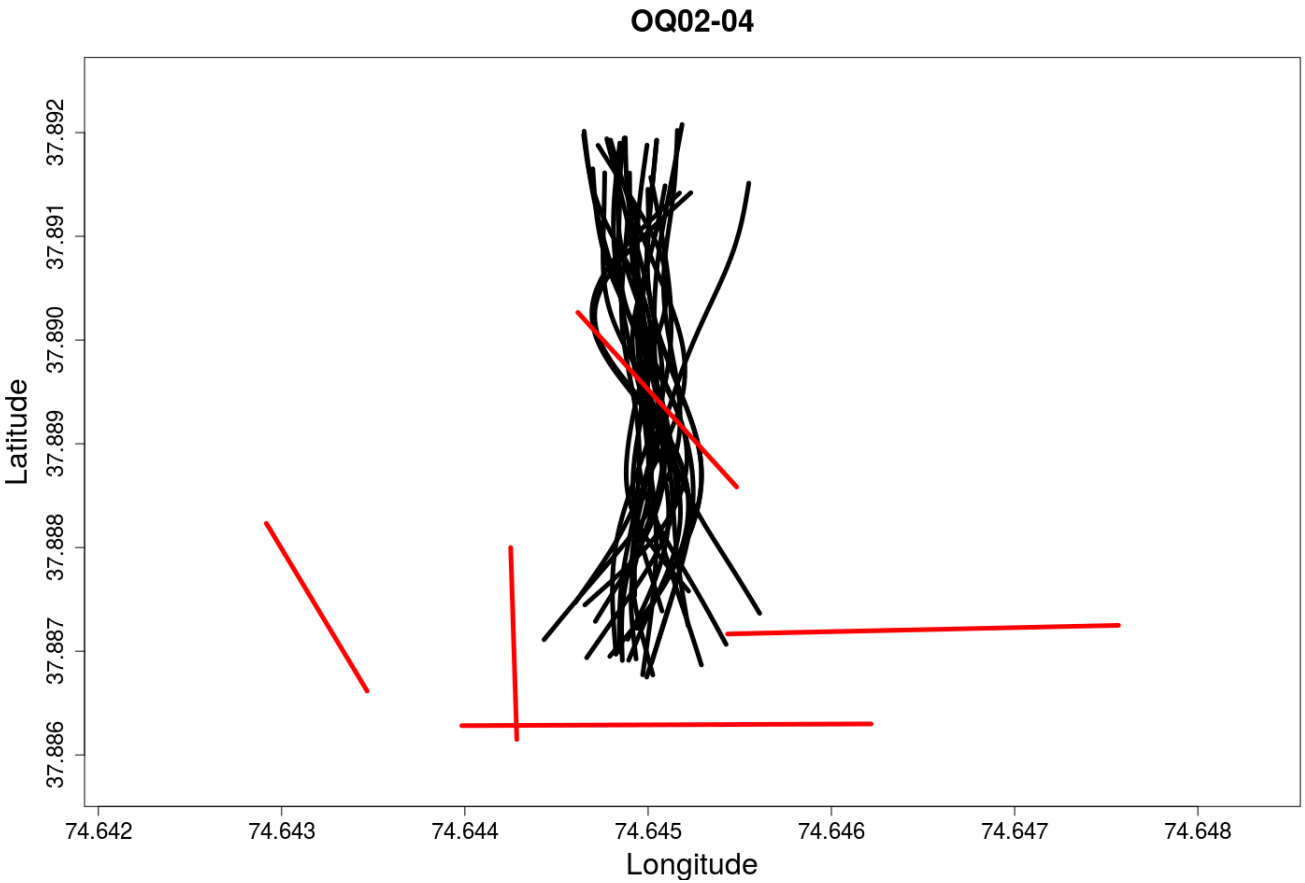

Figure 146: Relative positions of each tow in the set up (red lines) and depletion sequences (black) for depletion experiment OQ02-04.

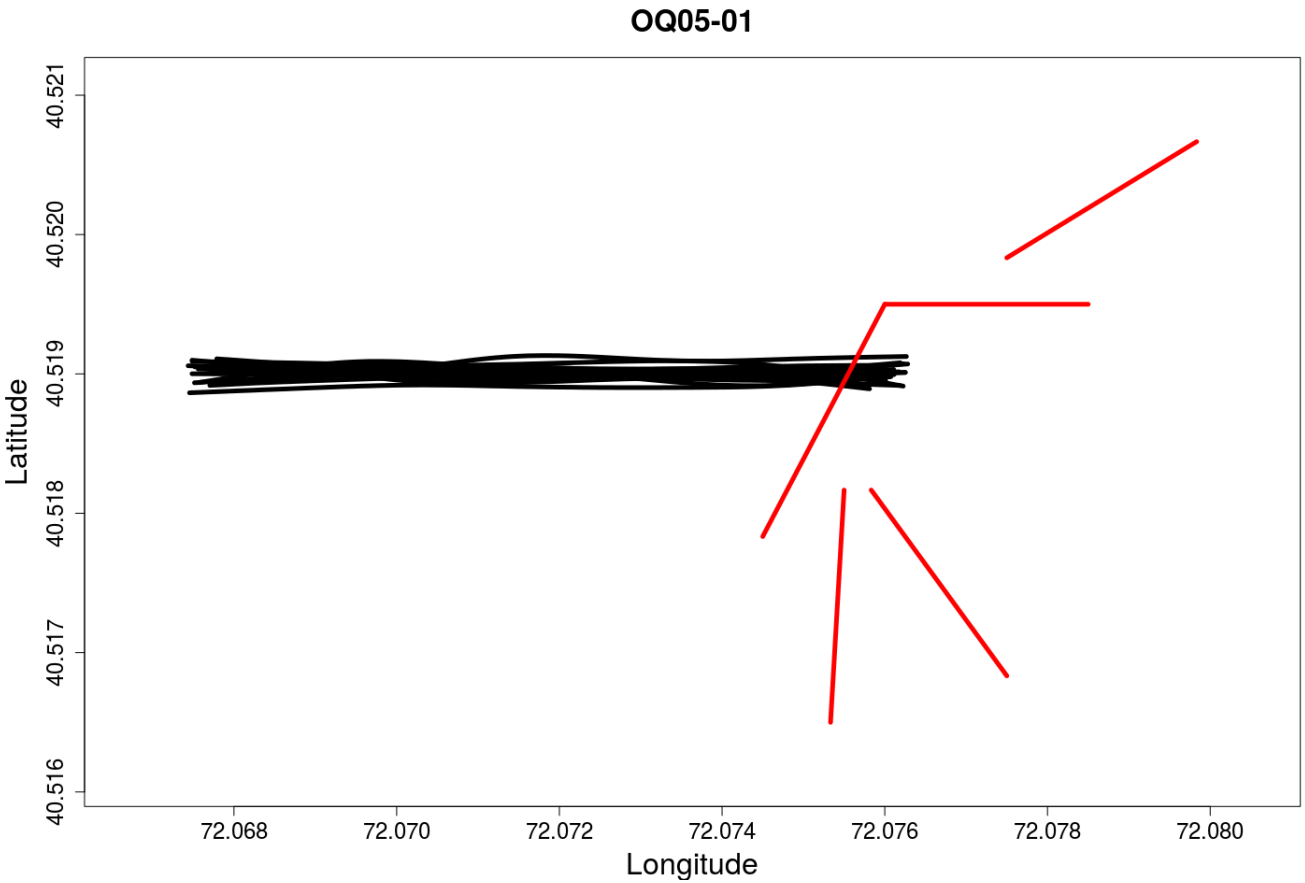

Figure 147: Relative positions of each tow in the set up (red lines) and depletion sequences (black) for depletion experiment OQ05-01.

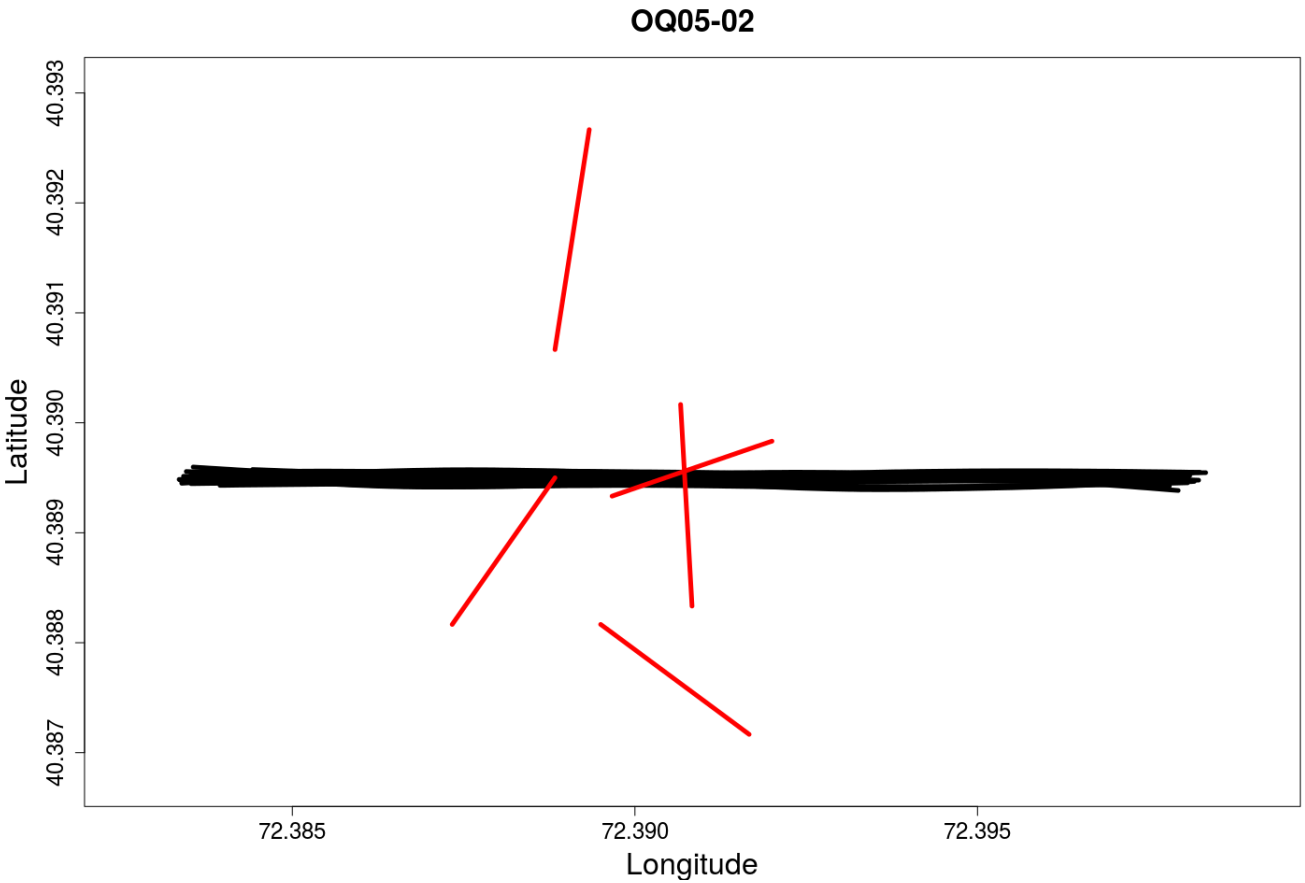

Figure 148: Relative positions of each tow in the set up (red lines) and depletion sequences (black) for depletion experiment OQ05-02.

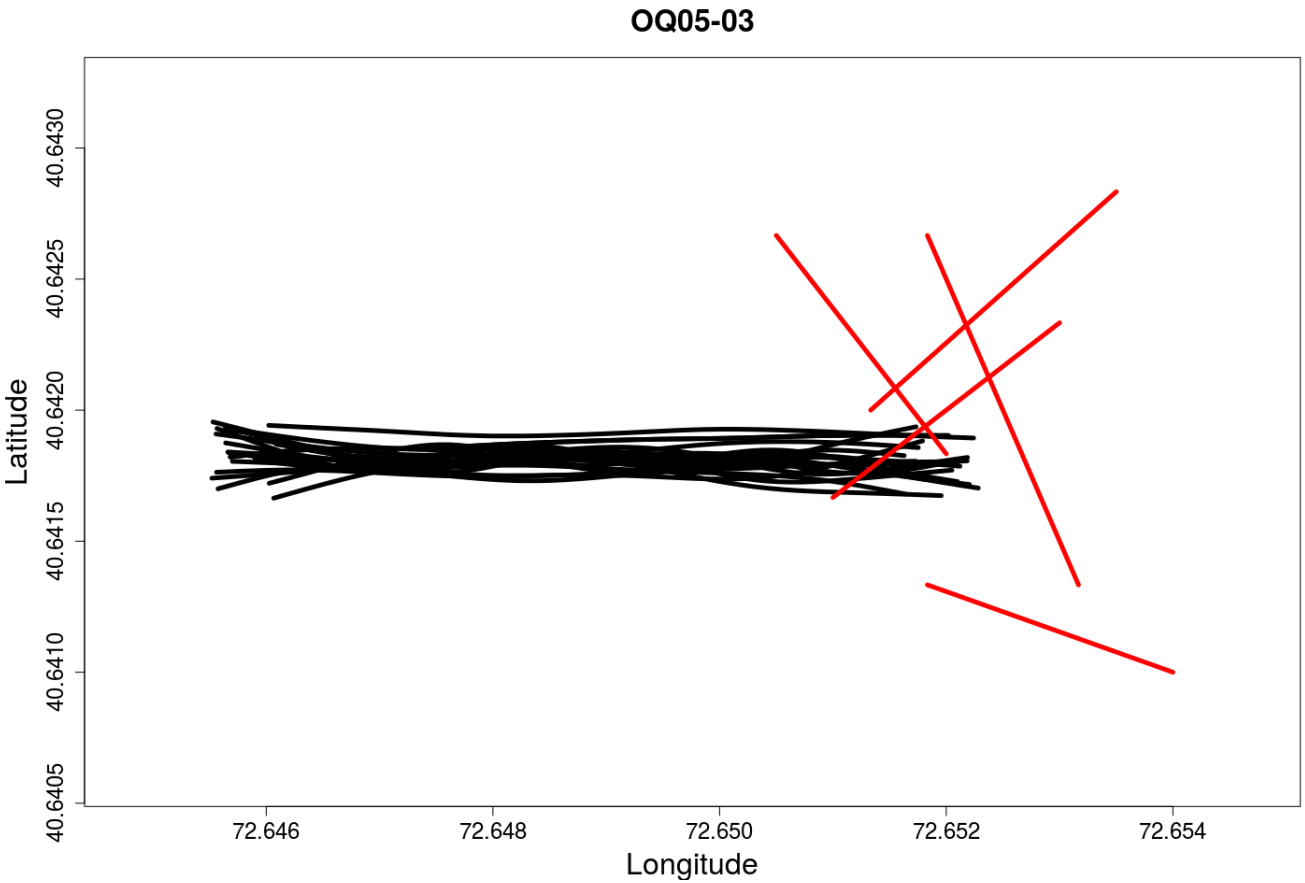

Figure 149: Relative positions of each tow in the set up (red lines) and depletion sequences (black) for depletion experiment OQ05-03.

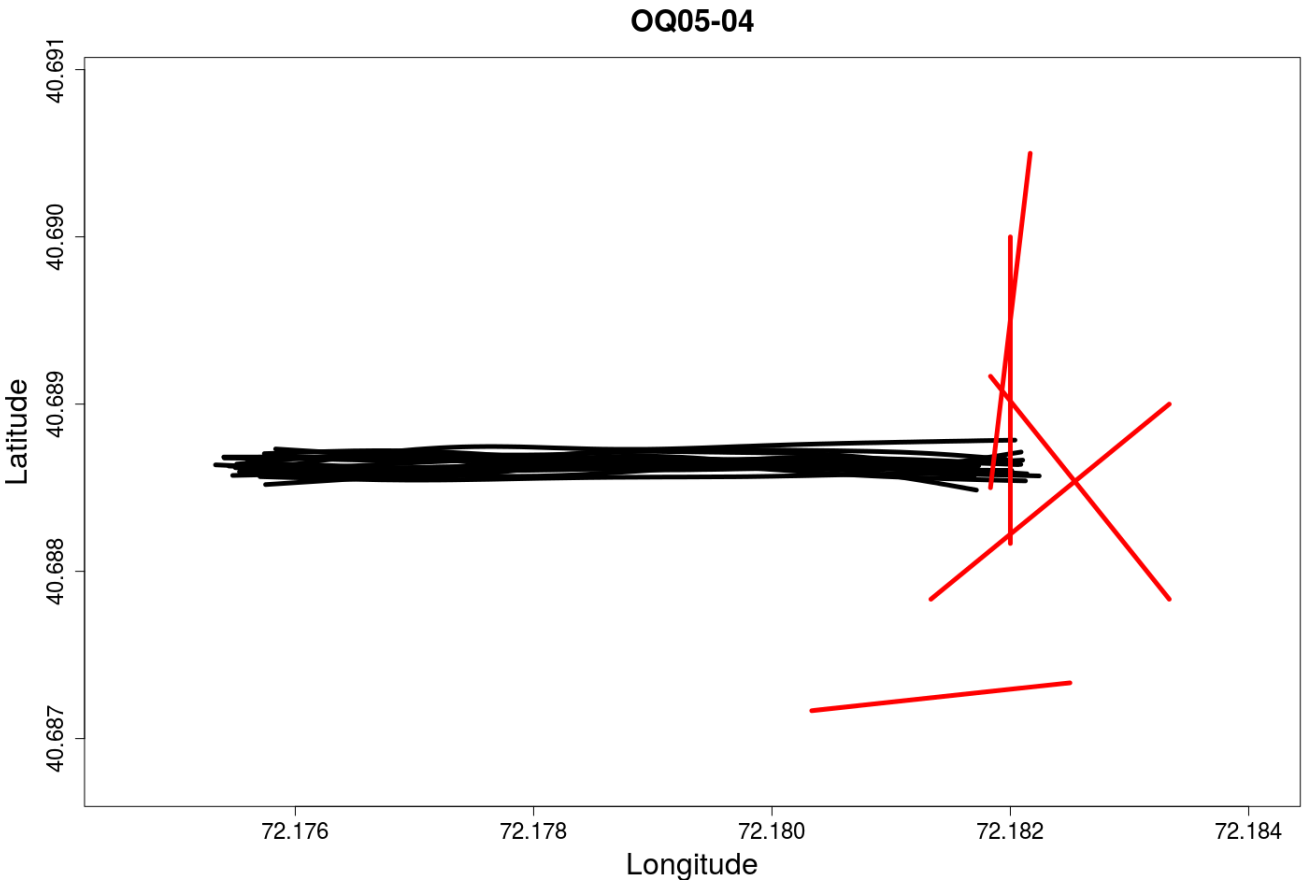

Figure 150: Relative positions of each tow in the set up (red lines) and depletion sequences (black) for depletion experiment OQ05-04.

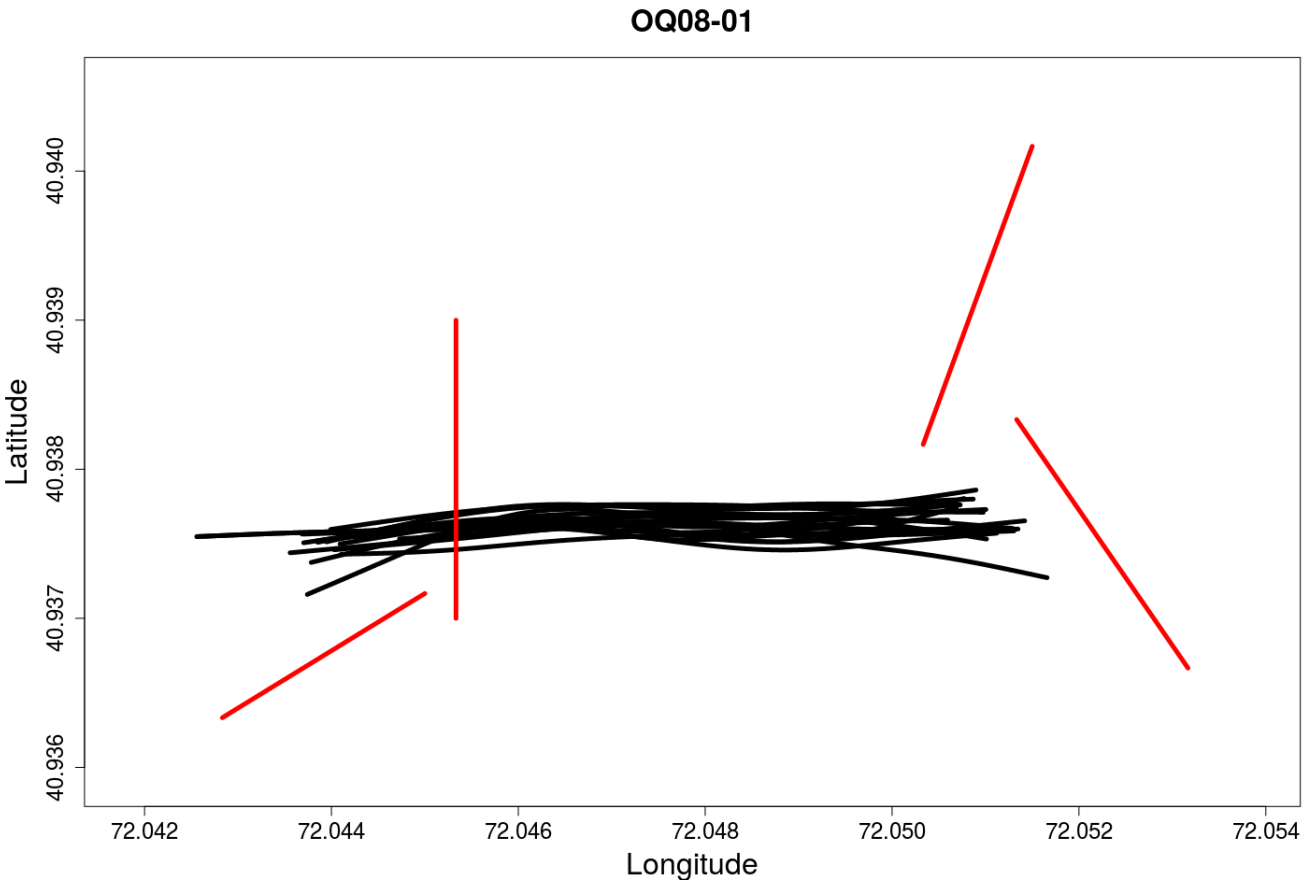

Figure 151: Relative positions of each tow in the set up (red lines) and depletion sequences (black) for depletion experiment OQ08-01.

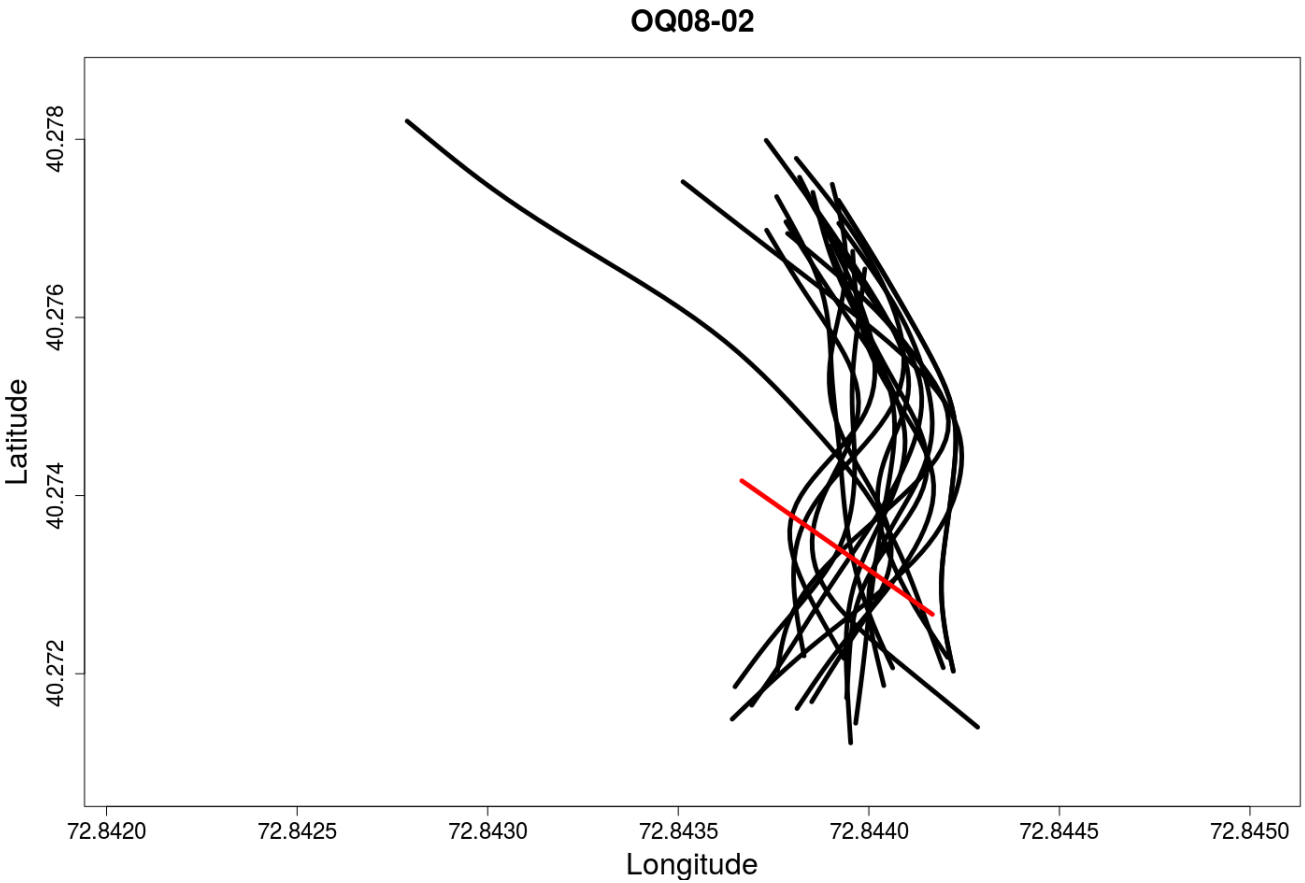

Figure 152: Relative positions of each tow in the set up (red lines) and depletion sequences (black) for depletion experiment OQ08-02.

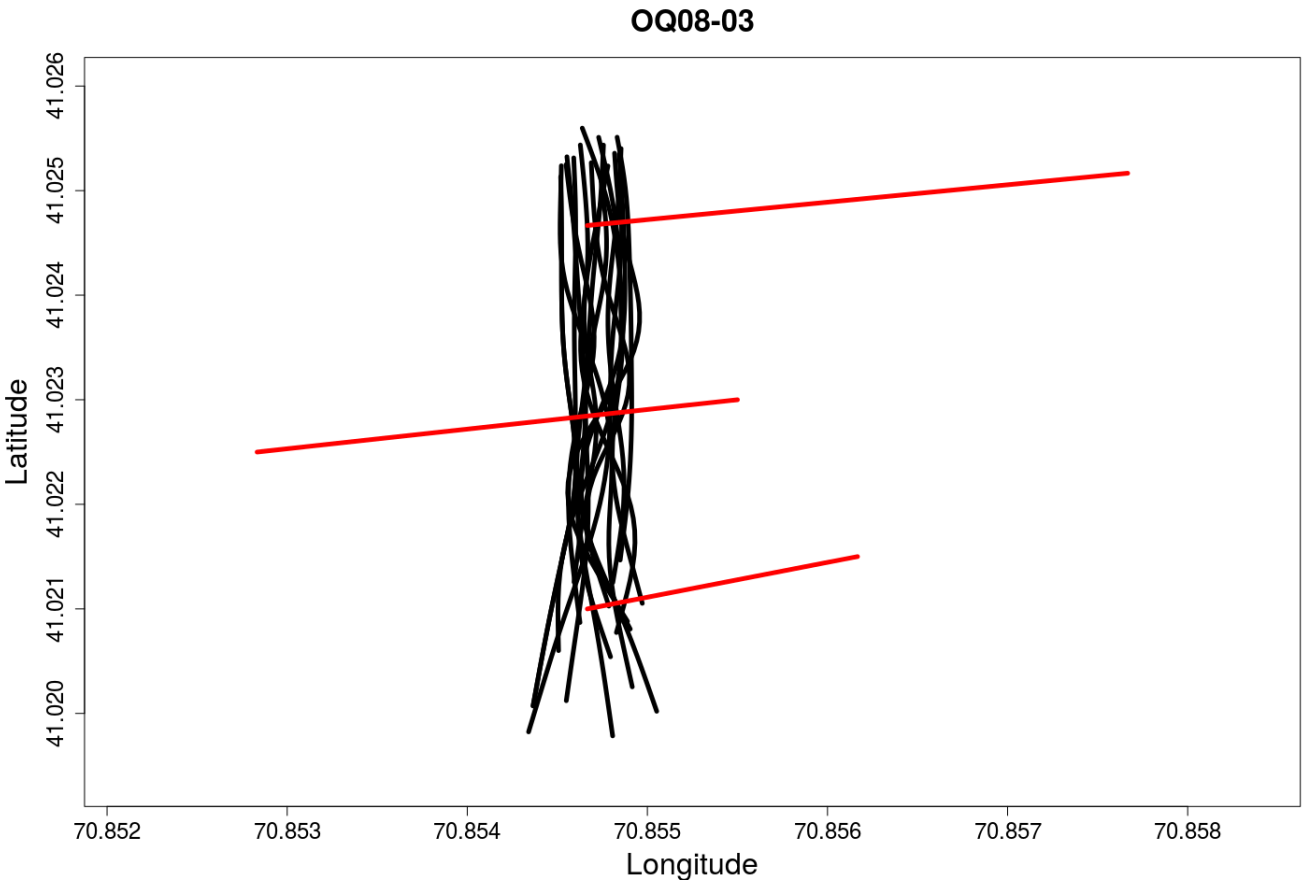

Figure 153: Relative positions of each tow in the set up (red lines) and depletion sequences (black) for depletion experiment OQ08-03.

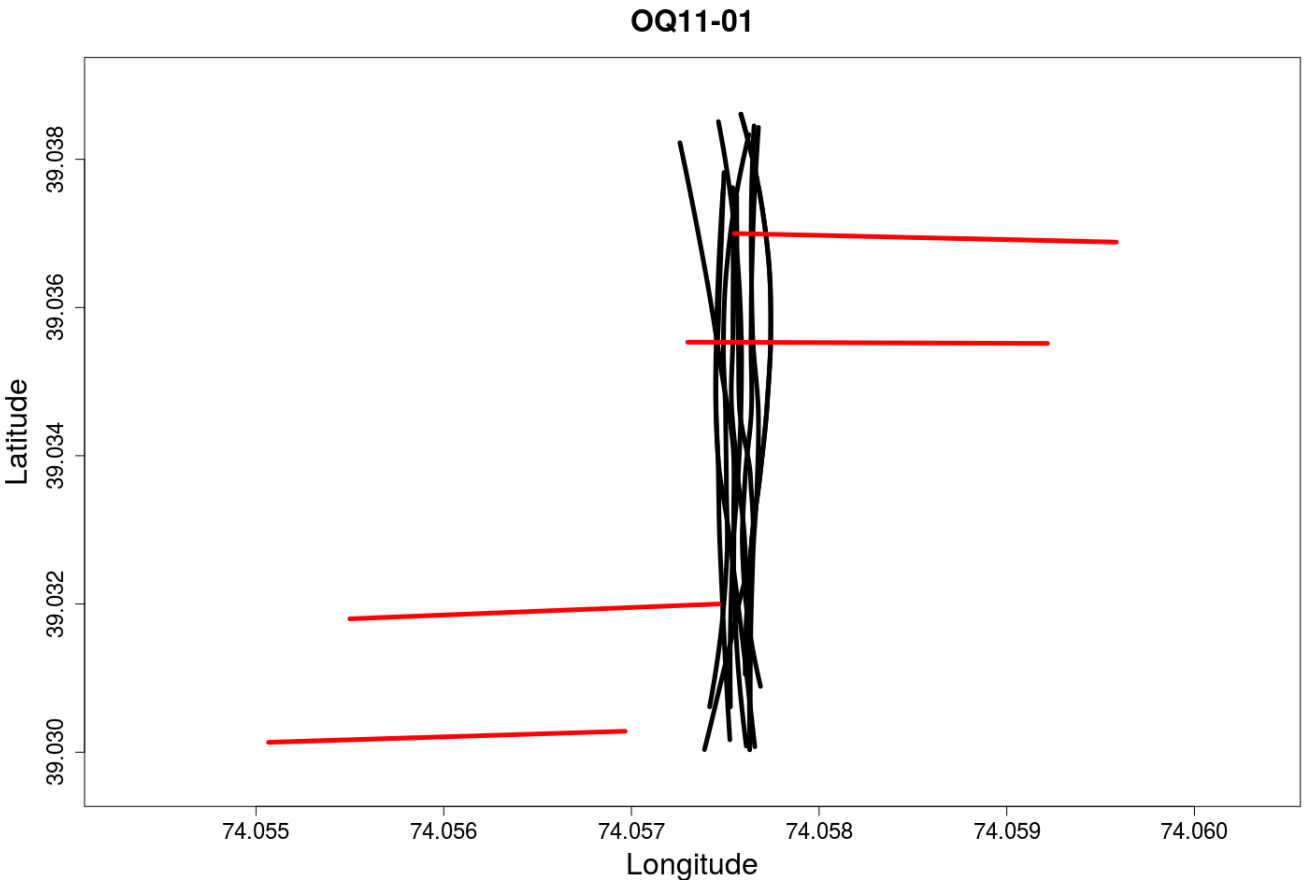

Figure 154: Relative positions of each tow in the set up (red lines) and depletion sequences (black) for depletion experiment OQ11-01.

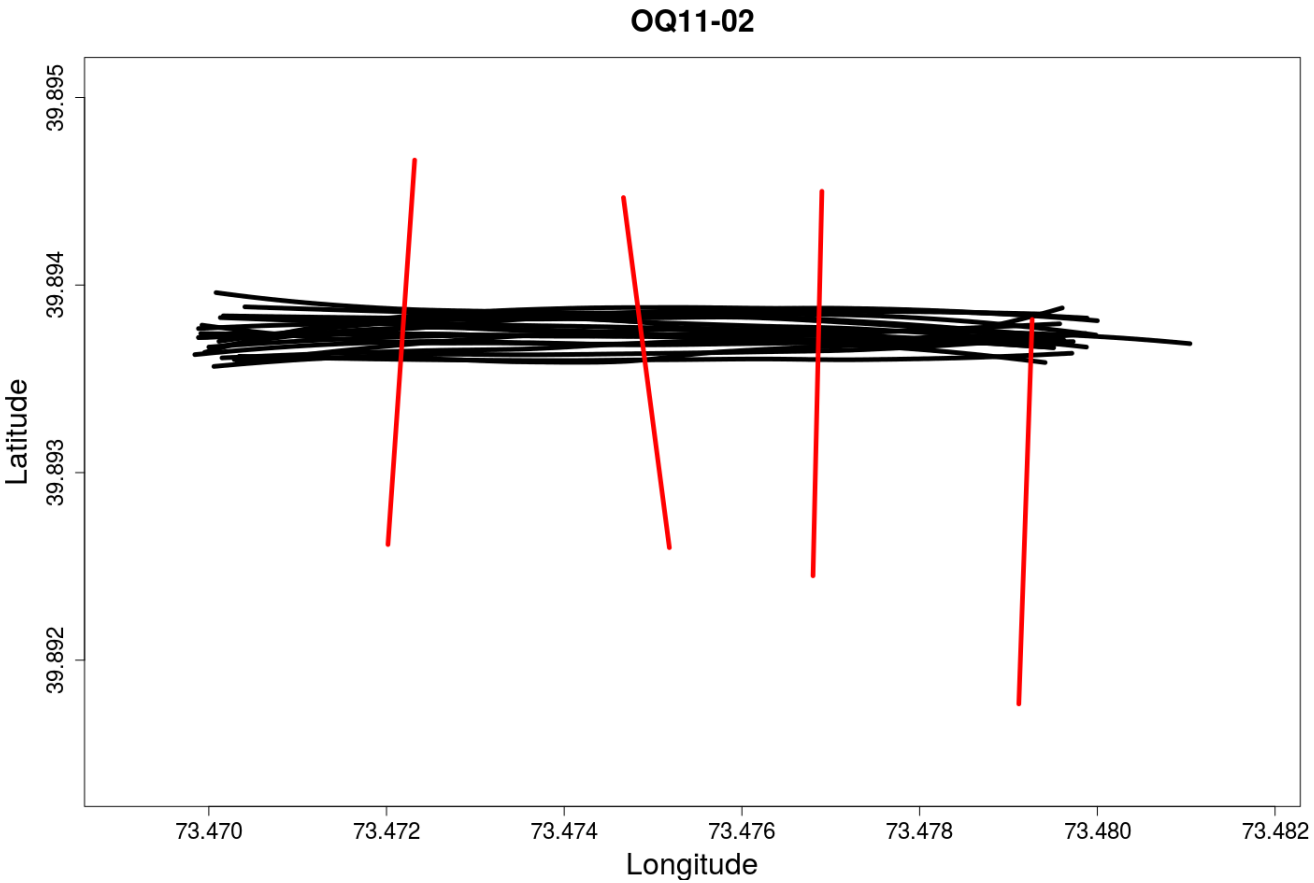

Figure 155: Relative positions of each tow in the set up (red lines) and depletion sequences (black) for depletion experiment OQ11-02.

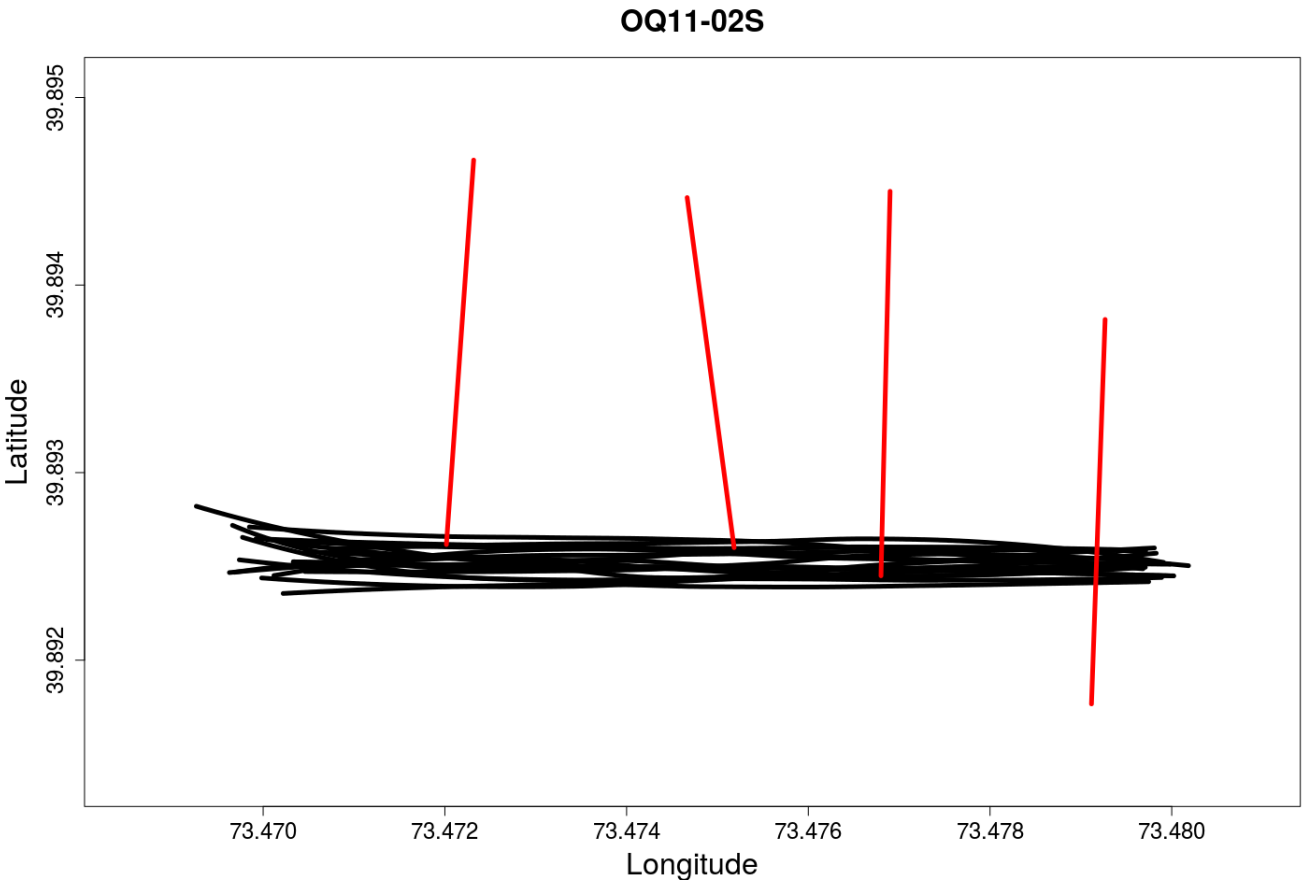

Figure 156: Relative positions of each tow in the set up (red lines) and depletion sequences (black) for depletion experiment OQ11-02S.

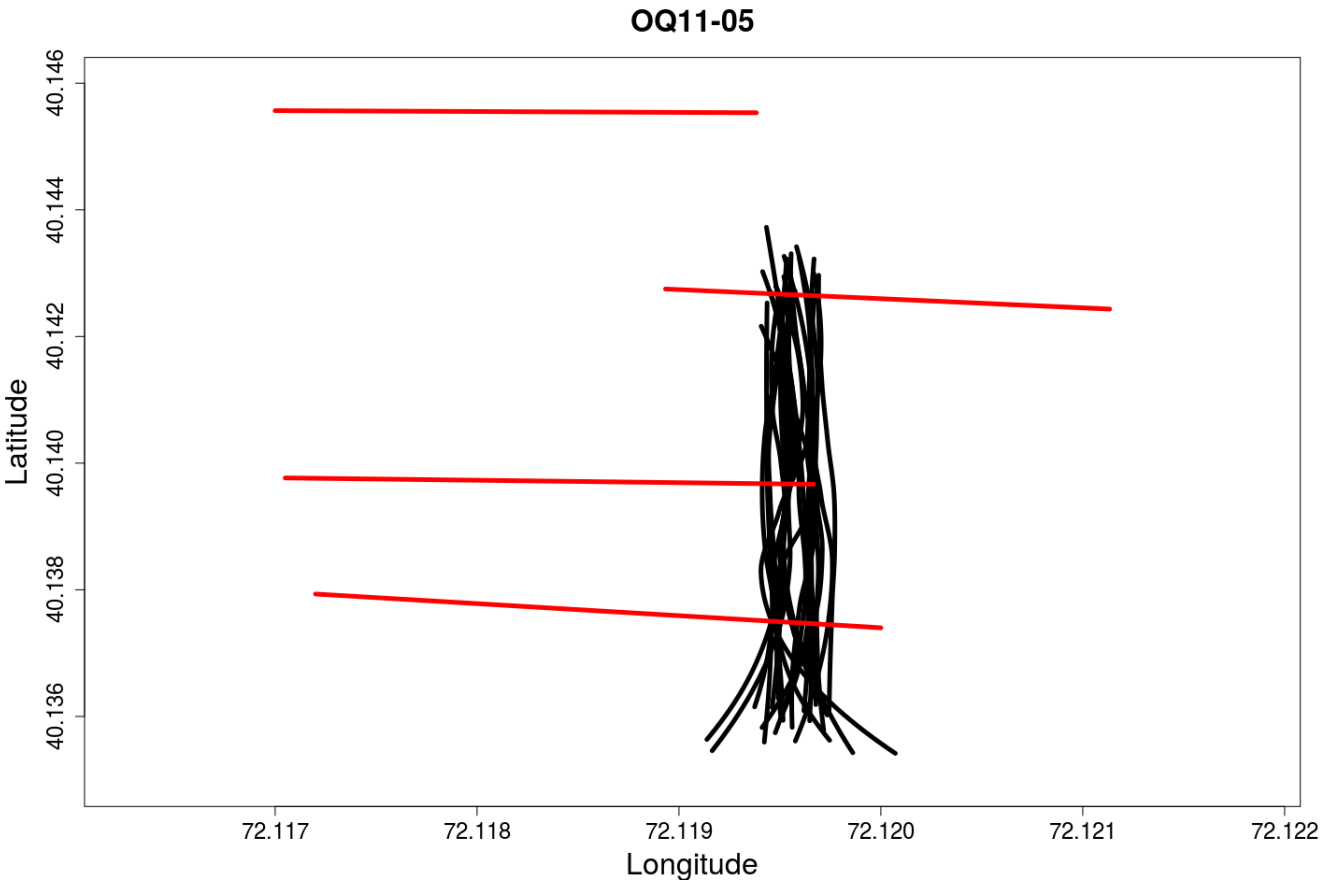

Figure 157: Relative positions of each tow in the set up (red lines) and depletion sequences (black) for depletion experiment OQ11-05.

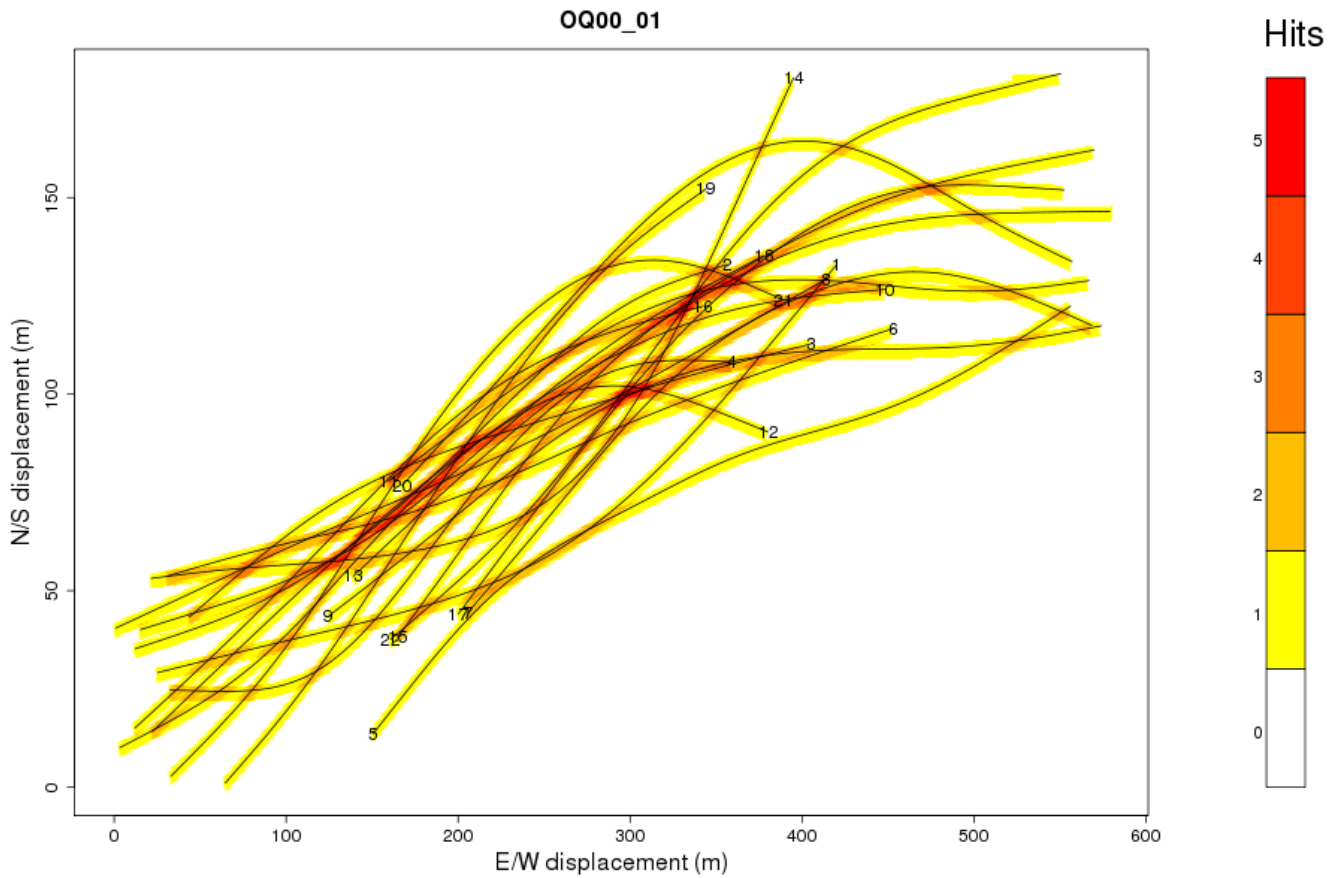

Figure 158: Depletion sequence for experiment OQ00-01, showing the number of passes made by the dredge over each cm^2 of the experimental area.

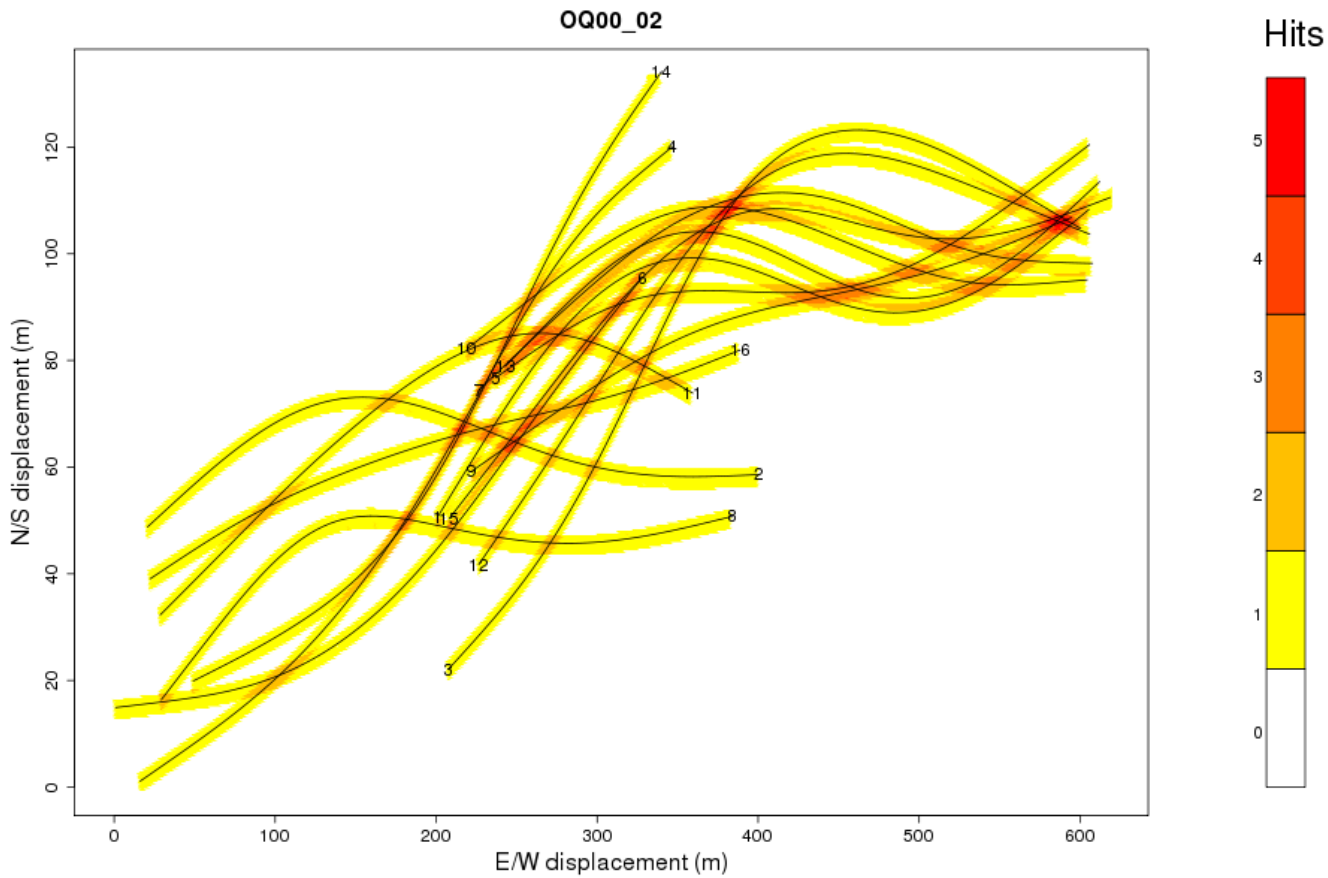

Figure 159: Depletion sequence for experiment OQ00-02, showing the number of passes made by the dredge over each cm^2 of the experimental area.

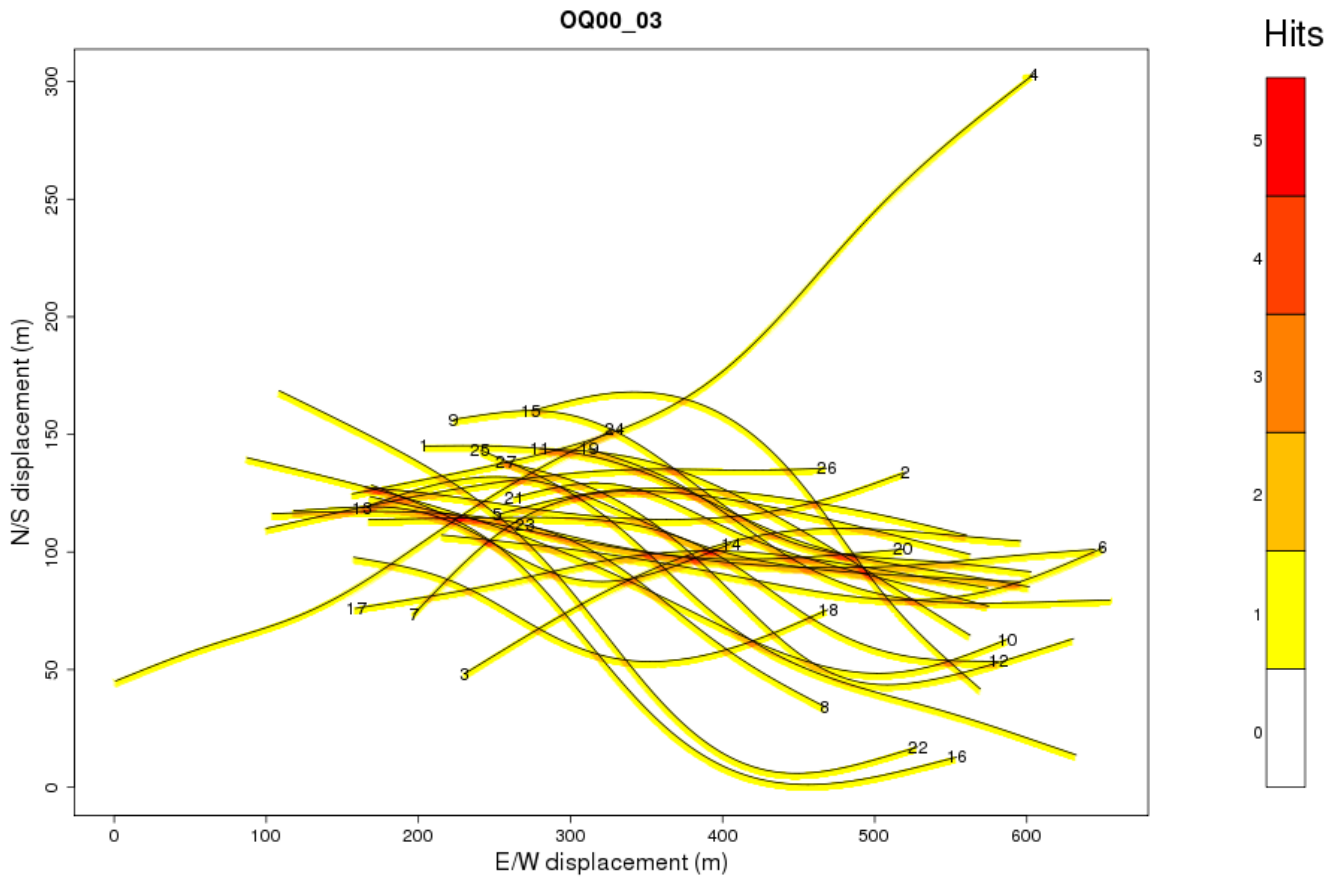

Figure 160: Depletion sequence for experiment OQ00-03, showing the number of passes made by the dredge over each cm^2 of the experimental area.

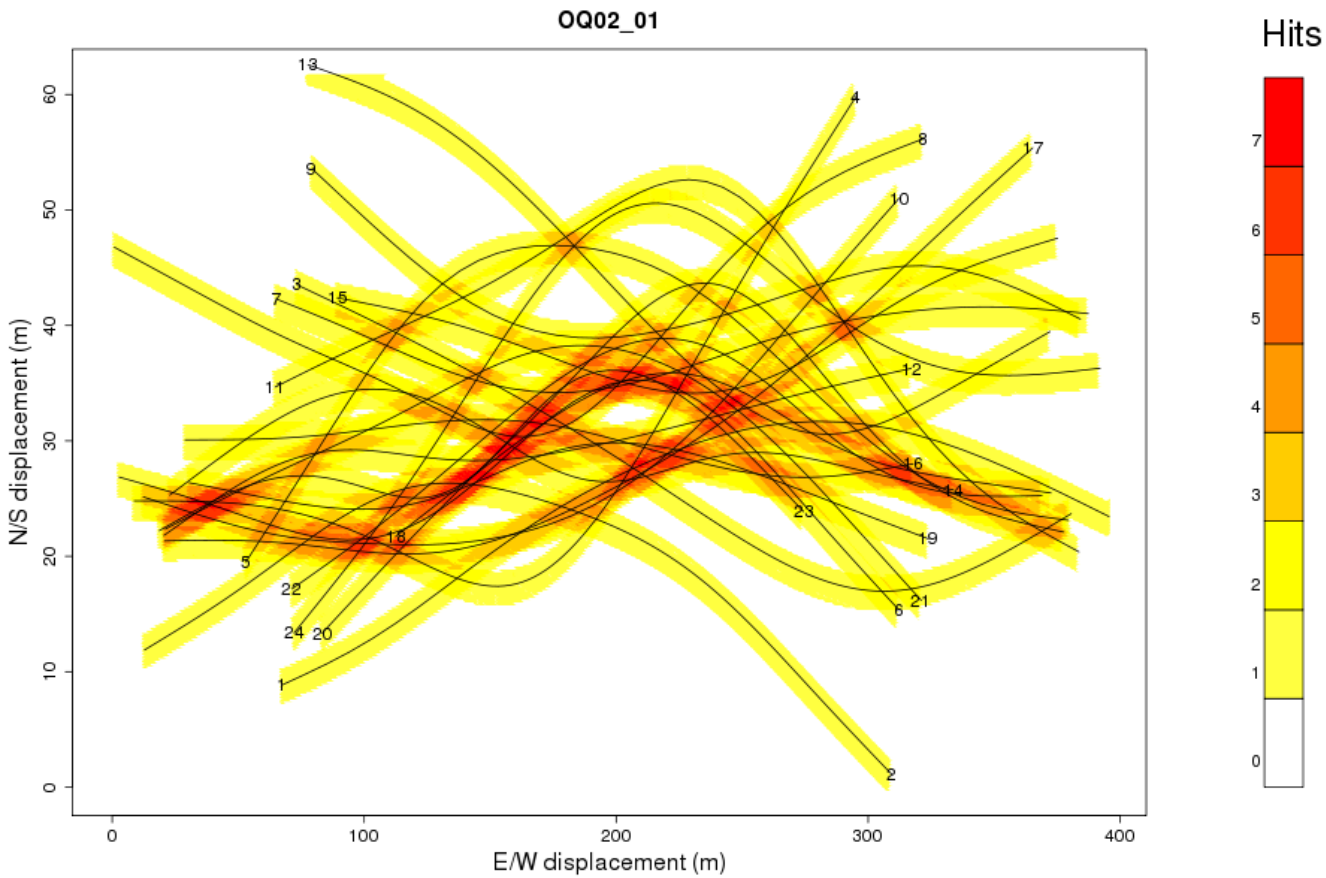

Figure 161: Depletion sequence for experiment OQ02-01, showing the number of passes made by the dredge over each cm^2 of the experimental area.

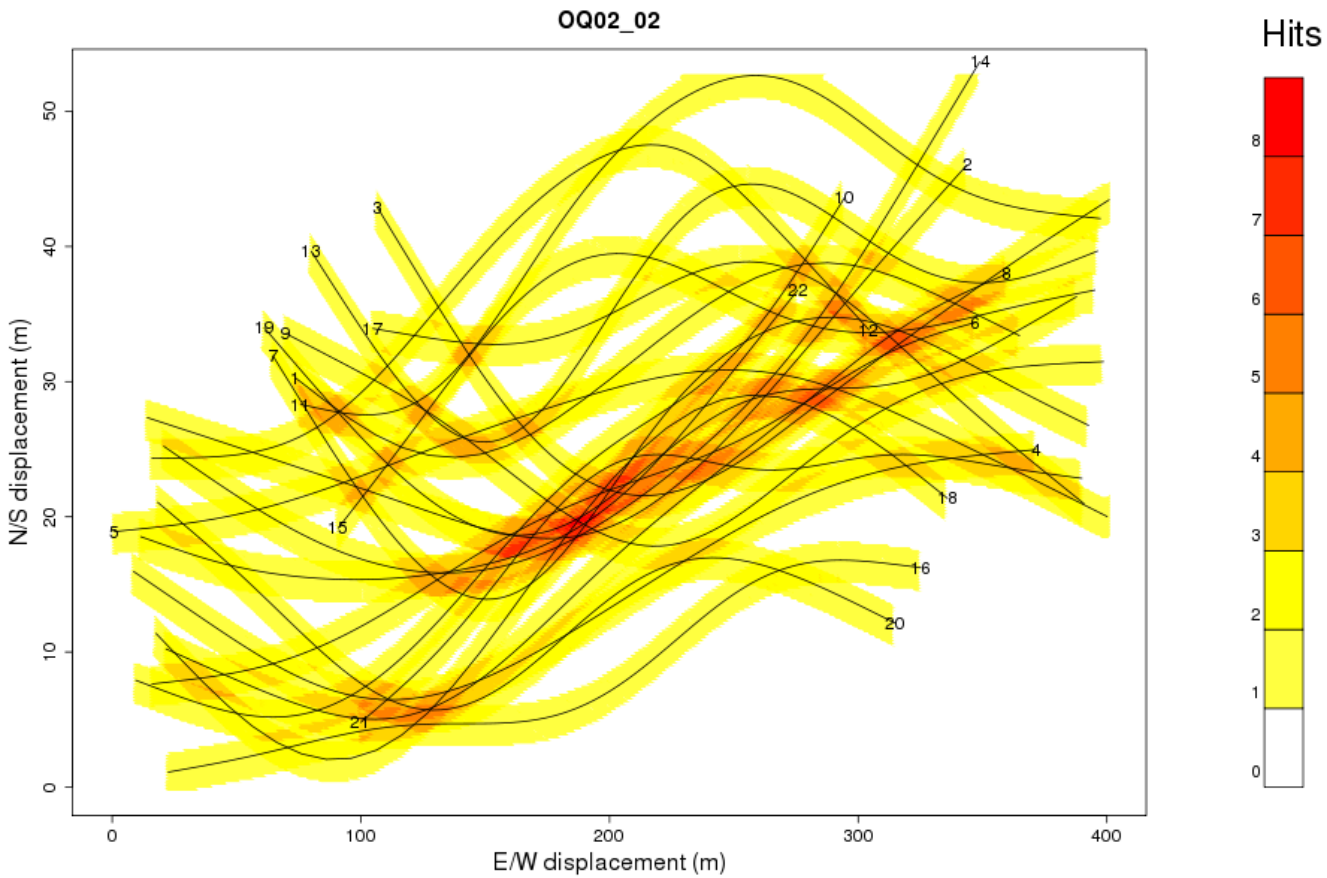

Figure 162: Depletion sequence for experiment OQ02-02, showing the number of passes made by the dredge over each cm^2 of the experimental area.

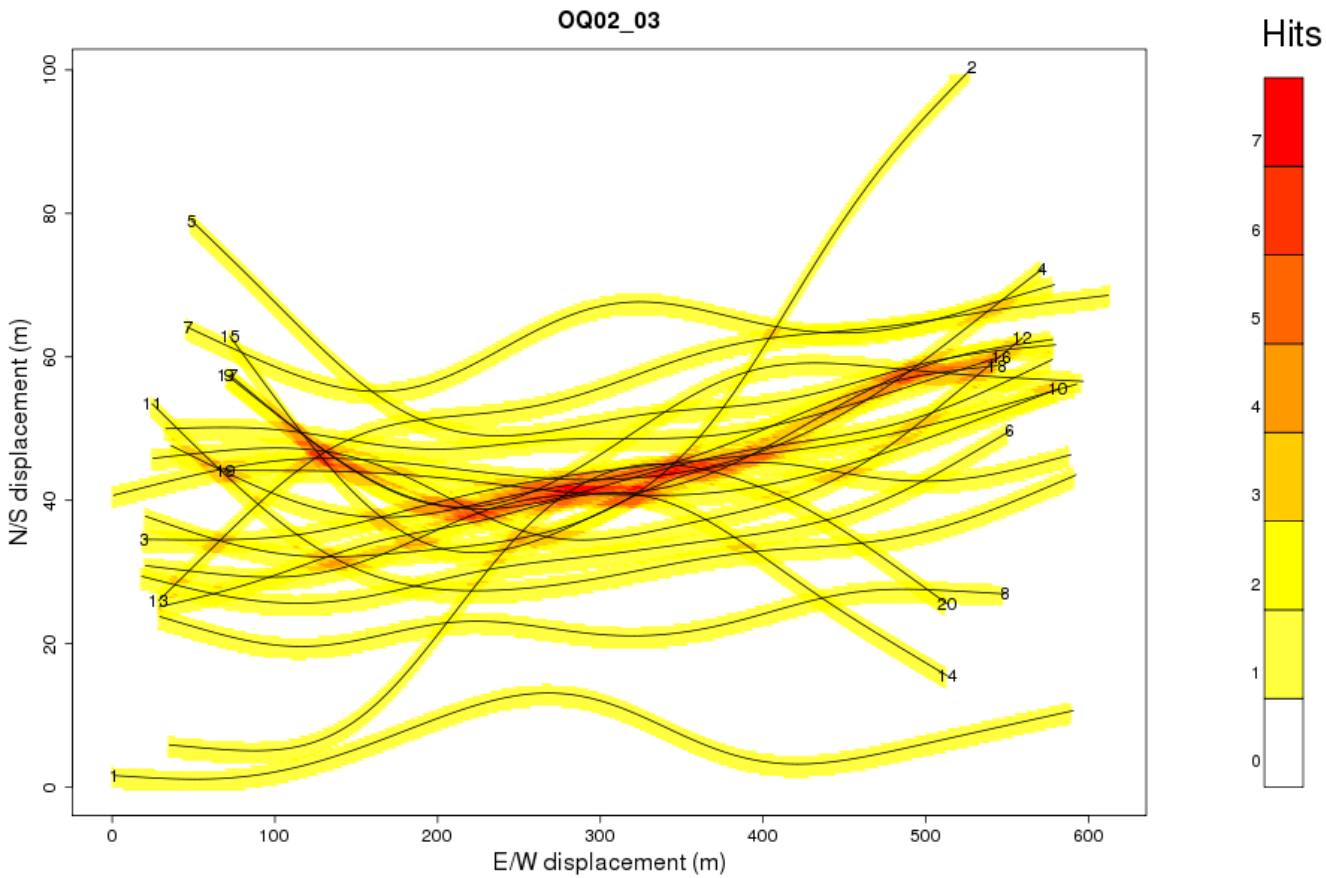

Figure 163: Depletion sequence for experiment OQ02-03, showing the number of passes made by the dredge over each cm^2 of the experimental area.

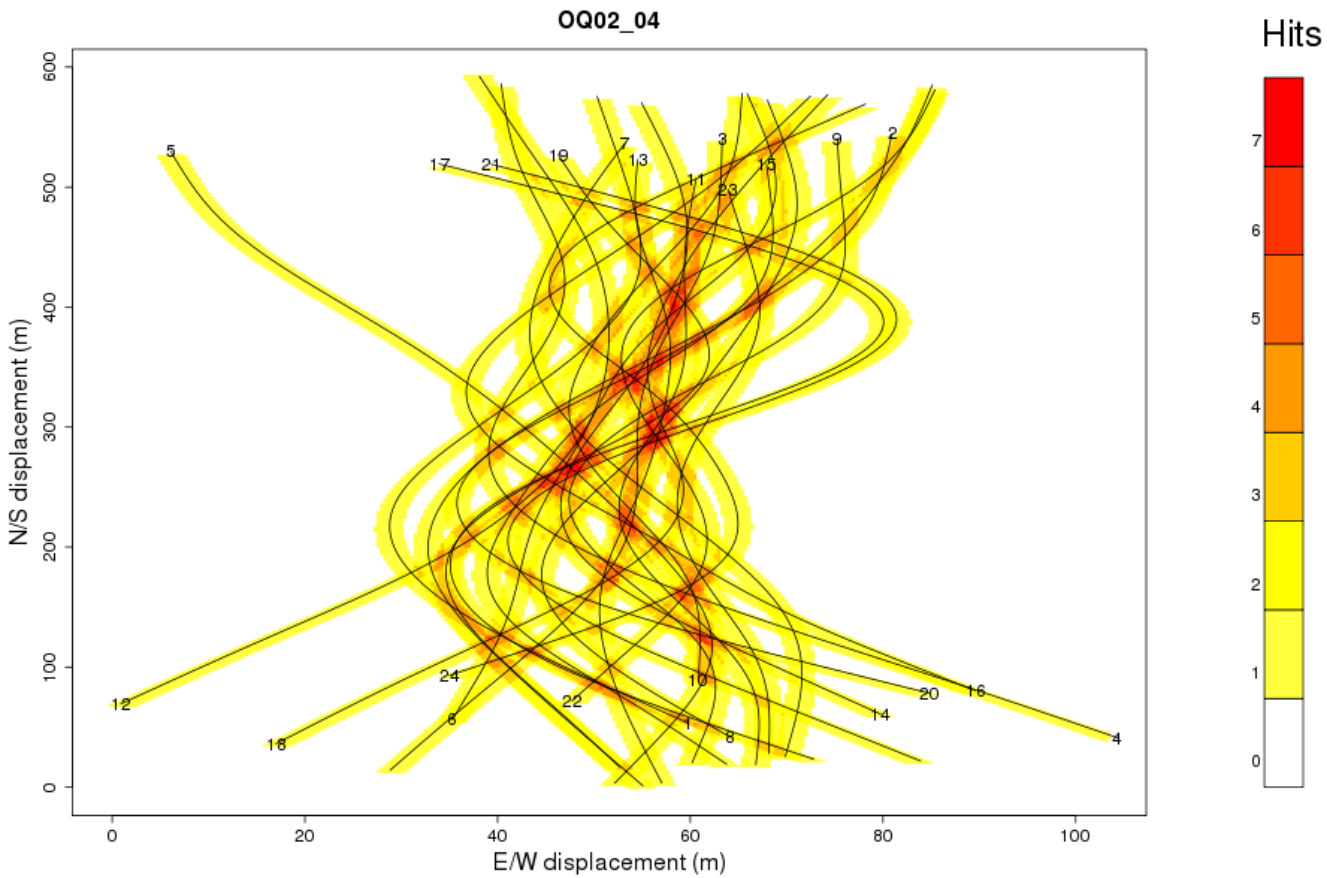

Figure 164: Depletion sequence for experiment OQ02-04, showing the number of passes made by the dredge over each cm^2 of the experimental area.

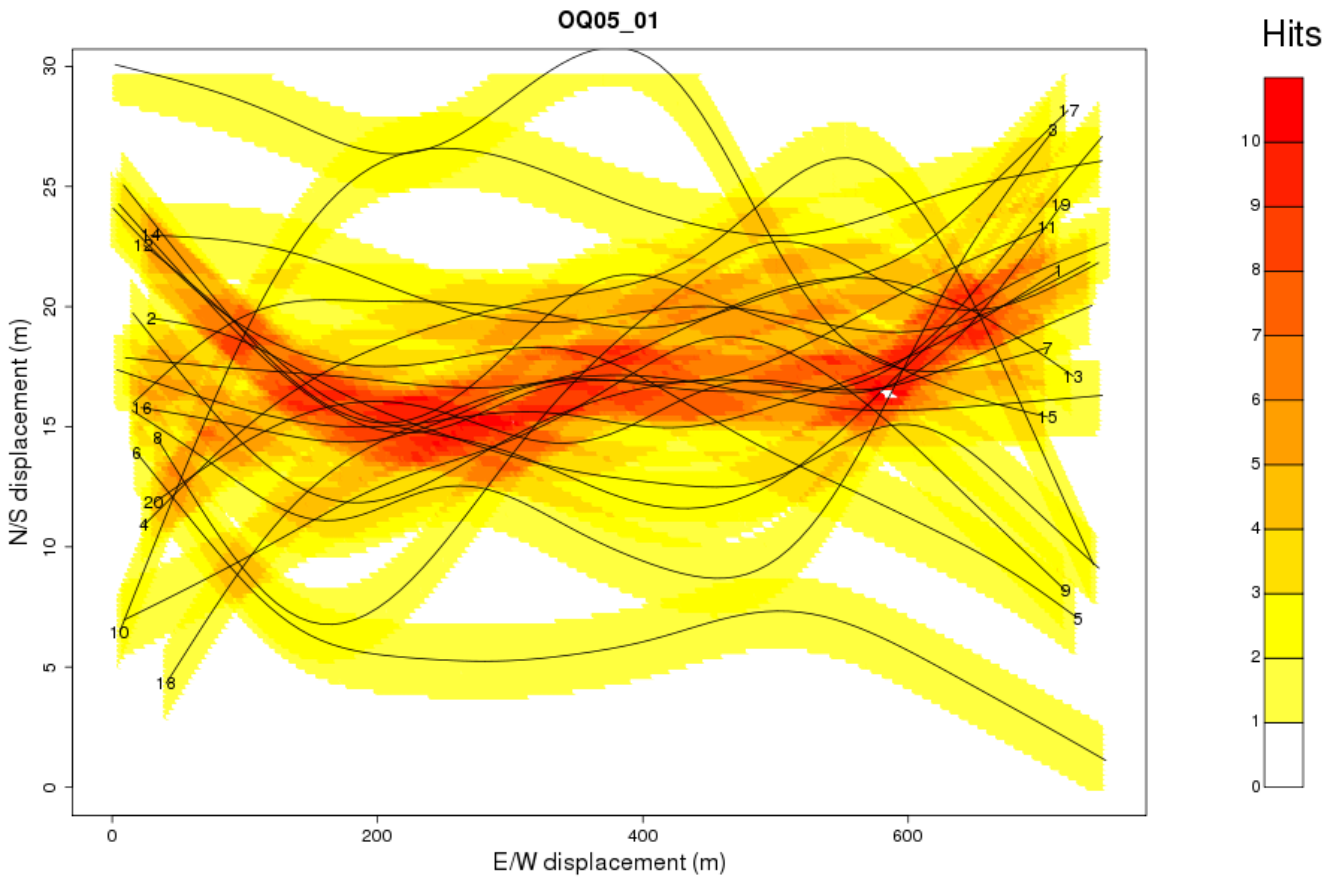

Figure 165: Depletion sequence for experiment OQ05-01, showing the number of passes made by the dredge over each cm^2 of the experimental area.

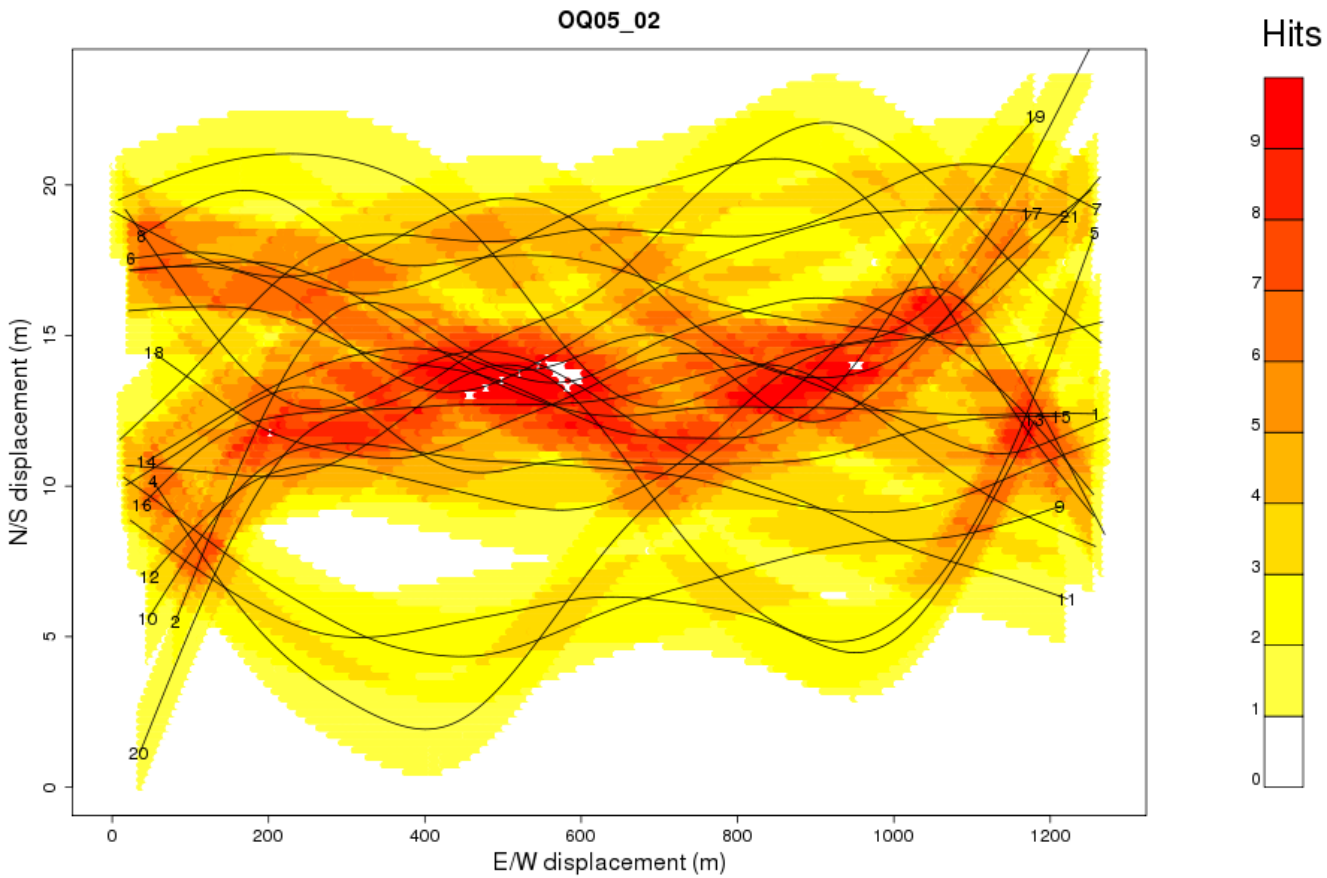

Figure 166: Depletion sequence for experiment OQ05-02, showing the number of passes made by the dredge over each cm^2 of the experimental area.

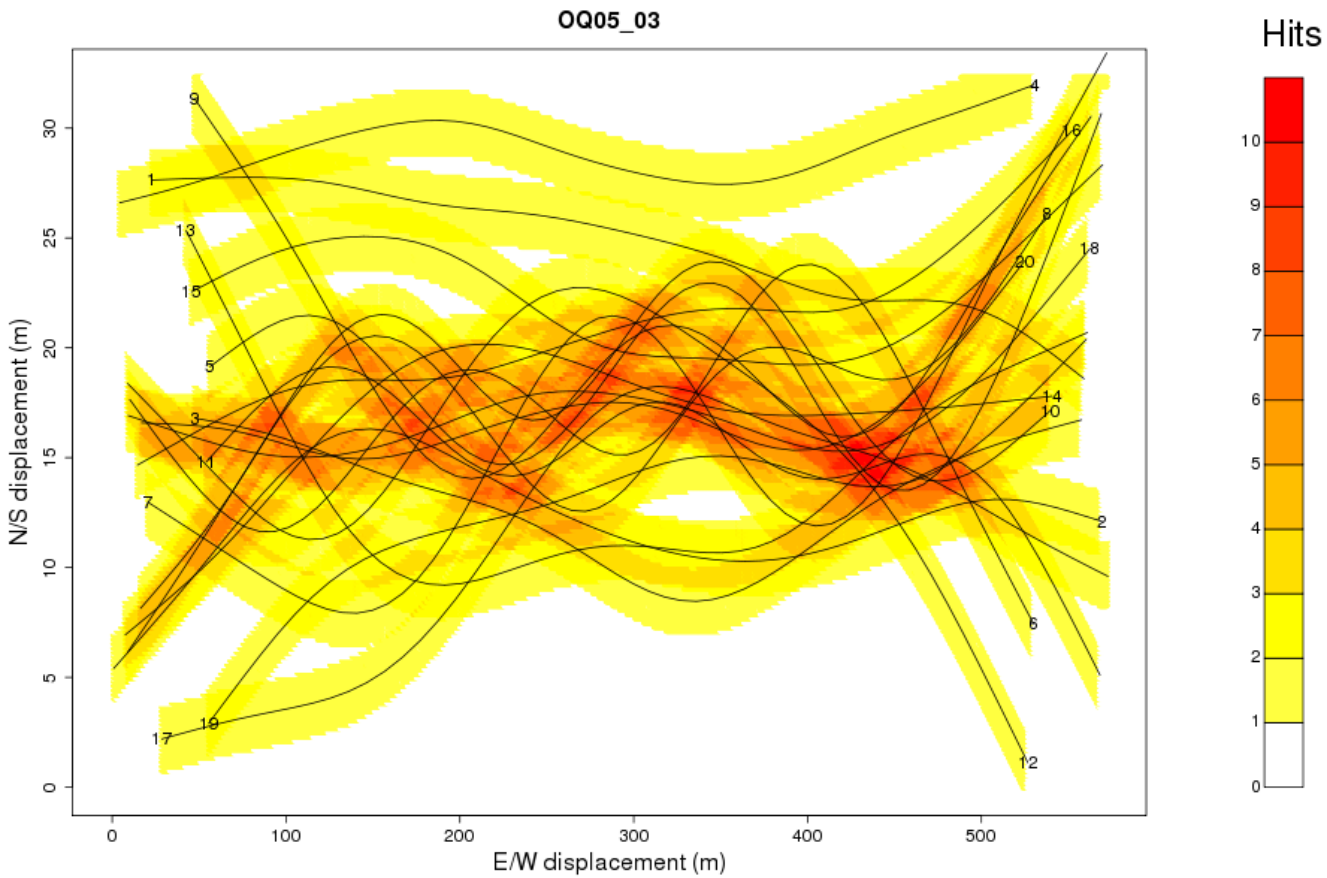

Figure 167: Depletion sequence for experiment OQ05-03, showing the number of passes made by the dredge over each cm^2 of the experimental area.

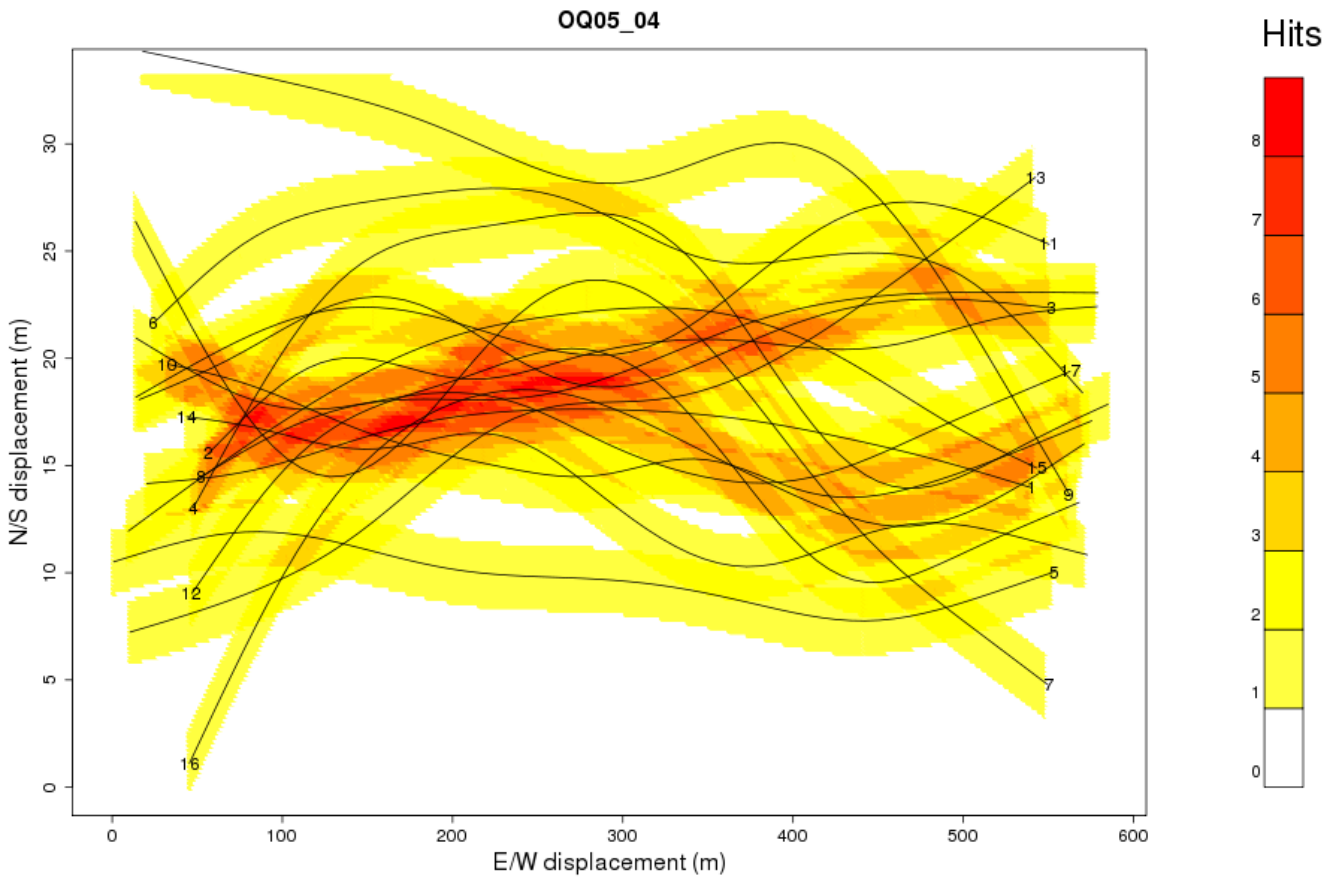

Figure 168: Depletion sequence for experiment OQ05-04, showing the number of passes made by the dredge over each cm^2 of the experimental area.

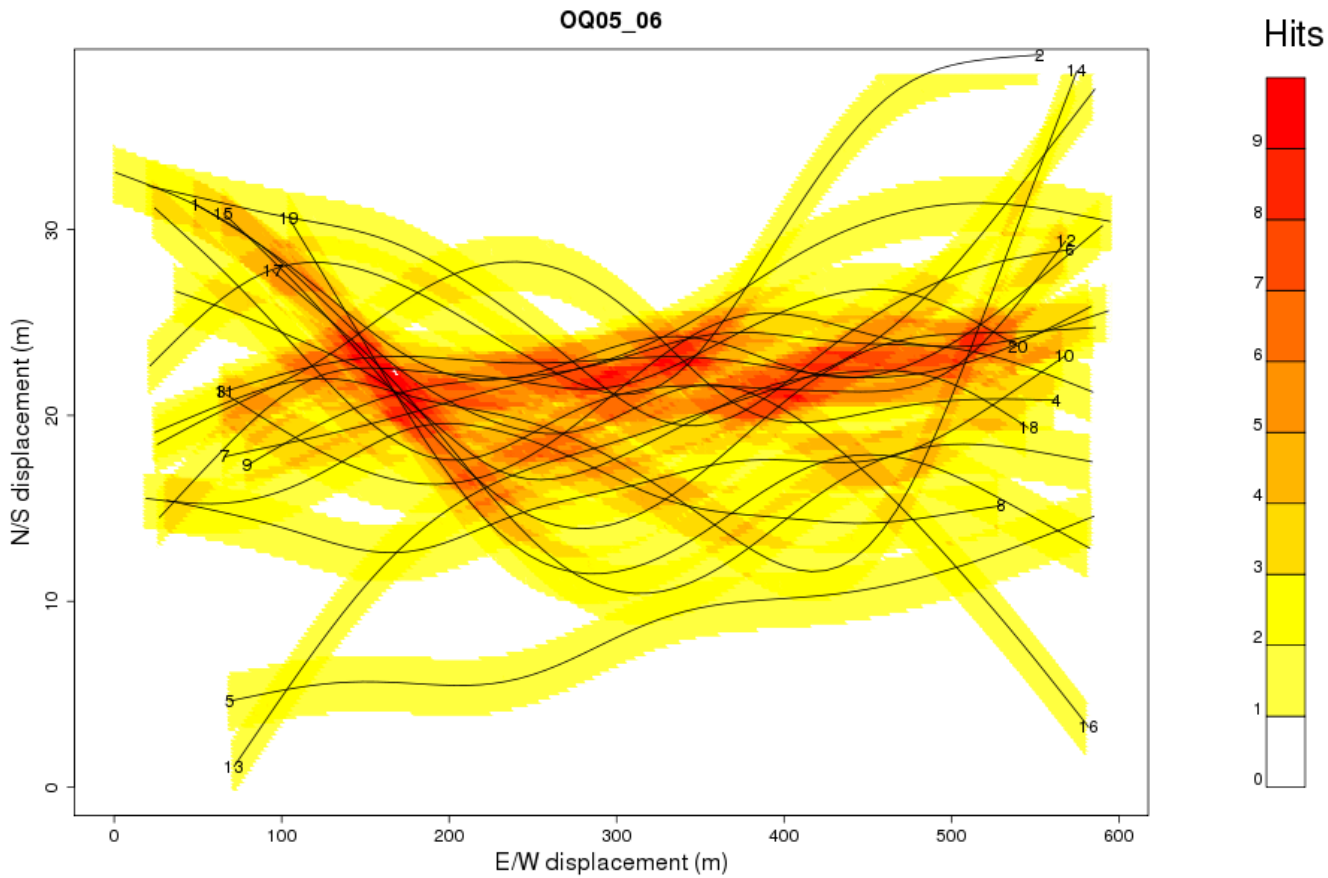

Figure 169: Depletion sequence for experiment OQ05-06, showing the number of passes made by the dredge over each cm^2 of the experimental area.

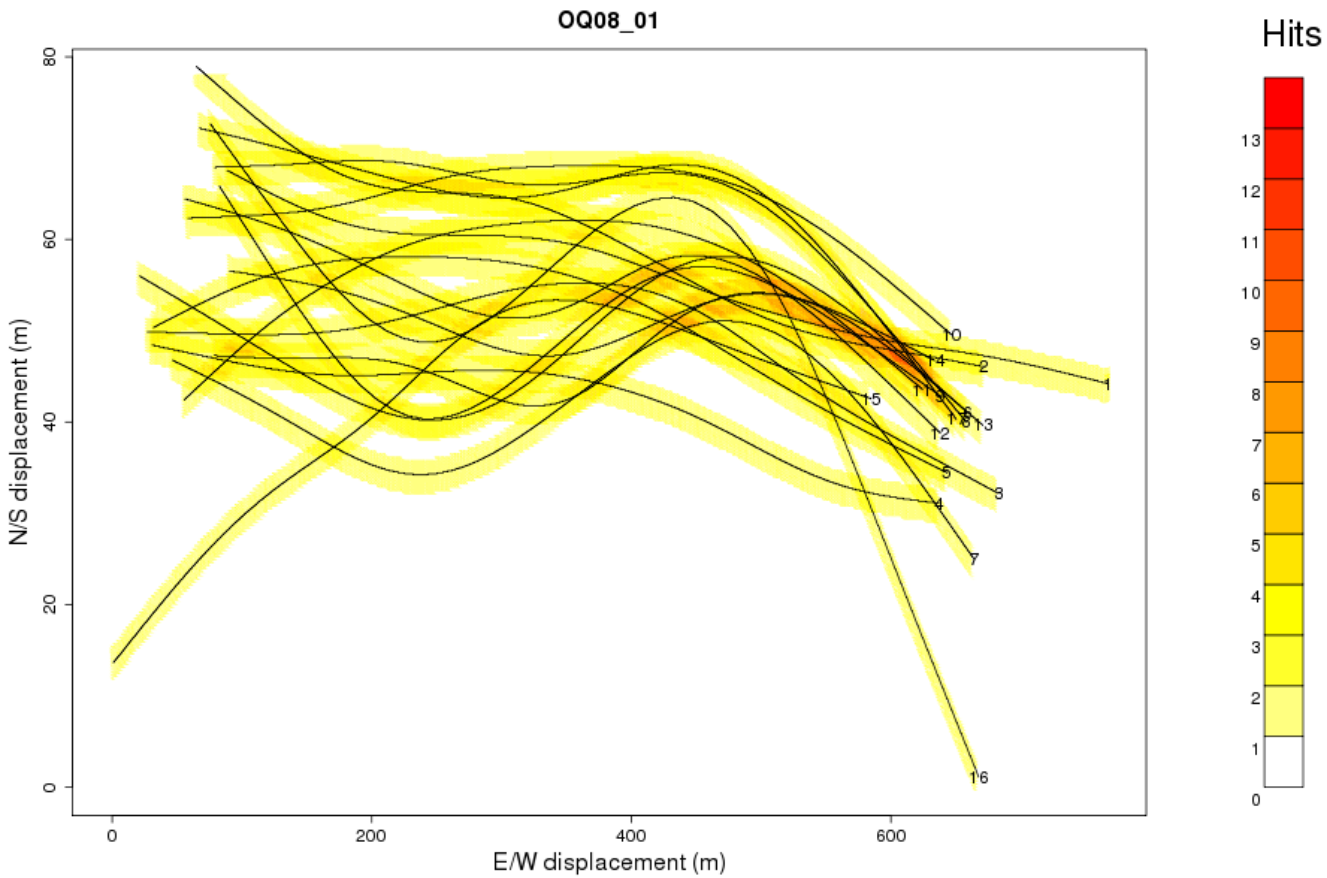

Figure 170: Depletion sequence for experiment OQ08-01, showing the number of passes made by the dredge over each cm^2 of the experimental area.

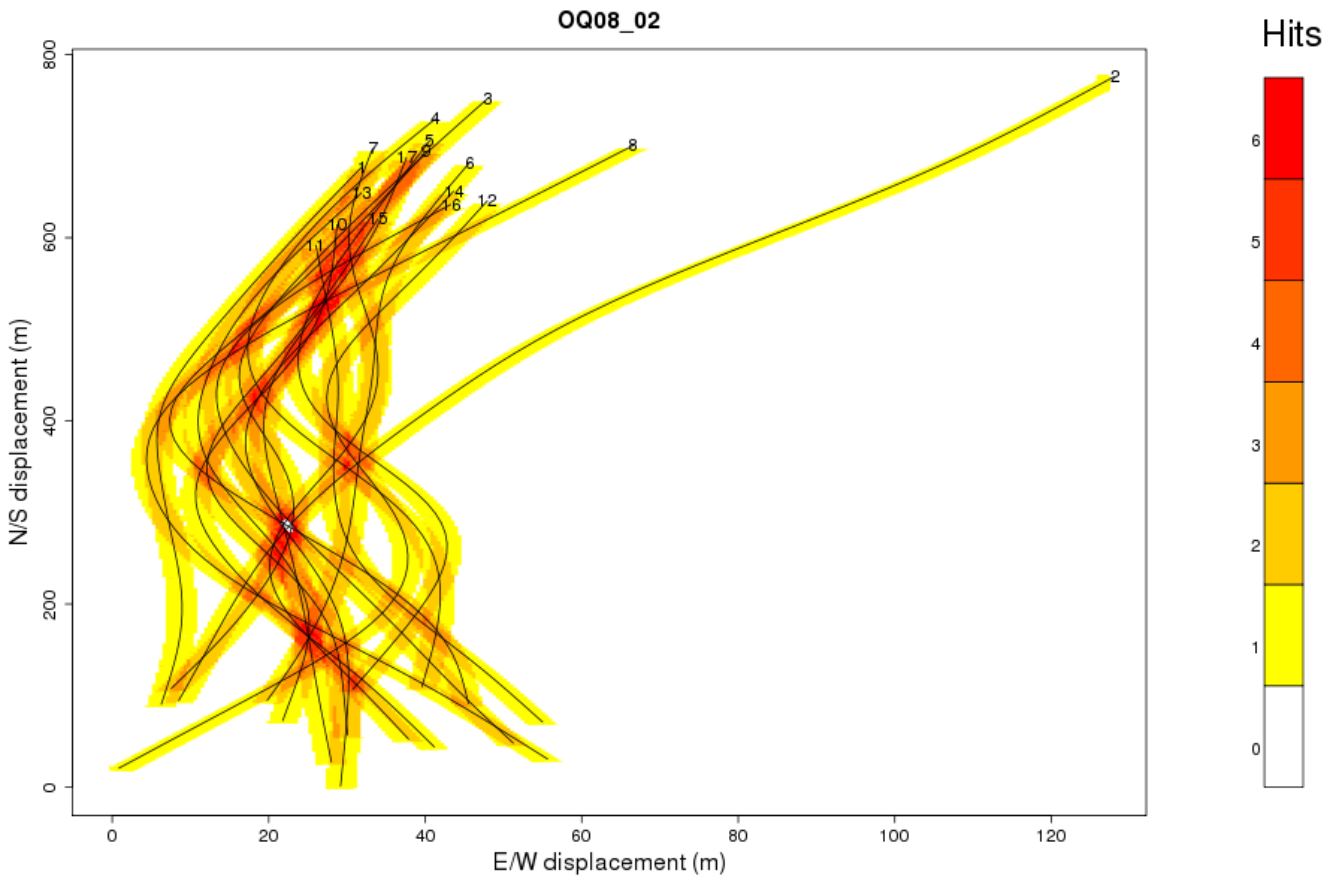

Figure 171: Depletion sequence for experiment OQ08-02, showing the number of passes made by the dredge over each cm^2 of the experimental area.

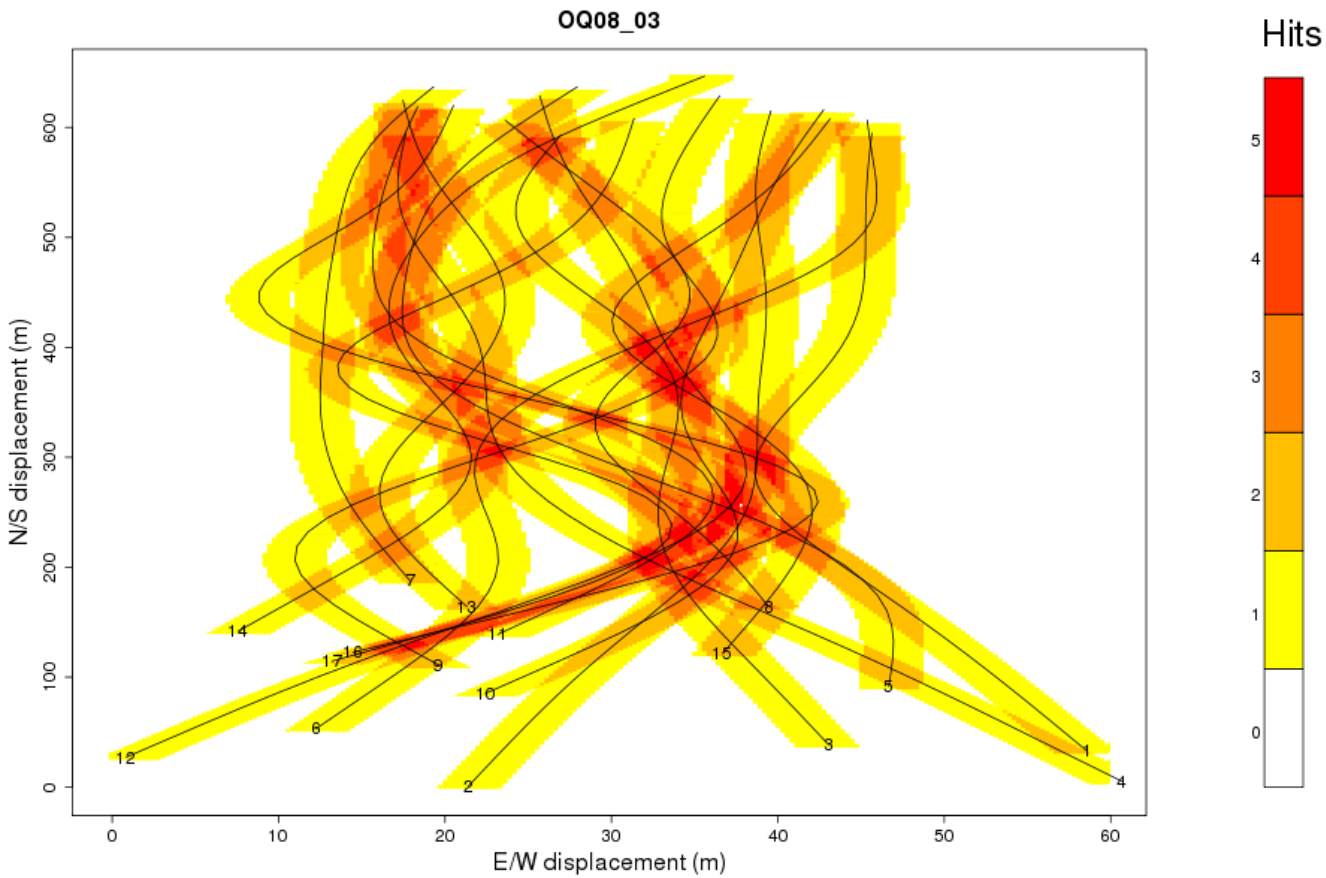

Figure 172: Depletion sequence for experiment OQ08-03, showing the number of passes made by the dredge over each cm^2 of the experimental area.

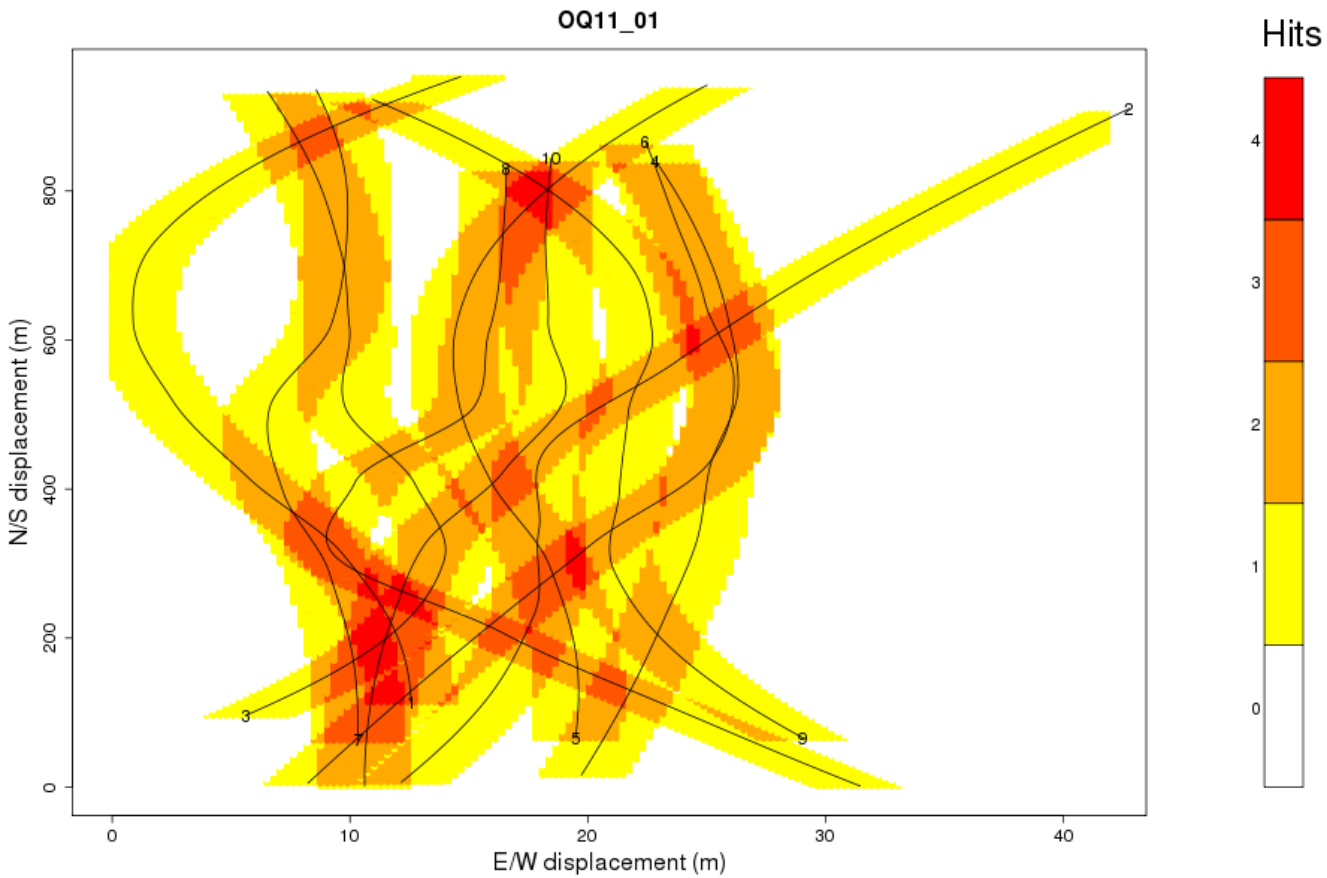

Figure 173: Depletion sequence for experiment OQ11-01, showing the number of passes made by the dredge over each cm^2 of the experimental area.

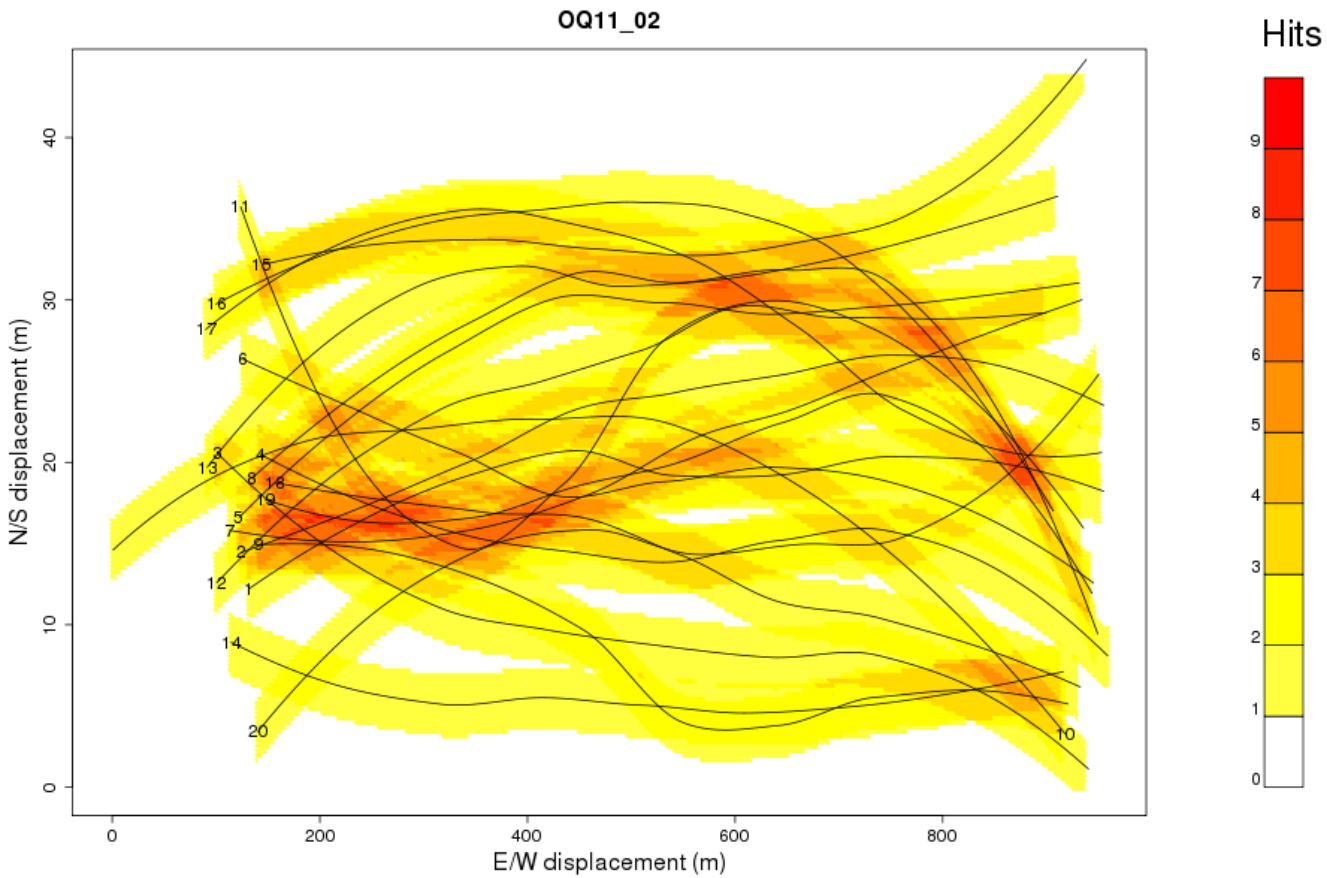

Figure 174: Depletion sequence for experiment OQ11-02, showing the number of passes made by the dredge over each cm^2 of the experimental area.

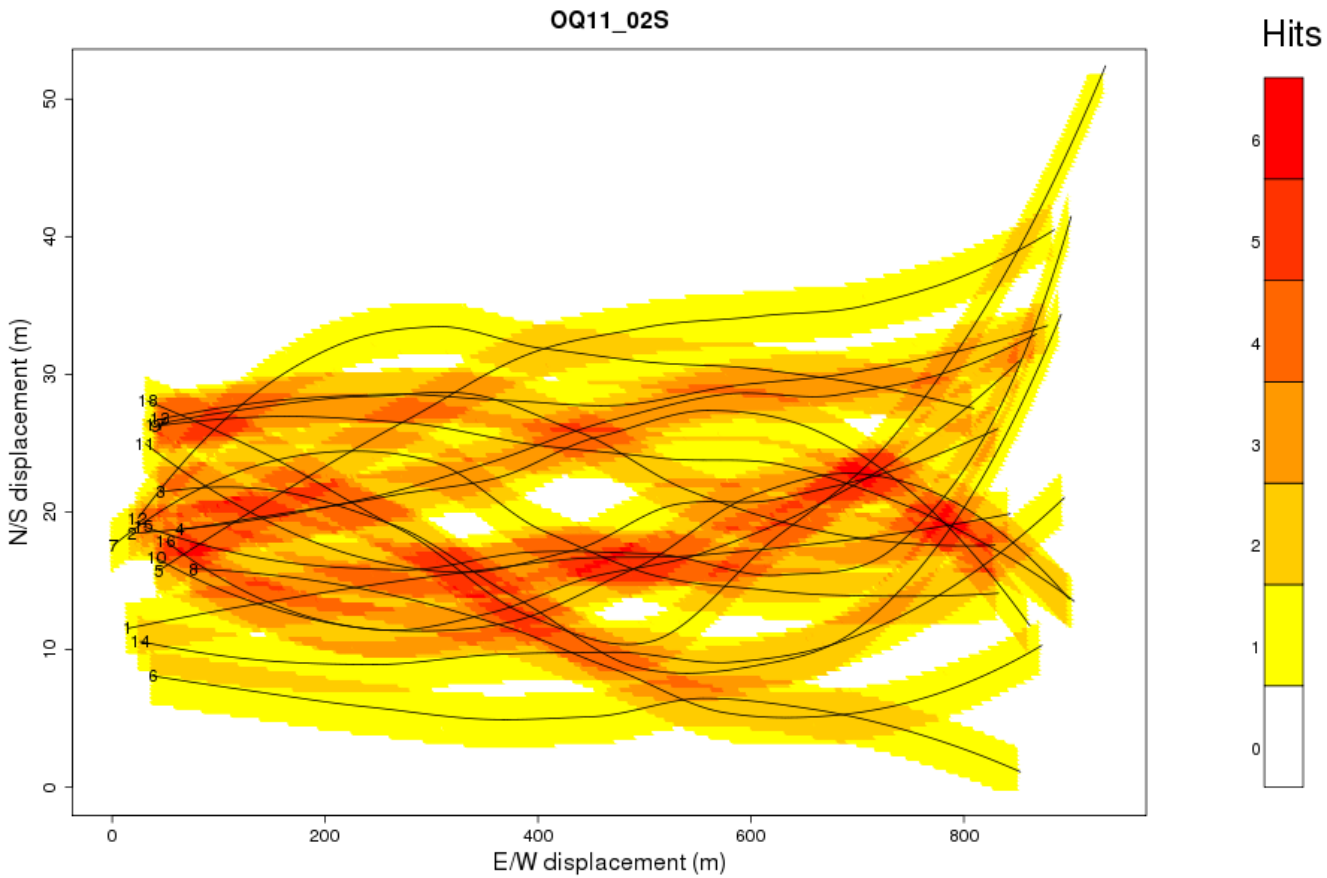

Figure 175: Depletion sequence for experiment OQ11-02S, showing the number of passes made by the dredge over each cm^2 of the experimental area.

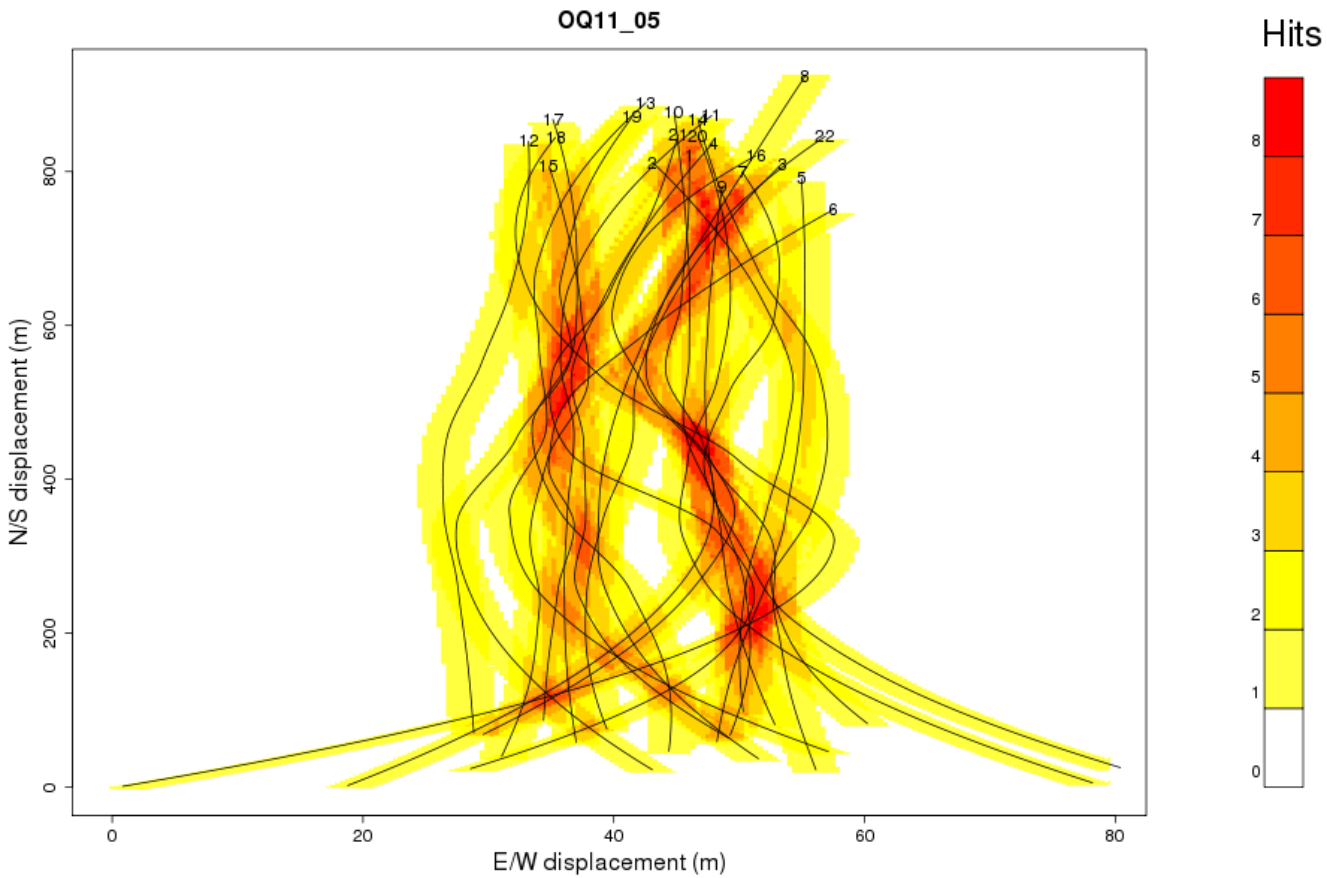

Figure 176: Depletion sequence for experiment OQ11-05, showing the number of passes made by the dredge over each cm^2 of the experimental area.

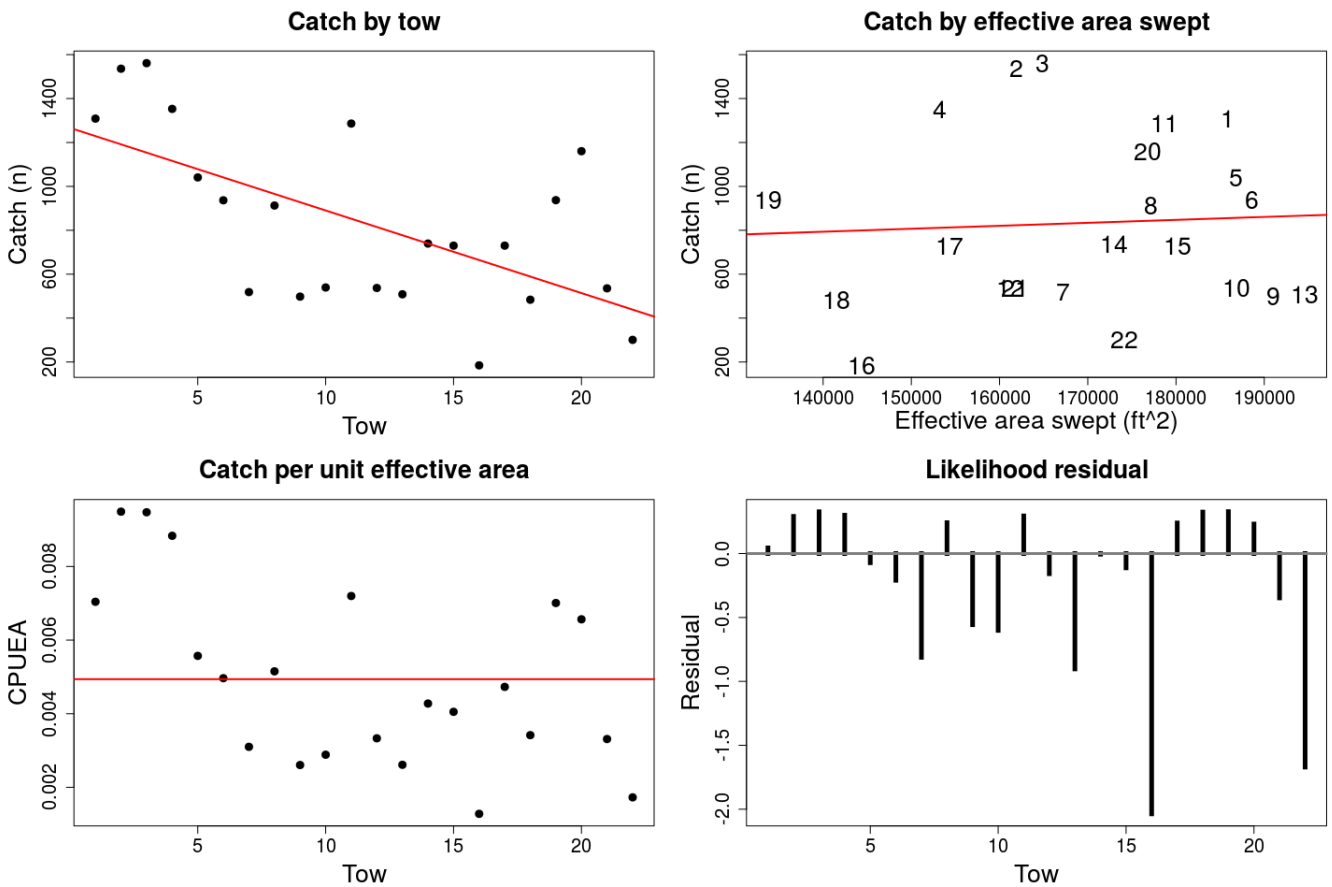

Figure 177: Diagnostic plots for ocean quahog depletion experiment OQ00-01. Catch by tow shows the catch recorded in each tow. This plot should show a declining trend over time. Catch vs. effective area swept shows the catch by the area swept by each tow, while accounting for the area in each tow that has already been fished. The numbers indicate the order of tows. This plot should show an increasing trend. CPUEA vs. tow shows the catch per unit of effective area by tow. This plot should not show a trend. Likelihood residual shows the fit of the model to each tow and should not indicate any patterns if the model has worked well.

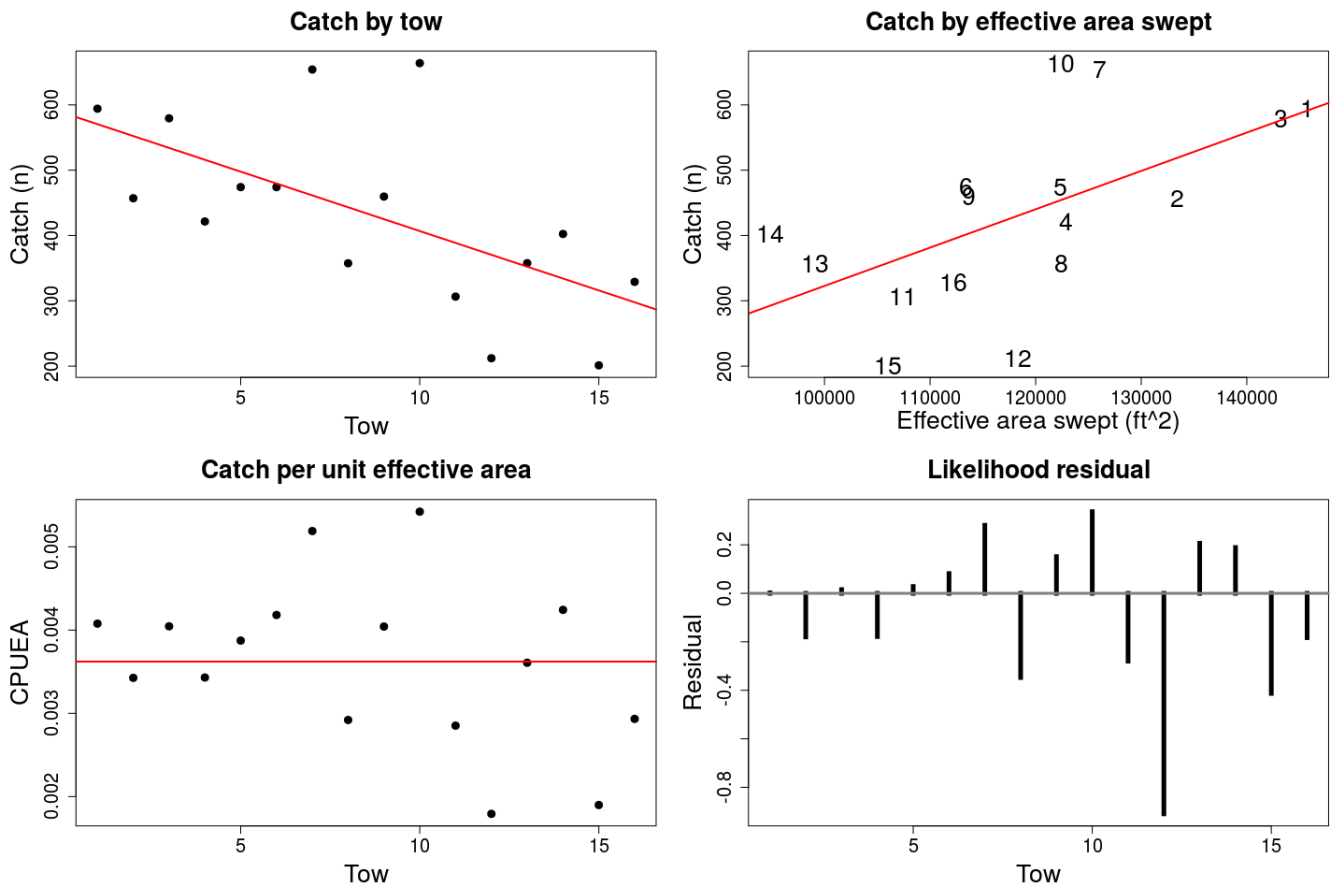

Figure 178: Diagnostic plots for ocean quahog depletion experiment OQ00-02. Catch by tow shows the catch recorded in each tow. This plot should show a declining trend over time. Catch vs. effective area swept shows the catch by the area swept by each tow, while accounting for the area in each tow that has already been fished. The numbers indicate the order of tows. This plot should show an increasing trend. CPUEA vs. tow shows the catch per unit of effective area by tow. This plot should not show a trend. Likelihood residual shows the fit of the model to each tow and should not indicate any patterns if the model has worked well.

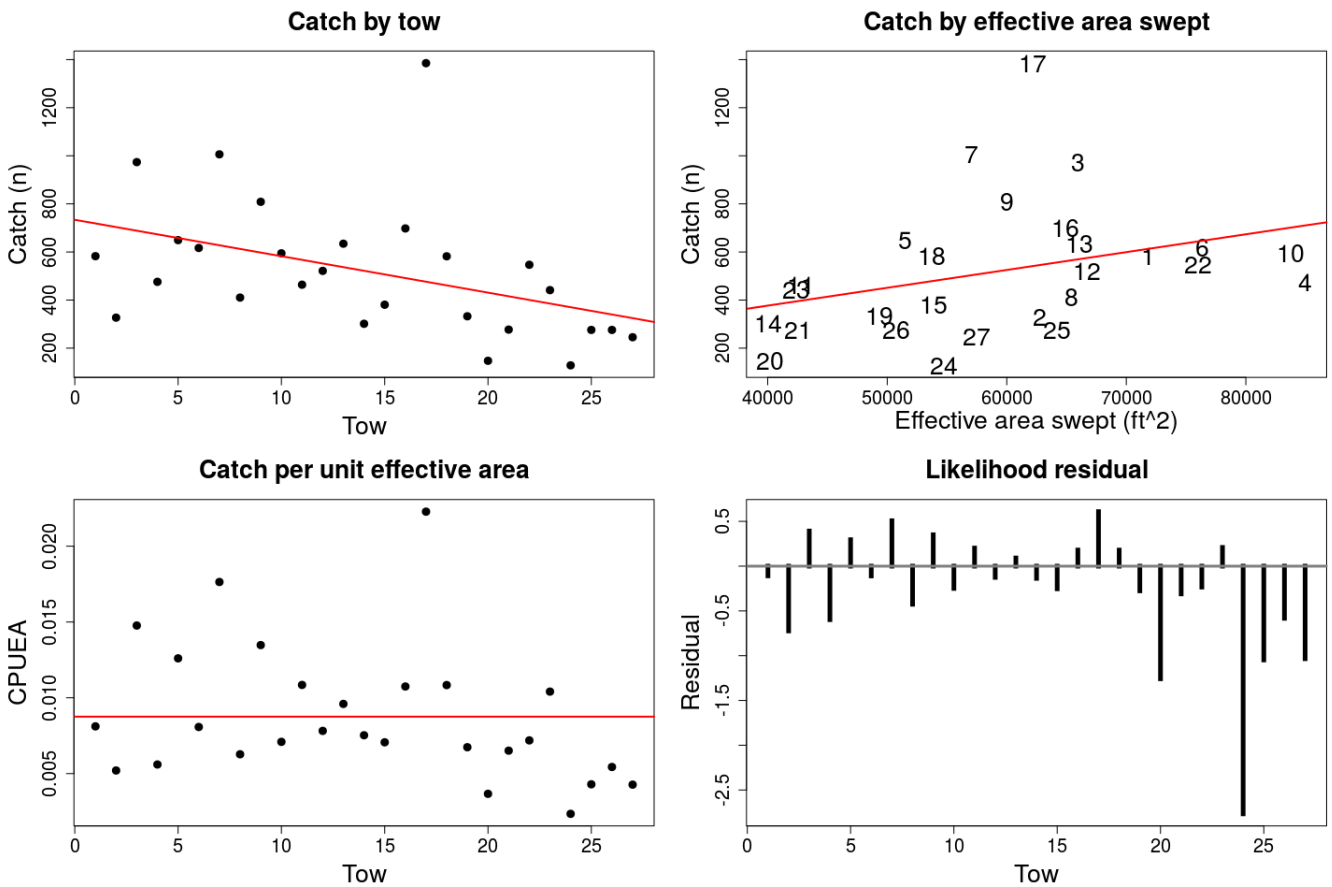

Figure 179: Diagnostic plots for ocean quahog depletion experiment OQ00-03. Catch by tow shows the catch recorded in each tow. This plot should show a declining trend over time. Catch vs. effective area swept shows the catch by the area swept by each tow, while accounting for the area in each tow that has already been fished. The numbers indicate the order of tows. This plot should show an increasing trend. CPUEA vs. tow shows the catch per unit of effective area by tow. This plot should not show a trend. Likelihood residual shows the fit of the model to each tow and should not indicate any patterns if the model has worked well.

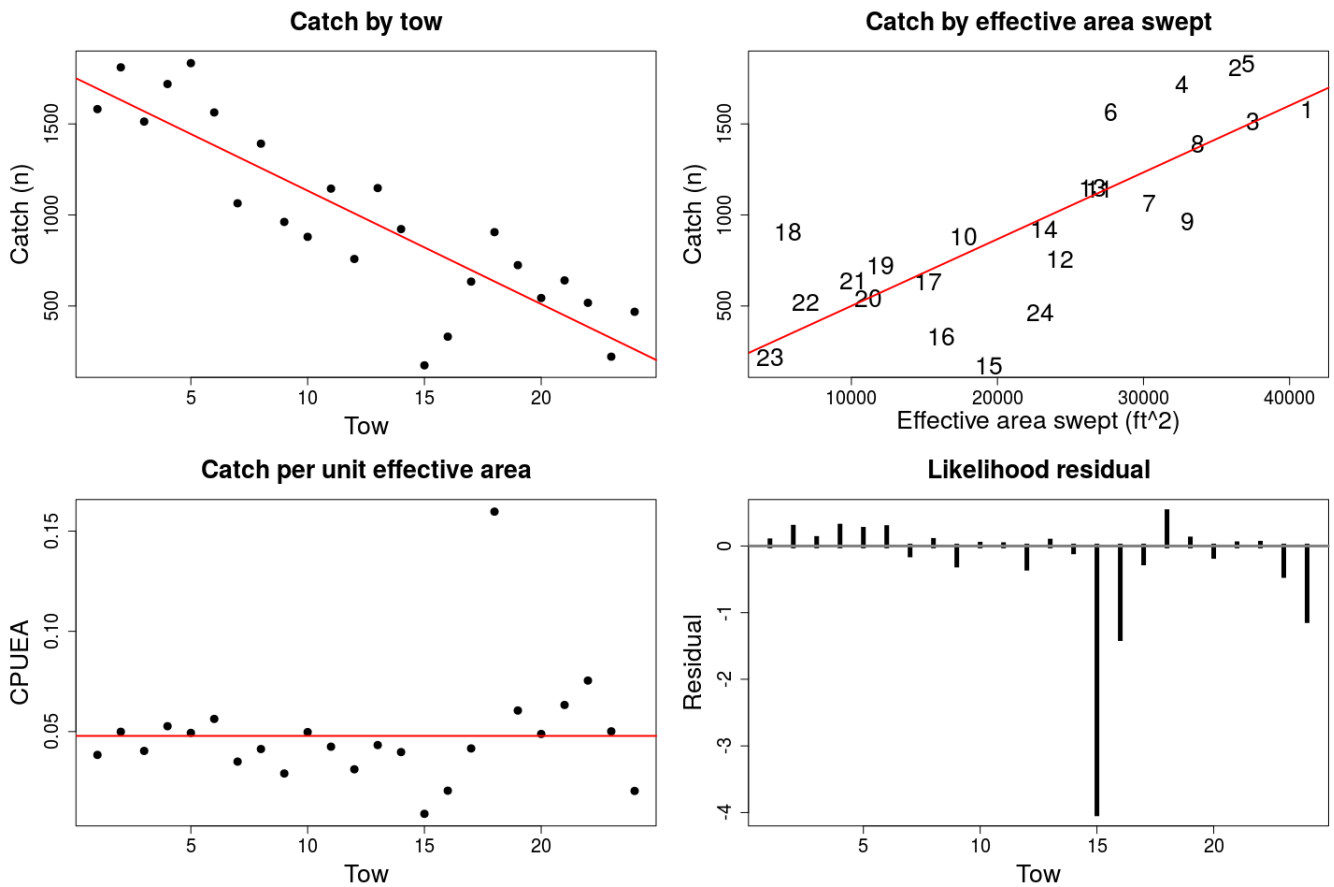

Figure 180: Diagnostic plots for ocean quahog depletion experiment OQ02-01. Catch by tow shows the catch recorded in each tow. This plot should show a declining trend over time. Catch vs. effective area swept shows the catch by the area swept by each tow, while accounting for the area in each tow that has already been fished. The numbers indicate the order of tows. This plot should show an increasing trend. CPUEA vs. tow shows the catch per unit of effective area by tow. This plot should not show a trend. Likelihood residual shows the fit of the model to each tow and should not indicate any patterns if the model has worked well.

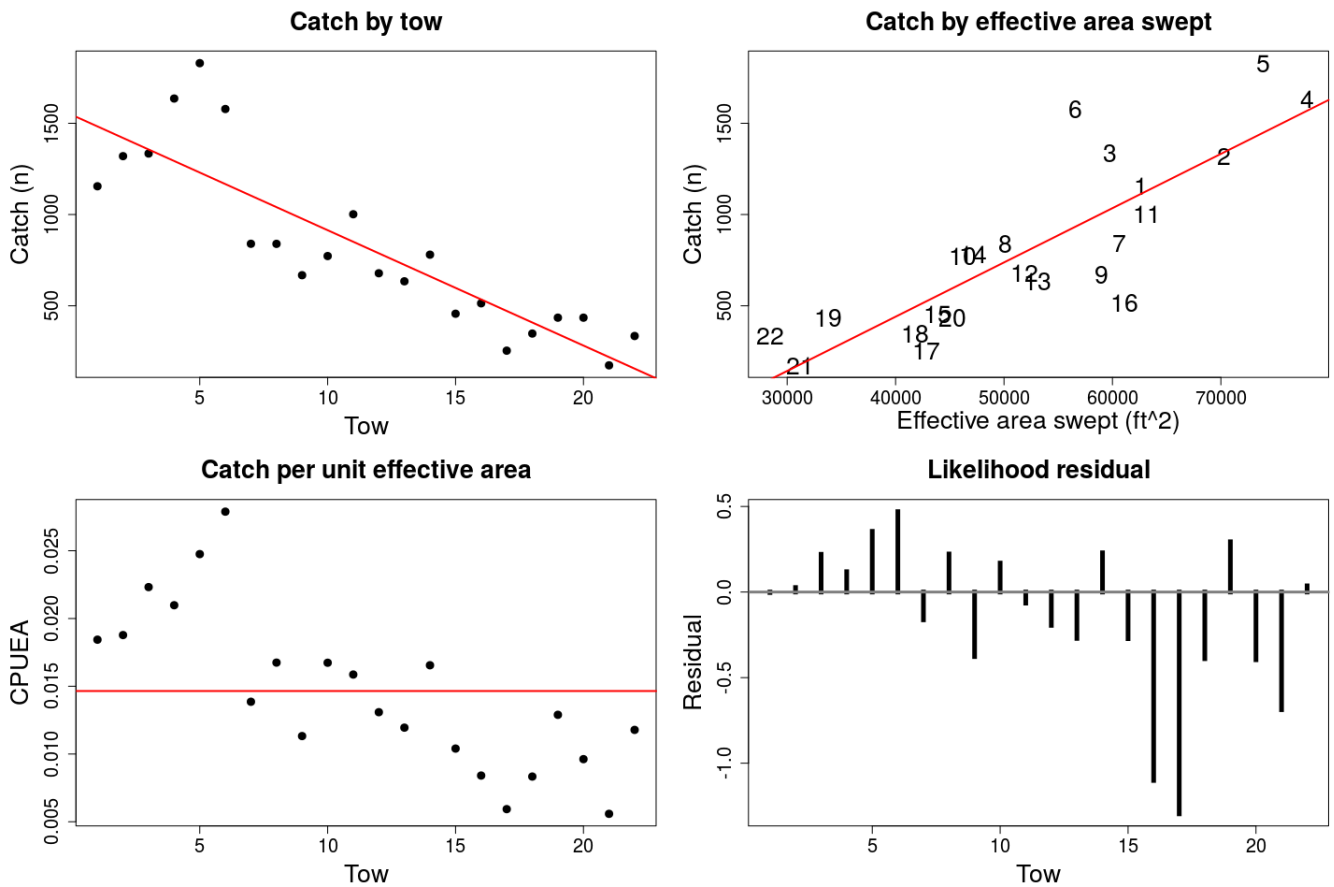

Figure 181: Diagnostic plots for ocean quahog depletion experiment OQ02-02. Catch by tow shows the catch recorded in each tow. This plot should show a declining trend over time. Catch vs. effective area swept shows the catch by the area swept by each tow, while accounting for the area in each tow that has already been fished. The numbers indicate the order of tows. This plot should show an increasing trend. CPUEA vs. tow shows the catch per unit of effective area by tow. This plot should not show a trend. Likelihood residual shows the fit of the model to each tow and should not indicate any patterns if the model has worked well.

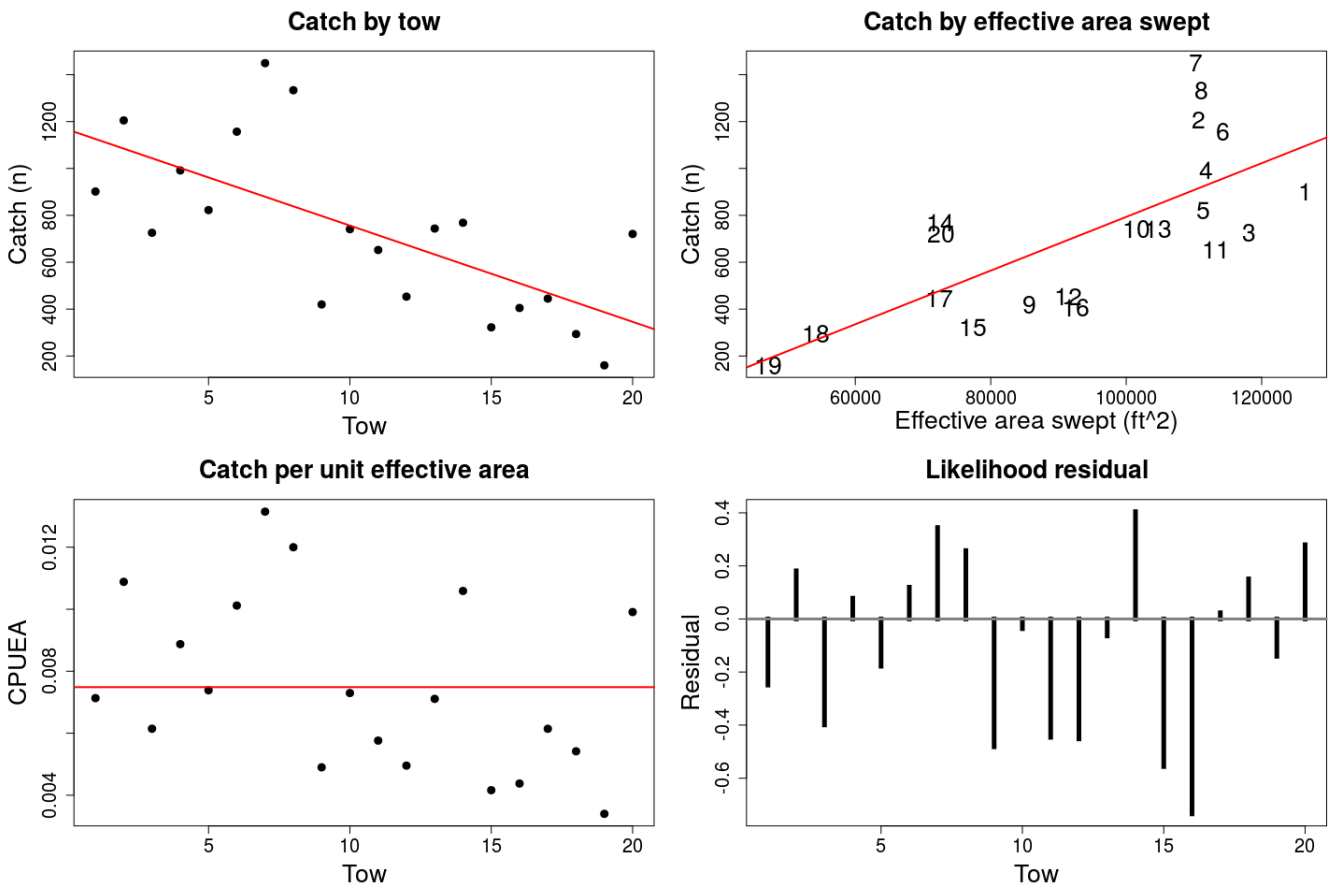

Figure 182: Diagnostic plots for ocean quahog depletion experiment OQ02-03. Catch by tow shows the catch recorded in each tow. This plot should show a declining trend over time. Catch vs. effective area swept shows the catch by the area swept by each tow, while accounting for the area in each tow that has already been fished. The numbers indicate the order of tows. This plot should show an increasing trend. CPUEA vs. tow shows the catch per unit of effective area by tow. This plot should not show a trend. Likelihood residual shows the fit of the model to each tow and should not indicate any patterns if the model has worked well.

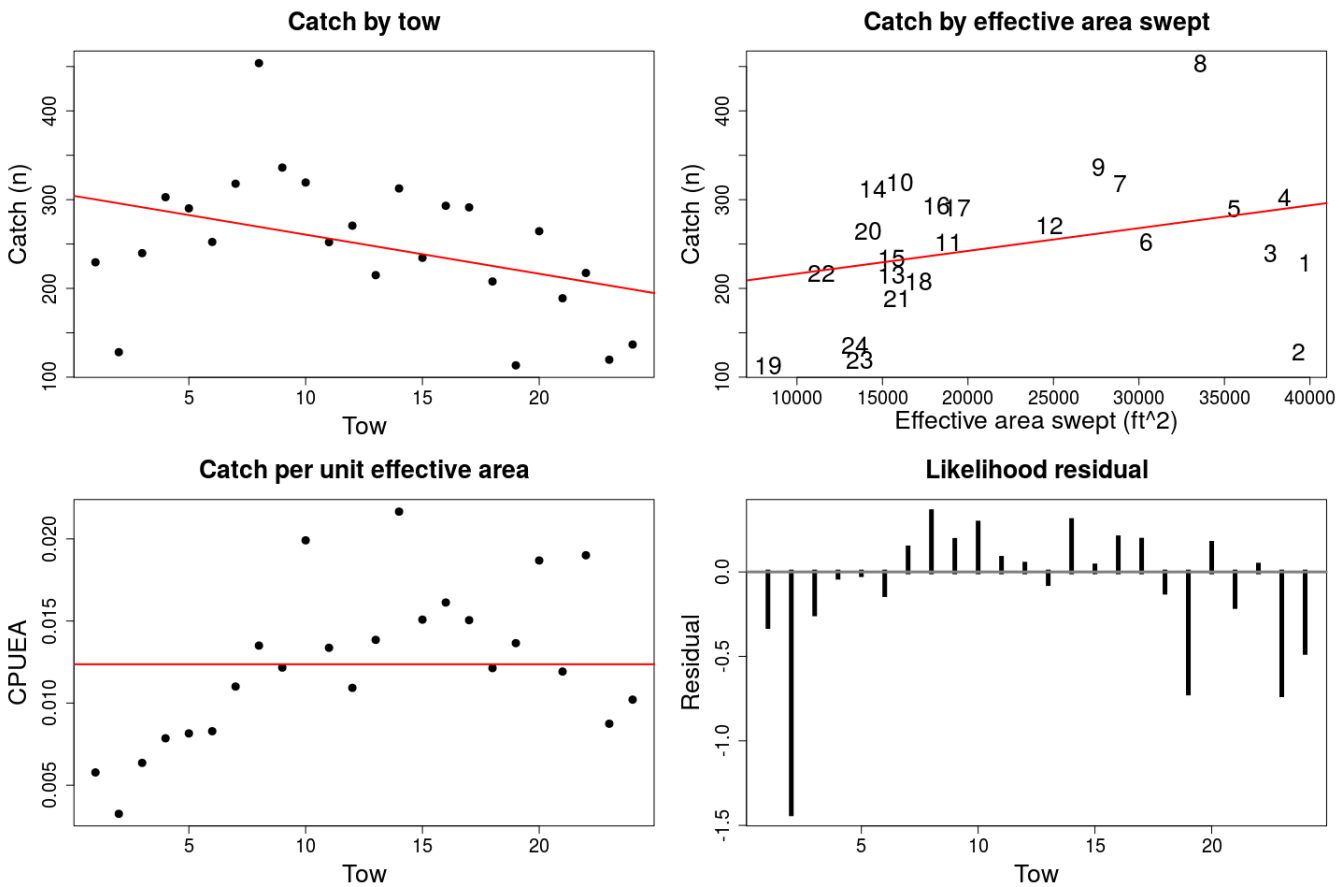

Figure 183: Diagnostic plots for ocean quahog depletion experiment OQ02-04. Catch by tow shows the catch recorded in each tow. This plot should show a declining trend over time. Catch vs. effective area swept shows the catch by the area swept by each tow, while accounting for the area in each tow that has already been fished. The numbers indicate the order of tows. This plot should show an increasing trend. CPUEA vs. tow shows the catch per unit of effective area by tow. This plot should not show a trend. Likelihood residual shows the fit of the model to each tow and should not indicate any patterns if the model has worked well.

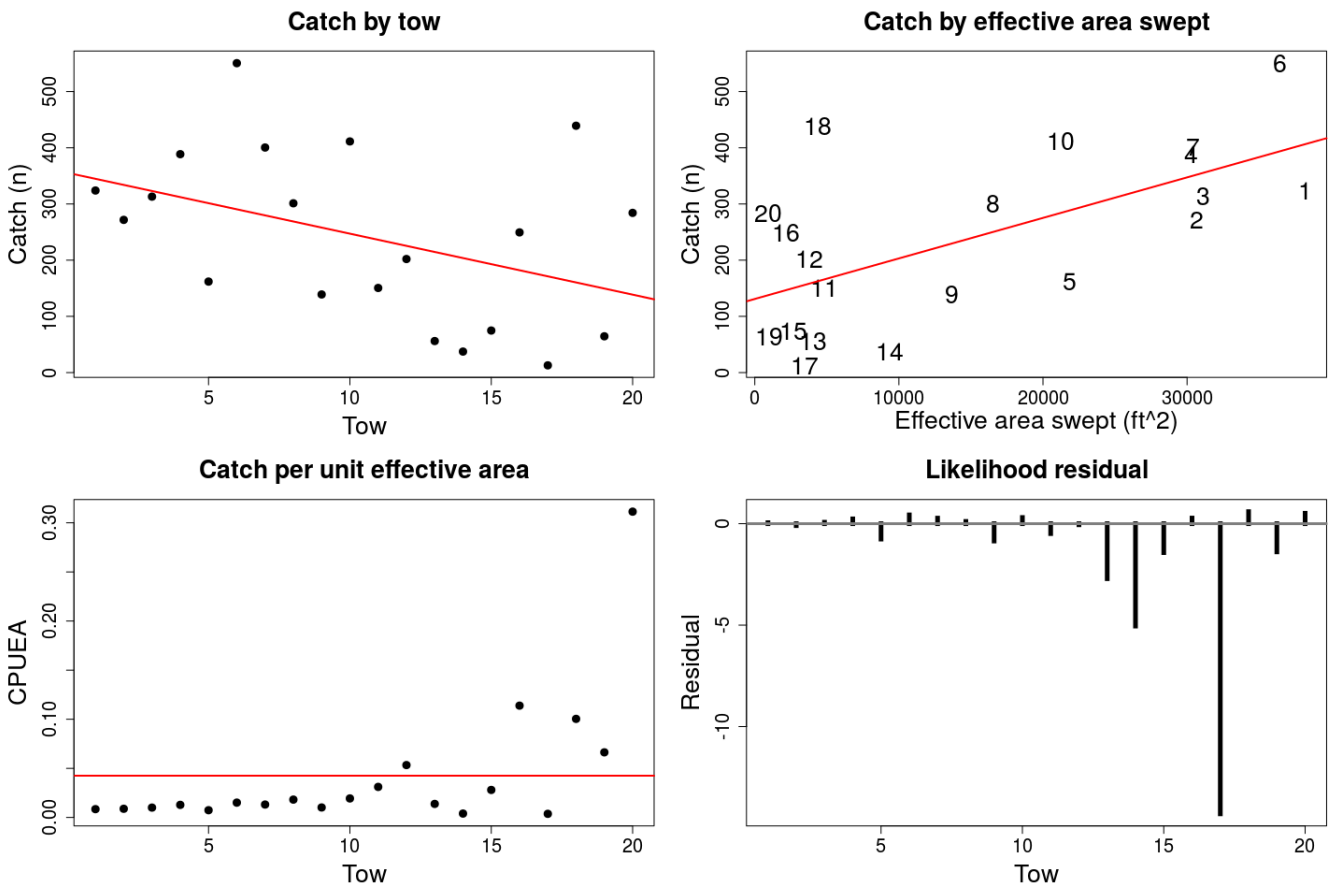

Figure 184: Diagnostic plots for ocean quahog depletion experiment OQ05-01. Catch by tow shows the catch recorded in each tow. This plot should show a declining trend over time. Catch vs. effective area swept shows the catch by the area swept by each tow, while accounting for the area in each tow that has already been fished. The numbers indicate the order of tows. This plot should show an increasing trend. CPUEA vs. tow shows the catch per unit of effective area by tow. This plot should not show a trend. Likelihood residual shows the fit of the model to each tow and should not indicate any patterns if the model has worked well.

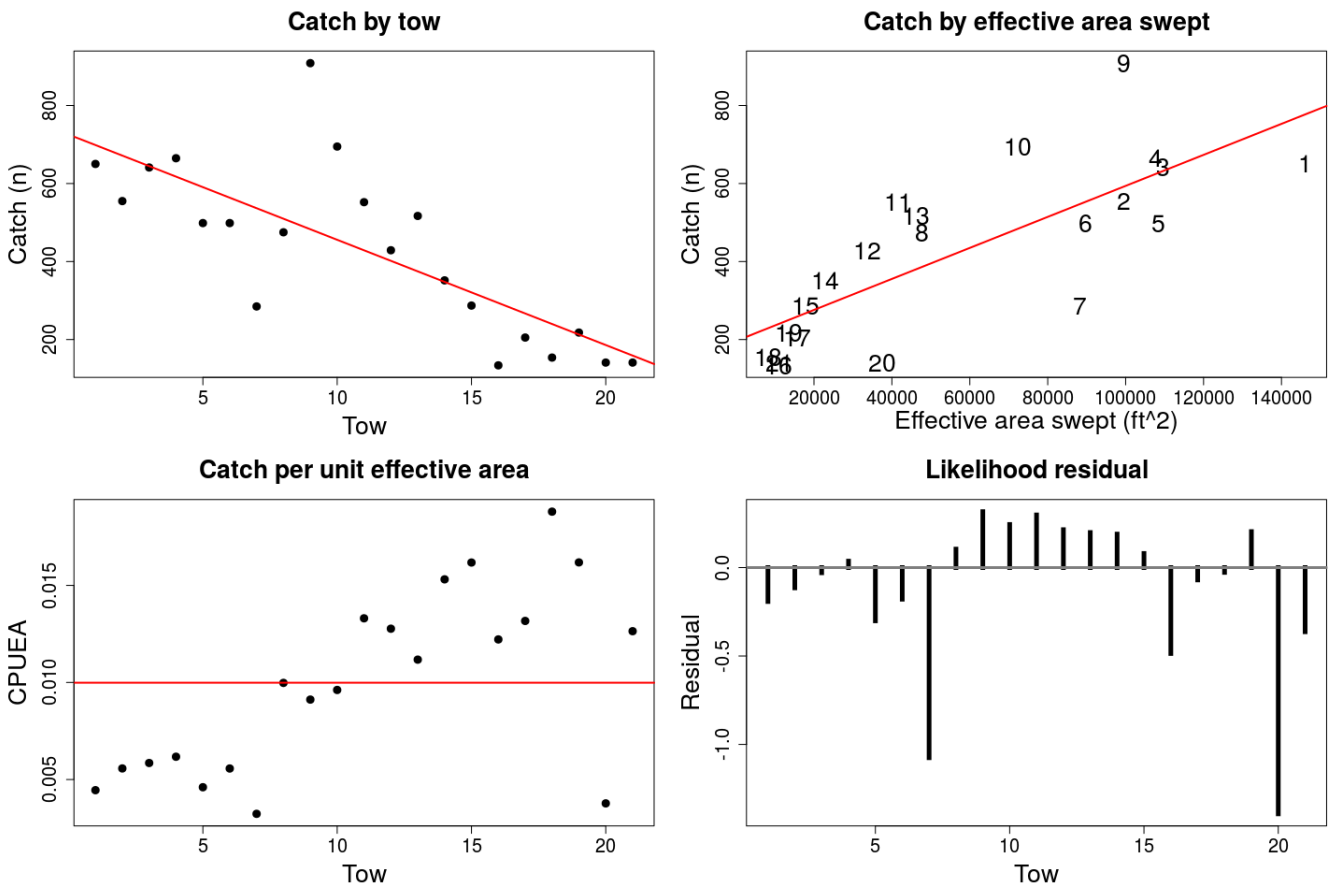

Figure 185: Diagnostic plots for ocean quahog depletion experiment OQ05-02. Catch by tow shows the catch recorded in each tow. This plot should show a declining trend over time. Catch vs. effective area swept shows the catch by the area swept by each tow, while accounting for the area in each tow that has already been fished. The numbers indicate the order of tows. This plot should show an increasing trend. CPUEA vs. tow shows the catch per unit of effective area by tow. This plot should not show a trend. Likelihood residual shows the fit of the model to each tow and should not indicate any patterns if the model has worked well.

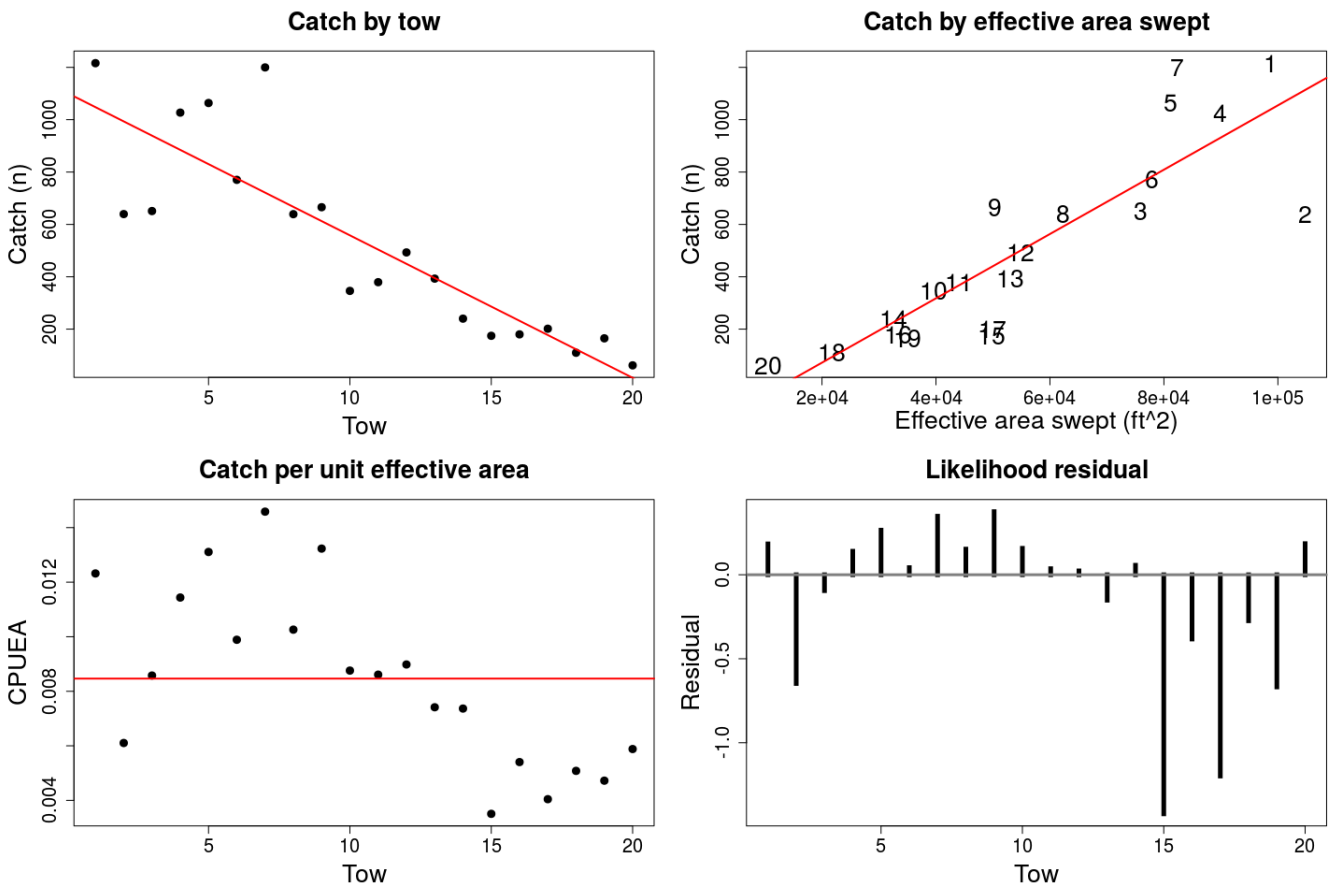

Figure 186: Diagnostic plots for ocean quahog depletion experiment OQ05-03. Catch by tow shows the catch recorded in each tow. This plot should show a declining trend over time. Catch vs. effective area swept shows the catch by the area swept by each tow, while accounting for the area in each tow that has already been fished. The numbers indicate the order of tows. This plot should show an increasing trend. CPUEA vs. tow shows the catch per unit of effective area by tow. This plot should not show a trend. Likelihood residual shows the fit of the model to each tow and should not indicate any patterns if the model has worked well.

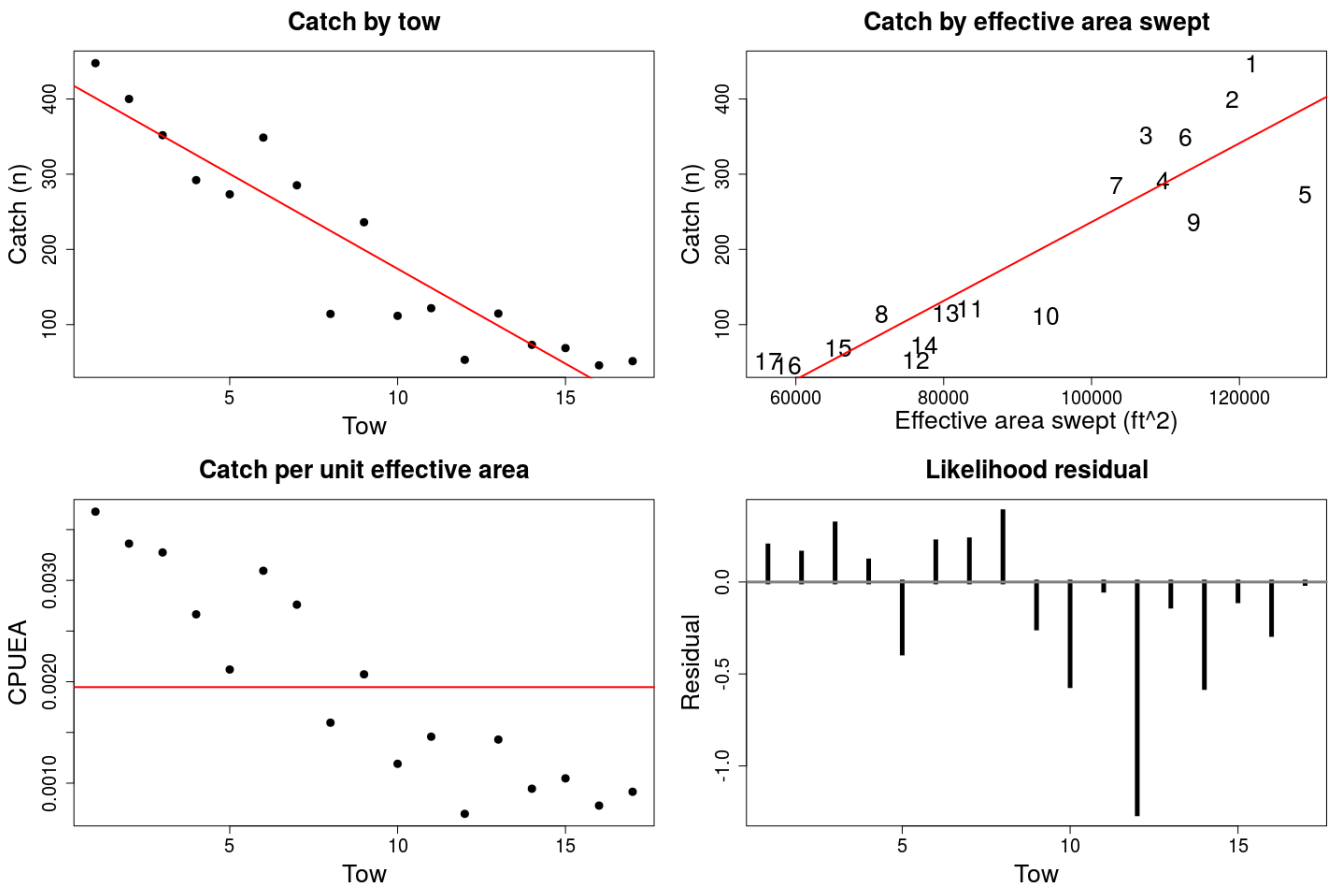

Figure 187: Diagnostic plots for ocean quahog depletion experiment OQ05-04. Catch by tow shows the catch recorded in each tow. This plot should show a declining trend over time. Catch vs. effective area swept shows the catch by the area swept by each tow, while accounting for the area in each tow that has already been fished. The numbers indicate the order of tows. This plot should show an increasing trend. CPUEA vs. tow shows the catch per unit of effective area by tow. This plot should not show a trend. Likelihood residual shows the fit of the model to each tow and should not indicate any patterns if the model has worked well.

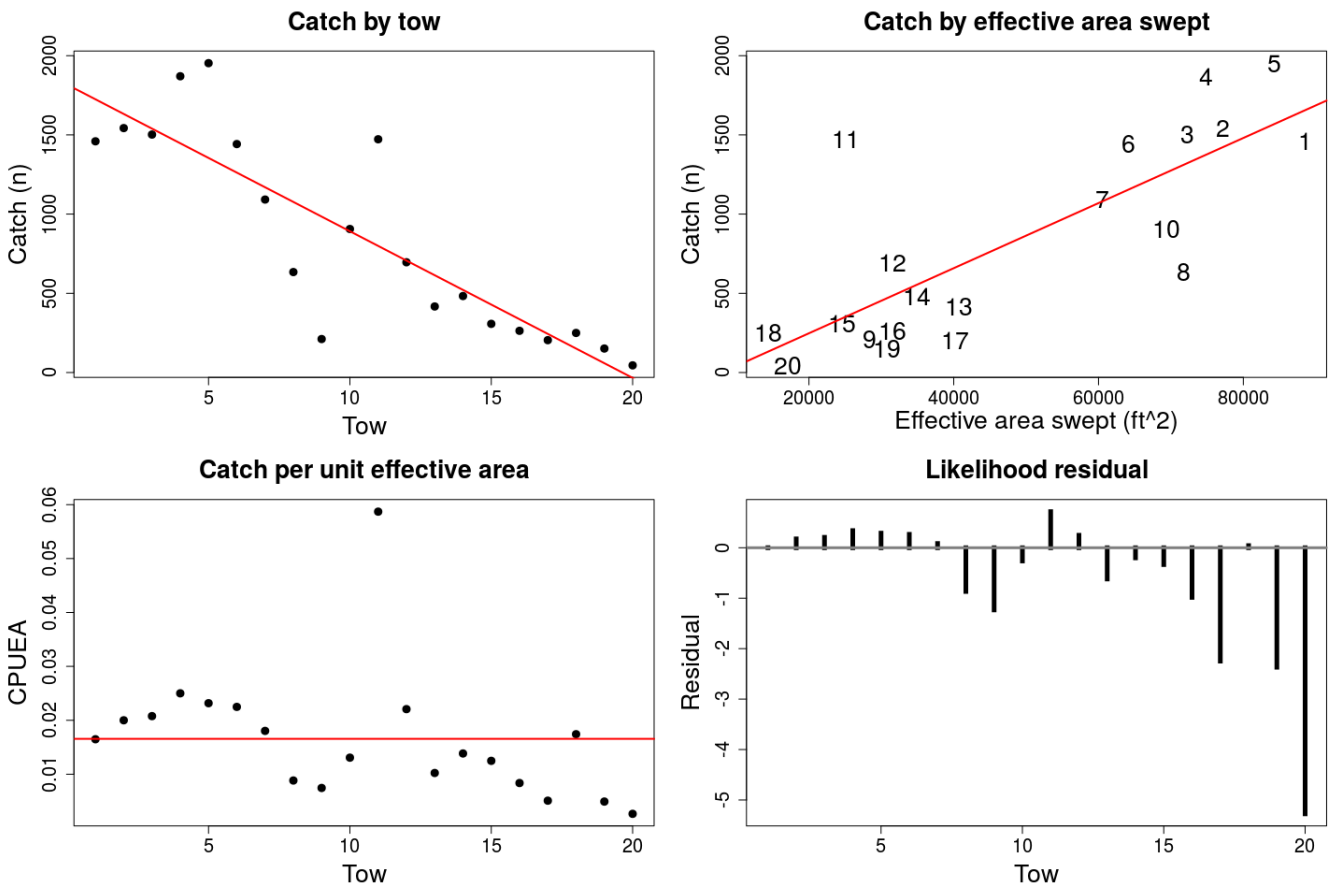

Figure 188: Diagnostic plots for ocean quahog depletion experiment OQ05-06. Catch by tow shows the catch recorded in each tow. This plot should show a declining trend over time. Catch vs. effective area swept shows the catch by the area swept by each tow, while accounting for the area in each tow that has already been fished. The numbers indicate the order of tows. This plot should show an increasing trend. CPUEA vs. tow shows the catch per unit of effective area by tow. This plot should not show a trend. Likelihood residual shows the fit of the model to each tow and should not indicate any patterns if the model has worked well.

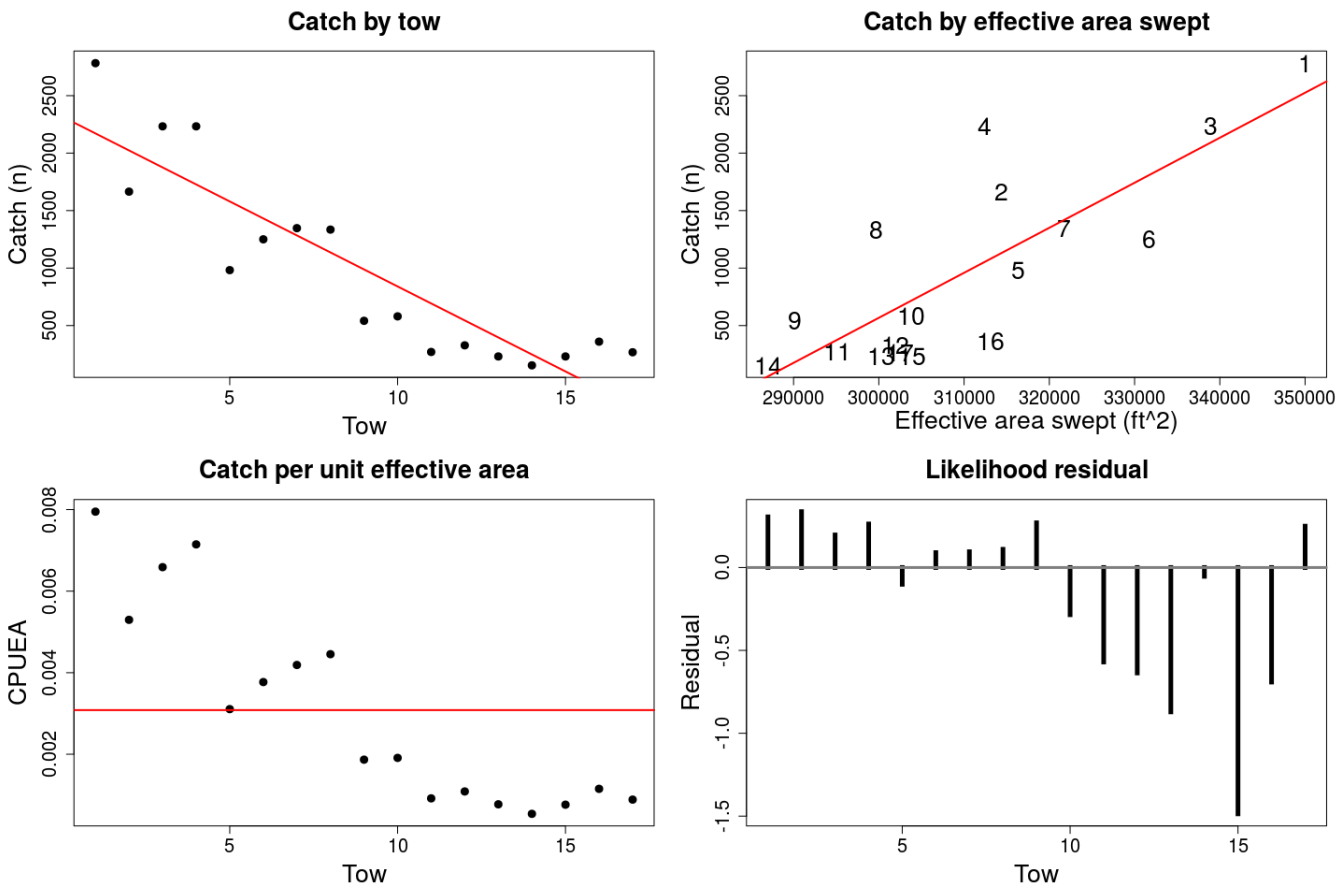

Figure 189: Diagnostic plots for ocean quahog depletion experiment OQ08-01. Catch by tow shows the catch recorded in each tow. This plot should show a declining trend over time. Catch vs. effective area swept shows the catch by the area swept by each tow, while accounting for the area in each tow that has already been fished. The numbers indicate the order of tows. This plot should show an increasing trend. CPUEA vs. tow shows the catch per unit of effective area by tow. This plot should not show a trend. Likelihood residual shows the fit of the model to each tow and should not indicate any patterns if the model has worked well.

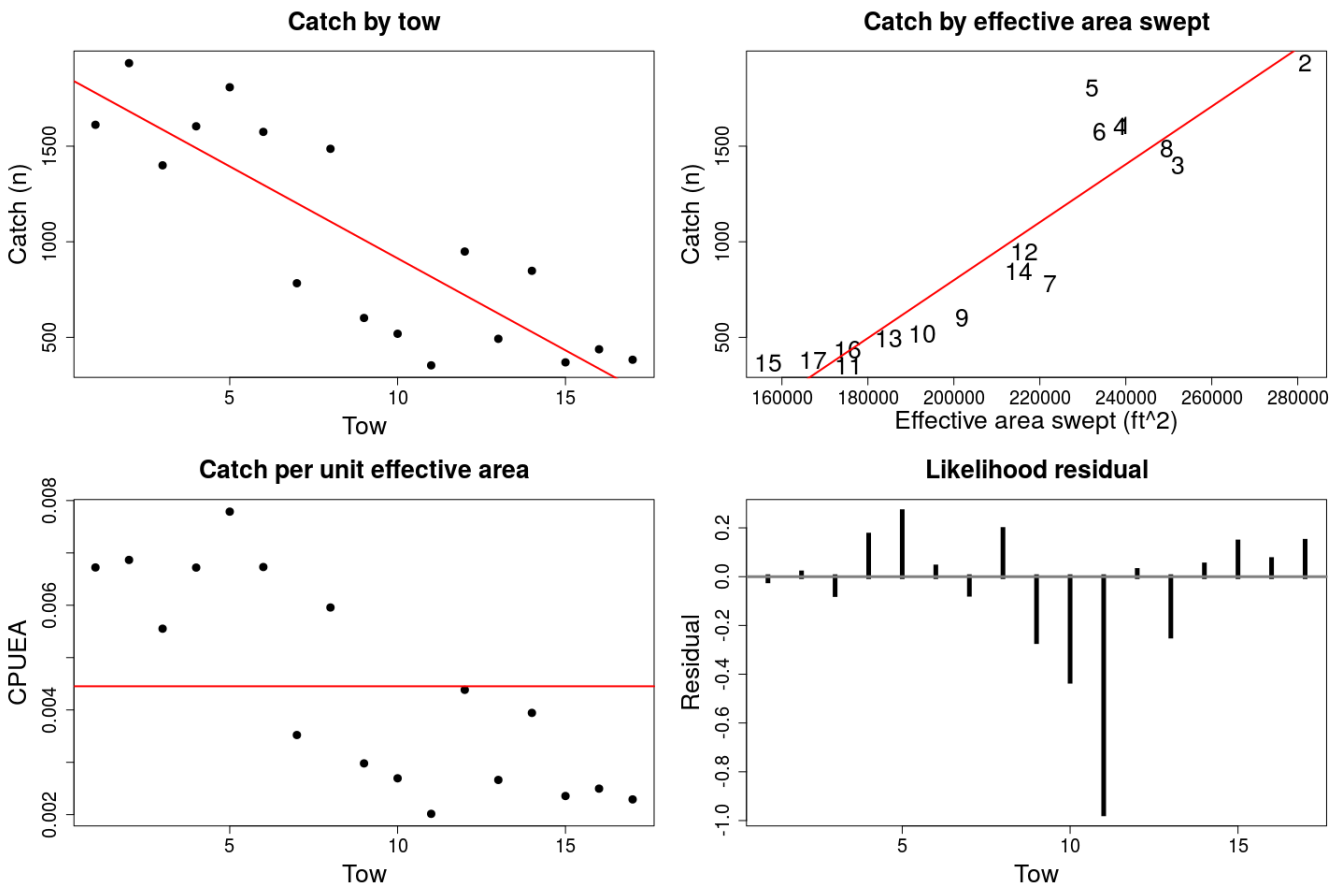

Figure 190: Diagnostic plots for ocean quahog depletion experiment OQ08-02. Catch by tow shows the catch recorded in each tow. This plot should show a declining trend over time. Catch vs. effective area swept shows the catch by the area swept by each tow, while accounting for the area in each tow that has already been fished. The numbers indicate the order of tows. This plot should show an increasing trend. CPUEA vs. tow shows the catch per unit of effective area by tow. This plot should not show a trend. Likelihood residual shows the fit of the model to each tow and should not indicate any patterns if the model has worked well.

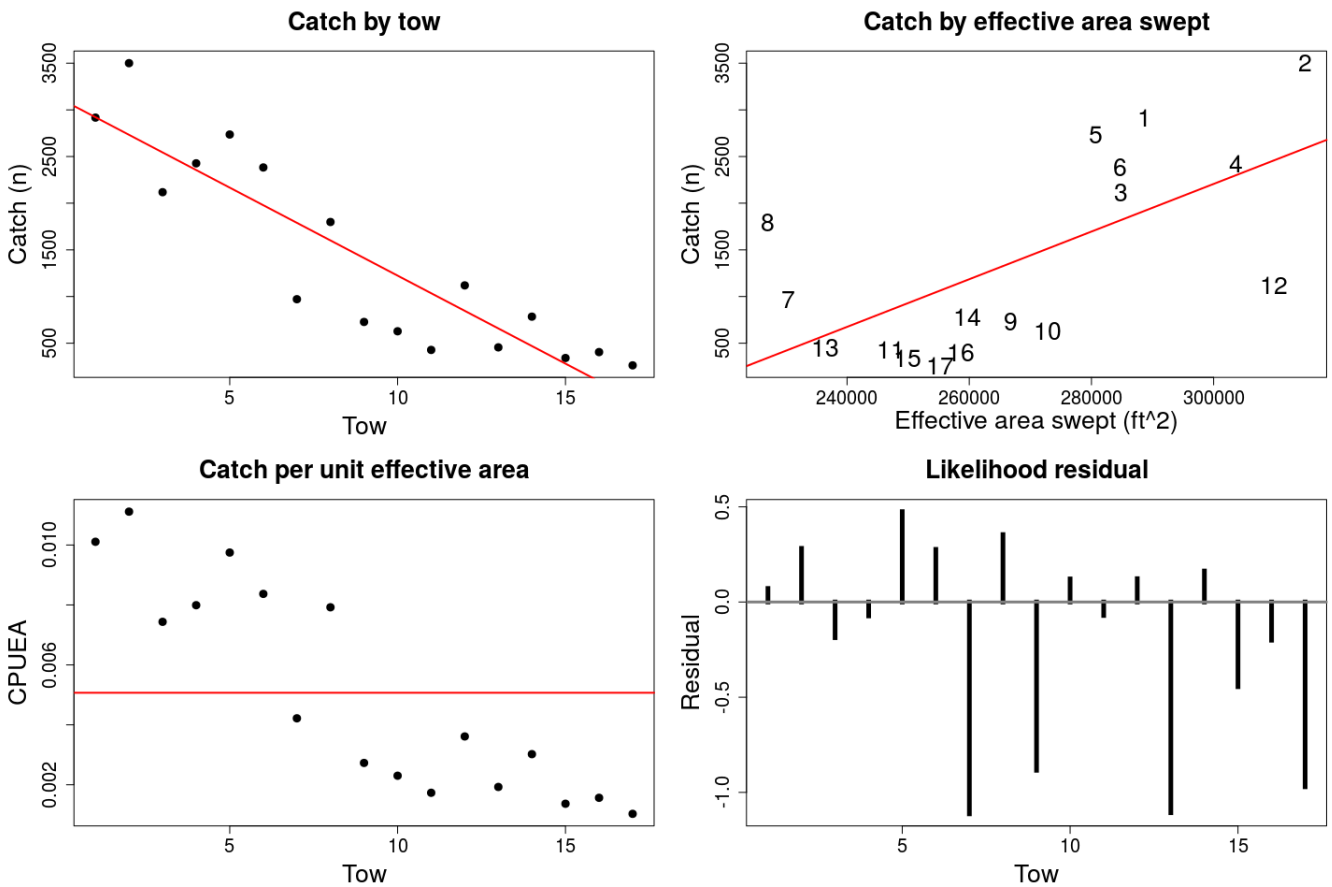

Figure 191: Diagnostic plots for ocean quahog depletion experiment OQ08-03. Catch by tow shows the catch recorded in each tow. This plot should show a declining trend over time. Catch vs. effective area swept shows the catch by the area swept by each tow, while accounting for the area in each tow that has already been fished. The numbers indicate the order of tows. This plot should show an increasing trend. CPUEA vs. tow shows the catch per unit of effective area by tow. This plot should not show a trend. Likelihood residual shows the fit of the model to each tow and should not indicate any patterns if the model has worked well.

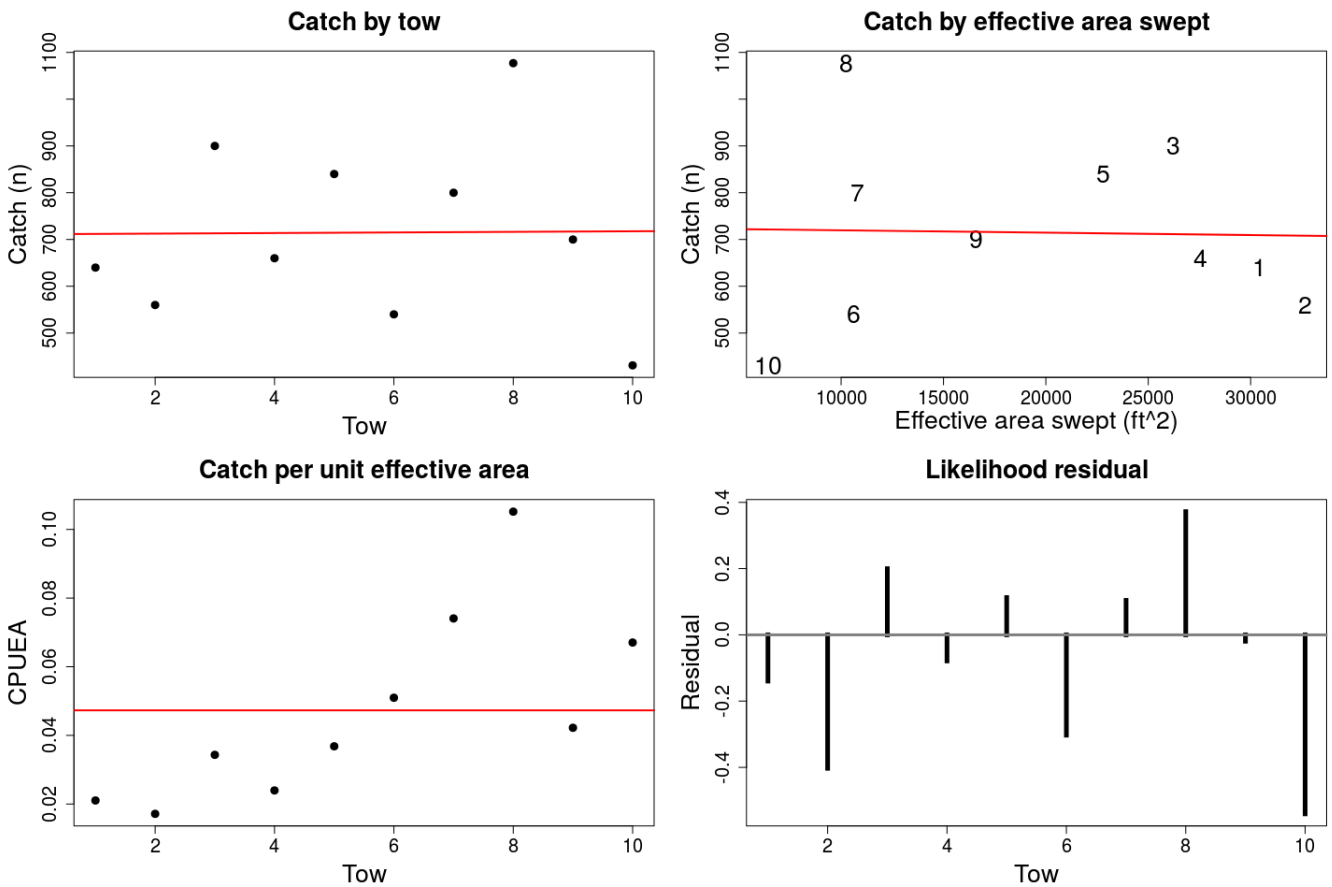

Figure 192: Diagnostic plots for ocean quahog depletion experiment OQ11-01. Catch by tow shows the catch recorded in each tow. This plot should show a declining trend over time. Catch vs. effective area swept shows the catch by the area swept by each tow, while accounting for the area in each tow that has already been fished. The numbers indicate the order of tows. This plot should show an increasing trend. CPUEA vs. tow shows the catch per unit of effective area by tow. This plot should not show a trend. Likelihood residual shows the fit of the model to each tow and should not indicate any patterns if the model has worked well.

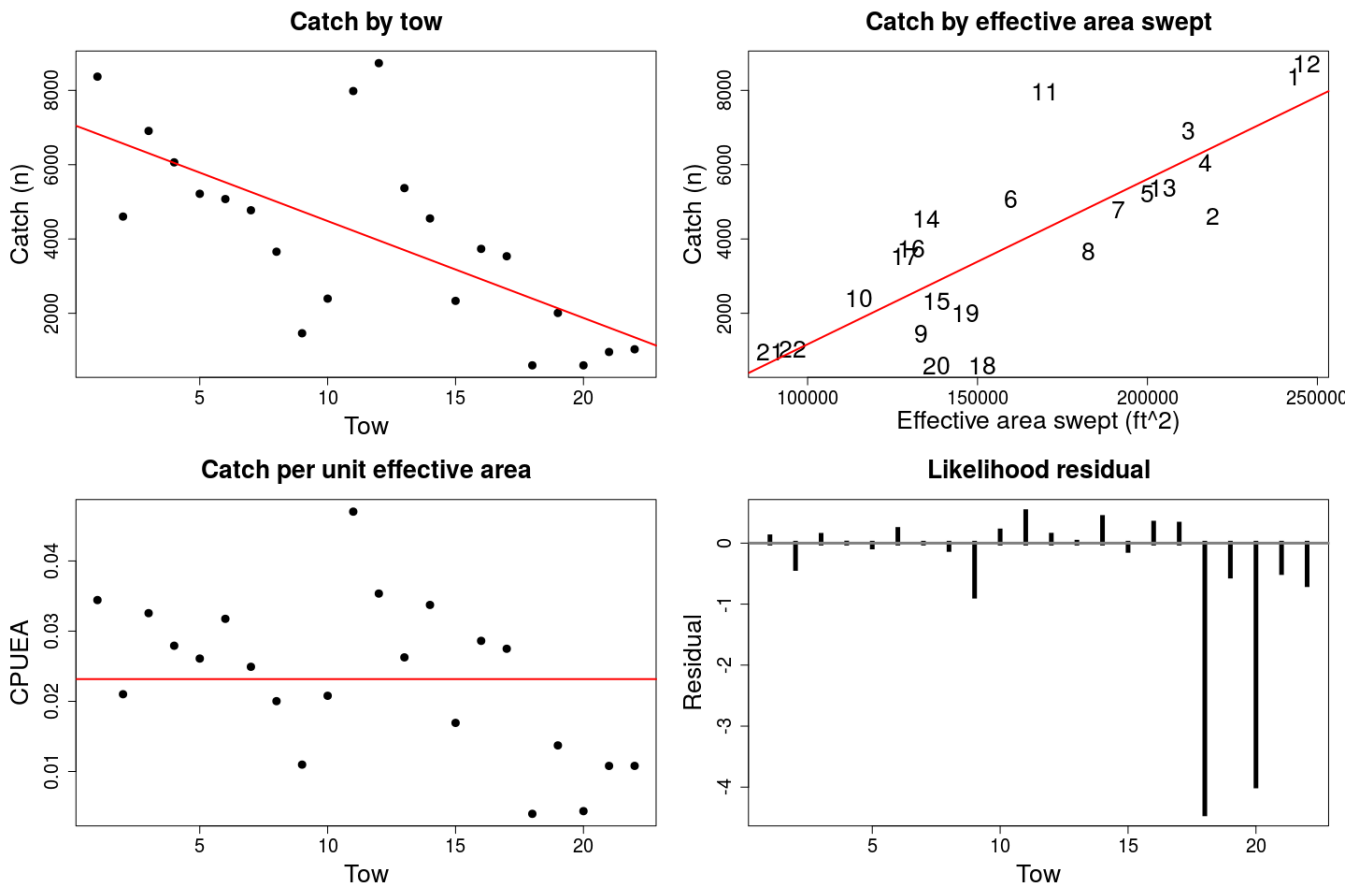

Figure 193: Diagnostic plots for ocean quahog depletion experiment OQ11-05. Catch by tow shows the catch recorded in each tow. This plot should show a declining trend over time. Catch vs. effective area swept shows the catch by the area swept by each tow, while accounting for the area in each tow that has already been fished. The numbers indicate the order of tows. This plot should show an increasing trend. CPUEA vs. tow shows the catch per unit of effective area by tow. This plot should not show a trend. Likelihood residual shows the fit of the model to each tow and should not indicate any patterns if the model has worked well.

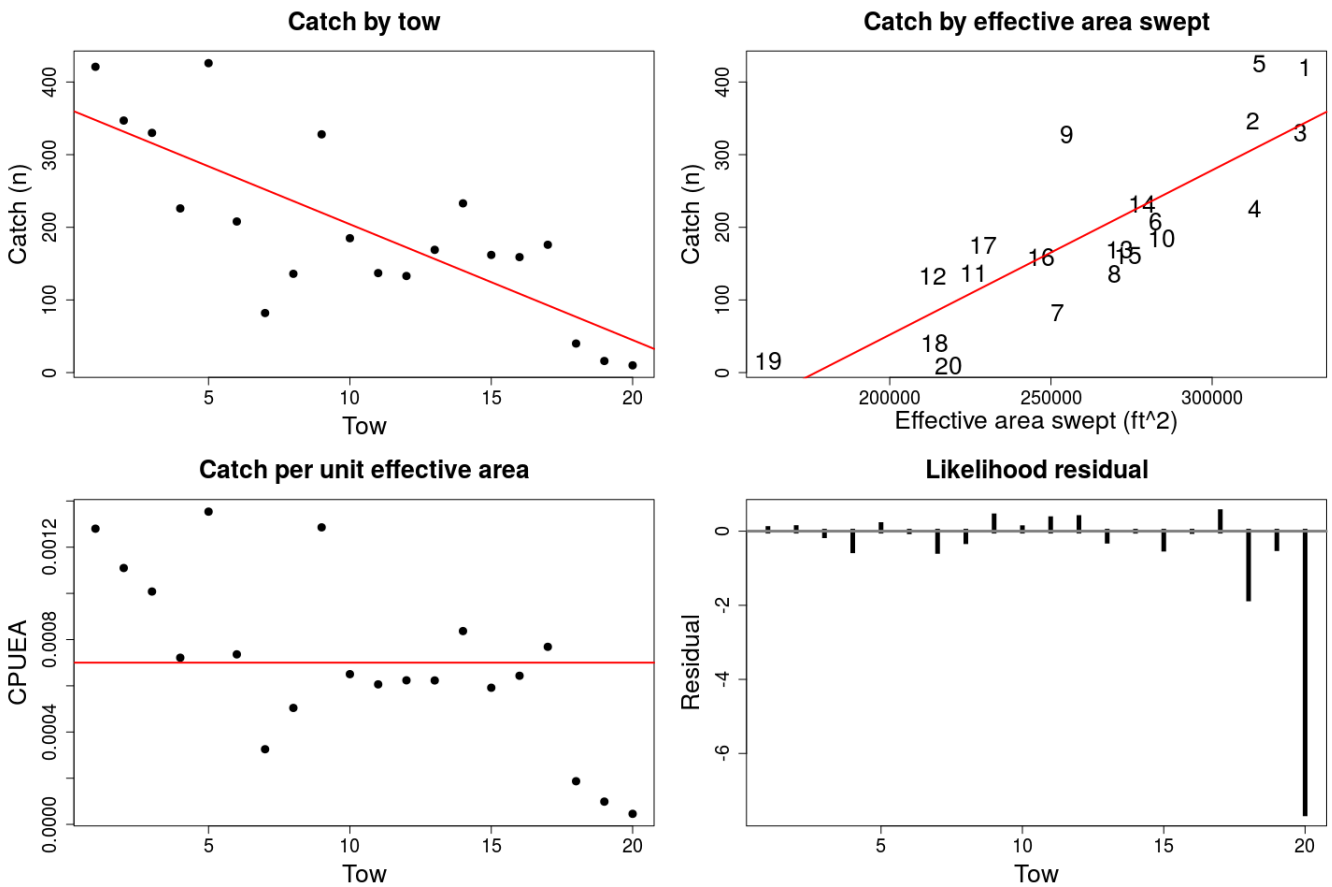

Figure 194: Diagnostic plots for ocean quahog depletion experiment OQSC11-02. Catch by tow shows the catch recorded in each tow. This plot should show a declining trend over time. Catch vs. effective area swept shows the catch by the area swept by each tow, while accounting for the area in each tow that has already been fished. The numbers indicate the order of tows. This plot should show an increasing trend. CPUEA vs. tow shows the catch per unit of effective area by tow. This plot should not show a trend. Likelihood residual shows the fit of the model to each tow and should not indicate any patterns if the model has worked well.

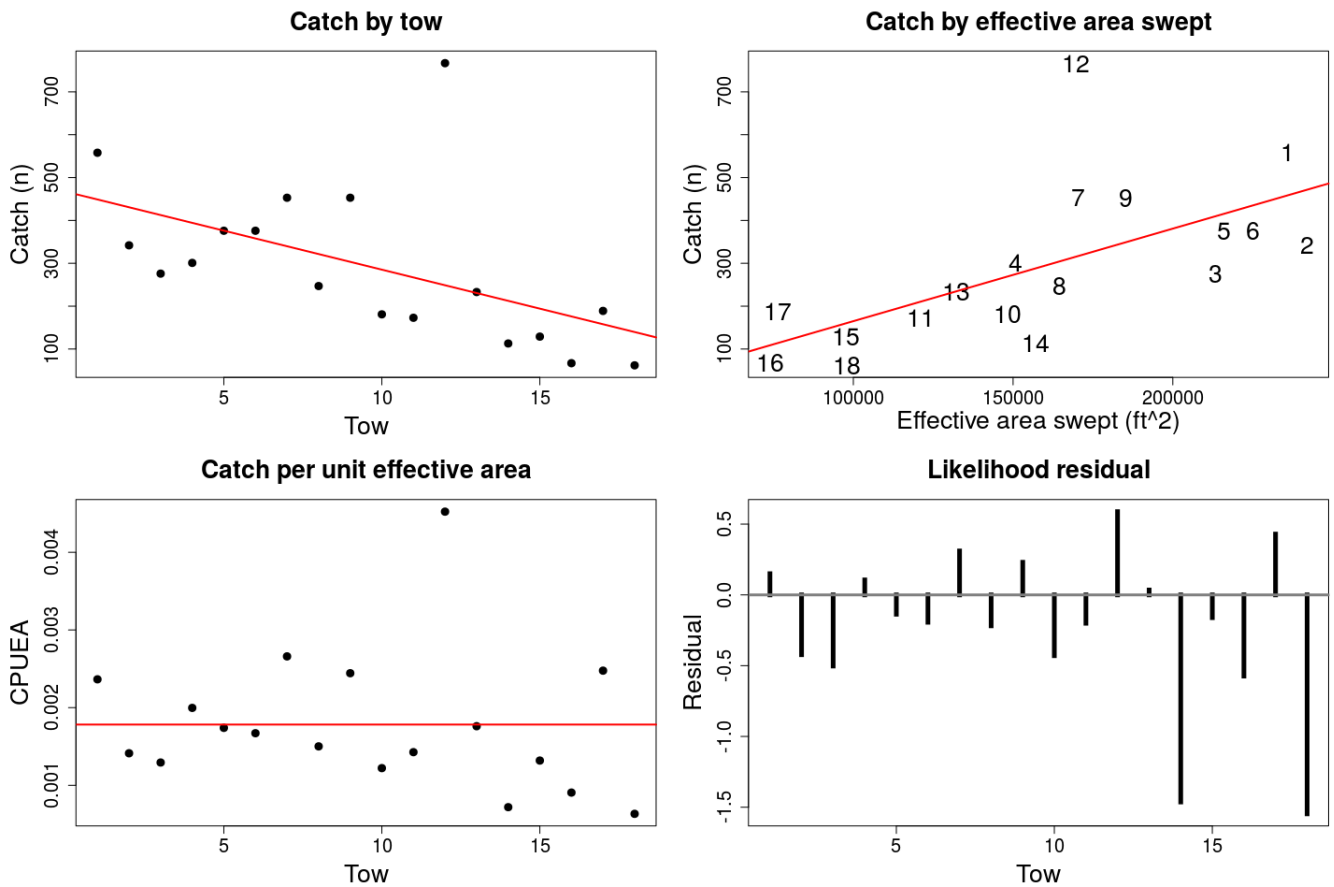

Figure 195: Diagnostic plots for ocean quahog depletion experiment OQSC11-02S. Catch by tow shows the catch recorded in each tow. This plot should show a declining trend over time. Catch vs. effective area swept shows the catch by the area swept by each tow, while accounting for the area in each tow that has already been fished. The numbers indicate the order of tows. This plot should show an increasing trend. CPUEA vs. tow shows the catch per unit of effective area by tow. This plot should not show a trend. Likelihood residual shows the fit of the model to each tow and should not indicate any patterns if the model has worked well.

Appendix 4 Prior distributions for survey catchability

Depletion experiments formed the basis for developing prior distributions for catchability in surveys. The Patch model (Rago et al. 2006; Hennen et al. 2012) estimates capture efficiency for a standard industry dredge similar to the MCD. The estimates of capture efficiencies that were judged to be well estimated (estimated efficiency < 1.0 and cv < 2.0; Figure 196) were combined to form a sample of capture efficiencies from which the prior distribution for survey catchability was generated. To smooth the distributions and weight estimates properly, the sample of capture efficiencies was resampled using a weighted bootstrap procedure, in which the weights were proportional to the inverse of the cv of each estimate (Figure 197). A beta distribution was fit to the resampled efficiency estimates and the mean and cv from this fit were used as the mean and cv for the prior distribution of capture efficiency in the assessment ($e_{MCD} = 0.608$, $cv_{MCD} = 0.262$; Figure 197).

Previous assessments (Northeast Fisheries Science Center 2009) used an estimator for RV survey dredge capture efficiency that was based on the ratio of observed density in the "set up tows" and the density estimate derived from depletion experiments conducted at the same site. Set up tows were conducted aboard the *RV Delaware II* using the survey dredge described above. They were 1-5 parallel tows evenly spaced over 1 km at the sites selected for depletion experiments. The set up tows were oriented perpendicularly to the expected direction of depletion tows in recent years. The estimator was:

$$e = \frac{d}{D} \tag{4}$$

where e is estimated survey efficiency, d is the observed density in set up tows and D is the estimated depletion experiment density. The implicit assumption of this analysis is that d and D reflect densities on the same ground and that the estimates of d and D are unbiased.

The estimates of capture efficiency from eq. 4 were subjected to the same resampling procedure as the estimates of capture efficiency for the MCD. Seventeen of the 19 depletion experiments resulted in useable RV efficiency estimates (Figure 198). The weighted frequency distribution of RV efficiencies was lower than that of MCD efficiency estimates (Figure 199) and the beta fit to that sample produced a lower mean and cv ($e_{RV} = 0.194\, cv_{RV} = 0.546$; Figure 199).

Figures

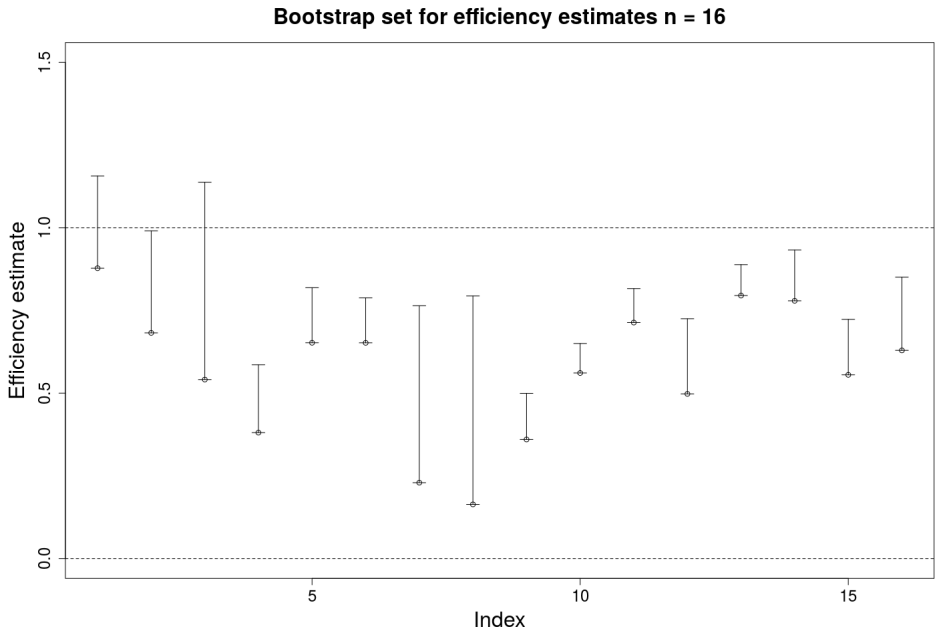

Figure 196: Efficiency estimates for each of the MCD depletion experiments for ocean quahog that resulted in estimated capture efficiencies < 1.0 and cv < 2.0. The cv associated with each estimate is shown as a vertical error bar, where the distance from the point estimate is the cv.

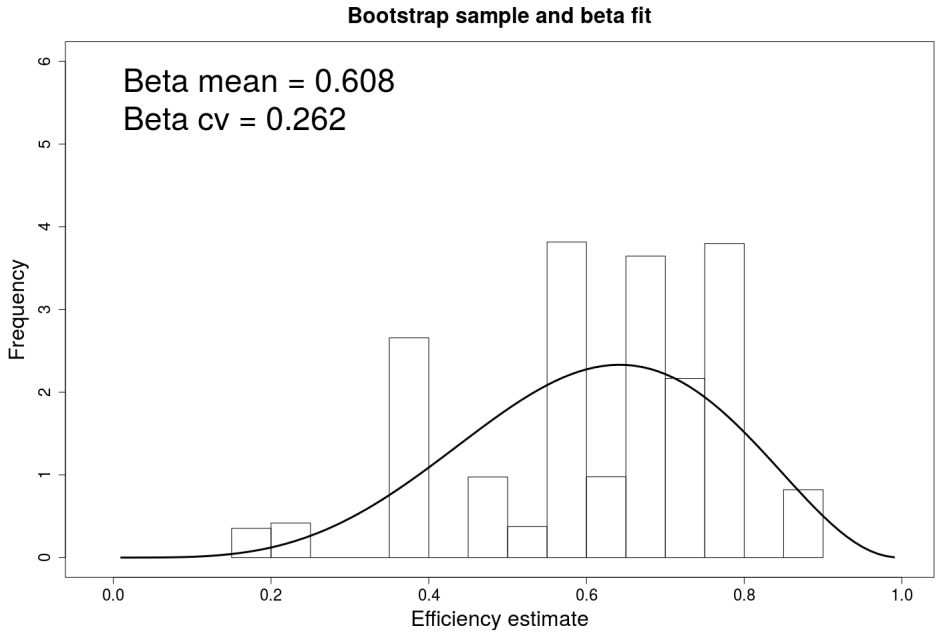

Figure 197: A beta distribution fit to the bootstrap sample of efficiency estimates for the MCD. The bootstrap sample was composed of those patch model estimates for ocean quahog that resulted in capture efficiencies < 1.0 and cv < 2.0. The weights for the bootstrap procedure were proportional to the inverse of the cv of each efficiency estimate.

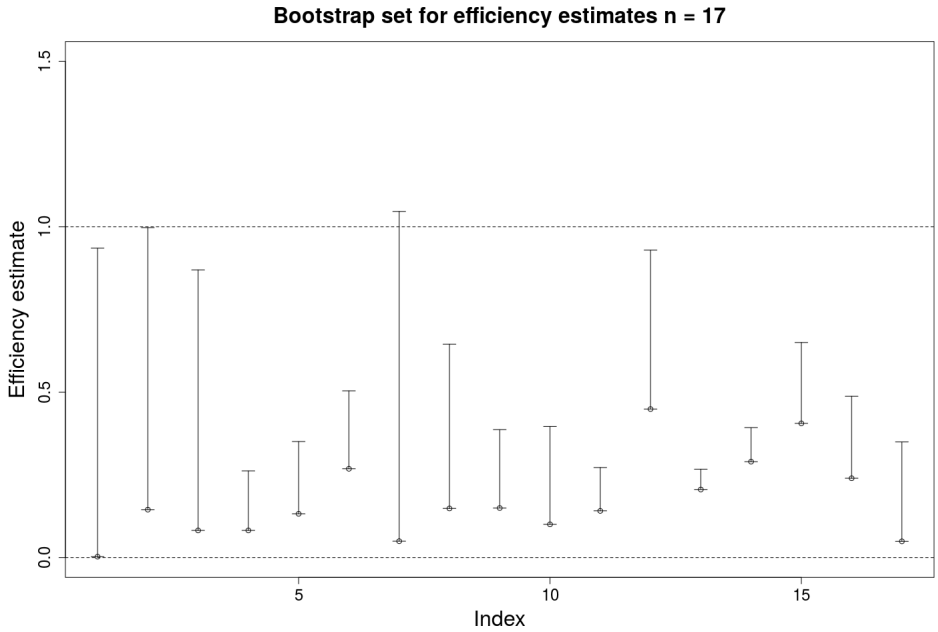

Figure 198: Efficiency estimates for each of the RD depletion experiments for ocean quahog that resulted in estimated capture efficiencies < 1.0 and cv < 2.0. The cv associated with each estimate is shown as a vertical error bar, where the distance from the point estimate is the cv.

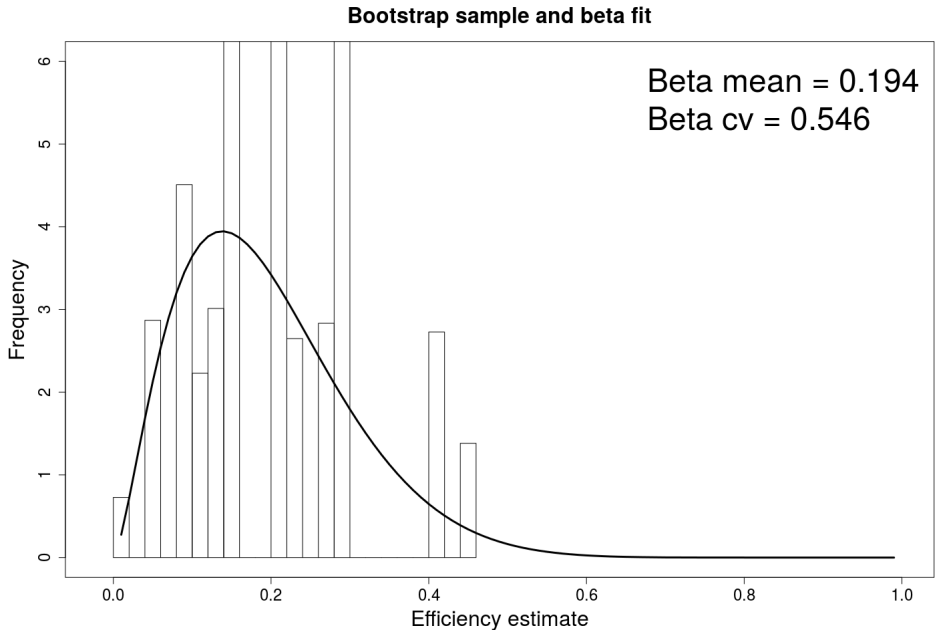

Figure 199: A beta distribution fit to the bootstrap sample of efficiency estimates for the RV. The bootstrap sample was composed of patch model estimates for ocean quahog that resulted in capture efficiencies < 1.0 and cv < 2.0. The weights for the bootstrap procedure were proportional to the inverse of the cv of each efficiency estimate.

Appendix 5 Depth and temperature changes

The distribution and biology of ocean quahog are potentially changing with potential effects on fishery productivity as ocean temperature changes. For example, increasing water temperature may result in changes to Atlantic surfclam growth (Munroe et al. 2016). Increasing water temperature may also be driving a shift in Atlantic surfclam distribution, to deeper water in the southern area (Weinberg et al. 2002). It is reasonable to assume that any responses to temperature would be strongest in the southern-most regions (SVA, DMV and NJ), and shallow habitat depth boundary, where ocean temperatures are warmest and probably nearest the warm water tolerance for ocean quahog.

Depth and temperature

Survey stations are distributed randomly relative to depth within a stratum and the same strata tend to be sampled over time within a region (Table 10). Therefore, if the depth distribution of ocean quahog were trending over time, the depth at which most of the animals were caught within a region might be expected to increase. Plots of the depth at which the median cumulative catch within each region occurs over time show this relationship in NJ (Figures 200 – 205). SVA does not have enough positive tows to draw conclusions. It should be noted that fishery behavior might contribute to these trends as well, as the shallower areas are preferred due to proximity to processors, if fishing is in relatively shallow water.

Temperature was recorded as part of the survey station data (beginning in 2002), and may be a useful indicator of habitat preference for ocean quahog. Plots of the temperature and depth recorded at each survey station over time, against the total number of ocean quahog caught are provided here (Figures 206 – 211). The results indicate that temperature and depth preferences vary by region, but appear to be relatively consistent over (recent) time. This may be indicative of local adaptation, or there may be other local factors, potentially correlated with temperature and depth, that influence habitat preference in each region.

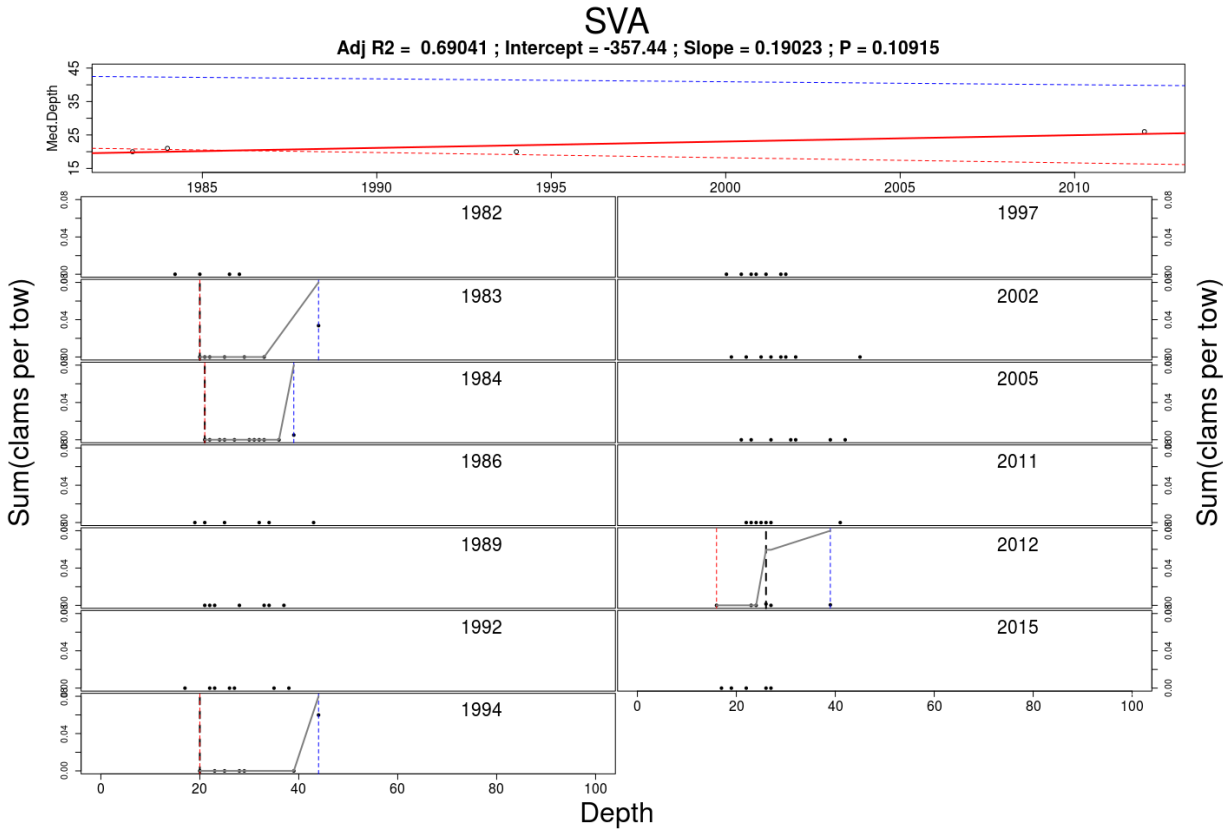

Figure 200: Total ocean quahog caught at depth by year in SVA. The points are clams caught aggregated by depth and the gray line is the cummulative sum of clams caught at depth. The dashed vertical line is the depth at which half of the cummulative total clams caught in that survey were taken. If the dashed vertical line is further to the right it indicates that more clams were caught in deeper water in that year. The top panel is a simple linear regression of median depth (the dashed vertical lines in each annual plot) over time. A positive slope indicates that a higher proportion of the total clams in a region were caught in deeper water in recent years. Inshore (shallow) strata were not well sampled in recent years and were excluded from this analysis.

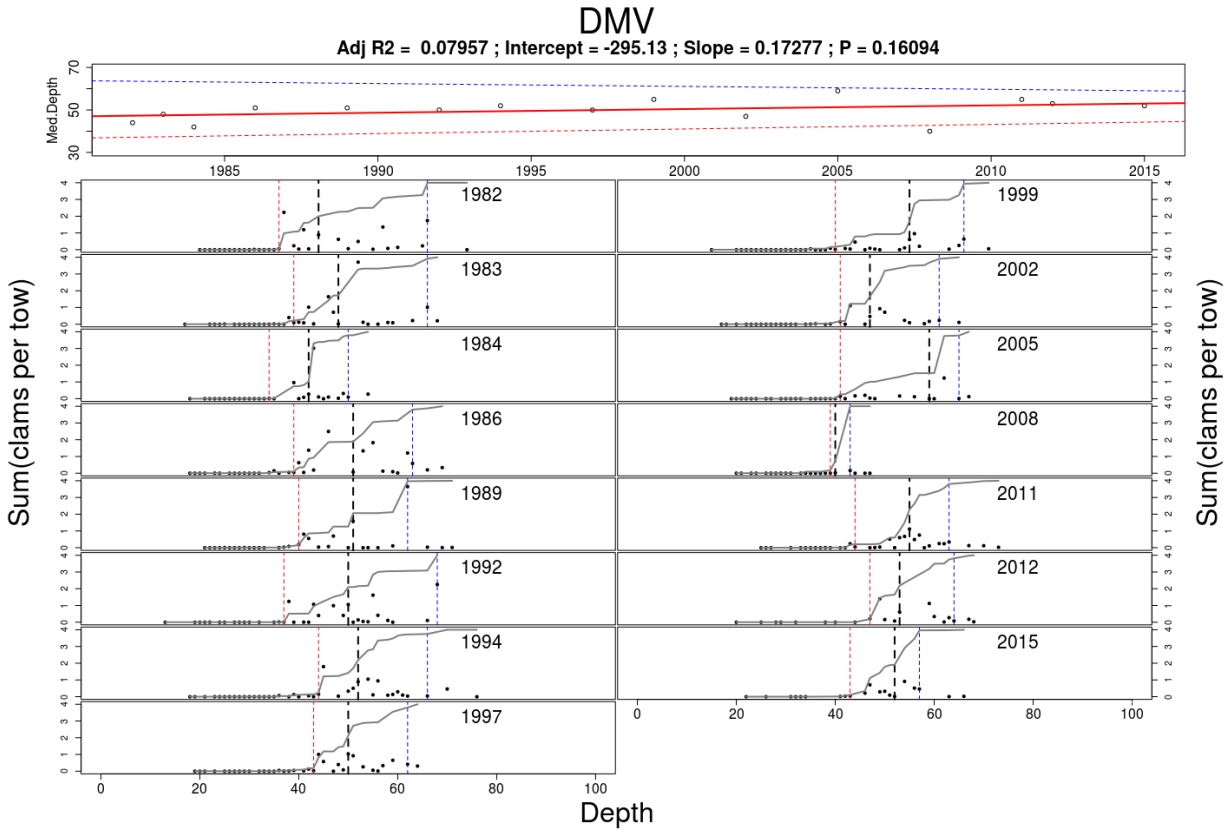

Figure 201: Total ocean quahog caught at depth by year in DMV. The points are clams caught aggregated by depth and the gray line is the cummulative sum of clams caught at depth. The dashed vertical line is the depth at which half of the cummulative total clams caught in that survey were taken. If the dashed vertical line is further to the right it indicates that more clams were caught in deeper water in that year. The top panel is a simple linear regression of median depth (the dashed vertical lines in each annual plot) over time. A positive slope indicates that a higher proportion of the total clams in a region were caught in deeper water in recent years. Inshore (shallow) strata were not well sampled in recent years and were excluded from this analysis.

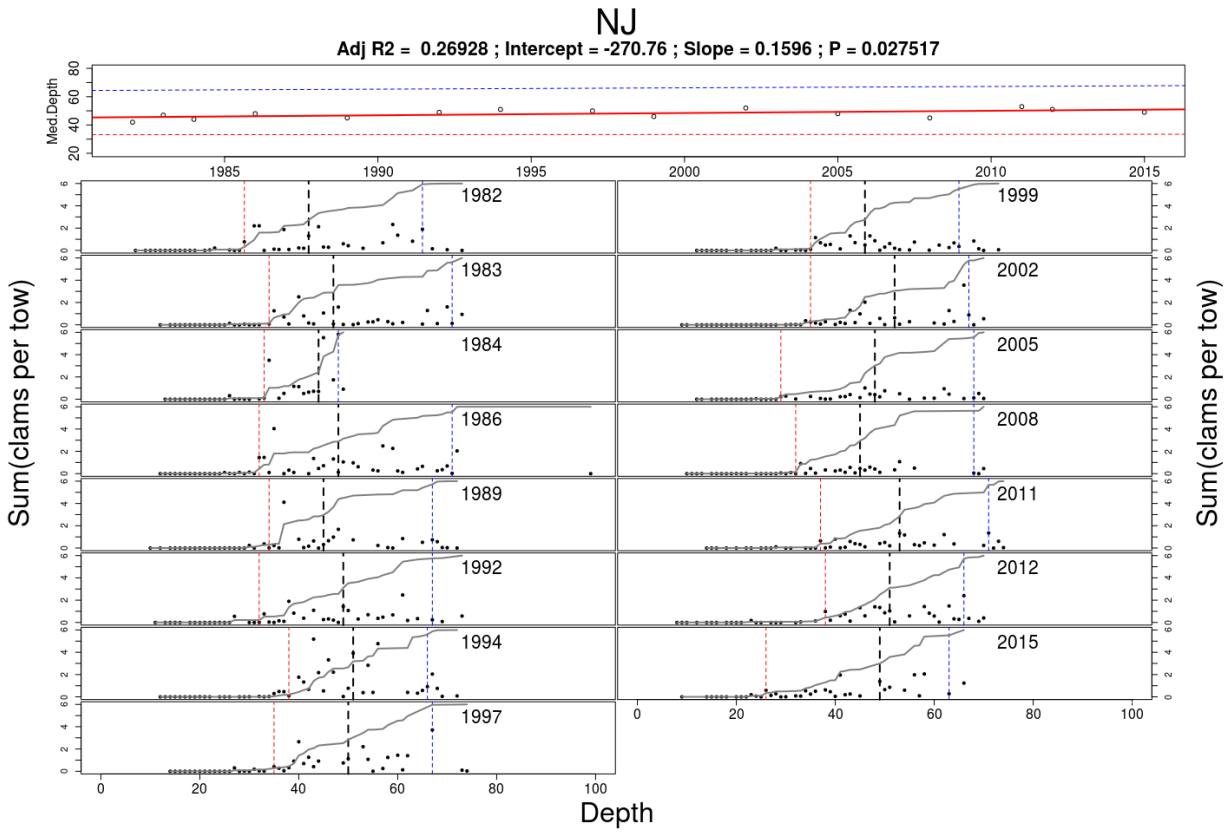

Figure 202: Total ocean quahog caught at depth by year in NJ. The points are clams caught aggregated by depth and the gray line is the cummulative sum of clams caught at depth. The dashed vertical line is the depth at which half of the cummulative total clams caught in that survey were taken. If the dashed vertical line is further to the right it indicates that more clams were caught in deeper water in that year. The top panel is a simple linear regression of median depth (the dashed vertical lines in each annual plot) over time. A positive slope indicates that a higher proportion of the total clams in a region were caught in deeper water in recent years.

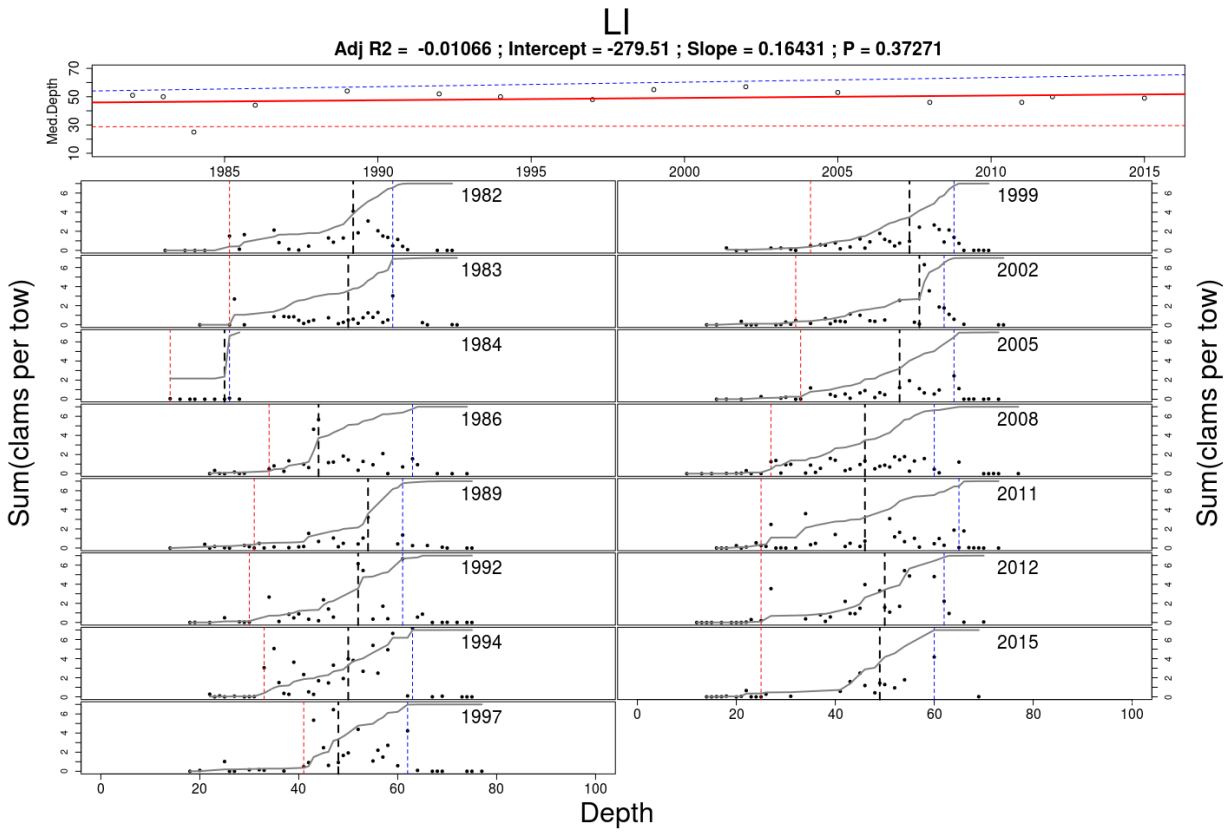

Figure 203: Total ocean quahog caught at depth by year in LI. The points are clams caught aggregated by depth and the gray line is the cummulative sum of clams caught at depth. The dashed vertical line is the depth at which half of the cummulative total clams caught in that survey were taken. If the dashed vertical line is further to the right it indicates that more clams were caught in deeper water in that year. The top panel is a simple linear regression of median depth (the dashed vertical lines in each annual plot) over time. A positive slope indicates that a higher proportion of the total clams in a region were caught in deeper water in recent years.

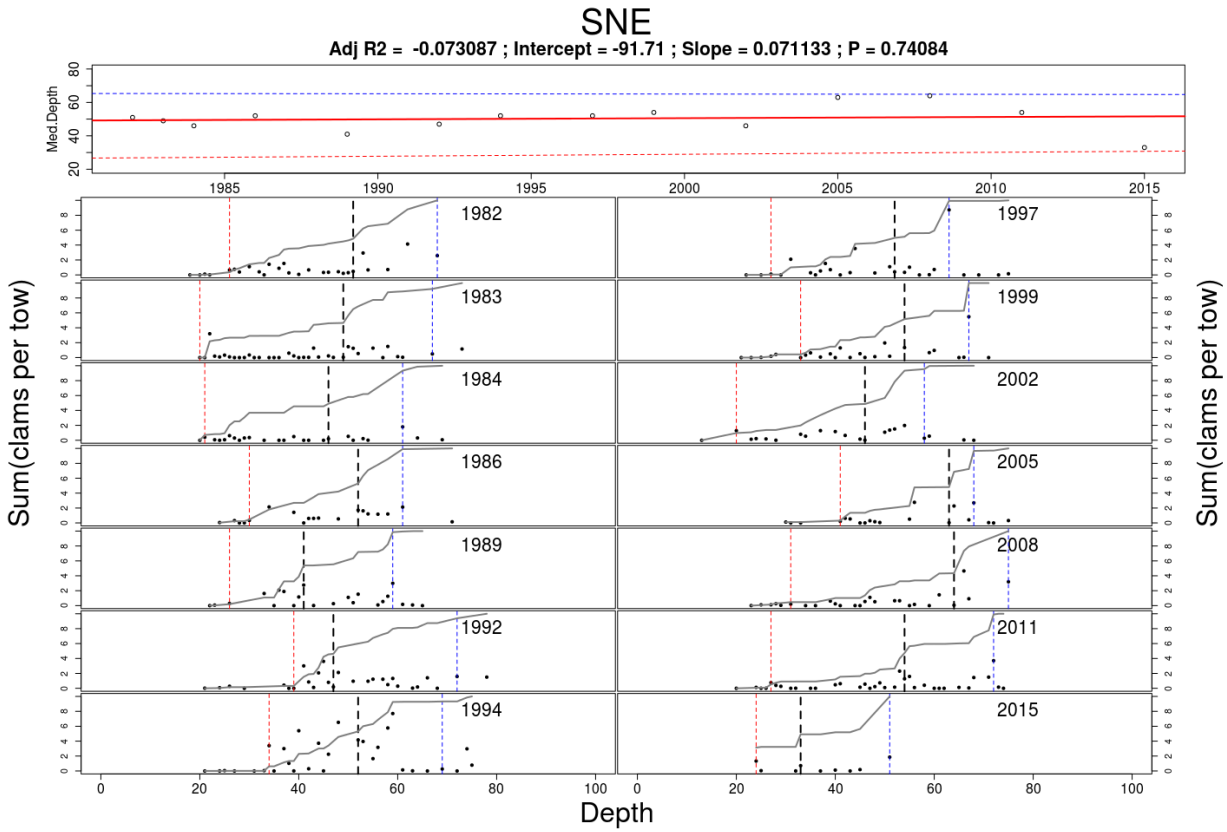

Figure 204: Total ocean quahog caught at depth by year in SNE. The points are clams caught aggregated by depth and the gray line is the cummulative sum of clams caught at depth. The dashed vertical line is the depth at which half of the cummulative total clams caught in that survey were taken. If the dashed vertical line is further to the right it indicates that more clams were caught in deeper water in that year. The top panel is a simple linear regression of median depth (the dashed vertical lines in each annual plot) over time. A positive slope indicates that a higher proportion of the total clams in a region were caught in deeper water in recent years.

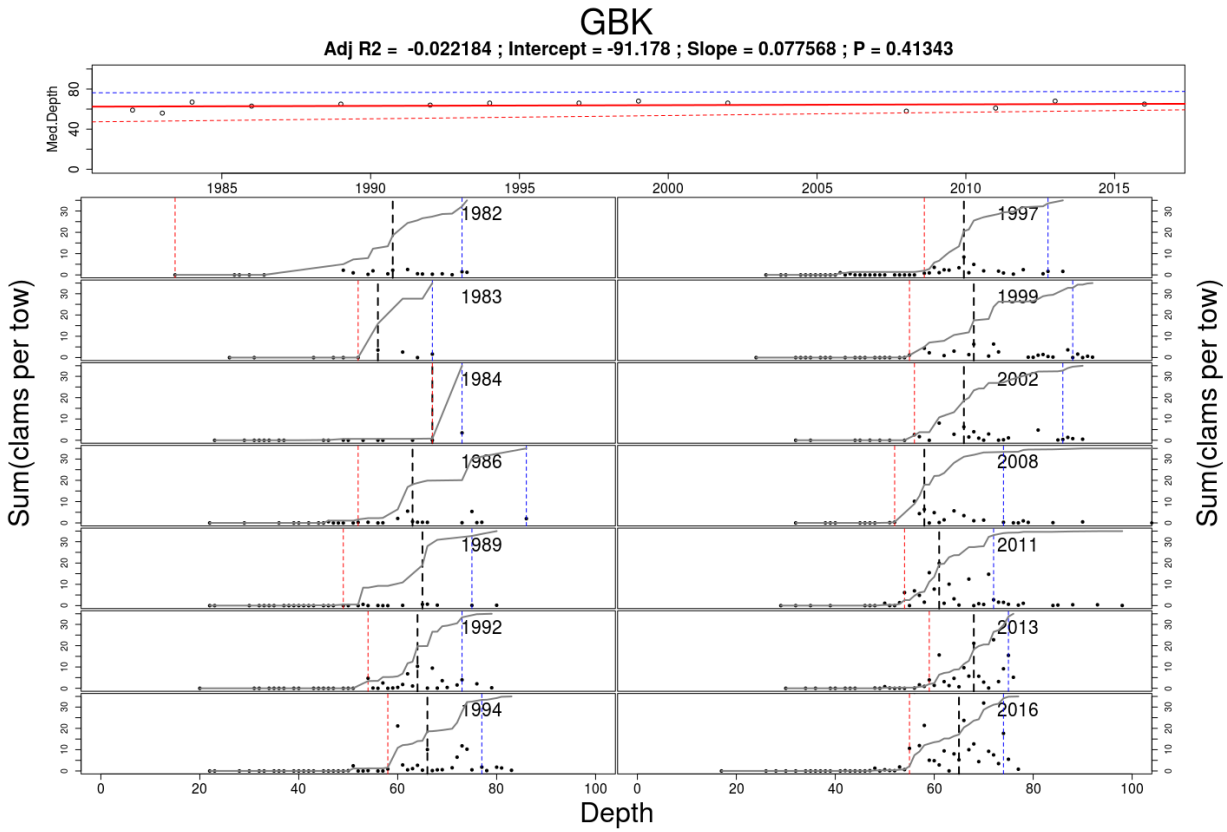

Figure 205: Total ocean quahog caught at depth by year in GBK. The points are clams caught aggregated by depth and the gray line is the cummulative sum of clams caught at depth. The dashed vertical line is the depth at which half of the cummulative total clams caught in that survey were taken. If the dashed vertical line is further to the right it indicates that more clams were caught in deeper water in that year. The top panel is a simple linear regression of median depth (the dashed vertical lines in each annual plot) over time. A positive slope indicates that a higher proportion of the total clams in a region were caught in deeper water in recent years.

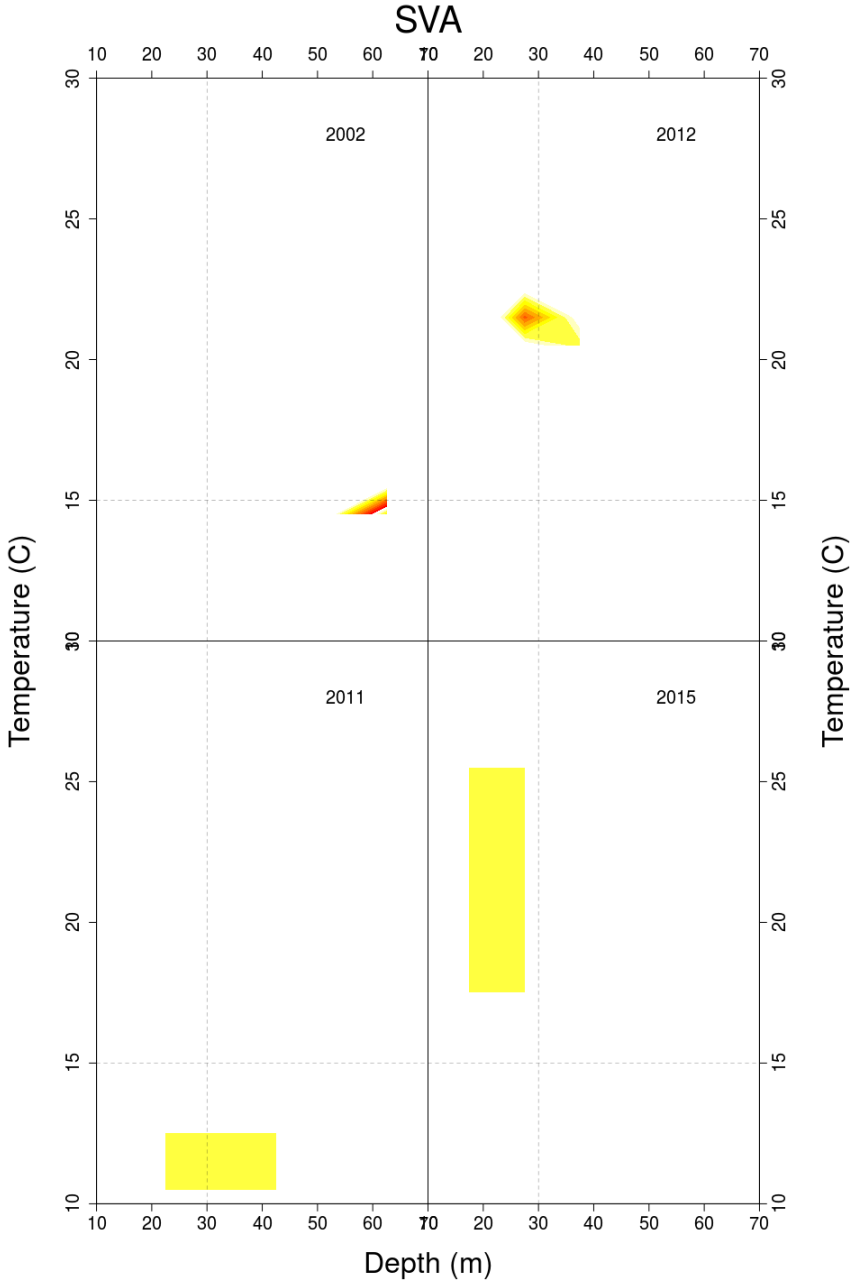

Figure 206: Total ocean quahog caught in the NEFSC clam survey at depth and temperature by year in SVA. Warmer colors in the contour represent larger catches. Catches are relative within each year and colors are not compareable across years. The dashed lines are drawn at 15° C and 30 m depth are for reference only.

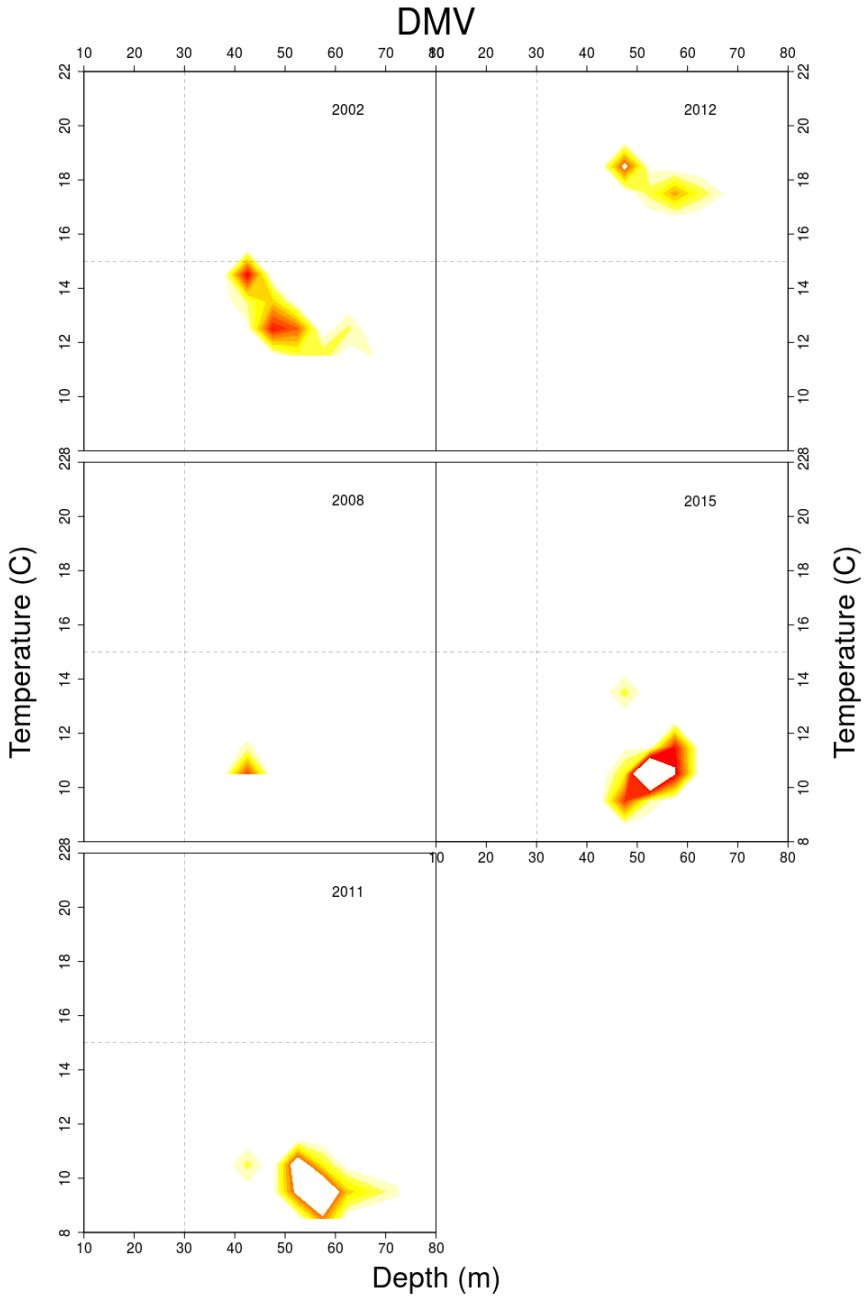

Figure 207: Total ocean quahog caught in the NEFSC clam survey at depth and temperature by year in DMV. Warmer colors in the contour represent larger catches. Catches are relative within each year and colors are not compareable across years. The dashed lines are drawn at 15° C and 30 m depth are for reference only.

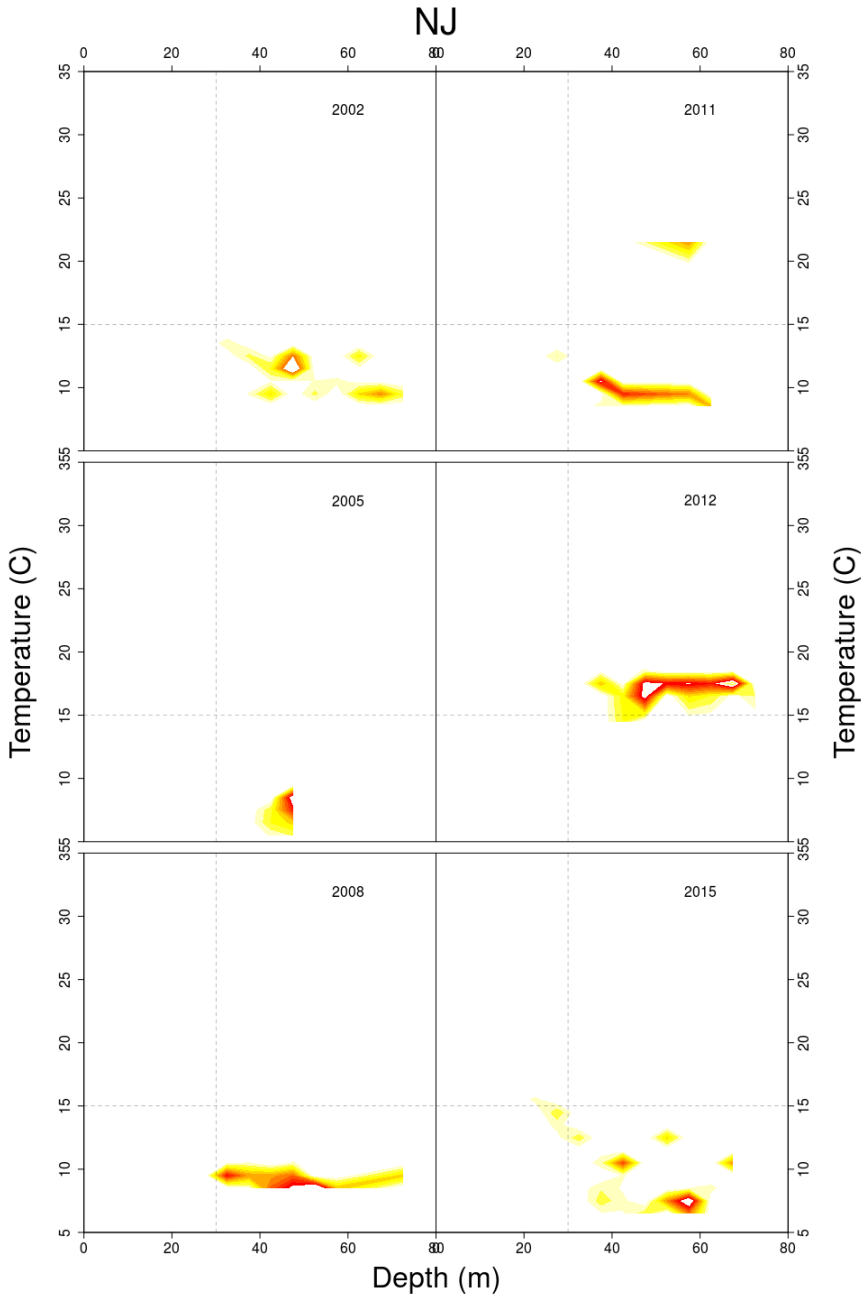

Figure 208: Total ocean quahog caught in the NEFSC clam survey at depth and temperature by year in NJ. Warmer colors in the contour represent larger catches. Catches are relative within each year and colors are not compareable across years. The dashed lines are drawn at 15° C and 30 m depth are for reference only.

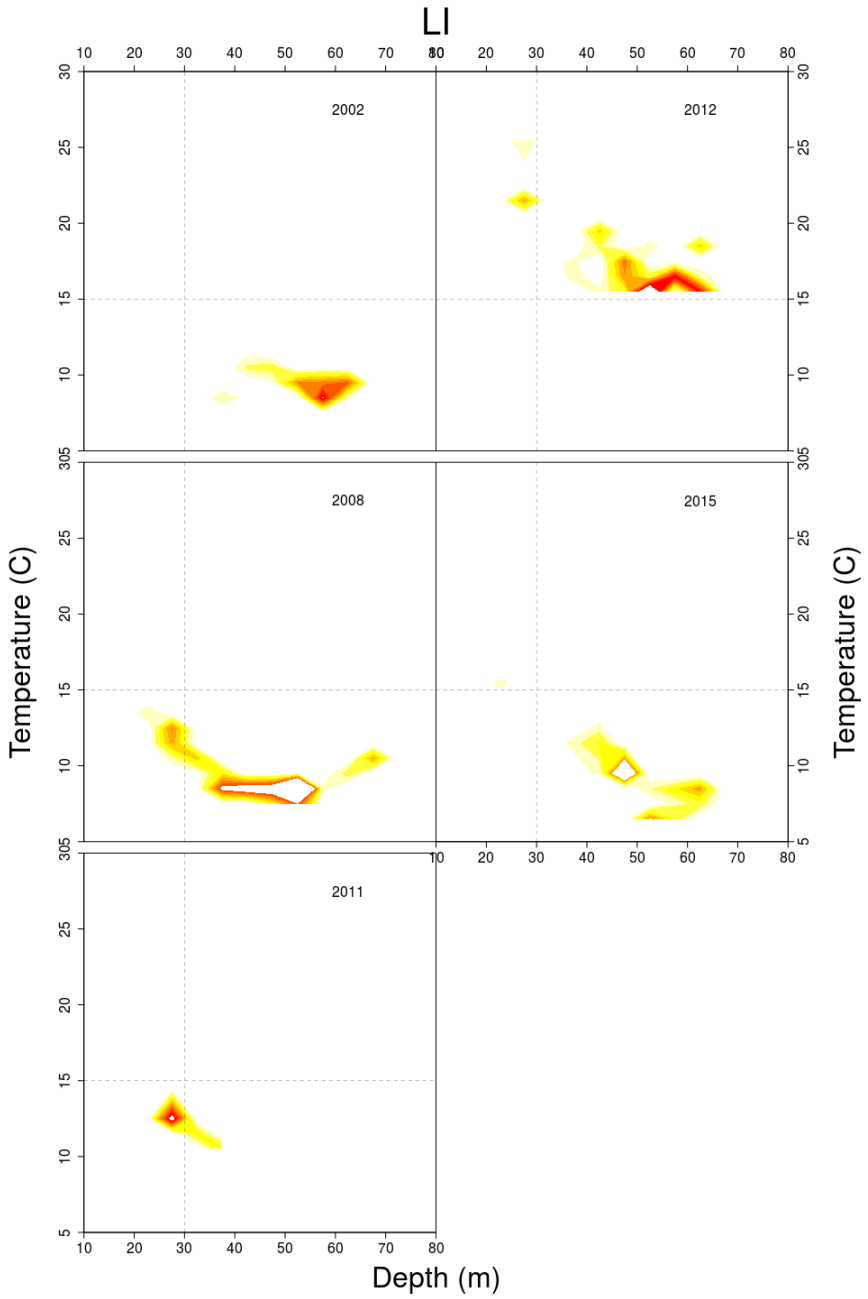

Figure 209: Total ocean quahog caught in the NEFSC clam survey at depth and temperature by year in LI. Warmer colors in the contour represent larger catches. Catches are relative within each year and colors are not compareable across years. The dashed lines are drawn at 15° C and 30 m depth are for reference only.

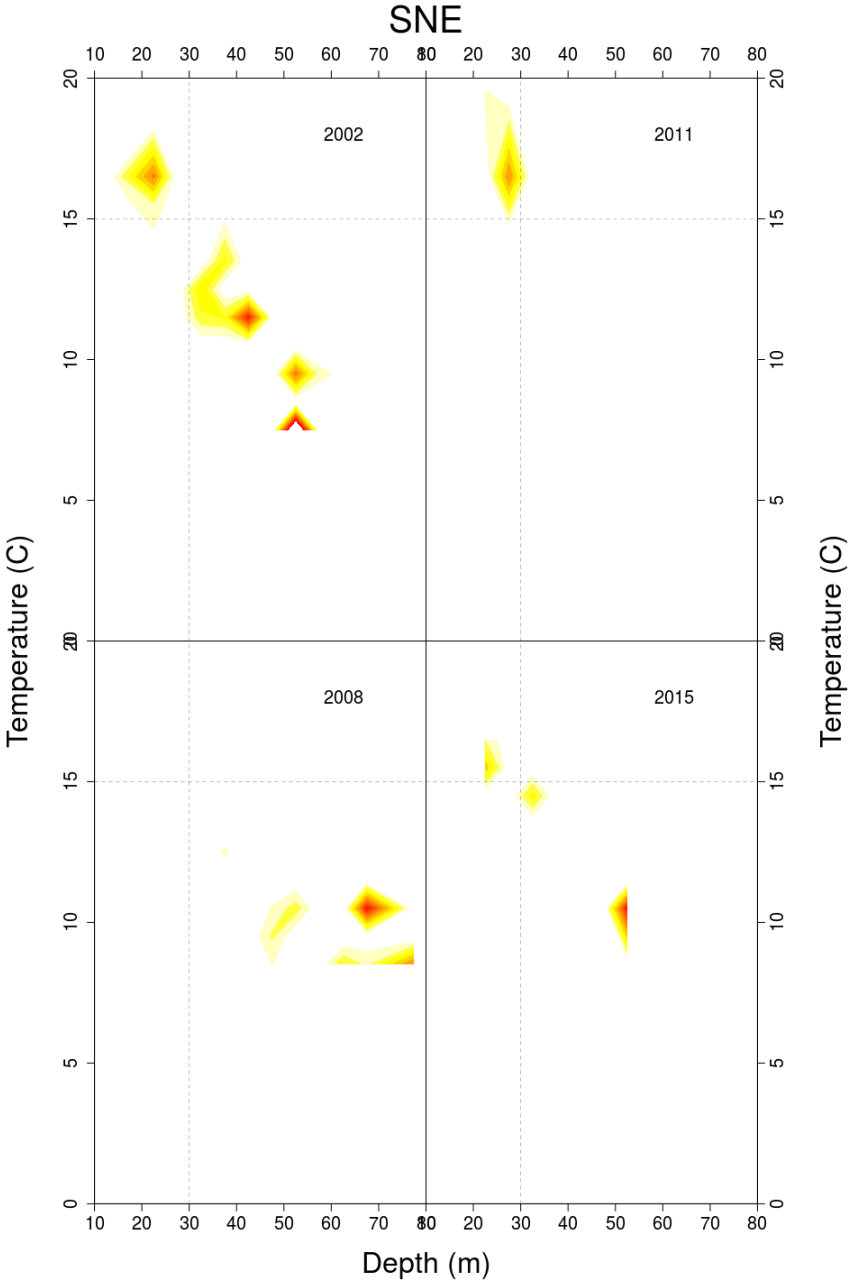

Figure 210: Total ocean quahog caught in the NEFSC clam survey at depth and temperature by year in SNE. Warmer colors in the contour represent larger catches. Catches are relative within each year and colors are not compareable across years. The dashed lines are drawn at 15° C and 30 m depth are for reference only.

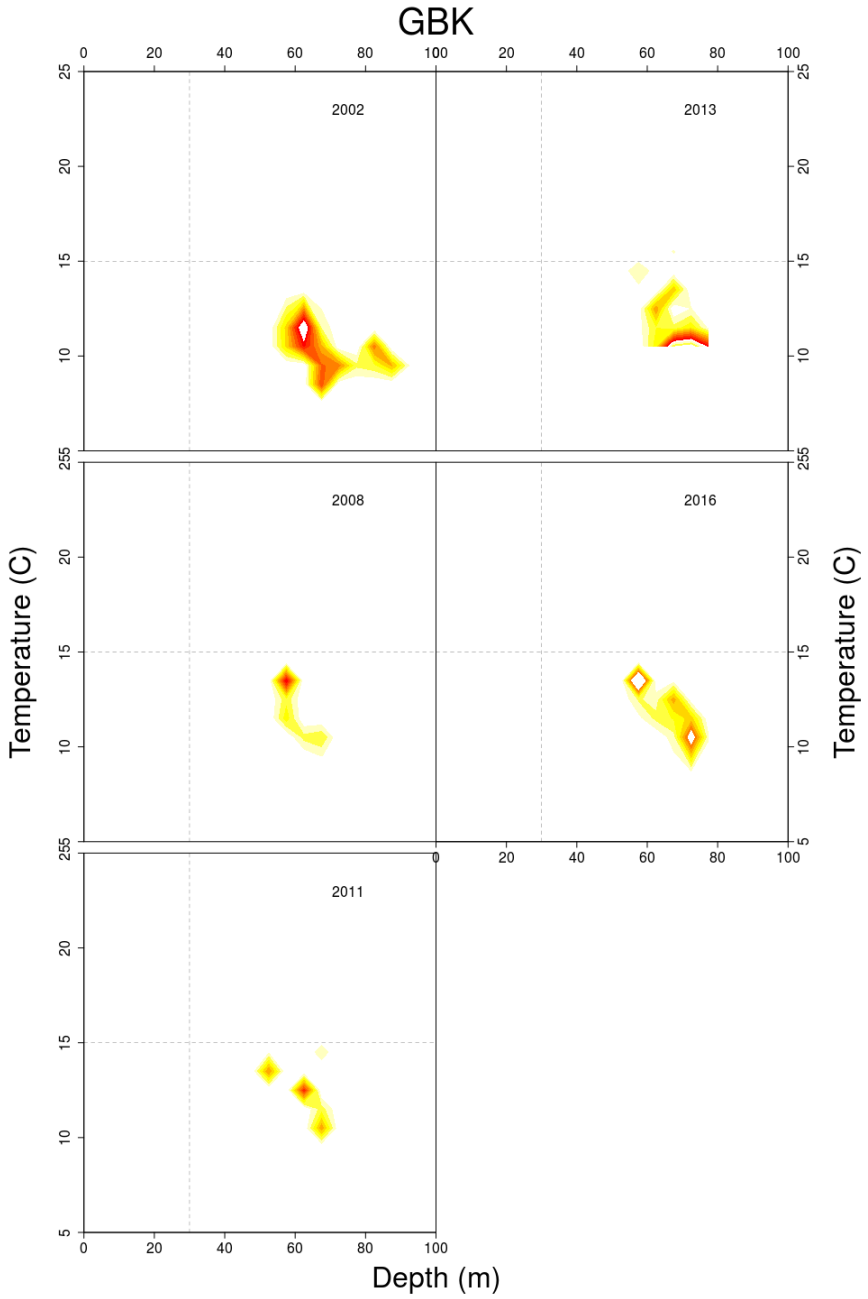

Figure 211: Total ocean quahog caught in the NEFSC clam survey at depth and temperature by year in GBK. Warmer colors in the contour represent larger catches. Catches are relative within each year and colors are not compareable across years. The dashed lines are drawn at 15° C and 30 m depth are for reference only.

Appendix 6 Build a bridge

The KLAMZ model configuration used for the 2013 update of the ocean quahog stock assessment (Chute et al. 2013) fit the survey data reasonably well (Figures 212 - 214).

In order to bring the model from 2013 up to date, NEFSC first replaced the lognormal prior distribution with the newly developed beta prior distribution (see Appendix 4). This formulation was somewhat illogical because the efficiency corrected swept area biomass values used as data here called ("`Efficiency_Corrected_Swept_Area_Fishable_Biomass`") were expanded from simple swept area biomass values by the efficiency estimated previously. The model converged and produced a fit with a different trend and scale than previous assessment (Figures 215 - 217), though these results should be discounted based on their internal inconsistencies as described above.

The MCD survey was included in step three, along with its prior distribution as described in Appendix 4. The addition of the new survey induced some changes in both trend and scale relative to the previous step, bringing it more in line with the results from the last assessment (Figures 218 - 220).

Finally, the model was tuned such that the input cv for the RV survey more closely matched the estimated goodness of fit cv. This change induced slight rescaling, but had minimal effect on trend (Figures 221 - 223).

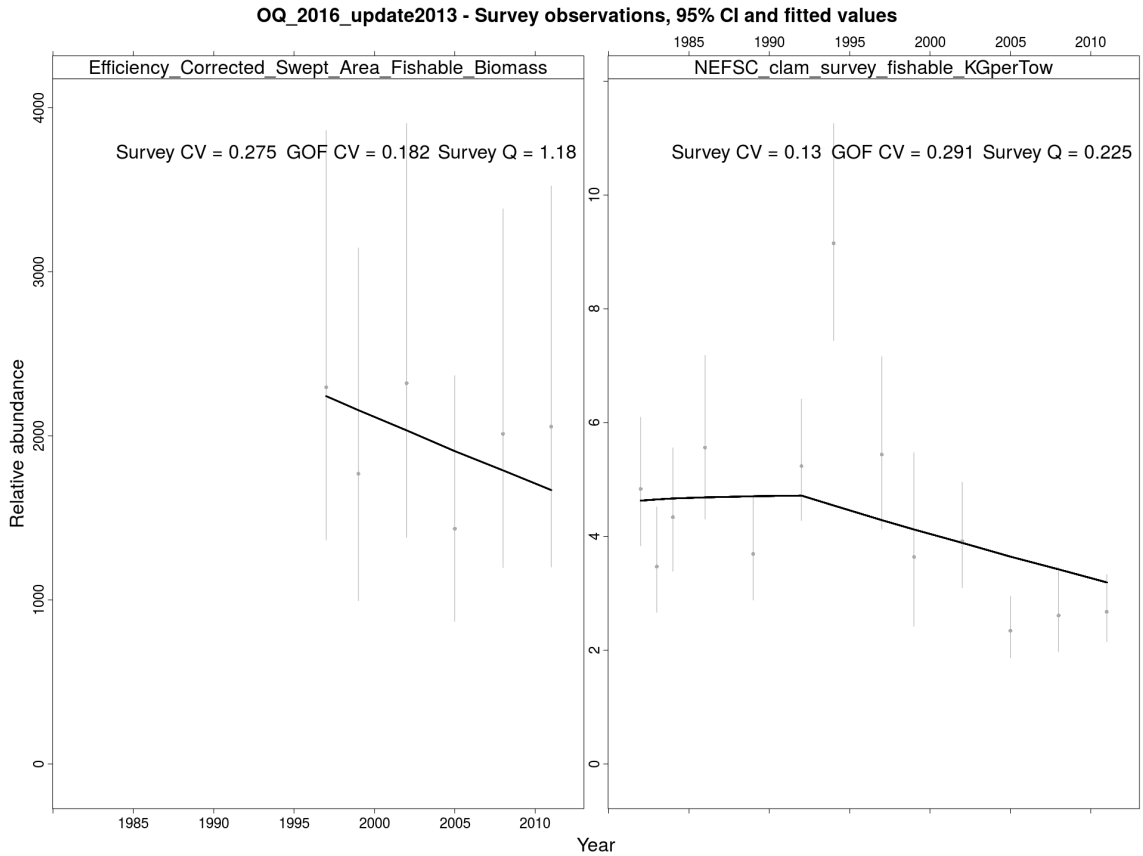

Figure 212: Southern area KLAMZ model fits to the ocean quahog survey data from the previous assessment (data through 2011). The input cv, model fit cv and survey q estimate for each of the surveys are shown in text in each of the panels.

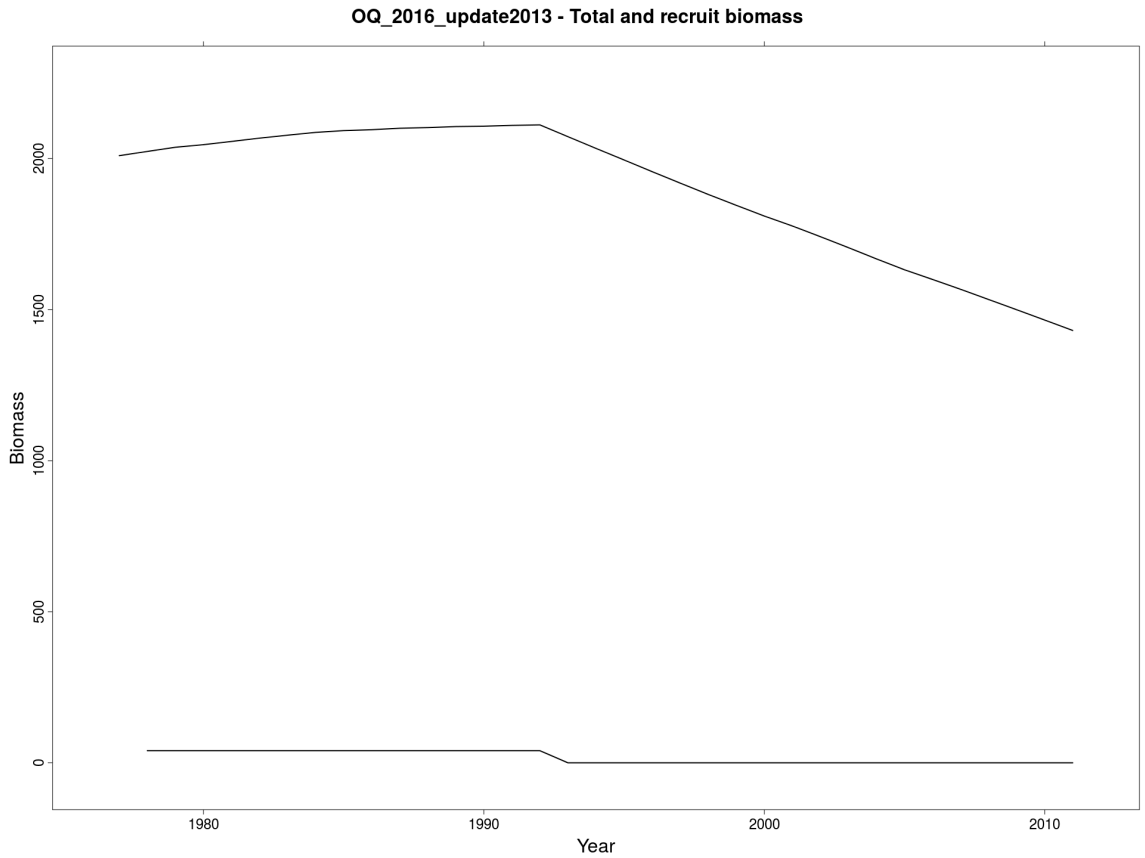

Figure 213: Total biomass and recruits from southern area KLAMZ model fits to the ocean quahog survey data from the previous assessment (data through 2011). Recruitment to the population included a step function in 1993.

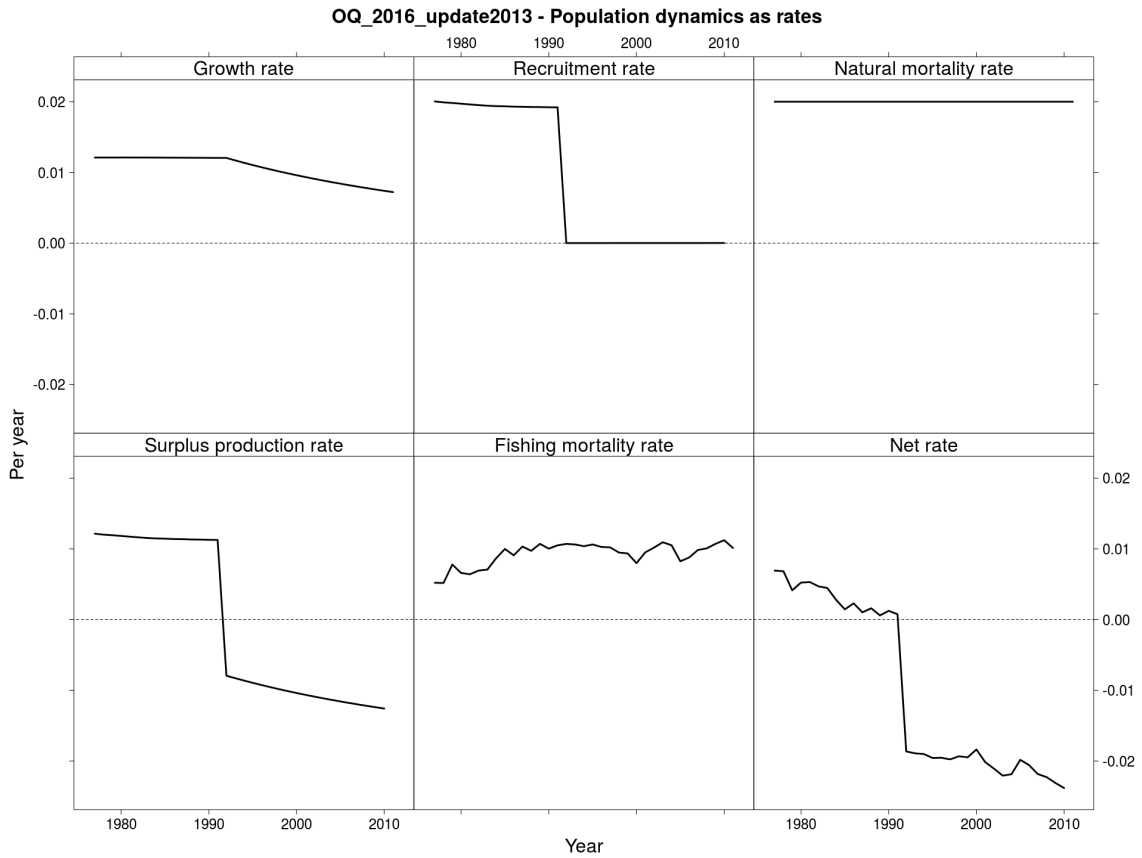

Figure 214: Population dynamics from southern area KLAMZ model fits to the ocean quahog survey data from the previous assessment (data through 2011) presented as rates. Fishing and natural mortality rates were low, and recruitment, growth and surplus production declined over time.

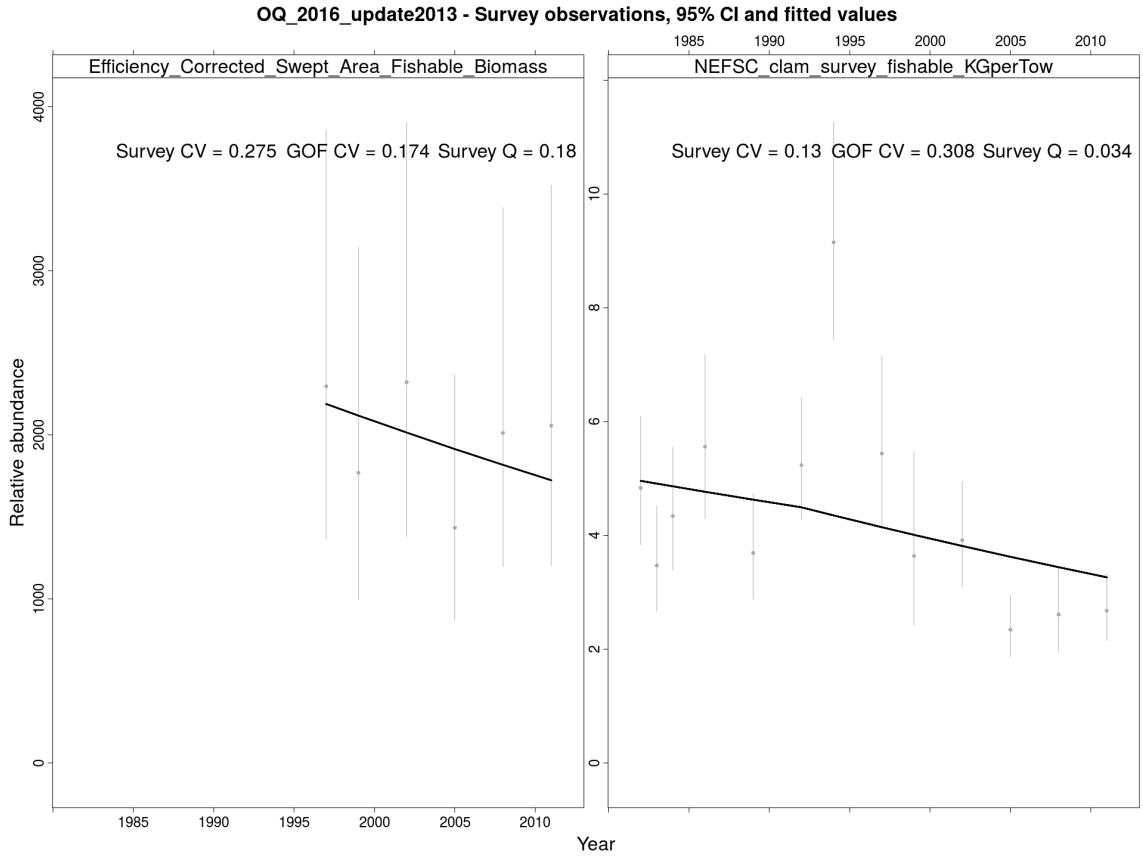

Figure 215: Southern area KLAMZ model fits to the ocean quahog survey data from the previous assessment (data through 2011), but including a beta prior with parameters estimated in the current assessment. The input cv, model fit cv and survey q estimate for each of the three surveys are shown in text in each of the panels.

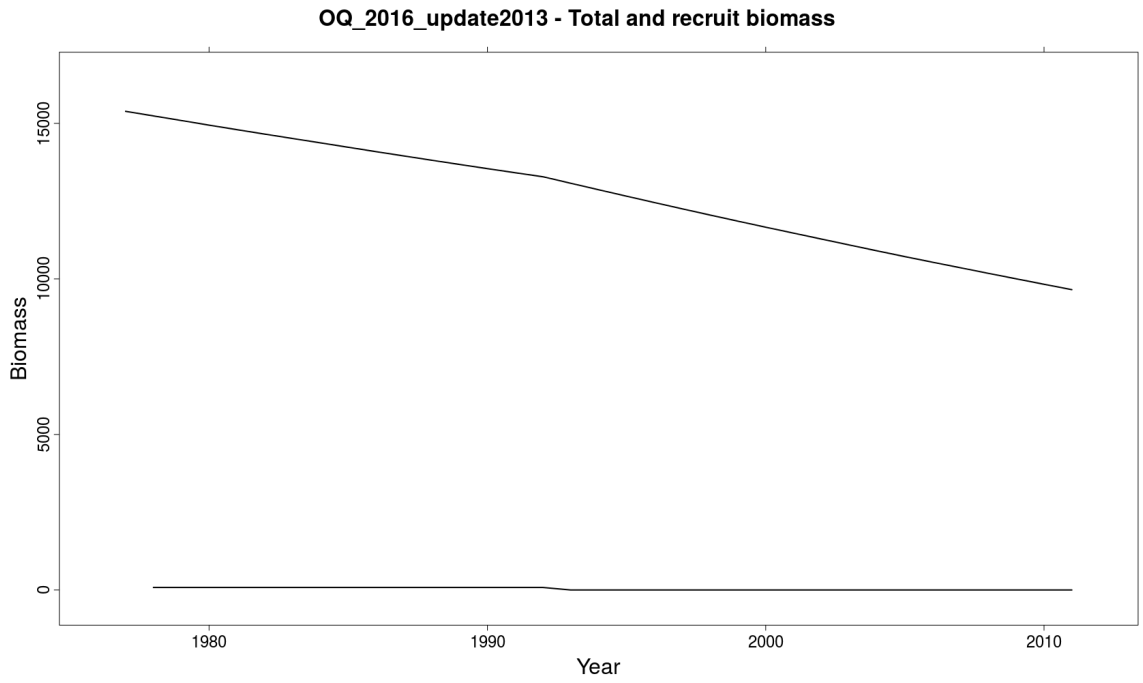

Figure 216: Total biomass and recruits from southern area KLAMZ model fits to the ocean quahog survey data from the previous assessment (data through 2011), but including a beta prior with parameters estimated in the current assessment. Recruitment to the population included a step function in 1993.

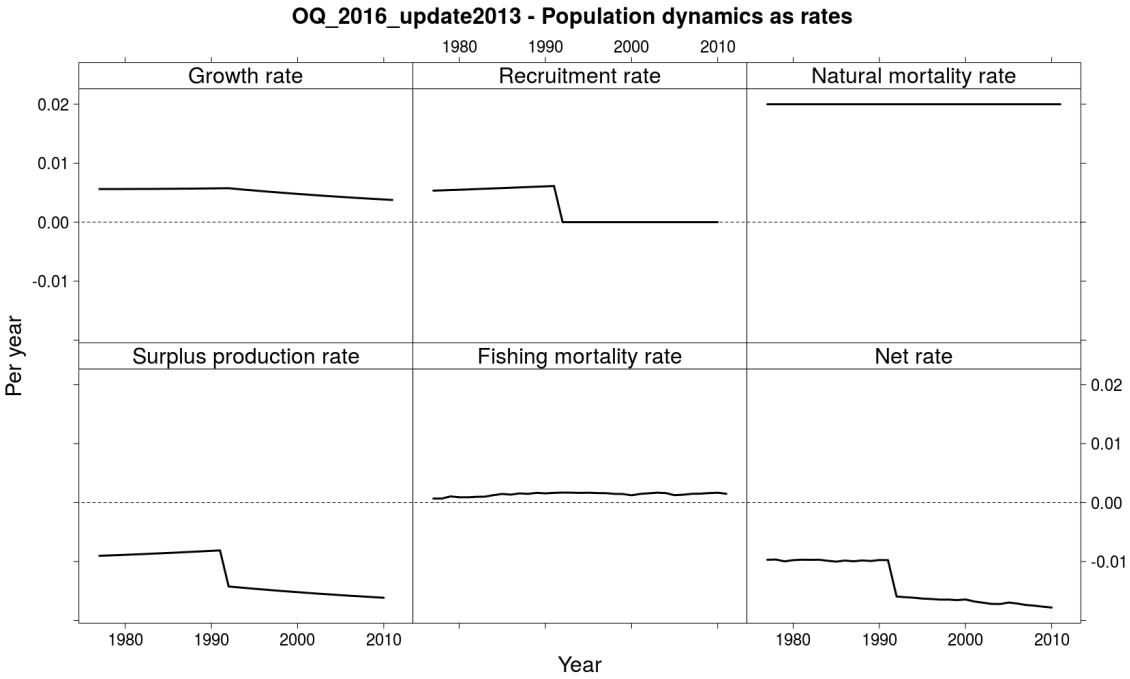

Figure 217: Population dynamics from southern area KLAMZ model fits to the ocean quahog survey data from the previous assessment (data through 2011), but including a beta prior with parameters estimated in the current assessment, presented as rates. Fishing and natural mortality rates were low, and recruitment, growth and surplus production declined over time.

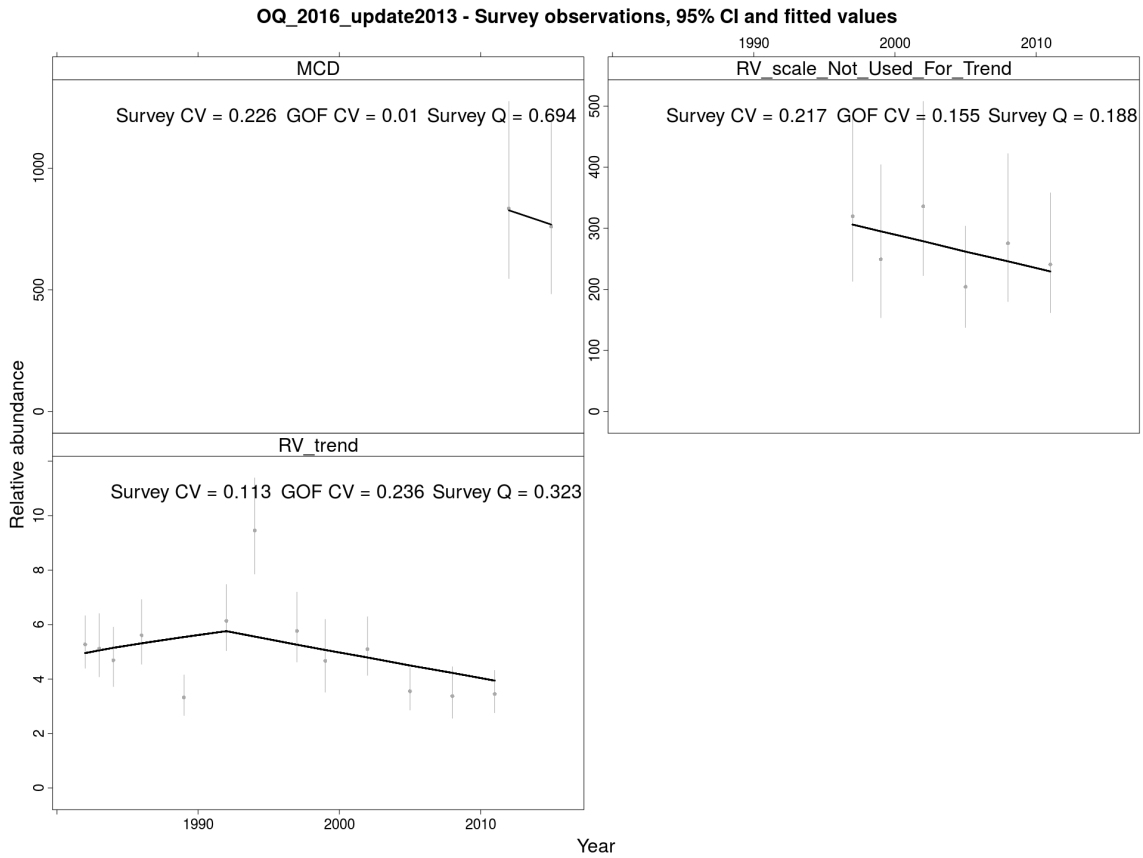

Figure 218: Southern area KLAMZ model fits to the ocean quahog survey data as above, but including new data with a new prior distribution for survey q. The input cv, model fit cv and survey q estimate for each of the surveys are shown in text in each of the panels.

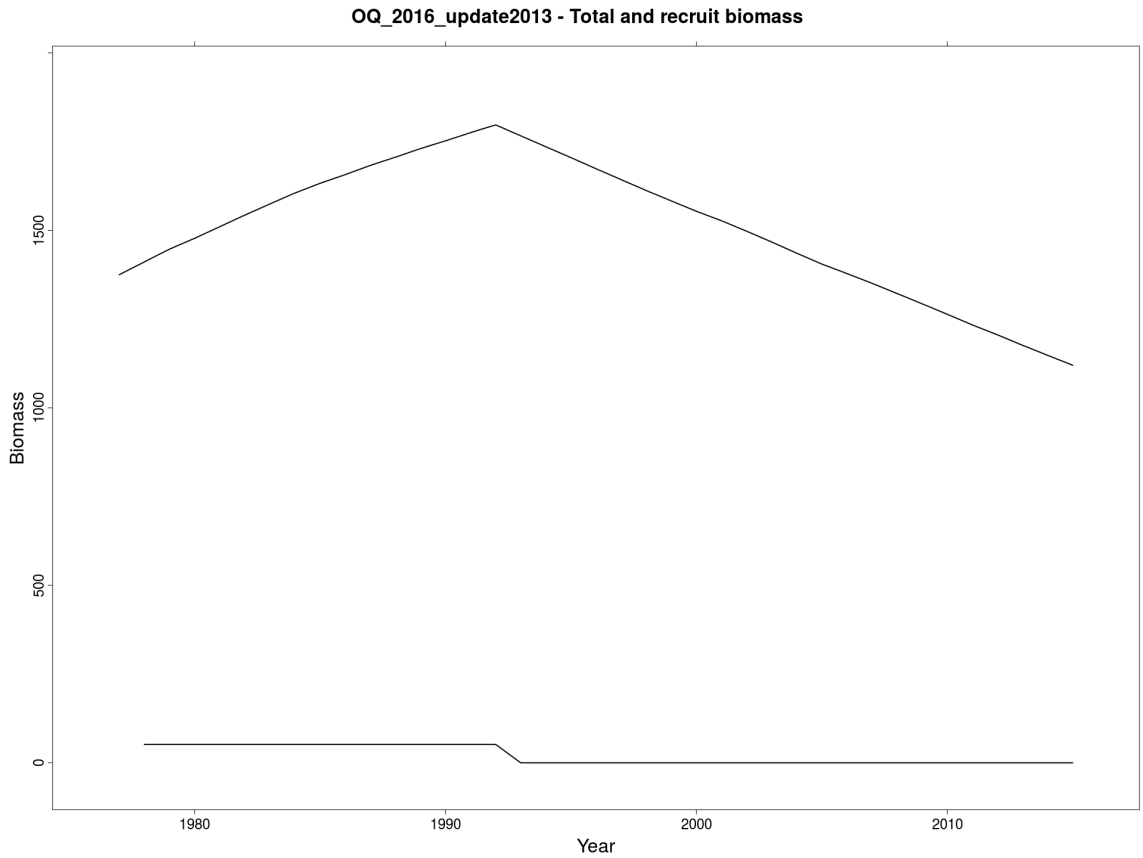

Figure 219: Total biomass and recruits from southern area KLAMZ model fits to the ocean quahog survey data as above, but including new data with a new prior distribution for survey q. Recruitment to the population included a step function in 1993.

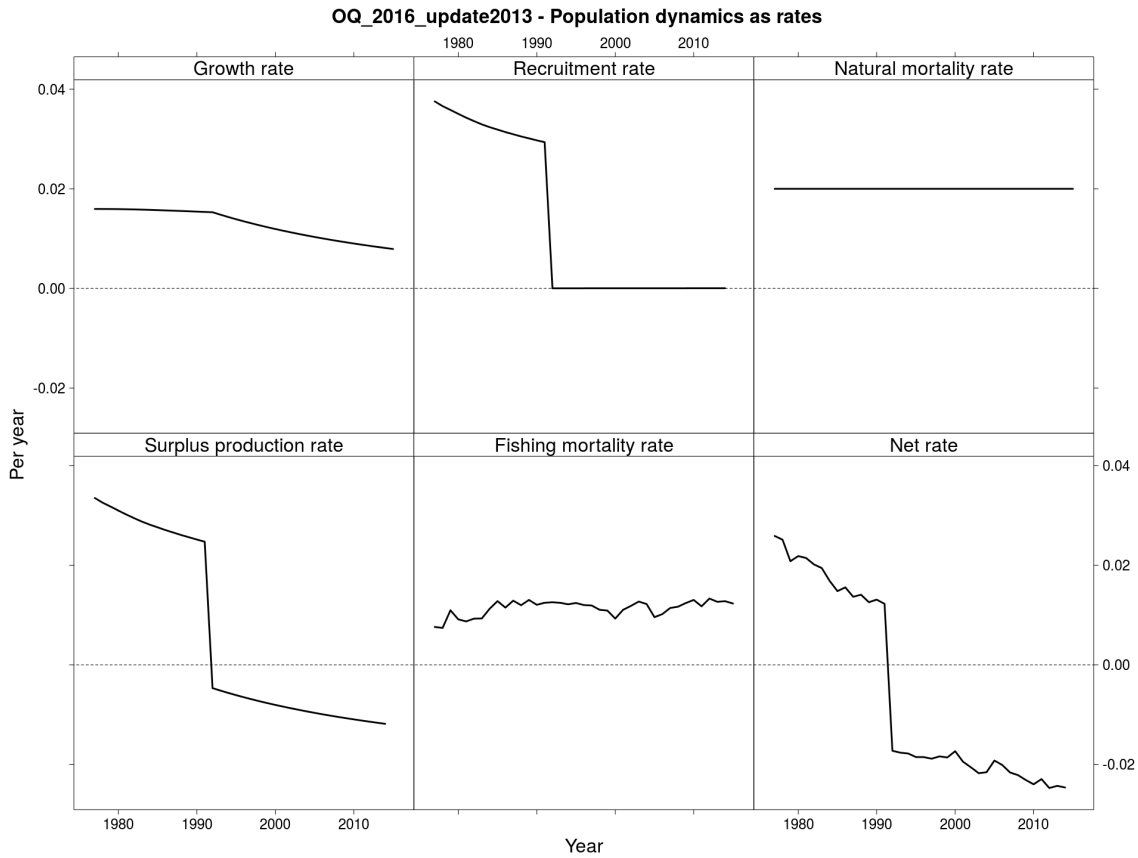

Figure 220: Population dynamics from southern area KLAMZ model fits to the ocean quahog survey data as above, but including new data with a new prior distribution for survey q, presented as rates. Fishing and natural mortality rates were low, and recruitment, growth and surplus production declined over time.

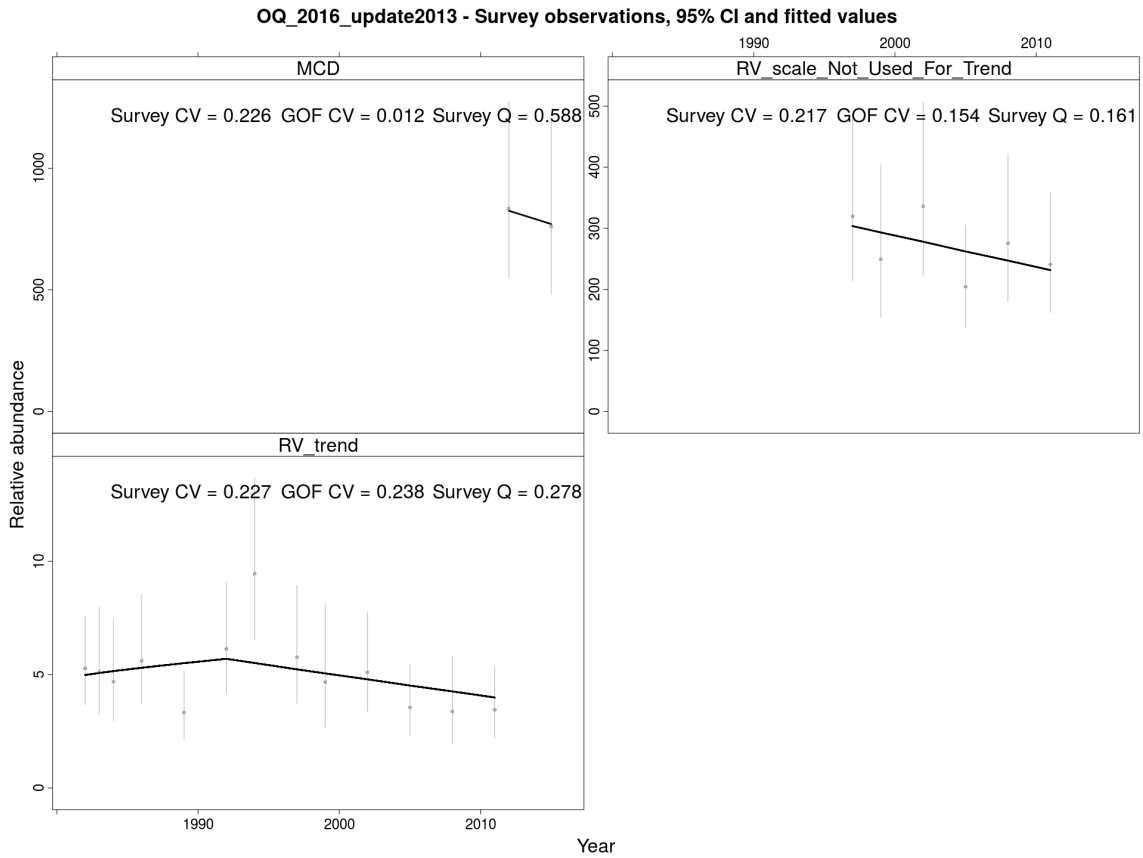

Figure 221: Southern area KLAMZ model fits to the ocean quahog survey data as above, but tuned so that the input cv on the RV survey is close to the goodness of fit cv estimated in the model. The input cv, model fit cv and survey q estimate for each of the surveys are shown in text in each of the panels.

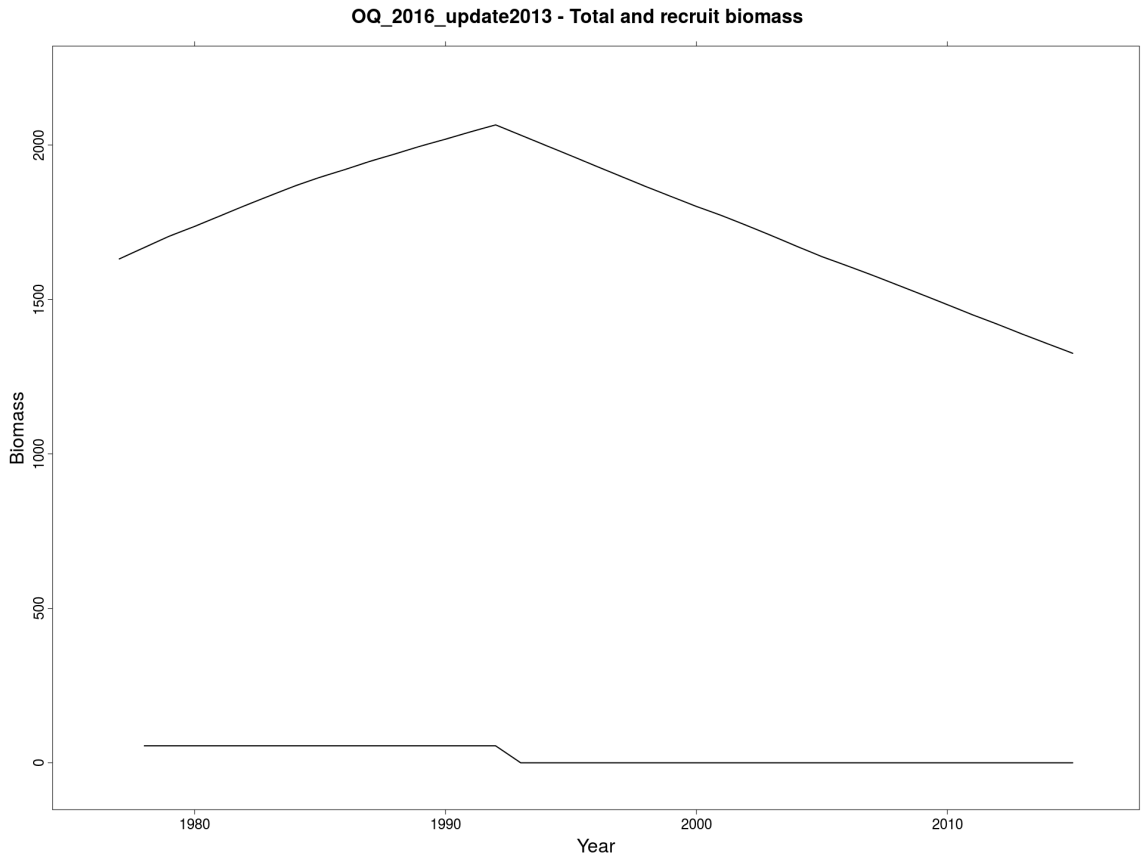

Figure 222: Total biomass and recruits from southern area KLAMZ model fits to the ocean quahog survey data as above, but tuned so that the input cv on the RV survey is close to the goodness of fit cv estimated in the model. Recruitment to the population included a step function in 1993.

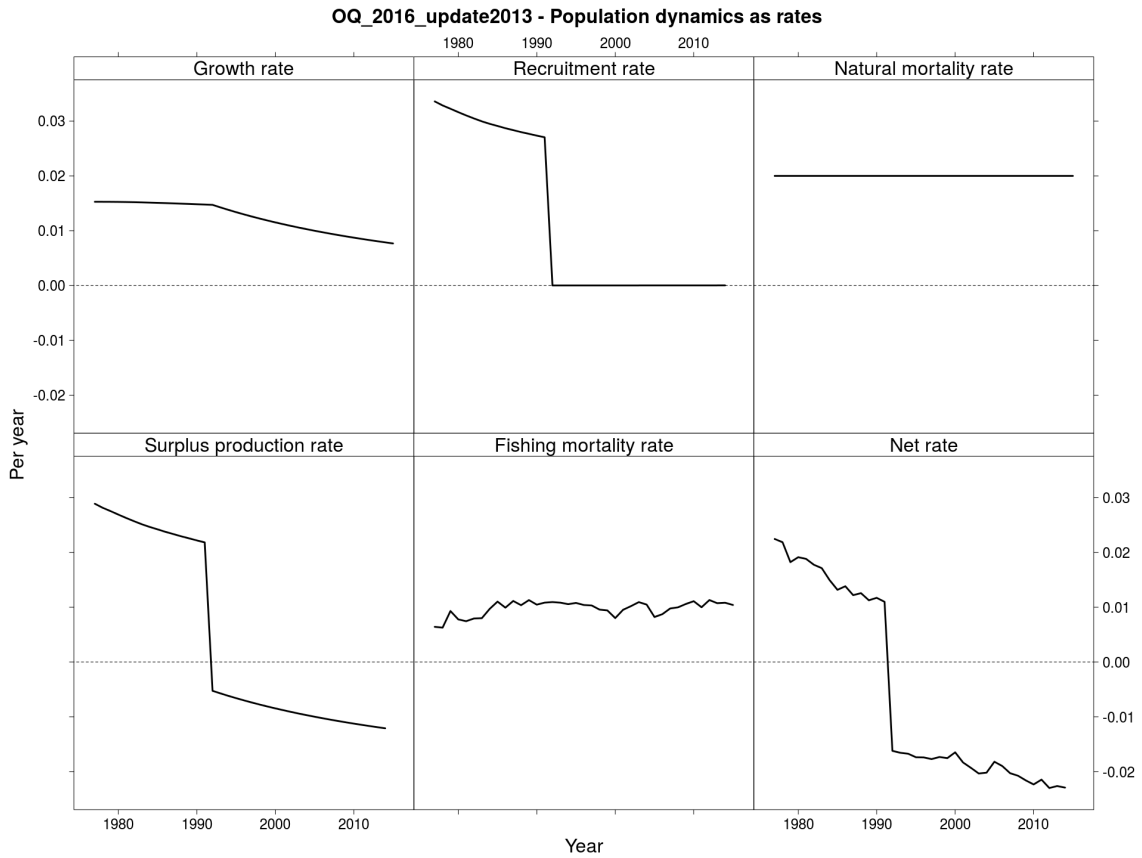

Figure 223: Population dynamics from southern area KLAMZ model fits to the ocean quahog survey data as above, but tuned so that the input cv on the RV survey is close to the goodness of fit cv estimated in the model, presented as rates. Fishing and natural mortality rates were low, and recruitment, growth and surplus production declined over time.

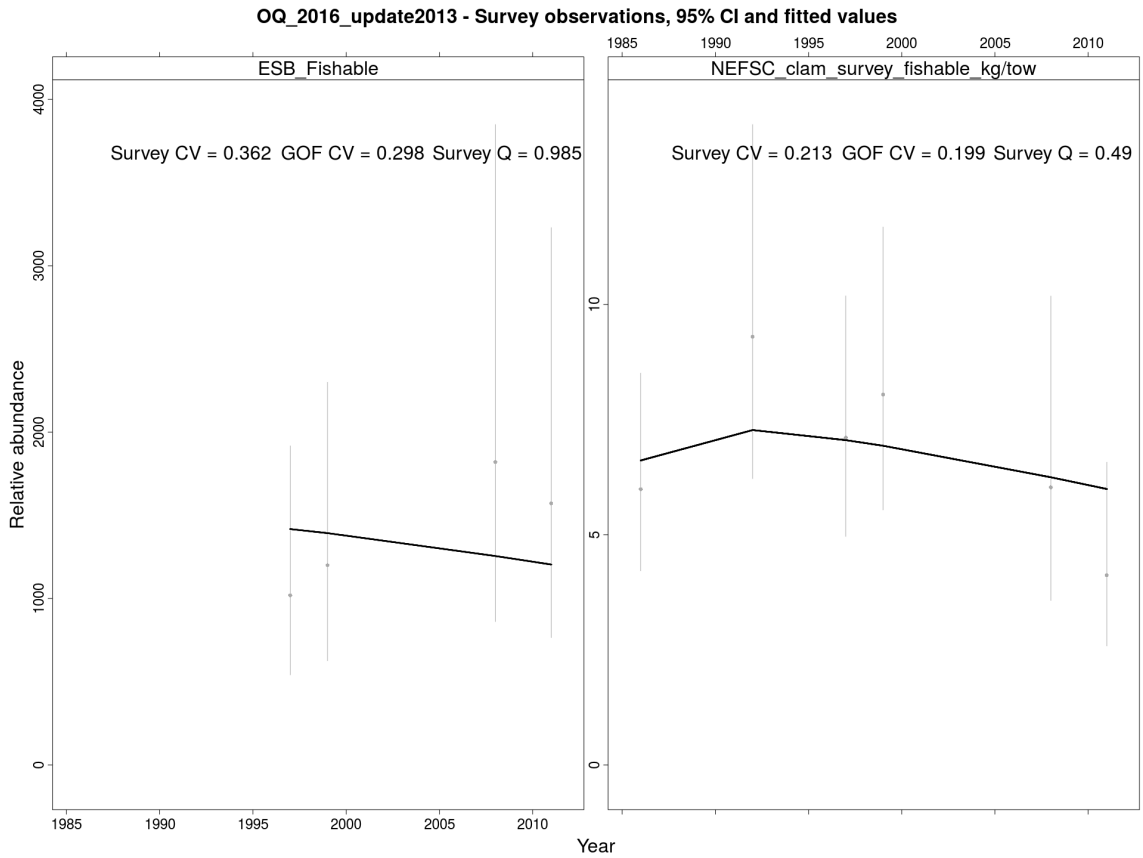

Figure 224: Northern area KLAMZ model fits to the ocean quahog survey data from the previous assessment (data through 2011). The input cv, model fit cv and survey q estimate for each of the surveys are shown in text in each of the panels.

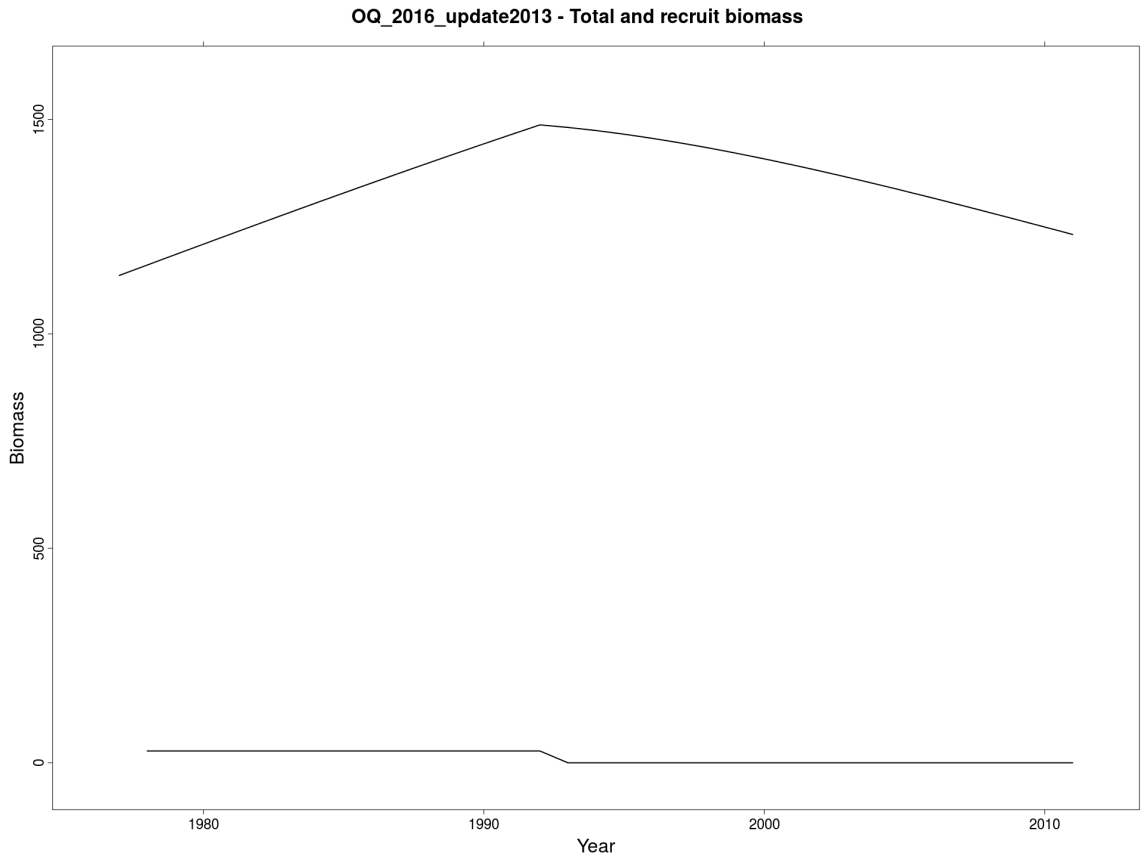

Figure 225: Total biomass and recruits from northern area KLAMZ model fits to the ocean quahog survey data from the previous assessment (data through 2011). Recruitment to the population included a step function in 1993.

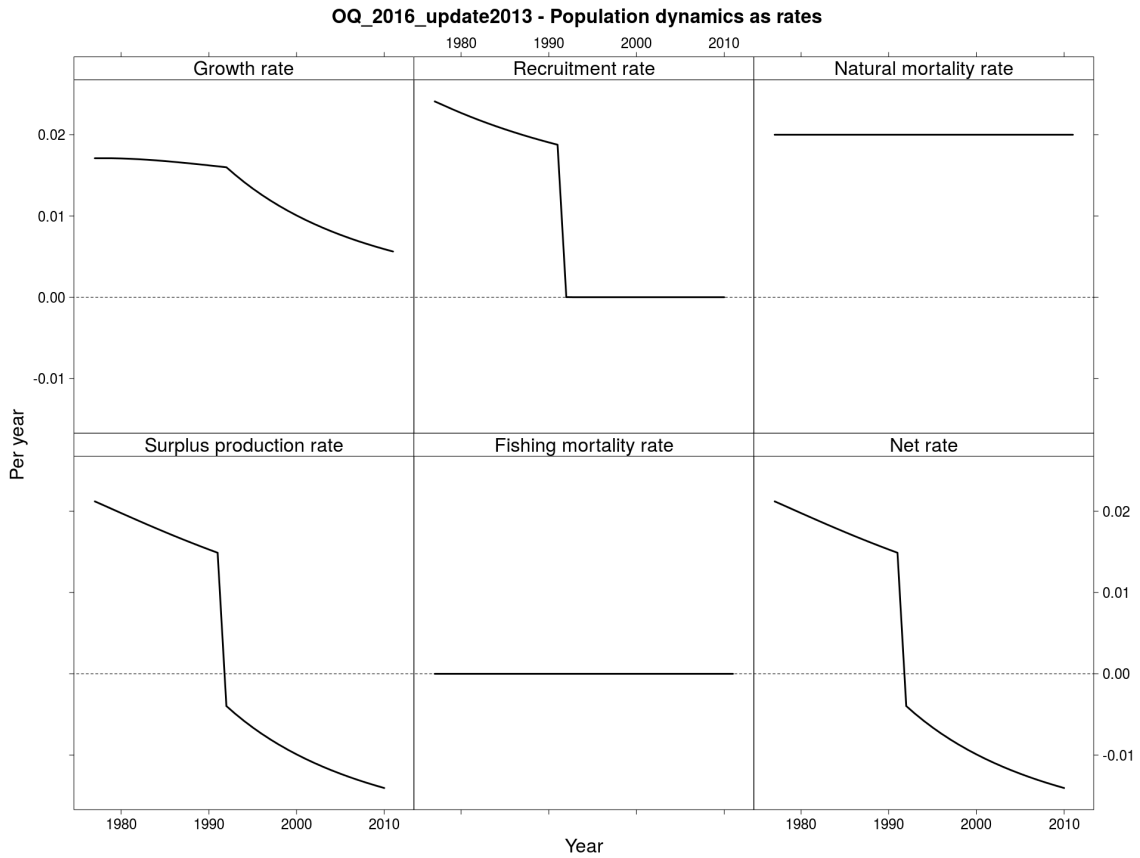

Figure 226: Population dynamics from northern area KLAMZ model fits to the ocean quahog survey data from the previous assessment (data through 2011) presented as rates. Fishing and natural mortality rates were low, and recruitment, growth and surplus production declined over time.

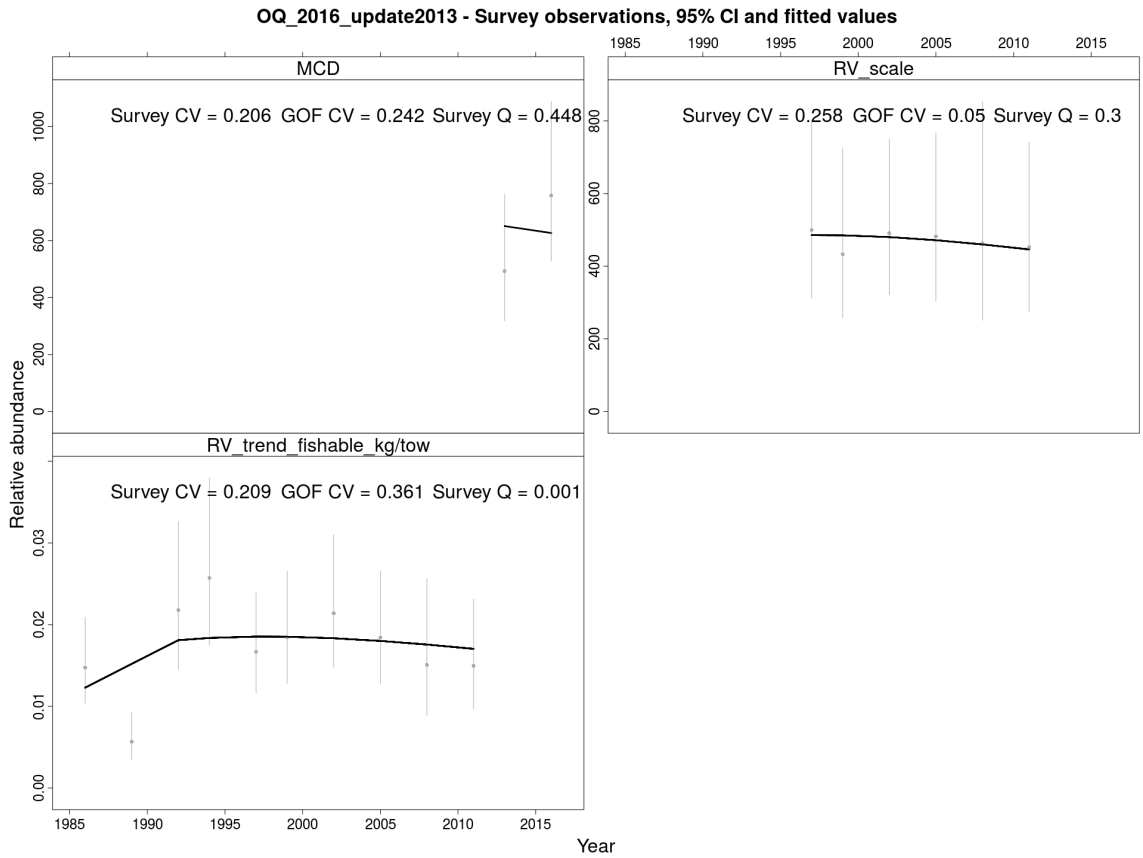

Figure 227: Northern area KLAMZ model fits to the ocean quahog survey data as above, but including new data with a new prior distribution for survey q. The input cv, model fit cv and survey q estimate for each of the surveys are shown in text in each of the panels.

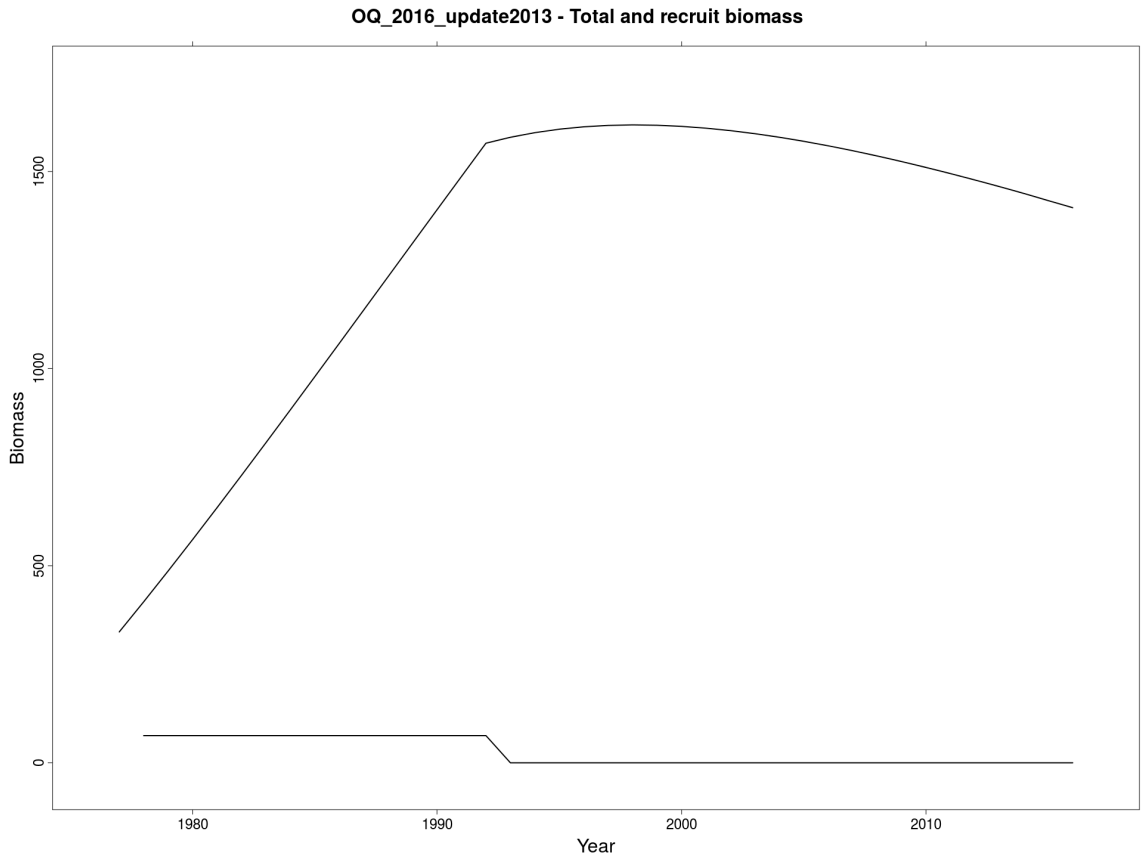

Figure 228: Total biomass and recruits from northern area KLAMZ model fits to the ocean quahog survey data. Recruitment to the population included a step function in 1993.

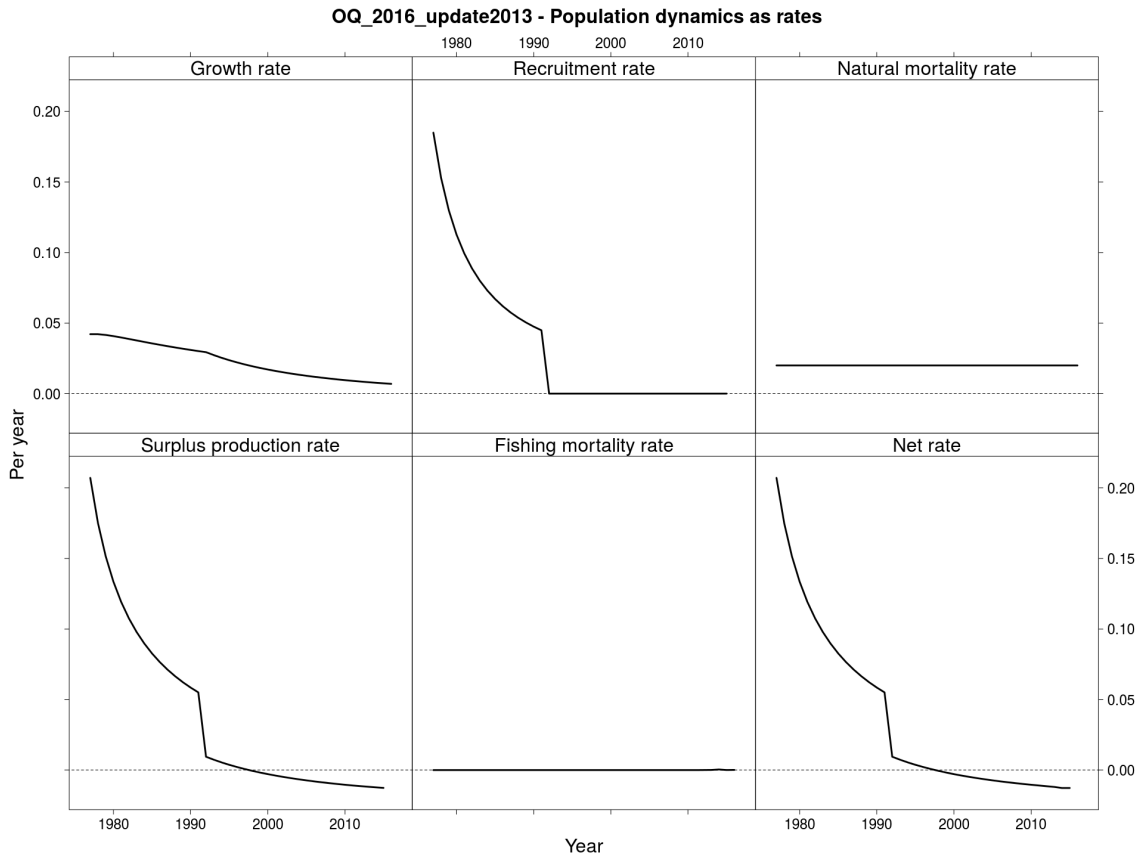

Figure 229: Population dynamics from northern area KLAMZ model fits to the ocean quahog survey data presented as rates. Fishing and natural mortality rates were low, and recruitment, growth and surplus production declined over time.

Appendix 7 Updated report on the ocean quahog resource in Maine waters

Introduction

The Maine fishery for ocean quahog, although harvesting the same species as the rest of the EEZ fishery (*Arctica islandica*), is prosecuted in a different way and fills a different sector of the shellfish market. Maine "mahogany ocean quahog" are harvested at a smaller size (starting at 38 mm or 1.5 inches in shell length, SL) and marketed as a less expensive alternative for *Mercenaria mercenaria* for home and restaurant consumption. The offshore beds targeted by the Maine fishery are made up of small ocean quahog, the maximum size being only about 75mm.

The Maine fishery began to expand into Federal waters in the 1980s due in part to paralytic shellfish poisoning (PSP) closures within state waters. In 1990 it was determined that this fishing activity conflicted with the Magnuson-Stevens Fishery Management Conservation Act which calls for the stock to be managed as a unit throughout its range. The Maine fishery was granted experimental status from 1990-1997. In 1998, the Maine fishery was fully incorporated under Amendment 10 of the surfclam/ocean quahog FMP and given an initial annual quota of 100,000 bushels based on historical landings data. There was no independent assessment of the resource available at that time. The State of Maine is responsible under Amendment 10 to certify harvest areas free of PSP and to conduct stock assessments.

In 2002 the State of Maine conducted a pilot survey to assess the distribution and abundance of ocean quahog along the Maine coast. This survey was a critical first step in establishing distribution, size composition and relative abundance information for the Maine fishery and for directing the design of the current survey work. While this initial survey provided valuable information it did not have the resources to estimate dredge efficiency and therefore was not able to estimate total biomass or biological reference points. The survey conducted in 2005 was focused on estimating dredge efficiency and mapping ocean quahog density on the commercial fishing grounds.

Estimates of biomass and mortality presented in this report are only for the two commercial beds south of Addison (west bed) and Jonesport/GreatWass (east bed), Maine. This approach was chosen due to available resources and because it was conservative. Other ocean quahog beds are known to exist along many parts of the Maine coast. If mortality targets can be met using the estimates from the primary fishing grounds then biomass outside the survey area can act as a *de facto* preserve.

Fishery Data

Data throughout this report are presented in metric units. In the case of landings and LPUE, values are reported in units of Maine bushels, which are about two-thirds the size of the "industry" bushels used as a measure of ocean quahog volume for the rest of the EEZ. To determine the meat yield of a Maine bushel of ocean quahog, all ocean quahog caught by the Maine survey (number and size composition estimated by subsampling) are converted to a total

meat weight then divided by the total number of bushels caught (known). Shell length is converted to meat weight using the equation

$$W = 4.97 \cdot 10^{-6} \cdot SL^{3.5696} \tag{5}$$

where W is meat weight and SL is shell length. The resulting meat yield (10.8 lbs) is for a Maine bushel of ocean quahog averaging around 57 mm SL.

Historically the bulk of ocean quahog fishing activity in Maine has taken place on two large ocean quahog beds just off the coast north of $43^o50'$ latitude: the east bed off the town of Addison and the west bed off Great Wass Island. The two beds cover an area of approximately 60 square nautical miles (Figure 230).

Harvesting takes place year round with the highest market demand during the summer holidays (Memorial Day through Labor Day). Most vessels in the Maine fleet are between 10.7-13.7 m (35-45 ft) and classified as "undertonnage" or "small" in issuing permits. All of the vessels use a "dry" dredge (having no hydraulic jets to loosen the sediments) with a cutter bar set by regulation at no more than 0.91 m (36 in). There are no restrictions on any other dimension of the dredge.

There are no size limits for this fishery, and there is no discarding. The ocean quahog fished from the two commercial beds off Maine are much smaller than most of the rest of the EEZ harvest, averaging between 50 and 60 mm SL (Figure 231), which suits the half- shell market. Even though size of individual ocean quahog has increased since the beginning of the fishery, all the catch brought up in a dredge is still acceptable for this market and are kept. The fishery has no regulatory closed days, although the beds are occasionally closed to fishing as a PSP precaution. Since the summer of 2007, there have been 77 days when the fishing areas were closed and 145 days when the open fishing areas were severely restricted in size due to PSP precautions. These closures usually happen during the summer months.

Maine ocean quahog landings have trended downwards since 2002 (Table 37, Figure 232). The exception to this trend is in 2006 when landings increased to 124,839 bushels after the re-opening of a highly productive portion of the fishing grounds that had been closed in previous years as a precaution against PSP. After the initial boost to landings from additional fishing ground, landings again began to decline. By the end of 2015 only 41,611 bushels out of a 100,000 bushel quota had been landed.

LPUE has been fairly stable since the early 1990s (Figure 232). Changes in LPUE were often the result of regulatory or fishing practice changes, such as the uptick in 2006 which mirrors the peak in landings from the re-opening of productive beds. Despite the intensity of the fishery, the fact that the LPUE has not fallen may be the result of the fishery moving onto the most productive beds (Figure 230), the ocean quahog growing larger in size, and the reduction in total effort since the early 2000s. Since 2008, the number of valid ocean quahog license holders has fallen from 47 to 29, and hours fished per year by the fleet has dropped by more than half in the past 10 years (Figure 233).

Incidental mortality for Maine ocean quahog is unknown. This is an important topic for future research, especially since Maine has a high level of dredging activity relative to the size of the

fleet. For example, in 2008 the ocean quahog fleet fished approximately 10,776 hours, equivalent to 64,656 tows at ten minutes each. Using standard industry dredge dimensions and tow speeds this level of fishing activity represents 31.42 nm^2 of bottom swept by commercial dredges per year. Five percent is added to ocean quahog landings before calculating exploitation rates to make up for incidental mortality, but it is just an estimate based on the fishery for larger ocean quahog in the rest of the EEZ.

Research Surveys

Surveys of the Maine ocean quahog resource were conducted in 2002, 2005, 2006, 2008 and 2011. With the limited funds dedicated for survey work on ocean quahog, it was decided to focus all survey efforts after 2002 on the two large ocean quahog beds off of Addison (west bed) and Great Wass Island (east bed) that are the primary commercial fishing grounds. Therefore survey estimates of biomass pertain only to these two beds and not to the coast of Maine as a whole. Vessel logbooks and the 2002 independent survey abundance indices show that the majority of the ocean quahog resource, and as a result the majority of fishing activity, occurs here.

The first step in designing the 2005 survey was to establish a 1 km^2 grid overlay (using Arcveiw 3.2) over the two beds. Based on number of days at sea available, it was estimated 260 stations could be completed during the survey, so the centers of 260 1 km^2 grids covering the commercial beds were selected as start points for survey tows. These points were transferred to The Cap'n Voyager Software for use on board the survey vessel.

In 2005 the west bed had been the only open fishing grounds for 3 years due to PSP closures. The east bed had been unfished for 3 years but had previously been a productive ocean quahog fishing ground. The 2006 survey took place 9 months after the east bed reopened. All areas were open during the 2008 and 2011 surveys.

Survey gear and procedures

The 2005 and 2006 surveys were conducted from the commercial vessel F/V Promised Land, a 12.8 m (42 ft) Novi Style dragger piloted by Capt. Michael Danforth. All survey tows during these two years were conducted using a dredge with the following dimensions: cutter bar 0.91 m (36 in), 2.44 m (8 ft) long x 1.83 m (6 ft) wide x 1.22 m (4 ft) high, overall weight 1,361 kg (3,000 lbs), bar spacing all grills 19.05 mm ($\frac{3}{4}$ in). The dredge used by the F/V Promise Land during normal fishing activity was used for the survey. After the 2006 survey, The F/V Promise Land was sold and the captain left the fishery. The vessel contracted for the 2008 and 2011 surveys, The F/V Allyson J4, was about the same size as the F/V Promise Land and the captain, Bruce Porter, had been a ocean quahog fisherman for 24 years. The dredge used in 2008 and 2011 was also built for commercial use with the same specifications as the dredge on the Promise Land. The only difference between the dredges was a custom extension on the Promise Land dredge that could hold more sediment, making it roughly 400 lbs heavier than the one used in 2008 and 2011 (Figure 234). During tow operations it was noted that the teeth on the cutter bar of the new dredge shined to depth of 3 inches just as they had in the original dredge. From this we assumed

that the new dredge was cutting to the same depth as the original. It was also felt that since the survey tows were short (two minutes compared to about ten minutes for a commercial tow) in order to avoid any overfilling and subsequent loss of catch the extensions on the catch box of the original dredge would not give it any advantage over the current dredge.

To conduct a survey station, the vessel approaches the center of the selected tow grid, and if suitable bottom is not present at the predetermined start point, the vessel starts crossing runs within the grid. If towable bottom cannot be found, then the grid location is deemed un-towable, a note is made, and the captain continues on to the next grid. When a suitable tow path is found within a grid the dredge is lowered to the bottom by free- spooling until the ratio of cable length to depth is 3:1. Once the desired cable length is reached the drum is locked, a two minute timer is started and a GPS point taken. The dredge is towed into the current at approximately 3.5 knots for two minutes, a second GPS point is taken and the dredge is brought to the surface. Before it is brought onboard, mud is cleaned from the dredge by steaming in tight circles keeping the dredge in the vessel's prop wash (Figure 235).

Once on board, the dredge is emptied and the catch photographed (Figure 236). The catch is placed on a shaker table (Figure 237), bycatch is noted and all live ocean quahog are sorted out. A 5 liter subsample of ocean quahog is taken from each tow to count and measure. The entire catch is processed if it is less than 5 L. The remainder of the catch is placed in calibrated buckets to determine total catch volume. The number of ocean quahog caught in a tow is estimated by counting the number of clams in the 5 L subsample and expanding to the total volume of the catch. All data are analyzed using Excel with variances calculated using a bootstrap program (10,000 iterations) written by Dr. Yong Chen at the University of Maine, Orono.

Tow distances were determined by The Cap'n Software and were checked using ESRI ArcInfo software. All data from each tow are standardized to a 200 m tow prior to further analysis. Due to a number of reasons such as placement of lobster gear, vessel availability and weather, the number of stations completed per survey has varied from 130 to 183.

Estimating dredge efficiency

Maine dry dredges are less efficient (2 to 17 percent, pers. comm. Robert Russell) than the hydraulic dredges used in the rest of the EEZ (up to 95 percent, Medcof and Caddy (1971)). A reliable estimate of dredge efficiency is needed to convert survey densities to a biomass estimate (NEFSC 2004). To assess the efficiency of the Maine dredge, boxcore samples were taken to directly estimate ocean quahog density, tows were then made in the same area with the survey dredge. Considering only ocean quahog of sizes available to the dredge, the ratio of density estimated from the dredge tows to density estimated from the boxcore samples is an estimate of survey dredge efficiency (Thorarinsdottir and Jacobson 2005). The estimated dredge efficiency was 17.9 percent, with a 95% bootstrap confidence interval of 8.0%-34.4%. More details of the dredge efficiency experiments can be found in Northeast Fisheries Science Center (2009), Appendix B2.

Dredge survey results

The original 2005 survey visited 259 potential tow grids. 71% of the stations were towable (183) and 29% were untowable, mostly due to inappropriate substrate, but sometimes due to the presence of fixed gear. During future surveys only the 183 towable grids were revisited. In 2006 130 tows were completed, in 2008, 181 tows were completed, and in 2011, 183 tows were completed.

Tow distance, catch volume and counts were all standardized to a 200m tow. For all surveys the highest concentration of biomass was in the eastern bed. The eastern section has had the most variable open and close status due to PSP. Substrate data (Figure 238) from Kelley et al. (1998) show the complexity of the substrate in the eastern section with highest ocean quahog densities found near the boundary of hard rocky substrate with gravels, sands or mud. Substrate data collected independently using sidescan imaging showed that substrate information was relatively accurate. However, in some cases substrate labeled as "sand" or "gravel-sand mix" near the most productive tows may have been shell hash from old ocean quahog beds that was seen in boxcores from the same area.

Size frequencies for all subsampled ocean quahog (n = 20,737 in 2005; 2,014 in 2006; 4,055 in 2008, 4,316 in 2011 and 4,045 in 2014) show the ocean quahog in the eastern bed were larger in the first two surveys but have converged in the 2014 survey (Figure 239). Cumulative size frequency distributions and a Kolmogorov-Smirnov test were used to test the null hypothesis that the size frequency distributions in the eastern and western areas were the same (Zar 1999). The null hypothesis was rejected (p=0.001). The size difference between the two beds does not currently exist. The increase in median shell size seen over the past nine years may be a result of the fishery targeting the smallest clam sizes for their markets and moving to new areas once remaining ocean quahog become too large.

Because the two beds had different size composition and densities, abundance and biomass were calculated separately for the two beds before making combined estimates for the entire survey area. Abundance estimates (see Table 38 and Figure 240) are calculated using a dredge efficiency that was estimated by applying 10,000 bootstrapped efficiency estimates from the three boxcore trips to 10,000 average abundance estimates from the surveys, and the swept area of the survey. Biomass estimates are made by dividing the population into 1 mm size bins based on survey size frequencies, then converting SL to W using eq. (5).

Growth and per recruit modeling

A sample of 83 ocean quahog from the east bed was recently (February 2013) aged at the University of Iowa, and although the data are preliminary, there is evidence that ocean quahog are growing faster and larger there than previously thought. Kraus et al. (1992) estimated a growth curve for Maine ocean quahog from the east bed which suggested Maine ocean quahog grow more slowly and to smaller sizes than ocean quahog from the mid-Atlantic bight, while the new data places east bed ocean quahog in the middle of the EEZ and Kraus et al. curves and more closely matches maximum shell heights and observed changing size distributions between years of the survey (Figure 241).

Biological and fishery parameters from a variety of sources were used to carry out a per recruit analysis for ocean quahog in Maine waters in 2005. The length-based per recruit model used was from the NOAA Fisheries Toolbox (Yield Per Recruit program,). Age at length and growth information was taken from Kraus et al. (1992). Length-weight parameters were from the 2002 Maine ocean quahog survey. Size at maturity estimates were based on Rowell et al. (1990) who found that ocean quahog females from Nova Scotia became fully mature at an average size of 49.2 mm. Fishery selectivity was modeled as a linear ramp function that was zero at 37 mm SL and one at 47mm, based on the facility of fitting live ocean quahog of increasing size through the grates of a commercial dredge by hand (19.05 mm, 3/4 in. bar spacing). Clams from 34mm to 38mm SL generally passed through the grate with some getting caught. After 41mm almost all clams were thick enough to be retained. The regression model for shell depth and shell length shows that a 19.05 mm ($\frac{3}{4}$ in) bar spacing is the thickness of an ocean quahog with 38.7 mm SL. The biological reference points estimated in per recruit modeling for ocean quahog were F_{max} =0.0561, $F_{0.1}$=0.0247 and $F_{50\%}$ =0.013 $y^{-}1$ (Figure 242). These may be reassessed when the new age and growth data has been fully vetted and can be used in the model.

Sensitivity analysis shows biological reference points from the per recruit model for ocean quahog are most sensitive to fishery selectivity parameters and, in particular, the length at which ocean quahog in Maine waters become fully recruited to the fishery. Commercial port sampling conducted in 2009 confirmed the size selectivity estimates used in the modeling (Figure 231).

Fishing mortality rate

Fishing mortality is estimated as catch in meat weight/average biomass. The survey biomass is used as a proxy for average biomass, as annual mortality rates are low. Following Northeast Fisheries Science Center (2004), the catch for each year used in fishing mortality estimation was landings plus a 5% allowance for incidental mortality to account for clams that are killed during fishing activity but not harvested. The level of incidental mortality in this fishery is an area for future investigation given the amount of gear contact time in very confined fishing areas. Maine ocean quahog catches, biomass estimates and F estimates for 2005, 2006, 2008 2011 and 2014 are given below.

Year	Med. Biomass (mt meats)	Landings (mt meats)+5% incidental mort.	F
2005	25,862	528	0.020
2006	19,012	642	0.033
2008	16,574	348	0.021
2011	19,577	446	0.023
2014	11,957	217	0.018

Fishing mortality estimates for 2008, 2011 and 2014 are roughly equal or below the F0.1 generated by the per recruit model, but higher than the F50%. It should be noted that Fishing mortality rates have remained low even as the surveyed stock has dropped to half the initial biomass surveyed in 2005. This is most likely a result of the greatly reduced fishing effort in recent years. Total fishing hours fell 67% between 2005 and 2015.

Stock Status

Since the entire population of ocean quahog in U.S. waters is managed as a single stock and overfishing definitions apply to the whole stock, it is not possible to evaluate the status of ocean quahog in Maine as the biomass represents less than 1% of the EEZ stock as a whole. It is not possible to compare or evaluate current biomass levels relative to biological reference points associated with maximum productivity, depleted stock or historical levels because no appropriate biological reference points or historical biomass estimates are available.

$F_{0.1}$ might be a reasonable reference point for managers if the goal is to maximize yield per recruit while preserving some spawning stock. Simulation analysis (Clark 2002) indicates that $F_{50\%}$ (1.3% per year) might be a reasonable reference point for managers if the goal was to preserve enough spawning potential to maintain the resource in the long term. However, preservation of spawning potential may not be necessary if recruitment originates mostly outside of Maine waters.

Table 37: Total Maine landings (ME bu.), landings (where effort and catch>0, +Landings), effort (hrs fished) and landings per unit effort (ME bu./hr, LPUE) from vessel logbooks for all vessel classes combined. Only records with both effort and catch data were used to calculate LPUE, which in most years are 100% of the logbook entries as can be seen by comparing columns two and three below.

Year	Total landings	+Landings	Effort	LPUE
1990	1018	1018	286	3.56
1991	36679	34360	17163	2.00
1992	24839	24519	13469	1.82
1993	17144	17144	5748	2.98
1994	21672	21672	5106	4.24
1995	37912	37912	5747	6.60
1996	47025	47025	8483	5.54
1997	72706	72706	11829	6.15
1998	72466	72152	11745	6.14
1999	93015	92285	11151	8.28
2000	121274	119103	12739	9.35
2001	110272	110272	13511	8.16
2002	147191	147191	19681	7.48
2003	119675	119675	17853	6.70
2004	102187	102187	19022	5.37
2005	100115	100115	17063	5.87
2006	121373	121373	14902	8.14
2007	102006	102006	14018	7.28
2008	66926	66926	10776	6.21
2009	56808	56808	9928	5.72
2010	56469	56469	9727	5.81
2011	65307	65307	9145	7.14
2012	65912	65912	7132	9.24
2013	58734	58734	6325	9.29
2014	46109	46109	5066	9.10
2015	41611	41611	5714	7.28

Table 38: Maine ocean quahog survey median abundance and biomass estimates.

Year	Bed	Med. abundance (10^9)	CV	Med. meat wt. (mt)
2005	west	1.73	39.5%	8653
	east	2.40	40.2%	17208
	combined	4.13	43.9%	25861
2006	west	2.00	41.0%	10166
	east	1.23	40.8%	8846
	combined	3.22	48.4%	19012
2008	west	0.71	40.1%	5471
	east	1.09	40.8%	11103
	combined	1.80	46.8%	16574
2011	west	0.75	40.2%	7053
	east	1.23	40.7%	13277
	combined	1.99	48.2%	20330
2014	west	0.50	40.4%	5904
	east	0.49	41.3%	6053
	combined	0.99	39.9%	11957

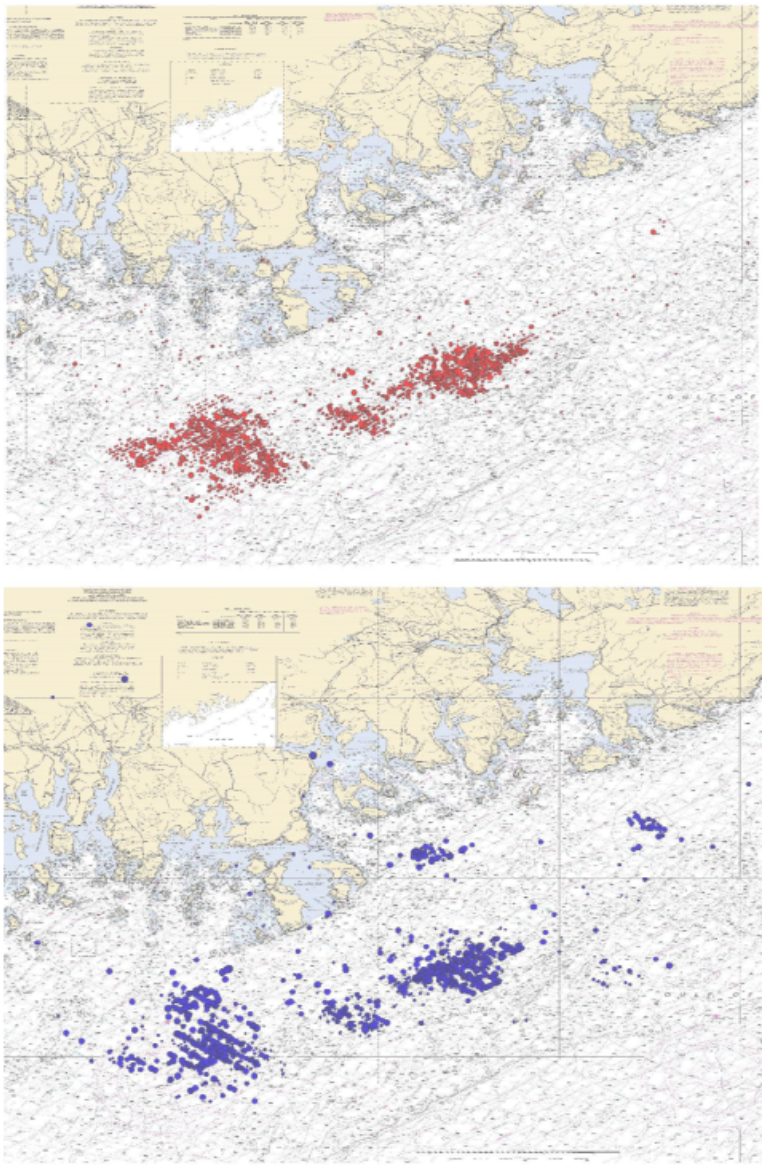

Figure 230: Locations of all reported commercial landings 2003-2008 (top) and 2009-2012 (bottom).

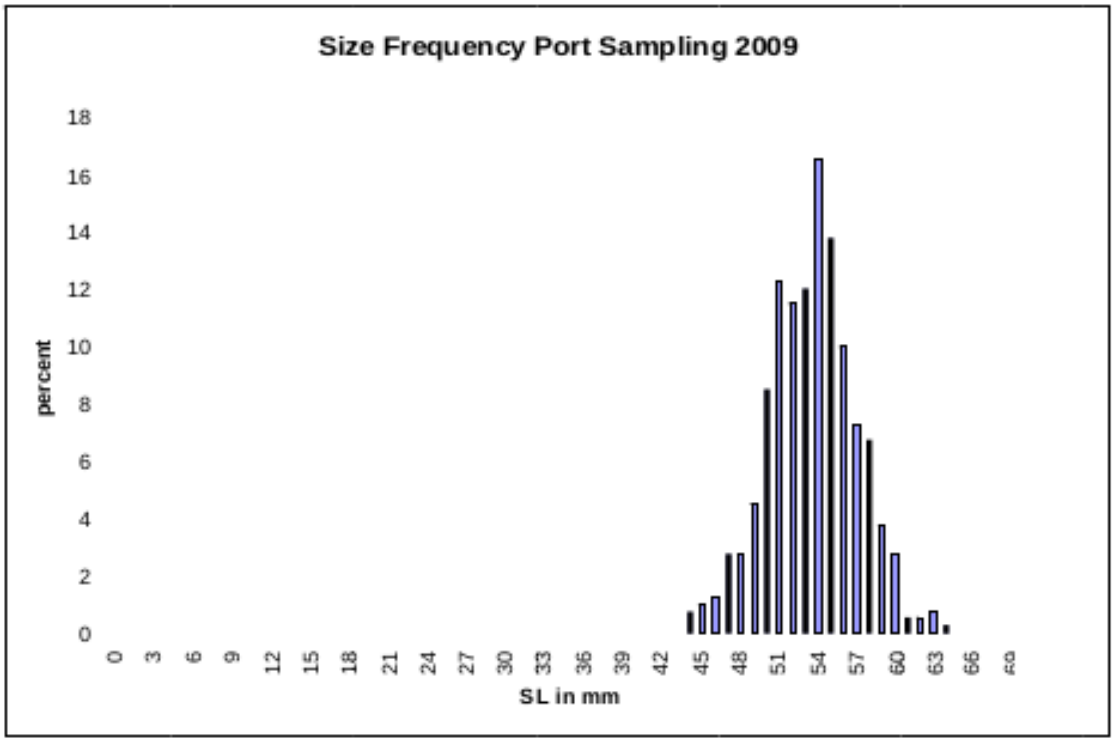

Figure 231: Size frequency for port samples collected in Jan- March 2009 from 6 different vessels.

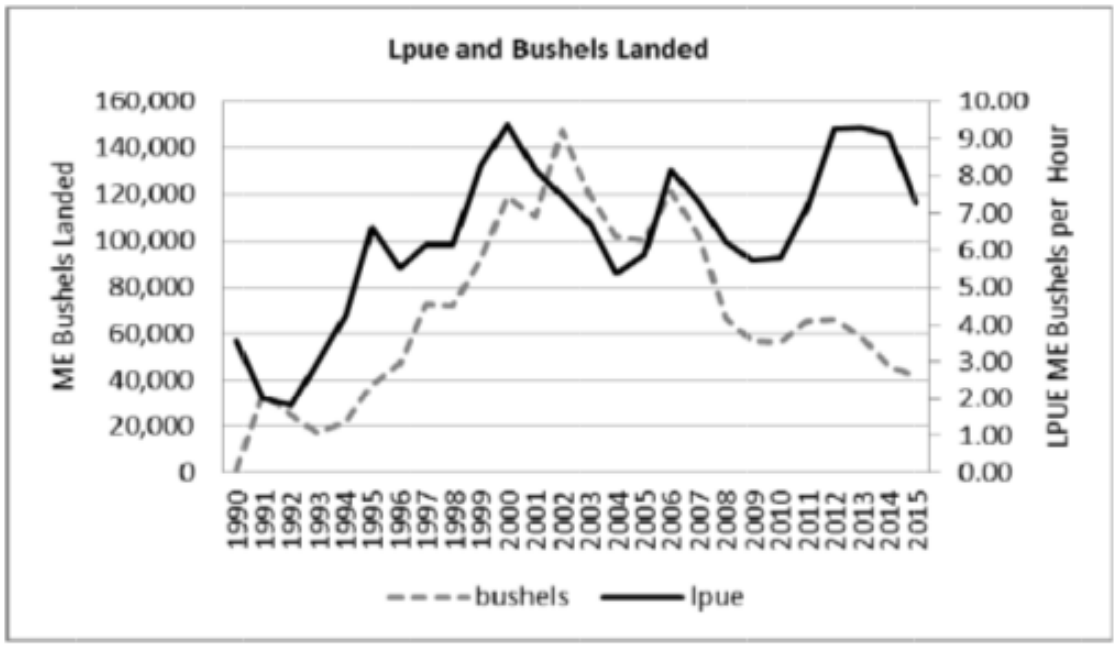

Figure 232: Commercial LPUE and Landings from clam industry logbooks.

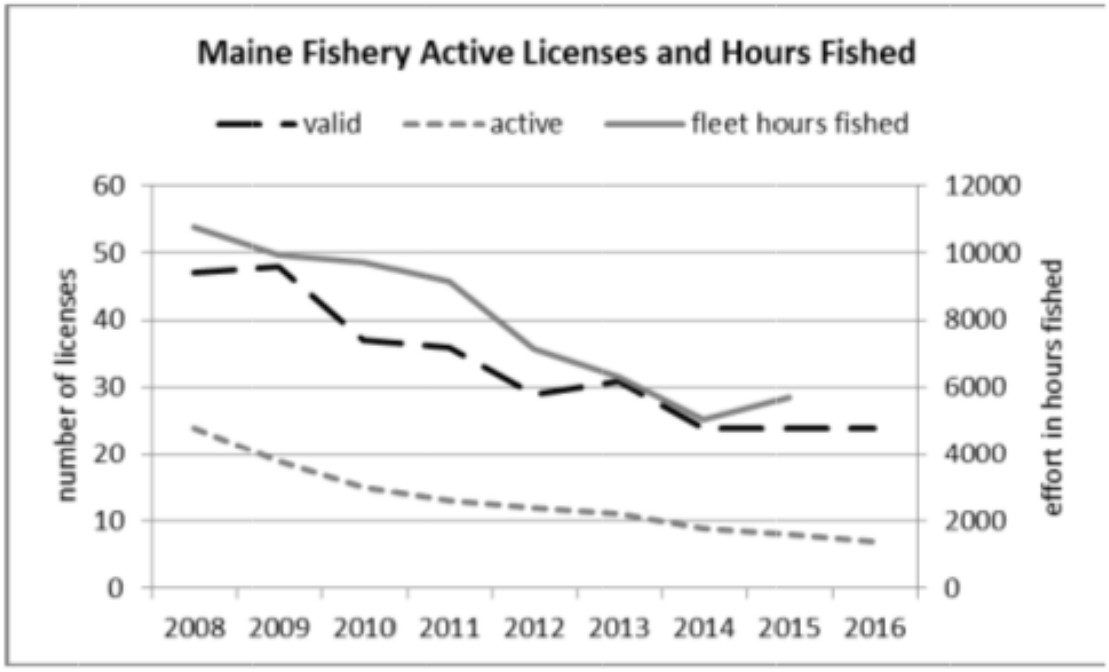

Figure 233: Number of valid and active (fished during the year) ocean quahog licenses for the Maine fishery, with fleet fishing effort through 2015 in thousands of hours shown by the solid line.

Figure 234: At left, the dredge used for the 2005 and 2006 surveys, weighing about 3,000 lbs. At right, the dredge used for the 2008, 2011 and 2014 surveys, weighing about 2,600 lbs.

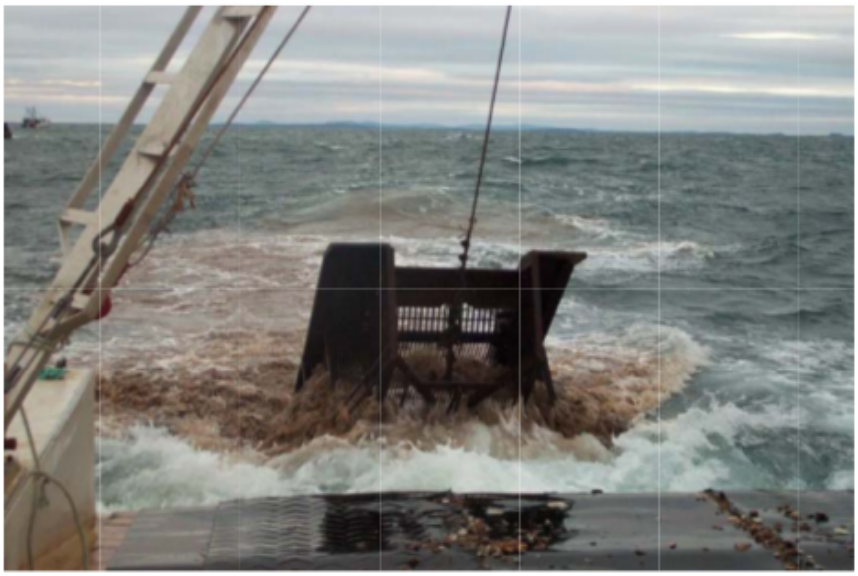

Figure 235: After being brought to the surface, the catch is washed and mud rinsed away in the propeller wash of the survey vessel.

Figure 236: Typical catch from a two-minute survey tow. Note very low bycatch and uniform size of clams.

Figure 237: Processing the survey catch on shaker table, used to remove shell fragments and mud. This step is performed in commercial operations as well.

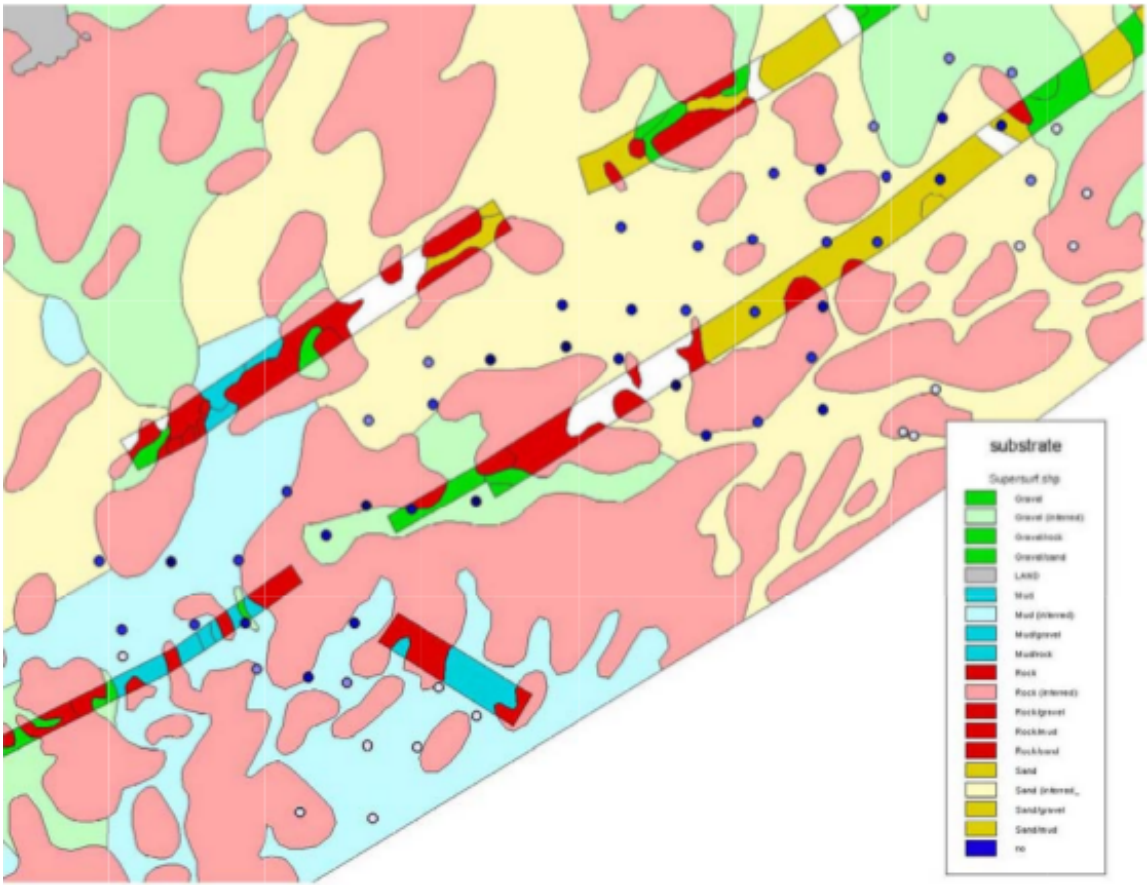

Figure 238: Substrate data from Kelly et al. (1998) showing coincidence of hard bottom edges with high density ocean quahog tows from eastern bed. The tow locations are the dark blue dots, while pink is rock, light blue is mud, yellow is sand and green is gravel substrate.

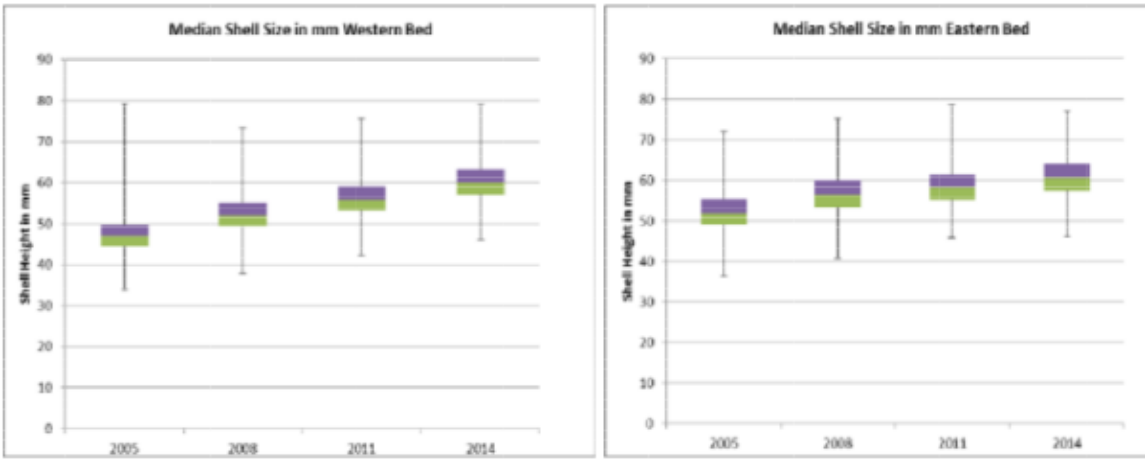

Figure 239: Growth in Maine ocean quahog between the 2005 and 2014 surveys for the west bed (top left) and the east bed (top right), These ocean quahog appear to be growing faster and to a larger size than previous Maine growth data (Kraus et al. 1992) would predict. For instance, the median growth of 13mm between 2005 and 2014 (nine years) in the western bed would be expected to take almost 60 years. There is no longer a size difference between the two beds.

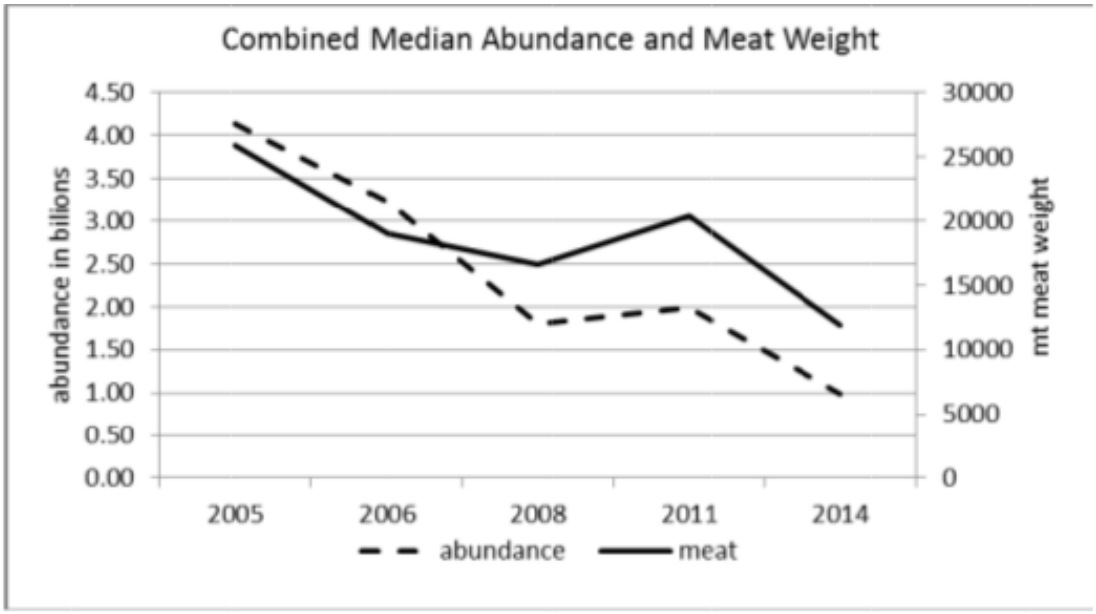

Figure 240: Estimates of abundance in billions of individual ocean quahog (top) and biomass in metric tons of meats for 2005 - 2014.

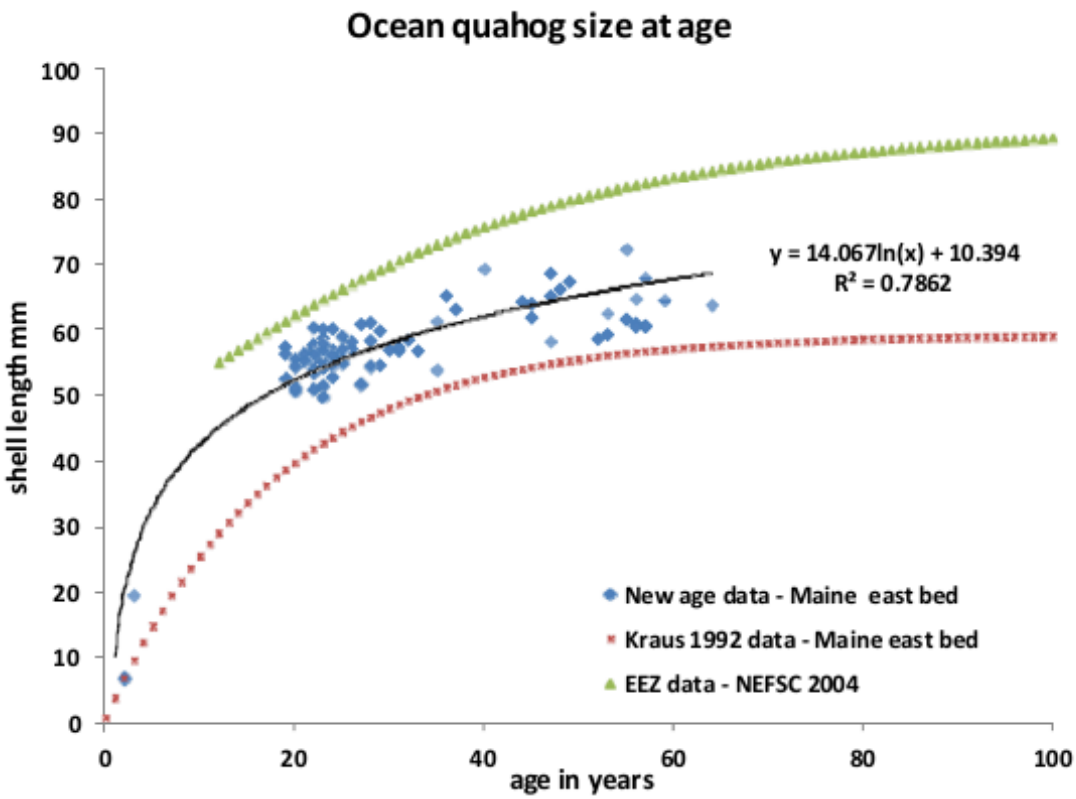

Figure 241: Ocean quahog shell length at age from a major commercial bed off the Maine coast (east bed), and the mid-Atlantic Bight. The blue symbols represent preliminary new age data from the Maine east bed, and the lines represent growth curves from published studies: (Kraus et al. 1992) (Maine east bed, bottom) and (Northeast Fisheries Science Center 2004), (Mid- Atlantic Bight, top).

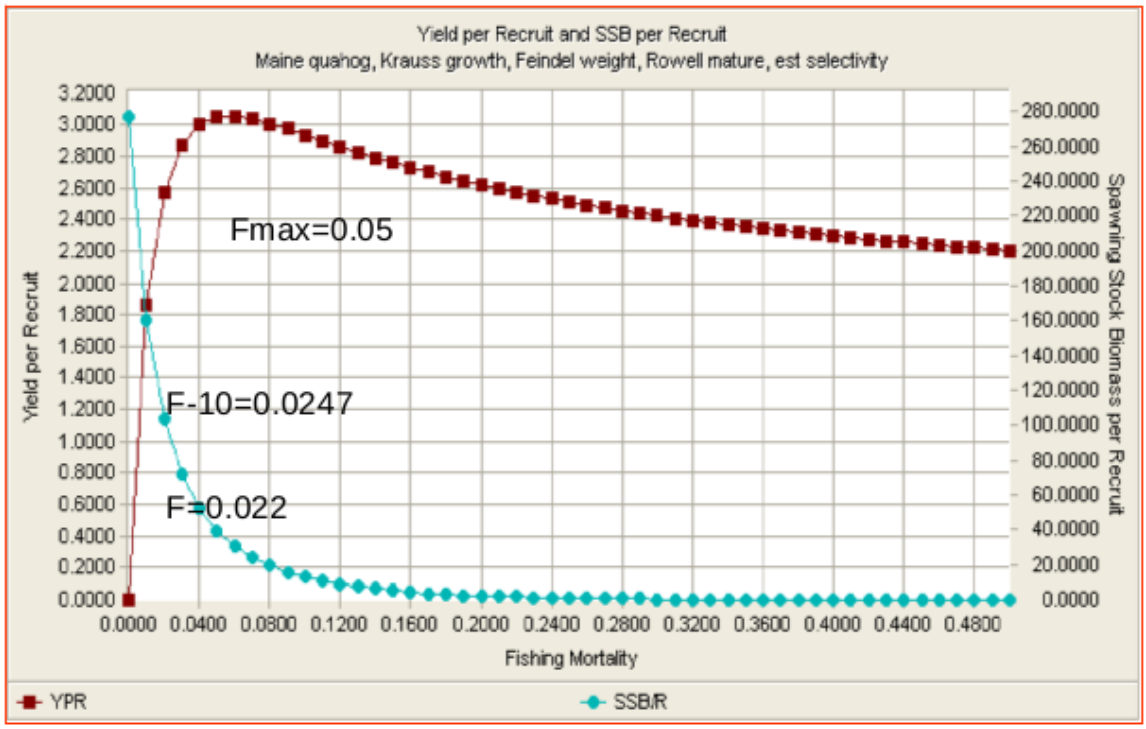

Figure 242: Results of yield per recruit analysis from 2005.

Appendix 8 Changes to MSE

In Hennen (2015) a management strategy evaluation (MSE) was developed to address outstanding questions regarding the optimal biological targets and thresholds for ocean quahog management. The performance of various target fishing mortality rates and various biomass reference points was tested in simulation over short (100 years) and long (1000 years) time horizons. The MSE concluded that the ocean quahog stock could be maintained over a long period of time with a relatively low biomass as long as the fishing mortality rate was kept low ($F < 0.03$). That MSE was modified for purposes of this assessment as described below.

Alterations

The reference point terminology used in Hennen (2015) did not translate well to current ocean quahog management and control rules. Therefore, the biomass (SSB) reference points used for the MSE presented are redefined as SSB_{Target}, which was the desired biomass, below which F is reduced due to management intervention, and SSB_{Cease}, the minimum acceptable biomass below which all fishing is stopped (Figure 243). SSB_{Cease} is not the same as $SSB_{Threshold}$, which is used to determine overfished status in the assessment, because the control rule for ocean quahog and overfishing definitions are not directly related. Overfished status would require managers to establish a rebuilding plan, which has its own set of established rules, but is primarily based on Council action and is beyond the scope of this MSE to model. Importantly, rebuilding plans usually allow some fishing and that may, in fact, fall on the line between SSB_{Cease} and SSB_{Target} such that this MSE does implicitly include the rebuilding plan that follows the control rule exactly. The difference being that the reduction in fishing in this MSE is triggered when the stock falls below SSB_{Target}, rather than at a later point such as $SSB_{Threshold}$.

A coding error resulted in correlated random numbers being generated, which affected the stochastic aspects of the simulated populations in the MSE. This problem was corrected in the current run and resulted in smoother trends in most variables. The difference can be seen in the comparison of Figure 245 and Figure 247.

Hennen (2015) used a growth model that followed Beverton-Holt dynamics

$$L_a = \begin{cases} 0.1 * L_{11} * a + 0.1 & \text{if } \ a < 11 \\ 94.2(1 - e^{(-0.04(a+8.7))}) & \text{if } \ a > 10 \end{cases} \tag{6}$$

The parameters in eq. (6), were averaged from the studies cited in Kilada et al. (2006). W_a and L_a refer to weight and length at age a respectively. Growth was made linear for the first 10 years (from approximately 1 to 5 cm) for lack of better information.

In this revised MSE, growth follows either a Beverton-Holt, or a Tanaka curve (Tanaka (1982); Figure 244).

$$L_a = \frac{1}{\sqrt{0.0019769}} log\left(20.0019769(a-0) + 2\sqrt{0.0019769^2(a-0)^2 + 0.0019769a}\right) + 82.5858 \quad (7)$$

The Tanaka growth equation allows for infinite growth (Figure 244). The affect of the alteration in growth can be seen in Tables 39 - 62 and Figures 248 - 249.

The range of biomass threshold values tested in the current MSE was expanded relative to (Hennen 2015).

Table 39: Average biomass ($\frac{S\hat{S}B}{SSB_0}$) over 100 years of managed fishing simulations at different levels of SSB_{Cease}, the biomass at which fishing is reduced to zero, (columns) and target fishing mortality (rows). Growth followed Beverton-Holt dynamics.

F_{Target}	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5
0.002	1.02	1.03	1.04	1.02	1.04	1.03	1.03	1.02	1.02	0.99
0.007	0.92	0.91	0.92	0.91	0.92	0.91	0.92	0.91	0.90	0.89
0.012	0.81	0.80	0.80	0.81	0.81	0.81	0.80	0.80	0.79	0.78
0.017	0.73	0.72	0.72	0.72	0.72	0.71	0.72	0.71	0.72	0.72
0.022	0.64	0.64	0.64	0.65	0.64	0.64	0.65	0.65	0.66	0.68
0.027	0.58	0.58	0.57	0.58	0.59	0.58	0.60	0.61	0.62	0.64
0.032	0.51	0.53	0.52	0.52	0.53	0.54	0.55	0.58	0.60	0.62
0.037	0.48	0.48	0.48	0.48	0.50	0.51	0.53	0.55	0.58	0.60
0.042	0.45	0.44	0.44	0.45	0.46	0.48	0.51	0.54	0.56	0.59
0.047	0.39	0.40	0.41	0.42	0.44	0.46	0.49	0.52	0.55	0.58
0.052	0.38	0.37	0.39	0.39	0.42	0.45	0.47	0.50	0.54	0.57
0.057	0.35	0.35	0.35	0.38	0.41	0.43	0.46	0.49	0.52	0.56
0.062	0.32	0.33	0.34	0.36	0.39	0.42	0.45	0.48	0.52	0.55
0.067	0.30	0.31	0.33	0.35	0.38	0.40	0.44	0.48	0.51	0.54
0.072	0.29	0.29	0.31	0.34	0.36	0.40	0.43	0.47	0.51	0.54
0.077	0.27	0.28	0.30	0.33	0.36	0.40	0.43	0.46	0.50	0.54
0.082	0.26	0.27	0.29	0.32	0.35	0.39	0.42	0.46	0.49	0.53
0.087	0.24	0.25	0.28	0.31	0.34	0.38	0.41	0.45	0.49	0.53
0.092	0.23	0.25	0.27	0.30	0.34	0.38	0.41	0.45	0.49	0.53
0.097	0.21	0.24	0.26	0.30	0.33	0.37	0.41	0.45	0.48	0.52
0.102	0.20	0.23	0.26	0.30	0.33	0.37	0.40	0.44	0.48	0.52
0.107	0.20	0.23	0.25	0.29	0.32	0.36	0.40	0.44	0.47	0.52
0.112	0.19	0.22	0.25	0.28	0.32	0.36	0.40	0.44	0.48	0.51
0.117	0.19	0.21	0.25	0.28	0.31	0.35	0.39	0.43	0.47	0.51
0.122	0.18	0.21	0.24	0.27	0.31	0.35	0.39	0.42	0.46	0.50
0.127	0.17	0.20	0.23	0.27	0.31	0.35	0.39	0.43	0.46	0.50
0.132	0.17	0.20	0.23	0.27	0.31	0.34	0.38	0.42	0.46	0.50
0.137	0.17	0.19	0.23	0.27	0.30	0.34	0.38	0.42	0.46	0.50
0.142	0.16	0.19	0.23	0.26	0.30	0.34	0.38	0.42	0.45	0.50
0.147	0.16	0.19	0.22	0.26	0.30	0.33	0.37	0.41	0.45	0.50
0.152	0.17	0.19	0.21	0.25	0.30	0.35	0.35	0.38	0.45	0.49

Table 40: Average biomass ($\frac{S\hat{S}B}{SSB_0}$) over 1000 years of fishing simulations at different levels of SSB_{Cease}, the biomass at which fishing is reduced to zero, (columns) and target fishing mortality (rows). Growth followed Beverton-Holt dynamics.

F_{Target}	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5
0.002	0.88	0.87	0.88	0.88	0.87	0.88	0.88	0.87	0.85	0.80
0.007	0.62	0.60	0.60	0.61	0.62	0.60	0.61	0.63	0.63	0.64
0.012	0.41	0.38	0.37	0.42	0.44	0.45	0.49	0.51	0.55	0.58
0.017	0.26	0.26	0.28	0.32	0.36	0.40	0.44	0.49	0.52	0.56
0.022	0.19	0.21	0.24	0.29	0.33	0.37	0.42	0.45	0.50	0.53
0.027	0.15	0.18	0.22	0.27	0.31	0.36	0.40	0.44	0.48	0.53
0.032	0.12	0.16	0.21	0.25	0.30	0.35	0.39	0.43	0.48	0.52
0.037	0.11	0.15	0.20	0.24	0.29	0.33	0.38	0.42	0.47	0.51
0.042	0.10	0.14	0.19	0.23	0.28	0.33	0.37	0.42	0.46	0.51
0.047	0.09	0.14	0.19	0.23	0.28	0.32	0.37	0.42	0.45	0.50
0.052	0.09	0.13	0.18	0.22	0.28	0.32	0.37	0.41	0.46	0.50
0.057	0.08	0.13	0.18	0.22	0.27	0.31	0.36	0.41	0.45	0.49
0.062	0.08	0.13	0.17	0.22	0.27	0.31	0.36	0.40	0.45	0.48
0.067	0.08	0.12	0.17	0.22	0.26	0.31	0.36	0.40	0.44	0.49
0.072	0.08	0.12	0.17	0.21	0.26	0.31	0.35	0.40	0.44	0.48
0.077	0.07	0.12	0.16	0.21	0.26	0.31	0.35	0.39	0.44	0.47
0.082	0.07	0.12	0.16	0.21	0.26	0.30	0.35	0.39	0.43	0.48
0.087	0.07	0.12	0.16	0.21	0.26	0.30	0.34	0.39	0.44	0.49
0.092	0.07	0.12	0.16	0.21	0.25	0.30	0.34	0.38	0.43	0.48
0.097	0.07	0.11	0.16	0.21	0.25	0.30	0.34	0.38	0.43	0.47
0.102	0.07	0.11	0.16	0.21	0.25	0.30	0.34	0.38	0.43	0.47
0.107	0.06	0.11	0.16	0.21	0.24	0.29	0.34	0.38	0.42	0.47
0.112	0.06	0.11	0.15	0.20	0.24	0.29	0.33	0.39	0.43	0.47
0.117	0.06	0.11	0.16	0.20	0.24	0.29	0.33	0.38	0.42	0.47
0.122	0.06	0.11	0.15	0.20	0.25	0.29	0.33	0.37	0.42	0.46
0.127	0.06	0.11	0.15	0.20	0.24	0.29	0.33	0.37	0.42	0.46
0.132	0.06	0.11	0.15	0.20	0.25	0.28	0.33	0.37	0.42	0.46
0.137	0.06	0.11	0.15	0.20	0.24	0.28	0.32	0.37	0.42	0.47
0.142	0.06	0.11	0.15	0.19	0.24	0.28	0.32	0.37	0.42	0.46
0.147	0.06	0.10	0.15	0.19	0.24	0.28	0.33	0.37	0.41	0.47
0.152	0.06	0.10	0.13	0.18	0.25	0.28	0.29	0.35	0.42	0.46

Table 41: Relative average yield over 100 years of managed fishing simulations at different levels of SSB_{Cease}, the biomass at which fishing is reduced to zero, (columns) and target fishing mortality (rows). Growth followed Beverton-Holt dynamics.

F_{Target}	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5
0.002	0.16	0.15	0.16	0.15	0.16	0.15	0.15	0.16	0.16	0.18
0.007	0.35	0.35	0.35	0.34	0.35	0.35	0.35	0.34	0.33	0.31
0.012	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.48	0.47	0.44
0.017	0.63	0.62	0.62	0.62	0.61	0.61	0.61	0.59	0.57	0.52
0.022	0.70	0.71	0.70	0.70	0.70	0.69	0.68	0.64	0.61	0.56
0.027	0.77	0.78	0.77	0.77	0.77	0.74	0.72	0.67	0.62	0.58
0.032	0.81	0.83	0.82	0.81	0.79	0.76	0.72	0.67	0.64	0.60
0.037	0.86	0.86	0.86	0.84	0.82	0.77	0.73	0.70	0.67	0.62
0.042	0.90	0.89	0.87	0.86	0.82	0.77	0.74	0.72	0.67	0.60
0.047	0.89	0.90	0.90	0.86	0.84	0.79	0.74	0.73	0.68	0.65
0.052	0.93	0.91	0.91	0.85	0.82	0.80	0.77	0.73	0.68	0.68
0.057	0.94	0.92	0.88	0.87	0.84	0.81	0.76	0.73	0.69	0.62
0.062	0.95	0.93	0.90	0.86	0.82	0.82	0.77	0.73	0.69	0.65
0.067	0.95	0.92	0.90	0.86	0.84	0.79	0.77	0.74	0.69	0.64
0.072	0.97	0.92	0.89	0.87	0.83	0.80	0.77	0.75	0.70	0.67
0.077	0.95	0.92	0.88	0.86	0.84	0.82	0.79	0.74	0.73	0.71
0.082	0.96	0.92	0.88	0.86	0.85	0.81	0.78	0.74	0.72	0.66
0.087	0.94	0.91	0.88	0.87	0.84	0.82	0.78	0.75	0.71	0.63
0.092	0.95	0.92	0.88	0.87	0.84	0.83	0.79	0.75	0.70	0.69
0.097	0.92	0.92	0.89	0.86	0.82	0.81	0.79	0.75	0.71	0.67
0.102	0.91	0.91	0.89	0.88	0.85	0.81	0.79	0.76	0.72	0.68
0.107	0.94	0.91	0.88	0.85	0.84	0.80	0.78	0.76	0.72	0.70
0.112	0.92	0.91	0.88	0.87	0.85	0.82	0.78	0.75	0.71	0.69
0.117	0.95	0.91	0.90	0.86	0.84	0.81	0.79	0.76	0.73	0.67
0.122	0.94	0.90	0.88	0.84	0.85	0.85	0.80	0.77	0.71	0.65
0.127	0.90	0.90	0.88	0.87	0.85	0.82	0.79	0.77	0.72	0.66
0.132	0.90	0.89	0.88	0.87	0.84	0.82	0.79	0.77	0.71	0.70
0.137	0.92	0.90	0.89	0.86	0.85	0.83	0.79	0.76	0.73	0.72
0.142	0.91	0.90	0.90	0.87	0.85	0.81	0.79	0.77	0.73	0.69
0.147	0.90	0.89	0.90	0.86	0.85	0.82	0.79	0.76	0.74	0.68
0.152	1.00	0.89	0.86	0.83	0.76	0.82	0.74	0.74	0.70	0.67

Table 42: Relative average yield over 1000 years of fishing simulations at different levels of SSB_{Cease}, the biomass at which fishing is reduced to zero, (columns) and target fishing mortality (rows). Growth followed Beverton-Holt dynamics.

F_{Target}	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5
0.002	0.46	0.46	0.48	0.47	0.47	0.46	0.46	0.47	0.46	0.52
0.007	0.80	0.81	0.79	0.81	0.80	0.80	0.78	0.78	0.76	0.72
0.012	0.92	0.88	0.87	0.90	0.94	0.90	0.93	0.88	0.87	0.85
0.017	0.80	0.81	0.83	0.86	0.86	0.96	0.88	0.91	0.85	0.91
0.022	0.75	0.81	0.82	0.85	0.89	0.90	0.96	0.89	0.90	0.91
0.027	0.70	0.69	0.78	0.86	0.87	0.93	0.92	0.93	0.90	0.88
0.032	0.56	0.74	0.75	0.82	0.86	0.91	0.92	0.85	0.89	0.90
0.037	0.59	0.71	0.73	0.86	0.86	0.89	0.87	0.97	0.94	0.91
0.042	0.60	0.70	0.71	0.78	0.87	0.83	0.91	0.93	0.91	0.89
0.047	0.56	0.66	0.76	0.79	0.90	0.88	0.92	0.98	0.90	0.95
0.052	0.58	0.66	0.74	0.77	0.87	0.84	0.95	0.98	0.92	0.95
0.057	0.56	0.65	0.75	0.84	0.86	0.89	0.90	0.95	0.92	0.88
0.062	0.54	0.65	0.77	0.82	0.86	0.93	0.95	0.93	0.92	0.92
0.067	0.53	0.65	0.76	0.83	0.87	0.85	0.89	0.97	0.95	0.89
0.072	0.55	0.65	0.72	0.82	0.84	0.86	0.91	0.91	0.89	0.92
0.077	0.53	0.66	0.71	0.79	0.87	0.93	0.90	0.92	0.93	0.94
0.082	0.53	0.64	0.71	0.80	0.88	0.92	0.90	0.93	0.93	0.93
0.087	0.52	0.66	0.73	0.78	0.85	0.90	0.90	0.96	0.92	0.92
0.092	0.53	0.66	0.75	0.78	0.85	0.94	0.88	0.86	0.93	0.84
0.097	0.52	0.64	0.73	0.85	0.86	0.94	0.94	0.88	0.95	1.00
0.102	0.51	0.65	0.68	0.82	0.84	0.91	0.92	0.94	0.91	0.95
0.107	0.52	0.62	0.72	0.88	0.86	0.86	0.87	0.96	0.89	0.93
0.112	0.51	0.64	0.71	0.79	0.83	0.88	0.91	0.93	0.92	0.99
0.117	0.53	0.64	0.75	0.79	0.85	0.89	0.86	0.97	0.97	0.89
0.122	0.53	0.63	0.73	0.79	0.87	0.93	0.89	0.90	0.90	0.88
0.127	0.51	0.63	0.71	0.76	0.88	0.89	0.91	0.93	0.87	0.94
0.132	0.51	0.64	0.70	0.77	0.85	0.86	0.91	0.94	0.90	0.92
0.137	0.52	0.65	0.72	0.79	0.81	0.91	0.91	0.93	0.94	0.93
0.142	0.47	0.63	0.71	0.81	0.84	0.86	0.87	0.93	0.96	0.85
0.147	0.48	0.62	0.72	0.78	0.85	0.92	0.93	0.89	0.91	0.84
0.152	0.74	0.51	0.48	0.61	0.91	0.68	0.74	0.88	0.99	0.81

Table 43: Relative average coefficient of variation in yield over 100 years of managed fishing simulations at different levels of SSB_{Cease}, the biomass at which fishing is reduced to zero, (columns) and target fishing mortality (rows). Growth followed Beverton-Holt dynamics.

F_{Target}	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5
0.002	0.019	0.019	0.020	0.019	0.020	0.020	0.019	0.021	0.024	0.031
0.007	0.047	0.048	0.046	0.047	0.047	0.048	0.046	0.048	0.050	0.064
0.012	0.077	0.079	0.079	0.077	0.075	0.078	0.079	0.082	0.094	0.148
0.017	0.103	0.106	0.108	0.109	0.110	0.108	0.115	0.129	0.170	0.204
0.022	0.137	0.134	0.139	0.135	0.138	0.144	0.165	0.199	0.232	0.279
0.027	0.163	0.169	0.169	0.169	0.175	0.194	0.224	0.254	0.300	0.335
0.032	0.201	0.191	0.196	0.203	0.229	0.251	0.278	0.316	0.340	0.379
0.037	0.224	0.219	0.226	0.238	0.272	0.296	0.324	0.353	0.382	0.419
0.042	0.242	0.248	0.266	0.290	0.306	0.350	0.368	0.388	0.422	0.478
0.047	0.281	0.277	0.292	0.326	0.342	0.384	0.407	0.417	0.464	0.480
0.052	0.294	0.306	0.329	0.366	0.384	0.410	0.429	0.458	0.497	0.508
0.057	0.328	0.339	0.370	0.385	0.410	0.435	0.474	0.491	0.522	0.575
0.062	0.350	0.374	0.389	0.417	0.443	0.461	0.495	0.519	0.548	0.595
0.067	0.380	0.398	0.424	0.449	0.478	0.508	0.521	0.544	0.591	0.638
0.072	0.395	0.431	0.455	0.476	0.505	0.530	0.550	0.576	0.613	0.653
0.077	0.434	0.455	0.486	0.503	0.513	0.542	0.575	0.610	0.624	0.639
0.082	0.454	0.483	0.512	0.529	0.542	0.564	0.601	0.622	0.662	0.703
0.087	0.481	0.505	0.527	0.549	0.572	0.587	0.623	0.644	0.682	0.739
0.092	0.508	0.518	0.551	0.568	0.593	0.612	0.641	0.680	0.716	0.724
0.097	0.529	0.545	0.566	0.587	0.618	0.641	0.667	0.694	0.732	0.756
0.102	0.561	0.566	0.597	0.607	0.632	0.659	0.676	0.709	0.751	0.783
0.107	0.575	0.596	0.622	0.632	0.657	0.687	0.711	0.725	0.779	0.786
0.112	0.589	0.611	0.630	0.644	0.680	0.698	0.726	0.753	0.804	0.815
0.117	0.592	0.634	0.645	0.679	0.698	0.719	0.748	0.770	0.807	0.856
0.122	0.616	0.649	0.673	0.701	0.703	0.721	0.750	0.787	0.851	0.886
0.127	0.649	0.666	0.690	0.706	0.726	0.748	0.780	0.810	0.868	0.910
0.132	0.674	0.687	0.716	0.722	0.748	0.777	0.800	0.810	0.880	0.890
0.137	0.682	0.695	0.716	0.741	0.765	0.783	0.816	0.850	0.894	0.904
0.142	0.717	0.723	0.734	0.754	0.777	0.815	0.845	0.860	0.902	0.954
0.147	0.737	0.734	0.750	0.781	0.792	0.821	0.854	0.889	0.927	1.000
0.152	0.627	0.777	0.821	0.821	0.817	0.861	0.902	0.880	0.973	0.973

Table 44: Relative average coefficient of variation in yield over 1000 years of fishing simulations at different levels of SSB_{Cease}, the biomass at which fishing is reduced to zero, (columns) and target fishing mortality (rows). Growth followed Beverton-Holt dynamics.

F_{Target}	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5
0.002	0.020	0.020	0.020	0.019	0.021	0.018	0.019	0.023	0.029	0.059
0.007	0.045	0.045	0.046	0.044	0.047	0.049	0.055	0.068	0.092	0.123
0.012	0.082	0.093	0.097	0.087	0.085	0.105	0.108	0.132	0.147	0.180
0.017	0.172	0.153	0.148	0.152	0.162	0.144	0.173	0.167	0.211	0.215
0.022	0.210	0.191	0.201	0.199	0.187	0.194	0.191	0.223	0.230	0.261
0.027	0.267	0.271	0.241	0.224	0.224	0.218	0.246	0.245	0.277	0.276
0.032	0.389	0.282	0.279	0.263	0.249	0.251	0.266	0.292	0.295	0.308
0.037	0.406	0.318	0.319	0.273	0.284	0.284	0.303	0.295	0.304	0.332
0.042	0.407	0.361	0.356	0.323	0.308	0.330	0.316	0.317	0.332	0.366
0.047	0.485	0.394	0.352	0.341	0.309	0.340	0.338	0.327	0.371	0.355
0.052	0.470	0.418	0.375	0.377	0.339	0.375	0.349	0.343	0.384	0.376
0.057	0.533	0.452	0.385	0.364	0.364	0.375	0.384	0.372	0.389	0.424
0.062	0.579	0.474	0.395	0.398	0.391	0.381	0.379	0.390	0.402	0.442
0.067	0.609	0.475	0.428	0.395	0.404	0.415	0.416	0.394	0.434	0.463
0.072	0.617	0.506	0.476	0.437	0.438	0.442	0.431	0.441	0.440	0.459
0.077	0.650	0.518	0.480	0.454	0.424	0.433	0.439	0.456	0.457	0.502
0.082	0.671	0.543	0.507	0.474	0.443	0.441	0.462	0.459	0.479	0.491
0.087	0.728	0.547	0.503	0.500	0.473	0.479	0.487	0.469	0.481	0.507
0.092	0.709	0.561	0.519	0.506	0.486	0.452	0.503	0.511	0.496	0.527
0.097	0.729	0.606	0.541	0.473	0.490	0.476	0.492	0.530	0.504	0.534
0.102	0.789	0.603	0.587	0.513	0.520	0.496	0.500	0.523	0.521	0.550
0.107	0.798	0.644	0.583	0.492	0.529	0.544	0.555	0.507	0.558	0.549
0.112	0.813	0.656	0.596	0.554	0.556	0.530	0.536	0.531	0.569	0.564
0.117	0.798	0.669	0.585	0.575	0.549	0.540	0.580	0.542	0.561	0.619
0.122	0.804	0.684	0.610	0.563	0.542	0.551	0.583	0.575	0.592	0.613
0.127	0.877	0.711	0.648	0.624	0.559	0.561	0.587	0.577	0.630	0.613
0.132	0.869	0.717	0.658	0.631	0.579	0.604	0.569	0.587	0.606	0.627
0.137	0.865	0.715	0.654	0.615	0.610	0.587	0.596	0.603	0.611	0.648
0.142	0.996	0.734	0.671	0.626	0.620	0.629	0.628	0.614	0.629	0.646
0.147	0.981	0.761	0.685	0.649	0.616	0.608	0.614	0.645	0.656	0.688
0.152	0.675	1.000	0.990	0.829	0.504	0.791	0.759	0.648	0.645	0.731

Table 45: Average biomass ($\frac{S\hat{S}B}{SSB_0}$) over 100 years of fishing simulations at different levels of SSB_{Target}, the biomass at which fishing is reduced linearly, (columns) and target fishing mortality (rows). Growth followed Beverton-Holt dynamics.

F_{Target}	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5
0.002	1.02	1.04	1.05	1.03	1.02	1.01	1.04	1.02	1.03	1.03
0.007	0.91	0.88	0.91	0.91	0.92	0.92	0.93	0.92	0.92	0.90
0.012	0.85	0.81	0.80	0.80	0.80	0.80	0.81	0.81	0.81	0.81
0.017	0.75	0.72	0.74	0.72	0.71	0.72	0.72	0.72	0.72	0.71
0.022	0.63	0.66	0.63	0.63	0.63	0.64	0.64	0.64	0.65	0.65
0.027	0.57	0.58	0.60	0.58	0.58	0.58	0.59	0.57	0.59	0.59
0.032	0.48	0.52	0.53	0.52	0.52	0.51	0.52	0.54	0.54	0.54
0.037	0.45	0.49	0.48	0.48	0.48	0.48	0.49	0.50	0.51	0.51
0.042	0.44	0.44	0.44	0.45	0.44	0.45	0.46	0.47	0.48	0.48
0.047	0.39	0.39	0.40	0.41	0.42	0.41	0.42	0.43	0.45	0.45
0.052	0.39	0.36	0.38	0.38	0.38	0.39	0.40	0.42	0.43	0.44
0.057	0.34	0.36	0.34	0.36	0.36	0.38	0.39	0.40	0.41	0.42
0.062	0.31	0.32	0.32	0.33	0.35	0.36	0.37	0.37	0.40	0.42
0.067	0.29	0.30	0.31	0.32	0.33	0.34	0.35	0.37	0.38	0.39
0.072	0.29	0.29	0.30	0.31	0.32	0.33	0.34	0.37	0.37	0.37
0.077	0.28	0.28	0.28	0.29	0.31	0.31	0.34	0.35	0.37	0.38
0.082	0.26	0.25	0.28	0.28	0.29	0.31	0.31	0.34	0.35	0.36
0.087	0.24	0.25	0.26	0.27	0.28	0.30	0.31	0.33	0.34	0.36
0.092	0.22	0.24	0.25	0.25	0.27	0.29	0.30	0.32	0.34	0.35
0.097	0.20	0.24	0.24	0.26	0.26	0.28	0.30	0.30	0.33	0.33
0.102	0.20	0.22	0.23	0.24	0.26	0.26	0.29	0.30	0.32	0.35
0.107	0.19	0.22	0.23	0.24	0.25	0.27	0.31	0.30	0.32	0.35
0.112	0.18	0.20	0.22	0.24	0.25	0.27	0.29	0.30	0.31	0.34
0.117	0.19	0.21	0.22	0.22	0.25	0.26	0.29	0.29	0.33	0.32
0.122	0.19	0.20	0.21	0.21	0.23	0.25	0.27	0.28	0.31	0.31
0.127	0.18	0.19	0.21	0.21	0.23	0.25	0.28	0.27	0.30	0.33
0.132	0.15	0.19	0.20	0.20	0.23	0.25	0.27	0.28	0.30	0.33
0.137	0.16	0.18	0.19	0.21	0.22	0.23	0.26	0.29	0.30	0.31
0.142	0.16	0.18	0.19	0.20	0.22	0.24	0.26	0.26	0.29	0.32
0.147	0.16	0.18	0.18	0.19	0.22	0.24	0.25	0.26	0.30	0.29

Table 46: Average biomass ($\frac{S\hat{S}B}{SSB_0}$) over 1000 years of fishing simulations at different levels of SSB_{Target}, the biomass below which fishing is reduced linearly, (columns) and target fishing mortality (rows). Growth followed Beverton-Holt dynamics.

F_{Target}	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5
0.002	0.87	0.87	0.89	0.87	0.90	0.87	0.87	0.88	0.87	0.87
0.007	0.63	0.58	0.56	0.64	0.60	0.61	0.62	0.59	0.61	0.60
0.012	0.52	0.43	0.44	0.38	0.43	0.40	0.42	0.44	0.44	0.47
0.017	0.19	0.24	0.26	0.27	0.32	0.33	0.34	0.38	0.39	0.39
0.022	0.15	0.20	0.22	0.24	0.25	0.30	0.31	0.33	0.34	0.35
0.027	0.16	0.18	0.19	0.18	0.22	0.25	0.29	0.32	0.32	0.35
0.032	0.12	0.15	0.18	0.19	0.20	0.23	0.25	0.27	0.30	0.33
0.037	0.10	0.15	0.16	0.18	0.19	0.22	0.26	0.27	0.29	0.28
0.042	0.10	0.14	0.16	0.15	0.18	0.22	0.22	0.26	0.28	0.28
0.047	0.09	0.13	0.12	0.15	0.18	0.21	0.21	0.23	0.28	0.28
0.052	0.09	0.12	0.16	0.14	0.17	0.21	0.22	0.24	0.27	0.29
0.057	0.08	0.12	0.14	0.13	0.17	0.21	0.23	0.23	0.27	0.28
0.062	0.07	0.12	0.09	0.13	0.17	0.20	0.22	0.22	0.27	0.31
0.067	0.07	0.11	0.09	0.13	0.17	0.18	0.18	0.23	0.26	0.26
0.072	0.07	0.11	0.09	0.13	0.17	0.20	0.23	0.23	0.26	0.24
0.077	0.07	0.11	0.08	0.12	0.16	0.18	0.22	0.23	0.27	0.28
0.082	0.07	0.11	0.13	0.12	0.16	0.19	0.18	0.22	0.26	0.27
0.087	0.07	0.11	0.13	0.12	0.15	0.19	0.18	0.21	0.24	0.26
0.092	0.06	0.10	0.12	0.12	0.16	0.19	0.20	0.21	0.25	0.27
0.097	0.06	0.10	0.13	0.12	0.15	0.16	0.20	0.21	0.25	0.23
0.102	0.06	0.10	0.07	0.11	0.15	0.16	0.17	0.21	0.24	0.28
0.107	0.06	0.10	0.07	0.11	0.15	0.19	0.22	0.21	0.25	0.27
0.112	0.06	0.10	0.12	0.11	0.15	0.19	0.22	0.21	0.24	0.25
0.117	0.06	0.10	0.12	0.11	0.16	0.18	0.21	0.21	0.25	0.22
0.122	0.06	0.10	0.12	0.11	0.14	0.18	0.17	0.21	0.25	0.24
0.127	0.06	0.10	0.14	0.11	0.15	0.17	0.21	0.21	0.24	0.26
0.132	0.05	0.09	0.11	0.11	0.14	0.18	0.20	0.21	0.24	0.26
0.137	0.05	0.10	0.06	0.11	0.14	0.16	0.19	0.21	0.25	0.24
0.142	0.05	0.10	0.09	0.11	0.14	0.17	0.17	0.20	0.22	0.27
0.147	0.05	0.09	0.07	0.10	0.14	0.17	0.16	0.20	0.24	0.22

Table 47: Relative average yield over 100 years of fishing simulations at different levels of SSB_{Target}, the biomass at which fishing is reduced linearly, (columns) and target fishing mortality (rows). Growth followed Beverton-Holt dynamics.

F_{Target}	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5
0.002	0.15	0.16	0.14	0.14	0.14	0.17	0.17	0.16	0.16	0.15
0.007	0.36	0.36	0.34	0.36	0.35	0.34	0.34	0.34	0.33	0.34
0.012	0.49	0.48	0.49	0.50	0.50	0.49	0.49	0.49	0.49	0.49
0.017	0.66	0.59	0.62	0.61	0.60	0.61	0.61	0.59	0.60	0.60
0.022	0.71	0.70	0.68	0.69	0.69	0.70	0.69	0.69	0.69	0.68
0.027	0.76	0.76	0.77	0.77	0.76	0.76	0.76	0.73	0.74	0.73
0.032	0.77	0.81	0.79	0.82	0.80	0.78	0.78	0.79	0.77	0.77
0.037	0.82	0.89	0.86	0.85	0.84	0.83	0.83	0.80	0.81	0.79
0.042	0.88	0.88	0.87	0.88	0.86	0.86	0.84	0.81	0.81	0.79
0.047	0.88	0.87	0.90	0.87	0.89	0.84	0.83	0.82	0.83	0.80
0.052	0.98	0.88	0.91	0.90	0.88	0.85	0.86	0.84	0.82	0.80
0.057	0.92	0.92	0.90	0.90	0.89	0.86	0.84	0.85	0.81	0.82
0.062	0.92	0.91	0.90	0.89	0.90	0.88	0.84	0.83	0.83	0.81
0.067	0.92	0.91	0.92	0.89	0.89	0.87	0.85	0.83	0.81	0.82
0.072	0.96	0.93	0.93	0.89	0.88	0.87	0.85	0.82	0.83	0.81
0.077	1.00	0.94	0.91	0.89	0.88	0.87	0.86	0.85	0.82	0.82
0.082	0.94	0.87	0.93	0.89	0.86	0.86	0.86	0.85	0.83	0.81
0.087	0.96	0.93	0.95	0.88	0.90	0.87	0.83	0.85	0.84	0.82
0.092	0.90	0.91	0.90	0.86	0.87	0.89	0.85	0.86	0.83	0.83
0.097	0.87	0.91	0.89	0.89	0.88	0.88	0.85	0.85	0.84	0.83
0.102	0.91	0.87	0.91	0.89	0.87	0.88	0.84	0.86	0.82	0.81
0.107	0.88	0.88	0.92	0.89	0.90	0.87	0.85	0.83	0.82	0.82
0.112	0.87	0.85	0.88	0.86	0.88	0.86	0.86	0.85	0.81	0.82
0.117	0.91	0.88	0.92	0.87	0.89	0.87	0.86	0.83	0.83	0.83
0.122	0.96	0.90	0.89	0.90	0.87	0.85	0.86	0.85	0.82	0.83
0.127	0.94	0.86	0.88	0.87	0.86	0.86	0.86	0.84	0.82	0.82
0.132	0.80	0.88	0.86	0.85	0.86	0.86	0.84	0.87	0.83	0.83
0.137	0.90	0.89	0.90	0.89	0.87	0.85	0.84	0.84	0.82	0.84
0.142	0.89	0.88	0.90	0.88	0.88	0.85	0.86	0.85	0.84	0.84
0.147	0.91	0.89	0.88	0.86	0.87	0.85	0.86	0.84	0.84	0.81

Table 48: Relative average yield over 1000 years of fishing simulations at different levels of SSB_{Target}, the biomass below which fishing is reduced linearly, (columns) and target fishing mortality (rows). Growth followed Beverton-Holt dynamics.

F_{Target}	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5
0.002	0.26	0.24	0.24	0.23	0.23	0.26	0.26	0.26	0.25	0.25
0.007	0.42	0.44	0.40	0.46	0.43	0.42	0.43	0.41	0.43	0.43
0.012	0.63	0.48	0.52	0.45	0.50	0.48	0.50	0.49	0.46	0.48
0.017	0.34	0.38	0.42	0.42	0.46	0.47	0.46	0.48	0.45	0.48
0.022	0.31	0.40	0.44	0.43	0.40	0.50	0.47	0.41	0.46	0.47
0.027	0.42	0.46	0.38	0.41	0.40	0.40	0.49	0.46	0.41	0.47
0.032	0.35	0.35	0.37	0.41	0.36	0.42	0.39	0.43	0.45	0.47
0.037	0.28	0.38	0.35	0.42	0.35	0.40	0.39	0.44	0.43	0.46
0.042	0.36	0.38	0.33	0.37	0.38	0.41	0.41	0.40	0.44	0.42
0.047	0.26	0.38	0.32	0.37	0.37	0.39	0.43	0.41	0.44	0.45
0.052	0.31	0.32	0.37	0.36	0.40	0.41	0.39	0.41	0.41	0.42
0.057	0.30	0.33	0.31	0.36	0.35	0.40	0.40	0.42	0.42	0.46
0.062	0.29	0.31	0.31	0.36	0.38	0.42	0.43	0.43	0.45	0.46
0.067	0.25	0.30	0.34	0.41	0.39	0.38	0.38	0.43	0.41	0.44
0.072	0.27	0.31	0.31	0.42	0.40	0.39	0.40	0.40	0.43	0.45
0.077	0.33	0.35	0.33	0.35	0.39	0.42	0.37	0.41	0.42	0.42
0.082	0.27	0.31	0.30	0.35	0.35	0.39	0.39	0.41	0.42	0.45
0.087	0.27	0.36	0.34	0.36	0.34	0.39	0.40	0.42	0.43	0.44
0.092	0.28	0.28	0.33	0.34	0.35	0.41	0.40	0.41	0.44	0.44
0.097	0.27	0.33	0.31	0.35	0.33	0.40	0.41	0.43	0.44	0.44
0.102	0.21	0.32	0.29	0.34	0.36	0.40	0.38	0.41	0.40	0.44
0.107	0.25	0.36	0.35	0.33	0.35	0.40	0.41	0.43	0.39	0.44
0.112	0.25	0.32	0.32	0.31	0.35	0.39	0.41	0.43	0.41	0.44
0.117	0.29	0.28	0.32	0.33	0.40	0.41	0.40	0.42	0.42	0.42
0.122	0.28	0.35	0.32	0.35	0.34	0.41	0.37	0.41	0.42	0.42
0.127	0.28	0.34	0.36	0.32	0.36	0.37	0.40	0.42	0.39	0.42
0.132	0.25	0.32	0.28	0.31	0.33	0.38	0.39	0.41	0.41	0.42
0.137	0.24	0.37	0.31	0.36	0.36	0.40	0.38	0.42	0.40	0.45
0.142	0.27	0.36	0.26	0.33	0.34	0.36	0.36	0.43	0.40	0.46
0.147	0.27	0.30	0.27	0.37	0.31	0.38	0.39	0.40	0.43	0.43

Table 49: Relative average coefficient of variation in yield over 100 years of fishing simulations at different levels of SSB_{Target}, the biomass at which fishing is reduced linearly, (columns) and target fishing mortality (rows). Growth followed Beverton-Holt dynamics.

F_{Target}	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5
0.002	0.020	0.019	0.019	0.018	0.020	0.020	0.020	0.020	0.019	0.020
0.007	0.045	0.051	0.052	0.047	0.047	0.047	0.045	0.048	0.047	0.049
0.012	0.077	0.075	0.078	0.078	0.077	0.080	0.075	0.077	0.079	0.079
0.017	0.111	0.107	0.103	0.109	0.105	0.109	0.109	0.106	0.111	0.110
0.022	0.151	0.138	0.137	0.137	0.143	0.136	0.138	0.141	0.145	0.146
0.027	0.168	0.158	0.166	0.168	0.168	0.178	0.173	0.178	0.187	0.194
0.032	0.211	0.205	0.193	0.195	0.206	0.204	0.214	0.217	0.226	0.229
0.037	0.226	0.216	0.222	0.215	0.231	0.228	0.247	0.263	0.271	0.276
0.042	0.232	0.243	0.257	0.260	0.265	0.271	0.289	0.303	0.307	0.327
0.047	0.296	0.277	0.283	0.286	0.287	0.327	0.319	0.332	0.345	0.358
0.052	0.292	0.321	0.305	0.308	0.330	0.353	0.363	0.380	0.389	0.399
0.057	0.326	0.330	0.348	0.349	0.363	0.374	0.406	0.410	0.425	0.413
0.062	0.348	0.384	0.379	0.385	0.386	0.411	0.425	0.439	0.441	0.456
0.067	0.387	0.406	0.396	0.412	0.407	0.430	0.447	0.465	0.480	0.482
0.072	0.390	0.454	0.412	0.438	0.460	0.469	0.474	0.504	0.495	0.504
0.077	0.406	0.433	0.453	0.465	0.476	0.491	0.505	0.529	0.541	0.542
0.082	0.456	0.483	0.475	0.501	0.512	0.517	0.532	0.538	0.553	0.557
0.087	0.483	0.467	0.491	0.529	0.529	0.542	0.562	0.558	0.571	0.577
0.092	0.514	0.545	0.535	0.551	0.571	0.562	0.573	0.591	0.586	0.603
0.097	0.548	0.558	0.553	0.550	0.577	0.575	0.594	0.599	0.605	0.623
0.102	0.607	0.554	0.568	0.591	0.571	0.586	0.629	0.621	0.646	0.656
0.107	0.603	0.602	0.574	0.606	0.618	0.624	0.639	0.655	0.673	0.672
0.112	0.626	0.623	0.598	0.643	0.639	0.658	0.658	0.667	0.694	0.691
0.117	0.586	0.646	0.626	0.652	0.650	0.652	0.696	0.695	0.704	0.701
0.122	0.618	0.627	0.651	0.664	0.679	0.684	0.700	0.712	0.725	0.717
0.127	0.629	0.670	0.680	0.704	0.690	0.705	0.715	0.718	0.747	0.746
0.132	0.717	0.687	0.715	0.709	0.721	0.728	0.744	0.733	0.743	0.766
0.137	0.718	0.681	0.699	0.717	0.719	0.728	0.756	0.758	0.793	0.765
0.142	0.704	0.719	0.723	0.742	0.751	0.763	0.769	0.765	0.791	0.784
0.147	0.742	0.728	0.758	0.738	0.782	0.775	0.780	0.796	0.799	0.828

Table 50: Relative average coefficient of variation in yield over 1000 years of fishing simulations at different levels of SSB_{Target}, the biomass below which fishing is reduced linearly, (columns) and target fishing mortality (rows). Growth followed Beverton-Holt dynamics.

F_{Target}	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5
0.002	0.018	0.020	0.018	0.017	0.018	0.018	0.020	0.018	0.019	0.020
0.007	0.034	0.047	0.053	0.036	0.045	0.042	0.043	0.051	0.043	0.046
0.012	0.047	0.077	0.069	0.092	0.071	0.088	0.081	0.098	0.109	0.107
0.017	0.250	0.182	0.166	0.171	0.140	0.134	0.136	0.134	0.159	0.151
0.022	0.300	0.224	0.182	0.194	0.211	0.171	0.183	0.210	0.196	0.185
0.027	0.210	0.189	0.262	0.231	0.243	0.256	0.209	0.221	0.255	0.225
0.032	0.315	0.320	0.300	0.263	0.310	0.264	0.279	0.279	0.262	0.253
0.037	0.431	0.279	0.327	0.294	0.349	0.305	0.325	0.295	0.298	0.276
0.042	0.324	0.340	0.359	0.348	0.338	0.317	0.335	0.340	0.318	0.332
0.047	0.524	0.368	0.434	0.364	0.350	0.372	0.336	0.347	0.339	0.331
0.052	0.462	0.436	0.391	0.377	0.383	0.369	0.389	0.374	0.378	0.373
0.057	0.489	0.442	0.470	0.417	0.437	0.411	0.414	0.392	0.401	0.362
0.062	0.522	0.482	0.497	0.432	0.424	0.398	0.404	0.405	0.390	0.393
0.067	0.609	0.544	0.474	0.413	0.435	0.426	0.458	0.410	0.427	0.404
0.072	0.646	0.597	0.568	0.419	0.443	0.460	0.465	0.476	0.437	0.417
0.077	0.505	0.494	0.521	0.500	0.490	0.444	0.499	0.473	0.471	0.471
0.082	0.681	0.614	0.600	0.519	0.539	0.477	0.487	0.473	0.475	0.453
0.087	0.654	0.489	0.568	0.558	0.584	0.513	0.497	0.481	0.473	0.482
0.092	0.666	0.699	0.610	0.569	0.558	0.493	0.514	0.519	0.494	0.463
0.097	0.678	0.597	0.636	0.554	0.607	0.514	0.527	0.491	0.506	0.492
0.102	0.950	0.621	0.710	0.582	0.584	0.528	0.570	0.543	0.561	0.526
0.107	0.836	0.586	0.580	0.644	0.643	0.561	0.551	0.525	0.573	0.521
0.112	0.862	0.655	0.670	0.714	0.617	0.585	0.578	0.553	0.577	0.525
0.117	0.707	0.795	0.692	0.682	0.577	0.550	0.617	0.560	0.597	0.551
0.122	0.928	0.619	0.690	0.697	0.668	0.564	0.610	0.594	0.585	0.563
0.127	0.717	0.668	0.666	0.723	0.634	0.633	0.621	0.577	0.635	0.602
0.132	0.835	0.753	0.787	0.742	0.696	0.637	0.628	0.616	0.615	0.601
0.137	1.000	0.630	0.775	0.685	0.680	0.638	0.660	0.606	0.670	0.582
0.142	0.881	0.677	0.925	0.705	0.698	0.687	0.686	0.615	0.665	0.599
0.147	0.894	0.850	0.878	0.694	0.783	0.669	0.668	0.639	0.634	0.633

Table 51: Average biomass ($\frac{S\hat{S}B}{SSB_0}$) over 100 years of fishing simulations at different levels of SSB_{Cease}, the biomass at which fishing is reduced to zero, (columns) and target fishing mortality (rows). Growth followed a Tanaka curve based on estimates of ocean quahog from Long Island.

F_{Target}	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5
0.002	1.04	1.04	1.04	1.05	1.04	1.03	1.01	0.97	0.51	0.55
0.007	0.94	0.94	0.94	0.94	0.94	0.94	0.92	0.90	0.58	0.56
0.012	0.84	0.85	0.86	0.85	0.86	0.85	0.83	0.81	0.73	0.57
0.017	0.78	0.79	0.77	0.78	0.78	0.78	0.75	0.72	0.65	0.56
0.022	0.71	0.71	0.72	0.70	0.71	0.71	0.68	0.67	0.65	0.58
0.027	0.66	0.66	0.66	0.66	0.67	0.65	0.64	0.64	0.62	0.60
0.032	0.60	0.62	0.61	0.62	0.61	0.61	0.62	0.59	0.61	0.61
0.037	0.57	0.57	0.58	0.57	0.58	0.58	0.57	0.58	0.59	0.60
0.042	0.54	0.53	0.53	0.54	0.54	0.55	0.56	0.55	0.57	0.58
0.047	0.51	0.49	0.50	0.50	0.50	0.51	0.52	0.53	0.56	0.58
0.052	0.47	0.47	0.48	0.49	0.48	0.50	0.51	0.52	0.55	0.57
0.057	0.45	0.45	0.45	0.45	0.46	0.48	0.50	0.51	0.54	0.57
0.062	0.40	0.42	0.42	0.43	0.44	0.46	0.49	0.51	0.53	0.56
0.067	0.41	0.40	0.41	0.41	0.43	0.45	0.48	0.49	0.52	0.56
0.072	0.38	0.38	0.39	0.39	0.41	0.44	0.46	0.49	0.52	0.54
0.077	0.36	0.37	0.37	0.38	0.40	0.43	0.45	0.48	0.51	0.53
0.082	0.34	0.35	0.36	0.38	0.40	0.42	0.45	0.48	0.51	0.54
0.087	0.33	0.33	0.35	0.36	0.39	0.41	0.44	0.47	0.50	0.54
0.092	0.32	0.32	0.33	0.36	0.37	0.41	0.43	0.46	0.49	0.52
0.097	0.30	0.31	0.33	0.34	0.37	0.41	0.43	0.46	0.49	0.53
0.102	0.30	0.30	0.31	0.34	0.36	0.39	0.43	0.45	0.49	0.52
0.107	0.28	0.29	0.31	0.33	0.36	0.39	0.42	0.45	0.48	0.52
0.112	0.28	0.28	0.29	0.32	0.35	0.38	0.42	0.45	0.48	0.50
0.117	0.27	0.27	0.29	0.32	0.35	0.38	0.41	0.45	0.49	0.51
0.122	0.26	0.27	0.28	0.31	0.35	0.38	0.41	0.44	0.47	0.51
0.127	0.24	0.26	0.28	0.31	0.34	0.37	0.41	0.44	0.47	0.51
0.132	0.24	0.24	0.27	0.30	0.33	0.37	0.40	0.44	0.48	0.49
0.137	0.24	0.24	0.28	0.30	0.33	0.36	0.40	0.43	0.47	0.49
0.142	0.22	0.24	0.26	0.29	0.33	0.37	0.40	0.43	0.47	0.50
0.147	0.22	0.23	0.26	0.29	0.33	0.36	0.39	0.43	0.46	0.50

Table 52: Average biomass ($\frac{S\hat{S}B}{SSB_0}$) over 1000 years of fishing simulations at different levels of SSB_{Cease}, the biomass at which fishing is reduced to zero, (columns) and target fishing mortality (rows). Growth followed a Tanaka curve based on estimates of ocean quahog from Long Island.

F_{Target}	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5
0.002	0.90	0.90	0.90	0.91	0.92	0.88	0.86	0.79	0.51	0.54
0.007	0.65	0.65	0.66	0.64	0.64	0.66	0.62	0.60	0.53	0.55
0.012	0.45	0.48	0.49	0.48	0.48	0.50	0.50	0.51	0.52	0.54
0.017	0.30	0.34	0.33	0.36	0.39	0.43	0.44	0.47	0.50	0.53
0.022	0.26	0.27	0.29	0.32	0.35	0.40	0.42	0.46	0.49	0.53
0.027	0.19	0.22	0.26	0.29	0.33	0.37	0.41	0.44	0.48	0.52
0.032	0.16	0.19	0.23	0.27	0.31	0.36	0.40	0.44	0.48	0.52
0.037	0.15	0.18	0.22	0.26	0.30	0.35	0.39	0.43	0.47	0.50
0.042	0.13	0.17	0.21	0.25	0.29	0.34	0.38	0.42	0.46	0.50
0.047	0.13	0.16	0.20	0.24	0.29	0.33	0.38	0.42	0.46	0.50
0.052	0.11	0.15	0.20	0.24	0.28	0.33	0.37	0.41	0.46	0.49
0.057	0.10	0.15	0.19	0.23	0.28	0.32	0.37	0.41	0.45	0.49
0.062	0.10	0.14	0.18	0.23	0.27	0.32	0.36	0.41	0.45	0.48
0.067	0.10	0.14	0.18	0.23	0.27	0.32	0.36	0.40	0.45	0.48
0.072	0.09	0.13	0.18	0.22	0.27	0.31	0.36	0.40	0.44	0.49
0.077	0.09	0.13	0.18	0.22	0.27	0.31	0.36	0.40	0.44	0.46
0.082	0.08	0.13	0.17	0.22	0.26	0.31	0.36	0.40	0.44	0.47
0.087	0.08	0.13	0.17	0.22	0.26	0.31	0.35	0.39	0.43	0.48
0.092	0.08	0.12	0.17	0.22	0.26	0.30	0.35	0.39	0.43	0.47
0.097	0.08	0.12	0.17	0.21	0.26	0.30	0.35	0.39	0.43	0.46
0.102	0.08	0.12	0.17	0.21	0.26	0.30	0.35	0.38	0.43	0.46
0.107	0.07	0.12	0.17	0.21	0.26	0.30	0.34	0.38	0.43	0.47
0.112	0.07	0.12	0.16	0.21	0.25	0.30	0.34	0.39	0.42	0.45
0.117	0.07	0.12	0.16	0.21	0.26	0.29	0.34	0.38	0.43	0.47
0.122	0.07	0.12	0.16	0.21	0.25	0.29	0.34	0.38	0.41	0.46
0.127	0.07	0.12	0.16	0.21	0.25	0.29	0.34	0.38	0.42	0.46
0.132	0.07	0.11	0.16	0.20	0.25	0.29	0.34	0.38	0.43	0.44
0.137	0.07	0.11	0.16	0.21	0.25	0.29	0.34	0.38	0.42	0.45
0.142	0.07	0.11	0.16	0.20	0.25	0.29	0.33	0.38	0.42	0.45
0.147	0.07	0.11	0.16	0.20	0.25	0.29	0.33	0.37	0.42	0.43

Table 53: Relative average yield over 100 years of fishing simulations at different levels of SSB_{Cease}, the biomass at which fishing is reduced to zero, (columns) and target fishing mortality (rows). Growth followed a Tanaka curve based on estimates of ocean quahog from Long Island.

F_{Target}	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5
0.002	0.11	0.12	0.12	0.11	0.11	0.12	0.12	0.12	0.12	0.12
0.007	0.25	0.26	0.26	0.26	0.26	0.25	0.25	0.23	0.22	0.21
0.012	0.39	0.39	0.39	0.39	0.39	0.39	0.38	0.36	0.33	0.27
0.017	0.49	0.49	0.49	0.49	0.49	0.49	0.48	0.45	0.39	0.31
0.022	0.57	0.57	0.57	0.57	0.57	0.57	0.54	0.52	0.47	0.36
0.027	0.64	0.64	0.64	0.64	0.64	0.63	0.60	0.57	0.49	0.41
0.032	0.69	0.69	0.70	0.70	0.69	0.67	0.67	0.57	0.54	0.48
0.037	0.74	0.74	0.74	0.74	0.74	0.72	0.66	0.61	0.56	0.48
0.042	0.78	0.78	0.78	0.78	0.76	0.75	0.70	0.61	0.57	0.49
0.047	0.82	0.80	0.82	0.80	0.77	0.74	0.69	0.61	0.58	0.53
0.052	0.85	0.84	0.85	0.84	0.81	0.76	0.71	0.65	0.61	0.55
0.057	0.88	0.87	0.88	0.84	0.81	0.76	0.72	0.65	0.60	0.55
0.062	0.86	0.89	0.88	0.86	0.80	0.76	0.74	0.66	0.60	0.59
0.067	0.92	0.91	0.90	0.86	0.81	0.77	0.74	0.66	0.59	0.60
0.072	0.91	0.91	0.91	0.86	0.82	0.78	0.72	0.66	0.60	0.59
0.077	0.92	0.93	0.91	0.85	0.84	0.76	0.73	0.71	0.63	0.57
0.082	0.93	0.94	0.92	0.89	0.83	0.78	0.75	0.69	0.63	0.59
0.087	0.97	0.93	0.94	0.88	0.84	0.80	0.73	0.69	0.64	0.56
0.092	0.96	0.95	0.91	0.91	0.80	0.80	0.72	0.66	0.61	0.56
0.097	0.97	0.96	0.92	0.88	0.86	0.82	0.74	0.68	0.63	0.59
0.102	0.98	0.96	0.93	0.87	0.86	0.80	0.74	0.68	0.63	0.59
0.107	0.96	0.97	0.94	0.89	0.85	0.80	0.75	0.68	0.62	0.61
0.112	1.00	0.95	0.90	0.89	0.83	0.79	0.74	0.69	0.66	0.60
0.117	0.99	0.96	0.91	0.88	0.84	0.80	0.74	0.68	0.64	0.57
0.122	0.99	0.98	0.90	0.89	0.87	0.80	0.72	0.69	0.64	0.60
0.127	0.99	0.95	0.94	0.88	0.87	0.82	0.74	0.70	0.63	0.62
0.132	0.98	0.92	0.91	0.88	0.84	0.80	0.74	0.73	0.63	0.61
0.137	1.00	0.93	0.95	0.89	0.86	0.81	0.75	0.72	0.61	0.61
0.142	0.99	0.96	0.92	0.88	0.86	0.83	0.76	0.71	0.67	0.61
0.147	0.99	0.94	0.92	0.89	0.86	0.82	0.72	0.69	0.64	0.60

Table 54: Relative average yield over 1000 years of fishing simulations at different levels of SSB_{Cease}, the biomass at which fishing is reduced to zero, (columns) and target fishing mortality (rows). Growth followed a Tanaka curve based on estimates of ocean quahog from Long Island.

F_{Target}	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5
0.002	0.39	0.42	0.42	0.38	0.37	0.40	0.41	0.42	0.43	0.44
0.007	0.68	0.69	0.69	0.70	0.70	0.68	0.67	0.67	0.66	0.68
0.012	0.86	0.88	0.90	0.87	0.86	0.86	0.81	0.80	0.83	0.82
0.017	0.79	0.87	0.82	0.84	0.84	0.87	0.81	0.84	0.89	0.84
0.022	0.82	0.84	0.85	0.84	0.85	0.90	0.84	0.92	0.92	0.89
0.027	0.71	0.76	0.86	0.85	0.85	0.86	0.88	0.90	0.89	0.88
0.032	0.69	0.76	0.81	0.84	0.87	0.88	0.90	0.87	0.91	0.91
0.037	0.72	0.74	0.81	0.85	0.88	0.85	0.88	0.85	0.85	0.84
0.042	0.67	0.75	0.77	0.88	0.84	0.87	0.89	0.89	0.95	0.93
0.047	0.69	0.73	0.76	0.78	0.83	0.84	0.86	0.81	0.85	0.94
0.052	0.63	0.71	0.80	0.85	0.87	0.94	0.90	0.88	0.87	0.80
0.057	0.61	0.72	0.81	0.81	0.80	0.86	0.88	0.86	0.88	0.83
0.062	0.59	0.70	0.74	0.84	0.82	0.85	0.85	0.88	0.85	0.97
0.067	0.65	0.71	0.73	0.81	0.90	0.88	0.91	0.86	0.86	0.92
0.072	0.60	0.66	0.76	0.81	0.82	0.87	0.89	0.85	0.90	0.91
0.077	0.59	0.68	0.74	0.82	0.83	0.81	0.84	0.89	0.84	0.93
0.082	0.59	0.68	0.78	0.85	0.82	0.86	0.92	0.84	0.84	0.76
0.087	0.63	0.68	0.76	0.84	0.85	0.84	0.86	0.84	0.80	0.83
0.092	0.61	0.69	0.75	0.84	0.80	0.89	0.84	0.82	0.78	1.00
0.097	0.57	0.68	0.75	0.80	0.87	0.89	0.88	0.81	0.77	0.80
0.102	0.60	0.67	0.75	0.81	0.78	0.79	0.88	0.86	0.82	0.78
0.107	0.57	0.69	0.80	0.81	0.86	0.87	0.83	0.81	0.84	0.84
0.112	0.59	0.65	0.72	0.78	0.80	0.84	0.83	0.91	0.87	0.84
0.117	0.58	0.65	0.73	0.82	0.79	0.84	0.83	0.84	0.85	0.76
0.122	0.61	0.65	0.75	0.81	0.86	0.80	0.82	0.82	0.81	0.76
0.127	0.56	0.68	0.75	0.80	0.82	0.91	0.82	0.90	0.74	0.90
0.132	0.55	0.65	0.75	0.77	0.78	0.85	0.87	0.88	0.81	0.81
0.137	0.63	0.65	0.76	0.82	0.85	0.87	0.83	0.90	0.79	0.86
0.142	0.59	0.67	0.72	0.75	0.84	0.89	0.88	0.84	0.84	0.77
0.147	0.56	0.65	0.73	0.78	0.84	0.91	0.79	0.83	0.78	0.74

Table 55: Relative average coefficient of variation in yield over 100 years of fishing simulations at different levels of SSB_{Cease}, the biomass at which fishing is reduced to zero, (columns) and target fishing mortality (rows). Growth followed a Tanaka curve based on estimates of ocean quahog from Long Island.

F_{Target}	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5
0.002	0.016	0.017	0.017	0.016	0.015	0.018	0.021	0.029	0.212	0.273
0.007	0.043	0.042	0.041	0.042	0.043	0.042	0.046	0.055	0.104	0.148
0.012	0.070	0.067	0.067	0.065	0.068	0.070	0.074	0.084	0.123	0.172
0.017	0.093	0.093	0.096	0.094	0.093	0.093	0.109	0.128	0.179	0.261
0.022	0.119	0.118	0.113	0.119	0.120	0.121	0.141	0.164	0.212	0.306
0.027	0.145	0.144	0.138	0.142	0.138	0.147	0.174	0.215	0.280	0.371
0.032	0.171	0.163	0.166	0.160	0.162	0.177	0.199	0.275	0.318	0.401
0.037	0.184	0.182	0.181	0.182	0.189	0.210	0.267	0.316	0.359	0.456
0.042	0.203	0.208	0.205	0.203	0.222	0.243	0.295	0.364	0.392	0.468
0.047	0.208	0.228	0.228	0.230	0.260	0.297	0.339	0.420	0.436	0.491
0.052	0.242	0.242	0.241	0.244	0.276	0.317	0.363	0.426	0.473	0.557
0.057	0.257	0.261	0.258	0.284	0.322	0.365	0.398	0.468	0.503	0.566
0.062	0.293	0.284	0.286	0.306	0.357	0.401	0.416	0.479	0.533	0.561
0.067	0.284	0.299	0.308	0.330	0.374	0.403	0.438	0.512	0.568	0.608
0.072	0.317	0.318	0.320	0.379	0.411	0.438	0.487	0.549	0.600	0.618
0.077	0.340	0.335	0.354	0.391	0.427	0.476	0.507	0.534	0.618	0.648
0.082	0.355	0.353	0.373	0.397	0.448	0.500	0.511	0.575	0.637	0.655
0.087	0.370	0.382	0.391	0.433	0.460	0.509	0.543	0.602	0.663	0.730
0.092	0.376	0.391	0.430	0.430	0.507	0.521	0.599	0.654	0.698	0.706
0.097	0.395	0.413	0.438	0.475	0.498	0.526	0.602	0.664	0.702	0.759
0.102	0.412	0.423	0.453	0.502	0.536	0.572	0.610	0.677	0.718	0.812
0.107	0.442	0.441	0.467	0.507	0.536	0.586	0.644	0.711	0.756	0.783
0.112	0.432	0.470	0.513	0.533	0.579	0.622	0.664	0.719	0.767	0.823
0.117	0.464	0.480	0.536	0.556	0.583	0.620	0.690	0.730	0.793	0.905
0.122	0.469	0.492	0.528	0.557	0.582	0.651	0.720	0.753	0.818	0.864
0.127	0.496	0.521	0.533	0.590	0.610	0.643	0.735	0.761	0.839	0.837
0.132	0.512	0.557	0.577	0.603	0.639	0.685	0.729	0.770	0.886	0.928
0.137	0.501	0.569	0.563	0.612	0.640	0.697	0.760	0.797	0.930	0.940
0.142	0.535	0.561	0.595	0.636	0.648	0.697	0.764	0.831	0.870	0.960
0.147	0.543	0.590	0.616	0.641	0.670	0.710	0.804	0.854	0.925	1.000

Table 56: Relative average coefficient of variation in yield over 1000 years of fishing simulations at different levels of SSB_{Cease}, the biomass at which fishing is reduced to zero, (columns) and target fishing mortality (rows). Growth followed a Tanaka curve based on estimates of ocean quahog from Long Island.

F_{Target}	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5
0.002	0.022	0.021	0.023	0.022	0.020	0.024	0.026	0.046	0.163	0.193
0.007	0.055	0.056	0.055	0.057	0.055	0.057	0.083	0.109	0.160	0.170
0.012	0.102	0.094	0.091	0.102	0.103	0.113	0.139	0.177	0.180	0.196
0.017	0.193	0.156	0.169	0.161	0.181	0.186	0.211	0.221	0.223	0.271
0.022	0.221	0.207	0.205	0.216	0.221	0.217	0.252	0.244	0.270	0.302
0.027	0.311	0.292	0.239	0.250	0.260	0.271	0.278	0.290	0.311	0.346
0.032	0.362	0.328	0.307	0.288	0.286	0.302	0.304	0.328	0.327	0.352
0.037	0.382	0.372	0.337	0.318	0.325	0.335	0.339	0.364	0.390	0.447
0.042	0.433	0.389	0.375	0.341	0.362	0.359	0.368	0.380	0.390	0.439
0.047	0.445	0.429	0.416	0.407	0.388	0.403	0.392	0.426	0.417	0.426
0.052	0.513	0.461	0.408	0.406	0.396	0.380	0.400	0.429	0.441	0.534
0.057	0.588	0.484	0.422	0.439	0.447	0.421	0.449	0.466	0.485	0.499
0.062	0.625	0.514	0.495	0.455	0.468	0.460	0.469	0.459	0.500	0.503
0.067	0.587	0.536	0.518	0.482	0.442	0.462	0.464	0.495	0.502	0.525
0.072	0.662	0.582	0.537	0.489	0.519	0.500	0.508	0.518	0.521	0.555
0.077	0.690	0.602	0.552	0.524	0.525	0.534	0.530	0.527	0.577	0.592
0.082	0.707	0.617	0.560	0.514	0.549	0.542	0.513	0.557	0.571	0.641
0.087	0.710	0.637	0.577	0.559	0.547	0.570	0.561	0.582	0.623	0.646
0.092	0.748	0.653	0.608	0.551	0.583	0.554	0.582	0.600	0.645	0.570
0.097	0.825	0.691	0.624	0.600	0.568	0.565	0.572	0.636	0.664	0.683
0.102	0.786	0.705	0.630	0.611	0.632	0.648	0.607	0.647	0.641	0.707
0.107	0.847	0.702	0.609	0.628	0.604	0.599	0.631	0.665	0.642	0.704
0.112	0.879	0.758	0.683	0.656	0.652	0.637	0.657	0.643	0.675	0.690
0.117	0.899	0.782	0.713	0.657	0.668	0.658	0.667	0.689	0.691	0.719
0.122	0.849	0.820	0.716	0.657	0.634	0.717	0.698	0.728	0.771	0.782
0.127	0.924	0.785	0.727	0.679	0.696	0.643	0.719	0.693	0.817	0.666
0.132	0.979	0.809	0.744	0.730	0.721	0.693	0.685	0.701	0.771	0.835
0.137	0.892	0.838	0.744	0.693	0.698	0.679	0.730	0.719	0.810	0.836
0.142	0.961	0.839	0.794	0.780	0.703	0.699	0.729	0.741	0.782	0.849
0.147	1.000	0.872	0.774	0.765	0.724	0.686	0.810	0.768	0.817	0.927

Table 57: Average biomass ($\frac{S\hat{S}B}{SSB_0}$) over 100 years of fishing simulations at different levels of SSB_{Target}, the biomass at which fishing is reduced relative to target fishing mortality, (columns) and target fishing mortality (rows). Growth followed a Tanaka curve based on estimates of ocean quahog from Long Island.

F_{Target}	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5
0.002	1.05	1.05	1.04	1.04	1.04	1.04	1.04	1.03	1.04	1.04
0.007	0.93	0.92	0.93	0.94	0.95	0.94	0.94	0.94	0.94	0.94
0.012	0.87	0.84	0.83	0.84	0.84	0.85	0.86	0.85	0.86	0.85
0.017	0.75	0.81	0.77	0.79	0.77	0.80	0.78	0.78	0.77	0.77
0.022	0.70	0.70	0.70	0.72	0.72	0.70	0.71	0.71	0.72	0.72
0.027	0.66	0.68	0.64	0.65	0.67	0.68	0.67	0.66	0.66	0.66
0.032	0.61	0.66	0.60	0.62	0.60	0.61	0.61	0.60	0.62	0.63
0.037	0.60	0.58	0.57	0.58	0.59	0.58	0.58	0.58	0.59	0.58
0.042	0.53	0.50	0.55	0.54	0.53	0.52	0.53	0.54	0.56	0.56
0.047	0.48	0.46	0.52	0.51	0.51	0.50	0.50	0.50	0.52	0.52
0.052	0.48	0.50	0.49	0.48	0.47	0.47	0.48	0.49	0.50	0.51
0.057	0.44	0.45	0.44	0.45	0.45	0.45	0.48	0.47	0.48	0.49
0.062	0.40	0.40	0.41	0.43	0.43	0.43	0.44	0.45	0.47	0.47
0.067	0.41	0.41	0.41	0.40	0.41	0.42	0.43	0.43	0.46	0.46
0.077	0.39	0.40	0.37	0.37	0.38	0.39	0.39	0.41	0.42	0.44
0.082	0.39	0.34	0.34	0.36	0.35	0.38	0.40	0.40	0.41	0.43
0.092	0.31	0.32	0.33	0.35	0.33	0.37	0.35	0.38	0.39	0.40
0.097	0.30	0.34	0.32	0.32	0.34	0.34	0.36	0.38	0.38	0.39
0.142	0.25	0.23	0.25	0.25	0.28	0.30	0.30	0.33	0.34	0.33

Table 58: Average biomass ($\frac{S\hat{S}B}{SSB_0}$) over 1000 years of fishing simulations at different levels of SSB_{Target}, the biomass at which fishing is reduced linearly, (columns) and target fishing mortality (rows). Growth followed a Tanaka curve based on estimates of ocean quahog from Long Island.

F_{Target}	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5
0.002	0.890	0.900	0.920	0.900	0.920	0.890	0.910	0.900	0.900	0.900
0.007	0.680	0.650	0.620	0.630	0.680	0.660	0.670	0.660	0.630	0.670
0.012	0.480	0.510	0.430	0.460	0.500	0.460	0.490	0.500	0.510	0.500
0.017	0.300	0.380	0.300	0.330	0.330	0.370	0.380	0.410	0.420	0.430
0.022	0.260	0.270	0.250	0.280	0.300	0.320	0.330	0.350	0.380	0.400
0.027	0.160	0.210	0.200	0.240	0.280	0.280	0.320	0.320	0.350	0.370
0.032	0.150	0.220	0.200	0.220	0.240	0.260	0.290	0.310	0.340	0.340
0.037	0.130	0.170	0.180	0.210	0.220	0.240	0.280	0.290	0.310	0.330
0.042	0.120	0.150	0.170	0.200	0.200	0.230	0.260	0.280	0.320	0.330
0.047	0.120	0.140	0.170	0.190	0.200	0.230	0.240	0.250	0.280	0.320
0.052	0.110	0.140	0.170	0.170	0.190	0.230	0.210	0.260	0.290	0.310
0.057	0.100	0.140	0.140	0.160	0.190	0.220	0.250	0.240	0.280	0.290
0.062	0.090	0.130	0.140	0.150	0.180	0.200	0.240	0.240	0.260	0.310
0.067	0.100	0.130	0.150	0.150	0.170	0.200	0.220	0.230	0.270	0.270
0.077	0.090	0.130	0.120	0.130	0.170	0.190	0.210	0.230	0.260	0.270
0.082	0.090	0.120	0.110	0.140	0.160	0.200	0.230	0.230	0.260	0.290
0.092	0.070	0.120	0.130	0.140	0.160	0.200	0.190	0.230	0.260	0.280
0.097	0.070	0.120	0.130	0.130	0.170	0.190	0.220	0.230	0.250	0.270
0.142	0.070	0.100	0.080	0.120	0.150	0.190	0.170	0.240	0.250	0.230

Table 59: Relative average yield over 100 years of fishing simulations at different levels of SSB_{Target}, the biomass at which fishing is reduced relative to target fishing mortality, (columns) and target fishing mortality (rows). Growth followed a Tanaka curve based on estimates of ocean quahog from Long Island.

F_{Target}	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5
0.002	0.10	0.11	0.11	0.10	0.11	0.11	0.10	0.11	0.11	0.11
0.007	0.23	0.25	0.24	0.25	0.24	0.24	0.24	0.25	0.25	0.24
0.012	0.36	0.35	0.36	0.37	0.37	0.37	0.37	0.37	0.37	0.37
0.017	0.47	0.47	0.47	0.47	0.46	0.46	0.46	0.46	0.46	0.46
0.022	0.52	0.53	0.53	0.53	0.54	0.53	0.54	0.54	0.54	0.54
0.027	0.61	0.61	0.59	0.60	0.60	0.60	0.61	0.60	0.60	0.59
0.032	0.66	0.66	0.65	0.65	0.65	0.66	0.66	0.65	0.65	0.64
0.037	0.71	0.69	0.69	0.71	0.70	0.69	0.70	0.69	0.69	0.68
0.042	0.74	0.72	0.74	0.75	0.74	0.72	0.73	0.73	0.69	0.71
0.047	0.75	0.73	0.77	0.76	0.77	0.75	0.75	0.74	0.74	0.71
0.052	0.82	0.81	0.81	0.80	0.79	0.78	0.79	0.77	0.75	0.75
0.057	0.82	0.82	0.81	0.81	0.81	0.80	0.81	0.77	0.75	0.75
0.062	0.78	0.80	0.82	0.85	0.84	0.82	0.79	0.79	0.77	0.74
0.067	0.85	0.85	0.85	0.84	0.83	0.83	0.82	0.77	0.78	0.77
0.077	0.92	0.93	0.86	0.85	0.86	0.85	0.82	0.80	0.77	0.77
0.082	0.95	0.87	0.85	0.87	0.84	0.84	0.83	0.81	0.78	0.78
0.092	0.90	0.89	0.92	0.94	0.88	0.87	0.82	0.79	0.78	0.78
0.097	0.88	0.97	0.92	0.90	0.88	0.83	0.82	0.83	0.79	0.79
0.142	1.00	0.90	0.94	0.88	0.89	0.85	0.85	0.82	0.78	0.79

Table 60: Relative average yield over 1000 years of fishing simulations at different levels of SSB_{Target}, the biomass at which fishing is reduced linearly, (columns) and target fishing mortality (rows). Growth followed a Tanaka curve based on estimates of ocean quahog from Long Island.

F_{Target}	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5
0.002	0.27	0.28	0.27	0.26	0.26	0.27	0.25	0.27	0.27	0.26
0.007	0.46	0.47	0.46	0.47	0.45	0.47	0.48	0.49	0.46	0.46
0.012	0.57	0.62	0.54	0.57	0.62	0.58	0.59	0.61	0.59	0.57
0.017	0.57	0.68	0.53	0.58	0.55	0.58	0.57	0.57	0.57	0.57
0.022	0.58	0.59	0.56	0.57	0.59	0.55	0.55	0.60	0.58	0.59
0.027	0.38	0.55	0.50	0.55	0.54	0.55	0.60	0.57	0.57	0.57
0.032	0.43	0.56	0.44	0.53	0.53	0.54	0.59	0.56	0.56	0.56
0.037	0.38	0.49	0.51	0.57	0.57	0.53	0.58	0.57	0.55	0.56
0.042	0.37	0.48	0.46	0.56	0.49	0.52	0.55	0.58	0.54	0.58
0.047	0.52	0.44	0.53	0.54	0.49	0.52	0.53	0.50	0.54	0.55
0.052	0.49	0.48	0.45	0.52	0.47	0.50	0.54	0.56	0.59	0.58
0.057	0.43	0.55	0.48	0.50	0.52	0.53	0.54	0.55	0.52	0.56
0.062	0.35	0.45	0.49	0.50	0.47	0.52	0.52	0.57	0.53	0.58
0.067	0.48	0.49	0.45	0.50	0.46	0.56	0.53	0.52	0.54	0.55
0.077	0.46	0.45	0.44	0.45	0.48	0.51	0.51	0.53	0.52	0.54
0.082	0.52	0.46	0.42	0.47	0.46	0.50	0.54	0.53	0.52	0.57
0.092	0.38	0.46	0.46	0.55	0.47	0.52	0.50	0.50	0.53	0.54
0.097	0.39	0.50	0.44	0.51	0.47	0.47	0.53	0.56	0.53	0.54
0.142	0.45	0.47	0.44	0.44	0.46	0.53	0.51	0.51	0.55	0.56

Table 61: Relative average coefficient of variation in yield over 100 years of fishing simulations at different levels of SSB_{Target}, the biomass at which fishing is reduced relative to target fishing mortality, (columns) and target fishing mortality (rows). Growth followed a Tanaka curve based on estimates of ocean quahog from Long Island.

F_{Target}	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5
0.002	0.011	0.013	0.015	0.014	0.016	0.015	0.014	0.017	0.016	0.016
0.007	0.041	0.044	0.038	0.040	0.040	0.039	0.038	0.039	0.040	0.037
0.012	0.061	0.062	0.069	0.066	0.062	0.060	0.063	0.063	0.064	0.064
0.017	0.101	0.083	0.092	0.085	0.093	0.083	0.087	0.085	0.088	0.090
0.022	0.114	0.111	0.117	0.110	0.107	0.110	0.113	0.115	0.111	0.113
0.027	0.152	0.129	0.142	0.135	0.131	0.127	0.125	0.134	0.138	0.142
0.032	0.161	0.136	0.162	0.147	0.156	0.152	0.151	0.160	0.161	0.166
0.037	0.161	0.166	0.173	0.166	0.166	0.172	0.173	0.175	0.177	0.187
0.042	0.185	0.211	0.190	0.183	0.191	0.199	0.201	0.205	0.232	0.227
0.047	0.209	0.229	0.192	0.209	0.205	0.214	0.223	0.241	0.235	0.259
0.052	0.221	0.218	0.224	0.227	0.232	0.236	0.235	0.252	0.263	0.278
0.057	0.240	0.235	0.239	0.249	0.252	0.258	0.263	0.292	0.313	0.310
0.062	0.281	0.281	0.270	0.262	0.265	0.263	0.289	0.304	0.325	0.348
0.067	0.255	0.277	0.270	0.288	0.296	0.300	0.303	0.346	0.354	0.368
0.077	0.281	0.283	0.310	0.332	0.328	0.338	0.357	0.393	0.410	0.412
0.082	0.288	0.330	0.360	0.337	0.364	0.369	0.378	0.404	0.423	0.425
0.092	0.363	0.358	0.353	0.338	0.377	0.392	0.442	0.459	0.466	0.468
0.097	0.396	0.340	0.369	0.398	0.387	0.437	0.456	0.454	0.487	0.481
0.142	0.461	0.532	0.488	0.558	0.535	0.570	0.583	0.627	0.644	0.627

Table 62: Relative average coefficient of variation in yield over 1000 years of fishing simulations at different levels of SSB_{Target}, the biomass at which fishing is reduced linearly, (columns) and target fishing mortality (rows). Growth followed a Tanaka curve based on estimates of ocean quahog from Long Island.

F_{Target}	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5
0.002	0.030	0.025	0.024	0.023	0.024	0.025	0.023	0.023	0.025	0.025
0.007	0.053	0.062	0.069	0.067	0.062	0.061	0.053	0.060	0.067	0.065
0.012	0.115	0.101	0.114	0.122	0.097	0.124	0.116	0.109	0.123	0.133
0.017	0.211	0.160	0.243	0.176	0.205	0.196	0.208	0.204	0.211	0.214
0.022	0.234	0.234	0.237	0.232	0.224	0.257	0.277	0.249	0.266	0.257
0.027	0.463	0.334	0.363	0.294	0.322	0.344	0.270	0.323	0.320	0.322
0.032	0.450	0.327	0.441	0.351	0.361	0.363	0.340	0.354	0.343	0.362
0.037	0.543	0.464	0.419	0.359	0.366	0.423	0.384	0.390	0.398	0.416
0.042	0.635	0.450	0.518	0.415	0.467	0.449	0.432	0.427	0.464	0.416
0.047	0.452	0.548	0.463	0.441	0.514	0.484	0.498	0.525	0.472	0.482
0.052	0.555	0.599	0.559	0.501	0.562	0.534	0.499	0.481	0.473	0.496
0.057	0.671	0.487	0.561	0.570	0.557	0.548	0.539	0.539	0.574	0.530
0.062	0.781	0.638	0.576	0.600	0.612	0.568	0.590	0.540	0.575	0.533
0.067	0.602	0.585	0.680	0.614	0.670	0.573	0.596	0.612	0.587	0.588
0.077	0.774	0.766	0.713	0.711	0.667	0.638	0.655	0.627	0.651	0.643
0.082	0.672	0.706	0.774	0.742	0.722	0.681	0.644	0.662	0.664	0.628
0.092	0.938	0.761	0.754	0.642	0.765	0.697	0.720	0.749	0.714	0.676
0.097	0.880	0.733	0.854	0.730	0.799	0.818	0.738	0.697	0.748	0.686
0.142	0.883	0.918	1.000	0.993	0.962	0.873	0.926	0.960	0.892	0.831

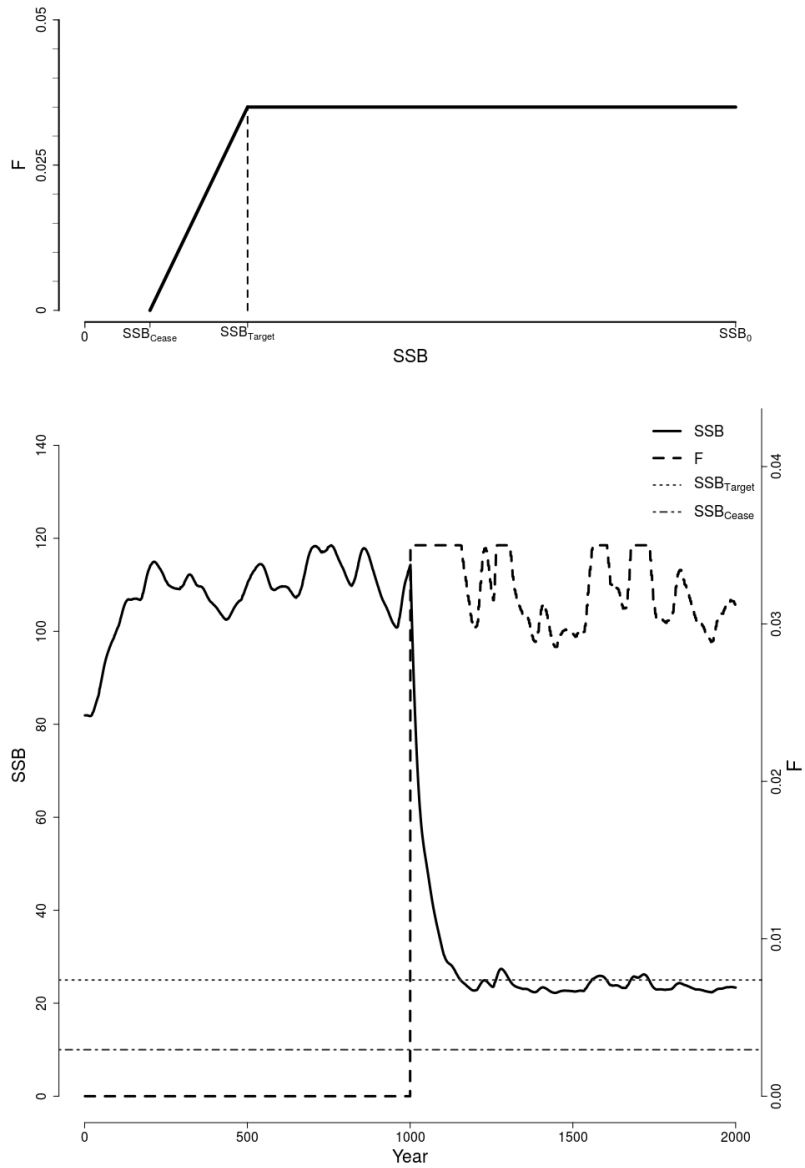

Figure 243: Control rule for ocean quahog in terms of F and SSB. Fishing mortality is constant unless SSB drops below SSB_{Target}, it then declines linearly until it reaches 0 at SSB_{Cease}. Panel (B) The control rule applied in a simulation run. Fishing mortality was constant when $SSB_t > SSB_{Target}$, and was reduced when $SSB_t < SSB_{Target}$. Simulated SSB units are arbitrary.

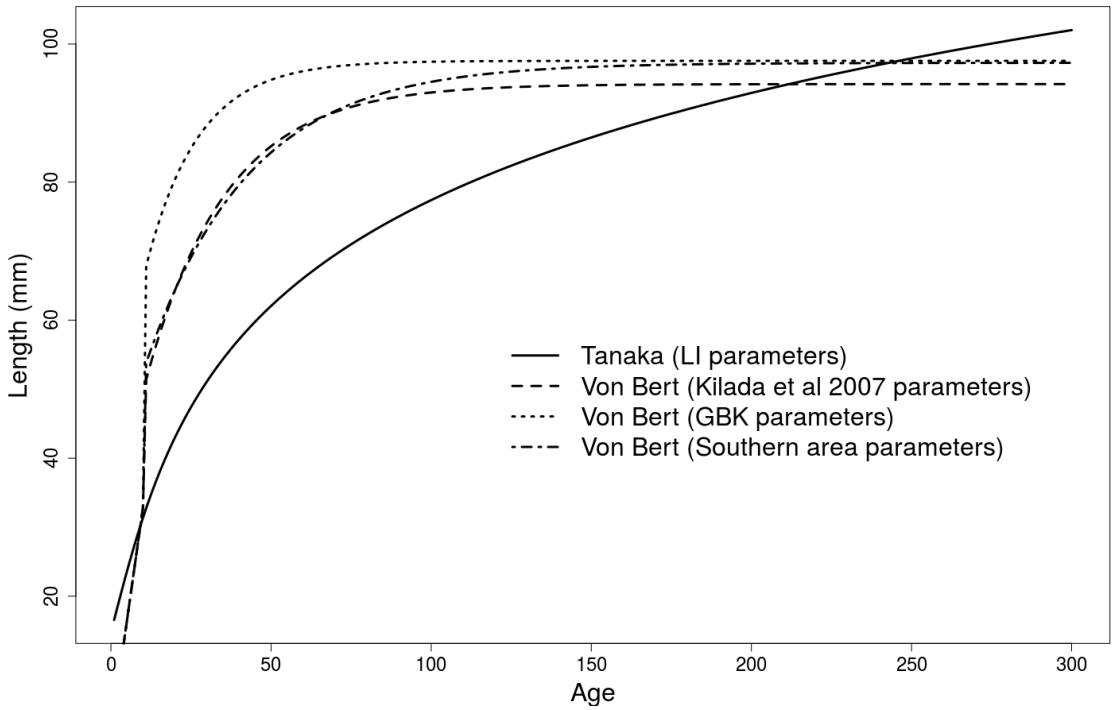

Figure 244: Tanaka growth curve compared to the Beverton-Holt growth curves used in the previous MSE analysis.

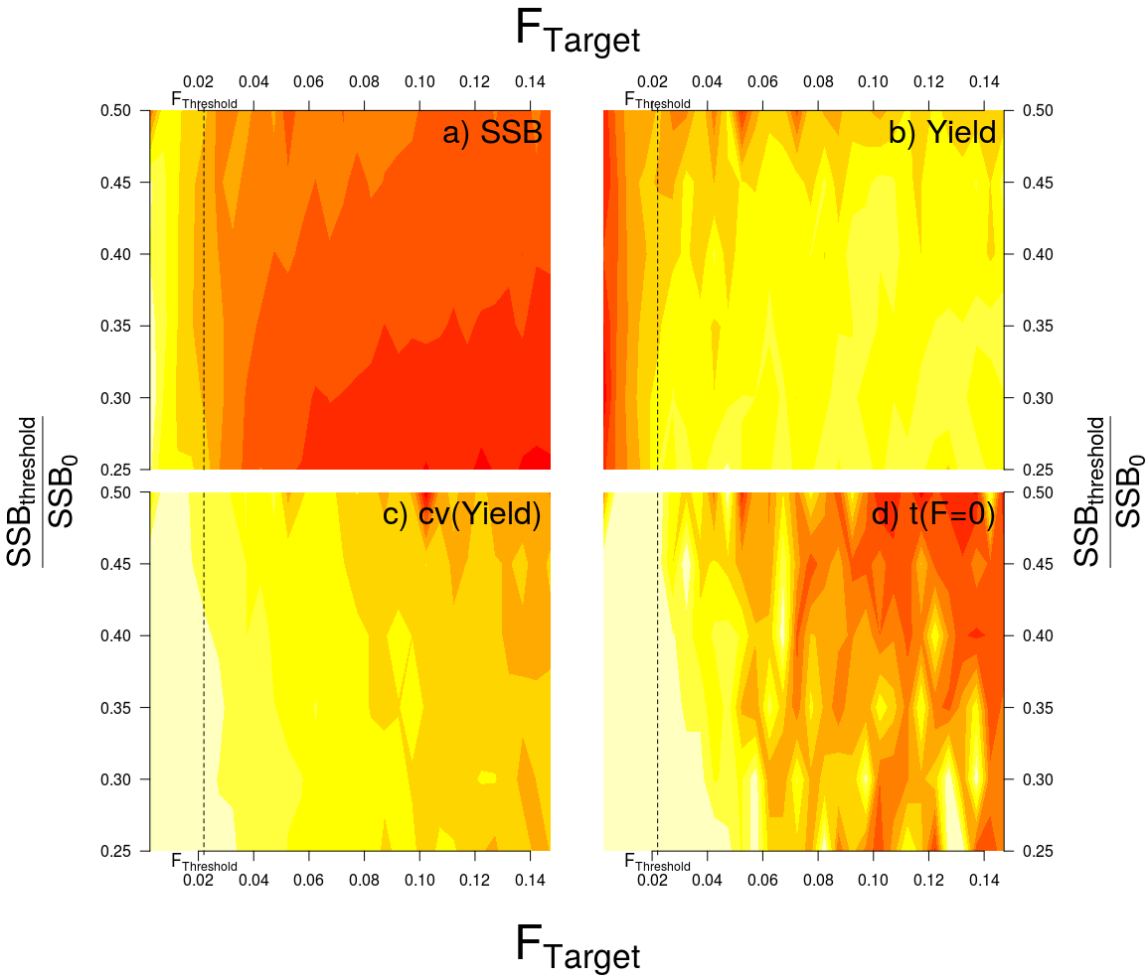

Figure 245: Contour plots showing the combined effects of F_{Target} and the fraction of SSB_0 that corresponds to the control rule threshold ($\frac{SSB_{threshold}}{SSB_0}$ over 100 years on: (a) $\frac{\overline{SSB}}{SSB_0}$, (b) $\frac{\overline{Y}}{SSB_0}$, (c) cv(Y) and (d) $t_{F=0}$. In each plot the darker colors are associated with less preferred values (*e.g.* in plot (a) the lowest $\frac{\overline{SSB}}{SSB_0}$ occurs on the right side, where F_{Target} is high, and in plot (c) the highest variation in yield occurs on the right side, where F_{Target} is high). The current $F_{Threshold}$ (0.022; Northeast Fisheries Science Center 2013) is marked with a dashed line. This plot was reproduced based on the results of Hennen (2015).

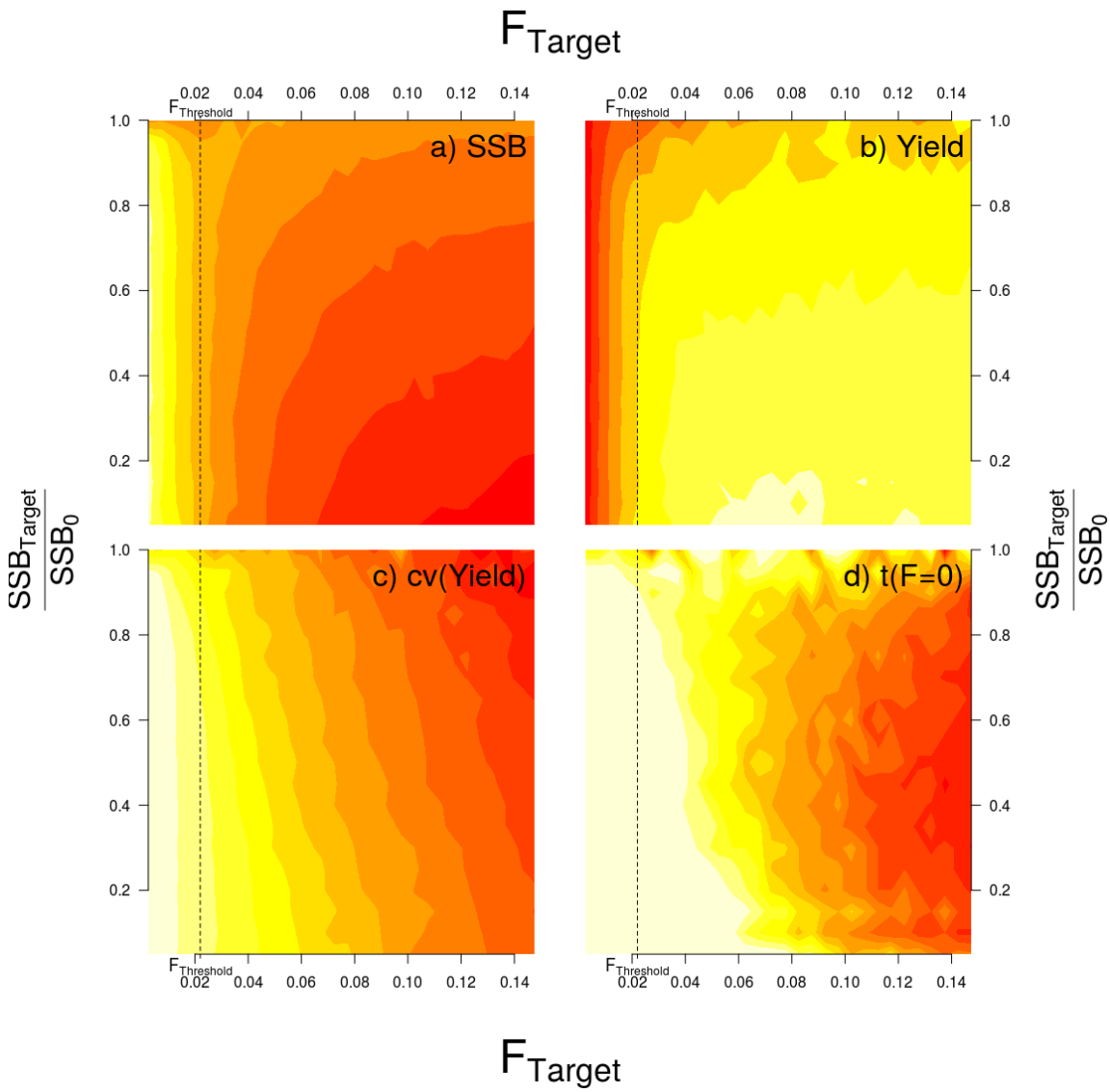

Figure 246: Contour plots showing the combined effects of F_{Target} and the fraction of SSB_0 that corresponds to the control rule target ($\frac{SSB_{Target}}{SSB_0}$ or SSB_{Target}) over 100 years on: (a) $\frac{\overline{SSB}}{SSB_0}$, (b) $\frac{\overline{Y}}{SSB_0}$, (c) cv(Y) and (d) $t_{F=0}$. In each plot the darker colors are associated with less preferred values (*e.g.* in plot (a) the lowest $\frac{\overline{SSB}}{SSB_0}$ occurs on the right side, where F_{Target} is high, and in plot (c) the highest variation in yield occurs on the right side, where F_{Target} is high). The current $F_{Threshold}$ (0.022; Northeast Fisheries Science Center 2013) is marked with a dashed line. In these simulations, a problem with the random number generator used in Hennen (2015) was corrected.

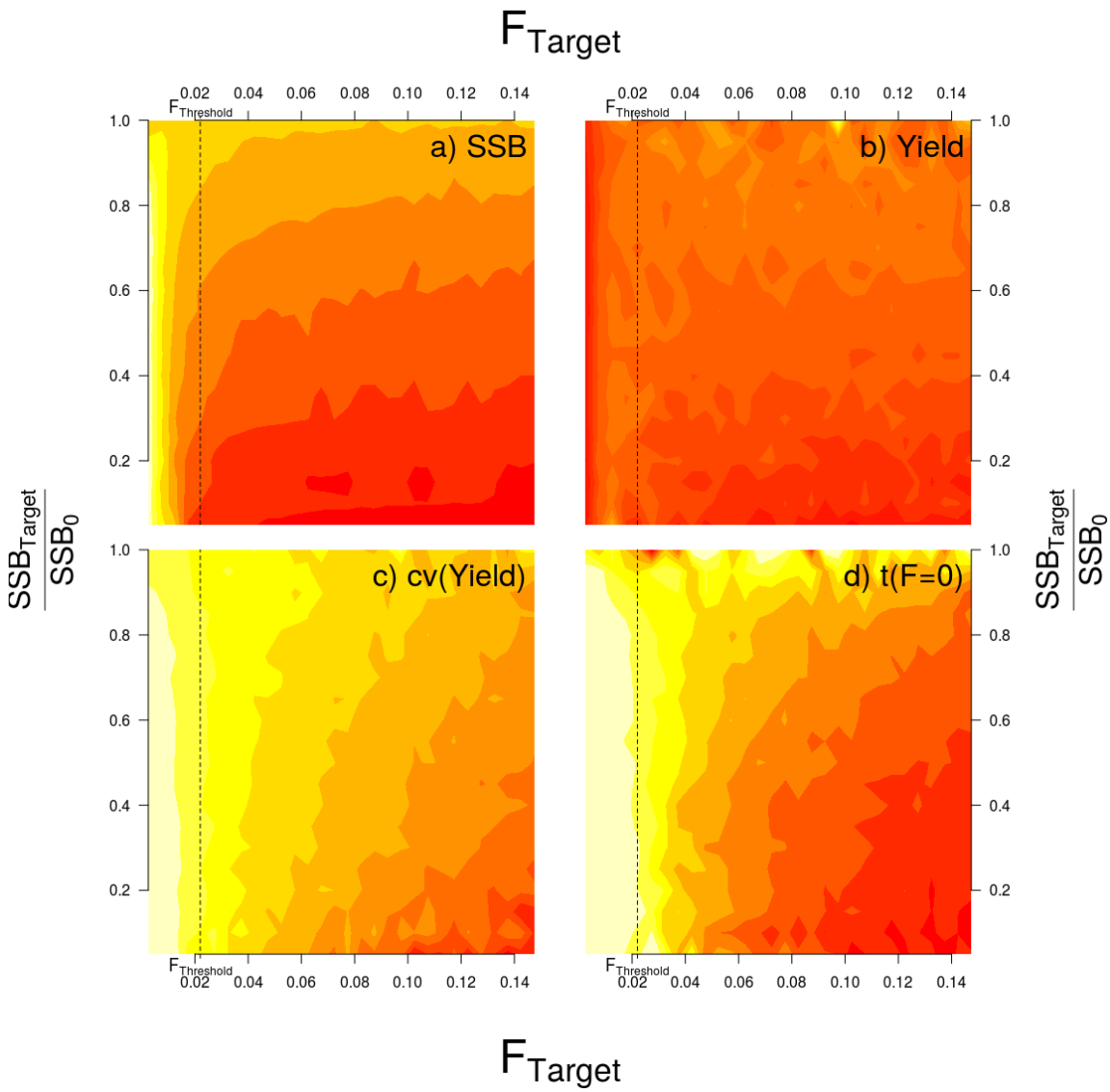

Figure 247: Contour plots showing the combined effects of F_{Target} and the fraction of SSB_0 that corresponds to the control rule target ($\frac{SSB_{Target}}{SSB_0}$ or SSB_{Target}) over 1000 years on: (a) $\frac{\overline{SSB}}{SSB_0}$, (b) $\frac{\overline{Y}}{SSB_0}$, (c) cv(Y) and (d) $t_{F=0}$. In each plot the darker colors are associated with less preferred values (*e.g.* in plot (a) the lowest $\frac{\overline{SSB}}{SSB_0}$ occurs on the right side, where F_{Target} is high, and in plot (c) the highest variation in yield occurs on the right side, where F_{Target} is high). The current $F_{Threshold}$ (0.022; Northeast Fisheries Science Center 2013) is marked with a dashed line. In these simulations, a problem with the random number generator used in Hennen (2015) was corrected.

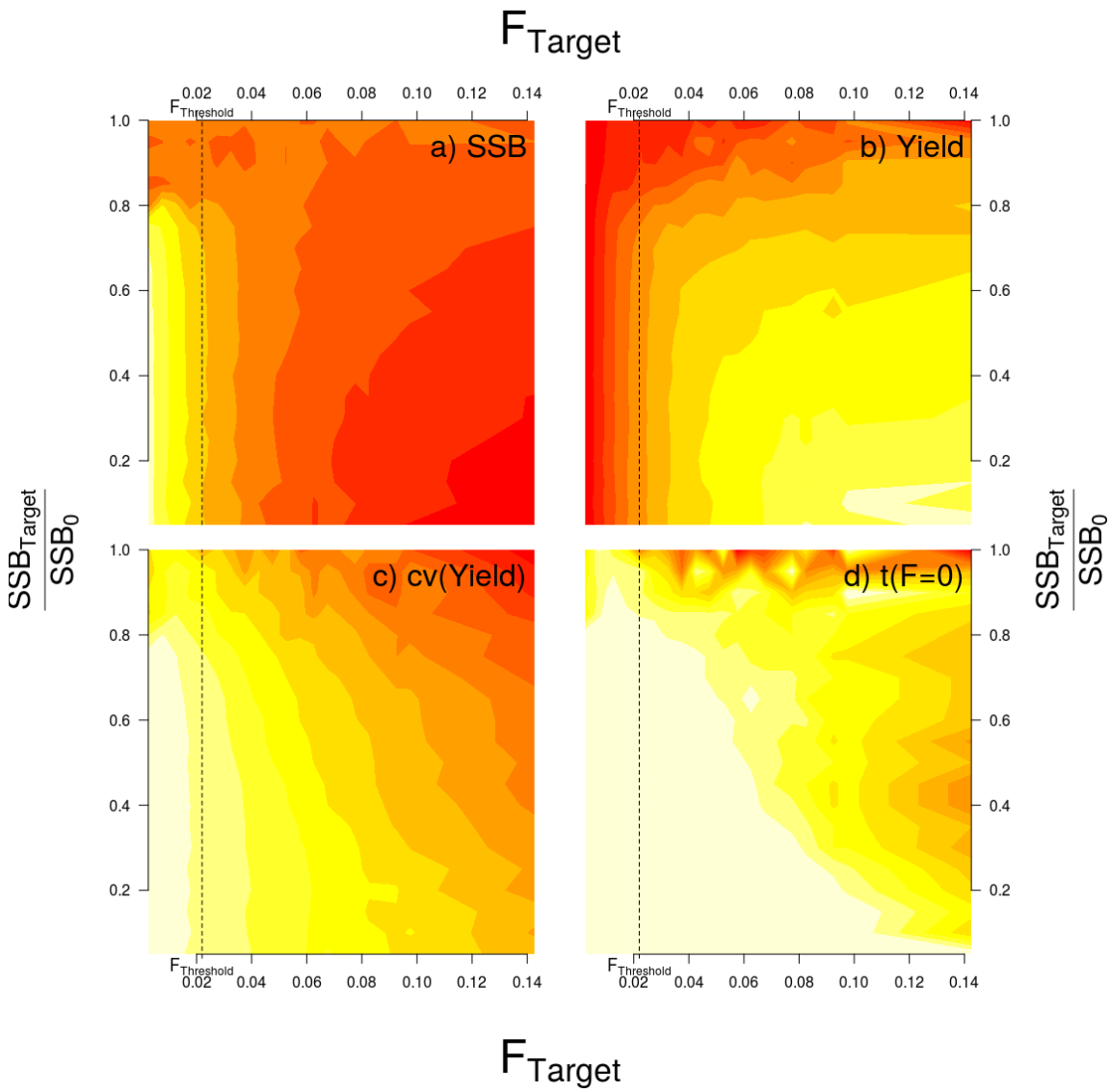

Figure 248: Contour plots showing the combined effects of F_{Target} and the fraction of SSB_0 that corresponds to the control rule target ($\frac{SSB_{Target}}{SSB_0}$ or SSB_{Target}) over 100 years on: (a) $\frac{\overline{SSB}}{SSB_0}$, (b) $\frac{\overline{Y}}{SSB_0}$, (c) cv(Y) and (d) $t_{F=0}$. In each plot the darker colors are associated with less preferred values (*e.g.* in plot (a) the lowest $\frac{\overline{SSB}}{SSB_0}$ occurs on the right side, where F_{Target} is high, and in plot (c) the highest variation in yield occurs on the right side, where F_{Target} is high). The current $F_{Threshold}$ (0.022; Northeast Fisheries Science Center 2013) is marked with a dashed line. In these simulations, the growth model used in Hennen (2015) was replaced with eq. 7.

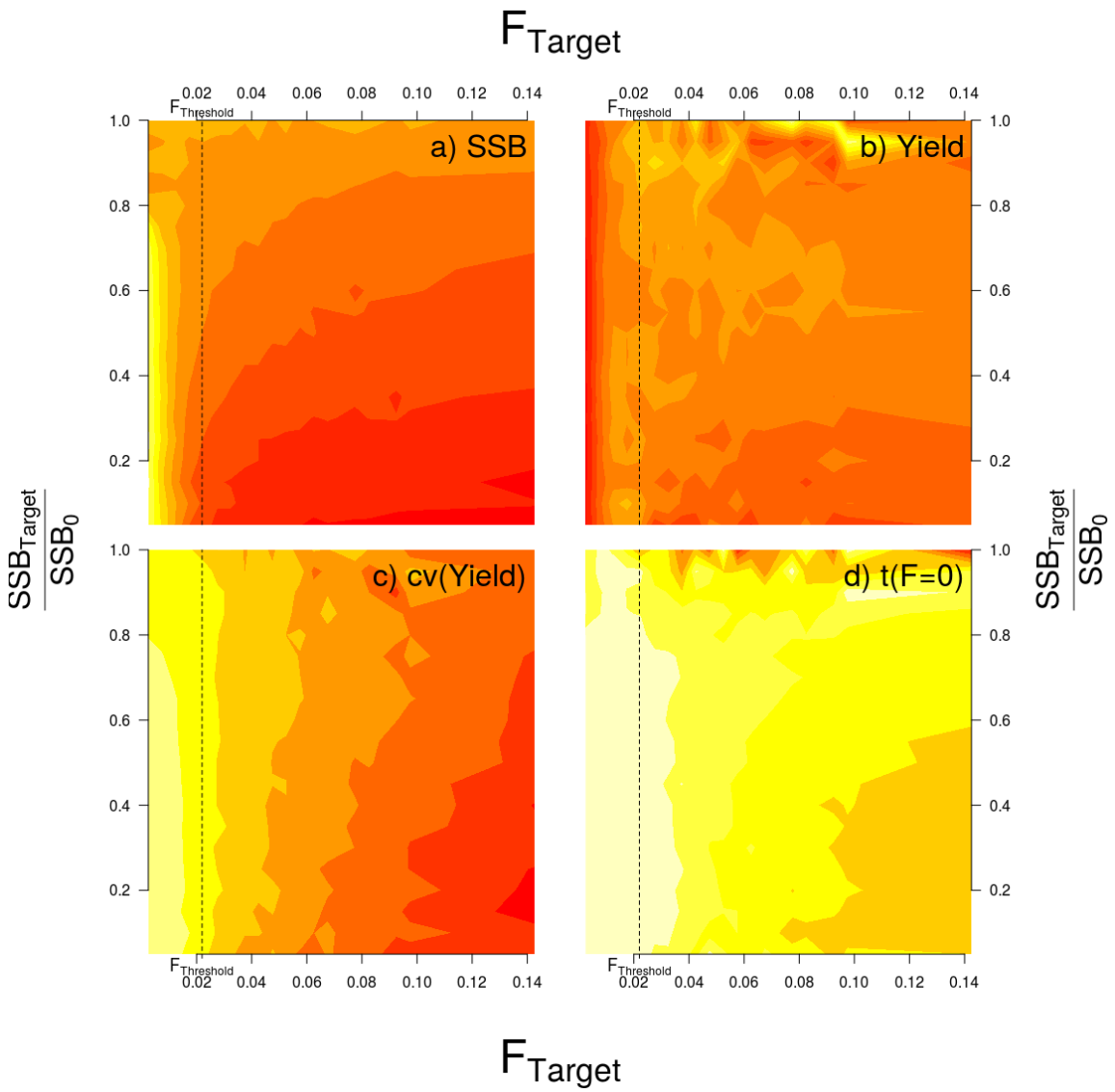

Figure 249: Contour plots showing the combined effects of F_{Target} and the fraction of SSB_0 that corresponds to the control rule target ($\frac{SSB_{Target}}{SSB_0}$ or SSB_{Target}) over 1000 years on: (a) $\frac{\overline{SSB}}{SSB_0}$, (b) $\frac{\overline{Y}}{SSB_0}$, (c) cv(Y) and (d) $t_{F=0}$. In each plot the darker colors are associated with less preferred values (*e.g.* in plot (a) the lowest $\frac{\overline{SSB}}{SSB_0}$ occurs on the right side, where F_{Target} is high, and in plot (c) the highest variation in yield occurs on the right side, where F_{Target} is high). The current $F_{Threshold}$ (0.022; Northeast Fisheries Science Center 2013) is marked with a dashed line. In these simulations, the growth model used in Hennen (2015) was replaced with eq. 7.

Appendix 9 Empirical ocean quahog assessment

Empirical estimates

Empirical biomass, fishing mortality and other estimates for ocean quahogs are based on survey data, catch data and field based estimates of size-selectivity and capture efficiency, but do not involve the SS3 or KLAMZ assessment models. However, empirical and assessment model approaches are not entirely independent because catch and survey data, size-selectivity and capture efficiency estimates used in empirical calculations were also used in stock assessment models. The primary purpose for developing empirical approaches is to check assessment model assumptions and estimates. However, empirical estimates might suffice if model based estimates were not accepted by reviewers. In summary, catch based "VPA" and minimum biomass/maximum fishing mortality calculations indicate that fishing mortality rates are low for the stock as a whole, while total stock biomass is high. Stock biomass is lower and fishing mortality rates are higher in the southern NJ and DMV regions than in GBK, SNE and LI in the north.

VPA

Empirical "VPA" estimates for ocean quahog were included in previous ocean quahog assessments (NEFSC 2009) and assume that recruitment, growth and natural mortality rates cancel so that changes in stock size are due to fishing. These assumptions are reasonable for a long-lived stock near its unfished equilibrium biomass, that is lightly exploited. VPA calculations were anchored at the average efficiency corrected swept area estimate for fishable biomass (1,361 thousand mt in the north and 1,671 thousand mt in the south) from surveys during 1997-2016 when areas were completely surveyed and relatively accurate tow distance measurements from sensor data were available. The capture efficiency estimates were means from field studies (e=0.194 during 1997-2012 and e=0.608 during 2012-2016). Fishable biomass was the sum of survey catch at length divided by survey selectivity at length (to approximate population size composition) then multiplied by fishery selectivity at size. The middle year for both regions = floor [(last year + first year) / 2] = 2006 so the averages were used as VPA biomass estimates for 2006 (B2006) and used to anchor calculations for other years. For example, the VPA biomass estimate B2007=B2006+C2006 where C2006 is catch biomass and $B_{2008} = B_{2007} + C_{2007}$ while $B_{2005} = B_{2006} - C_{2005}$ and $B_{2004} = B_{2005} - C_{2004}$. Fishing mortality rates were calculated from the ratio of catch and biomass in the same year (e.g. $F_{2006} = C_{2006}/B_{2006}$) and nearly identical to mortality rates that would have been obtained by solving the catch equation because mortality rates were low. Results indicate that fishable biomass during 1978-2016 was stable in the north while declining at an average rate of about 1% per year (range 0.5% -1.2%) in the south. Stock biomass declined by about 0.6% per year (range 0.3%-0.7%) in the stock as a whole (Figures 250-251).

Minimum swept area fishable biomass

Lower bounds for stock size and upper bounds for fishing mortality during 2012-2016 were calculated using mean fishable biomass per tow from surveys and assume that survey capture efficiency was one (so that swept area biomass estimates are smaller than true fishable biomass). Years prior to 2012 were excluded because of changes in capture efficiency and because the analysis focused on recent conditions. The data were from two surveys in the south during 2012 and 2015 and two surveys in the north (GBK) during 2013 and 2016 (Table 63). CVs for the biomass estimates were the CVs for the survey data plus 0.15 to account for uncertainty in selectivity, tow distance and stock area. Catch includes landings plus 5% for incidental mortality.

Mean minimum swept-area biomass and catch for the whole stock during 2012-2016 was estimated as the sum of the four regional estimates divided by 2 (Table 63). The variance (standard error squared) of mean whole stock biomass was the sum of the squared standard errors for the four regional estimates divided by 4. Lower bounds for the 95% confidence intervals around biomass were estimated using gamma distributions with shape and scale parameters from the point estimate, variance and method of moments. Fishing mortality was catch divided by biomass and the upper 95% bound was catch divided by the lower bound for biomass.

The lower 95% bound for whole stock fishable biomass during 2012-2016 was 1,683 thousand mt and the upper bound for whole stock F was 0.013 (Table 63). Upper bounds for the two annual F estimates ranged 0.0004-0.0005 in the north and 0.036-0.038 in the south.

Smoothed survey trends

This analysis of smoothed survey trends for ocean quahogs is based on generalized additive model (GAM) regression and mean kilograms per square meter for all size groups in surveys beginning in 1997 that covered the entire region (1997, 1999, 2002, 2008, 2011, 2013, 2016 on GBK and 1997, 1999, 2002, 2005, 2008, 2011, 2012, 2015 in the south). The change to a modified commercial dredge for survey work in 2012 was accommodated by multiplying survey catches for 2012-2016 by the ratio of mean estimated capture efficiencies in the two gears (research dredge/modified commercial dredge = 0.194/0.608 =0.319). Years prior to 1997 were not used because sensor data was not available for accurate estimation of tow distance which changed from year to year and is sensitive to depth.

The GAM used to calculate trends for the northern (GBK) and southern areas was: gam1 = gam(kgpertow2 $\sim$ te(yr) + dredge, data = d2, weights = kg2.invarwt, link = "log") where kgpertow2 is mean kg per square meter after adjusting for changes in relative capture efficiency and s() is a thin-plate smooth regression function with $\leq$ 5 degrees of freedom. The term dredge is a dummy variable that potentially accommodates differences between the old and new survey beginning in 2012, beyond the differences in swept area and estimated dredge efficiency. The term kg2.invarwt is an inverse variance weight based on the stratified random CVs for mean kg per square meter. A 95% confidence interval for the trend line (width +/- 1.96 times the point-wise standard error for the fitted curve) understates uncertainty because the variances of relative capture efficiency and gear selectivity were not included.

The dredge term was not included in final models because it was never statistically significant. The final model for GBK explained 98% of the total deviance with about 6 parameters, however the estimated trend was implausible because it was too variable to represent changes in a very long lived species like ocean quahogs with low recruitment and almost no fishing (Figure 252). The estimated trend for the southern region was nearly linear suggesting a decline of about 16% during 1997-2015 or about 0.8% per year (Figure 252).

The same modeling approach was used for individual regions in the south (4%-78% of total deviance explained using 2-3 parameters, Figure 253). Results show relatively strong declines in ocean quahog biomass in the DMV region since 1997 with mixed trends to the north.

Changes in stock distribution

The proportion of total stock biomass in the GBK, SNE, LI, NJ, and DMV regions was calculated for years in which the survey covered the entire stock (1986, 1989, 1992, 1994, 1997, 1999, 2002, 2008 and 2011 using the old survey dredge). The new survey covers half of the stock each year so 2012 (south) and 2013 (north) were combined and labeled 2012, while 2015 (south) and 2016 (north) were combined and labeled 2015. Mean catch weight per tow (kg m-2) for all size groups in each region was converted to population weight per tow using experimentally derived selectivity curves and then multiplied times the area of each region. Changes in tow distance measurements and capture efficiency were ignored because they tend to cancel out in calculating annual proportions.

Results (Figure 254) show that ocean quahog biomass has become concentrated in the northernmost GBK region since the mid-1980s, while declining in the southern NJ and DMV regions.

Table 63: Empirical lower 95% bounds for fishable ocean quahog biomass and 95% upper bounds for fishing mortality during 2012-2016 based on survey swept-area biomass assuming capture efficiency e = 1. The CV is from the survey mean weight per tow plus 15%. Confidence interval bounds are based on gamma distributions with shape and scale parameters from the method of moments. Fishing mortality for the whole stock is the average annual catch/average whole stock biomass. Biomass and catch are in units of 1000 mt. F is equal to catch/biomass, and the last two columns are biomass 95% upper bound (BLB) and F 95% upper bound (FUB).

Area	Year	Biomass	CV	Catch	F	Shape	Scale	BLB	FUB
South	2012	911	0.3	16.66	0.0183	11.47	79.45	463	0.036
GBK	2013	718	0.28	0.17	0.0002	12.44	57.71	376	0.0005
South	2015	819	0.33	14.32	0.0175	9.25	88.63	379	0.0377
GBK	2016	917	0.25	0.22	0.0002	15.73	58.27	521	0.0004
Whole stock	Mean	1683	0.15	15.68	0.0093	47.21	35.64	1237	0.0127

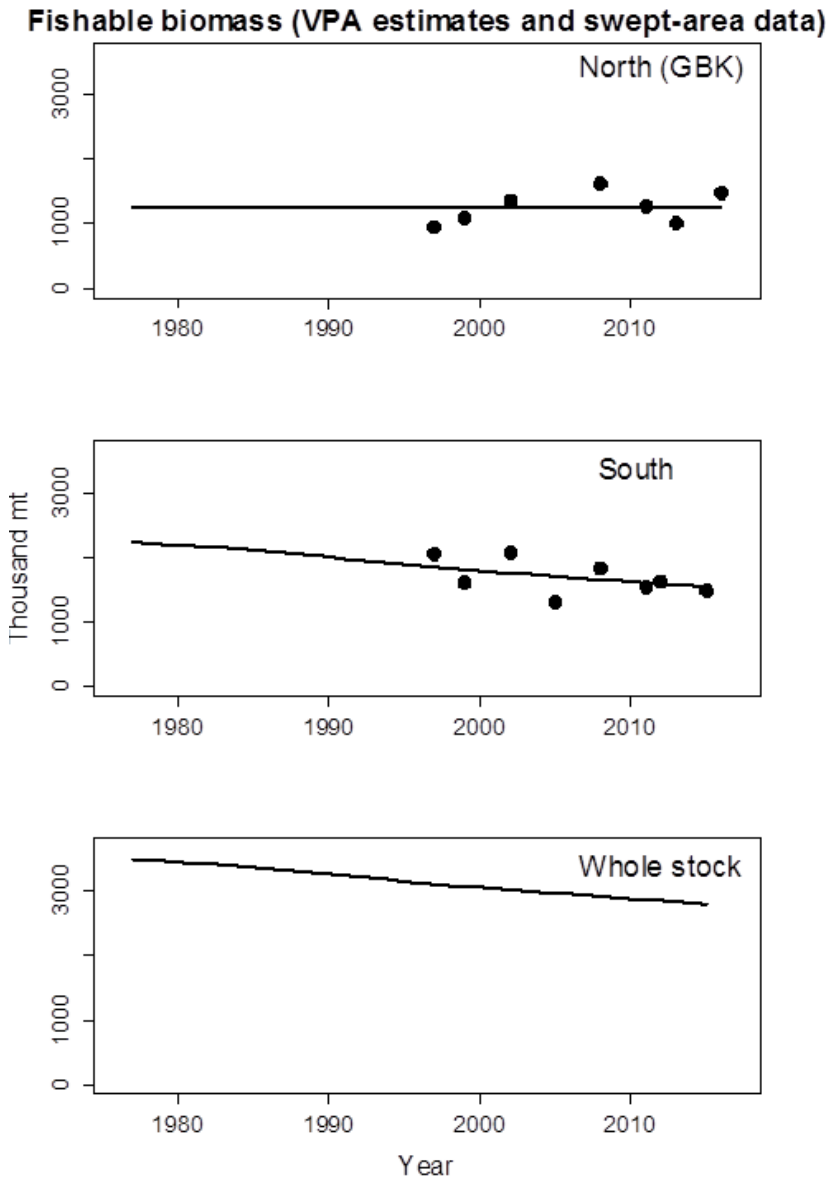

Figure 250: VPA fishable stock biomass estimates for ocean quahog during 1978-2016 with efficiency corrected swept-area biomass data from surveys during 1997-2016 in the northern and southern areas.

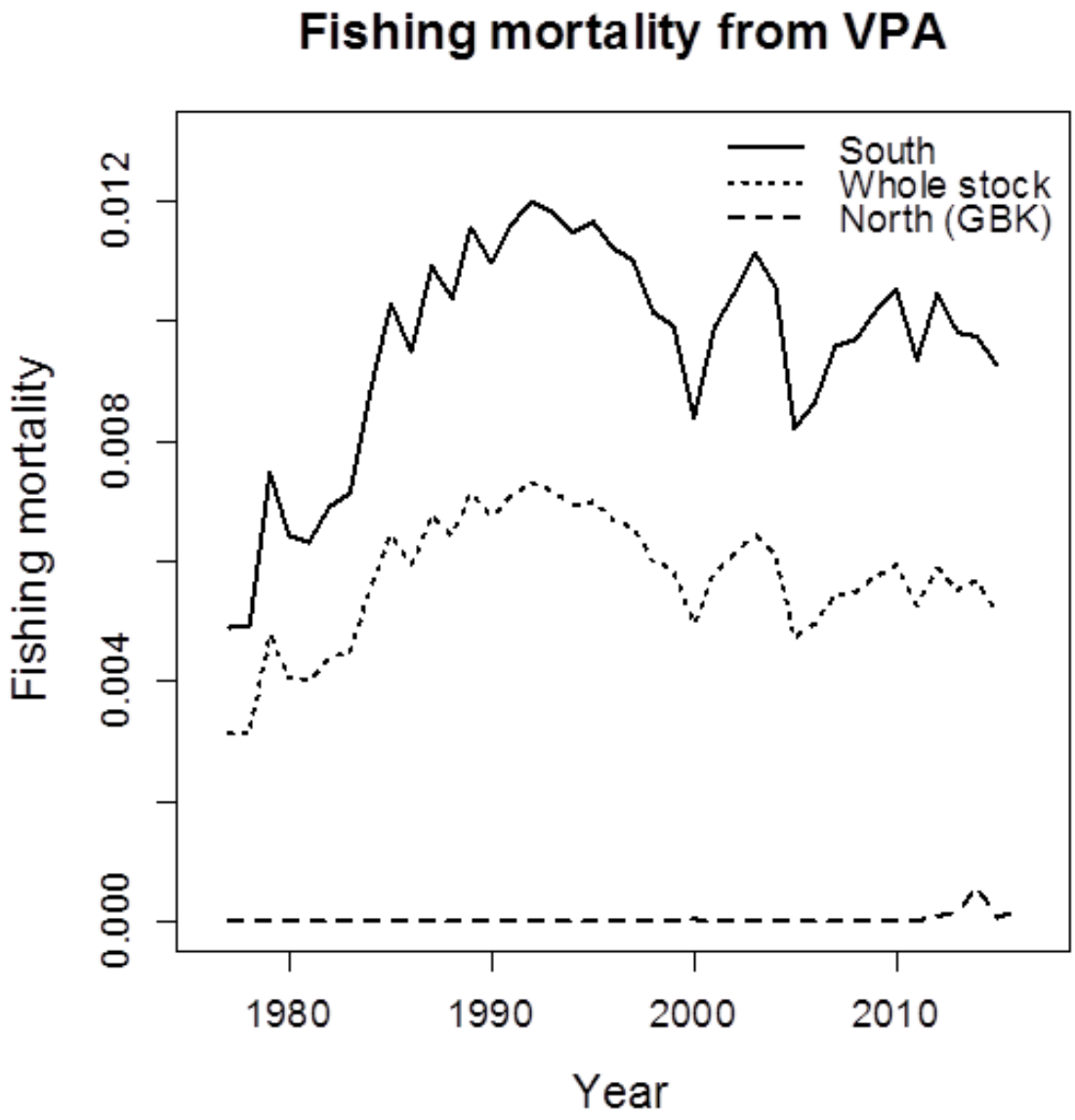

Figure 251: VPA fishing mortality estimates for ocean quahog during 1997-2016.

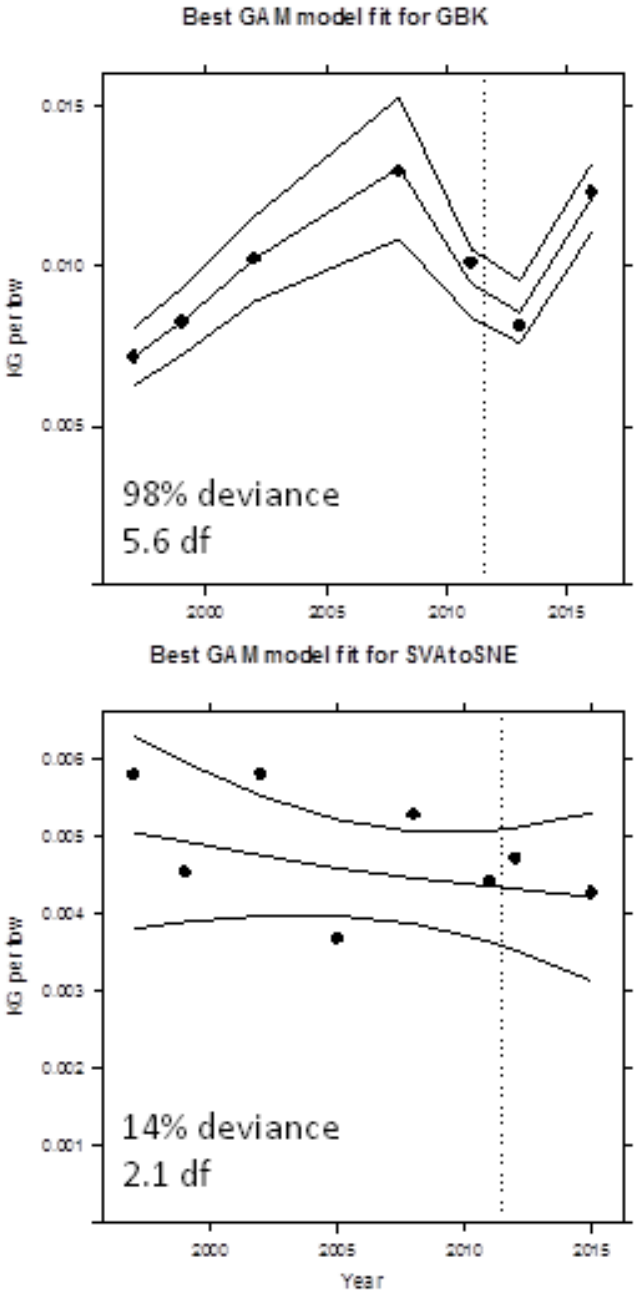

Figure 252: Smoothed survey trends for ocean quahog in the north (GBK) and south during 1997-2016 with a 95% confidence interval. The vertical line shows the introduction of a new survey dredge in 2012. Annotations give the percent of total deviance explained and effective degrees of freedom for the fitted lines.

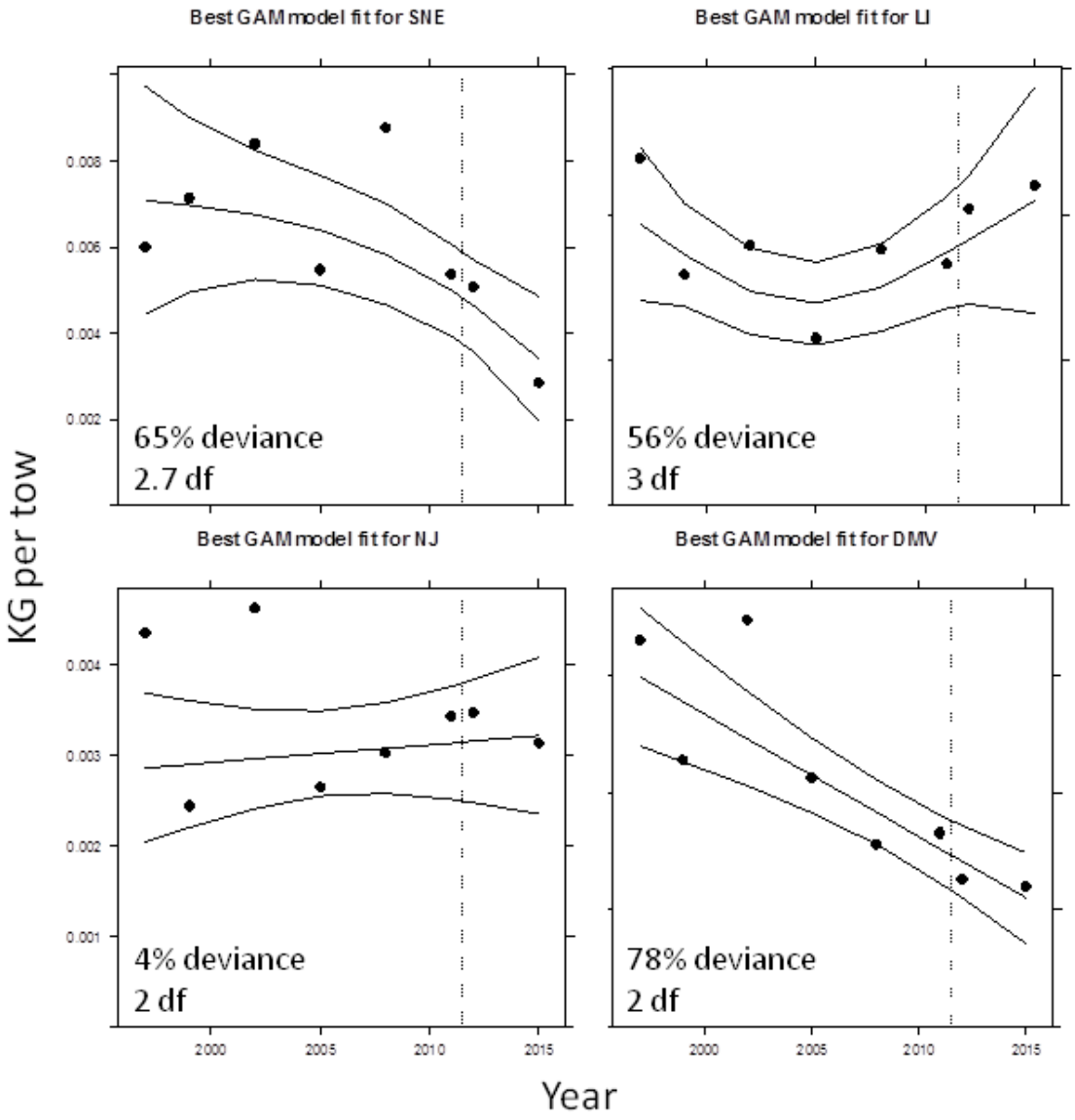

Figure 253: Smoothed survey trends for ocean quahog in the Southern New England (SNE), Long Island (LI), New Jersey (NJ) and Delmarva (DMV) regions (all part of the southern area) during 1997-2015 with a 95% confidence interval. The vertical line shows the introduction of a new survey dredge in 2012. Annotations give the percent of total deviance explained and effective degrees of freedom for the fitted lines.

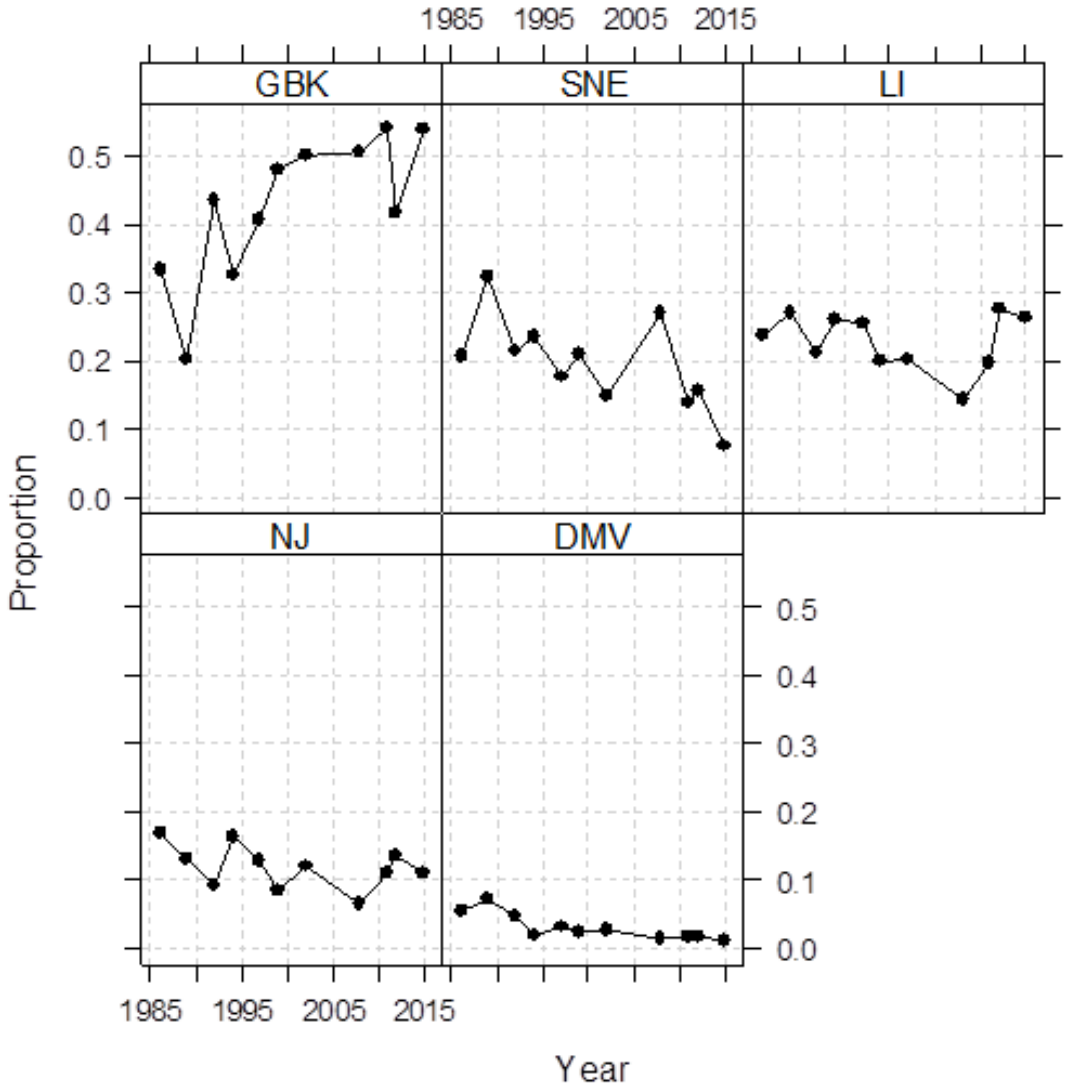

Figure 254: Proportions of total ocean quahog stock biomass in each region during 1986-2016 based on years in which the entire stock was surveyed using the old survey dredge. Data collected with the new survey dredge during 2012 (south) and 2013 (north) were combined and labeled 2012 to cover the entire stock area. Similarly, data for 2015 and 2016 were combined and labeled 2015. The estimates for a single year sum to one.

Appendix 10 Appendix to the SAW Assessment ToR

Clarification of Terms used in the SAW/SARC Terms of Reference

On "Acceptable Biological Catch" (DOC Nat. Stand. Guidel. Fed. Reg., v. 74, no. 11, 1-16-2009):

Acceptable biological catch (ABC) is a level of a stock or stock complex's annual catch that accounts for the scientific uncertainty in the estimate of [overfishing limit] OFL and any other scientific uncertainty. . . " (p. 3208) [In other words, OFL ABC.]

ABC for overfished stocks. For overfished stocks and stock complexes, a rebuilding ABC must be set to reflect the annual catch that is consistent with the schedule of fishing mortality rates in the rebuilding plan. (p. 3209)

NMFS expects that in most cases ABC will be reduced from OFL to reduce the probability that overfishing might occur in a year. (p. 3180)

ABC refers to a level of "catch" that is "acceptable" given the "biological" characteristics of the stock or stock complex. As such, [optimal yield] OY does not equate with ABC. The specification of OY is required to consider a variety of factors, including social and economic factors, and the protection of marine ecosystems, which are not part of the ABC concept. (p. 3189)

On "Vulnerability" (DOC Natl. Stand. Guidelines. Fed. Reg., v. 74, no. 11, 1-16-2009):

"Vulnerability. A stocks vulnerability is a combination of its productivity, which depends upon its life history characteristics, and its susceptibility to the fishery. Productivity refers to the capacity of the stock to produce MSY and to recover if the population is depleted, and susceptibility is the potential for the stock to be impacted by the fishery, which includes direct captures, as well as indirect impacts to the fishery (e.g., loss of habitat quality)." (p. 3205)

Participation among members of a SAW Assessment Working Group:

Anyone participating in SAW assessment working group meetings that will be running or presenting results from an assessment model is expected to supply the source code, a compiled executable, an input file with the proposed configuration, and a detailed model description in advance of the model meeting. Source code for NOAA Toolbox programs is available on request. These measures allow transparency and a fair evaluation of differences that emerge between models.

Appendix 11 Survey performance 2016

Introduction

The 2016 survey covered a portion of the stock area including the SNE and most of GBK subareas. There were 189 total tows and two selectivity tows. At least some sensor information was recorded on every tow. Therefore there were 187 standard survey tows on which sensors were deployed and sensor data was recorded.

The 2016 survey used a modified commercial dredge with 3 on board data recorders. There was an inclinometer (Star Oddi) and two (Madge Tech) pressure sensors: one in the pump manifold measuring the pressure in the hydraulic jets used to loosen the sediments around clams and one measuring the ambient pressure at fishing depth. The inclinometer measured the pitch, roll, and yaw of the dredge as it was towed and was used to determine if the dredge was in a fishing position, which was the basis for determining "time fishing" on each tow. The pressure sensors were used to make sure that the pump was achieving sufficient pressure to maintain capture efficiency.

Survey performance

Sensors deployed during the 2016 survey suggest speed over ground was slightly less than 2012, but consistent with the years since (Figure 255). Pump pressure was close to the 2012 median (Figure 255) and well within the confidence bounds observed then. Neither pump pressure nor vessel speed appeared to be less than expected based on ship board instruments during operations and the sensor data have substantial coefficients of variation. The values observed are probably well within normal operating tolerance and are probably not suggestive of changes in dredge performance.

Determination of time fishing

The determination of time fishing, the "fishing seconds" for each tow was based on a measurement of the pitch of the dredge during each second of the tow. Roll and yaw were relatively stable for the large modified commercial dredge and rarely fluctuated from baseline levels during fishing events. Pitch was recorded by an inclinometer which functioned consistently. Data from each instrument was smoothed using a 7 second moving average and then parsed for time above or below the median fishing angle for that tow.

In order to account for median pitch $> 0^o$, the determination of time fishing was based on a critical deviation from median pitch, rather than an absolute critical pitch angle. The choice of critical deviation has implications for the calculation of tow distance for each tow. When the dredge is above or below the critical deviation it is assumed to be pitched too steeply for the blade to penetrate the sediment. If the dredge is pitched within Δ_{crit} (the critical deviation) of $\tilde{\phi}_t$ (the median pitch for tow t), it assumed to be near enough to parallel to the bottom that the blade should penetrate and thus be actively fishing.

An ideal critical deviation is as close to zero as possible, but not so small that it includes poor dredge performance seconds. When the dredge is bouncing over rough terrain it is unlikely to be fishing effectively and those seconds should be excluded. There is however, a certain amount of pitch that is within fishing tolerance and a certain amount of noise in the data. If the critical deviation is too small, many seconds when the dredge is actually fishing would be excluded, which would tend to bias estimates of tow distance down. It is therefore important to find a critical deviation that is neither too small, nor too large.

The choice of Δ_{crit} was informed by an examination of the total and average tow distances based on different critical deviations. Total tow distance summed across all tow and average tow distance over all tows was compared when different values of Δ_{crit} were used. In general higher values of Δ_{crit} result in longer tows because the dredge is considered to be in fishing position for a greater proportion of the tow (Figure 256). We selected a Δ_{crit} of 4° because it produced an average tow distance that was near the nominal tow distance (0.25 nm, a value equal to the nominal tow speed 3 kt multiplied by the nominal tow time 5 min) and because it seemed reasonable based on examination of the engineering schematic of the dredge being used (*Figure not yet available*).

Time fishing during the 2016 survey was less than the nominal tow time in most cases due to the lower average tow speed discussed above (Figure 257).

Effects of depth

Depth is typically associated with longer tows due to the scope of the towing wire that must be deployed to assure good dredge performance. Additional scope requires longer retrieval times and may result in some additional time fishing while the slack in the wire is spooled up. This effect was evident (though noisy) during the 2016 survey (Figure 257).

Temperature

Temperature was recorded from the dredge and averaged over fishing seconds for all tows during the 2016 survey (Figure 258). Temperature was correlated with depth (Figure 258).

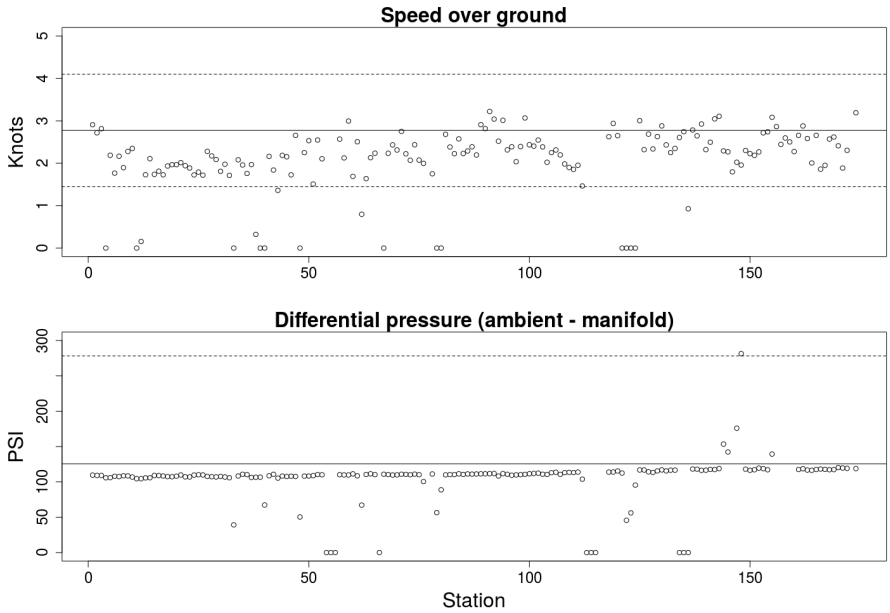

Figure 255: Speed over ground and differential pressure for each tow in the 2016 survey. The solid horizontal line is the median and the dashed horizontal lines are the 95% normal confidence bounds observed speed over ground in 2012. Differential pressure is the difference between the pressure in the dredge manifold, which indicates the absolute pressure realized by the dredges hydraulic jets, and the ambient pressure at fishing depth. The solid horizontal line is the median and the dashed horizontal lines are the 95% normal confidence bounds observed differential pressure in 2012. Instrument failure or lost data are represented by differential pressure equal to 0.

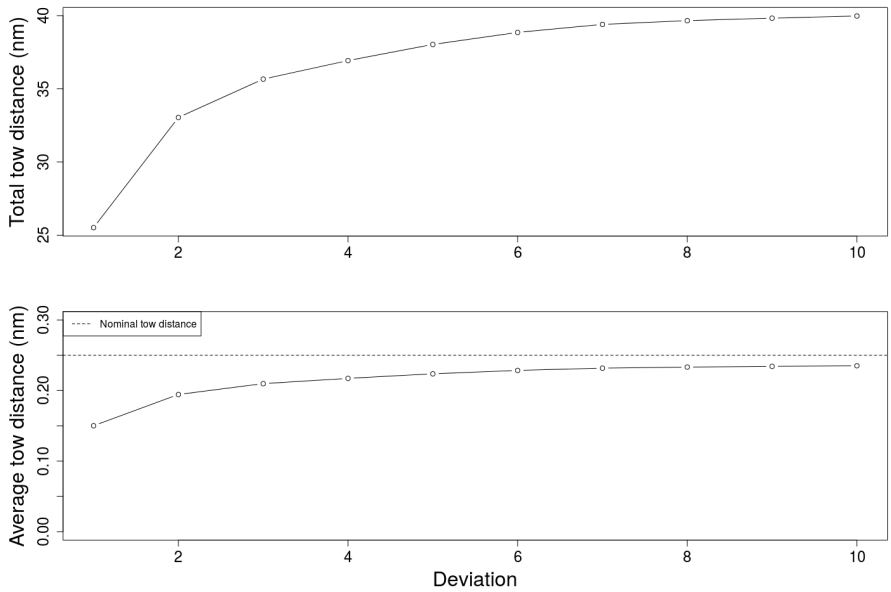

Figure 256: Average and total tow distance over all stations by critical deviation angle. The dashed line in the lower figure represents the nominal tow distance.

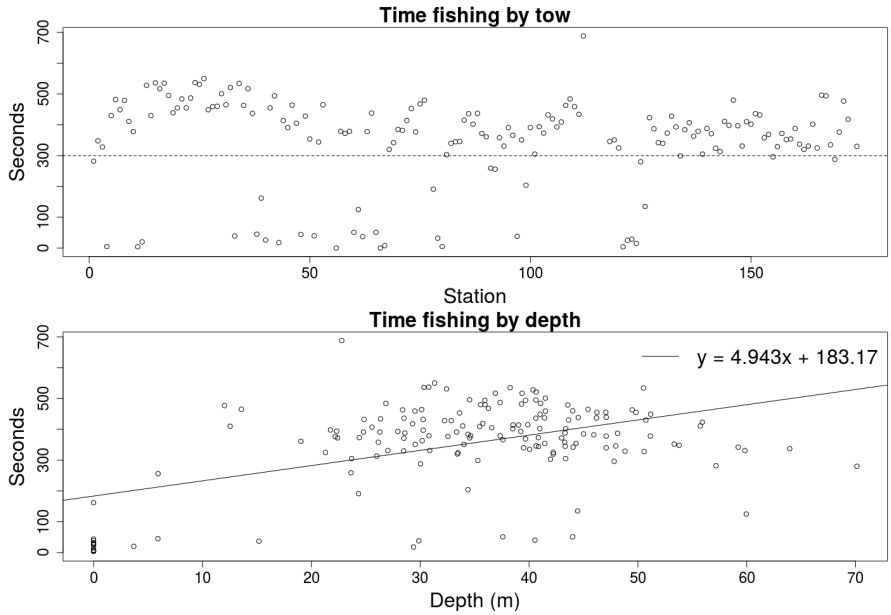

Figure 257: Time fished by station and depth. Depth significantly predicts tow time. The p value for slope was < 0.001, though the results were noisy and $R^2 < 0.14$ for the regression line shown.

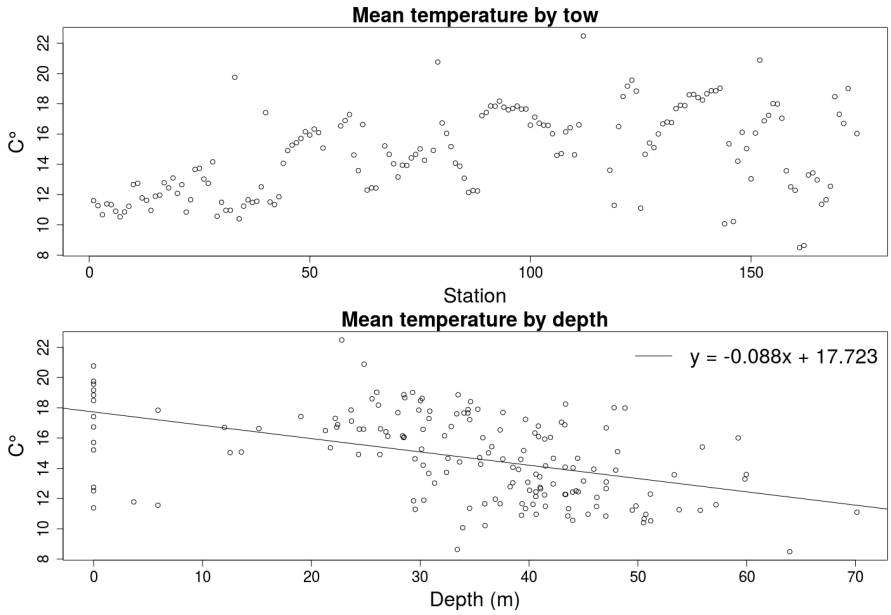

Figure 258: Temperature by station and depth. Depth significantly predicts temperature. The p value for slope was < 0.001 and $R^2 > 0.43$ for the regression line shown.

Appendix 12 Attendees and agenda from working group meetings

Meeting 1

Attendees: Larry Jacobson, Kelsey Kuykendall, Sara Pace, Chase Long, Jessica Coakley, Eric Powell, Tom Hoff, Toni Chute, Doug Potts, Bob Glenn, Dan Hennen, Tom Alspach, Dave Wallace, Jon Duquette, Vic Nordahl, Nancy McHugh.

Ocean quahog stock assessment for SAW/SARC 63 (October 17-18) and
Clam survey design (October 19-20) meetings

Clark Conference Room, NEFSC, Woods Hole, MA

-

Quahog assessment

1) Welcome, door code, introductions - Larry
2) TOR - Larry
3) Major assessment topics (VMS, new survey, MSE update, growth, reanalysis of depletion studies through 2011, and ??) - Larry
4) Management (MAFMC) update - Jessica
5) Research activities (NEFSC, academics, other agencies)
    a. Age and growth - Roger/Eric
    b. Stock-recruit? - Eric
    c. Other?
6) Commercial data (ITQ fishery) - Dan
7) Industry perspectives - Larry
8) Survey (federal) - Dan
    a. Sensor data and gear performance
    b. Trends
    c. Swept-area stock size
9) Fishery and survey (ME) – Robert/Toni

Clam survey (surfclams and ocean quahogs)

1) TOR, rights and responsibilities - Larry
2) Review (BRIEF-mostly for benefit of outsiders)
    a. Life history/distribution/fishery/management/stock status - Larry
    b. Original (brief) and current (detailed) survey operations - Vic
    c. Selectivity and depletion studies - Dan
    d. Assessment, EFH, ecosystem and other data uses – Dan/others
3) Objectives (management, assessment, ecosystem, EFH and other?) -Larry
    a. List
    b. Current problems. Objectives satisfied? Room for improvement?
4) Analyses to date
    a. Larry's work
    b. Appendix 14 in surfclam assessment - Toni
    c. Ancillary data analysis - Powell
    d. Scallop example and clam calculations - Stephen Smith
    e. Habitat suitability modeling for witch flounder - Friedland
       WEDNESDAY AT 2 PM
5) Work for next meeting - Larry

Meeting 2

Attendees: Larry Jacobson, Jessica Coakley, Eric Powell, Tom Hoff, Toni Chute, Doug Potts, Dan Hennen, Tom Alspach, Dave Wallace, Mike Bergman, Vic Nordahl.

Ocean quahog SAW Working Group & Clam Survey Working Group
Clark Conference Room, NEFSC, Woods Hole, MA
December 19-23 (Monday-Friday)
Draft Agenda

Go to front desk in main building when you first arrive to obtain parking permits make security arrangements.

Start at 1 pm on Monday and at 9 am otherwise. Finish at 5 pm except at noon on Friday.

We will work on the quahog assessment from Monday till mid- or late Wednesday and then spend the rest of the week on the clam survey (but plans can change).

Conference call: Tel: 886-836-6169 (Participant code: 5443237)

Web conference:
https://noaast.adobeconnect.com/r6egmbhh6oz/
Conference number: 866 836-6169

Ocean quahog SAW Working Group

Meeting materials at: http://www.nefsc.noaa.gov/invertebrates/SARC-63_Ocean_quahogs/ (and subdirectory Mtg_2) – username "invertebrates", password "rule"

1) Introductions, arrangements and meeting materials, rapporteur
2) TOR
3) Business from last meeting
    a. Survey data
    b. Habitat
4) Growth
    a. More growth curves
    b. Cohort biomass
    c. Pop Dy model
5) Maine fishery for mahogany quahogs (Wednesday AM, probably)
6) Estimate F, B and uncertainty
    a. KLAMZ, build a bridge and SS3
    b. Sensitivity analyses
    c. Historical and standard retrospective analysis
    d. Empirical assessment results
7) Reference points
    a. Current (old)
    b. Updated

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