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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