Terms of Reference

1. **1.** Characterize commercial catch including landings, effort, and discards.
2. **2.** Estimate fishing mortality, spawning stock biomass, and stock biomass for the current and previous years. Characterize uncertainty of the estimates.
3. **3.** Update or redefine biological reference points (BRPs; estimates or proxies for *BMSY*, *BTHRESHOLD*, and *FMSY*). Comment on the scientific adequacy of existing and redefined BRPs.
4. **4.** Evaluate stock status with respect to the existing BRPs, as well as with respect to updated or redefined BRPs (from TOR 3).
5. **5.** Develop and apply analytical approaches and data that can be used for conducting single and multi-year stock projections and for computing candidate ABCs (Acceptable Biological Catch).
   a. Provide numerical short-term projections (3-4 years). Each projection should estimate and report annual probabilities of exceeding threshold BRPs for *F*, and probabilities of falling below threshold BRPs for biomass. In carrying out projections, consider a range of assumptions about the most important uncertainties in the assessment (alternate states of nature).
   b. If possible, comment on the relative probability of the alternate states of nature and on which projections seem most realistic.
   c. Describe this stock's vulnerability to becoming overfished, and how this could affect the choice of ABC.
6. **6.** Review, evaluate and report on the status of SARC/Working Group research recommendations listed in recent SARC reviewed assessments. Identify new research recommendations.

Clarification of terms used in the terms of reference:

(The text below is from DOC National Standard Guidelines, Federal Register, vol. 74, no. 11, January 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…" (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.

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

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.

Executive Summary

A) This assessment for ocean quahog in the US EEZ is based on biological information, fishery-dependent data for 1978-2008 and NEFSC clam survey data for 1982-2008. Based on assessment data, the ocean quahog population is an unproductive stock with infrequent and limited recruitment. After three decades of fishing at a relatively low *F*, the stock as a whole it is being fished down towards its target biomass reference point, which is defined as 50% of biomass during 1978 (pre-fishery) based on assessment recommendations.

B) Ocean quahogs in the US EEZ are not overfished and overfishing is not occurring. Total fishable stock biomass (all regions) during 2008 was 2.905 million mt, which is above the current and recommended management target of 1.790 million mt. The fishing mortality rate during 2008 for the exploited region (all areas but GBK) was $F = 0.01$ y^{-1}, which is below the current $F_{25\%} = 0.0517$ y^{-1} and recommended $F_{45\%}=0.0219$ threshold reference points. The recommended $F_{45\%}$ mortality threshold is based on harvest policies for long lived West Coast groundfish, which are probably more productive than ocean quahogs. The $F_{45\%}$ recommendation should be revisited in the next assessment.

C) Fishing effort declined in the EEZ fishery from about 40 thousand hours per year during 1990-1995 to about 25 thousand hours per year recently. The number of active vessels in the EEZ in 2008 was the lowest level on record. LPUE for the EEZ stock as a whole has been stable since 1982 but is currently higher in northern areas (LI and SNE) than in the south (NJ and DMV). Landings have declined since the peak of 22,000 mt during 1992 to 15,000 mt during 2009.

D) The ocean quahog fishery has shifted north over the last two decades as catch rates declined in the original fishing grounds off Delmarva and New Jersey. In the 1980s, the bulk of the fishing effort was off Delmarva and southern New Jersey, with some fishing off southern New England. In the early 1990s effort fell by half in the Delmarva region while effort increased south of Long Island until about 40% of total effort was concentrated there. By the late 1990s, most of the fishing effort had moved to the Southern New England region. In the early 2000s, the majority of fishing effort was in the Long Island region. By the late 2000s only 22% of total effort was in the Delmarva and New Jersey regions.

E) Cooperative ocean quahog depletion experiments conducted in connection with the 1997-2008 NEFSC clam surveys were used to estimate the efficiency of the NEFSC survey dredge. Results of depletion experiments are important in estimating biomass and fishing mortality. Three more successful depletion experiments were carried out this year for a total of 15. Based on all experiments to date, the median NEFSC survey dredge efficiency is 0.169.

F) During the 2008 NEFSC clam survey, which consisted of 453 stations, the electrical cable powering the dredge pump was replaced at station 241 with a longer one, and the dredge pump was replaced at station 170. As a result, special analyses were conducted to determine the effects of these changes on survey catch rates. Based on the results, effects of the

replacement electrical cables and pumps on catches during the 2008 survey could not be distinguished statistically from zero.

G) Dredge tows completed during the 2008 survey tended to be shorter than tows from the 1997, 1999, 2002 and 2005 surveys although differences between 2008 and 2002 were small. Considerable effort was devoted to examining sensor data to determine why survey tows during 2008 were shorter than in previous surveys. The evidence was inconclusive.

H) The estimates of biomass and fishing mortality for the EEZ stock in this assessment do not include the Maine "mahogany" quahog fishery. Maine stock biomass is small (~1% relative to the rest of the EEZ) with fishing effort concentrated in a small area. A stock assessment for ocean quahogs in Maine waters is presented as Appendix B2.

I) Current BRPs were reviewed. The current threshold reference point for fishing mortality $F_{25\%}$=0.0517 y^{-1} is a poor proxy for F_{MSY} in a long-lived species like ocean quahog with natural mortality rate M=0.02 y^{-1}. In absence of simulations for ocean quahog, the best available information is Clark's (2002) simulation analyses of F_{MSY} proxies applicable to long lived West Coast groundfish and a follow-up workshop report (PFMC 2000, reproduced here as Appendix B7). The workshop report recommends an F_{MSY} proxy of $F_{40\%}$ for relatively productive Pacific whiting and flatfish, $F_{45\%}$ for other groundfish, and $F_{50\%}$ for *Sebastes* spp. (rockfish) and *Sebastolobus* spp. (thornyheads). The Invertebrate Subcommittee could not choose between $F_{40\%}$ and $F_{50\%}$ as F_{MSY} proxies. After discussion, $F_{45\%}$ was recommended as the F_{MSY} proxy for ocean quahogs. New recommended reference points are not referred to as MSY reference points because the productivity of the ocean quahog stock is currently unknown.

J) The new recommended biomass target of 1.837 million mt is one-half of the 1978 pre-fishery biomass (virgin biomass probably fluctuated due to infrequent recruitment). The new recommended $B_{Threshold}$ which is 40% of the 1978 biomass (1.432 million mt), which can be compared to the current $B_{Threshold}$ which is 25% of virgin biomass. The recommended $B_{Threshold}$ is ad hoc, but probably better than the current value.

K) Managers will have to decide whether the new fishing mortality threshold should be compared to estimated fishing mortality for the exploited portion of the stock (excluding GBK where no fishing takes place) or to the whole stock. Fishing does not occur on GBK (which current contains about 45% of stock biomass) because of the risk of PSP (paralytic shellfish poisoning).

   a. The current FMP requires comparison of the threshold reference point to fishing mortality in the exploited portion of the stock only. Most other FMPs compare reference points to mortality rates for the whole stock.

   b. This current approach should help maintain higher productivity for a sessile spatially non-homogenous stock like ocean quahogs. MSY theory is difficult to apply to stocks like ocean quahogs because MSY mortality levels for the stock as a whole result in under-exploitation of the unfished portion (with foregone yield) while the fished portion of the stock is over exploited (resulting in foregone yield).

c. Industry sources expect ocean quahog fishing to begin on Georges Bank soon. This assessment contains no direct advice on harvest of ocean quahogs across the entire stock. Almost all fishery calculations use growth curves and other data for the currently exploited portion of the stock. Harvest policies for ocean quahog should be reconsidered when and if a fishery develops on Georges Bank

L) KLAMZ model projections were run with varying "states of nature", a range of possible values for natural mortality (M=0.015, 0.02 and 0.025) and biomass levels. The projections were also run with four landings policies (status quo, FMP minimum quota, FMP maximum quota, and FMP current quota) and five target fishing mortality policies ($F_{0.1}$, $F_{25\%}$, $F_{40\%}$, $F_{45\%}$ and $F_{50\%}$). Both stochastic and deterministic (which approximate median values from stochastic projections) results indicate that overfished (low biomass) stock conditions and overfishing are not likely to occur by 2015 *at current catch levels* under any of the states of nature.

M) In 2008, fishable stock biomass in SVA, DMV and NJ was less than half of pre-fishing (1978) levels. In contrast, stock biomass in the more northern regions of LI and SNE increased after 1978 to due to a recruitment event and growth, and then began to decrease in the early 1990s when recruitment declined and the fishery gradually began to move north into these areas. The LI, SNE and GBK regions contained about 67% of total fishable biomass during 1978 and contained about 84% of the total fishable biomass during 2008. The GBK region, which is currently not fished due to risk of PSP contamination, contained about 32% of total fishable biomass during 1978 and about 45% during 2008.

N) Recruitment events appear to be localized and episodic (i.e. often separated by decades) although survey length composition data show that a very low level of recruitment occurs on a continuous basis. Based on survey length composition data and published studies, some recruitment has been evident in LI, SNE and GBK during recent years. The potential contribution of recent recruitment to stock biomass and productivity is unknown.

O) Fishing mortality rates are relatively low for the ocean quahog stock as a whole and stock biomass is relatively high. However, ocean quahogs are an unproductive stock that is likely vulnerable to overfishing. If overfished (depleted biomass) conditions occur, one or more decades will be required to rebuild the stock.

Introduction

Ocean quahogs (*Arctica islandica*) in the US Exclusive Economic Zone (EEZ, federal waters only) and a small component in Maine (MNE) state waters are regarded as a single stock. However, the EEZ and MNE components have different biological characteristics and support different fisheries that are managed separately. The EEZ fishery (with landings of about 15,000 mt meats during 2008) is managed by under a single individual transferable quota (ITQ) system that was established for ocean quahog and Atlantic surfclam (*Spisula solidissima*) in 1990. Murawski and Serchuk (1989) and Serchuk and Murawski (1997) provide detailed information about the history and operation of the EEZ fishery. The smaller MNE fishery (with landings of about 200 mt meats during 2008) is managed under a separate quota system. This report focuses primarily on the ITQ fishery but includes a brief summary of key results for ocean quahogs in Maine waters. Appendix B2 gives detailed stock assessment information about ocean quahogs in Maine waters.

The ocean quahog stock is often broken down into smaller regions (listed below) based on biology, fishery characteristics, and history. These designated regions are important in understanding the fishery but have no legal importance beyond the distinctions between Maine, Georges Bank (GBK, see below) and the EEZ as a whole.

Region	Abbreviation
US exclusive economic zone	EEZ
Georges Bank	GBK
Southern New England	SNE
Long Island	LI
New Jersey	NJ
Delmarva	DMV
Southern Virginia and North Carolina	SVA
Mid-Atlantic Bight (Delmarva to Long Island)	MAB
Maine	MNE

Entire stock vs. the exploited region

Data and analysis for ocean quahogs in the EEZ are presented in this assessment for the "entire" or "whole" stock and for the "exploited region" only (Figure B1). "Entire" and "whole" stock refers to ocean quahogs in the entire EEZ. The "exploited region", in contrast, excludes Georges Bank (GBK) because the GBK region has been closed to ocean quahog harvesting since 1990 when paralytic shellfish poison (PSP) was detected. The Mid-Atlantic Bight (DMV to LI) includes most of the exploited region where the fishery originally operated.

Interest in reopening GBK for ocean quahog fishing has increased recently because catch rates on southern fishing grounds are relatively low and a large fraction (nearly 50%) of the fishable biomass is found there. Sampling was carried out during 2008 to determine if PSP is still a problem. Industry sources expect the fishery on GBK to reopen in the near future.

Fishable stock vs. exploited region

The "fishable stock" and "exploited region" are not synonymous for ocean quahogs in this report. "Fishable" ocean quahogs are quahogs large enough to be taken in the commercial fishery based on the size selectivity curve for commercial fishing gear (Figure B2).

Units of measurement

Body size in ocean quahogs is measured in terms of shell length (SL), which is the longest anterior-posterior distance along the axis of an intact specimen.

Vessel size categories and units of measure for ocean quahogs used in this assessment are described below. Commercial data are reported in units of "industry bushels" in logbooks and often converted to saleable meat weights (which include all soft tissues within the shell) for use in this assessment.

Unit	Equivalent
Industry or Mid-Atlantic bushel (Industry bu)	1.88 ft^3
Maine (US standard) bushel (Maine bu)	1.2448 ft^3
Industry bushels x 10	Pounds meat wt
Industry bushels x 4.5359	Kilograms meat wt
Maine bushel	0.662 industry bushels
Cage	32 Industry bushels
Vessel ton class 1	1-4 gross registered tons (GRT)
Vessel ton class 2	2-50 GRT
Vessel ton class 3	51-150 GRT

Previous assessments

Stock assessments for ocean quahog in the EEZ were completed by the NEFSC (1995; 1998; 2000; 2004; 2007a). The last assessment (NEFSC 2007a) concluded that the EEZ ocean quahog resource was not overfished and that overfishing was not occurring.

Fishing mortality rates during 2005 for the MNE stock component was near the $F_{0.1}$ level (NEFSC 2007a).

Biological characteristics[2]

Ocean quahogs are common in the eastern Atlantic as far south as Spain, around Iceland, and in the western Atlantic as far south as Cape Hatteras (Theroux and Wigley 1983; Thorarinsdottir and Einarsson 1996; Lewis et al. 2001). They can be found at depths of 10-400 m, depending on latitude (deeper water habitats are utilized in the south, Theroux and Wigley 1983; Thompson et al. 1980).

The US stock is almost completely within the EEZ at depths of 25-95 m. Dahlgren et al. (2000) found no genetic differences between samples taken along the US coast from Maine to Virginia based on mitochondrial cytochrome *b* gene frequencies.

The natural mortality rate and longevity of ocean quahogs are uncertain. Ocean quahogs are certainly long-lived. Individual specimens are commonly aged at over 200 yrs (Jones 1980; Steingrimsson and Thorarinsdottir, 1995; Kilada et al., 2007; Strahl et al. 2007). Early studies of populations off New Jersey and Long Island (Thompson et al. 1980; Murawski et al. 1982) demonstrate that clams ranging in age from 50-100 years are common. Wanamaker et al., (2008) aged two ocean quahogs at 287 and 405 y, making the latter specimen possibly the oldest non-colonial animal ever documented. Based on longevity estimates of around 200 y, adult ocean quahogs in the EEZ and off Iceland are assumed to die from natural causes at the rate of about 2% annually (instantaneous rate of natural mortality M=0.02 per year). In particular, about 1% of a cohort is expected to survive after 230 y when M=0.02. Kilada et al estimated M to be 0.03 and 0.10 for the Sable Bank and St Mary's Bay populations in Canadian waters based on age–frequency data for unexploited populations.

Ocean quahogs grow slowly after the first years of life (Lewis et al. 2001; Kilada et al. 2007). Maximum size is typically about 110 mm in shell length (SL) although larger specimens are

2 See Cargnelli et al. (1999) for additional information.

found. Individuals large enough to recruit to the fishery grow only 0.51-0.77% per year in meat weight and < 1 mm per year in shell length (Figure B3). Growth is faster in GBK than further south in the MAB (Figure B3).

Maturity and recruitment information for ocean quahogs in the US EEZ is scant (see review in Cargnelli et al. 1999) but size and age at maturity appear to be variable. Off Long Island, the smallest mature quahog found was a male 36 mm long and 6 years old; the smallest and youngest mature female was 41 mm long and 6 yr old (Ropes et al. 1984). Some clams in this region are still sexually immature at ages of 8-14 years (Thompson et al. 1980; Ropes et al. 1984). Females are more common than males among the oldest and largest individuals in the population (Ropes et al. 1984; Fritz 1991).

The shell length maturity relationship used in this assessment (Figure B2) is from data for Icelandic ocean quahogs (Thorarinsdottir and Jacobson, 2005). The curve indicates that 10%, 50% and 90% of female ocean quahog mature at 40, 64, and 88 mm SL (2, 19, and 61 y, based on the growth curve in Lewis et al., 2001 for MAB). Based on the size range of samples (G. Thorarinsdottir, pers. comm.), the maturity curve is probably valid for ocean quahog in the size range used to estimate fishing mortality. Maturity occurs at roughly 10 mm before, and about 10 years before, recruitment to the fishery (Figure B2).

Shell length-meat weight (SLMW) relationships are important for ocean quahogs because survey catches in number are converted to meat weights based on shell length for many analyses. SLMW relationships in this assessment are region-specific (Table B9) and the same as in the last assessment (NEFSC 2007a). They were estimated using a mixture of frozen and fresh samples. Relationships were re-estimated based on large number of fresh samples taken during the 1997-2008 surveys (Appendix B8). The updated relationships will be used in the next ocean quahog assessment but were not ready in time for use here.

Recruitment patterns

Recruitment events are regional and infrequent in ocean quahog (Powell and Mann 2005, Harding et al. 2008). Small ocean quahogs in survey length composition data indicate that recruitment occurs at a very low level during most years, particularly in northern areas (Figures B24 through B29). However, survey data collected during 1982-2008 show only three noteworthy recruitment events in LI, SNE and GBK (Figures B25 through B27) over regional spatial scales. Because growth is so slow, there are delays of one to three decades between larval settlement and production of recruits to the fishery. Ocean quahogs reach 64 mm SL (50% maturity) at age 12 y in GBK and 19 y in MAB (Figure B2). In contrast, ocean quahogs reach 73 mm (50% commercial selectivity) at age 13 y in GBK and 28 y in MAB (Figure B3). Each of the three recruitment events observed since 1980 were produced while spawning biomass in the same region was unfished or nearly unfished. Recruitment patterns in ocean quahog at reduced biomass levels after fishing are a major uncertainty (NEFSC 2007a).

Commercial and Recreational Catch
(TOR-1)

Mandatory logbooks have been the principle source of fishery data (landings, fishing locations and fishing effort) for the ITQ fishery since 1980. Landings and quotas for the ITQ fishery are reported in different units than landings and quotas for the fishery off Maine. In particular, "industry" bushels (1.88 ft^3) are used for the ITQ component and "Maine" bushels (1.2448 ft^3) are used for the Maine component. Biomass and landings from both fishery components are reported in this assessment as meat weights, unless otherwise noted.

Total EEZ landings (including both ITQ and Maine fishery components) were relatively high during 1987-1996 with a peak of 22,500 mt meats (Tables B1 and B2; Figure B4) or 4.9 million ITQ bushels (see Table B3 for all landings in bushels) during 1992. After 1996, landings declined to a low of about 15,000 mt during 2000 and then increased again to a high of 19,000 mt during 2003. Landings declined after 2003 to about 14,000 mt during 2005, the lowest level since 1981. After 2005, landings increased slightly to about 15,500 mt. Industry sources report that low landings during the most recent years were due to low market demand. Landings by the Maine component of the fishery were only 1.2% of total EEZ landings during 1990-2008.

Landings from Maine waters increased steadily from 75 mt in 1992 to relatively high levels (≥ 326 mt annually) during 2000-2003 (Tables B2 and B3). Maine landings decreased after 2003, but remained over 300 mt through 2007. Only 201 mt were landed in 2008, the lowest level since 1997.

Landings by the ITQ component averaged 83% of the EEZ quota during 1990-2008 (Table B1). In contrast, the 100,000 Maine bushel quota allocated for ocean quahog in Maine waters was usually exhausted during 1999-2008 with vessels leasing ITQ shares in some years to harvest more than 100,000 mt meats from Maine waters (Tables B2 and B3).

Landings of quahogs from state waters south of Maine are effectively zero because ocean quahogs are found offshore in relatively deep water. There are no recreational landings of ocean quahogs because commercial clam dredges are required to harvest them, and because they provide an industrial product with no recreational value.

Prices

Nominal ex-vessel prices for ITQ ocean quahog landings (expressed as dollars per ITQ bushel) increased by about 66% after 1990 (Table B4 and Figure B5). In real terms, prices stayed fairly stable except for a 30% jump from 2000 to 2001, followed by a steady decline. Prices during 2006-2008 stabilized at about $3.20 a bushel.

Prices for ocean quahog harvested in Maine waters (expressed as dollars per ITQ bushel for the sake of comparison) were roughly ten times higher than prices for ocean quahogs harvested in the rest of the EEZ (Table B4 and Figure B5). In real dollars, Maine prices have fallen about 50% since their peak in the early nineties.

Fishing effort

Total hours fished annually in the ITQ fishery component decreased from a peak of about 40,000 hr per year during 1991-1994 to about 30,000 hr per year during 1996 to 2004, and then to about 20,000 hr per year during 2005-2008 (Table B5 and Figure B6). The total number of trips in the ITQ fishery decreased steadily from about 3000 trips per year during 1991 to about 1200 trips per year during 2008 (Figure B7). In contrast, hours fished and trips increased in the Maine fishery component during 1991-2005, but declined afterward. The number of active permits (vessels with landings during the year in question) in the ITQ fishery remained relatively constant during 1996-2003 but declined by 50% from 2004 to 2006 and has remained stable at around 30 permits ever since (Figure B8). The number of active permits and fishing effort (hours fished and numbers of trips) is high in Maine waters relative to other regions in the EEZ.

Landings per unit effort (LPUE)

LPUE (expressed in bushels landed per hour fished) in the ocean quahog fishery is a better measure of fishing success than a measure of stock abundance because changes in abundance or biomass may be masked by movement of fishing effort to areas where ocean quahog density and catch rates remain high. In spite of these potential problems, LPUE and NEFSC clam survey data are highly correlated for southern areas (DMV and NJ) where significant levels of fishing occurred over long periods of time (NEFSC 2007a).

LPUE declined by about 60% in the DMV and NJ regions after the mid-1980s to about 60-80 bushels per hour in recent years (Table B6 and Figure B9). LI and SNE show relatively high LPUE levels of about 160 and 180 bushels per hour that have been relatively stable since 2000. The LPUE for the ITQ fishery as a whole has been remarkably constant since the early 1980s (Table B6) at between 100 and 150 bushels per hour because the fishery moves to new grounds when LPUE declines.

The break-even LPUE (where variable costs and revenues are the same) reported in NEFSC (2004) for the EEZ fishery was 80 bushels h^{-1}. This estimate was higher than previously reported (NEFSC 2001) because of inflation, increased steaming time to relatively distant fishing grounds, operation of new larger vessels, and increased costs for food, fuel, insurance, etc. It was not possible to update the estimate of break-even LPUE because of extreme variability in the price of fuel.

In the Maine fishery (Figure B10), standardized LPUE increased to over 6 bushels an hour during 1991-2000, and decreased afterwards, and has fluctuated between 4 and 5.5 bushels per hour for the last 8 years.

NEFSC (2007a) standardized LPUE data by adjusting for vessel, month and vessel size effects. Estimated trends were very similar to trends in nominal LPUE. Standardized LPUE data are not presented in this assessment.

Spatial patterns in fishery data

Spatial patterns are important in interpreting fishery data and in managing fisheries for sessile and unproductive organisms like ocean quahogs. The ocean quahog stock is a complicated spatial mosaic with scattered productive and profitable fishing grounds where abundance is high and where fishing mortality tends to be concentrated. The size of a productive ocean quahog fishing ground appears to be less than the size of a ten-minute square (TMS, 10' x 10' $\cong$ 100 nm^2), which is the smallest spatial strata reported on logbooks and used in this stock assessment. As described in NEFSC (2004), spatial patterns in cumulative landings, cumulative effort and LPUE reflect a shift in the distribution of the fishery to offshore and northern grounds. During the 1980s, nearly all of the landings and fishing effort were from the southern DMV and NJ regions. As LPUE declined there, fishing effort and landings shifted offshore and north to the LI and SNE regions. During 2008, the southern DMV and NJ regions accounted for only about 15% of landings and fishing effort while the bulk of landings and effort (outside of Maine waters) were from LI.

Fishery data by ten-minute square (TMS)

Vessels that fish for ocean quahogs in the EEZ are required to report landings and fishing effort by TMS for each trip in mandatory logbooks. TMS are identified by six digit numbers. For example, TMS 436523 is a ten-minute square that lies within the one-degree square with southeast corner at 43^o N and 65^o E. TMS are formed by dividing one-degree squares further into six columns and six rows that are 10' wide. Columns are numbered 1-6 counting from west to east and the column number is given in the TMS name before the row number. Rows are numbered 1-6 counting from north to south. Thus, TMS 436523 is the ten-minute square whose southeast corner is at 43^o 30' N and 65^o 40' E.

Landings (Figure B11) during 1981-1990 were concentrated in relatively few TMS that were primarily in the south and relatively inshore. Over time, TMS with highest landings shifted offshore and north. Landings during 2001-2008 were concentrated in the LI region.

Fishing effort (Figure B12) was concentrated in a few southern TMS during 1980-1990 with three adjacent TMS having effort levels higher than 1,000 h per year and appreciable fishing effort south of 38^o N. Fishing effort spread into additional offshore and northern TMS during 1991-1995 and 1996-2000. After 1995, there were few or no TMS with effort levels above 1000 h per year. During 2001-2008, there was no fishing effort south of 38^o N.

LPUE (Figure B13) was relatively high inshore and south during 1980-1990 with ten TMS that had LPUE $\geq$ 161 ITQ bushels h^{-1}. LPUE in the area below 40^o S was generally high. LPUE declined in the south and fishing effort spread northward during 1991-1995 where LPUE was relatively high. During 1996-2000, the fishery continued to move northward into the SNE region where catches were profitable. By the 2001-2005 time period, LPUE was often $\leq$ 80 ITQ bushels h^{-1} below 40^o S.

Trends for important TNMS

Trends in landings and LPUE during 1980-2005 were plotted for individual TMS that were important to the fishery (Figures B14 through B16). Important TMS were selected by sorting TMS according to total cumulative landings during 1980-1990, 1991-1995, 1996-2000, 2001-2005 and 2006-2008 and then selecting the top 20 TMS during each time period. All of the TMS selected in this manner were combined to form a single a single set of TMS that were important to the fishery at some time during 1980-2008.

Trends in LPUE for individual TMS tend to be relatively high during the first years of exploitation and then tend to decline as effort, annual landings and cumulative landings increase over time (Figures B14 through B16). Decreasing trends in LPUE appear strongest in southern areas such as TMS 377422 to 397326 with the longest history of exploitation. LPUE does not appear to increase in a TMS once fishing effort decreases.

Unlike LPUE which is highest in the first years of exploitation, landings and fishing effort tend to peak after 5-10 years of exploitation while LPUE is still relatively high and then to decrease over a 5-10 y period as grounds are fished down (Figures B14 through B16). In some TMS with low recent LPUE levels (e.g. TMS 387443-397316), fishing effort has increased recently with some increase in landings.

Bycatch and discard

Landings and catch are almost equal in the ocean quahog fishery because discards are nil. Discard of ocean quahogs in the ocean quahog fishery does not occur because undersize animals are automatically released by automatic sorting equipment. However, some incidental mortality occurs. Based on Murawski and Serchuk (1989), NEFSC (2004) assumed incidental mortality rates of $\leq$ 5% for ocean quahog damaged during fishing but not handled on deck. As in previous assessments, fishing mortality and other stock assessment calculations in this report assume 5% incidental mortality rates (i.e. landings x 1.05 = assumed catch).

Bycatch of ocean quahog probably occurs in fishing for Atlantic surfclam. Discard quantities have not been quantified but are probably minor. Off DMV and SVA in the southern end of the ocean quahog's 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). However, mixed loads of surfclams and ocean quahogs are not acceptable to processors and it is not practical to sort catches at sea, so vessels tend to avoid areas where both species might be caught together.

Bycatch and discard of ocean quahogs in other fisheries is nil. Ocean quahogs are not vulnerable to bottom trawls, scallop dredges (because they are too deep in sediments), and hook and line gear.

Commercial size selectivity

The commercial fishery selectivity curve used in this assessment is from Thorarinsdottir and Jacobson (2005) who estimated selectivity of commercial dredges that harvest ocean quahogs off Iceland. Based on this commercial selectivity curve ($s_L = 1/\left(1+e^{7.63-0.105L}\right)$ where L is shell length in mm) about 10%, 50% and 90% of ocean quahogs are available to the fishery at 51, 72, and 93 mm SL (9, 28 and 86 y, based on the growth curve for MAB in Figure B3).

Dredges and towing speeds used in the US fishery are very similar to those used in the selectivity experiments. The dredge used for selectivity experiments was 24 ft (7.35 m) in length, 5 ft (1.5 m) high and 12 ft (3.65 m) wide. The cutting blade was 10 ft (3.05 m) wide and set to penetrate sediments to a depth of 3 in (8 cm). The dredge was made of steel bars with intervening spaces of 1 ¼ in (3.5 cm) and was towed at about 2.1 knots (3.9 km h^{-1}). Water pressure supplied to jets on the dredge from a pump on the ship was about 109 psi (7.5 bars). Water pressure levels in the US fishery are usually lower (~80 psi) but water pressure probably has relatively little effect on size selectivity. Fishery selectivity curves are used in tracking trends in fishable biomass, estimating fishing mortality and in calculating biological reference points.

Commercial size-composition data

Commercial length composition data collected by port agents from landings samples (Table B7) indicate that the size composition of ocean quahogs captured in the DMV region differed during 1987-1994, 1995-2000 (when they were smaller) and 2001-2008 (Figure B17). Lengths for DMV during 1987-1994 and 2001-2008 were similar. The only exception is 2007, when port samples from the DMV region showed slightly larger harvested quahogs.

Commercial length composition data for NJ were stable during 1982-2002 with smaller ocean quahogs landed during 2003-2008 (Figure B18). Length data for LI include relatively high proportions of large individuals (11-12 cm SL) during 1997-1999 (Figure B19). Length data for SNE during 1998-2005 were generally stable but with smaller ocean quahogs landed during 1997-2000 (Figure B20). According to NEFSC (2004), smaller sizes landed from SNE during 1997-2000 were due to vessels targeting specific beds with relatively small ocean quahogs that had relatively high meat yield.

Port sampling levels were increased in the SNE and LI regions during recent years due to increased landings and fishing effort levels (Table B7). Increased port sample frequencies reflect movement of the fishery onto northern grounds in SNE and LI.

Mortality and Stock Biomass
(TOR-2)

Mortality and stock biomass estimates for ocean quahog in the US EEZ are based on triennial NEFSC clam surveys, cooperative survey studies that include depletion experiments used to measure survey dredge efficiency, fishery, and other data.

NEFSC clam surveys

Survey data used in this assessment were from surveys conducted during 1982-2008 by the *R/V Delaware II* during the summer (June-July), using the standard NEFSC survey hydraulic dredge with a submersible pump. The current survey dredge which has been used since 1982 has a 152 cm (60 in) blade and 5.08 cm (2 in) mesh liner to retain relatively small ocean quahogs and Atlantic surfclams. The survey dredge differs from commercial dredges in that it is smaller (5 ft blade instead of 8-12.5 ft), has a small mesh liner, and the pump is mounted on the dredge instead of the deck of the vessel. The survey dredge is useful for ocean quahogs as small as 50 mm SL (size selectivity described below). Changes in ship construction, winch design, winch speed and pump voltage that may have affected survey dredge efficiency are summarized in Table A7 of NEFSC (2004). Each of these factors has been constant since the 2002 survey.

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 NEFSC 2004).

NEFSC clam surveys are organized around NEFSC shellfish strata and stock assessment regions (Figure B1). Most ocean quahog landings originate from areas covered by the survey. The survey did not cover GBK during 1982, 1983, 1984 or 2005. Individual strata in other areas were sometimes missed (Table B8). Strata not sampled during a particular survey are "filled" for assessment purposes by borrowing data from the same stratum in the previous and/or next survey, if data are available (NEFSC 2004). Survey data are never borrowed from surveys further back than the previous survey or beyond the next survey. Despite research recommendations, a model based approach to filling survey holes has not yet been developed, although the approach appears practical based on results for Atlantic surfclam (NEFSC 2007a).

Surveys follow a stratified random sampling design, allocating a pre-determined number of tows to each stratum. Stations used to measure trends in ocean quahog abundance are either random or nearly random. The few "nearly" random tows were added in previous surveys in a quasi-random fashion to ensure that important areas were sampled. Other non-random stations are occupied for a variety of purposes but not used to estimate relative trends in ocean quahog abundance.

A standard tow is nominally 0.125 nm (232 m) in length (i.e. 5 minutes long at a speed of 1.5 knots). However, sensor data indicate that the actual tow lengths depend on depth and are generally longer than 0.125 nm (Weinberg et al. 2002 and see below).

Occasionally, randomly selected stations are found too rocky or rough to tow. Beginning in 1999, these cases trigger a search for fishable ground in the vicinity (0.5 nm) of the original station (NEFSC 2004). If no fishable ground is located, the station is given a special code (SHG=151) and the research vessel moves on to the next station. The proportion of random stations that cannot be fished is an estimate of the proportion of habitat in a stratum or region that is not suitable habitat for ocean quahog. These estimates are used for calculating ocean quahog swept-area biomass (see below).

Following all successful survey tows, all ocean quahogs and Atlantic surfclams in the survey dredge are counted and shell length is measured to the nearest mm. A few very large catches are subsampled. Mean meat weight (kg) per tow is computed with shell length-meat weight (SLMW) equations from NEFSC (2004).

Survey tow distance and gear performance in trend analysis

For trend analysis, tow distances are based on start and stop locations recorded for each tow. The catch at each station is standardized to a "nominal" tow distance of 1.5 nm for trend analysis.

"Successful" tows suitable for trend analysis are identified using "HG" (haul and gear) database codes ≤ 36, which are recorded at sea by the watch chief following each tow based on criteria used consistently since the late 1970's. Sensor data are not used to calculate tow distance for trend analyses because sensor data are not available prior to 1997. Sensor data are used, however, to calculate tow distance and monitor gear performance during tows for depletion, repeat station and other types of experimental studies conducted since 1997 (see below).

Survey tow distance and gear performance based on sensor data

After the 1994 survey, sensors were used to monitor depth (ambient pressure), differential pressure, voltage, frequency (hertz) and amperage of power supplied to the dredge, *x*-tilt (port-starboard angle), *y*-tilt (fore-aft angle, effectively the "angle of attack" of the dredge) and ambient temperature during survey fishing operations. At the same time, sensors on board the ship monitor electrical frequency, GPS position, vessel bearing and vessel speed. Most of the sensor data are averaged and recorded at 1 second intervals.

Good tows have characteristic sensor data patterns that are easy to interpret (Figure B31). Anomalous patterns indicate potential problems with the tow or sensors. Differential pressure, amperage and *y*-tilt can be particularly important. Differential pressure is the pressure of water pumped through jets in front of the dredge blade to loosen the sediments. Amperage measures the work done by the pump in moving water through the jets. If water is blocked at the entrance to the pump, then both amperage and differential pressure will be low. If water is blocked downstream of the pump, then amperage will be low and differential pressure will be high. As described below, *y*-tilt can be used to determine if the dredge is on the bottom with the blade in the sediment.

NEFSC (2007a) developed a quantitative system for identifying tows with poor performance based on *y*-tilt and differential pressure sensor data that was applied to the 2005 NEFSC clam survey (see Appendix A3 in NEFSC 2007a). The *y*-tilt criterion which was part of this quantitative system was dropped after reconsideration in this assessment (Appendix B3) for 3 reasons: i) the *y*-tilt sensors appear to be strongly affected by vibration, ii) the existing procedure for calculating tow distances (see below) already indentifies periods when the dredge is not fishing, and iii) because the standard database "SHG" code eliminates many of the problematic tows before sensor data are examined. The revised criteria based on differential pressure only was applied to the 2008 and retroactively to 2005 surveys (but not to the 1997-2002 surveys due to lack of time).[3,4] Affects on the 2005 survey were modest with only one additional tow shifted from the poor to good performance categories.

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3 The criterion for differential pressure is a time-weighted approach that penalizes problematic high and low pressures. The weights depend on the extent of the deviation from normal operating range of 35-40 psi. The weighting system for differential pressure data P_t is:

$W_t = 2 *(P_t-40)/40$ when the differential pressure $P_t > 40$ psi

$W_t = 2 * ((35-P_t)/35 \times 0.83)$ when $P_t < 35$ psi

$W_t = 1$ otherwise

A tow is judged to have poor performance when the weighted time outside the normal range > 25%. See Appendix B3 for more information.

4 Stations with poor performance based on sensor data in the 2005 survey: 1, 2 , 4,17,20,22,23,24,25,26,28,29,30,31,32, 33,34,45,48,56,58,67,75,76,108,218,225,262,282,405,411,413,414,417, 422,423,424.
Stations in the 2008 survey: 15, ,29,35,43,45,48,52,65,95,99,119,137,138,141,150,164,165,169,175,197,198,206,209,226,227,229,241,242,245, 246,248,249,250,252,254,257,258,262,263,288,290,291,293,305,306,307,308,309,310,317,326,358,366,394,402, 403,424,430,433,434,435,436,437,438,448,452,453.

Survey gear selectivity

NEFSC (2004) estimated selectivity curves for ocean quahogs in the NEFSC clam dredge based on catches by a commercial dredge with a chicken-wire mesh liner during 2003 and survey catches in the same area during 2002. The selectivity curve $s_L = 1/\left(1+e^{8.122-0.119L}\right)$ indicates that 50% of ocean quahogs are fully available to the NEFSC clam dredge at about 68 mm SL, which can be compared to about 73 mm for commercial dredges (Figure B21). The survey dredge tends to take smaller ocean quahogs than commercial dredges because of the relatively small 50 mm (2 in) liner in the survey dredge. Based on sizes retained by the survey dredge (NEFSC 2004), the survey dredge selectivity curve is reliable for ocean quahogs ≥ 50 mm SL.

Survey, stock and fishable abundance and biomass

The survey size selectivity curve with survey catch and size composition data for ocean quahogs ≥ 50 mm SL was used to estimate relative abundance and size composition for the stock as a whole. In particular, $N_L = n_L/s_L$ where N_L is mean stock numbers or biomass per tow at length L in the stock as a whole, n_L is survey catch and s_L is survey selectivity.

Abundance and length composition for the fishable stock (i.e. of a size available to the fishery) were estimated by adjusting stock estimates for fishery selectivity. In particular, $\eta_L = \phi_L N_L$ where η_L is fishable abundance and ϕ_L is fishery selectivity. Fishable abundance can be estimated directly from survey data for ocean quahogs ≥ 50 mm SL using $\eta_L = n_L \phi_L / s_L$ (Figure B21).

Calculations of stock abundance and biomass occasionally produce very large estimates for small sizes where selectivity is small (near zero) when ratios n_L/s_L become very large. Calculation of fishable abundance and biomass from ocean quahog survey data does not suffer from this problem because the adjustment for small sizes is relatively modest (Figure B21).

Survey Trend Results

Based on survey data, abundance and biomass of relatively large quahogs (70+ mm SL) declined during 1997-2008 in all areas but GBK (Table B10 and Figures B22 and B23). The declines in southern areas where the bulk of fishing has occurred (DMV and NJ) appear clear. The apparent trends in SNE and LI since 1997 are not as clear and may be due to sampling error or changes in survey catchability.

Based on survey data for small ocean quahogs (< 70 mm SL, Table B11 and Figure B24), recruitment during 1997-2008 was about average in DMV, higher than average in NJ, SNE and GBK, and below average in LI.

Survey length composition data (Figures B25 through B29) and the distribution of catches in the 2008 survey (Figure B30, lower panel) provide additional information about recruitment. In particular, survey length composition data for LI for 1982 are bimodal with a lower mode at 65-70 mm SL in 1982 due to a strong recruitment event. Based on the growth curve for the MAB (Figure B3), ocean quahogs 65-70 mm SL are about 21-26 y old. The mode gradually shifted to the right over time as the year class grew. By 2005 (23 y later), the strong year class had grown to be indistinguishable from other ocean quahogs in the region. This historical recruitment event is evident in recruit trends for LI, which increased during the 1960-1970's and generally decreased afterwards (Figure B24).

Survey size composition data for SNE during 2005 and 2008 (Figure B26) show a recent recruitment event that is also apparent in the survey trend data for the same years (Figure B24). The lower mode during 2005 and 2008 was at approximately 50-60 mm SL. Based on the MAB growth curve, ocean quahogs 50-60 mm SL are about 9-15 y old. This strong year class is located southeast of Cape Cod based on catch locations in the 2008 survey (Figure B30, bottom panel). LPUE data show relatively high catch rates in the corresponding TMS southeast of Cape Cod at approximately 40^{o} 30' N 69^{o} 40'E (Figure B13).

Size composition data from the 2008 survey show an apparent recent recruitment event in the GBK region as there is a strong mode at about 60-65 mm SL (Figure B25). Based on a growth curve for GBK from Lewis et al. (2001), ocean quahogs 60-65 mm SL on GBK are 7-10 y old. Small ocean quahogs appear sporadically in survey length composition data for GBK during 1982-2002.

The geographic distribution of survey catches for small ocean quahogs (<70 mm SL, Figure B30) and trends for the same sizes (Figure B24) show that small ocean quahogs are most common in the north (LI, SNE and GBK). Large ocean quahogs (70+ mm SL, Figure B30) have the highest densities in the SNE and GBK regions although appreciable densities are also found in LI and offshore in the NJ region.

2008 clam survey

The 2008 clam survey consisted of 453 stations. The total number of useful random stations (with database HG codes ≤ 36) was 337. There were 97 useful nonrandom stations of which three were to identify areas of high recruitment, seven were test tows, and 87 were repeat tows to test for gear effects or setup tows for commercial depletion experiments.

As described below, sensor data (Figure B31) provide additional useful information about gear performance. GPS position information, speed- and course over ground, and amperage data are available for all stations in the 2008 survey. Survey sensor package (SSP) data from the 2008 survey are available for stations 1-405 and backup sensor data are available for tows 406-453. The backup sensor data include ambient pressure but not y-tilt, manifold pressure or voltage.

There were at least three potentially important events during the 2008 clam survey that might affect dredge gear performance and capture efficiency (Figures B32 and B33): a new pump was installed on the dredge and used starting at station 170 due to failure of the original equipment, a new electrical cable to send power to the pump was installed and first used at station 241 so that the dredge could be deployed in relatively deep water, and a new SSP sensor data package was installed and first used at station 270. Mean differential pressure, voltage and amperage calculated for each tow during periods when the dredge was fishing effectively (smoothed y-tilt ≤ 5.16^{o}, see below) reflect each of these events (Figure B33). Based on these data, and in comparison to previous surveys (Figure A29 in NEFSC 2007a), sensor data indicate no major gear performance issues during the 2008 clam survey.

Tow distance

The NEFSC survey dredge is assumed to be effectively fishing when the angle of attack (y-tilt, after smoothing with a 7-second moving average) is less than 5.16^{o}. The 5.16^{o} figure is a standard criterion which corresponds to the dredge blade extending 1 inch into the sediments based on the geometry of the dredge (NEFSC 2003). The criterion was selected based on sensitivity analysis; tow distance estimates were not sensitive to small changes in the critical angle around 5.16^{o} (NEFSC 2003). Tow distances from sensor data are not used in trend analysis but are very important in depletion studies and other types of studies where absolute estimates of quahog density are required.

The procedures used to calculate 2008 survey tow distances were the same as in NEFSC

(2007a). The first step was to replace missing speed over ground and inclinometer data (which occur infrequently) for each station with interpolated values from a cubic spline. The second step was to smooth the original plus interpolated speed over ground and inclinometer data using a centered seven second moving average (e.g. the smoothed value for t = 3 seconds was the average for t = 1 to 7 seconds).[5] The final step was to compute the effective tow distance for each tow d_j using:

$$d = \frac{\sum_t \delta_t s_t}{3600}$$

where t is for a one-second time interval, δ_t was a dummy variable equal to one when the dredge was fishing effectively (smooth y-tilt ≤ 5.16^o), zero otherwise, s_t was smoothed speed over ground (knots) and 3600 is the number of seconds per hour.

Tows during the 2008 survey tended to be shorter than tows during the 1997, 1999, 2002 or 2005 surveys although differences between 2008 and 2002 were relatively small (Figure B34 and see below). Median tow distances for 1999 to 2005 are similar and longer (0.19-0.22 nm). As pointed out in NEFSC (2003), the median tow distance for 1997 (0.26 nm) was larger than median tow distances from other surveys because a slower winch was used to retrieve the survey dredge (Table C7 in NEFSC 2003).

Year	Median Tow Distance (NM)
1997	0.26
1999	0.22
2002	0.19
2005	0.21
2008	0.16

The relatively short tow distance during 2008 triggered a detailed analysis of all available data to determine the possible causes.

Tow distance and depth

Relationships between tow distance and depth differed among surveys (Figure B35). As expected based on medians, tow distance was relatively low during 2008 at all depths (Figure B35). Regression relationships for depth and tow distance were statistically significant and the best model for the entire set includes separate regression lines for each survey (NEFSC 2007a). However, a single regression model (see below) fit to all of the available data (surveys combined) might be useful in future for predicting tow distance based on depth (Figure B36). The combined model indicates that tow distance increases by 0.0014 nm (2.6 meters) for each additional meter of depth.

Parameter	Estimate	SE
Intercept	0.1635	0.003
Depth	0.0014	0.0001
Residual standard error		0.0479

5 Steps 1-2 were done in SAS (note that interpolation precedes smoothing). proc expand data=sdata1 out=sdata2 to=second; by station; ID TowTime; convert TiltY=SmoothAngle / transform=(cmovave 7); convert GPS1_SOG=SmoothSOG / transform=(cmovave 7); run;

Residual degrees of freedom	1497
Multiple R^2	22%

Short tow distance in 2008 survey

Considerable effort was devoted to examining sensor data to determine why survey tows during 2008 were shorter than in previous surveys. A number of possible explanations were considered and four principal hypotheses were examined: 1) the dredge during 2008 may have been towed at relatively high angle of attack (high *y*-tilt) possibly due to minor differences in gear; 2) *y*-tilt sensors were not calibrated during 2008 in the same manner as during 2005; 3) survey protocols differed slightly in the two surveys; or 4) tow distance estimates from SSP sensor data are sensitive to assumptions about the critical angle for effective fishing. Unfortunately, it was not possible to completely eliminate any of these possible explanations.

If *y*-tilt sensors were calibrated so that the apparent *y*-tilt based on sensors was greater than the actual *y*-tilt, then distance estimates based on sensor data may be too low during 2008 but survey data trends would be unaffected. On the other hand, if the angle of attack was actually higher during 2008 or survey protocols differed, then the distance estimates for 2008 should be unbiased but trend estimates may be affected to the extent that the efficiency of the dredge changed.

Station records for successful random tows (survey SHG codes ≤136) indicate that the average duration (based on start and stop times recorded on the bridge), average nominal tow distance (based on ships GPS start and stop locations) and average depth were similar for the 2005 and 2008 surveys. Survey personnel were interviewed but could not recall any changes in protocol. The captain of the R/V Delaware was involved in both the 2005 and 2008 surveys. The chief scientist and watch chiefs were very familiar with clam survey operations. The crewman who operated the winch during 2005 was present in 2008 and on duty 12 h each day, and trained the new operator. The winch and hawser were the same as during the 2005 survey.

Incorrect calibration or mechanical errors affecting y-tilt sensor were considered as a potential cause for the apparently shorter tow distances. To test this hypothesis, tow distance was plotted against depth in the 2008 survey for successful random tows using different symbols for tows with the original and replacement SSP equipment (Figure B37). The relationships between depth and tow distance were very similar indicating that the units were calibrated and working in the same manner. It is still possible, however, that both of the *y*-tilt sensors used during 2008 were calibrated incorrectly.

Tests show that tow distance estimates are not sensitive to the critical angle (5.16^o) assumed in tow distance calculations. A sensitivity analysis in NEFSC (2003) was repeated using data from the 2005 and 2008 surveys (Figure B38). Results indicate that median tow distances for all of the surveys since 1997 are robust to assumptions about critical angle in the range of $4\text{-}6^o$, which includes the current 5.16^o criterion.

Additional analyses used sensor data from successful random tows during the 2005 and 2008 surveys (Figure B39). All of these analyses used sensor data that were collected between the first and last seconds of each tow during which the smoothed *y*-tilt was less than or equal to 5.16^o (while the dredge was potentially fishing). In particular, the proportion of time on bottom that the dredge was effectively fishing (i.e. proportion of time between the first and last seconds of the tow with smoothed *y*-tilt ≤ 5.16^o), depth, speed over ground, and the mean and standard deviation of unsmoothed *y*-tilt and *x*-tilt were calculated for each tow. The statistical distribution of each variable in each survey was described graphically using box plots with notches that approximate 95% confidence intervals for each median (Figure B39). In addition, linear correlation coefficients were calculated between each pair of variables in each survey (Tables B12 and B13).

Based on box plots (Figure B39) distributions of speed over ground while dredges were potentially fishing were similar for 2005 and 2008 although median speed over ground was slightly lower during 2008. Median time on bottom (difference between the first and last second when the dredge was effectively fishing) was lower in 2008 by about 0.01 hr (36 seconds, which amounts to about 12% of a five minute tow). The proportion of time that the dredge was effectively fishing was lower during 2008. In particular, the median proportions differed by only about 0.01 but the distribution of the proportions was skewed towards smaller values in 2008.

The median *y*-tilt was about 2.5^o during 2005 and 3.7^o during 2008 (Figure B39). As expected, these values were less than the $5.16\,^o$ criterion used to estimate tow distance. The standard deviations for *y*-tilt measurements were similar during both surveys.

The biggest and most surprising (though possibly least important) difference between the 2005 and 2008 surveys was between *x*-tilt measurements (Figure B39). In particular, *x*-tilt values were almost always negative during 2005 and almost always positive during 2008. The standard deviations for *x*-tilt measurements were similar in both surveys. It is possible that the reversal of sign was due to changes in the orientation of the *x*-tilt sensors within the SSP package during 2005 and 2008.

There were 19 out of 36 "substantial" correlations among sensor variables from the 2008 survey compared to 5 out of 29 for the 2005 survey (Tables B12 and B13). In this analysis, "substantial" correlations had an absolute value ≥ 0.5. Many of the substantial correlations were expected (i.e. correlations involving tow time, proportion of time effectively fishing, y-tilt, SD y-tilt and depth). However, several of the substantial correlations were surprising and may help explain the short tow distances during 2008.

Tow time and proportion of time effectively fishing were positively correlated during 2008 but not during 2005. This result suggests the dredge performed better during longer tows during 2008.

The negative correlation between tow time and speed over ground during 2008 (but not 2005) was surprising because survey protocols are designed to achieve both a constant time (5 minutes) at specified speed (1.5 kt). In the experience of survey personnel, start and stop times used for this purpose are clear and easy to determine. In principle, speed over ground could have been determined very accurately on the bridge based on GPS. The correlation in 2008 suggests, however, that tow time and speed may have been adjusted to obtain the desired distance.

The negative correlation between *x*-tilt and *y*-tilt and between *x*-tilt and depth during 2008 (but not 2005) indicates that dredge performance during 2008 was more sensitive to depth. The positive correlations between *y*-tilt and speed over ground as well as between the SD of *y*-tilt and speed over ground indicate that dredge performance was more sensitive to speed during 2008 than during 2005.

Repeat tow analysis for cable and pump effects

Repeat tow analyses were conducted to estimate effects of different electrical cables and pumps on catch rates during the NEFSC survey. As described above, the original ("old") electrical cable used to send power to the dredge pump at the beginning of the survey was replaced at station 241 because it was too short to accommodate deep stations. The original ("old") pump was replaced and station 170 due to a malfunction.

Two types of repeat tows were carried out in connection with the 2008 NEFSC clam survey to quantify the potential effects of changes in the pump and electrical cables used on the survey dredge. "DE2DE2" repeat stations were occupied twice by the *R/V Delaware II* (e.g. with the old and then the new cable or pump). "DE2FV" stations were occupied first by the *R/V Delaware II* (with either cable or plump) and afterwards by the *F/V Endeavor*.

Ratio estimators and a linear model analysis (see below) indicate potential cable and pump effects for ocean quahog tows during the 2008 survey were not significantly different from zero. The two ratio estimator and linear model analyses were not completely independent because they used almost the same survey data.

Background

Both electrical cables used during the 2008 survey were the same type and model. Both were purchased from the same vendor in one order prior to the 2005 clam survey. The old cable used during the 2008 survey was used during the 2005 survey also. It was shortened between surveys by removing a section near the end between the end of the 2005 survey and beginning of the 2008 survey, however, because the steel cable used to retrieve the dredge during the 2005 survey had shed wire splinters that penetrated the covering of the electric cable on the end near the dredge.

DE2DE2 repeat stations

Ocean quahog catches (50+ mm SL) were standardized using sensor tow distance to a standard area swept (5 ft x 0.15 nm = 4557 ft^2 = 423 m^2) for use in all analyses. If the sensor based tow distance was missing for a station, then the median tow distance for successful random tows during 2008 was used instead. Pairs of stations were omitted if either tow was "unsuccessful" based on sensor data (NEFSC 2007a) or had a database HG code > 36. DE2DE2 repeats with zero quahog catch in both tows would not affect estimates and were also omitted. Based on these criteria, repeat station data were available for 17 DE2DE2 repeat stations (Table B14).

The DE2DE2 repeat station data were more useful for detecting potential cable effects than pump effects. All of the original tows were made with the old cable and all of the repeat tows were made with the new cable. Five of the original tows were made with the old pump and all of the repeat tows were made with the new pump (Table B14). Fortunately, differential pressure data indicate that pump effects were likely minor because differential pressure was within the normal operating range before and after the new pump was installed (Figure B33).

The null hypothesis of no cable effect was not rejected because the ratio estimator (sum of catches with new cable / sum of catches with old cable) for DE2DE2 repeat stations was 0.8 (SE 0.22) and the 95% confidence interval (0.36, 1.23) included one (Figure B40).

DE2FV repeat stations

The repeat stations used in this analysis included random and nonrandom stations occupied by the Delaware originally during the survey and later by the commercial vessel (Table B15). Some of the survey stations were setup tows for depletion experiments that could be treated as if they were repeated by the first one or two tows in the ensuing commercial depletion experiment (see below). Length composition data were used to calculate numbers of quahogs 90 mm SL or larger, which were adjusted to the same area swept (423 m^2).

Only quahogs over 89 mm SL were used because commercial and survey selectivity curves indicate that ocean quahogs are at least 85% selected at 90 mm SL and the 90 mm cutoff is used in commercial depletion studies that involve the *R/V Delaware II* and a wide range of commercial vessels.

Forty-five stations had survey or commercial catches larger than zero (Table B15 and Figure

B41). Ratio estimators (sum of survey catches / sum of commercial vessel catches) are given below. The difference between the ratio estimators for the new pump with the old and new cables is 0.3520-0.2849=0.0671, the variance is 0.008+0.0006=0.0086, and the 95% confidence interval is (-0.11, 0.24). Thus, DE2FV ratio estimators indicate that the new cable reduced capture efficiency by about (0.3520 - 0.2849) / 0.3520=20% but the difference is not statistically significant (see below). The ratio estimate 0.31 for all of the data indicates that the capture efficiency for the survey dredge was about 31% of the capture efficiency for the commercial dredge.

DE2 configuration	Ratio	N	Var	SE	CV	Low 95% CI	Hi 95% CI	Bias
New pump-Old cable	0.3520	14	0.0080	0.0893	0.2538	0.1769	0.5271	0.0040
New pump-New cable	0.2849	28	0.0006	0.0238	0.0835	0.2383	0.3316	0.0016
Old pump-Old cable	0.4798	3	0.0708	0.2661	0.5546	-0.0418	1.0013	-0.0200
All	0.3183	45	0.0015	0.0386	0.1211	0.2427	0.3939	0.0013

Linear model analysis

Step-wise linear models were fit to the DE2FV data to refine estimates and produce variances that characterize uncertainty in estimated pump and cable effects. The dependent variable was the log of survey catch / commercial catches. Records with zero survey or commercial catches were omitted from linear models because the log of the catch ratio was undefined. A total of 41 observations were available for linear model analysis. Sample size was N=24 for pairs that had survey tows with the new pump and new cable, N=14 for survey tows with the new pump and old cable, and N=3 for survey tows with the old pump and old cable (Table B15).
Models considered in the analysis ranged from:

logRatio ~ 1

that hypothesizes a constant log ratio with no pump or cable effects to

logRatio ~Pump*ElecCable

that hypothesizes pump and electrical cable effects plus their interaction (i.e. different cable effects for each type of pump). The "best" model with the lowest AIC score was identified and estimated by the stepwise search.

The best linear model was the simplest case with logR = -1.277 (se 0.116, $p<e^{-13}$) indicating a constant log ratio with no pump or cable effects. The ratio of survey/commercial catches implied by this model is $e^{-1.277} = 0.28$ (CV=0.12) with an approximate 95% CI (0.22-0.35).

Depletion studies and survey dredge efficiency

Survey dredge efficiency estimates are important in this assessment because they help scale relative trends to actual biomass levels in modeling and because they can be used to estimate swept-area biomass directly. By definition, dredge efficiency estimated in depletion experiments is the probability of capture (i.e. of being handled on deck) for an ocean quahog that is in the path of the dredge and large enough to fully selected by the gear. Effects of shell length and size selectivity on catches and efficiency estimates are accommodated in depletion study analyses by restricting analysis to ocean quahogs 90 mm SL or larger, which have high size selectivity (≥ 0.85) in both survey and commercial clam dredges (Figure B21).

In brief, depletion experiments usually begin with "setup" tows by the *R/V Delaware II* during the NEFSC clam survey. "Survey density" is calculated for each tow by dividing the catch by area swept, which is the dredge width times the distance traveled while the dredge was effectively fishing based on sensor data (i.e. where while y-tilt ≤ 5.16°).

Mean survey density for each depletion experiment site is calculated by averaging the survey density from each setup tow. After the setup tows are completed, additional overlapping tows are made repeatedly by the same or different vessel over the area immediately adjacent to the setup tows until a significant decline in catch per tow is noted. Care is taken to ensure that setup tows are close to each other with little or no overlap and close to the corresponding depletion tows.

Vessel position is used as a proxy for dredge position during depletion experiments. Experiments during 1997-1998 used Loran-C to track the position of the depletion vessel with positions recorded by hand on datasheets at 30 second intervals. GPS with stored data has been used since 2002 to record position data at 6-30 second intervals. Setup tows have always been tracked by GPS at 1 second intervals. In other words, the frequency and type of information has been consistent for setup tows by the *R/V Delaware II* but has varied for depletion tows by commercial vessels.

One "Delaware II" depletion experiment has been completed for ocean quahog (experiment OQ1999-01 DE2 in Tables B16 and B17). In Delaware II depletion experiments, the research vessel carries out both the setup and depletion tows.

A relatively large number of commercial depletion experiments have been carried out (Tables B16 and B17). Commercial depletion experiments use a commercial vessel to make depletion tows after setup tows are made by the *R/V Delaware II*. Commercial depletion experiments are the preferred approach to estimating survey dredge efficiency because commercial dredges perform consistently with high efficiency and deplete the experimental site faster. Commercial dredges are inherently more efficient than the NEFSC survey dredge because water jets run at higher pressure on commercial boats and commercial dredges are heavier and less prone to vibration. Moreover, they are larger so that there is less uncertainty about their location. Bar spacing and sorting equipment on deck are usually adjusted to enhance retention of relatively small ocean quahogs before a depletion study. However, even with these adjustments to gear, commercial dredges catch relatively lower proportion of small quahogs than survey dredges, which have a small mesh liner.

In Delaware II depletion experiments, the survey dredge efficiency is estimated directly. In commercial depletion studies with setup tows, the estimated survey dredge efficiency (e) is:

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

where D is the estimated density from the Patch model and d is the mean survey density for the site. One disadvantage of commercial depletion experiments is the extra variance in estimated dredge efficiency due to the variance in mean survey density d. Variance of mean survey density tends to be high because the number of setup tows is typically 3-5 (Table B16).

Survey dredge efficiency estimates are available in NEFSC (2007a) for 12 depletion experiments with setup tows (11 commercial and 1 Delaware II), out of 16 total depletion experiments conducted during 1997 and 2005 (Tables B16 and B17). Three additional new commercial depletion experiments with setup tows were carried out (OQ2008-3 in SNE and OQ2008-1 and OQ2008-2 in LI, Figure B32) following the 2008 NEFSC clam survey by the *F/V Endeavor* with scientific staff from Haskin Shellfish Research Laboratory and NEFSC (Tables B16 and B17; Figures B42 through B44).

As described above, the electrical cable and pump were replaced during the 2008 survey (Figure B32). The original electrical cable and new pump were used for setup tows during the first experiment (OQ2008-01), while the new electrical cable and new pump were used during the second and third experiments (OQ2008-02 and OQ2008-03).

2008 depletion experiment methods

The *F/V Endeavor* used a 12.5 ft clam dredge that operated at a differential pressure of about 60 psi (measured at depth in the manifold of the dredge). At each depletion site, the number of bushels of clams was counted for every tow and fractional bushels were estimated by eye. In addition, one full bushel was counted and measured and an additional full bushel was counted on every fifth tow, beginning with tow two.

The survey sensor package (including GPS) was mounted on the dredge used by the F/V Endeavor during 2008, but was operational at only 106 out of a total of 232 stations due to lack of time between tows to charge batteries (particularly during depletion tows) and lack of staff to operate the unit on leg 3 of the survey. The total number of stations (232) includes stations used for ocean quahog and Atlantic surfclam depletion experiments, repeat tows, and surfclam size selectivity studies.

The start and end of fishing (when the dredge was on the bottom) was easy to determine by visual examination of SSP y-tilt and pressure sensor data. Based on SSP data, the angle of attack for the commercial dredge used by the F/V Endeavor was not prone to excess variability in y-tilt (Figure B45).

To determine tow distance at stations without SSP data, a backup pressure (depth) sensor and a backup GPS were used. The resolution of the backup pressure sensor is 4-5 meters. Backup pressure and GPS data were recorded every five seconds, in contrast to every second on the SSP. For these reasons, backup sensor data are more difficult to use in estimating dredge paths.

To develop a means to estimate tow start and stop time using backup sensor data, times on and off bottom from SSP data for OQ2008- 1 and OQ2008-02 (34 stations total) were compared to visually determined times on and off bottom from backup pressure sensor and backup GPS data. Visually determined time off bottom estimates were similar to time-off-bottom estimates based on SSP data. However, subjectively determined time-on-bottom values were greater than the SSP time on bottom values about 15-20 seconds. Time on bottom was difficult to judge because the commercial dredge was deployed using winches that do not spool freely as the dredge is deployed.

After some experimentation, 15 seconds were subtracted from the subjective time on bottom estimates from backup sensor data. The adjusted time on bottom estimates for the 34 test stations differed from SSP time on bottom values by only 4 seconds on average, with positive differences as likely as negative differences. This alternate approach was used to identify time on and off bottom based on backup sensors for all commercial tows.

See Appendix B4 for a detailed description of the cooperative survey work by the *F/V Endeavor* during 2008 and calculation of tow distances.

Patch model

The Patch model (Rago et al. 2006) was used to analyze all of the depletion experiment data used in this assessment (Table B16). Estimates for the 1997-2005 surveys are from NEFSC (2007a). Estimates for the 2008 survey (Tables B16 and B17) are described below. The Patch model is a standard approach used in NEFSC stock assessment work for a variety of shellfish and sedentary demersal finfish including Atlantic sea scallops NEFSC (2004b), ocean quahog (NEFSC 2004; 2007a), Atlantic surfclam (NEFSC 2003; 2007a) and goosefish (NEFSC 2005). The most important characteristics of the Patch model are that it is spatially explicit and it is not necessary to assume that ocean quahogs mix randomly across the entire site after each depletion tow.

The Patch model estimates three parameters for each depletion experiment: initial ocean quahog density D; depletion dredge efficiency e, and a measure of variance k in catch data. Cell width in the Patch model was assumed to be twice the dredge width. The "gamma" parameter in the Patch model, used to measure indirect effects on catches (e.g. ocean quahogs lost from the study site without being counted on deck), was fixed at the ratio of the dredge width and cell width (γ=0.5) so that no indirect effects were assumed to occur.

Parameters are estimated by maximizing the likelihood of the observed catch data under the assumptions that the dredge path is known and that the catches are sampled from a negative binomial distribution. In computing the likelihood for the catch in each tow, the model considers the number of times each grid sampled during the tow had been sample during previous tows and adjusts the predicted catch for each tow accordingly. Likelihood profiles are used to compute confidence intervals for all model estimates and residual plots (observed – predicted catches) are used to judge model fit.

Modeling procedures

Revised procedures described in the last ocean quahog assessment (NEFSC 2007a) were used without modification for ocean quahog in this assessment. In particular, latitude and longitude data generated during the tows by GPS were smoothed with cubic splines (Figures B46 through B48). The smoothed latitude and longitude position data were interpolated along straight lines between the smoothed points to a distance of 5 ft. The grid size for 2008 commercial depletion experiments was 25 ft because the dredge was 12.5 ft wide.

As described above, SSP data were available for the OQ2008-1 and OQ2008-3 experiments, but not for the OQ2008-2 experiment. Patch model analyses in this assessment used the adjusted tow paths based on backup sensor data described above, instead of tow paths based on SSP data, to enhance interpretation and comparability of results. Otherwise, differences in start time calculations would have been confounded with effects of different electrical cables.

Survey dredge efficiency and other Patch model estimates

There were 2-4 setup and 17 depletion tows for depletion experiments completed during 2008 (Tables B16 and B17). All of the setup tows used in the analysis were located within approximately 300 m of the depletion tows. All setup tows for the same site used the same combination of electrical cable and pump. All setup tows used in the analysis were successful based on HG codes and analysis of sensor data (Appendix B3). Sensor tow distances were available for all setup tows with the exception of station 355 in OQ2008-03, which used the median tow distance for all successful tows during 2008.

Patch model fit to commercial depletion catch data was poor for OQ2008-1 but reasonably good for OQ2008-2 and for OQ2008-3 (Figures B49 through B51). Commercial dredge efficiency estimates for the OQ2008-1 and OQ2008-3 experiments were on their upper feasible bound (1.0). The area in Long Island where the OQ2008-1 and OQ2008-3 experiments was conducted has a relatively thin layer of sand on top of peat. The thin layer of sand tends to concentrate ocean quahogs near the surface where they are easy to catch (Pers. comm. E. Powell, Rutgers Shellfish Research Laboratory, Port Norris NJ).

The average survey dredge efficiency estimate for 2008 was 0.320 and estimates ranged from 0.207 to 0.467 (Table B17). The mean estimate for 2008 is relatively high compared to the "best" median estimate of 0.165 and mean estimate of 0.248 from the twelve depletion studies completed during 1997-2005 (Table B17). However, the individual and mean estimates for 2008 fall well within the range and distribution of estimates from depletion studies during 1997-2005 (Table B17).

The mean Patch model density estimate for 2008 was 0.091 quahogs per ft^2, which is similar to the estimate 0.097 quahogs per ft^2 in NEFSC 2007a from earlier studies (Table B17).

With the new data (*N*=15), the new median best estimate of survey dredge efficiency is 0.169 (mean 0.264, Table B18). A 90% confidence interval calculated by bootstrapping the fifteen estimates (15,000 iterations) had bounds of 0.154-0.285.

Based on Patch model estimates (Table B18), The *F/V Endeavor* appears to have consistently high efficiency for ocean quahogs. The estimates of commercial efficiency for 2008 experiments ranged 0.78 to 1.0.

Uncertainty and sensitivity

A vessel towing at 3 knots (a typical commercial tow speed) will travel 25 ft (the width of the grids used in analysis of 2008 depletion study data, see below) in 4.9 seconds (NEFSC 2007a). Thus, variability in start time estimates adds uncertainty to position data that may affect Patch model estimates to some (probably minor) degree.

As described above, the electrical cable and pump were replaced during the 2008 survey. The original electrical cable and new pump were used for setup tows during the OQ2008-01 experiment, while the new cable and new pump were used during the OQ2008-02 and OQ2008-03 experiments. Different cables (and any other gear differences in general) may cause changes in actual dredge efficiency if pump voltage and pressure change. The variance of survey dredge efficiency estimates has not been fully characterized, but is probably substantial based on the variability of estimates within and between years (Table B16). For these reasons, it is probably better to view the full set of depletion experiment dredge efficiency estimates as a distribution with an underlying mean and variance (Table B18). Individual estimates and estimates for a single survey are too imprecise to be used directly in making survey-specific estimates of survey dredge efficiency.

The accuracy of position information, smoothing, choice of grid size and assumptions about indirect effects are important considerations and uncertainties. The accuracy of position data for the ship as a proxy for position of the dredge probably depends on many factors and has probably varied among depletion experiments (NEFSC 2007a). Sensitivity analyses in NEFSC (2007b) showed that smoothed position data produce higher estimates of initial density and lower estimates of dredge efficiency than unsmoothed position data.

Dredge efficiency is harder to estimate for ocean quahogs than Atlantic surfclams (NEFSC 2007b) because ocean quahogs are found in deeper water (which makes dredge position data less reliable) and because they burrow deeper into sediments depending on environmental conditions (and are probably sampled less efficiently).

Results indicate that uncertainty in Patch model estimates is greater than depicted in likelihood profile confidence intervals (Figures B49 through B51). Preliminary results seem to indicate that the statistical properties of estimates vary among experiments in a complicated manner that depends on the spatial distribution of depletion tows, number of tows, accuracy of position data and on the density, variance in density and spatial distribution of ocean quahogs.

The gamma parameter is theoretically estimable but estimation has proven difficult in practice because the estimate for gamma is correlated with other estimates in the model and dependent on assumptions about cell size (Rago et al. 2006). Efficiency and density estimates from the Patch model tend to decrease as the assumed level of γ and indirect effects increases (Rago et al. 2006).

Assumptions about grid size reflect a compromise between the accuracy of position data and the tenability of the assumption that animals mix within cells after each tow. Patch model estimates for ocean quahog are moderately sensitive to the changes in the assumed grid size. In particular, efficiency estimates tend to increase and density estimates tend to decrease as the grid size increases (NEFSC 2007a).

Efficiency corrected swept area biomass

Efficiency corrected swept area biomass (ESB) was estimated for years when NEFSC clam surveys collected sensor data (1997, 1999, 2002, 2005 and 2008) (Table B19). ESB results are used primarily as prior information for use in fitting other stock assessment models.

ESB for ocean quahog (Table B19) was calculated:

$$B = \frac{B'}{e}$$

where:

$$B' = \frac{\overline{\chi} A'}{a}(1+\phi)u$$

In ESB calculations, e is the best estimate of survey dredge efficiency for ocean quahogs, $\overline{\chi}$ is mean catch of fishable ocean quahogs per standard tow based on sensor data (kg tow^{-1}, see below), A' is habitat area (nm^2), a= 0.00012405 nm^2 tow^{-1} is the area that would be covered by the 5 ft wide survey dredge during a standard tow of 0.15 nm, and u=10^{-6} converts kilograms to thousand metric tons. Tow length thing again. B' is the minimum swept-area biomass prior to correction for survey dredge efficiency.

The term ϕ used in ESB calculations is the fraction of total biomass in deep water strata off LI (strata 32 and 36), SNE (strata 40, 44, 48) and GBK (strata 56, 58, 60 and 62) that were sampled only during 1999. According to NEFSC (2000), deep water strata accounted for 0%, 2% and 13% of total biomass in the LI, SNE and GBK regions during 2005. Data for deep water strata sampled only during 1999 are otherwise omitted in calculations and, in particular, calculation of mean catch per tow $\overline{\chi}$.

Habitat area for ocean quahogs in each region was estimated:

$$A' = Au$$

where $\underline{u}$ is the proportion of random tows in the region not precluded by rocky or rough ground (ocean quahogs occupy smooth sandy habitats), and A is the total area computed by summing GIS area estimates for each survey stratum in the region. Estimates for u in this assessment are the same as in NEFSC (2007a).

Mean catch per standard tow ($\overline{\chi}$) is the stratified mean catch of fishable ocean quahog for individual tows after adjustment to standard tow distance based on tow distance measurements from sensor data (d_s):

$$\chi_i = \frac{C_i d}{d_s}$$

Only random tows were used in calculations of ESB. Tows without sensor data, with gear damage or poor pump performance were excluded from ESB calculations. Following NEFSC (2004a), and as described above, tow distance was measured for each station assuming that the dredge was fishing when the blade penetrated the substrate to a depth of at least one inch. Thus, the tow distance at each station was the sum of the distance covered while the dredge angle was $\leq 5.16^{o}$.

ESB estimates for the entire ocean quahog stock during 1997-2005 (Table A15, NEFSC 2004a) were computed using a formula that facilitated variance calculations (see below):

$$B_{total} = \frac{B'_{total}}{e} = \frac{\sum_r B'_r}{e}$$

Catch-ESB Mortality estimates

Fishing mortality rates were estimated directly from the ratio of catch (landings plus an assumed 5% incidental mortality allowance) and ESB data for each region and year (Table B20). The primary purpose for these calculations was as a check on model based fishing mortality estimates. Ocean quahog biomass levels may change slowly, fishing and natural mortality rates are low for ocean quahogs, and the survey during June provides a good approximation to average biomass. It was advantageous to use the ratio estimator because the surveys occur in June and because it was easy to include a wide range of uncertainties in variance calculations (see below).

Uncertainty in ESB and mortality estimates

Variance estimates for ESB and related mortality estimates are important in using and interpreting results (Tables B19 and B20; Figures B52 and B53). Formulas for estimating ESB and mortality for a single region are products and ratios of constants and random variables. Random variables in calculations are typically non-zero (or at least non-negative) and can be assumed to be approximately lognormal. Therefore, we estimated uncertainty in ESB and related mortality estimates using a formula for independent lognormal variables in products and ratios (Deming 1960):

$$CV\left(\frac{ab}{c}\right) = \sqrt{CV^2(a) + CV^2(b) + CV^2(c)}$$

where *ln(ab/c)*, *ln(a)*, *ln(b)* and *ln(c)* are normally distributed. The accuracy of Deming's formula for ESB estimates was checked by comparison to simulated estimates (NEFSC 2002). CVs by the two methods were similar as long as variables in the calculation were log normally distributed. In addition, distributions of the simulated products and ratios were skewed to the right and appeared lognormal.

CV estimates for terms used in ESB and related estimates (Tables B19 and B20) were from a variety of sources and were sometimes just educated guesses. The CV for best estimate of survey dredge efficiency (*e*) was 0.21, calculated by bootstrapping the median (15,000 bootstrap iterations) (Table B18). For lack of better information, CVs for sensor tow distances (*d*), area swept per standard tow (*a*), total area of region (*A*), percent suitable habitat (*u*), and catch were all assumed to be 10%. The CV for area swept (*a*) is understood to include variance due to Doppler distance measurements and variability in fishing power during the tow due, for example, to rocky or muddy ground.

ESB for combined stock assessment areas was estimated as described above. Variance calculations accommodated covariance among regional estimates due to using a single estimate of survey dredge efficiency:

$$CV^2(B_{total}) = CV^2(e) + CV^2(B'_{total})$$

"VPA" estimates

VPA estimates of biomass and fishing mortality (Figure B54) for ocean quahogs are useful as a way to verify estimates from the KLAMZ model and for regions where the KLAMZ model is not applicable (see below). Surprisingly, for such a crude approach, VPA biomass estimates for the stock in the exploited region are similar to survey trends (not used in calculating VPA) and estimates from other more sophisticated modeling approaches (Figure B55).

Assuming no recruitment and that growth exactly balances natural mortality, ocean quahog biomass on January 1st and annual fishing mortality rates can be estimated for each region using a simple virtual population analysis or "VPA" approach (NEFSC 2004a). Efficiency corrected swept-area biomass estimates for 2002, 2005 and 2008 are averaged and used as the estimated biomass in 2005 which "anchors" the calculations as they work forward and backward in time. Averages for 2002-2008 are used in place of the 2005 ESB because the estimates for individual years are not precise (Table B19).

The VPA biomass estimate for January 1, 2005 is:

$$b_{2005} = \frac{B_{2002} + B_{2005} + B_{2008}}{3} - \frac{C_{2005}}{2}$$

where b_y is the VPA biomass estimate for January 1 in year y, B_y is the efficiency corrected swept area biomass for June in year y, C_{2005} is total catch weight (landings plus a 5% allowance for incidental mortality). The first ratio on the right-hand side is average efficiency corrected swept-area biomass during 2002-2008 and used as an estimate of biomass in June of 2005. Catch for 2005 is divided by two prior to subtraction because NEFSC clam surveys occur during June, when the year is half over.

Biomass estimates for years before 2005 (up to the beginning of 2009) were calculated:

$$b_{y<2005} = b_{2005} + \sum_{i=y}^{2004} C_i$$

Biomass estimates for years after 2005 were calculated:

$$b_{y>2005} = b_{2005} - \sum_{i=2005}^{y-1} C_i$$

Fishing mortality rates from VPA estimates were calculated by solving the catch equation with instantaneous rates for natural mortality and somatic growth both zero. Based on these equations, the VPA biomass estimate for GBK ocean quahogs is the mean of ESB estimates for 2002, 2005 and 2008 (1,651 thousand mt meats) because no catch occurs there.

KLAMZ model

KLAMZ (technical description in Appendix B6) is a forward projecting stock assessment model based on the Deriso-Schnute delay-difference equation (Deriso 1980; Schnute 1985; Quinn and Deriso 1999). The delay-difference equation is an implicitly age structured population dynamics model that is mathematically identical to common age-structured models if fishery selectivity is "knife-edged", somatic growth follows the von Bertalanffy equation, and natural mortality is the same for all individuals in the modeled population. Knife-edge selectivity means that all individuals alive in the model during the same year experience the same fishing mortality rate. Natural mortality rates and growth parameters can change from year to year in the KLAMZ model but are assumed to be the same for all individuals alive during each year. The model is implemented in AD Model Builder and Excel but only the AD Model Builder version was used in this assessment.

The main assumptions in the KLAMZ model for ocean quahog are: recruitment is the same in all years (and possibly zero) or follows a “step” pattern with one constant level during early years and a different constant level during later years (see below); fishery selectivity is knife-edged; the natural mortality rate is low or constant, and growth in weight can be described by a von Bertalanffy growth curve. Recruitment is assumed to follow a simple function (and inevitably estimated to be very low for ocean quahogs) because no reliable recruitment index current exists, recruitment levels appear to be very low based on survey data, and trends in stock dynamics appear primarily due to fishing mortality.

Recruitment to the ocean quahog fishery is not knife-edged and actually occurs at sizes of about 51-86 mm SL (Figure B21). Under these circumstances, KLAMZ can be used to track trends in fishable (instead of total) biomass. Fishable biomass is dominated by relatively large individual ocean quahogs that are readily captured. Survey data used in the KLAMZ model are in units of mean kg per standard tow for the “fishable” portion of survey catches (Table B10).

Despite simplifying assumptions, KLAMZ has proven to be a relatively robust model with little or no retrospective bias which has been used successfully in for a relatively large number of stocks. It provides useful estimates of long-term biomass and fishing mortality, performs relatively well with very limited information about age and growth and when explicitly age-structured models are difficult to apply. One of the chief reasons for the utility of the KLAMZ model is statistical simplicity. The model used for ocean quahog, for example, estimates only 2-4 parameters.

Model configurations

KLAMZ model estimates were for ocean quahogs in the DMV, NJ, LI and SNE regions or for the stock in the exploited region (entire stock less GBK) during 1977-2008. The model was not used for SVA because survey data for SVA are noisy and incomplete. Configurations of the KLAMZ model for ocean quahog in each region were similar to the “best” configurations identified in the last assessment (NEFSC 2007a) following a thorough analysis of a wide range of alternate configurations. Changes are highlighted in the descriptions below. The most important changes are use of the step function recruitment pattern for LI, SNE and the exploited region. A KLAMZ model was applied to the stock in the exploited region for the first time in this assessment.

Data used in KLAMZ models for ocean quahog in this assessment were: NEFSC clam survey biomass trends and associated CV’s for 1982-2008 (mean kg per tow of fishable biomass by region and year, Table B10); efficiency corrected swept-area biomass estimates for 1997-2008; and catch during 1977-2008 (landings in Table B2 with amounts for region unknown prorated by region with landings, plus a 5% allowance for incidental mortality). LPUE data are included in the model (Table B6) but only for comparative purposes (i.e. they had nil effect on model estimates). Catch data for ocean quahogs were assumed accurate and not estimated in the model. Efficiency corrected swept-area biomass (ESB) estimates for 1997-2008 are used as “prior” information that helps scale of model estimates, but were not used to measure trends because the survey data provides trend information (see below).

NEFSC clam survey and swept-area biomass data for 1994 were omitted for all stock areas because electrical voltage supplied to the pump on the survey dredge was set to 480 v, rather than 460 v, artificially increasing dredge efficiency during the 1994 survey (NEFSC 2004). In addition, survey and swept area biomass data for GBK during 1982-1984, 1989, 2002 and 2005 were also omitted because of poor survey coverage during those years.

Assumptions about growth are the same as in the last assessment. In particular, the growth parameters $\rho = e^K$ (where K=0.0176 is the von Bertalanffy growth parameter for weight), $J_t = w_{k-1}/w_k$ = 0.9693 (where w_j is predicted weight at age j) are constant and the same for all regions (NEFSC

2004). These growth parameters mean that quahogs in the model are slow growing, and that quahogs recruit to the fishery (reach 70 mm SL) at age *k*=26 (Figure A62, NEFSC 2004). Growth patterns differ among regions (Lewis et al. 2001) but ocean quahogs are difficult to age and there is too little information available to use region-specific growth curves (NEFSC 2000). The MAB growth curve was used for all regions where fishing occurs and the growth curve for GBK was used in the model for GBK (Lewis et al., 2001; Figure B3). The assumed natural mortality rate was M=0.02 y^{-1}, except in sensitivity analyses.

An assumed level of variance in instantaneous somatic growth rates (IGR) for old recruits is used to help estimate the initial age structure of ocean quahogs in the initial years of the model (Appendix B6). However, as described in NEFSC (2007a), this constraint is unimportant because estimated age structures were stable due to assumptions about recruitment and low mortality rates.

ESB data are important in KLAMZ models for ocean quahogs as a source of information about biomass scale. To use ESB data as a measure of scale while ignoring trend (see Appendix B6), the likelihood component for trends in ESB data were set to 10^{-6} so that the survey scaling parameter Q was calculated but the trend was ignored. Information in ESB data about biomass scale is contained in the estimated survey scaling parameter Q.

As described in Appendix B6, the likelihood of the survey scaling factor is calculated assuming that estimates of Q are from a lognormal distribution:

$$L = 0.5\left[\frac{\ln(Q)-\tau}{\varphi}\right]^2$$

where L is the negative log likelihood, $\varphi = \sqrt{\ln(1+CV)}$ and $\tau = \ln(\overline{q}) - \frac{\varphi^2}{2}$ is the mean of the log normal distribution. For ocean quahog ESB data, the mean of the prior $\overline{q} = ln(1) = 0$ if ESB data measure stock biomass accurately and CV=0.21 is the bootstrap coefficient of variation (standard deviation / mean) for the median survey dredge efficiency used in calculating ESB (Table B18).

Parameters estimated

KLAMZ models for ocean quahog in this assessment estimate two to four parameters by maximum likelihood and numerical optimization. The parameters potentially estimated are logarithms of: 1) biomass at the beginning of 1977, 2) escapement biomass (total biomass less biomass of new recruits) at the beginning of 1978, and 3) annual recruitment biomass (which is assumed constant over time for each region with one parameter or constant during two time periods with two parameters). In models where recruitment was too low to estimate, recruitment was fixed at an assumed value near zero (1 kg y^{-1}) which reduced the number of parameters estimated.

Fishing mortality rates are calculated solving the catch equation numerically. Survey scaling parameters were calculated using a closed form maximum likelihood estimator.

Variance estimates

Variances for biomass and fishing mortality estimates and for model parameters can be estimated by the delta method using exact derivatives calculated by AD Model Builder libraries, by bootstrapping, or by MCMC (Appendix B6). Estimates in this assessment were from the delta method or bootstrapping.

KLAMZ Results-DMV

As in previous assessments (NEFSC 2004; 2007a), estimated recruitment was near zero and hard to estimate in preliminary runs for DMV. The annual recruitment level was therefore fixed at very low value (1 kg y^{-1}) in final runs. Survey data generally indicate that recruitment has been low in DMV since 1978 (Figure B24) although some small ocean quahogs are present (Figure B30).

The KLAMZ model for ocean quahog in the DMV area (Figure B56) fit NEFSC survey and LPUE data well (LPUE data did not affect model estimates). The CV of arithmetic scale residuals (26%) for NEFSC survey data was smaller than the mean CV (35%) for mean kg/tow survey data but within the range of observed values (21%-53%). The estimated survey scaling parameter for ESB data was Q=0.96 indicating that the model was able to match the observed ESB biomass levels on average during 1995-2008 using the catch data and trends in NEFSC survey data.

Based on KLAMZ model results, biomass of ocean quahogs in DMV declined steadily after 1978 (Figure B56). Estimated fishable biomass during 2008 was 30% of the estimate for 1978 (Figure B56).

KLAMZ Results-NJ

The KLAMZ model for ocean quahog in the NJ area (Figure B57) fit NEFSC survey and LPUE data well (LPUE data did not affect model estimates). The CV of arithmetic scale residuals (43%) for NEFSC survey data was larger than the mean (19%) and range (14%-24%) of CV values for mean kg/tow survey data. The estimated survey scaling parameter for ESB data was Q=0.96 indicating that the model was able to match the observed ESB biomass levels on average during 1995-2008 using the catch data and trends in NEFSC survey data.

Based on KLAMZ model results, biomass of ocean quahogs in NJ declined steadily after 1978 (Figure B57). Estimated fishable biomass in NJ during 2008 was 40% of the estimate for 1978.

KLAMZ Results-LI

Preliminary KLAMZ model fits for ocean quahog in the LI area indicated that the model with constant recruitment was not able to match the apparently increasing abundance trends before 1994 and decreasing abundance trend afterwards without estimating an implausible survey scaling parameters Q=0.48 (Figure B58). A step function recruitment model with different levels of constant recruitment before and after a specified point in time was therefore used instead. A series of runs with the change in recruitment occurring at 1990 to 1999 indicated 1994 was the best change year for recruitment (Figure B59). The step function for LI allows for a higher level of recruitment prior during 1977-1993 (Figure B60) while a strong year class was recruiting to the fishery (Figures B24 and B28) and a lower level afterward.

The model (Figure B61) with step function recruitment fit the survey and LPUE data for ocean quahogs better than the model with constant recruitment (LPUE data did not affect model estimates) and the change in total likelihood indicated that the additional parameter was statistically significant. The CV of arithmetic scale residuals (25%) for NEFSC survey data was larger than the mean (18%) but within the range (14%-28%) of CV values for mean kg/tow survey data. The estimated survey scaling parameter for ESB data was Q=1.04 indicating that the model was able to match the observed ESB biomass levels on average during 1995-2008 using the catch data and trends in NEFSC survey data.

Based on KLAMZ model results (Figure B61), biomass of ocean quahogs in LI increased steadily after 1978 until 1993 when recruitment decreases and fishing mortality increased to maximum levels. Estimated fishable biomass in LI during 2008 was 89% of the estimate for 1978 and 70% of the maximum estimated biomass during 1992 (Figure B61).

KLAMZ Results-SNE

The KLAMZ model for ocean quahog in the SNE area (Figure B62) with a single recruitment parameter did not fit the apparently increasing trend in survey data prior to 1994 and decreasing trend afterwards. A step function recruitment model was therefore used instead. A series of runs with the change in recruitment occurring at 1990 to 1996 indicated 1993 was the best change year for recruitment (Figure B63). The step function for LI allows for a higher level of recruitment prior during 1977-1992 (Figure B64) while a strong year class was recruiting to the fishery (Figures B24 and B28) and a lower level afterward.

The model with step function recruitment (Figure B65) fit NEFSC survey and LPUE data better (LPUE data did not affect model estimates) and the change in total likelihood indicated that the additional parameter was statistically significant. The CV of arithmetic scale residuals (27%) for NEFSC survey data was smaller than the mean CV (35%) for mean kg/tow survey data but was within the range of observed values (18%-47%). The estimated survey scaling parameter for ESB data was Q=1.04 indicating that the model was able to match the observed ESB biomass levels on average during 1995-2008 using the catch data and trends in NEFSC survey data.

Based on KLAMZ model results, biomass of ocean quahogs in SNE increased steadily and then declined after 1992 when recruitment declined and fishing mortality increased dramatically (Figure B65). Estimated fishable biomass in SNE during 2008 was 99% of the estimate for 1978 and 78% of the maximum estimated biomass during 1994.

KLAMZ Results-GBK

The KLAMZ model for ocean quahog in the GBK area fit NEFSC survey data well although only 5 survey observations were available (Figure B66). The CV of arithmetic scale residuals (21%) for NEFSC survey data was smaller than the mean CV (18%) for mean kg/tow survey data but within the range of observed values (18%-27%). Only three ESB observations were available for GBK. The estimated survey scaling parameter for ESB data was Q=1.01 indicating that the model was able to match the observed ESB biomass levels on average during 1995-2008 and trends in NEFSC survey data to some extent. Trends in survey and ESB data were conflicting. The survey data varied without trend during 1986-2008. The shorter (and higher variance) ESB data for 1997, 2000 and 2008 showed a consistent increase.

Based on KLAMZ model results, biomass of ocean quahogs in GBK increased steadily after 1978. Estimated fishable biomass during 2008 was 13% higher than the estimate for 1978 (Figure B66).

KLAMZ Results-exploited region

The KLAMZ model for ocean quahog in the exploited stock area (Figure B67) fit NEFSC survey trends reasonably with a single recruitment pattern. However, the model with step function recruitment was significantly better based on log likelihood. A series of runs with the change in recruitment occurring at 1990 to 1996 indicated 1993 was the best change year for recruitment (Figure B68). The step function allows for a higher level of recruitment prior during 1977-1992 (Figure B69) and a lower level afterward.

The model with step function recruitment (Figure B70) fit NEFSC survey data better but fit LPUE poorly (LPUE data did not affect model estimates). Lack of fit to LPUE data was probably due to the fishery shifting its distribution across the large area modeled to maintain relatively high catch rates. The CV of arithmetic scale residuals (21%) for NEFSC survey data was larger than the mean (13%) and range (10%-14%) of CV values for mean kg/tow survey data. The estimated survey scaling parameter for ESB data was Q=1.06 indicating that the model was able to match the observed ESB biomass levels on average during 1995-2008 using the catch data and trends in NEFSC survey data.

Based on KLAMZ model results (Figure B70), biomass of ocean quahogs in entire stock area less GBK declined after 1978 and then more steeply after 1994 when recruitment declined and fishing mortality was relatively high. Estimated fishable biomass during 2008 was 62% of the estimate for 1978.

Biomass estimates from the KLAMZ model for the exploited region were similar to the sum of biomass estimates from regional KLAMZ models for DMV, NJ, LI and SNE plus VPA estimates for SVA, and to the sum of regional VPA estimates (Figure B55). Despite this high degree of consistency, 95% confidences intervals from the model for the exploited stock were wide (e.g. 1513 to 3981 thousand mt in 1978 and 1056-2195 thousand mt in 2008) indicating considerable uncertainty in estimated biomass (Figure B55).

Retrospective patterns

A retrospective analysis was carried out using the KLAMZ model for the exploited region by using 2000-2008 as the terminal year in the model (Figure B71). Estimates did not tend to change between runs unless a year with a survey (2002, 2005 or 2008) was dropped. There was no evidence of the typical retrospective pathology. Terminal years tended to be similar in all runs. Historical pre-1983 estimates changed in a random manner between runs, suggesting that recruitment during the first time period (1978-1992) was difficult to estimate.

"Best" biomass estimates

Biomass and fishing mortality estimates from regional KLAMZ models were used as the best estimates of biomass and fishing mortality for ocean quahogs in DMV, NJ, LI, SNE and GBK during 1977-2008 (Tables B21 and B22; Figures B72 through B74). VPA biomass estimates were used for SVA because a KLAMZ model was not available. Biomass estimates for the exploited stock and total stock are the sums of regional estimates. Fishing mortality rates for SVA, the exploited stock and total stock were calculated by solving the catch equation for F using observed landings, biomass and instantaneous rates of recruitment and growth for the appropriate region during the year.

. CVs for best biomass and fishing mortality estimates in DMV, NJ, LI, SNE and GBK are asymptotic estimates from KLAMZ model runs. The CVs for biomass and fishing mortality in the exploited region are from the KLAMZ model for the exploited region (regional variances were not used to avoid assumptions about independence in errors among regions during the same year). CVs for fishing mortality in the entire stock were assumed the same as for the exploited region. CVs for biomass and fishing mortality in SVA were assumed to be the same as the average CV for ESB (0.96, Table B19) in SVA.

As noted before, biomass estimates for ocean quahogs are not sensitive to choice of modeling approach (Figure B55). In addition, updated estimates for recent biomass and fishing mortality in this assessment are similar to estimates and projections in the last assessment (NEFSC 2007a, Figure B73), even for the LI and SNE models which assumed constant recruitment patterns in NEFSC (2007a) and two-step recruitment patterns in this assessment.

Biological Reference Points
(TOR-3)

Managers use biological reference points (BRPs) for fishing mortality and stock biomass in dealing with ocean quahogs and other species in the US EEZ. BRPs for management targets and management thresholds are required. Targets are BRPs that represent desirable stock conditions. Thresholds are BRPs that identify undesirable stock conditions.

BRPs for US fisheries are generally linked in policy to maximum sustained yield (MSY). In particular, the overfishing threshold is often F_{MSY}, MSY, or a proxy for either F_{MSY} or MSY. Fishing mortality levels at or higher than the F_{MSY} threshold constitute overfishing. Managers may choose any fishing mortality target level < F_{MSY} as a target for healthy stocks.

Similarly, the target reference point for biomass ("stock size") is B_{MSY}, which is the stock biomass level that produces MSY when the stock is harvested at F_{MSY}. Policy for choosing biomass thresholds is specified in the National Standard Guidelines. To the extent possible, the stock size threshold should equal whichever of the following is greater: 1) one-half the MSY stock size; or 2) the minimum stock size at which rebuilding to the MSY level would be expected to occur within 10 years if the stock or stock complex were exploited at the maximum fishing mortality threshold.

Current BRPs for ocean quahog

The Atlantic Surfclam and Ocean Quahog Fishery Management Plan (FMP, Amendment 12) specifies $B_{Target} = B_{MSY}$, which is assumed be one-half of virgin biomass *for the whole stock*, and $F_{Target} = F_{0.1}$ for the *exploited region only* (whole stock less GBK) The biomass and fishing mortality thresholds are $B_{Threshold} = \frac{1}{2} B_{MSY}$ and $F_{Threshold} = F_{25\%}$ (the fishing mortality rate that reduces life time egg production for an average female to 25% of the average level with no fishing). The FMP does not specify whether the thresholds apply to the whole stock or exploited region only. Based on the last assessment, current estimates for the fishing mortality BRPs are $F_{Target} = F_{0.1} = 0.0275\ y^{-1}$ and $F_{Threshold} = F_{25\%} = 0.0517\ y^{-1}$.

Previous assessments and reviews concluded that $F_{25\%}$ is a poor threshold reference point because it is a poor proxy for F_{MSY} in a long-lived species like ocean quahog with assumed natural mortality rate $M = 0.02\ y^{-1}$ (NEFSC 2007a; 2007b). Simulation analyses in Clark (2002) indicate that long-term yield from unproductive fish stocks is maximized at fishing mortality rates of $F_{45\%}$ or lower. The same simulations show that fishing at $F_{25\%}$ would eventually result in spawning stock biomass levels less than 25% of the virgin level, which is below the B_{MSY} estimate of one-half virgin biomass. Thus, the current proxies for F_{MSY} and B_{MSY} are not compatible.

Revised and recommended fishing mortality rate reference points

Per recruit reference points (Table B23) for ocean quahogs are from a length-based per-recruit model in the NEFSC Stock Assessment Toolbox.[6] The length-based approach is better for ocean quahogs because fishery selectivity and maturity have been estimated in terms of shell length. Biological and fishery parameters (Table B24) in per recruit models were the same as in the last assessment (NEFSC 2007a).

The problem of choosing an F_{MSY} for ocean quahogs is difficult because we have relatively little experience with unproductive stocks like ocean quahogs. More importantly, MSY theory may not be applicable to ocean quahogs because low productivity may preclude economically viable

6 Contact Alan Seaver (Alan.Seaver@noaa.gov), Northeast Fisheries Science Center, Woods Hole, MA, USA for information and access to the Stock Assessment Toolbox.

levels of sustained catch. Productivity is low for the stock as a whole and particularly in the south because recruitment events have been infrequent and regional, growth is slow, and there is a long lag time between spawning and recruitment to the mature or fishable stock. There is a chance that fishing on Georges Bank could be sustainable, as growth and potential recruitment rates are relatively high. It is probably not possible to maintain a sustainable fishery on the currently exploited region where recruitment and growth rates are very low. For these reasons, recommended reference points in this assessment are described as thresholds and targets but not as proxies for F_{MSY} or B_{MSY} related reference points.

Quahog specific simulation analyses were not performed for this assessment. In absence of simulations for ocean quahog, the best available information is Clark's (2002) simulation analyses of F_{MSY} proxies applicable to long lived west coast groundfish. The west coast ground fishery includes a substantial number of long-lived fishes that are managed based on Clark's (2002) simulation analyses. F_{MSY} proxies for west coast groundfish were considered at a workshop that resulted in specific recommendations for stocks with a range of life history characteristics (Appendix B7). In particular, the workshop recommended $F_{40\%}$ for relatively productive Pacific whiting and flatfish, $F_{45\%}$ for other groundfish, and $F_{50\%}$ for *Sebastes* spp. (rockfish) and *Sebastolobus* spp. (thornyheads).

The Invertebrate Subcommittee considered $F_{40\%}$ and $F_{50\%}$ as fishing mortality thresholds for ocean quahogs (Table B25). $F_{50\%}$ might be better for ocean quahogs because *Sebastes* spp. are shorter lived, grow faster and reproduce on a more regular basis than ocean quahogs. On the other hand, ocean quahogs have some characteristics that might enhance productivity to some extent (e.g. lack of fishing on Georges Bank). High quality landings and low levels of indirect and discard mortality probably enhance stock assessment information for ocean quahogs and reduce the chances for inadvertent overfishing. After discussion, the subcommittee decided to "split the difference" and recommend $F_{45\%}$ as the fishing mortality threshold which the SARC 48 then accepted.

The current $F_{Threshold}$ for ocean quahogs ($F_{25\%}$) is compared to fishing mortality rates for the exploited portion of the quahog stock (i.e. the whole stock less GBK) to determine if overfishing is occurring. This approach is the result of a policy decision taken by the Mid-Atlantic Fishery Management Council and is unique to ocean quahogs. In the absence of clear policy, the Invertebrate Subcommittee makes no recommendation regarding how fishing mortality should be calculated for comparison to the fishing mortality threshold.

MSY theory may not be applicable to ocean quahogs, as described above. However, from a technical point of view mortality rates calculated for the whole stock including Georges Bank do not describe conditions on either the exploited portion or unexploited portions of the stock (Hart 2003). In particular, fishing mortality may be higher than desired on the exploited portion (resulting in foregone yield and relatively low biomass conditions) and zero on the unexploited portion (resulting in foregone yield).

Very little simulation or other information was available for recommending biomass reference points for ocean quahog. The current proxy was therefore retained as a target reference point except that the target was defined as one-half of the fishable (fully selected) biomass during 1978 (under pre-fishery conditions) instead of one-half of virgin biomass. Fishable biomass during 1978 (pre fishery) was used in place of virgin biomass because it is the only available estimate of stock size under unfished conditions. Results in this assessment indicate that virgin biomass likely varied in long slow cycles prior to fishing as infrequent strong year classes slowly grew to fishable size.

The recommended biomass threshold of 1.432 mmt (40% of the pre-fishery biomass during

1978) is an *ad hoc* approach judged to be more realistic than the current threshold (25% of virgin biomass). It is possible that a higher threshold may be required, particularly if the stock on GBK is found to be unproductive.

The growth curve used in calculations was for the ocean quahogs in the Mid-Atlantic Bight that did not include growth data from the GBK area where growth is faster and maximum size is larger (Lewis et al., 2001). Growth and recruitment assumptions should be revisited if managers decide to apply threshold fishing mortality rates to the whole stock (including GBK) or if a fishery develops on GBK.

Uncertainty in biological reference points

Ocean quahogs (including GBK) may or may not have the potential for supporting sustainable catches in the long term. Some recruitment and growth occurs each year but at low levels. Much depends on the response of the stock on Georges Bank to fishing, where growth and potential recruitment rates are relatively high. It is probably not possible to maintain a sustainable fishery on the currently exploited region where recruitment and growth rates are very low.

It is probably constructive and technically valid to view the ocean quahog fishery and fishing on Georges Bank is as an adaptive management experiment. The stock (including Georges Bank) may or may not support a sustainable fishery, the answer should be clear after a decade or two of fishing on Georges Bank, and managers should be prepared to react in either case. Policy and management actions in the event the fishery is not sustainable should be considered carefully beforehand. One obvious option would be to discontinue fishing, for ocean quahogs, potentially for a decade or more, if stock biomass reaches its biomass threshold.

In conducting the adaptive management experiment, it is important that removal rates are low enough to provide one or two decades for increased recruitment following fishing because the lag time between spawning and recruitment to the fishery is relatively long. At high fishing mortality rates, it would be theoretically be possible to eliminate the spawning biomass before recruitment has a chance to occur.

Threshold reference points were sensitive to assumptions about natural mortality. The range of values for $F_{45\%}$ was 0.017, 0.019 and 0.027 y^{-1} at assumed natural mortality levels of M=0.015, 0.02 and 0.025 y^{-1}. Thus, there is considerable uncertainty associated with uncertainty in M. Uncertainty in biomass reference points is probably about the same as relative uncertainties in fishing mortality thresholds.

Stock Status
(TOR-4)

Ocean quahogs in the US EEZ are not overfished and overfishing is not occurring. Total fishable stock biomass (all regions) during 2008 was 2.905 million mt (Table B21), which is above the current and recommended management target of 1.790 million mt. As shown in Figure B74, there is nil probability based on model results that 2008 biomass for the entire stock was below the management target. The fishing mortality rate during 2008 for the stock in the exploited region was F= 0.01 y^{-1} (Table B22) which is below the current $F_{25\%}$ = 0.0517 y^{-1} and recommended $F_{45\%}$=0.0219 threshold reference points. As shown in figure B74, there is nil probability based on model results that fishing mortality during 2008 exceeded the current or recommended threshold values. For comparison, the fishing mortality rate for the entire fishable stock (all areas) during 2008 was 0.0055 y^{-1}.

Biological condition of the EEZ stock

The ocean quahog population is relatively unproductive. Total biomass is gradually declining and approaching the recommended biomass target (½ virgin of the unfished biomass during 1978) after about three decades of relatively low fishing mortality (Figure B74).

Based on survey data (Figure B23), LPUE data (Figure B9) and best estimates for 1977-2008 (Figure B72), declines in stock biomass have occurred in southern regions (SVA, DMV and NJ) where the fishery has been active longest and where little recruitment has occurred. During 2008, fishable stock biomass in SVA, DMV and NJ was less than half of pre-fishing (1978) levels (Figure B72). In contrast, stock biomass in northern regions LI and SNE increased after 1978 to due to recruitment and growth and then began to decrease in the mid-1990s when fishing commenced (Figure 72). Biomass in the unfished GBK region appears to have increased gradually since 1978 (Figure B72).

The LI, SNE and GBK regions in the north contained about 67% of total fishable biomass during 1978 and about 84% of the remaining fishable biomass during 2008 (Figures B75 and B76). The GBK region, which is currently not fished due to risk of PSP contamination, contained about 32% of total fishable biomass during 1978 and about 45% during 2008 (Figures B75 and B76).

Recruitment biomass is remarkably low (< 48 thousand mt during all years, Figure B77) for a stock with biomass levels in excess of 3 million mt during 1978-2008 (Figure B75). Almost all recruitment since 1978 occurred in northern regions (LI, SNE and GBK). Estimated recruitment declined during 1992-2000. Since 2000, recruitment (about 17 thousand mt per year) has occurred almost entirely on GBK (Figure B75).

Fishing effort and mortality

Fishing effort has shifted to offshore and northern grounds over time as catch rates and abundance in the south declined (Figure B6). Analysis of LPUE data for individual 10-minute squares indicates considerable fishing-down on fishing grounds that historically supplied the bulk of landings (Figure B12). There is no indication that LPUE increased on historical grounds after fishing effort was reduced.

Fishing mortality rates during 2008 are relatively low for the entire stock (F=0.0056 y^{-1}) and for the exploited stock (F=0.01 y^{-1}), which excludes GBK (Figure B64). Fishing mortality rates in southern areas declined over the last decade to low levels (F = 0.0, 0.003 and 0.0047 y^{-1} for SVA, DMV and NJ during 2008). Fishing mortality rates for LI increased abruptly during 1992 as effort increased, declined and then increased to F=0.0193 y^{-1} during 2008. Fishing mortality rates for SNE increased after 1995 to levels above 0.01 y^{-1} during 1997-2000 and then decreased to 0.0041 y^{-1} during 2008.

Survey size composition (Figures B26 and B30) and fishery data (Figure B13) indicate a strong year class in a relatively small area within SNE off the southwest coast of Cape Cod. Growth rates in this area (which is intermediate between the MAB and GBK) are uncertain but these recruits are expected to enter the fishery over the next decade. Survey data for GBK (Figures B24, B25 and B30) where growth is faster indicate a recent recruitment event that has already reached fishable sizes (Figure B73). This recruitment was not detected until 2008 because of low coverage during the 2002 and 2005 surveys.

Productivity under fishing

Questions about the potential productivity of ocean quahog are becoming important as the stock is fished down from high virgin levels to B_{MSY}. Uncertainties about productivity are closely related to choice of accurate F_{MSY} and B_{MSY} proxies and to other decisions that affect sustainability and fishery profitability.

Ocean quahogs in the EEZ do not currently show a clear increase in stock productivity due to higher recruitment and increased growth rates, which would be expected as biomass declines to B_{MSY} levels. Indeed, estimated recruitment in northern regions began to decrease in about 1993 (Figure B77) as the fishery moved into the northern LI and SNE regions. Given the long periods between settlement and recruitment and slow growth once ocean quahogs reach fishable size, any increase in stock productivity may be delayed (Powell and Mann 2005).

Biological condition of ocean quahog in Maine waters
See Appendix B2.

Projections
(TOR-5)

Median stochastic projections were similar to corresponding deterministic projections (Table B26). As with the deterministic results, stochastic projections indicate that overfished (low biomass) stock conditions are not likely to occur by 2015 under any of the states of nature or management actions considered (Table B27). Overfishing relative to the true $F_{45\%}$ mortality threshold is not likely to occur under status-quo landings or at the minimum landings level specified in the FMP (Table B27). However, there is some probability of overfishing at the current quota and maximum landings level specified in the FMP, particularly if natural mortality $M \leq 0.02$ (Table B27).

Based on deterministic and stochastic projections, overfishing relative to the true $F_{45\%}$ would occur by 2015 under most of the states of nature considered. Most of these results are artifacts, however, because $F_{45\%}$ is one of the most conservative harvest policies considered and harvest at the relatively aggressive $F_{40\%}$, $F_{20\%}$, $F_{0.1}$ policies would constitute overfishing relative to $F_{45\%}$ by definition.

Projections indicate that landings levels based on $F_{45\%}$ and $F_{50\%}$ and exploited stock biomass would not result in F values for the entire stock larger than $F_{45\%}$ under any of the states of nature.

Stochastic biomass projections (Figure B79) indicate that changes in biomass are likely to be gradual under all harvest policies and states of nature considered. Projected fishing mortality estimates (Figure B80) show that some of the harvest policies considered are relatively aggressive in comparison to the status-quo catch policy.

Projection methods

Projected fishable biomass, fishing mortality and landings during 2010-2015 were calculated in two ways. The first method is a relatively simple approach used in the last assessment that has proven to be useful and reliable. The simple approach works well for ocean quahogs because stock biomass changes very slowly under current conditions. The principle advantage of the simple approach is that it provides projection information for each separate region based on regional conditions, as well as for the exploited region and total stock area. The principle disadvantage is that the uncertainty calculations for the simple approach are relatively crude.

The second approach provides stochastic projections based on the KLAMZ model for ocean quahogs in the exploited portion of the stock. This more complicated method captures uncertainty in 2008 biomass in addition to uncertainty in estimated recruitment levels. The stochastic approach is similar to the methods used for finfish in the US. Stochastic calculations for quahogs are slightly more complicated, however, because they involve interpreting projections for the stock in the exploited region (less GBK) in terms of the entire stock area.

All projections were started in 2008, the last year with best estimates from stock assessment models for ocean quahogs. At the time the projections were done, reasonable "anticipated" estimates of landings for 2009 were available. Therefore, all projections used actual landings for 2008 and anticipated landings for 2009 (17,690 mt meats = 3.9 million bu).

The range of harvest polices (management actions) used in projections (Table B28) included four constant landings policies (status quo, FMP minimum, FMP maximum, and FMP current quota) and five target fishing mortality policies ($F_{0.1}$, $F_{25\%}$, $F_{40\%}$, $F_{45\%}$ and $F_{50\%}$). As described below, the constant F policies were simulated by calculating a target landings level corresponding to the intended fishing mortality rate policy and the best estimate of 2008 biomass. Total catch impacting the stock in projections was landings plus 5% for assumed incidental mortality.

States of nature assumed in projections involved a range of possible values for natural mortality (M=0.015, 0.02 and 0.025) and a range of biomass levels. Deterministic projections used a range of possible biomass levels in 2008, while stochastic projections included uncertainty in 2008 biomass automatically based on bootstrap results.

Projections with F assumed known are unrealistic because F cannot be controlled directly by managers and is never truly known. Annual catch limits, in contrast, can be specified by managers and landings may be known. In practice, managers specify a landings level for ocean quahogs that are expected to generate a "target" or expected level of F. Therefore, projections in this assessment for ocean quahogs involving a target level of F (e.g. $F_{45\%}$) were carried out by calculating the catch in approximately the same manner as managers would do in managing the actual fishery based on the best biomass estimate for 2008. For example, projections with target $F= F_{45\%}$ were carried out using catch $C=F_{45\%}$ x B_{2008} for years 2010-2015.

Some of the possible states of nature considered in simulation analyses involve different levels of natural mortality M that imply different underlying biomass levels. However, managers are expected to use only the best estimates of biomass during 2008 (assuming M=0.02) in setting catch limits for 2010-2015. Therefore, management actions (landings and catch levels) are always calculated based on the best biomass estimates with M=0.02. Management decisions considered in projection analyses involve choices among harvest policies (e.g. maintain status quo landings/catch or harvest at the $F_{45\%}$ level), rather than choices among biomass estimates.

Reference points and states of nature

Mortality reference points used in simulations to determine the probabilities of overfishing were based on the true state of nature in the scenario tested**.** For example, scenarios with true M=0.015 used $F_{45\%}$=0.017 in comparisons while scenarios with true M=0.20 used $F_{45\%}$=0.0219 (Table B23). The true value of the $F_{45\%}$ reference point depends on the state of nature because the reference point depends on M (Table B23). Mortality reference points and the state of nature are linked in comparisons because the goal of the analysis is to evaluate the probability that fishing mortality in the ocean quahog stock will exceed the true value of the threshold reference point in 2015.

Biomass reference points were not adjusted for the assumed true value of M in deterministic projections although estimated biomass in 1978 and derived biomass reference points depend on natural mortality. The best method for simultaneously incorporating uncertainty in M, 1978 biomass and 2008 biomass was not clear and probably too complicated for simple deterministic calculations.

For stochastic projections, biomass reference points were adjusted for the assumed true value of M. In particular, the threshold biomass was 40% of the estimated biomass during 1978 based on original model runs for the exploited area and for GBK with the appropriate level of *M*.

Simple deterministic methods

In deterministic projections, bounds for true biomass in 2008 were B_{low}=1,438 and B_{high}=1,899 thousand mt meats for the exploited portion of the stock. The bounds were taken from an 80% bootstrap confidence interval (2000 iterations) analysis with the KLAMZ model for the exploited area. As described above, biomass in GBK during 2008 was assumed to be in the same proportion as the best estimates for 2008. Adjusting for the proportion of the biomass on GBK during 2008 (45%), the bounds for biomass of the entire stock are 2,633 and 3,475 thousand mt.

Deterministic projections are generally similar to the medians of results from more complicated stochastic projections (Jacobson and Cadrin 2004). Deterministic projection calculations for ocean quahog in this assessment use the following equations to represent biomass dynamics:

$$X = G + r - M - F$$

$$B_{t+1} = B_t e^X$$

$$F = \frac{C}{B} \quad or \quad C = FB$$

where X is the net instantaneous annual rate of change, G is the instantaneous rate for somatic growth in weight, r is the rate for recruitment, $M = 0.02$ y^{-1} is the rate for natural mortality rate, F is the rate for fishing, C is catch (e.g. landings + 5%), and B is fishable biomass. When catch is assumed known, the fishing mortality rate F can be calculated iteratively. When F is known, catch can be calculated directly.

Instantaneous rates for recruitment and growth during 2009-2015 were assumed to be the same as in 2008 (Table B29). Proportions of total catch in each region during 2010-2015 were assumed to be the same as in 2008 (Table B27). Proportions of stock biomass in each region during 2008 were assumed to be the same as in best estimates for 2008 (Table B29).

Simple projections are probably best interpreted as medians. Some crude measures of uncertainty are, however, available. Uncertainty in deterministic projections is roughly the same as uncertainty in the best biomass estimates for 2008 because recruitment is very low and projections are short-term. Thus, CVs for best estimates of 2008 biomass (based on the variance of 2008 biomass estimates from KLAMZ models for the exploited region and for GBK) can serve as estimates of uncertainty for projected biomass in 2015. If uncertainty in biomass is lognormal, then bounds for an asymmetric 80% confidence interval can be computed approximately as the median estimate multiplied or divided by $e^{1.28\sigma}$ where $\sigma = \sqrt{\ln\left(CV^2 + 1\right)}$. If uncertainty in biomass is lognormal, and uncertainty in assumed catches is zero, then fishing mortality is also lognormal with the same CV as for biomass (Deming 1960).

CVs and standard deviations for uncertainty in projected biomass and fishing mortality from best estimates, with standard deviations (σ).

Region	Total less GBK	Total
CV	0.101	0.135
σ	0.101	0.135
$1/e^{1.28\sigma}$	0.879	1.138
$e^{1.28\sigma}$	0.841	1.189

Deterministic projections for biomass and fishing mortality levels were compared to a range of reference points. Overfishing was judged "likely" for a scenario if projected median fishing mortality exceeded the threshold reference point. Threshold reference points were compared to median fishing mortality for both the exploited portion of the stock and the entire stock area. Overfished stock status was judged likely if projected median biomass for the entire stock was lower than the biomass threshold.

Stochastic projection methods

Uncertainty in biomass and estimated recruitment from the KLAMZ model for ocean quahogs in the exploited and GBK regions was estimated by bootstrapping survey data and KLAMZ models for the two regions (2000 iterations). Projections were carried out for the exploited region using each bootstrap biomass estimates for 2008 as the starting point and assuming recruitment during 2009-2015 at the estimate from the model. See technical documentation for the KLAMZ model in Appendix B6 for detailed description of bootstrap and projection methods.

For simplicity, biomass on GBK during 2000-2015 in projections was assumed the same as in 2008 and uncertainty in GBK biomass was ignored. Thus, stochastic projection calculations for the entire stock ignore key uncertainties but hopefully provide useful (though understated) estimates of uncertainty for the stock as a whole. This is a topic for future research and projections in the next assessment should include the full range of uncertainty for the entire stock.

Distributions of projected biomass and fishing mortality in 2015 from stochastic projections were compared to a range of reference points. The range of natural mortality values considered in stochastic projections (M=0.015, 0.02 and 0.025) was the same as in deterministic projections. It was not necessary to assume a range in 2008 biomass estimates because the stochastic projection analyses include uncertainty in estimated biomass automatically via the bootstrap step. Projections under an assumed state of nature with M=0.015, for example, started with fitting KLAMZ models for the exploited portion of the stock and for GBK with M=0.015 assumed in the model. The resulting model for the stock in the exploited region was bootstrapped and then projections were carried out for each management action considered.

The separation of the exploited region and GBK necessitates additional steps in making comparisons of reference points to whole stock conditions. Biomass reference points were always calculated for the entire stock area based on KLAMZ estimates for1978 biomass for the exploited region and for Georges Bank at the appropriate level of M. Therefore projected values of 2015 biomass for the exploited stock area plus the estimated biomass in 2008 on GBK were compared to biomass reference points so that biomass comparisons were whole stock biomass to whole stock reference point.

Managers currently compare fishing mortality reference points to fishing mortality for the exploited stock area only. They may choose, however, to compare mortality reference points to fishing mortality for the whole stock. Projected fishing mortality rates for the entire stock were calculated from estimates for the exploited stock only by solving the catch equation for whole stock F using catch $C = \frac{F^x}{F^x + M} B^x \left(1 - e^{F^x + M}\right)$, whole stock biomass $B = B^x + B^{GBK}$ and the assumed true value of M. In these equations F is the fishing mortality estimate for the whole stock in 2015, F^x and B^x are projected estimates for the exploited stock in 2015, and B^{GBK} is the estimated biomass from the KLAMZ model for GBK during 2008. The estimates F^x, B^x and B_{GBK} were from KLAMZ models that used the value of M assumed true under the state of nature.

Vulnerability to overfishing

Ocean quahogs are an unproductive stock that is vulnerable to overfishing. If overfished (depleted biomass) conditions occur, one or more decades will be required to rebuild the stock. Current fishing mortality rates are roughly 0.01 y^{-1} for the exploited area and roughly 0.005 y^{-1} for the stock as a whole (Figure B73). In contrast, the recommended fishing mortality threshold is $F_{45\%}$=0.0219 y^{-1}. The recommended mortality threshold was based on simulation analyses for west coast groundfish and may not be appropriate for ocean quahogs, which are probably less productive than the longest-lived west coast groundfish. Traditional southern fishing grounds in the DMV and NJ regions declined after 1990 to less than ½ of their unfished biomass (Figure B72) while fishing mortality averaged about 0.01 y^{-1} (Figure B73).

Productivity (due to somatic growth and recruitment) is higher in the north (LI, SNE and GBK) but very low in the south (DMV and NJ). Recruitment to the stock as a whole declined from about 48 thousand mt y y^{-1} before 1993 to about 17 thousand mt y^{-1} after 1993 (Figure B77). Most of the recruitment during 2005 was on GBK where a relatively strong year class is reaching fishable size. A strong but very regional recruitment event in SNE southwest of Cape Cod is expected to reach fishable size over the next decade.

Projection analyses indicate that ocean quahog biomass will decline very slowly during 2010-2015 under most of the harvest rates considered in projections (Figure B79). However, there is appreciable probability of $F_{2015} > F_{45\%}$ in the exploited stock if landings during 2010-2015 are at the current quota or maximum quota levels specified in the FMP (Table B27). Fishing mortality rates for the entire stock in 2015 are unlikely to exceed F45% under any harvest policy (Table B27).

Research Recommendations
(TOR-6)

Recommendations from the previous assessment and recommendations for future research are described below.

Recommendations from last assessment (SAW 44)

1) The *R/V Delaware II* may not be available for use on NEFSC clam surveys after 2008, and it appears likely that the clam survey will become a cooperative effort with sampling done by a commercial vessel. Both the *R/V Delaware II* and a commercial vessel should be used during 2008 so that catch rates, efficiency and selectivity patterns for the two vessels can be compared and calibrated. Planning should commence immediately.
Completed. See cruise report from F/V Endeavor in Appendix B4.

2) Fishing mortality and biomass reference points used as proxies for *FMSY* and *BMSY* should be

reevaluated in the next assessment.
Completed. Several proxy reference points were evaluated in the present assessment.

3) Additional estimates of survey dredge efficiency from cooperative depletion studies are required.
Completed. Three additional depletion studies were conducted in 2008.

4) Develop a length (and possibly age) structured stock assessment model for ocean quahogs that makes better use of survey and fishery length composition data which may provide better estimates of recruitment trends.
Not attempted in the present assessment.

5) Conduct further experimental work to determine the relationship between dredge efficiency, depth, substrate and clam density. A comprehensive study coincident with the next NEFSC clam survey would be most useful. The experimental design should include sufficient contrast in variables that may affect dredge efficiency.
Completed. The relationships were evaluated and no obvious relationship was detected at this time.

6) Cover GBK in the next NEFSC clam survey.
Completed. A full survey was conducted in this region in 2008.

7) Investigate the survey data from GBK during the 1989 survey to determine why it is low relative to survey observations during earlier years. This may be important in determining if biomass is increasing in GBK.
This is no longer an important issue.

8) Survey strata with no tows are a particular problem in the GBK region. The current procedure for filling holes in survey data involves borrowing data from adjacent surveys. This may not be optimal for ocean quahog surveys and GBK in particular. In the next assessment, consider filling holes in the GBK survey data using a model with stratum and year effects.
Not attempted due primarily to limited time. The current approach was considered adequate for ocean quahogs that have slow population dynamics, and was continued in the present assessment. Years when borrowing was substantial (e.g. 1989, 2002 and 2005) were excluded from the KLAMZ model of GBK.

9) Evaluate possible increasing trends in biomass for ocean quahog on GBK.
Completed. This was evaluated directly in the KLAMZ model.

10) Evaluate effects and contribution of recruitment to stock productivity.
Completed. This was evaluated directly in the KLAMZ model.

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.
Not attempted. No new estimates of the biological parameters were obtained in the present assessment.

12) Survey dredge and commercial dredge efficiency estimates should be reevaluated by field work

during the next NEFSC clam survey. The next survey may be the last opportunity to estimate survey dredge selectivity. The commercial dredge selectivity curve was used in this assessment was estimated from field studies done off Iceland (Thorarinsdottir and Jacobson, 2005) where conditions may differ. Repeat tow experiments (i.e. survey stations reoccupied by commercial vessels) may be useful for this purpose.
Completed in part. Efficiency comparisons were conducted but there were no selectivity studies for the commercial dredge for ocean quahogs.

13) In the next assessment, projection calculations should be carried out using a model that is basically the same as the primary stock assessment model used to estimate biomass and fishing mortality (e.g. delay-difference population model in KLAMZ).
Completed. The projection model uses the same equations as the KLAMZ model in addition to a simple deterministic approach.

14) Recommendations for future depletion studies:

- It was difficult to find areas with high concentrations of ocean quahog for depletion experiment sites during 2005. However, areas with lower densities of ocean quahog can be used if depletion tow distance is increased.
Completed. The 2008 survey design included areas of lower densities for the depletion studies,

- Revised estimators for survey dredge efficiency based on commercial depletion experiments and setup tows use data for relatively large ocean quahogs (i.e. 90+ mm) only. Future depletion sites should contain reasonably high densities of large individuals.
Completed. The 2008 survey design included areas of high densities of >90mm ocean quahogs.

- In the future, every effort must be made to collect and record precise location data at short time intervals during depletion studies.
Completed. Location data were collected at a time interval of <= 5 seconds in the 2008 depletion studies.

- Collect length and bushel count data from survey and depletion tows more frequently (e.g. every 1-2 tows). It might be advantageous to measure fewer individuals sampled from more tows.
This change was not implemented in the 2008 depletion studies because the existing protocol was considered adequate.

- Analyze results from previous depletion studies to determine if differences between bushel counts and length composition data from different tows in the same depletion experiment are significantly different. Use the results to modify sampling protocols as appropriate.
No detailed analyses were attempted.

- 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.
This was not attempted in the present assessment but it would be useful to conduct this analysis in

the future.

- It would be useful to analyze efficiency estimates in terms of season because ocean quahogs are believed to change their depth in sediments on a seasonal basis.
This was not attempted in the present assessment but it would be useful to conduct this analysis in the future

15) The next stock assessment should review the M=0.02 y^{-1} assumption for ocean quahog.
Not completed although projection and reference point calculations considered a range of M values.

16) In the next assessment, KLAMZ model runs with two recruitment parameters should be explored for LI and SNE. Survey length composition show more recruitment prior to 1994 than afterwards. Model fit was not as good for SNE as other regions.
Completed. The present assessment incorporated two recruitment parameters for these regions and for the exploited stock as a whole.

17) KLAMZ model runs for GBK should be explored further in the next assessment.
Completed.

New Recommendations (in rough order of priority)
1) The next survey should be conducted by a commercial vessel that is more efficient in sampling ocean quahogs compared to *R/V 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. A considerable amount of planning and preparation for this transition has already occurred. The survey should commence immediately in 2010 on a 15 days at sea per year schedule.

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

3) Carry out simulations to determine optimum proxies for F_{MSY} and B_{MSY} in ocean quahogs, given their unusual biological characteristics.

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.

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.

6) Estimate relationships between size and number of eggs produced. Determine spawning frequency if possible.

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.

8) Better information about maturity at length is required.

9) There has been progress in improving port sampling for ocean quahogs 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.

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

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.

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

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.

14) Conduct further analyses to determine the relationship between dredge efficiency, depth, substrate, and clam density.

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.
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.

17) Investigate model formulations that accommodate spatial heterogeneity.

18) Examine existing underwater photographs of ocean quahogs to evaluate the potential use of HABCAM or other optical surveys for surveying ocean quahogs and for measuring their habitat.

19) Further analysis of commercial vessel performance in making standardized tows would be advantageous to supplement work already completed.

20) Regions used in a 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.

21) It may be advantageous to use survey strata that are appropriate for ocean quahogs and surfclams per se, rather than for all shellfish including scallops and other shellfish.

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

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