A. STOCK ASSESSMENT OF SILVER HAKE FOR 2010

Terms of Reference:

1. Estimate catch from all sources including landings, discards, and effort. Characterize the uncertainty in these sources of data, and estimate LPUE. Analyze and correct for any species mis-identification in these data.

2. Present the survey data being used in the assessment (e.g., regional indices of abundance, recruitment, state surveys, age-length data, etc.). Characterize the uncertainty and any bias in these sources of data.

3. Evaluate the validity of the current stock definition, and determine whether it should be changed. Take into account what is known about migration among stock areas.

4. Estimate annual fishing mortality, recruitment and stock biomass (both total and spawning stock) for the time series (integrating results from Silver hake TOR-5), and estimate their uncertainty. Include a historical retrospective analysis to allow a comparison with previous assessment results.
5. Evaluate the amount of silver hake consumed by other species as well as the amount due to cannibalism. Include estimates of uncertainty. Relate findings to the stock assessment model.

6. State the existing stock status definitions for "overfished" and "overfishing". Then update or redefine biological reference points (BRPs; estimates or proxies for BMSY, BTHRESHOLD, and FMSY; and estimates of their uncertainty). If analytic model-based estimates are unavailable, consider recommending alternative measurable proxies for BRPs. Comment on the scientific adequacy of existing BRPs and the "new" (i.e., updated, redefined, or alternative) BRPs.

7. Evaluate stock status (overfished and overfishing) with respect to the existing BRPs, as well as with respect to the "new" BRPs (from Silver hake TOR 6).

8. 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; see Appendix to the TORs).

    a. Provide numerical short-term projections (3 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 (e.g., terminal year abundance, variability in recruitment).

b. Comment on which projections seem most realistic, taking into consideration uncertainties in the assessment.
c. Describe this stock's vulnerability to becoming overfished, and how this could affect the choice of ABC

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

Executive Summary

A new assessment model for silver hake (ASAP, Legault and Restrepo 1998) was attempted based on a "combined" (i.e. North + South) assessment area including estimates of fishery landings, discards, and predator consumption, by age class. While the SARC-51 Review Panel felt that the ASAP model represented an advance for the stock assessment, the ASAP results were not accepted due to difficulties in reconciling the inconsistent interpretations from the steep age profiles in the fishery and survey data. An Index Model (AIM) was also explored; however, the diagnostics were not adequate for stock status determination. Therefore, this assessment is based on trends in the three year moving averages for the age-aggregated, fall survey biomass indices (1973-1982) using the arithmetic means rather than the previous delta approach and the three year averages of exploitation indices (total catch/fall survey biomass index). These form the basis for the updated reference points for both the northern and southern management areas.

Based on the reference points in the existing FMP, silver hake is not overfished and overfishing is not occurring in both the northern or southern management areas. For the northern area, the three year delta mean biomass index from the NEFSC fall bottom trawl survey in Albatross units during 2007-2009 (6.79 kg/tow) was above the biomass threshold (3.31 kg/tow) and slightly above the biomass target (6.63 kg/tow). The three year average exploitation index (landings divided by survey biomass index for 2007-2009 (0.13) in the north was less than the exploitation threshold and target (2.57). In the southern area, the three year survey biomass index in Albatross units (1.39 kg/tow) was greater than the biomass threshold (0.89 kg/tow) but below the biomass target (1.78 kg/tow). The three year exploitation index for 2007-2009 (4.33) in the south was below the overfishing threshold (34.39) and target (20.63) .

Based on the updated and accepted reference points from SAW/SARC-51 in 2010, the northern stock of silver hake is not overfished and overfishing is not occurring. The three year arithmetic mean fall biomass index for 2007-2009 in Albatross units (6.20 kg/tow), was above the management threshold (3.21 kg/tow) but below the target (6.42 kg/tow). The three year average exploitation index for 2007-2009 (0.20 kt/kg) was below the management threshold (2.78 kt/kg). In the south, silver hake is also not overfished and overfishing is not occurring. The three year average arithmetic mean biomass, also based on the NESFC fall bottom trawl survey data for 2007-2009 in Albatross units (1.11 kg/tow), was above the biomass threshold (0.83 kg/tow) but below the target (1.65

kg/tow). The three year average exploitation index, for 2007-2009 (5.87 kt/kg) (Figure A9) was below the overfishing threshold (34.19 kt/kg)

Given that the ASAP model was not accepted as a basis for providing management advice, ASAP-based multiyear projections are not provided.

The scientific information available on silver stock structure (morphometrics, tagging, discontinuous larva distribution, homogeneous growth and maturity) is equivocal. Therefore, it was concluded that there was no strong biological evidence to support either a separate or combined silver hake assessment. The role of silver hake in the ecosystem was assessed using diet data. It was apparent that silver hake constitute an important link in the food web. Estimates of silver hake removals from the system from predatory based consumption suggest that consumption can be approximately 10 times higher than total catch. These consumption estimates were useful to inform both scaling of biomass estimates and the magnitude of mortalities for silver hake in the system.

Introduction

Hake Working Group Meetings

Three meetings were held in preparation of the 2010 silver hake assessment

1. Hake fishermen's/stakeholder's meeting – August 6, 2010 – UMASS School of Marine Science and Technology (SMAST), Fairhaven, MA. Participants include fishermen Dan Farnham and Bill Phoel. Also in attendance were David Goethel (Oversight Committee chair), Andrew Applegate (staff) Steve Cadrin (SSC and WG chair, SMAST), Pingguo He, Klondike Jonas, Yuying Zhang, Tony Wood, and Daniel Goethel (SMAST), Loretta O'Brien, Michele Traver, Katherine Sosebee and Larry Alade (NEFSC), and Dick Allen (advisor at large). A summary of the discussions is in Appendix A1.

2. Data Meeting – September 7-10, 2010, NEFSC Woods Hole MA. Participants included Steve Cadrin (WG Chair), Assessment leads (Larry Alade, Kathy Sosebee , Michele Traver), Rapporteurs (Jessica Blaylock and Julie Nieland), Mark Showell (DFO), Andy Applegate (NEFMC Staff), NEFSC (Loretta O'Brien, Mark Terceiro, Chris Legault, Tim Miller, Dave Richardson, Ayeisha Brinson, Jiashen Tang, Janet Nye, Mike Palmer, Paul Rago, Josef Idoine, Jon Hare), Moira Kelly (NERO), SMAST(Tony Wood, Yuying Zhang, Saang-Yoon Hyun)

3. Model Meeting – October 25-29, 2010, NEFSC, Woods Hole, MA. Participants included Steve Cadrin (WG chair), Assessment leads ((Larry Alade, Kathy Sosebee , Michele Traver), Rapporteurs (Jessica Blaylock and Julie Nieland), Mark Showell (DFO), Andy Applegate (NEFMC Staff), Dan Farnham (Fisherman and Industry Advisor), NEFSC (Loretta O'Brien, Paul Nitschke, Mark Terceiro, Jay Burnett, Chris Legault, Liz Brooks, Tim Miller, Jon Deroba, Rich McBride, Jim Weinberg, Paul Rago, Josef Idoine, Jon Hare, Janet Nye, Dave Richardson, Laurel Col, Jason Link), SMAST(Tony Wood, Yuying Zhang, Dan

Goethel). The groups met by correspondence after the meetings, including a WebEx meeting on November 5, 2010 to report updates on silver hake analyses, provide guidance on reference points and discuss plans for report development.

This Working Group (WG) report includes products from all three meetings and contributions from all participants. It also has edits which reflect the outcome of the SAW/SARC51 peer review.

Biology

Silver hake also known as whiting, *Merluccius bilinearis* range from Newfoundland to South Carolina. In U.S. waters, silver hake are managed as two separate stocks (Almeida 1987a). The northern silver hake stock inhabits Gulf of Maine - Northern Georges Bank waters, and the southern silver hake stock inhabits Southern Georges Bank - Middle Atlantic Bight waters (Figure A1). Silver hake migrate in response to seasonal changes in water temperatures, moving toward shallow, warmer waters in the spring. They spawn in these shallow waters during late spring and early summer and then return to deeper waters in the autumn (Brodziak et al. 2001). The older, larger silver hake especially prefer deeper waters. During the summer, portions of both stocks can be found on Georges Bank, whereas during the winter, fish in the northern stock move to deep basins in the Gulf of Maine, while fish in the southern stock move to outer continental shelf and slope waters. Silver hake are widely distributed, and have been observed at temperature ranges of 2-17° C (36-63° F) and depth ranges of 11-500 m (36-1,640 ft). However, they are most commonly found between 7-10º C (45-50º F) (Lock and Packer 2004).

Female silver hake are serial spawners, producing and releasing up to three batches of eggs in a single spawning season (Collette and Klein-MacPhee eds. 2002). Major spawning areas include the coastal region of the Gulf of Maine from Cape Cod to Grand Manan Island, southern and southeastern Georges Bank, and the southern New England area south of Martha's Vineyard. Peak spawning occurs earlier in the south (May to June) than in the north (July to August). Over one-half of age-2 fish (20 to 30 cm, 8 to 12 in.) and virtually all age-3 fish (25 to 35 cm, 10 to 14 in.) are sexually mature. Silver hake grow to a maximum length of over 70 cm (28 in.) and ages up to 14 years have been observed in U.S. waters, although few fish older than age 6 have been observed in recent years (Brodziak et al. 2001).

Fishery Regulations

The following briefly outlines the current small mesh multispecies regulations (based on the small mesh exemption program) for the New England whiting fishery to provide context for interpreting the fishery and model results.

1. 1994 & 2000 - Exempted fisheries allows vessels to fish for specific species such as whiting or northern shrimp in designated areas using mesh sizes smaller than the minimum mesh size allowed (Gulf of Maine, Georges Bank, Southern New England, Mid-Atlantic : 6.5-inch square or diamond) under the Regulated Mesh Area (RMA) regulations .
2. Permits

a. Open access Category K Multispecies
b. Limited Access Category A-F (non Days-at-Sea fishing)

3. No Size Limits
4. 500 lbs at sea transfer limit.
5. 2003 - Possession limits vary by exemption area
    a. 3,500 lbs if mesh < 2.5 inches (63.5mm)
    b. 7,500 lbs if mesh <=3.0 inches (76.2mm)
    c. 30,000 lbs if mesh > 3.0 inches (76.2mm)
    d. No Red Hake possession limit

TOR 1. Estimate catch from all sources including landings, discards, and effort. Characterize the uncertainty in these sources of data, and estimate LPUE. Analyze and correct for any species mis-identification in these data.

Commercial Landings

Silver hake landings (Tables A1, Figures A2-A4) increased substantially during the 1960's due to direct fishing by distant water fleets (DWF) operating in the U.S. waters. Nominal landings of silver hake from the northern stock were significantly higher than those from the southern stock during the mid-1950's through the mid-1960's and fell below the southern stock starting in the late 1960's due to the expansion of the DWF in the southern region. Landings in the north peaked to over 94,000 mt in 1964 and have steadily declined substantially since 1975. Despite the departure of the DWF in 1976, landings continue to further decline and have been less than 10,000mt per year after 2002 (Table A1, Figure A3).

Nominal domestic landings from the southern silver hake stock have varied between 5,000-27,000 mt, (Table A1, Figure A4). However, between 1960 and 1980, distant-water fleet landings of southern silver hake were very high, peaking at about 280,000 mt in 1965 and around 100,000 mt in 1974. Distant-water fleet landings diminished in the mid-1980s, and total landings have since continued to gradually decrease. In 2009, total landings were near a historic low at 7,000 mt.

Maine and Massachusetts have been the primary states in which silver hake from the northern stock have been landed (Table A2). Rhode Island became important in the 1980s and Connecticut in the 1990s. For landings of the southern stock, Rhode Island and Massachusetts were historically important, with New York, New Jersey and Connecticut increasing in importance (Table A3).

The otter trawl has been the principal gear used in the both stocks with some landings in the northern stock coming from the shrimp trawl fishery until the early 1990s with the use of the Nordmore grate (Tables A4-A5, Figures A5-A6). In recent years, sink gill net has increased slightly in importance, although there are significant landings from the other category, which includes unknown gears.

The seasonality of landings from the two stocks is different, with most of the northern stock landings occurring in the second half of the year and the first half of the year accounting for a approximately less than 20% of the annual. Landings from the southern stock appear to be landed more consistently throughout the year than in the north (Tables A6-A8, Figures A7-A8).

Silver hake are landed in seven commercial categories: unclassified round, medium, small, dressed, juvenile, king and large. The vast majorities of landings are reported as round or dressed market category, with other market categories appearing sporadically over time (Tables A9-A10, Figures A9-A10). King silver hake were separated starting in 1981, with smalls appearing in 1982. Large silver hake were further separated in 2004. A juvenile market category appeared in 1994 and was a larger component of the southern stock landings (Tables A9-A10, Figures A11-A12).

A sympatric species of hake, offshore hake, is often landed as silver hake (Garcia-Vazquez et al 2009). In 1991, landings of offshore hake began to be separated, although the extent to which this is actually occurring is still unknown. The geographical distribution of offshore hake is limited to the southern stock of silver hake. Therefore, landings from the northern stock are considered to be silver hake while southern landings are potentially a mixture of silver and offshore hake. In order to estimate landings of silver hake from the southern region, two alternative methods were developed.

Length-based species composition

The first method used the port length samples directly. Length samples of silver and offshore hake were combined by stock (Tables A11-A13). In examining the silver hake length samples by market category, it appeared that most of the market categories were similar in length composition to the round category (Figures A11-A12). Therefore, only three market categories were used for stratification: round, king, and large. Even with the reduction of market categories, pooling over years was required to get an adequate number of fish (Table A14). The length-weight equations by season from Wigley et al 2003 were applied to the samples and used to estimate the landings numbers at length for each market category.

For the southern stock, length compositions for each species were estimated for the spring and fall surveys from 1968-2009. The species length-weight equations were then applied to determine weight-at-length by species. The proportions at length by species for both number and weight were applied to the commercial landings-at-length to estimate landings-at-length by species (Figures A13-A14). The lengths had to be grouped into intervals to avoid zero cells in the survey. To hind-cast the species proportions back to 1955, the average proportion of silver hake for the time series was used and applied to the total silver hake landings.

Depth-based species composition

This method relates survey catch composition to Vessel Monitoring System (VMS) derived commercial landings from 2004-2009 using survey depth as an explanatory factor to develop a model that predicts the hake species landings composition. Offshore and silver hake composition (R_{23}) in the trawl survey tows were modeled as a two parameter logistic function of average depth. Only survey tows with silver hake, offshore hake or both were fitted and mean depth was the dependent variable.

$$R_{23} = \frac{e^{a+b*depth}}{1+e^{a+b*depth}}$$

For each stratum group, survey (winter, spring, and fall), and sets of time series, the catch and depth data were fitted by a non-linear least squares, weighted by the number of positive tows in a stratum, using the Marquardt method (Marquardt 1963) to aide convergence. R^2 and Wald 95% confidence intervals (Cook and Weisberg 1990) were calculated for parameters a, b, D50, and the range to evaluate goodness of fit. Fitting the data with the a two parameter logistic non-linear regression using maximum likelihood estimation and iteratively reweighted least squares approaches was attempted, but did not improve the results.

The parameter estimates for 1985-2009 were applied to the depth association with the VMS-derived commercial landings at depth (Applegate 2010). The model ratio of offshore to silver hake were assigned to landings from each group depth zone, survey season, and survey stratum group and summed for the calendar year (Applegate 2010). The final landings from this method were greater than 90% of the total landings reported by dealers in 2004-2009.

Annual model estimates of silver hake landings for the southern stock area ranged from 4,207 – 6566 mt in 2003-2009, representing 88-95% of the total hake landings **(Table A15)**. Although the depth based landings were derived from VMS effort distribution, hindcast estimates were used for 2003 because the model based estimates appeared to be biased due to small vessels (i.e. fished inshore and catch silver hake) were underrepresented when multispecies VMS requirements first became effective.

Estimates of offshore hake landings ranged between 290 – 893 mt and 5 – 12% of total hake landings **(Table A15)**. These estimates are considerably higher than those reported by either dealers or by fishermen on Vessel Trip Reports (VTR).

Given that VMS data for 2004 – 2009 were deemed acceptable for direct estimation of silver and offshore hake landings composition, landings prior to 2004 (1955 – 2003) were hindcasted to generate longer time series of removal for assessments and for developing biological reference points. Although the hindcast procedure allowed the distribution of catch to vary between statistical areas, the distribution of catch <u>within</u> these intermediate depth statistical areas was assumed to be constant, equal to the average depth distribution observed by VMS during 2004-2009. Details of the hindcasting methodology can be found in Applegate (2010).

The estimated silver hake landings from the depth based logistic model, including the hindcasting, rose from a low of 12,891 mt in 1955 (93% of the total) to over 282,000 mt in 1990 (92% of the total), then declined to 4207 mt in 2006 (90% of the total). Recent landings totaled 5,006-6,406 mt (93 - 95%). Silver hake as a proportion of total hake landings ranged from 87% in 1971, 1976, 1978-1980 to 98% in 1988 and 1996 (Table A16).

Hindcast and model based estimates of offshore hake landings were an order of magnitude greater than that reported by dealers. Landings rose from 951 mt in 1955 (7.0% of the total) to 24,198 mt in 1965 (8% of the total). Offshore hake as a proportion of total hake landings ranged from 2% in 1971, 1976, 1978-1980 to 13% in 1988 and 1996 (Table A16).

The resulting silver hake landings for the two methods are given in Table A15. On average, the two methods gave similar results, with the length-based model averaging 96% silver hake while the depth-based method averaged 94% silver hake. Conversely, there were some differences in the offshore hake estimates with the depth based method averaging approximately 7% and 4% for the length-based method (Table A16, Figure A15).

Given the similarity between both models, the SARC Panel agreed that the results from both methods will have undetectable differences in the assessment results. For the purpose of this assessment, the length-based estimator was considered more suitable primarily due to the number of years hindcasted (1955-1967) relative to the depth-based approach (1955-2003). It was also recognized that the length based approach provided an advantage of estimating fishery age composition which was not readily available in the depth-based method. .

Sampling Intensity

The level of port sampling has generally been strong since the mid-1990's with higher sampling in the south relative to the north. In 2007, over 17,000 length measurements were taken in the southern area resulting in peak sampling intensity of 326 lengths per 100 mt. In the north sampling intensity increases substantially in 2006 and 2007 (115 and 107 lengths per mt respectively). In the recent years, sampling intensity has somewhat declined in both stock areas but more substantially in the north due to very low observed landings (Table A17). Overall, sampling intensity for the silver hake fishery has certainly improved compared to pre-1994 period, particularly in the south.

Commercial Discards

Discard estimates were re-calculated in this assessment. The ratio-estimator used in this assessment is based on the methodology described in Rago et al. (2005) and updated in Wigley et al (2007). It relies on a d/k ratio where the kept component is defined as the total landings of all species within a "fishery". A fishery is defined as a homogeneous group of vessels with respect to gear type (longline, otter trawl, shrimp trawl, sink gill net, and scallop dredge), quarter, and area fished (GOM-NGBK, SGBk-MA), and for otter trawls, mesh size (<= 5.49", > = 5.5 "). All trips were included if they occurred within this stratification regardless of whether or not they caught hakes.

The discard ratio for hakes in stratum h is the sum of discard weight over all trips divided by sum of kept weights over all trips:

$$\hat{R}_h = \frac{\sum_{i=1}^{n_h} d_{ih}}{\sum_{i=1}^{n_h} k_{ih}} \quad (1)$$

Where d_{ih} is the discards for hakes within trip i in stratum h and k_{ih} is the kept component of the catch for all species. R_h is the discard rate in stratum h. The stratum weighted discard to kept ratio is obtained by weighted sum of discard ratios over all strata:

$$\hat{R} = \sum_{h=1}^{H} \left(\frac{N_h}{\sum_{h=1}^{H} N_h} \right) \hat{R}_h \quad (2)$$

The total discard within a strata is simply the product of the estimate discard ratio R and the total landings for the fishery defined as stratum h, i.e., $D_h=R_hK_h$. Cells with < three trips were imputed using annual averages by gear type and region. To hind-cast the discards to 1981 (the first year in which there was no industrial fishery), discards/total landings by half year for the first three years (1989-1991 for otter trawl, sink gill net, and shrimp trawl; 1992-1994 for longline and scallop dredge) were averaged and the rate applied to the total landings from the dealer database. For the otter trawl fisheries, the mesh sizes were combined for the hind-cast.

Discards from the longline and sink gill net fishery were minimal for silver and offshore hake in both stock areas (Table A18-A21). Discards from the otter trawl fisheries have been significant and variable.

The same problem with species identification that exists in the landings was found in the Fisheries Observer Program (FOP) data. There are discards of offshore hake estimated for the north. The geographical distribution of offshore hake is limited to the southern stock of silver hake and therefore, any discards from the northern stock are considered to be silver hake. In order to estimate discards of silver hake from the southern region, only the length-based estimator was employed.

The observer discard length samples of silver and offshore hake were combined by stock (Tables A22-A25). Enough length samples were available for large and small mesh otter trawls in both regions and sink gill net and shrimp trawl in the north. Pooling over years was still required to get an adequate number of fish (Tables A26-A27). The length-weight equations by season from Wigley et al 2003 were applied to the samples and used to estimate the landings numbers at length for each market category. The discards-at-length were raised to the total discards including all the gear types to account for as much of the removals as possible.

For the southern stock, length compositions for each species were estimated for the spring and fall surveys from 1968-2009. The species length-weight equations were then applied to determine weight-at-length by species. The proportions at length by species for both number and weight were applied to the commercial discards-at-length to estimate discards-at-length by species. The lengths had to be grouped into intervals to avoid zero cells in the survey. To hind-cast the species proportions back to 1981, the average proportion of silver hake for the time series was used and applied to the total silver hake discards.

Silver hake discards in the north were approximately 23% of the total catch in years 1981-2009 (Tables A28-A30). Total discards peaked to over 2,900mt in 1982, declined substantially in 1993 to a low of 37mt in 2006 and increased 14% from 2008 (167mt) to 2009 (190mt). In the south, the proportion of discards to total catch in years 1981-2009 was similar to the north (22%), peaked in 1989 (~6500mt), declined substantially in the mid 1990's with a brief increase in 1999 to levels observed in the early 1980's (3500mt). Total discards of silver hake in the south decreased 19% from 2008 (1033mt) to 2009 (839mt).

Catch at age

Due to the lack of commercial age data from the commercial fishery, age compositions for landings and discards were derived from the NEFSC bottom trawl survey age-length keys (ALK) from 1973-2009. Commercial length for both landings and discards frequencies were estimated by half years from the length-based estimator as described above. The silver hake age-length keys were then calculated for both the fall and spring then applied to the length-based landings (1973-2009, Tables A31-A33) and discards (1981-2009, Tables A34-36) by half years (i.e. spring ALK for the half 1 and fall ALK for half2) to capture seasonal differences in the fishery. The fall age-length keys were not available for fall 1974. Therefore adjacent age-length key from 1973 were borrowed to impute commercial landings at ages for half 2 based on minimal differences observed in the mean size at age in the fall survey during the early 1970's.

The catch at age composition of silver hake catches in the fishery has shown a general truncation in the age structure since the late 1980's with fewer availability of fish older than age-6 in the population (Tables A37-A39, Figures A16-A18). In the north, vast majority of the catches were dominated by ages 2-4 in the 1970's, partly supported by the strong 1972 year class. By the early 1980's, ages 2 and 3 declined severely but remained stable through the late 1980's. There were a few strong year classes around the 1990's contributing to moderate expansions in ages 2 and 3. Age-4 continues to decline with further reductions in age-5 in the fishery. However, it appears that there was a 2006 year class which appears to have contributed to the increase in age 3 in 2009 (Table A37, Figure A16).

Similarly in the south, majority of the catches were also dominated by ages 2-4 in the 1970's, supported by the 1972 year class but declined drastically around the early 1980's with moderate expansions in ages 2 and 3 during the 1990's. The age-4 group continues to decline with further truncation in the age structure. However, there have been increased catches of age-1 during the early 1990's probably and recently in the last five years. This is probably due to increased demand for small hake in the Spanish market (comm. Andy Applegate) in the 1990's and more recently, probably related to over the side bait sales (Table A38, Figure A17).

Summary of the combined stock area catches are summarized in Table A39 and in Figure A18. The perception of the age structure does not change relative to the north and south. Similar properties such observed in the north and southern areas such as the truncation of older fish and the dominance of ages 2 and 3 in the recent years still persists.

Mean Weights at age

The overall fishery weights at age were calculated from the landings and discards weighted by the respective catch at age for the north, south and combined area stock. (Tables A40-A42, Figures A19-A21). The mean weight at age (kg) were quite similar but variable between for fish greater than age-4 particularly since the mid 1980's. Only slight variations in mean weights at age were apparent during the mid 1990's - mid 2000's which are likely related to variations in year class strength as they become recruited to the fishery.

Commercial Fishing Effort

There are currently no estimates of CPUE or effort for this species. Given the uncertainties given with species identification above and the major changes in management noted in the introduction, CPUE is not likely to be a good indicator of stock status. In particular, the fishery in the north has been limited in areas they can fish with small mesh. These are not necessarily to good silver hake fishing areas. Over time, the fishery has also changed from one dominated by a distant water fleet that took substantial quantities of everything to a much smaller fishery that may be driven more by prices and regulation than abundance.

TOR 2. Present the survey data being used in the assessment (e.g., regional indices of abundance, recruitment, state surveys, age-length data, etc.). Characterize the uncertainty and any bias in these sources of data.

Data Source: The primary sources of biological information for silver hake are based on the annual fishery independent surveys conducted by the Northeast Fisheries Science Center (NEFSC). The surveys were conducted using a random stratified sampling design which allocates samples relative to the size of the strata, defined by depth. The surveys extend from the Gulf of Maine to Cape Hatteras, in offshore waters at depths 27-365 meters, and have been conducted in the fall since 1963 and in the spring since 1968. The winter bottom trawl survey began in 1992 and was specifically designed for flatfish, however, the deeper survey strata were not sampled until 1998 (Figure A22). The winter trawl survey does not cover the Georges Bank area because the survey was designed specifically for flatfish in the southern region. Details on the stratified random survey design and biological sampling methodology may be found in Grosslein (1969), Azarovitz (1981) and Sosebee and Cadrin (2006). Other surveys used in the analysis of silver hake are NEFSC shrimp survey (1985-2009), Massachusetts Division of Marine Fisheries (1978-2009) fall and spring surveys and Rhode Island (1979-2010), Connecticut (1984-2009), and Maine-New Hampshire (2000-2009) state surveys.

Transform: Survey estimates were computed using both delta transformation and arithmetic means for numbers and weight. The Whiting Plan Development Team (PDT) has used the delta mean for assessing stock status. The delta transformation uses only the positive tows for log transformation given the following equation (syrjala 2000):

$$\hat{M}_\delta = \begin{cases} \frac{m}{n} e^{\bar{y}} \psi_m\left(\frac{1}{2}s_y^2\right) & m > 1, \\ \frac{1}{n} x_1 & m = 1, \\ 0 & m = 0 \end{cases}$$

m = number of non - zero tows

n = total number of tows

$$\hat{V}_\delta = \begin{cases} \frac{m}{n} e^{2\bar{y}} \left[\psi(2s_y^2) - \frac{m-1}{n-1}\psi_m\left(\frac{m-2}{m-1}s_y^2\right)\right] & m > 1, \\ \frac{1}{n} x_1^2 & m = 1, \\ 0 & m = 0 \end{cases}$$

Examination of the differences between the delta and arithmetic means revealed that use of the delta transformation did not reduce the variability of the survey and may have increased interannual variability (See offshore Hake assessment). If a survey has a high variance, the back-transformation may be biased high. The delta transformation was also more sensitive to the handling of missing weights. Prior to 2001, the data for weights were recorded to the nearest 0.1 kg and if a tow contained only a single small fish, the weight was entered into the data as zero. Since the delta transform uses the positive tow, how this is handled has an impact on the result. There were three options: taking out the zeros, leaving in the zeros, and filling in zeros using a length-weight equation. Since these options did not affect the arithmetic as much as the delta mean, the decision was made to use the arithmetic and length-weight options for any new analyses.

Several surveys were explored to provide indices of relative abundance. The properties of each survey are summarized in Table A43. Based on the stock definition provided in TOR 3, survey indices for the assessment was based on data from all strata that have been sampled consistently (NEFSC fall and spring survey). However, future work will explore other surveys as sensitivity analyses in the assessment.

The NEFSC strata set used for the northern area are: 20-30 and 36-40. The NEFSC strata used for the southern management area are: 1-19 and 61-76. The combined strata set are: 1-30, 36-40, and 61-76 (Figure A22). Survey age composition were estimated for the north, south and combined areas from 1973-2009 for when survey ages were available. Of special note, fall 1974 was never aged for both the north and south regions, and therefore age-length key from 1973 was borrowed to impute ages for 1974. As discussed earlier, the mean size at age for both years were similar. The 2009 and 2010 survey values were calibrated to the Albatross IV by using seasonal length-based calibration coefficients. Details on the estimation of the calibration coefficients may be found in Miller et al. 2010. The strata set for the shrimp survey is 1-12, with no calibration needed for 2009. The strata set for the winter surveys are: 1-3, 5-7, 9-11, 13-14, 61-63, 65-67, 69-71, and 73-75. No calibration was also needed for the winter survey, as it was discontinued in 2007. Massachusetts Division of Marine Fisheries data was separated into northern and southern areas. The northern strata set used were 18-36 and the southern strata set used were 11-17 (Figure A23).

Minimum swept area abundance and biomass were calculated by using swept area conversions of 0.0112 for the NEFSC fall and spring surveys, 0.004 for NEFSC shrimp survey, 0.0131 for the NEFSC winter survey, and 0.003846208 for Massachusetts Division of Marine Fisheries (MADMF) fall and spring surveys. Swept area estimates were not calculated for the other state surveys. Swept area estimates at age were also calculated for the NEFSC fall and spring surveys, in the northern, southern, and combined management areas.

Silver hake survey distribution suggests that most of the higher catches for silver hake are in the Gulf of Maine and on Georges Bank in the fall, whereas they are along the shelf edge in the spring. In the spring of the 1970s, most of the silver hake seemed to be in the Gulf of Maine and southern New England, with few on Georges Bank. However, even though the areas did not change through the 1980s and 1990s, the density did. It seems a bit scarcer during this time period. In the fall, there seems to be more silver hake on Georges Bank than in the spring, though most of the catch weight is in the Gulf of Maine (Figures A24-A35).

Calibration: In 2009 the *NOAA* ship *Henry B. Bigelow* replaced the *R/V Albatross IV* as the primary vessel for conducting spring and fall annual bottom trawl surveys for the Northeast Fisheries Science Center (NEFSC). There are many differences in the vessel operation, gear, and towing procedures between the new and old research platforms

(NEFSC Vessel Calibration Working Group 2007). To merge survey information collected in 2009 onward with that collected previously, we need to be able to transform indices (perhaps at size and age) of abundance from the *Henry B. Bigelow* into those that would have been observed had the *Albatross IV* still been in service. The general method for merging information from these two time series is to calibrate the new information to that of the old (Pelletier 1998).

Specifically we need to predict the relative abundance that would have been observed by the *Albatross IV* ($\hat{R}_A$) using the relative abundance from the *Henry B. Bigelow* (R_B) and a "calibration factor" (ρ),

$$\hat{R}_A = \rho R_B . \tag{1}$$

To provide information from which to estimate calibration factors for a broad range of species, 636 paired tows were conducted with the two vessels during 2008. Paired tows occurred at many stations in both the spring and fall surveys. Paired tows were also conducted during the summer and fall at non-random stations to improve the number of non-zero observations for some species. Protocols for the paired tows are described in NEFSC Vessel Calibration Working Group (2007).

The methodology for estimating the calibration factors was proposed by the NEFSC and reviewed by a panel of independent scientists in 2009. The reviewers considered calibration factors that could potentially be specific to either the spring or fall survey (Miller et al. 2010). They recommended using a calibration factor estimator based on a beta-binomial model for the data collected at each station for most species, but also recommended using a ratio-type estimator under certain circumstances and not attempting to estimate calibration factors for species that were not well sampled. In the case of offshore hake, using silver hake calibration factors as a proxy was better than not using any calibration factors.

Since the review, it has become apparent that accounting for size of individuals can be necessary for many species. When there are different selectivity patterns for the two vessels, the fraction of available fish of a given size taken by the two gears is different. Therefore, the ratio of the mean catches by the two vessels will change with size. Under these circumstances, the estimated calibration factor that ignores size reflects an average ratio weighted across sizes where the weights of each size class are at least in part related to the number of individuals at that size and the number of stations where individuals at that size were caught. Applying calibration factors that ignore size effects to surveys conducted in subsequent years when the size composition is unchanged should not produce biased predictions (eq. 1). However, when the size composition changes, the frequency of individuals and number of stations where individuals are observed at each size changes and the implicit weighting across size classes used to obtain the estimated calibration factor will not apply to the new data. Consequently, the predicted numbers per tow that would have been caught by the *Albatross IV* will be biased.

For silver hake, we fit a suite of beta-binomial models that made different assumptions on the relationship of the calibration factor to length. The models ranged from those that were constant with respect to length to logistic and double-logistic functions of length. A season-specific model was chosen based on AIC_c for silver hake where a logistic functional form for the spring and a double-logistic form for the fall provided the best fit (Table A44, Figure A36). To estimate weight per tow for the 2009 and 2010 surveys, the length-weight equations by season from Wigley et al. 2003 were applied to the length frequencies.

North Survey trends:
The NEFSC fall survey biomass steadily increased continuously through the 1970s, peaked in 1998 at 40,462 metric tons and then declined to 3,672 metric tons in 2005, lowest in the time series. Biomass has increased in the last few years and is currently at 14,748 metric tons, a 31% increase from 2008 (11,285 mt; Table A45, Figure A37).

The NEFSC spring survey has been quite variable. There was a large peak in 2001, with 22,309 mt and then considerably declined until 2006, with 915 mt. Since then,the biomass has increased and estimated at 5,673 mt in 2009 (Table A46, Figure A38).

The NEFSC shrimp survey swept area biomass was at its highest early in the time series, in 1987 with 149,508 metric tons. It dropped substantially to 16,302 metric tons in 1988. The survey continued to vary until thereafter, then declined to an all time low of 9,501 metric tons in 2006. Biomass in 2009 was 16,239 mt, a 42% decrease from 2008 (27,980 mt) (Table A47, Figure A39).

The MADMF fall surveys indicate two large spikes in silver hake swept area biomass, 1986 and 2000, with over 2,000 mt. The most recent years have seen a decrease, with 2009 only catching 651 mt (Table A48, Figure A40).

The MADMF spring surveys have much lower values than the fall. Only in 1987 and 2000 were there over 1,000 mt caught. In 2004, the spring survey saw its lowest catch of silver hake in the time series, with only 47 mt. It has since increased to 225 mt in 2009 (Table A49, Figure A41).

The MENH fall survey has been variable without trend but the spring survey peaked in 2002 at approximately 12 kg/tow, declined sharply in 2006 to 1.6 kg/tow and has steadily increased in the last three years (Table A50, Figures A42-A43).

North Age Composition: Fall survey age composition shows a general truncation of older age fish with less availability of fish older than age 6. Ages-1 and 2 are the abundant in the survey. The strongest year class over the time series was in 1997 with over 400,000 fish. In 2006, there was a moderate size year class which contributed to the expansion of age-3 in 2009. Since the late 1980's and early 1990's, Age 4 and 5 has declined significantly consisting of only 1% of the survey catch (Table A45, Figure A44).

Similar to the fall survey, majority of the spring survey catches consist of ages 1 and 2's and very few fish older than age-5. There has been several strong year classes since the mid-1980's contributing to significant expansion of age 2's and moderately for age-3. A marginal increase was noted for age-4 in the early 2000, but has declined in the recent years (Table A46, Figure A45).

South Survey Trends
The NEFSC fall survey swept area biomass was higher during the 1970's and 1980's than any other part of the time series. Biomass peaked in 1985 at 11,760 metric tons then steadily declined the 1990's to approximately 2,600mt in 1994 then briefly increased in 2001 to over 6,700 metric tons. Biomass has as averaged around 4,000mt in the last 10year and approximately around 3,600 metric tons, a and currently at 3,600 metric tons in 2009, a 20% decrease since 2008 (4,513 metric tons; Table A51, Figure A46).

The NEFSC spring survey had considerably higher biomass than the fall survey. It was fairly high in the 1970s, averaging over 11,000 metric tons. It then decreased through the 1980s and 1990s, with a large spike in 1996 at 20,553 metric tons. In 1997, it fell to 2,142 metric tons. In 2010, it has increased to 3,783 metric tons (Table A52, Figure A47).

The NEFSC winter survey has a very short time series, 1992-2007. The swept area biomass was fairly stable throughout the time series. The largest biomass was in 1993 with almost 8,000 metric tons. It stayed considerably lower than that until it was discontinued in 2007 (Table A53, Figure A48).

The MADMF fall surveys indicate very low swept area biomass. There were only three years in the time series where the catch was over 50 metric tons. In 2007, the biomass plummeted from 25 metric tons down to 0.04 metric tons. The most recent years have increased moderately, with 2009 catching 0.22 metric tons (Table A54, Figure A49).
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The MADMF spring survey has much higher values than the fall, but has generally declined over time. In 1987, there was over 2,000 metric tons caught. In 2003, the spring survey saw its lowest catch of silver hake in the time series, with only 2 metric tons. It has recently increased to 26 metric tons in 2009 (Table A55, Figure A50).

Survey trends for Rhode Island state survey has been variable without trend. The Connecticut survey on the other hand was highest early in the time series but has been low ever since (Table A56, Figures A51-A52).

South Age Composition: Similar to the north, the south has also experienced a general truncation in the age structure with fewer older fish than age-6 in both the fall and the spring survey. Despite the consistent appearance of strong year classes in the last decade, there has been a substantial decline of age 4 and 5 in the surveys. However, the spring survey showed an unusual increase of age-3 in 1989 with approximately 260,000 fish. It is unclear for the sudden increase in age-3. This is likely due to aggregation of this size class during the survey (Tables A51-A52, Figures A53-A54).

Combined North and South
The NEFSC combined area fall survey is driven by the northern region peaking in 1998,

with 42,353 metric tons and was extremely low in 2005 at 6,773 metric tons. It has increased recently with biomass at approximately 18,000 metric tons in 2009 (Table A57, Figure A55). In 1975, the spring survey had its highest biomass in the time series, at 37,136 metric tons. Then it hit an extremely low point at 4,725 metric tons in 1997. The survey had smaller spikes in 2000 and 2001 where the catch was over 20,000 metric tons. In 2009, the swept area biomass increased to 13,278 metric tons (Table A58, Figure A56). Similar pattern in the age structure was also observed in the combined stock areas as in the northern region (Tables A57-A58, Figures A57-A58).

TOR 3. Evaluate the validity of the current stock definition, and determine whether it should be changed. Take into account what is known about migration among stock areas.

Two subpopulations of silver hake are assumed to exist within the U.S. EEZ (Almeida 1987a). Analyses of morphometrics (Conover et al. 1961, Almeida 1987a) are the primary basis for this delineation further supported by otolith microconstituent (Bolles and Begg 2000). However, genetic analyses of the population structure have been inconclusive (Schenk 1981). The northern silver hake stock inhabits the Gulf of Maine - Northern Georges Bank waters, and the southern silver hake stock inhabits Southern Georges Bank - Middle Atlantic Bight waters (Figure A22). These boundaries were established at SAW 11(Brodziak et al. 2005).

While it is likely that the northern and the southern stocks mix on Georges Bank, the degree of mixing and movement among the management areas are unknown (Almeida 1987a, Helser et al. 1995, Helser 1996). Silver hake are known to spawn in the Gulf of Maine, southern New England, and on the southern flank of Georges Bank. Therefore, it is likely that silver hake larvae are entrained in the clockwise gyre on Georges Bank leading to larvae settlement in either management areas. Recent analyses of an icthyoplankton survey suggest the southern stock is larger (>90% of the larvae density) than the northern stock (Richardson et al. 2010). This is also consistent with Nye et al. 2009, suggesting a northern shift in the center of biomass for southern stock of silver hake. This is in contrast with the NEFSC trawl survey, which suggests a much larger stock in the northern area (Figure A59). Additionally, in the Gulf of Maine, there were no larvae observed, although adult spawners were present. This further suggests that there is probable transport of silver hake larvae from north to south and adults are migrating across the traditional stock boundaries which also implies that reproductive isolation between the two stock areas is unlikely.

NEFSC trawl surveys indicate a generally continuous distribution of silver hake from the Gulf of Maine to the southern New England/Mid-Atlantic Bight (Figures A24 and A30). However, the relative density of silver hake has varied through time between the northern and southern management areas. Population density as measured by the NEFSC fall bottom trawl survey increased in northern area during the mid-1980's, declined in 2000's and has continue to increase in the recent years. In contrast, density in the southern area showed decreases in the 1990's with a temporary increase in 2000 and declined in the last few years (Figure A60). Relative to the fall survey, the spring survey trends are highly variable and difficult to interpret the trends (Figure A60). This indicates that it is likely that mixing is occurring during the adult life stage. However, the degree of mixing cannot be determined.

Analyses of silver hake size at age data have shown that growth tends to vary in time and among areas (Helser 1996). Particularly, there were consistent differences between growth in the Gulf of Maine and southern New England/Mid Atlantic Bight areas. However, Helser showed that growth patterns on Georges Bank and in the Gulf of Maine were indistinguishable in the 1980's and 1990's and that growth rate changes dynamically on Georges Bank. In the last assessment, Brodziak et al. (2005) reported that there were negligible differences in growth between the northern and southern stock areas. For the purpose of this assessment, a decadal analyses on silver mean size at age from 1973-2009 for the fall and spring by sex was conducted. Results suggest that not only does silver hake exhibit sexually dimorphism but also very little differences were observed in the growth patterns between the northern and the southern stock areas (Figures A61 – A64).

Patterns in silver hake median age at maturity from the spring NEFSC bottom trawl survey (1980-2009) were estimated for both the northern and southern management areas in this assessment. The observed proportion of fish mature at age was fitted a logistic model using a nonlinear least square estimator. Model results in Figure A61 shows that there is no meaningful geographic variation in age at maturity. Annual trends in median age at maturity were also consistently similar between the north and the south management areas with synchronous increases around the early 1990's from 1.6yrs to approximately of 2.3yrs through late 1990's and early parts of 2000 and declined in the recent years to levels estimated in the early 1980's (A50 = 1.6yrs, Figure A65).

In summary, based on the scientific information available on silver stock structure (morphometrics, tagging, discontinuous larva distribution, homogeneous growth and maturity), it was concluded that there were no strong biological evidences to support either a separate or a single stock structure for silver hake. For the purpose of this assessment, a separate north-south and a combined stock model formulation was explored.

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

Assessment History

Stock assessments of the silver hake resources were conducted as early as 1968 using catch curves on catch at age data, with more formal assessment methods using Virtual Population Analysis (VPA) during the next two decades. During the next two decades, VPAs were enhanced in various ways using tuning methods with auxiliary research survey data using age-aggregated *ad hoc* techniques. During the early 1990s both Laurec-Shepherd and ADAPT tuning methods based on statistical fitting were attempted and assessment results were accepted with reservation. However, subsequent VPA assessments were rejected due to high degree of uncertainty and instability in parameter estimates (Brodziak et al 2001). Due to these difficulties of the population assessments, the southern and northern stock of silver hake are based on an index of exploitation and biomass derived from NEFSC resource assessment surveys.

In this assessment, two models were attempted, An Index Method (AIM) and the Age Structure Assessment Program (ASAP). While the ASAP model provided major advancement in the assessments, the results were not accepted due difficulties reconciling the inconsistent interpretations of the steep age profiles. The AIM model was also not accepted because it did not provide adequate diagnostics for stock status determination. Thus, this assessments was based on trends in the three year moving averages for the age-aggregated, fall survey biomass indices (1973-1982) using the arithmetic means rather than the previous delta approach (SAFE2003) and the three year averages of exploitation indices (total catch/fall survey biomass index) for both the northern and southern management areas.

A bridge between the current and last assessment

The NEFSC fall Survey biomass (delta mean kg/tow) and the relative exploitation index (landings/delta mean kg/tow) were computed for both the northern and southern stock areas. Survey biomass for the north declined recently and near the target levels used for management while the southern survey biomass has generally increased in recent years and also near the management target. The exploitation rate index for the southern stock is higher than for the northern stock throughout the time series. The exploitation index show high values during 1963-1977 followed by a period of low values during 1978-1993. Since 1994, the northern exploitation continues to decline and the southern values have varied without trend. Overall, the exploitation rate indices suggest that exploitation rates in recent years are much lower than during the 1960’s and 1970’s when foreign distant water fleets intensively harvested silver hake (Table A59, Figures A66-A67).

For this assessment, the “delta” estimators were replaced with the arithmetic means (i.e. no log transform was applied) because the delta transformation tends to inflate the survey variances and were sensitive to treatment of tows with no catch. Also, the previous exploitation index based on the ratio of landings to the fall delta survey biomass was also updated to include discards to better characterize removals from the commercial catch (landings + discards) relative to the fall survey biomass. Since discards are reliably estimated since 1989, relative exploitation index is now defined as the ratio of the commercial total catch to the arithmetic fall biomass survey (Table 60, Figure A68-69). It is noted that historical discarding, particularly in the Distant Water Fleet, has likely been very small. Therefore, comparison of relative exploitation index based on catch/biomass with reference points based on landings over biomass is justified.

Revised Assessment Method

An Index Method (AIM)

The AIM model is a simple approach for examining the relationship between survey data and catch in data poor stock assessments. AIM is designed to address the question of whether a given rate of fishing mortality is likely to increase or decrease the population size. Survey data are used to define a relative rate of increase and the ratio of catch to survey indices provides a measure of relative fishing mortality. Theoretically the model can identify a stable point about which the stock will neither increase nor decrease in response to a fixed harvest rate. The model assumes that the resource dynamics are approximately linear with relatively minor influence of density dependent effects or variable environmental or ecological factors. Such conditions often typify stocks that have been historically harvested at high fishing rates and are therefore at low population sizes. AIM is both an analytic and graphing approach. The analytical methods can be used to define relative Fs for replacement and the graphical methods can be used to identify transient conditions that are relevant to implementation of any model. The details of the methodology are described below.

- ✓ Population biomass at time t can be written as a linear combination of historical population biomasses
- ✓ Recruitment is proportional to population biomass
- ✓ Fishing mortality is proportional to catch divided by an index of population size (relative F).
- ✓ The rate of change in population biomass is a monotonically decreasing function of relative F.
- ✓ Smoothing methods can be used to identify underlying trends.
- ✓ Randomization methods can be used to develop sampling distributions of test statistics
- ✓ Graphical methods can help identify linkages among variables

Relative F is defined as the ratio of catch to an index of population abundance. A three-year centered average of the abundance index is chosen as the measure of average stock size.

$$relF_{j,s,t} = \left(\frac{C_{s,t}}{\frac{I_{j,s,t-1} + I_{j,s,t} + I_{j,s,t+1}}{3}} \right) \qquad (1)$$

Where $relF_{j,s,t}$ = relative F for relative index j for stock s at time t

$C_{s,t}$ = catch or landings of stock s at time t (in units of weight)
$I_{j,s,t}$= Index of abundance j for stock s at time t expressed in terms of average weight per tow

The population size at any given time can be viewed as a weighted sum of previous recruitment events. For a population with a maximum age of A years, the population in year t consists of the recruits from year t-1, t-2, …t-A. At high levels of total mortality, the contributions from the earliest recruitments, say t-k-1 to t-A will diminish in importance such that the population can be viewed as the sum of recruitments from t-1 to t-k years.

Using the linearity assumption defined above, we can employ basic life history theory to write abundance at time t as a function of the biomasses in previous time periods. The number of recruits at time t (R_t) is assumed to be proportional to the biomass at time t (B_t). More formally,

$$R_t = S_o \, Egg \; B_t \qquad (2)$$

where **Egg** is the number of eggs produced per unit of biomass, and $\mathbf{S_o}$ is the survival rate between the egg and recruit stages. Survival for recruited age groups at age a and time t ($S_{a,t}$) is defined as

$$S_{a,t} = e^{-F_{a,t} - M_{a,t}} \qquad (3)$$

where F and M refer to the instantaneous rates of fishing and natural mortality, respectively. We also need to consider the weight at age a and time t ($W_{a,t}$) and the average longevity (A) of the species.

Using these standard concepts we now write the biomass at time t as a linear combination of the A previous years. Without loss of generality, we can drop the subscripts on the survival terms and assume that average weight at age is invariant with respect to time. Further, set the product S_o Egg equal to the coefficient α. The biomass at time t can now be written as

$$B_t = R_{t-1} S^1 W_1 + R_{t-2} S^2 W_2 + R_{t-3} S^3 W_3 + .. + . R_{t-(A-1)} S^{A-1} W_{A-1} + R_{t-A} S^A W_A \quad (4)$$

Substituting Eq. (2) into Eq. (4) leads to

$$B_t = \alpha B_{t-1} S^1 W_1 + \alpha B_{t-2} S^2 W_2 + \alpha B_{t-3} S^3 W_3 + .. + .\alpha B_{t-(A-1)} S^{A-1} W_{A-1} + \alpha B_{t-A} S^A W_A \, (5)$$

If the population is replacing itself, then the left hand side of Eq. 5 will equal the right hand side. The replacement ratio can then be defined as

$$\Psi_t = \frac{B_t}{\alpha B_{t-1} S^1 W_1 + \alpha B_{t-2} S^2 W_2 + \alpha B_{t-3} S^3 W_3 + .. + .alphaB_{t-(A-1)} S^{A-1} W_{A-1} + \alpha B_{t-A} S^A W_A} \quad (6)$$

Substituting observed values of abundance indices into Eq 6 leads to

$$\Psi_t = \frac{\frac{I_t}{q}}{\alpha \frac{I_{t-1}}{q} S^1 W_1 + \alpha \frac{I_{t-2}}{q} S^2 W_2 + \alpha \frac{I_{t-3}}{q} S^3 W_3 + .. + \alpha \frac{I_{t-(A-1)}}{q} S^{A-1} W_{A-1} + \alpha \frac{I_{t-A}}{q} S^A W_A} \quad (7)$$

By noting that the q's cancel out, and letting $\varphi_j = \alpha S^j W_j$, Eq. 6 simplifies to

$$\Psi_t = \frac{I_t}{\sum_{j=1}^{A} \phi_j \quad I_{t-j}} \quad (8)$$

All of the I_t and φ_j are positive, and at equilibrium $I_t = I_{t+1}$ and $I_t = \sum \varphi_j I_{t-j}$ both hold. Therefore $\sum \varphi_j = 1$. When the population is not at equilibrium the parameter Ψ becomes a measure of the non equilibrium state of the population and a measure of whether the population is increasing or decreasing relative to prevailing fishery and ecosystem conditions.

It would be desirable to express the parameters of φ_j weighting terms as function of the underlying parameters. Analyses of other stocks with more detailed information, such as Georges Bank haddock, has suggested that setting the φ_j to 1/A is a reasonable approximation. Equations 2 to 8 are a long way of justifying that the ratio of current stock size to a moving average of the previous A years of stock size can be used as a measure of population growth rate. This ratio embeds some life history theory into the basis for the ratio and simultaneously provides a way of damping the variations in abundance owing to measurement error. A ratio defined as I_t/I_{t-1} has been found, as expected to be much more noisy measure of population change.
Further details on the AIM methodology may be found in Working Group (2002) and the NOAA Fisheries Toolbox (NFT) 3.1 (2010a) software package http://nft.nefsc.noaa.gov/AIM.html. The relationship between $\mathbf{\Psi_t}$ and $\mathbf{relF_t}$ can be expressed as

$$\ln(\Psi_t) = a + b\ln(relF_t) \quad (9)$$

The usual tests of statistical significance do not apply for the model described in Eq. 9. The relation between $\mathbf{\Psi_t}$ and $\mathbf{relF_t}$ is of the general form of Y/X vs X where X and Y are random variables. The expected correlation between Y/X and X is less than zero and is the basis for the oft stated criticism of spurious correlation. To test for spurious correlation we developed a sampling distribution of the correlation statistic using a randomization test. The randomization test is based on the null hypothesis that the catch and survey time series represent a random ordering of observations with no underlying association. The randomization test was developed as follows:

1. Create a random time series of length **T** of $\mathbf{C_{r,t}}$ from the set $\{\mathbf{C_t}\}$ and $\mathbf{I_{r,t}}$ from the set $\{\mathbf{I_t}\}$ by sampling with replacement.

2. Compute a random time series of relative F ($\mathbf{relF_{r,t}}$) and replacement ratios ($\mathbf{\Psi_{r,t}}$)
3. Compute the r-th correlation coefficient; say $\boldsymbol{\rho_r}$ between ln($\mathbf{relF_{r,t}}$) and ln($\mathbf{\Psi_{r,t}}$).
4. Repeat steps 1 to 3 K times.
5. Compare the observed correlation coefficient $\mathbf{r_{obs}}$ with the sorted set of $\boldsymbol{\rho_r}$
6. The approximate significance level of the observed correlation coefficient $\mathbf{r_{obs}}$ is the fraction of values of $\boldsymbol{\rho_r}$ less than $\mathbf{r_{obs}}$

It should be emphasized that relF is not necessarily an adequate proxy for Fmsy, since this parameter only estimates the average mortality rate at which the stock was capable of replacing itself. Thus, while relF defined as average replacement fishing mortality is a necessary condition for an F_{msy} proxy, it is not sufficient, since the stock could theoretically be brought to the stable point under an infinite array of biomass states. The relF at replacement does however provide some guidance on the contemporary rate of harvesting and its potential impact on future stock abundance.

Application of AIM to Silver Hake

AIM was applied to the combined stock of silver hake using catches and the NEFSC fall and spring bottom trawl survey indices (Table A61). Relative F was defined as the ratio of catch to a centered 3-year average of survey abundance (Eq. 1) and the replacement ratio was defined as a 5-year moving average of previous stock sizes (Eq. 8). The relationship between catch, survey, relative F and the replacement ratio for the fall and spring survey indices are depicted in Figures A70 and A71, respectively. Neither of the randomization tests resulted in significant statistical relationship between the replacement ratio and relative F (Table A61). Bootstrap estimation of the relative F at replacement were imprecise (Table A62, Figure A72) and are not appropriate measures of Fmsy proxies. Graphical results suggest some underlying causes for the absence of a strong statistical relationship. Relative F has been declining continuously for both the fall (Figure A70) and spring (Figure A71) survey indices but the population indices do not suggest any significant rate of change over time. The relationship between replacement ratio is barely negative despite a nearly 60-fold range in catches and a 27-fold range in relative F. The relationship between relative F and survey abundance is instructive (the left center plot in Figures A70-A71). It suggest three temporal stanzas in which the population abundance has declined by comparable amounts from about 8 to 3 kg/tow, when relative F has varied by 30,000 to 70,000 mt/kg/tow between 1968 and 1977 and when relative F varied from 5,000 to 15,000 mt/kg/tow between 1978 and 2000. In the third stanza, from 2001 to 2009 the surveys have fluctuated from 4.0 kg/tow to about 1kg/tow even though relative F has not exceeded 7108 mt/kg/tow for the fall survey and 12,099 mt/kg/tow in the spring survey. At a minimum these stanzas suggest major changes in the population abundance indices and exploitation rates. It is not possible from these data alone to identify causal factors but it does suggest that more advanced modeling will need to account for these changes in apparent productivity and/or natural mortality.

Age Structure Assessment Program (ASAP)

> **[SAW51 Editor's Note: The SARC-51 peer review panel concluded that no single silver hake ASAP model run provided a suitable basis for providing management advice. The silver hake ASAP model and results, which are described here and in Appendices A2-A6, are included in this report mainly to document the ASAP modeling runs that the Hake Working Group provided to the SARC for peer review.]**

Silver hake has been assessed based on survey index of relative exploitation and the 3 year moving average from the survey biomass since 1994(NEFSC 2006). Given some of the changes that have occurred in the fishery (gear, selectivity, targeting, and management), and the change to a new survey vessel (for which a calibration cannot be estimated), the importance of age structure (maturity and growth), and the limited projection capability of the index method, alternative assessment methods were considered for this benchmark. The new assessment model is ASAP (Age Structured Assessment Program v2.0.20, Legault and Restrepo 1998), which can be obtained from the NOAA Fisheries Toolbox (http://nft.nefsc.noaa.gov/). As described at the NFT software website, ASAP is an age-structured model that uses forward computations assuming separability of fishing mortality into year and age components to estimate population sizes given observed catches, catch-at-age, and indices of abundance. Discards can be treated explicitly. The separability assumption is partially relaxed by allowing for fleet-specific computations and by allowing the selectivity at age to change in blocks of years. Weights are input for different components of the objective function which allows for configurations ranging from relatively simple age-structured production models to fully parameterized statistical catch at age models.

The objective function is the sum of the negative log-likelihood of the fit to various model components. Catch at age and survey age composition are modeled assuming a multinomial distribution, while most other model components are assumed to have lognormal error. Specifically, lognormal error is assumed for: total catch in weight by fleet, survey indices, stock recruit relationship, and annual deviations in fishing mortality. Recruitment deviations are also assumed to follow a lognormal distribution, with annual deviations estimated as a bounded vector to force them to sum to zero (this centers the predictions on the expected stock recruit relationship). For more technical details, the reader is referred to the technical manual (Legault 2008).

Model Formulations
The assessment model formulations were structured to consider sensitivity to a number of model inputs. To deal with stock structure, separate North and South stock assessments were considered as well as a single combined stock treatment. These models will subsequently be referred to as North, South, and Combined for brevity. Natural mortality was thought to have a large component due to predation. This was dealt with explicitly by including estimates of consumption in the model as a separate "fishery" fleet (referred to as Consumption model hereafter), or implicitly by considering a single value for natural mortality (referred to as the No-Consumption model hereafter). In the Consumption model formulation, a value of M=0.15 was specified for all ages and all years to comprise all sources of natural mortality *other than* consumption. In the No-Consumption model, a single value of M=0.4 was specified for all ages and all years. The value of M=0.4 was justified by consideration of a maximum observed age of 14. Given M=0.4, the expected cumulative survival to age 14 would be about 0.5%.

Model Inputs
All models considered included catch by a directed fleet beginning in year 1973. Although total landings estimates exist before 1973, there was no age composition, and initial modeling suggested poor identifiability of initial conditions when the model runs started earlier than 1973. All models considered also included estimated discards beginning in 1981. Structurally, discards were included as a separate "fleet" in the model. Treating discards as a separate fleet allowed more flexibility for including total discards in 1981-1988 without any corresponding age composition in addition to years 1989 where estimates of total discards and age composition are both available. These two fleets were the only removals that were modeled for the No Consumption models. For the Consumption models, an additional fleet was modeled to represent removals from predation. The estimated mortality from the "fleet" of predators was then considered to be an additional source of natural mortality (generally termed "M2"). Estimates of total annual natural mortality at age from the Consumption models was then calculated as 0.15+M2 (age, year), and cumulative survival to age 14 could then be compared to the M=0.4 model.

All models included the NEFSC spring and fall bottom trawl surveys. Minimum swept area abundances, annual estimated CV, as well as the age composition for each survey were used in the model.

The model assumed a plus group at age 6. Initial model model runs dealt with the stock as a single unit (Combined runs). An exhausting, albeit not exhaustive, number of model specifications were explored for the Combined run. Exploratory runs examined model sensitivity to estimating a stock recruit function versus estimating an average recruitment with annual deviations; estimating age-specific selectivity for the surveys versus forcing the survey to have a flat-topped selectivity; “breaking” the survey time series into two separate series or maintaining a continuous time series; and adding or removing selectivity “blocks” to the directed and bycatch fleets. In considering these various model iterations, diagnostics were examined to determine if the fit improved. Specifically, the pattern of residuals in age composition for catch and indices, residuals in the fit to total catch and annual index values, components of the objective function in addition to total objective function and number of estimated parameters, as well as the “believability” of the estimated selectivity patterns. With regard to the last criterion (“believability” of estimated selectivity), this was somewhat subjective, however the models tended towards solutions with sharply domed selectivities for both the directed fleet and the surveys (it was also sharply domed for the discard fleet, but that was a sensible result). As there was nothing biological to suggest that fish at ages 5 and beyond would have very low catchability (i.e., no known behavioral aspects, no strong swimming capabilities), nothing gear related that would suggest lower catchability (no outswimming otter trawls, no other known gear interactions), and no known market conditions that would favor smaller fish, the group found it hard to reconcile selectivities of 0.10 on the 6+ group, when fish in the plus group had been estimated in the catch age composition early in the time series.

Model Results—Combined model

Model formulations for both the Consumption and No Consumption model were run in tandem. Although objective function values were not directly comparable between these two model treatments, owing to differences in the underlying data, residual diagnostics, overall fits, and retrospective patterns were compared. After much deliberation, the group agreed to the following base configuration: Consumption model that did not split the survey indices and forced a selectivity=1 for ages 2 and older; two selectivity blocks for the directed fleet (the break occurred between 1988 and 1989) and one single selectivity block for the bycatch fleet. With all models considered, there was a strong correlation between the selectivity estimated for the directed fleet and the selectivity of the surveys. Forcing the flat-top for the survey indices caused the selectivity estimates for the directed fleet to also be flat-topped. For this selectivity pattern, the age composition residuals were acceptable, although the residuals from fits to the total catch and overall index values showed strong time trends. This was a fairly consistent trade-off seen in many of the model diagnostics, wherein improvements in the fit to age composition data were accompanied by a deteriorated fit to the total data (either total catch or total index values). Thus, selecting the ‘best’ model depended to some extent on the amount of confidence that one had in the age composition data relative to the data streams of total catch and the indices. Complete model diagnostics can be found in the **Appendix A2**. (“Base_model_diagnostics_Consumption_Flat-top Survey”).

Retrospective pattern of Base Combined model

A retrospective analysis on the base model using a seven year peel was conducted to examine the stability of the model estimates for fishing mortality, recruitment and spawning stock biomass. Due to the change in selectivity block beginning in 1989, it was difficult to interpret the earliest peels because there was an imbalance in the number of parameters being estimated versus number of years with additional data. However, it was noted that the Consumption models had the lowest retrospective bias (Figures A73-A74, Table A63).

Sensitivity analyses to Base Combined model

For completeness, sensitivity to the model decisions adopted in the base model are summarized in Table A63 and in Figures A75-A77. Eight additional runs are described in this table. Only one run for the No Consumption model is described. While this model offered good diagnostics, and good retrospective analysis results, two of the parameters for selectivity at age were estimated at the upper bound of 1.0. When those parameters were subsequently fixed at 1.0, instead of attempting to estimate them, no hessian was obtained for the model. Because of this instability, the model was not explored further. As an intermediate to the Consumption and No Consumption runs, a model was explored where the natural mortality at age was calculated as 0.15 + $M2_{age,year}$. This model is directly comparable to the No Consumption model as it has exactly the same data, the only difference being the fixed value specified for $M_{age,year}$. Compared to the model with M=0.4 for all years and all ages, the total objective function was 71 points greater, and therefore did not provide a better fit to the data.

The remaining six sensitivity runs were all Consumption models with different numbers of selectivity blocks for the directed and bycatch fleet, and with survey selectivity at age estimated or fixed for ages 2 and older. Model diagnostics and the objective function value favored models that had 2 selectivity blocks for the directed fleet (with the break in 1988/1989) and one selectivity block for the bycatch fleet over the alternatives of 1 selectivity block for each, or 3 selectivity blocks for the directed fleet and 2 selectivity blocks for the bycatch fleet. The motivation for introducing selectivity blocks, and the year that they were introduced, was an attempt to account for changes in the fishery composition (disappearance of foreign fleets) and pertinent regulations (mesh size and trip limits). After the number of selectivity blocks was decided, comparisons were made between a flat-topped survey selectivity (the proposed base model) and a formulation that estimated selectivity at age for the surveys (with only age 2 selectivity fixed at 1.0). The overall objective function for the base model was 4526, while for the model that estimated survey selectivity it was 4491. Thus, the model that estimated survey selectivity improved the objective function by 35 at the cost of adding 8 parameters to the model. And, as mentioned previously, there is the trade-off between fitting age composition data or fitting the total data series better. The other comparison between these two models is the retrospective diagnostics: the Combined base model had relative biases ranging from 26-41% while the sensitivity model that estimated survey selectivity at age had relative biases ranging from 32-62%. Finally, when estimating survey selectivity at age, the model estimated very steep domes with <10% selectivity in the plus group for the directed fleet and both surveys. These two models were considered the best contenders of the models explored, and the working group selected the base model (described above) based on the disbelief of such severe domes and the better retrospective diagnostics.

In general, the No Consumption models had lower retrospective analysis diagnostics compared to the Consumption models. Within the Consumption models, decreasing the selectivity blocks improved the retrospective diagnostics while enforcing a flat-top selectivity worsened the retrospective diagnostics (Table A63).

The intensive examination of model formulations was first explored for the Combined runs, as the likelihood of 'stock' mixing was thought to be high. If stock mixing were occurring, it would result in catch being attributed disproportionately among stocks, and the potential for the survey indices to be more reflective of the seasonal magnitude of mixing rather than any particular stocks' trend in abundance. This was the motivation for the group spending nearly all of the available time on the Combined models. In order to address the terms of reference to explore sensitivity to assumptions of stock structure, some North and South models were explored, but they were simple sensitivities on the structure that had been selected as the base model for the Combined model.

Silver Hake ASAP Results
Attempts were made to assess silver hake by separating the northern and southern data. However, none of the runs examined had assessment diagnostics which were deemed suitable. The working group recommended a combined analysis of data from both areas, meaning a single stock, as the best performing model, but this was ultimately not accepted by the SARC-51 Review Panel as a basis for management advice. Issues encountered in the northern and southern stock assessments are briefly described below, followed by a more detailed description of the recommended model formulation assuming a single stock.

Northern Silver Hake
Four runs were examined for the northern silver hake data. Two of the runs included consumption data while the others did not. Of the set of runs which included consumption forced a flat-topped selectivity patterns in the survey indices while the other allowed domed selectivity. The same selectivity patterns were also assumed for the runs without consumption. All four runs assumed time invariant selectivity patterns for each fleet and assumed recruitment deviations occurred relative to a constant mean, as opposed to being relative to a stock-recruitment relationship (Appendices A3-A6).

The run which did not include consumption estimates set natural mortality to 0.4 for all years and ages. The predicted commercial landings are well below the observed values at the start of the time series when the foreign fleets were operating, but then well above the observed values near the end of the time series. These are large deviations in both absolute and relative terms and are a strong indication that the model is not fitting the data well. However, when a domed selectivity is allowed, the fit the landings show an improvement in the absolute and relative magnitude of the residuals. The fit to the discards also exhibits a pattern of underestimating the observed values early in the time series and overestimating them recently. However, these deviations are small in both absolute and relative terms and so are less of a concern. The opposite is true early in the time series when domed selectivity is allowed in the survey with a good fit to the time series in the recent years. The landings and discards at age both have patterns in the residuals, especially at ages one and two. The input effective sample size appears to be a bit high for the commercial landings, where only approximately 20% of the output effective sample sizes are greater than the input values. The input and output effective sample sizes for the discards are better matched. Neither of the survey indices are fit well, with patterns in the residuals and large magnitudes for the standardized residuals, but to a lesser degree when domed selectivity is allowed in the survey. The observed magnitude and patterning of the residuals is an indication that the input CV for the surveys is too small relative to the ability to fit the indices. The age composition for both indices is not fit well, with long periods of the same sign of residuals for ages one and two especially. The input effective sample sizes for both indices are too high relative to the output effective sample sizes. The catchability coefficients for both indices are above one, indicating that the estimated population is smaller than the minimum swept area biomass estimated from the surveys. This can occur if the assumed swept area of a tow is too small, for example due to herding of fish, but is generally an indication that there may be a problem in the run. In contrast, when domed selectivity is allowed the catchabilities estimates were well below one which agrees with the very strong dome estimated in the survey with less than 5% of ages 5 and 6 selected in the survey. The implication of such selectivity pattern resulted in unrealistic estimate of spawning stock biomass reaching approximately 6million metric tons in the recent years and an expansion of age 6+ in the population which is contradictory to the both the fishery and the survey. Thus, these runs were not considered acceptable by the working group.

The two runs which did include consumption set the base natural mortality to 0.15 and then entered the consumption time series as an additional fleet. The main difference between these two runs is the selectivity pattern for the two indices where the run which allowed a dome did in fact estimate a strong dome for both indices. However, qualitatively the results from the two runs were still quite similar and are described together here. These runs fit the commercial landings and discards much better than the runs which did not include consumption. The fit to the consumption time series was not fit as well and the landing or discards. The absolute magnitude of the lack of fit to the consumption time series is quite high, but the relatively small standardized deviations indicate that the uncertainty in the consumption values is being appropriately modeled. The age composition for the commercial landings and discards still exhibit patterns in the residuals, especially at ages one and two. There are no age composition residuals for the consumption fleet, meaning that the selectivity patterns should not be estimated. However, the two runs did in fact estimate selectivity patterns based on a double logistic form. These parameters could be estimated because priors were set on the values. However, the resulting selectivity patterns do not make intuitive sense with low selectivity at age one, the age which typically has the highest consumption selectivity. The input effective sample size for the commercial landings is slightly high relative to the output effective sample size, but more closely matched for the commercial discards. The survey indices are fit better than the runs without consumption in terms of there not being a strong pattern in the residuals. However, the magnitude of the standardized residuals is still quite large, indicating that the input CV for the indices is too small relative to how closely the indices can be modeled. The age composition for index 1 is fit reasonably well while index two shows patterns in the residuals for ages one and two. The input effective sample size for both the indices is too high relative to the output effective sample size. The catchability coefficients are more reasonable than the runs without consumption, indicating a relative efficiency of the net around 0.5. The catch due to the consumption fleet appears to be quite small in five of the first six years in the time series, which is due to low sampling of predators during this time period instead of a true change in consumption. The mortality rate due to consumption is generally greater than one after the first six years in the time series, with some years above two. This high mortality contrasts with the fishing mortality rates of less than 0.3 for most years. Note that the plot showing the relative spawners (SSB/S0) is treating consumption as a mortality that is not included when computing S0, which it typically would be since it is a form of natural mortality. If this plot was made including consumption mortality as a natural mortality, then the relative spawners would be much closer to one than currently shown.

Southern Silver Hake Stock
For the southern region, similar model runs were conducted as in the northern region. However, the models in the south had convergence problem which is likely attributed to model mis-specification (i.e. inaccurate definition of stock boundaries). One possible hypothesis is that the model is having difficulties resolving the lack of coherence between the removals from the fishery and the trends in the survey due to possible migration patterns of silver hake to the northern region. The shift in the population density over time will then reflect seasonal distribution in the survey rather than stock specific trend of abundance as explained above.

Combined Silver Hake Stock
A number of the issues seen in the northern silver hake runs are also apparent in this combined run. Specifically, commercial landings are not fit well at the start of the time series, consumption landings are mostly underestimated, strong patterns are seen in the age composition residuals for all three fleets, the indices are not well fit in terms of either trends in residuals or the magnitude of the standardized residuals, strong patterns are seen in the age composition residuals for index, the relative spawners plot has the same issue as the northern silver hake assessment with consumption, and consumption in the early years appears low. The inclusion of age composition data for the consumption fleet is an improvement relative to the northern silver hake runs, as now there is information to estimate selectivity for this fleet. The estimated selectivity pattern for the consumption fleet is more traditional than the northern silver hake runs, with highest selectivity at age one and decreasing selectivity at older ages. This means that the effect of consumption will be mainly to increase recruitment to account for this additional mortality, but it will not have a large impact on the adult population. However, there is an indirect impact caused by this selectivity pattern because the base natural mortality is 0.15 compared to 0.4 when consumption is not included. Since there is essentially no consumption mortality at old ages, the net effect is to reduce natural mortality on the old fish, which means fishing mortality must be high to prevent old fish from appearing in the age composition.

Given the series of model exploration for North, South and the combined management area formulation, the working group recommended the Consumption model with 2 selectivity block in the directed fleet with a single selectivity in the bycatch fleet. However, this was not accepted by the SARC-51 Review Panel as a basis for management advice.

Fishing Mortality
Fishing mortality on ages 3+ varied between 0.5 and 1.0 from 1973 to 1995 then increased and varied between 1.0 and 2.0 from 1996 to 2008. The fishing mortality rate in 2009 is estimated to be 0.77 (80% confidence interval 0.58 – 0.95). Note that the variance estimates include some consumption based mortality estimates. Given the very low mortality on older ages in the population, the influence of consumption on the variance is minimal to negligible (Appendix A2, Table A64).

Recruitment
Recruitment at age-1 was relatively low in the early part of the time series, which may be an artifact of consumption mortality being underestimated during this time period. Since then, recruitment has varied without trend between 400 million and 1.1 billion fish annually. The number of age-1 fish in 2009 is estimated to be 742 million fish (80% confidence interval 616 – 867 million fish (Appendix A2, Table A65).

Spawning Stock Biomass
Spawning stock biomass varied around 70 thousand mt during the early part of the time series, but this again could be an artifact due to the low consumption mortality during this time. Spawning stock biomass decreased to approximately 33 thousand mt in 1978 and slowly declined to 55 thousand mt in 2006, but has since increased. Spawning stock biomass in 2009 is estimated to be 23 thousand mt (80% confidence interval 19.5-26.8 thousand mt (Appendix A2, Table A65).

Natural Mortality
Estimate of Natural mortality (M1+M2) was highest and most variable for age-1 ranging between 0.2 and 1.5 from 1973-1995. Natural mortality declined substantially in 1997 by approximately 70% resulting in natural mortality estimate of 0.5. This was also when consumption was relatively low due to very low recruitment. The natural mortality rate in 2009 is estimated to be 1.2 (Appendix 2 and Table A66).

TOR 5. Evaluate the amount of silver hake consumed by other species as well as the amount due to cannibalism. Include estimates of uncertainty. Relate findings to the stock assessment model.

Food habits were evaluated for a wide range (14) of fish predators that eat silver hake and commonly occur in NEFSC bottom trawl surveys. The amount of food eaten and the type of food eaten were the primary food habits data examined. From these data, per capita consumption, total consumption of silver hake, and an estimate of the amount of silver hake removed by these fish predators were calculated. Combined with abundance estimates of these predators, an amount of silver hake removed by these predators was then calculated. Consumption estimates of silver hake were presented as an estimate that is biased towards conservative values because consumption by birds, marine mammals, large pelagic fish and organisms outside of the survey area were not included. Moreover, swept-area biomass estimates for many of predators were based on bottom trawl survey data (without adjustments for bottom trawl catchability), although stock assessment results were used for some predators, such that predator abundance estimates and associated silver hake consumption would be mostly underestimates as well.

Methods

Every predator that contained silver hake was identified from the NEFSC FHDBS. From that original list, a subset of predators (Table A67) was examined to elucidate which predators consistently ate silver hake, determined by "rules of thumb" that include having a diet composition of >1% for any five year block, and with >5tows for each two year block and > 10 stomachs for each three year block.

Annual consumption estimates were calculated on a seasonal basis (two 6 month periods) based on spring and fall bottom trawl surveys and for each predator species. Although the food habits data collections started quantitatively in 1973, not all species of silver hake predators were sampled during the full extent of this sampling program, thus we start our time series here in 1977 (Link and Almeida (2000). This sampling program was a part of the NEFSC bottom trawl survey program (Azarovitz 1981; NEFC 1988). There are various ways to integrate seasonally, but we took the simple sum of the two seasonal estimates in this analysis. We have also done the analyses for various size classes of predators in other instances, but here we have integrated across all predator size classes to come up with a total consumption of silver hake for each predator.

This approach followed previously established and described methods for estimating consumption, using an evacuation rate model methodology. For further details, see Durbin et al. (1983), Ursin et al. (1985), Pennington (1985), Overholtz et al. (1991, 1999, 2000, 2008), Tsou & Collie (2001a, 2001b), Link & Garrison (2002), Link et al. (2006, 2008, 2009), Methratta & Link (2006), Link & Sosebee (2008), Overholtz & Link (2007, 2009), Tyrrell et al. (2007, 2008), Link and Idoine (2009), Moustahfid et al. (2009a, 2009b), and NEFSC (e.g., 2006, 2007a, 2007b, 2008, 2010a, 2010b). The main data inputs are mean stomach contents (S_i) for each silver hake predator i, diet composition (D_{ij}) where the subscript j refers to silver hake as a prey item, and T is the bottom temperature taken from the bottom trawl surveys (Taylor et al. 2005). Units for stomach estimates are in g. We note that we estimated S and D for two-year time blocks to ensure data-density sufficiency for all predators in both seasons and for both stocks; temperature (T) was estimated annually for both seasons and both stock areas.

As noted, to estimate per capita consumption, the gastric evacuation rate method was used (Eggers 1977, Elliott and Persson 1978). There has been copious experience in this region using these models (see references listed above). The two main parameters, α and β, were set to 0.004 and 0.115 respectively based upon prior studies and sensitivity analyses (NEFSC 2007a, 2007b). The exception is that α was set to 0.002 for elasmobranch predators consistent with and to reflect their slightly lower metabolism than teleost fishes.

Using the evacuation rate model to calculate consumption requires two variables and two parameters. The per capita consumption rate, C_{it} is calculated as:

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

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

$$E_{it} = \alpha e^{\beta T} \qquad ;$$

and is formulated such that estimates of mean stomach contents (S_{it}) and ambient temperature (T; here used as bottom temperature from the NEFSC bottom trawl surveys for either season (Taylor & Bascuñán 2000, Taylor et al. 2005)) are the only data required. This was done for each predator i (species) for each time period t (season and year). The parameters α and β are set as values chosen noted above. The parameter γ is a shape function is almost always set to 1 (Gerking 1994).

Once daily per capita consumption rates were estimated for each silver hake predator, those estimates were then scaled up to a seasonal estimate. This was done by multiplying the number days in each half year, which were then multiplied by the diet composition D_{ij} that was silver hake, to estimate the seasonal per capita consumption of silver hake. That is, once per capita consumption rates were estimated for each silver hake predator in a temporal period (t), those estimates were then scaled up to a seasonal estimate ($C'_{it} = C_{fall}$ or C_{spr}) by multiplying the number days in each half year:

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

These were then multiplied by the diet composition D_{ijt} that was silver hake, to estimate the seasonal per capita consumption of this fish C_{ijt}:

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

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

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

Once these were summed to provide an annual estimate (or the following could be done seasonally and the summed), they were then scaled by the total stock abundance of each predator to estimate the amount of silver hake removed by any of the predators included in the study. We used a swept area estimate of abundance from bottom trawl survey estimates for most predators and recent stock assessment estimates for five of the fourteen (Table A57). Those predators that had stock assessment values were used directly. These consumption estimates were then scaled by the total stock abundance to estimate a total amount of silver hake (j) removed by any predator i, C_{ij}:

$$C_{ij} = C'_{ij} \cdot N_i \qquad ,$$

where N_i is the estimate of abundance for each predator for each year.

We note that there are several ways to combine variance estimators in these consumption approaches. Estimates of variance for each variable and data type were calculated, namely about *S*, *DC*, and *N*. Further particulars of these estimators for the stomach contents and diet composition can be found in Link and Almeida (2000). There are three main ways to present variance about the estimates of consumption. One is to calculate a triple variance estimator that scales to the mean of each parameter (*S*, *DC*, and *N*). Another is to evaluate the maximal CV across all three parameters, across both seasons, and across all species of predator and then carry the largest value for each annual estimate of consumption. Finally, since from prior studies we know that the largest source of variance is associated with the estimates of abundance (scaled to the number), one can take the maximal CV across all predators and seasons for abundance and use that as a proxy for the variance about the consumption estimate. Here we adopted a modification of the third option, using the maximal CVs (associated with abundance estimates) and adopted mild adjustments for D_{ij} and S_i on a percentage basis (again, those CVs and means usually are minimized by the scale of the abundance means). The maximum from all predator sets were then used to portray variance for the total amount of silver hake consumed by these fishes. These range from 0.1 to 1.0 and in practice most were on the order of 0.35-0.50.

These predator species-specific consumptions were then summed across all *i* predators to estimate a total amount of silver hake removed by the predators included in this study. Upon further inspection by season, stock area, and predator species, it was determined that pollock *DC* were excessively variable, resulting in some notably anomalous and indefensible outputs; thus we removed pollock as a predator from the final estimates of consumption. Thus, these C_{ij} were then summed across all *i* predators (excluding pollock) to obtain an estimate a total amount of silver hake removed by these silver hake predators, C_j:

$$C_j = \sum_i C_{ij} \quad .$$

We show both the total consumption, total by species, and total by stock area. We also contrast these estimates with silver hake landings to provide a sense of contrast and magnitude. We also present these consumption estimates as 3 year moving averages to smooth the high degree of inter-annual variability common for these food habits data.

Sizes of silver hake in predators were also calculated as proportions by length in 5 cm bins for each year (combined across predators) across the time series. These can be used to inform the allocation of consumption to those size classes of fish overlapping with the fishery (or survey estimates). In this assessment, the consumption estimates were rescaled to conform with the current model formulation (i.e. age 1-6+). Survey age length keys were used to derive the proportion at length for Age-0 to adjust the consumption at length for each year. This makes the assumption that the survey length distribution within a given age is similar to consumption. For simplicity purposes, a constant probability was used based on an aggregated age-length key across seasons and geographical areas for the combined assessment. Table A68 summarizes the probability used in the analyses. On average, this resulted in a 40% decrease from the original consumption estimates (Figure A78).

Total consumption was modeled as a separate fleet in the Age Structured Assessment Program (Legault, 2008) to provide estimate of natural mortality based consumption (M2). Detail on the model structure and assumption regarding natural mortality and selectivity are provided in TOR4.

Results

Total consumptive removals by all consistent silver hake predators, using swept area abundance estimates of the predators, has varied through time ranging between peaking at 4,000 mt in 1975 and peaking at 165,000mt in 1985. This was followed by a brief decline during the early to mid 1990s and increased substantially in 1999 to approximately 135,000 mt. In the last decade, consumption has declined and averaged approximately 70,000 mt in the last five years (Figure A79, Table A69).

Spatially the consumption was approximately equally distributed between the northern and southern stocks (Figure A80), with higher peak values observed in the northern stock.

Although the consumption of silver hake occurred in thirteen predators, the majority of the consumption was attributable to goosefish (Figures A81-A82). For predators with swept area estimated abundance, these were generally lower than those stocks with abundance estimates obtained from stock assessments (summer flounder, goosefish, bluefish, cod), but were dominated by spiny dogfish (Figure A81-A82). These findings were consistent for both the northern and southern stocks combined (Figure A81)

The size of most of the silver hake consumed was <20 cm (Figure A83), yet some large fishes were also eaten. Over 50% of the silver hake eaten in most years were < 15 cm. We note that this loosely corresponds to the age 0 size class. The proportions also varied by size over the years (Table A70, Figure A81).

These estimates of silver hake consumed by the consistent fish predators in this study were compared to total catch (Figures A79-A80). Silver hake catches and consumption estimates were distinct for much of the time series, with landings higher earlier in the time series (1970s), but with consumption the dominant source of removal since the 1980s. Given this caveat, we note that consumption is approximately 10 times higher than catch in the 2000s.

TOR 6. State the existing stock status definitions for "overfished" and "overfishing". Then update or redefine biological reference points (BRPs; estimates or proxies for BMSY, BTHRESHOLD, and FMSY; and estimates of their uncertainty). If analytic model-based estimates are unavailable, consider recommending alternative measurable proxies for BRPs. Comment on the scientific adequacy of existing BRPs and the "new" (i.e., updated, redefined, or alternative) BRPs.

Existing Reference Points

The northern silver hake stock overfishing definition (NEFMC 2003) uses a relative exploitation index (total landings divided by NEFSC autumn survey biomass index) as a proxy for fishing mortality. The northern stock is considered ***overfished*** *when the 3-year average biomass is less than ½ the B_{MSY} proxy (B_{MSY} proxy = 6.63 kg/tow).* ***Overfishing*** *occurs when the 3-year average exploitation index is greater than 2.57, the F_{MSY} proxy (the average exploitation index during 1973-1982), and is used as both a target and threshold value for fishing mortality for the northern stock (NEFSC 2006)*

The southern silver hake stock is considered to be ***overfished*** *when the three-year moving average of the NMFS autumn survey weight per tow index is less than half of the B_{MSY} proxy (B_{MSY} proxy = 1.78 kg/tow) (NEFMC 2003).* ***Overfishing*** *is considered to be occurring in the silver hake southern stock when the exploitation index (landings divided by the three-year moving average of the delta-distributed fall survey biomass index) exceeds the F_{MSY} threshold proxy of 34.39 (NEFMC 2002).*

There are currently no BRPs for a combined (i.e., north + south) stock.

New Reference Points

In the absence of an agreed ASAP model run, the newly accepted reference points (in kg/tow in Albatross units) for both the northern and southern silver hake stocks are as follows:

> *Silver hake is overfished when the three-year moving average of the fall survey weight per tow (i.e. the biomass threshold) is less than one half the B_{MSY} proxy, where the B_{MSY} proxy is defined as the average observed from 1973-1982. The most recent estimates of the biomass thresholds are 3.21 kg/tow for the northern stock and 0.83 kg/tow for the southern stock.*
>
> *Overfishing occurs when the ratio between the catch and the arithmetic fall survey biomass index from the most recent three years exceeds the overfishing threshold. The most recent estimates of the overfishing threshold, are 2.78 kt/kg for the northern stock and 34.19 kt/kg for the southern stock of silver hake.*

Overfishing threshold estimates were based on annual exploitation ratios (catch divided by arithmetic fall survey biomass) averaged from 1973-1982. Catch per tow is in "Albatross" units.

TOR7. Evaluate stock status (overfished and overfishing) with respect to the existing BRPs, as well as with respect to the "new" BRPs (from Silver hake TOR 6).

Based on the biological reference points in the existing FMP, the northern stock of silver hake is not overfished and overfishing is not occurring. The three year delta mean biomass index (Figure A66), based on NEFSC fall bottom trawl survey data for 2007-2009 (6.79 kg/tow), was above the management threshold level (3.31 kg/tow) and slightly above the target level (6.63 kg/tow). The three year average exploitation index (landings divided by biomass index, Figure A66) for 2007-2009 (0.15) was below the single management threshold/target (2.57).

Similarly, based on the existing BRPs the southern stock of silver hake is not overfished and overfishing is not occurring. The three year delta mean biomass index (Figure A67) based on NEFSC fall bottom trawl survey data for 2007-2009 (1.39 kg/tow) was above the management threshold level (0.89 kg/tow) but below the target level (1.78 kg/tow). The three year average exploitation index (Figure A67) for 2007-2009 (4.33) was below both the management threshold (34.39) and the management target level (20.63).

Based on new biological reference points from SARC 51, the northern stock of silver hake is not overfished and overfishing is not occurring. The three year arithmetic mean biomass index (Figure A68), based on NEFSC fall bottom trawl survey data in Albatross units for 2007-2009 (6.20 kg/tow), was above the management threshold (3.21 kg/tow) and below the target (6.42 kg/tow). The three year average exploitation index (catch divided by biomass index, Figure A68) for 2007-2009 (0.20 kt/kg) was below the overfishing threshold (2.78 kt/kg).

Based on new biological reference points from SARC 51, the southern stock of silver hake is not overfished and overfishing is not occurring. The three year arithmetic mean biomass index (Figure A69), based on NEFSC fall bottom trawl survey data in Albatross units for 2007-2009 (1.11 kg/tow), was above the management threshold (0.83 kg/tow) and below the target (1.65 kg/tow). The three year average exploitation index (catch divided by biomass index, Figure A69) for 2007-2009 (5.87 kt/kg) was below the overfishing threshold (34.19 kt/kg).

TOR 8. 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; see Appendix to the TORs).

a. Provide numerical short-term projections (3 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 (e.g., terminal year abundance, variability in recruitment).

b. Comment on which projections seem most realistic, taking into consideration uncertainties in the assessment.

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

Stock projections were not carried out because the results from the ASAP model were not accepted for stock determination. However, with recent increases in stock biomass in the north, relatively stable biomass in the south and average recruitments in both areas, with low fishing mortality rates; qualitative analyses suggest that it is unlikely that the northern and southern stocks of silver hake will decline significantly in the short-term. Despite this assertion, uncertainties in the assessment exist due to the unknown cause of age truncation in the age-structure and the unknown magnitude of species mixing in the catch.

Summary

The population dynamics of silver hake in the northwest Atlantic have changed through time. In particular, patterns in growth and spatial distribution have changed substantially over the last 40years. Age structure, fish growth and spatial distribution reflect stock productivity. The current age structure indicates very little rebuilding of age-6 and older has occurred. It is likely that the lack of rebuilding of the age structure may have resulted from the continued high fishing mortality rates following the cessation of the distant water fleet.

Survey trends indicate that biomass in the northern area is high and low for the southern stock area. The incoherence of the survey trends relative to the levels of removals in the southern area is likely due to movement and therefore the survey trend may reflect seasonal abundances rather that trends for the southern stock. Although the evidence for silver hake stock structure is equivocal, a combined area model formulation appears to be more robust and stable relative to the north-south split.

Silver hake population constitutes an important link in the food web. Estimates of consumption of silver hake is on the same order of magnitude as estimates of silver hake stock landings, but consistently higher than landings. This is true for the combined evaluation and for both stocks. Estimates of predatory removal of silver hake via consumption are likely conservative given nature of these consumption estimates. These consumption estimates should be useful to inform both the scaling of biomass estimates and the magnitude of mortalities for silver hake. These estimates are likely to be quite informative to the dynamics of silver hake, as they represent a major source of removals and internal dynamics (cannibalism) that is being accounted for.

Silver hake are cannibalistic. Over 870 occurrences occurred out of over 49,000 silver hake stomachs sampled and recorded in the Food Habits Database, or roughly 2% of every hake caught consumed hake. For perspective, another species thought to be highly cannibalistic, the goosefish (*Lophius americanus*), only had 0.1% incidence of cannibalism. On average, silver hake comprised 12% of the silver hake diet composition (by weight), a significant, consistent and important prey item. This poses some potential tautologies of estimating silver hake abundance to then estimate silver hake cannibalism, which in turn can inform assessment models to estimate silver hake abundance. To accommodate this, we used swept area abundance estimates for silver hake as a predator of silver hake to help scale the total silver hake consumed by silver hake. Cannibalism has implications for recruitment as well, and we are exploring alternative models of stock-recruit relationships to ascertain how much cannibalism can influence those dynamics.

The accepted catch and survey index-based BRPs do not incorporate age structure and do not provide any measures of uncertainty. No age-based analytical model formulations (ASAP) were accepted, nonetheless, the model results were informative. Based on the collective knowledge of the fishery and the surveys, the most likely model (Run 6) did provide indications of trend that were in agreement with the declining age 3+ spawning numbers from the autumn NEFSC survey. Status quo BRPs are not considered appropriate to set ABC. Recent catches have been considerably less than historical ones, however, 3+ numbers in the autumn surveys have been declining since the early 1990s under such catches possibly for reasons other than only fishing (Figures A86-A87).

Research to address fishery selectivity and stock composition (mixing of northern and southern components) and the extent of stock distribution is needed to reconcile the issues regarding selectivity in the current ASAP model formulation.

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

SAW1 (1985)

- Re-analysis of VPA incorporating new stock definitions is currently underway
- By-catch and discard of young silver hake in the shrimp fishery a potential source of significant juvenile mortality
- CPUE indices for southern-and northern stocks need to be reconstructed with different standard fleets
- Consistency of surveys and analytical assessments for tracking cohorts will be examined
- Predatory impact of silver hake is likely significant

SAW17 (1994)

- The subcommittee strongly recommends that the stock structure of this resource be closely examined in order to determine the most appropriate aggregation of landings at age and survey data.
- The subcommittee recommends that the survey series be evaluated to 1) determine appropriate strata sets to account for possible differences in distribution between years, 2) determine evidence of mixing between stocks, 3) determine effect of transformations (e.g., logarithmic or delta) in reducing the impact of unusually high tows.
- The subcommittee recommends that the adequacy of the statistical design of the sea sampling program for estimating discards of silver hake be evaluated. The subcommittee notes that this evaluation should be done across several species and that sampling designs need to reflect the priorities given to each species.
- Sea sampling is not yet substitutable for port sampling. Thus, port samples for length composition are essential to estimate landings at age. Since age-structures collected in the survey do not adequately cover commercially caught fish, the

subcommittee recommends that age structures be collected from either the port sampling or sea sampling programs.

- The subcommittee recommends that the spring and summer Canadian surveys be evaluated for use as tuning indices and as indicators of silver hake geographical distribution.
- The developing fishery for juvenile silver hake should be carefully monitored to establish whether it is targeting concentrations of small fish or sampling landing catches that otherwise would have been discarded. From a scientific basis it would be beneficial to take observers aboard that target silver hake, optimally when participating in an experimental fisheries program. This data collection effort is needed to accumulate catch statistics, measure the length composition of landings and discards, and provide adequate sea sampling to determine discard rate.
- There is a need for a market category designation and adequate sampling for small silver hake (<18cm) to properly quantify the magnitude of the landings of these juvenile fish.
- MARMAP data should be examined to gain information on egg and larval silver hake distribution with respect to aggregation of spawning adults.

SAW32 (2001) and SAW42 (2006)

- Develop survey information that covers the offshore range of the population.
- Conduct surveys of spawning aggregations on the southern flank of Georges Bank.
- Investigate bathymetric demography of population.
- Investigate spatial distribution, stock structure and movements of silver hake within Georges Bank, the Gulf of Maine, and the Scotian shelf in relation to physical oceanography.
- Quantify age-specific fecundity of silver hake.

New Research Recommendations (from data and model meetings)

- Studies to estimate discard mortality should be conducted.
- Investigate silver and offshore hake data in deepwater surveys (e.g., monkfish survey).
- Consider hydrographic information in conjunction with the larval indices. This is not currently available, but work is in progress to be able to back-calculate spawning areas.
- Information on consumption by more predators (including mammals, highly migratory species (HMS)) needs to be included.
- Examine diel (day/night) variation in consumption of hakes.
- Validation of the ageing method for silver hake via tagging, radiocarbon, or tetracyclin research needs to be conducted.
- More comprehensive analysis of silver hake stock structure based on DNA (expanded genetic analysis) needs to be conducted.

- Investigate stock identification questions for silver hake by using samples from Tom Helser and Bill Phoel.
- Take M matrix from consumption model and put into model without consumption.

Sources of Uncertainty

1. The mis-reporting of silver hake in thee landings as offshore hale and vice-versa introduces considerable uncertainty in removals. Landings of silver hake may be over-reported and landings of offshore hake may be under-reported.
2. Survey data indicate relatively large silver hake may move around Georges Bank from South stock area to the northern. Uncertainty about north-south movements of adult silver hake is important because of uncertainty about linkages between the northern and southern stock areas.
3. The decreasing trend in abundance of relatively old and larger individuals. These reductions have occurred despite normal growth patterns, low fishing mortality rates and relative high biomass. This possibility of increased natural mortality due to predation is likely which was explored in this assessment.
4. Consumption
    a. Minimum swept area estimates for some predator abundance does not account for q for all predators; these are likely lower estimates of predator abundance and thus these consumption estimates should be viewed as conservative estimates. Although stock assessment estimates of abundance were used for some predators, using a full range of abundance estimates from stock assessments for more predators would also likely increase the estimates noted here.
    b. Is the α too low compared to literature? These too may be somewhat conservative, but are within the range of those generally reported. Again, these should be viewed as conservative estimates.
    c. Some fish predators that did not consistently eat silver hake (e.g. pollock, some of the skates) were not included in the analysis.
    d. Also, these estimates did not include a wide range of other (non-fish) predators known to consume silver hake (e.g., seabirds, squids, marine mammals), nor did they include silver hake cannibalism, which is suspected to be significant. Collectively this relatively limited set of predators thus may result in these being fairly conservative estimates of overall predatory removals of silver hake.
    e. Spatio-temporal overlap considerations between predators and silver hake were assumed.
    f. The degree of tautology due to silver hake cannibalism (i.e. estimating consumption based upon silver hake abundance, to better estimate silver hake abundance) is worth noting and addressing in further detail at some point in the future.

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