C. RED HAKE STOCK ASSESSMENT FOR 2010

Executive Summary

Red hake, *Urophycis chuss*, is a demersal gadoid species distributed from the Gulf of St. Lawrence to North Carolina, and is most abundant from the western Gulf of Maine through Southern New England waters (Bigelow and Schroeder 1953). Red hake are separated into northern and southern stocks for management purposes. The northern stock is defined as the Gulf of Maine to Northern Georges Bank region, while the southern stock is defined as the Southern Georges Bank to Mid-Atlantic Bight region.

Nominal red hake commercial landings in the northern stock peaked at 15,000 mt in 1972 and 1973, followed by a sharp decline in 1977 corresponding to the departure of the distant water fleets. Landings then averaged 1000 mt from 1977-1994, but declined to average only 100 mt through 2009. In the southern stock, nominal landings peaked at over 100,000 mt in 1965 with a secondary peak of over 60,000 in 1972. Landings then averaged 2000 mt from 1977-1994, but declined to average 900 mt through 2009. Discards from the northern stock averaged 1300 mt in the early 1980s, declined to about 250 mt from 1995-2000 and have averaged 100 mt through 2009. Discards from the southern stock averaged 4000 mt in the 1980s, declined to about 1000 mt from 1995-2000 and have averaged 700 mt through 2009. Recreational landings were much more significant in the south with catch averaging 300 mt compared to less than 3 mt in the north through the time series.

Catch data are a major source of uncertainty for this stock assessment, because of potentially mixed reported landings with white hake and uncertain identification to species by observers. Therefore, a length-based model was developed to estimate the proportion of red hake caught from the total hake catch (red and white hake combined). The model estimates for the north were generally lower than the nominal and the large peak in landings in the 1970s is eliminated. The landings for the south were also lower but the trend was similar. The Hakes Working Group was not comfortable with the complete change in trend in the north, so nominal catch was used in the assessment.

For the northern stock, total biomass indices were derived for two time series. The fall survey shows an increase from 1970 through 2002 followed by a decline through 2005. The spring survey increases from 1970 through 1980, but declines through 1990, increases again through 2002 and then is consistent with the fall survey.For the southern stock, the spring survey increases from 1970 through 1980, but declines through 2005, with a slight increase through 2009.

Total consumptive removals by all consistent red hake predators, using swept area abundance estimates of the predators, were consistently around 5 thousand mt per year during the late 1970s to late 1990s; more recently these removals have averaged approximately 10 thousand mt in the 2000s. These minimum estimates of red hake consumed by the consistent fish predators in this study were compared to total catch. Catch and minimum swept area estimates of consumption were approximately equal for much of the time series, with landings a little higher earlier in the

time series (1970s), but with consumption the dominant source of removals more recently averaging more than five times higher than catch.

For the northern stock, exploitation indices were derived for two time series. The fall survey shows very high exploitation in the 1960s and early 1970s, followed by a drop to low values from 1977 through the rest of the time series. This coincides with the departure of the distant water fleet. The second time series for exploitation was derived using the spring survey and shows a similar trend.

There is only one time series for the southern stock and it is based on the spring survey. The same peak is evident in the 1960s-1970s followed by a decline. However, exploitation increased from the late 1970s through 2005, with a slight decline in 2002. Exploitation has declined since 2005.

Although some statistical catch at age models (SCALE and SS3) were attempted, the diagnostics were not adequate for stock status determination or fishery management. Therefore the assessment is based on An Index Method (AIM) analyses for the northern and southern stocks which use the catch and spring survey data from 1980-2009 and is the basis for proposed biological reference points.

Based on current biological reference points in the existing FMP, the northern stock of red hake is not overfished and overfishing is not occurring. The three year delta mean biomass index, based on NEFSC fall bottom trawl survey data for 2007-2009 (2.87 kg/tow), was above the management threshold level (1.6 kg/tow) and slightly below the target (3.1 kg/tow). The three year average exploitation index (landings divided by biomass index) for 2007-2009 (0.03) was below both the target (0.39) and the threshold (0.65).

Based on current biological reference points in the existing FMP, the southern stock of red hake is not overfished and overfishing is unknown. The three year delta individual mean weight index, based on NEFSC fall bottom trawl survey data for 2007-2009 (0.10 kg/individual), is below the management threshold (0.12 kg/individual) but the three year average recruitment index (5.95 num/tow) is above the threshold value (4.72 num/tow).

Based on new recommended biological reference points from SAW/SARC-51, the **northern** stock of red hake is not overfished and overfishing is not occurring. The three year arithmetic mean biomass index, based on NEFSC spring bottom trawl survey data in Albatross units for 2008-2010 (2.42 kg/tow), was above the proposed management threshold (1.27 kg/tow) and close to the target (2.53 kg/tow). The exploitation index (catch divided by biomass index) for 2009 (0.103 kt/kg) was below the threshold (0.163 kt/kg).

Based on new recommended biological reference points from SAW/SARC-51, the **southern** stock of red hake is not overfished and overfishing is not occurring. The three year arithmetic mean biomass index, based on NEFSC spring bottom trawl survey data in Albatross units for 2008-2010 (0.95 kg/tow), was above the proposed management threshold (0.51 kg/tow) and slightly below the target (1.02 kg/tow). The exploitation index (catch divided by biomass index) for 2009 (1.150 kt/kg) was below the threshold (3.038 kt/kg).

Stochastic projections were not performed for this assessment. However, applying the Relative F reference points to the three-year average biomass index allows catches of 394 mt in the north and 2897 mt in the south.

Terms of Reference

For each stock or combined,

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 that are being used in the assessment (e.g., regional indices of abundance, recruitment, state surveys, age-length data, etc.). Characterize the uncertainty in these sources of data.
3. Evaluate the validity of the current stock definition, and determine whether this should be changed. Take into account what is known about migration among stock areas.
4. Estimate measures of annual fishing mortality, recruitment and stock biomass (both total and spawning stock) for the time series, and characterize their uncertainty. Include a historical retrospective analysis to allow a comparison with previous assessment results.
5. State the existing stock status definitions for the terms "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.
6. Evaluate stock status (overfished and overfishing) with respect to the existing BRPs, as well as with respect to the "new" BRPs (from Red hake TOR 5).
7. 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.

8. 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.

Hake Working Group (HWG) Meetings

Three meetings were held in preparation of the 2010 red 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), (Loretta O'Brien, Paul Nitschke, Mark Terceiro, Jay Burnett, Chris Legault, 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.

Fishery Regulations

The following 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

Introduction

Red hake, *Urophycis chuss*, is a demersal gadoid species distributed from the Gulf of St. Lawrence to North Carolina, and is most abundant from the western Gulf of Maine through Southern New England waters. Red hake are separated into northern and southern stocks for management purposes. The northern stock is defined as the Gulf of Maine to Northern Georges Bank region, while the southern stock is defined as the Southern Georges Bank to Mid-Atlantic Bight region (Figure C1). Both red hake stocks were last assessed in the fall of 1990.

Red hake migrate seasonally, preferring temperatures between 5 and 12° C (41-54° F) (Grosslein and Azarovitz 1982). During the spring and summer months, red hake move into shallower waters to spawn, and during the winter months move offshore to deep waters in the Gulf of Maine and the edge of the continental shelf along Southern New England and Georges Bank. Spawning occurs from May through November, with primary spawning grounds on the southwest part of Georges Bank and in the Southern New England area off Montauk Point, Long Island (Colton and Temple 1961).

Red hake do not grow as large as white hake, and normally reach a maximum size of 50 cm (20 in.) and 2 kg (4.4 lbs.) (Musick 1967). However, females are generally larger than males of the same age, and reach a maximum length of 63 cm (25 in.) and a weight of 3.6 kg (7.9 lbs.) (Collette and Klein-MacPhee eds. 2002). Although they generally do not live longer than 8 years, red hake have been recorded up to 14 years old. In the northern stock, the age at 50% maturity is 1.4 years for males and 1.8 years for females, and the size at 50% maturity is 22 cm (8.7 in.) for males and 27 cm (10.6 in.) for females (O'Brien et al. 1993). In the southern red hake stock, the age at 50% maturity is 1.8 years for males and 1.7 years for females, and the size at 50% maturity is 24 cm (9.5 in.) for males and 25 cm (9.8 in.) for females (O'Brien et al. 1993).

Red hake prefer soft sand or muddy bottom, and feed primarily on crustaceans such as euphausiids, decapods, and rock crabs as well as fish such as haddock, silver hake, sea robins, sand lance, mackerel and small red hake (Bowman et al. 2000). Primary predators of red hake include spiny dogfish, cod, goosefish, and silver hake (Rountree 1999). As juveniles, red hake seek shelter from predators in scallop beds, and are commonly found in the mantle cavities of (or underneath) sea scallops. In the fall, red hake likely leave the safety of the scallop beds due to their increasing size and to seek warmer temperatures in offshore waters (Steiner et al. 1982).

TOR1. 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 Fishery Landings

Following the arrival of distant-water fleets in the early 1960s, nominal commercial landings from both stocks combined peaked at 113,500 mt in 1966 (Table C1, Figure C2). Nominal landings then declined sharply to 12,500 mt in 1970, increased to 76,200 mt in 1972, and then declined steadily with increased restrictions on distant-water fishing effort. Prior to implementation of the Magnuson Fisheries Conservation and Management Act (MFCMA) in 1977, distant-water fleets accounted for approximately 80-90% of the nominal landings from both stocks. Between 1977 and 1986, landings generally declined due to restrictions placed on distant water fleets, and foreign landings ceased in 1987 (Table C1, Figure C3). Red hake landings continued to decline afterwards, and averaged only 1,400 mt per year during 1996-2000. Nominal red hake landings then declined further to average 770 mt between 2001 and 2009. Red hake are often sold as bait over the side. These landings are not reported in the dealer database, but are supposed to be reported on Vessel Trip Reports (VTR). All the landings tables include whatever landings are reported in the totals. Due to some confidentiality issues, they are not reported separately.

The northern red hake stock had significantly lower commercial landings than the southern stock through the mid-1970s (Table C1, Figure C2). In 1973, total commercial landings peaked at 15,288 mt but have since declined progressively. After 1976, landings declined considerably due to the withdrawal of the distant water fleet. Commercial landings declined to less than 100 mt in 2005 and have remained low (Table C1, Figure C3).

During 1962 to 1976, landings from the southern red hake stock were much higher than those from the northern stock (Table 1, Figure C2). However, southern red hake landings decreased sharply after 1966 and also after 1976 due to restrictions on distant water fleets. The southern stock landings continued to decrease, and reached a record low of 356 mt in 2005 before increasing to 575 mt in 2009 (Table C1, Figure C3).

Commercial landings in the northern stock generally came from Massachusetts with smaller amounts landed in Maine and Rhode Island (Table C2). The primary states in which red hake were landed in the southern stock are Rhode Island, New Jersey, and New York (Table C3). Massachusetts was a historically important port, with some of the industrial fleet landings probably landed there.

Otter trawls in both regions accounted for the majority of the commercial landings of red hake, although the assumption was made that both the industrial fishery and the bait fishery are from otter trawl (Tables C4-C5). This assumption is likely valid since otter trawls were the main reported gear type throughout the history of the fishery.

Commercial landings from the northern stock are taken primarily in the summer months, mainly June through October (Table C6) although in the last five years, significant landings have only occurred in July, August and September. Commercial landings from the southern stock occur more evenly during the year (Table C7).

Species and Length Composition of Landings

Identification of hakes is uncertain in the commercial landings. An alternative method to estimate landings by species (red/white) was developed. Landings by region, half year, and, in the case of white hake, market category (Tables C8-C10) were converted to length composition. Market categories of white hake were aggregated as they were done in the white hake assessment (NEFSC 2001, 2008). The port samples by half year, region, and market were used (Tables C11-C13). In general, there were marginally adequate numbers of fish measured for red hake in the south and white hake in the north (Tables C14-C15). Pooling over years by species within a region was required to get an adequate number of fish, particularly for red hake in the north and white hake in the south (Table C16-C17). 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.

Length compositions for each species for the two regions (GOM-NGBK Offshore strata 20-30, 36-40; SGBK-MA – Offshore strata 1-19, 61-76) were estimated for the spring and fall surveys. 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. The lengths had to be grouped into intervals to avoid zero cells in the survey. All fish greater than 70 cm were set to be white hake. Landings from 1964-2009 were hind-cast using the average proportion of red hake by region over the entire time series.

The landings that result from this method are very different than the nominal landings in the north (Table C18, Figure C4) but fairly similar for the southern landings (Table C18, Figure C5). The HWG decided that the hind-cast landings were too uncertain and that the increase seen in the northern stock disappears (and becomes white hake during that time). Therefore, nominal landings will be used for the assessment.

The length compositions from the raw length samples and the length-based model estimates show different patterns for the northern stock (Figures C6-C7). The raw data (only showing years which had red hake length samples) are noisy with some years having fairly small fish (i.e. 1992 and 2007). When the data are pooled to estimate the length compositions and split using survey proportions, trends of these small fish are evident from 1992-1996 and 2006-2009. In the southern stock, the length compositions are fairly similar (Figures C8-C9).

Commercial Fishery Discards

Discard estimates were 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:

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

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:

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

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., $D_h = R_h K_h$.

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.

The main sources of red hake discards in the north were the two small-mesh trawl fisheries, including the shrimp trawl fishery, at least until the early 1990s, with the implementation of the Nordmore grate in that fishery (Table C19). The small-mesh trawl fishery in the south is also the largest contributor to discards of red hake, with large-mesh trawl and scallop dredge catching some significant amounts (Table C20). Discards from the longline and sink gill net fisheries were minimal in both regions.

Discards from the northern stock averaged 1300 mt in the early 1980s, declined to about 250 mt from 1995-2000 and have averaged 100 mt through 2009 (Figure C10). Discards from the southern stock averaged 4000 mt in the 1980s, declined to about 1000 mt from 1995-2000 and have averaged 700 mt through 2009 (Figure C11).

Species and Length Composition of Discards

The same problem with species identification that exists in the landings is found in the Fisheries Observer Program data. The same length-based method used for commercial landings was used to split discards. Discards were estimated for white hake using the same method as for red hake (Tables C21-C22). 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 (Tables C23-26). Pooling over years was still required to get an adequate number of fish (Tables C27-30). To hind-cast the species proportions back to 1981, the average proportion of red hake for the time series was used and applied to the total red and white hake discards. This method resulted in slightly different discard estimates for the north (Table C31, Figure C10) and almost imperceptible differences in the south (Table C31, Figure C11). To be consistent with landings, the nominal discards were used for the assessment. The length compositions from the nominal discards and the length-based model estimates show very little difference in either stock (Figures C12-C15).

Recreational Catch

USA recreational landings of red hake were estimated by stock using data provided by NOAA MRFSS from 1981-2009 (Table C32). Landings prior to 1981 were hind-cast for the north using an average proportion of the total landings. The southern stock had estimates previously derived (NEFC 1990) and these were used directly. Recreational landings were much more significant in the south with catch averaging 300 mt compared to less than 3 mt in the north through the time series (Figure C16). The number of length samples taken in the recreational fishery is sparse for the northern stock, so the southern stock length frequencies were used for both stocks (Figure C17).

Commercial Fishing Effort and LPUE

There are currently no estimates of CPUE or effort for this species. Given the uncertainties given above with species identification 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 areas for good red hake fishing. 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 by-catch fishery that may be driven more by prices of silver hake and regulation than abundance.

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

Data Source: The primary sources of biological information for red 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 C18). 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.

The NEFSC spring and fall survey estimates were calculated for northern, southern and combined management regions. The NEFSC strata used for the northern area are offshore strata 20-30 and 36-40. The NEFSC strata used for the southern management area are: offshore strata 1-19 and 61-76. The combined strata set is: offshore 1-30, 36-40, and 61-76.The strata set for the shrimp survey is shrimp strata 1-12. The strata set for the winter surveys is: offshore strata 1-3, 5-7, 9-11, 13-14, 61-63, 65-67, 69-71, and 73-75. Massachusetts Division of Marine Fisheries data was separated into northern and southern areas. The northern strata used were MADMF 18-36 and the southern strata used were 11-17 (Figure C19).

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

Transform: NEFSC spring and fall 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:

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

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 the variability between years (Figure C20). 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 are 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 (Figure C21).

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),

$$\hat{R}_A = \rho R_B . \qquad (3)$$

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.
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 red 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. For red hake, the working group decided to use a season-specific double-logistic model relating the calibration factor to length due to it providing the best fit to the data with respect to AIC_c (Table C33-34, Figure C22). Note that the minima for both logistic components in the fall were assumed equal to 0 (e^{-100}) due to poorly estimated variance of model coefficients in the fully parameterized model. To estimate weight pre tow for the 2009 and 2010 surveys, the length-weight equations by season from Wigley et al 2003 were applied to the length frequencies.

Survey Data Results: Distribution maps for red hake show that there are higher concentrations of red hake by catch weight (kg) during the NEFSC spring surveys than the NEFSC fall surveys. There were less red hake caught in the middle of Georges Bank in the spring than the fall. They tended to be more in the Gulf of Maine and along the shelf, than in the middle of the bank. The maps are broken into 5-year blocks, by season, for the duration of the time series (Figures C23-C34).

<u>North</u>
The fall survey biomass steadily increased during the 1970s, spiked in 2000 at its highest of 12,118 metric tons and then decreased until 2005, where the stock declined to 2,486 metric tons. Biomass has increased the past few years and is currently at 5,086 metric tons in 2009, a 24% increase from 2008 (Table C35, Figure C35).

The spring survey biomass was variable during the 1970s, with many peaks and valleys. There was a large spike in 1981, where it increased to 13,594 metric tons. In 1982, the biomass index dropped sharply to 4,551 metric tons, a decline of 67%. The stock was quite low in 1990, and then increased until 2002, where the stock was at 9,543 metric tons and then considerably declined until 2006, with 1,952 metric tons. Since then, the minimum swept area biomass has increased again to 4,326 metric tons, a 122% increase over 2006 (Table C36, Figure C36).

The shrimp survey swept area biomass was quite low during the early part of the time series. The lowest point was in 1994, at 3,262 metric tons. Biomass continued to slowly increase, until it spiked in 2002 with an all time high of 64,925 metric tons. Then biomass declined by 74% to 17,194 metric tons in 2003. The 2009 estimate is currently at 13,164 metric tons (Table C37, Figure C37).

The lowest biomass estimate from the MADMF fall surveys was in 1987, where there were only 447 metric tons caught. Then biomass increased through the 1990s, where it hit a maximum value in 2000 of 3,842 metric tons. A decline occurred between 2002 and 2008, although 2009 increased by 83% over 2008 (Table C38, Figure C38).

The MADMF spring surveys have extremely low biomass estimates. There were two spikes early in the time series, in 1979 and 1981, with catches of 3,888 metric tons and 5,129 metric tons, respectively. The biomass declined considerably in 1982 and stayed low until a small bump in 2000 with 1,414 metric tons. The survey biomass then declined to its lowest value in 2004 of 75 metric tons. It increased by 226% in 2009, to 245 metric tons (Table C39, Figure C39).

The trends for all the fall surveys are in general agreement showing an increase through 2000, a decline through 2005 and an increase over the last few years (NH data in Table C40, Figure C40). The spring surveys also show a general agreement with higher values in the 1980s, declining through 1995, increasing through 2002, and followed by a decline until the last couple of years (NH data in Table C40, Figure C41).

South

The fall survey swept area biomass was higher during the 1970s and 1980s than any other part of the time series. Biomass peaked at 20,002 metric tons in 1983 before dropping drastically by 80% to 3,905 metric tons in 1984. The stock has continued to decline until 2005. Biomass has increased slightly and is currently at 3,368 metric tons (Table C41, Figure C42).

Similar to the fall survey, the spring survey swept area biomass was higher during the 1970s and early part of the 1980s. After 1981, when the biomass was 15,201 metric tons, it declined to reach a low value of 511 metric tons. Biomass continued to increase to 3,460 metric tons in 2010, a 577% increase since 2004 (Table C42, Figure C43).

The winter survey has a very short time series, 1992-2007. The swept area biomass was high during the early part of the time series, with 18,483 metric tons in 1993. The survey biomass then declined, hitting its lowest value in 2003 at only 159 metric tons. The biomass varied until the winter survey was discontinued in 2007 (Table C43, Figure C44).

The MADMF fall survey in the southern region has much smaller biomass than in the northern region. The survey was variable at best with many peaks and valleys throughout the time series. In 2004, the survey was at its lowest point with 0.22 metric tons of swept area biomass. In 2009, there was an increase of 645% to 1.64 metric tons than in 2004 (Table C44, Figure C45).

The MADMF spring survey has larger swept area biomass than the MADMF fall survey. The early part of the time series has greater values than the latter. The highest biomass was estimated in 1987 with 894 metric tons, where 2003 was the lowest, at 0.36 metric tons. In 2009, the swept area biomass was 6.92 metric tons (Table C45, Figure C46).

The trends for all the fall surveys are much noisier than in the northern area (RI and CT data in Table C46, Figure C47). The spring surveys also show great deal of noise (RI and CT data in Table C46, Figure C48).

Combined

The fall survey swept area biomass, combining both the northern and southern management areas, had a steep decline to 4,467 metric tons in 1974 from 17,737 metric tons in 1972. Then the biomass increased substantially to 28,807 metric tons in 1983. After a considerable drop in 1986, the biomass estimates were stable throughout the rest of the time series. The biomass in 2009 was 8,454 metric tons (Table C47, Figure C49).

In the spring survey, biomass peaked at 30,831 metric tons and 28,794 metric tons in 1978 and 1981, respectively. Biomass then declined until 1998, when biomass increased slightly. There was a 75% decline from 11,337 metric tons in 2002 to 2,812 metric tons in 2003. The stock increased since then and was 9,022 metric tons in 2009 (Table C48, Figure C50).

Length Composition

The length compositions from the fall survey show a large proportion of very small fish in the northern stock (Figure C51). There has also been a truncation of size of fish with very few fish caught that are greater than 40 cm. The spring survey length composition has many fewer small fish (except for 1974) but shows the same size truncation (Figure C52).

In the south, the young-of-the-year are very dominant in the length composition, but the size truncation is less noticeable, possibly since there may have already been truncation before the time series started (Figure C53). However, the spring survey shows some truncation occurring in the late 1980s and early 1990s, with fewer fish greater than 35 cm caught in the survey (Figure C54). The winter survey shows more young fish than the spring, possibly because the survey used a cookie sweep and was able to capture small fish and, more importantly, the scallops that they inhabit (Figure C55).

Estimates of Consumption of Red Hake

Every predator that contained red hake was identified from the NEFSC FHDBS. From that original list, a subset of predators (Table C49) was examined to elucidate which predators consistently ate red hake, determined by "rules of thumb" that include having a diet composition of >1% for any five year block, and with >5 tows 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 red hake predators were sampled during the full extent of this sampling program, thus the time series used here begins 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 the simple sum of the two seasonal estimates was used in this analysis. The analyses were done for various size classes of predators, and then were integrated across all predator size classes to come up with a total consumption of red 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 red hake predator i, diet composition (D_{ij}) where the subscript j refers to red 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.

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 (size and 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 red 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 red hake, to estimate the seasonal per capita consumption of red hake. That is, once per capita consumption rates were estimated for each red 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 red 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 seasonally and the summed), they were then scaled by the total stock abundance of each predator to estimate the amount of red hake removed by any of the predators included in the study. Swept area estimates of abundance from bottom trawl survey estimates were used for all predators (Table C49). These consumption estimates were then scaled by the total stock abundance to estimate a total amount of red hake (*j)* removed by any predator *i*, C_{ij}:

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

where N_i is the estimate of abundance for each predator for each year. These C_{ij} were then summed across all *i* predators to obtain an estimate a total amount of red hake removed by these red hake predators, C_j:

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

Total consumptive removals by all consistent red hake predators, using swept area abundance estimates of the predators, were consistently around 5 thousand mt per year during the late 1970s to late 1990s; more recently these removals averaged approximately 10 thousand mt in the 2000s (Figure C56). For more explicit presentation of the step-by-step data series used to derive the consumptive removal results, please contact the working group, as has been done for similar prior assessments (e.g., NEFSC 2007a, 2007b).

These minimum estimates of red hake consumed by the consistent fish predators in this study were compared to total catch (Figure C56). Catch and minimum swept area estimates of consumption were approximately equal for much of the time series, with landings a little higher earlier in the time series (1970s), but with consumption the dominant source of removal more recently averaging more than five times than catch (Figure C57).

Estimates of predatory removal of red 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 red hake. The estimates of consumption also imply that there has been a change in natural mortality over time. This is likely to be important in any model attempts.

There were enough red hake measured in the stomachs of the predators to pool over the entire time series (n=612). In the future, it may be useful to break into time periods. More than half of the fish measured are between 3 and 8 cm with the mode at 4 cm (Figure C58).

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

Two subpopulations of red hake are assumed to exist within the U.S. EEZ based largely by analogy with silver hake (NEFC 1986). No morphometric or genetic analyses of the population structure have been conducted. The northern red hake stock inhabits Gulf of Maine - Northern Georges Bank waters, and the southern red hake stock inhabits Southern Georges Bank - Middle Atlantic Bight waters (Figure C1). These boundaries were established at SAW 2.

Distribution

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. 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 C23 and C24). However, the relative density of red 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 and then declined in the 2000's (Figure C35). In contrast southern area showed stability through 1982 with a drop in 1983 and a progressive decline through 2004. Since 2004, there has been a slight increase (Figure C42). The spring trends indicate a stable biomass through 1987 followed by a decline through 1995 (Figure C36). Biomass increased through 2000 followed by a decline. The southern trends in the spring are similar to that of the fall survey (Figure C43). The proportion of the total biomass in each area has changed from 80% in the 1960s to 60-80% in the north in the last decade (Figure C59). This could indicate movement, differential mortality, or both.

Growth and Maturity

In addition to morphology, genetics, and recruitment trends, growth is often a factor in deciding whether to assess adjacent populations as separate stocks or as one combined stock. Comparisons of growth parameters k and L_∞ (Roomian and Jamili 2011, for example) and growth plots (Brooks and Ortiz 2004, for example) may be confounded by the covariance between these two parameters when simultaneously fitted to size at age data. Similar data can be fit equally well with Von Bertalanffy growth parameters having a low k and high L_∞, and vice versa, unless there are sufficient age samples for old fish. Comparison of plots with associated age data to demonstrate variance around the fitted curves can also lead to subjective mis-interpretation (e.g. determination that growth is not different when in fact it is).

A plot of mean size at age with confidence intervals, one population along the abscissa and one along the ordinate is an alternative and possibly more informative way of comparing growth characteristics between two populations. Similarities in size at age will appear along a slope=1, while differences in growth are readily identifiable as horizontal or vertical deviations from the slope=1 line and the confidence intervals show whether that deviation is significantly different from the other population. Distance between successive ages represents the annual growth increment, which of course declines with age as the fish size approaches L_∞. Another advantage of this approach is that it can be readily applied to cohorts and grouped by time frame, examining the growth of fish that have experienced similar environmental characteristics and food availability.

Age determination of red hake by reading otoliths is described in Penttila and Dery 1988, Chapter 9. Dery's otolith analysis concluded that red hake otoliths in the northern stock area were considerably more difficult to interpret than those from red hake captured in the southern stock area, due to "numerous and sometimes prominent checks", factors that "blur the [sic] distinction between annular zones".

The analysis also indicates that otoliths from red hake captured in the northwestern and eastern part of the Bay of Fundy (Gulf of Maine) varied from the otolith morphology for red hake captured elsewhere and had intermediate characteristics with white hake, suggesting the possible existence of hybridization in that area.

Red hake from the spring and fall surveys have been aged from 1970 to 1985. Before 1975 (1957-1974 cohorts), age 1 to 3 red hake appear to have the same growth rates in the northern and southern stock areas. Then age 4+, growth appears to slow in the southern area and continue to a higher L_∞ in the northern stock area (Figure C60a, Figure C61a). Age 4 to 10 red hake are always larger in the north than in the south.

This general pattern of large, old red hake in the northern stock area persists for the 1975-1985 cohorts (Figure C60b, Figure C61b)). Size at age is also relatively consistent between the two cohort time series.

There are also slight differences in size at maturity between stocks although the differences are in one direction for males and the opposite for females (Figure C62).

Although the large, older fish in the northern stock area would argue for separate population modeling and stock dynamics, there appears to be considerable uncertainty in the interpretation of red hake ages in the northern stock area, due to the aforementioned otolith anomalies, potential hybridization with white hake, and possible differential exploitation patterns between the two areas. It is equivocal whether not there are two stocks, one stock or more. There is not enough information to come to a definitive conclusion.

TOR 4. Estimate measures of annual fishing mortality, recruitment and stock biomass (both total and spawning stock) for the time series, and characterize their uncertainty. Include a historical retrospective analysis to allow a comparison with previous assessment results.

Historical Retrospective

The last assessments for these stocks were conducted in 1990 and at the time both stocks were considered to be "under-exploited".

In this assessment, three models were attempted. They were An Index Method (AIM), Stock Synthesis (SS3) and Statistical Catch-at-Length (SCALE). While all three had problems, AIM was considered to be most useful for guidance on reference points and stock status. The other models needed more time to be developed properly.

AIM model

> **[SAW51 Editor's Note, Aug. 11, 2011: The AIM method described in this section mentions using a three-year centered average of the abundance index. This is just one possible way that AIM can be applied. Depending on model performance and diagnostics, the survey index averages used in AIM might instead be based on longer or shorter time series, or even based on single point estimates from individual survey abundance indices. In the 2011 red hake stock assessment, the AIM analysis and relative F were based on survey indices from single years, and not on the three-year average described in Equation 1 (below). Following the SARC51 peer review, analyses by Dr. Paul Rago demonstrated that, for red hake, the AIM model performed better using the one-year approach than with smoothed three-year averages.]**

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

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

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, have 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 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.

AIM was applied to northern and southern stocks of red hake using 1963-2009 catches which include commercial landings and discards described as “Raw C2”. An alternative catch series from 1980 to 2009, which includes recreational catch, described as “Catch 3” was also applied to both northern and southern red hake. Results of these analyses are described separately in subsequent sections. Each section consists of two tables and three graphs. For all applications Relative F was defined as the ratio of catch to 1-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 for each scenario. Although none of the randomization tests resulted in significant statistical relationship between the replacement ratio and relative F, The HWG decided that the results of the shorter series were considered “best” for purposes of reference point proxies and stock status. This was instead of any more subjective look at the survey and catch data.

Application of AIM to Red Hake, Northern Stock, catch series “Raw C2”

AIM was applied to northern red hake using catches derived from the method denoted as “Raw C2”, and the NEFSC fall and spring bottom trawl survey indices (Table C50). Randomization tests for the fall and spring surveys revealed no significant statistical relationship between the replacement ratio and relative F (Table C51). In fact the randomization test suggested a low probability of obtaining test statistics greater than those observed. Relative F at replacement was poorly specified for both the fall (Figure C63) and spring surveys (Figure C64). The 90% confidence intervals for both surveys (Table C51, Figure C65) were very wide suggesting no information about the relationship between population growth rate and relative F. The six panel plots for the fall and spring surveys (Figures C63 and C64, respectively) suggest that despite a continuously decreasing relative F neither the replacement ratio nor the surveys have any consistent trends. The relationship between the relative F and survey indices suggests that the surveys appear to be changing over time. The large pulse in landings during the early 1970s followed by relatively low catches resulted in about a 3 fold increase in stock size by the early 1980s but the absence of population response in the following three decades since then suggests that factors other than fishing mortality may be responsible.

Application of AIM to Red Hake, Southern Stock, catch series “Raw C2”

AIM was applied to southern red hake using catches derived from the method denoted as “Raw C2”, and the NEFSC fall and spring bottom trawl survey indices (Table C52). Randomization tests for the fall and spring surveys revealed no significant statistical relationship between the replacement ratio and relative F (Table C53).

Trends in relative F for the fall (Figure C66) and spring (Figure C67) surveys are remarkably similar owing to similar trends in survey abundance. Abundance indices in both fall and spring surveys show increases since 2000 but remain well below rates observed before 1980. Estimated relative F at replacement for both fall and spring surveys is about 2,200 mt/kg/tow. Bootstrap estimates suggested about a 3-fold range of estimates in the 90% confidence interval (Figure C68)

Relative F at replacement was poorly specified for both the fall (Figure C66) and spring surveys (Figure C67). The 90% confidence intervals for both surveys (Table C53, Figure C68) were very wide suggesting relatively little information about the relationship between population growth rate and relative F. The relationship between the relative F and survey indices suggests that the functional relationship appears to be changing over time. The large pulse in landings during the late 1960s and early 1970s, followed by relatively low catches, was matched with consistently low survey indices. The phase plane plot of survey indices and relative F (left middle panel

Figures C66-C67) suggests three separate stanzas wherein the survey declined by similar ranges while the relative F varied by progressively smaller ranges (1967-1976, 1977-1994, 1995-2009). Such changes in the southern stock suggest that factors other than fishing mortality may be responsible for the declines in abundance.

[SAW51 Editor's Note, Aug. 11, 2011: In the 2011 red hake stock assessment for the N and S stocks, the AIM analysis and relative F's were based on survey indices from single years, and not based on the three-year average described in the AIM Methods (e.g., Equation 1).]

Application of AIM to Red Hake, Northern Stock, catch series "Catch3 short"

In the preceding sections analyses of the relationship between the replacement ratio and relative F suggested nonstationarity. More specifically, the rate of increase in stock size with respect to relative F appeared to be decreasing over time. The reduced duration of the time series for catch was designed to address the potential changes in natural mortality suggested by the consumption estimates. The working group considered another catch estimate, denoted as "Catch 3" for the period 1980-2009 for both the Northern and Southern stocks of red hake.

For northern red hake the continuous declines in landings and relatively small range of change in survey abundance resulted in a steady decline in relative F in the fall survey (Table C54, Figure C69). The replacement ratio varied about 1.0 until 2000 when it fell to low levels before rising sharply in 2009. A similar response was observed in the spring survey (Figure C70). The estimated relative Fs at replacement were nearly identical (162 and 163.1 mt/kg or 0.162 and 0.163 kt/kg; Table C55) but the spring survey estimate had a slightly smaller confidence interval. Bootstrap estimates of relF at replacement had some extreme values (Figure C71). Randomization tests suggest that the probability of observing correlations less than the observed value were 26 to 38% (Table C55).

Application of AIM to Red Hake, Southern Stock, catch series "Catch3 short"

The truncated catch time series was also considered for the southern stock of red hake (Tables C56-C57, Figures C72-C74). Catch estimates for the southern red hake stock consist of two stanzas of landings of about 5000 mt before 1994 and roughly half as much annually since then (Table C56, Figures C72-C73). Both the fall and spring surveys declined consistently during the high catch stanza and have recently increased since the early 2000s. The increase in replacement ratio since 2000 was preceded by near halving of relative F in the late 1990s from its peak value (Figures C72-C73).

The phase plane plots of survey and relative F again suggest similar population responses to exploitation but differing slopes before and after 1994. Fall and spring relative fishing mortalities at replacement are similar, 2300 vs 3038 mt/kg (2.300 vs 3.038 kt/kg; Table C57). The relative F at replacement for the fall and spring surveys have overlapping confidence intervals but randomization tests suggest that the degree of association between relative F and the replacement ratio is not significant.

AIM Model Choice

Although none of the randomization tests resulted in significant statistical relationship between the replacement ratio and relative F, the HWG decided that the results of the shorter series were considered “best” for purposes of reference point proxies and stock status. This was instead of any more subjective look at the survey and catch data at least until an analytical assessment can be developed in the future.

[SAW51 Editor's Note: The red hake SCALE and SS3 model description and results, which are described below, are included in the report mainly to document the modeling that the Red Hake Working Group provided to the SARC-51 for peer review. The results from these two models were not accepted as a basis for providing management advice.]

Stock Synthesis Model (SS3)

A forward-projecting statistical catch-at age model (Stock Synthesis 3 version 3.11c, NOAA Fisheries Toolbox (NFT) 3.1 (2010c)) was attempted to be used to estimate fishing mortality rates and stock sizes for the northern stock, southern stock and combined areas. The first attempts at modeling used the length-based model estimated catches and fit stock-recruitment relationships using both Ricker and Beverton-Holt. The results were promising, but the stock-recruitment relationships caused some problems including some negative SSBmsy estimates). After the HWG decided to use the nominal catch in the models, there were no improvements to the fits of any of the models with stock-recruitment relationships. Therefore, the SR alternative to not fit a SR relationship was used for the remainder of the models.

Other issues involved fits to the length compositions (Figure C75), particularly the fall survey in which the small fish are under-estimated in the model. The HWG decided that this may be due to a peculiarity of red hake. The survey may be catching more small fish before they settle and inhabit scallop shells. This may result in an unusual selectivity pattern not available in any current model. So the Age-0 fish were removed from the fall survey and used as a recruitment index as well as the Age-1 spring survey data.

Another length fitting problem was initially thought to be a major model problem (Figure C76). In all the model runs, there is a knife-edge increase at 55 cm. On further inspection, it was due to the binning of length data above 55 cm. The length bins above 5 cm were single cm intervals until 55 cm at which time a 5 cm and then a 10 cm bin was used. After this was changed to cm intervals through 80 cm, the fits were better, although in recent years there is some problem with the model estimating more large fish than in any of the data (Figure C77).

One of the final model runs used four fleets of catch data (landings, discards, recreational catch and consumption) and four survey indices (spring, fall, spring recruitment and fall recruitment). The fits to the survey data were not very good and showed some patterning in the residuals (Figure C78). The main problem was in the fit to the length composition of the consumption data. The single length composition did not fit the model predicted length composition (Figure C79). Several tweaks were attempted to solve this, including changing the size at age 1, moving the time of consumption from mid-year to the beginning of the year, and removing consumption to be replaced with an age-varying natural mortality. None of these options were successful and most of the variations did not converge. Therefore, no SS3 models were accepted at this time, although the HWG thought that it was worthwhile to pursue for the next assessment.

Statistical Catch-at-Length Model (SCALE)

Introduction

Incomplete or lack of age-specific catch and survey indices often limits the application of a full age-structured assessment (e.g. Virtual Population Analysis and many forward projecting age-structured models). Stock assessments will often rely on the simpler size/age aggregated models (e.g. surplus production models) when age-specific information is lacking. However the simpler size/age aggregated models may not utilize all of the available information for a stock assessment. Knowledge of a species growth and lifespan, along with total catch data, size composition of the removals, recruitment indices and indices on numbers and size composition of the large fish in a survey can provide insights on population status using a simple model framework.

The Statistical Catch At LEngth (SCALE,NOAA Fisheries Toolbox (NFT) 3.1 (2010b)) model, is a forward projecting age-structured model tuned with total catch (mt), catch at length or proportional catch at length, recruitment at a specified age (usually estimated from first length mode in the survey), survey indices of abundance of the larger/older fish (usually adult fish) and the survey length frequency distributions. The SCALE model was developed in the AD model builder framework. The model parameter estimates are fishing mortality and recruitment in each year, fishing mortality to produce the initial population (Fstart), logistic selectivity parameters for each year or blocks of years and Qs for each survey index.

The SCALE model was developed as an age-structured model that does NOT rely on age-specific information on a yearly basis. The model is designed to fit length information, abundance indices, and recruitment at age which can be estimated by using survey length slicing. However the model does require an accurate representation of the average overall growth of the population which is input to the model as mean lengths at age. Growth can be modeled as sex-specific growth and natural mortality or growth and natural mortality can be model with the sexes combined. The SCALE model will allow for missing data.

Model Configuration

The SCALE model assumes growth follows the mean input length at age with predetermined input error in length at age. Therefore a growth model or estimates of the average mean length at age is essential for reliable results. The model assumes static growth and therefore population mean length/weight at age are assumed constant over time.

The SCALE model estimates logistic parameters for a flattop selectivity curve at length in each time block specified by the user for the calculation of population and catch age-length matrices or the user can input fixed logistic selectivity parameters. Presently the SCALE model cannot account for the dome shaped selectivity pattern.

The SCALE model computes an initial age-length population matrix in year one of the model as follows. First the estimated populations numbers at age starting with age-1 recruitment get normally distributed at one cm length intervals using the mean length at age with the assumed standard deviation. Next the initial population numbers at age are calculated from the previous age at length abundance using the survival equation. An estimated fishing mortality (Fstart) is also used to produce the initial population. This F can be thought of as the average fishing mortality that occurred before the first year in the model. Now the process repeats itself with the total of the estimated abundance at age getting redistributed according to the mean length at age and standard deviation in the next age (age+1).

This two step process is used to incorporate the effects of length specific selectivities and fishing mortality. The initial population length and age distribution is constructed by assuming population equilibrium with an initial value of F, called F_{start}. Length specific mortality is estimated as a two step process in which the population is first decremented for the length specific effects of mortality as follows:

$$N^{*}_{a,len,y_1} = N_{a-1,len,y_1} e^{-\left(PR_{len} F_{start} + M\right)}$$

In the second step, the total population of survivors is then redistributed over the lengths at age *a* by assuming that the proportions of numbers at length at age *a* follow a normal distribution with a mean length derived from the input growth curve (mean lengths at age).

$$N_{a,len,y_1} = \pi_{len,a} \sum_{len=0}^{L_\infty} N^{*}_{a,len,y_1}$$

where

$$\pi_{len,a} = \Phi\left(len + 1 \mid \mu_a, \sigma_a^2\right) - \Phi\left(len \mid \mu_a, \sigma_a^2\right)$$

where

$$\mu_a = L_\infty\left(1 - e^{-K(a-t_0)}\right)$$

Mean lengths at age can be calculated from a von Bertalanffy model from a prior study as shown in the equation above or mean lengths at age can be calculated directly from an age-length key. Variation in length at age a = σ_s^2 can often be approximated empirically from the growth study used for the estimation of mean lengths at age. If large differences in growth exist between the sexes then growth can be input as sex-specific growth with sex-specific natural mortality. However catch and survey data are still fitted with sexes combined.

This SCALE model formulation does not explicitly track the dynamics of length groups across age because the consequences of differential survival at length at age a do not alter the mean length of fish at age a+1. However, it does more realistically account for the variations in age-specific partial recruitment patterns by incorporating the expected distribution of lengths at age.

In the next step the population numbers at age and length for years after the calculation of the initial population use the previous age and year for the estimate of abundance. Here the calculations are done on a cohort basis. Like in the previous initial population survival equation the partial recruitment is estimated on a length vector.

$$N^*_{a,len,y} = N_{a-1,len,y-1}\, e^{-\left(PR_{len}F_{y-1} + M\right)}$$

second stage

$$N_{a,len,y} = \pi_{len,a} \sum_{len=0}^{L_\infty} N^*_{a,len,y}$$

Constant M is assumed along with an estimated length-weight relationship to convert estimated catch in numbers to catch in weight. The standard Baranov=s catch equation is used to remove the catch from the population in estimating fishing mortality.

$$C_{y,a,len} = \frac{N_{y,a,len}\, F_y\, PR_{len}\left(1 - e^{-\left(F_y PR_{len} + M\right)}\right)}{(F_y \; PR_{len}) + M}$$

Catch is converted to yield by assuming a time invariant average weight at length.

$$Y_{y,a,len} = C_{y,a,len} W_{len}$$

The SCALE model results in the calculation of population and catch age-length matrices for the starting population and then for each year thereafter. The model is programmed to estimate recruitment in year 1 and estimate variation in recruitment relative to recruitment in year 1 for each year thereafter. Estimated recruitment in year one can be thought of as the estimated average long term recruitment in the population since it produces the initial population. The residual sum of squares of the variation in recruitment $\sum(\mathrm{Vrec})^2$ is then used as a component of the total objective function. The weight on the recruitment variation component of the objective function (Vrec) can be used to penalize the model for estimating large changes in recruitment relative to estimated recruitment in year one.

The model requires an age-1 recruitment index for tuning or the user can assume relatively constant recruitment over time by using a high weight on Vrec. Usually there is little overlap in ages at length for fish that are one and/or two years of age in a survey of abundance. The first mode in a survey can generally index age-1 recruitment using length slicing. In addition numbers and the length frequency of the larger fish (adult fish) in a survey where overlap in ages at a particular length occurs can be used for tuning population abundance. The model tunes to the catch and survey length frequency data using a multinomial distribution. The user specifies the minimum size (cm) for the model to fit. Different minimum sizes can be fit for the catch and survey data length frequencies.

The number of parameters estimated is equal to the number of years in estimating F and recruitment plus one for the F to produce the initial population (Fstart), logistic selectivity parameters for each year or blocks of years, and for each survey Q. The total likelihood function to be minimized is made up of likelihood components comprised of fits to the catch, catch length frequencies, the recruitment variation penalty, each recruitment index, each adult index, and adult survey length frequencies:

$$\mathrm{L_{catch}} = \sum_{years} \left(l\,\mathrm{n}(Y_{\mathrm{obs,y}} + 1) - \ln\left(\sum_{a} \sum_{len} \mathrm{Y_{pred,len,a,y}} + 1 \right) \right)^2$$

$$L_{catch\_lf} = -N_{eff} \sum_{y} \left(\sum_{inlen}^{L_\infty} \left(\left(C_{y,len} + 1\right) \ln\left(1 + \sum_{a} C_{pred,y,a,len} \right) - \ln\left(C_{y,len} + 1\right) \right) \right)$$

$$\mathrm{L_{vrec}} = \sum_{y=2}^{Nyears} \left(Vrec_y\right)^2 = \sum_{y=2}^{Nyears} \left(R_1 - R_y\right)^2$$

$$\sum L_{rec} = \sum_{i=1}^{Nrec} \left[\sum_{y}^{Nyears} \left(\ln\left(I_{rec_i, inage_i, y}\right) - \ln\left(\sum_{len}^{L_\infty} N_{y, inage_i, len} * q_{rec\,i} \right)\right)^2 \right]$$

$$\sum L_{adult} = \sum_{i=1}^{Nadult} \left[\sum_{y}^{Nyears} \left(\ln\left(I_{adult_i, inlen+_i, y}\right) - \left(\sum_{a} \sum_{inlen_i}^{L_\infty} \ln\left(N_{pred,y,a,len} * q_{adult\,i}\right)\right)\right)^2 \right]$$

$$\sum L_{lf} = \sum_{i=1}^{Nlf} \left[-N_{eff} \sum_{y} \left(\sum_{inlen_i}^{L_\infty} \left(\left(I_{lf_i, y, len} + 1\right) \ln\left(1 + \sum_{a} N_{pred,y,a,len}\right) - \ln\left(I_{lf_i, y, len} + 1\right)\right)\right)\right]$$

In equation L_{catch_lf} calculations of the sum of length are made from the user input specified catch length to the maximum length for fitting the catch. Input user specified fits are indicated with the prefix "in" in the equations. LF indicates fits to length frequencies. In equation L_{rec} the input specified recruitment age and in L_{adult} and L_{lf} the input survey specified lengths up to the maximum length are used in the calculation.

$$Obj\ \ fcn = \sum_{i=1}^{N} \lambda_i L_i$$

Lambdas represent the weights to be set by the user for each likelihood component in the total objective function.

Application to red hake

Various model formulations were attempted for the northern stock, southern stock and combined stocks. These included different natural mortalities, the alternative catch series, and different time series. All models had issues with the absence of older ages (sizes) at the end of the time series and lack of fit to the catch at the beginning of the time series. The model run done starting the time series in 1980, but the model does not fit to the declining trend in catch. The model also had a very strong retrospective pattern (Figures C80a-c). Since consumption cannot be added to SCALE as it is configured, it will no longer be considered as a potential candidate model for this red hake assessment.

5. ***State the existing stock status definitions for the terms "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.***

The overfishing definitions are taken from NEFMC (2000, 2003) and are as follows:

*The northern stock of red hake is overfished when the three-year moving average of stock biomass, derived from the fall survey, is below **1.6 kg/tow**. If an analytical assessment is available for northern red hake, then the three-year moving average will be replaced with the terminal year biomass estimate and compared with the biomass reference points.*

*Overfishing occurs when the ratio between catch and survey biomass exceeds **0.65**, the proxy for FMSY. When biomass is less than 3.1 kg/tow (the biomass target), the stock is overfished when fishing mortality is above a rate that declines linearly to zero when biomass equals the minimum biomass threshold (1.6 kg/tow).*

In 1998 the Overfishing Definition Review Panel (Applegate et al. 1998) concluded that MSY and F reference points could not be determined for southern red hake because the time series of landings and survey biomass indices did not include a period of stable landings at high biomass levels. The Panel noted that discarding could be significant, especially in the scallop and trawl fisheries. Habitat destruction was also thought to be prohibiting stock recovery since juveniles rely on intact scallop beds for shelter. However, in recent years the scallop stock has been recovering, but red hake biomass indices have not increased.

*The southern stock of red hake is in an overfished condition when the three-year moving average weight per individual in the fall survey falls below the 25th percentile of the average weight per individual from the fall survey time series 1963-1997 (0.12) **AND** when the three-year moving average of the abundance of immature fish less than 25 cm falls below the median value of the 1963-1997 fall survey abundance of fish less than 25 cm (4.72).*

In previous SAFE Reports, the Whiting Monitoring Committee (WMC) noted problems associated with the overfishing definition for southern red hake. Although the current definition is intended to identify overfished (i.e. low biomass) stock conditions, it is a better indication of overfishing (high exploitation rate) conditions. The WMC recommends that the overfishing definition for the southern stock of red hake be revisited after a benchmark stock assessment is completed.

The Hake Working Group examined both the fall and spring surveys and decided that the spring had more consistency in the AIM results (smaller confidence intervals for the relative F). The Hake Working Group also agreed with the WMC about the problems associated with the existing biomass reference point for the southern stock of red hake. Therefore the HWG proposes new BRPs (in kg/tow in Albatross units) for both northern and southern red hake stocks as follows:

> *Red hake is overfished when the three-year moving average of the spring survey weight per tow (i.e., the biomass threshold) is less than one half of the BMSY proxy, where the BMSY proxy is defined as the average observed from 1980 – 2010. The current estimates of Bthreshold for the northern and southern stocks are 1.27 kg/tow and 0.51 kg/tow, respectively.*

Overfishing occurs when the ratio between catch and survey biomass exceeds 0.163 kt/kg and 3.038 kt/kg, respectively, derived from AIM analyses from 1980-2009.

Applying the BMSY proxy to the replacement F allows for an MSY of 412 mt and 3086 mt for the northern and southern stocks, respectively.

The biomass reference points could be considerably different depending on the time series used to develop the average. For instance, if the entire time series was used, the B*MSY proxy* would be 2.43 kg/tow for the north and 1.61 for the south. If a shorter time series was chosen, for example 1990-2010, the two reference points would be 2.17 and 0.58, respectively. Other stocks have used the entire time series, but instead of the average, used the 75th percentile of the series (NEFSC 2007b). This would also change the reference points to 3.22 and 2.25 kg/tow, respectively. The Working Group chose the intermediate to reflect the potential increase in natural mortality suggested by the consumption estimates.

The 80% confidence intervals around the Freplacement for the north are from 0.062-0.240 kt/kg/tow (Figure C71) and for the south are 2.240 -3.700 kt/kg/tow (Figure C74).

6. Evaluate stock status (overfished and overfishing) with respect to the existing BRPs, as well as with respect to the "new" BRPs (from Red hake TOR 5).

Based on current biological reference points in the existing FMP, the northern stock of red hake is not overfished and overfishing is not occurring. The three year delta mean biomass index (Figure C81), based on NEFSC fall bottom trawl survey data for 2007-2009 (2.87 kg/tow), was above the management threshold level (1.6 kg/tow) and slightly below the target (3.1 kg/tow). The three year average exploitation index (landings divided by biomass index, Figure C82) for 2007-2009 (0.03) was below both the target (0.39) and the threshold (0.65).

Based on current biological reference points in the existing FMP, the southern stock of red hake is not overfished and overfishing is unknown. The three year delta individual mean weight index (Figure C83), based on NEFSC fall bottom trawl survey data for 2007-2009 (0.10 kg/individual), is below the management threshold (0.12 kg/individual) but the three year average recruitment index (5.95 num/tow) is above the threshold value (4.72 num/tow).

Based on new recommended biological reference points from SARC 51, the northern stock of red hake is not overfished and overfishing is not occurring. The three year arithmetic mean biomass index (Figure C84), based on NEFSC spring bottom trawl survey data in Albatross units for 2008-2010 (2.42 kg/tow), was above the proposed management threshold (1.27 kg/tow) and slightly below the target (2.53 kg/tow). The exploitation index (catch divided by biomass index, Figure C85) for 2009 (0.103 kt/kg) was below the threshold (0.163 kt/kg).

Based on new recommended biological reference points from SARC 51, the southern stock of red hake is not overfished and overfishing is not occurring. The three year arithmetic mean biomass index (Figure C86), based on NEFSC spring bottom trawl survey data in Albatross units for 2008-2010 (0.95 kg/tow), was above the proposed management threshold (0.51 kg/tow) and slightly below the target (1.02 kg/tow). The exploitation index (catch divided by biomass index,

Figure C87) for 2009 (1.150 kt/kg) was below the threshold (3.038 kt/kg).

7. 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.

Stochastic projections were not performed for this assessment. However, applying the Relative F reference points to the three-year average biomass index allows catches of 394 mt in the north and 2897 mt in the south.

8. 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.

SAW 1 - 1985

1. Updated VPA based on new stock boundaries will be undertaken
   Attempted several analytical models with no success.

2. A re-analysis of growth rate
   This assessment estimated growth parameters for the "new" stock definitions as well as smaller regions.

3. Predator/prey considerations for red hake are important
   This assessment estimated consumption of red hake by the major predators.

4. CPUE indices need to be re-calculated given new stock boundaries
   CPUE is no longer considered a valid abundance index for this species due to the management changes that have occurred in the last twenty-five years.

New Research Recommendations

- Studies to estimate discard mortality should be conducted.
- Develop explicit process and criteria for the application of length-based (vs. constant) calibration coefficients (other than purely statistical criteria such as AIC, etc.). It may be useful, if enough data exist, to attempt a cross validation with a subset of data.
- Information on consumption by more predators (including mammals, highly migratory species (HMS)) needs to be included.

- Diel (day/night) variation in consumption of hakes.
- Validation of the ageing method for red hake via tagging, radiocarbon, or tetracyclin research.
- More comprehensive analysis of red hake stock structure based on DNA (expanded genetic analysis).
- Perform a stock reduction analysis
- Continue developing an analytical assessment with Stock Synthesis or ASAP as more age data are available.
- Continue ageing the available samples.

Sources of Uncertainty

8. Catch data are uncertain given the identification issues between red and white hake, as well as possible hybridization between the two species.
9. Stock structure is not known and has been assumed by analogy with silver hake.
10. Growth estimates are from a time of assumed high mortality and should be revisited when data become available.
11. Natural mortality is unknown.
12. 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 red hake (e.g. some of the skates, other gadids) were not included in the analysis.
    d. Also, these estimates did not include a wide range of other (non-fish) predators known to consume red hake (e.g., seabirds, squids, marine mammals), nor did they include red 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 red hake.
    e. Spatio-temporal overlap considerations between predators and red hake were assumed. This work was done for both red hake stocks combined and could be reevaluated for both stocks separately.

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