Atlantic wolffish

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Executive Summary

Atlantic wolffish in the Gulf of Maine and Georges Bank regions inhabit the southern edge of the species distribution. Analyses herein were limited to the stock component completely within United States waters, which excluded some historically important transboundary portions of Georges Bank. There is currently no fishery management plan for the Atlantic wolffish in U.S. waters. Wolfish are associated with rough topography. Catchability of wolffish is low in NEFSC trawl surveys due to this habitat preference. Atlantic wolffish are long-lived (22 years), late maturing, and of low fecundity. Males guard the eggs in nests in the fall. Larger wolffish are caught in the spring survey compared to the fall, perhaps due to nest guarding behavior. All fishery independent survey indices show a declining trend in abundance over the time series. The commercial catch has also declined steadily since 1983. However there is no size truncation in the catch over the time series. A wolffish growth study from the 1980s in the Gulf of Maine and Georges Bank region was done by Nelson and Ross (1992). The DCAC model, AIM model, and simple exploitation ratios were examined for this assessment and presented to the Data Poor Stocks Peer Review Panel. A forward projection model, Statistical Catch At Length (SCALE), which tunes to size and age data from trawl survey recruitment and adult indices, total catch, and catch size distributions along with overall growth information, was developed for this assessment. This model was accepted by the Peer Review Panel as a basis for determining the biological reference points (BRPs) for Atlantic wolffish. The SCALE model had difficulty estimating selectivity due to the sparse data. Two different selectivity regimes were chosen to determine BRPs and their influence on stock status, using $F_{40\%}$ as a proxy for F_{MSY}. The maturation schedule of wolffish in U.S. waters is uncertain and this influences BRPs derived from the SCALE model. The sensitivity of these non-parametric BRPs was tested with a range of knife edge maturity cutoffs. Early Data-Poor Stocks Working Group meetings indicated that, given the wolffish life history, $F_{50\%}$ may be an appropriate proxy for F_{MSY} and this was presented as a third option to the Panel. Based on all SCALE model runs, the stock in 2007 is at a low biomass level (23% to 45% of B_{MSY}) and is overfished (*assuming a $B_{THRESHOLD}$ of ½ B_{MSY}). The Peer Review Panel concluded that $F_{40\%}$ is a reasonable F_{MSY} proxy and that its value is probably <0.35. The overfishing status is uncertain, and the ratio of F_{2007} to F_{MSY} falls in the range of 56% to 158%. MSY is likely in the range of 138-149 mt and SSB_{MSY} is likely in the range of 794-1,011 mt.

(*Editor's note: This assumption about the definition of $B_{THRESHOLD}$ was confirmed with the Chairman of the Peer Review Panel after the December meeting.)

Section 1. Provide the current exact, legal definitions for overfished and overfishing given in the FMP (if the definition was revised with an official FMP amendment, then give that def.). (NEFSC staff should consult with appropriate RO and Council staff that is on the DPWG to get this info).

NONE

Section 2. List the current Biological Reference Points (parameters and values). (e.g., the proxy for B_{MSY} is the 3-yr average of survey catch per tow from years 19xx to 19yy. The estimate is zzz kg/tow). Include the targets and thresholds for both overfishing and overfished, if those definitions exist.

NONE

Section 3. Explain the logic/justification for why the current definitions were adopted.

NA

Section 4. Explain weaknesses with the current definitions (e.g., not easily measured, not logical, outdated, etc.). If they are OK, say so.

NA

Section 5. (If a change to the BRPs is being recommended by the WG:) Recommend biological reference points (BRPs) and measurable BRP and MSY proxies. Provide justification for the recommendation. Be as specific as possible. If something might be proposed that is not yet measurable, then make that clear and explain what is needed to make it measurable.

A range of biological reference points were available to the Data Poor Stocks Review Panel via the forward projecting SCALE model under various model scenarios. Non-parametric biological reference points (BRP) were developed for both the selectivity L_{50} = 90 run (Run 1) and the slope = 0.15 run (Run 2) within the SCALE model using $F_{40\%}$ as a proxy for F_{MSY}. A range of knife edge maturity values were used in estimating the BRPs. Maturity as 40+ cm, a 65+ cm and 75+ cm cutoffs were used as bounds taken from NEFSC survey results and literature. The Data Poor Working Group suggested $F_{50\%}$, may be an appropriate proxy for a species which is long lived, late maturing and has low fecundity. $F_{50\%}$ BRPs were then developed for the slope =0.15 scenario. SCALE Run 2 was accepted by the Data Poor Stocks Peer Review Panel.

SCALE run	1			2			3		
Selectivity	L_{50} = 90			slope = 0.15			slope = 0.15		
Length of maturity	40	65	75	40	65	75	40	65	75
F_{MSY} proxy	$F_{40\%}$	$F_{40\%}$	$F_{40\%}$	$F_{40\%}$	$F_{40\%}$	$F_{40\%}$	$F_{50\%}$	$F_{50\%}$	$F_{50\%}$
F_{MSY}	0.70	0.51	0.39	0.35	0.25	0.20	0.195	0.154	0.128
F_{max}	> 0.8	> 0.8	> 0.8	0.60	0.60	0.60	0.60	0.60	0.60
YPR	0.871	0.841	0.809	0.854	0.829	0.788	0.783	0.728	0.678
SSB per Recruit	5.987	5.247	4.686	5.792	5.166	4.548	7.629	6.796	6.050
Initial Recruits (000s)	171	171	171	175	175	175	172	172	172
MSY (mt)	149	144	138	149	145	138	135	125	117
SSB_{MSY} (mt)	1,024	898	802	1,011	902	794	1,314	1,171	1,042
SSB_{07} (mt)	405	293	209	457	339	249	447	330	242
F_{07}	0.516	0.516	0.516	0.195	0.195	0.195	0.202	0.202	0.202
SSB_{07}/SSB_{MSY}	40%	33%	26%	45%	38%	31%	34%	28%	23%
F_{07}/F_{MSY}	74%	101%	132%	56%	78%	98%	104%	131%	158%

Section 6. Provide supporting information for Section 5.

Basic Biology and Ecology

Geographic Range

Atlantic wolffish (*Anarhichas lupus*) can be found in northern latitudes of the eastern and western North Atlantic Ocean (Figure 1). In the north and eastern Atlantic they range from eastern Greenland to Iceland, along northern Europe and the Scandinavian coast extending north and west to the Barents and White Sea's. In the northwest Atlantic they are found from Davis Straits off of western Greenland, along Newfoundland and Labrador and continue southward through the Canadian Maritime Provinces to Cape Cod, USA. They are found infrequently in southern New England to New Jersey (Collete and Klein-MacPhee 2002). Northeast Fishery Science Centers Bottom Trawl surveys have only encountered 1 fish southwest of Martha's Vineyard, Massachusetts since 1963.

Habitats

Atlantic wolffish are demersal and prefer complex habitats with large stones and rocks which provide shelter and nesting sites (Pavlov and Novikov 1993). They are occasionally seen in soft sediments such as sand or mud substrate and likely forage for food sources in these habitats (Collete and Klein-MacPhee 2002; Falk-Petersen and Hansen 1991). They are believed to be relatively sedentary and populations localized. Tagging studies from Newfoundland, Greenland and Iceland indicate that most individuals were recaptured within short distances, ~8km, of the original tagging sites (Templeman 1984; Riget and Messtorff 1988; Jonsson 1982). Three significantly longer migrations were reported in Newfoundland ranging from 338 – 853 km (Templeman 1984).

Atlantic wolffish occupy varying depth ranges across its geographic range. In the Gulf of Maine they inhabit depths of 40 – 240 m, in Greenland and Newfoundland 0 – 600 m, in Iceland 8 – 450 m and in Norway and the Barents Sea from 10 – 215 m (Riget and Messtorff 1988; Albikovskaya 1982; Templeman 1984; Jonsson 1982; Falk-Petersen and Hansen 1991). In U.S. waters, abundance appears to be highest in the southwestern portion of the Gulf of Maine, from Jefferies Ledge to the Great South Channel, corresponding to the 100 m depth contour (Nelson and Ross 1992). Similarly, abundance is highest in the Browns Bank, Scotian shelf and northeast peak of Georges Bank areas in the Canadian portion of the Gulf of Maine (Nelson and Ross 1992). Atlantic wolffish in Newfoundland and Icelandic waters were identified as most abundant in depths 101 – 350 m and 40 - 180 m, respectively (Albikovskaya 1982; Jonsson 1982).

Temperature ranges where Atlantic wolffish occurs also deviate slightly with geographic region. Historically in the Gulf of Maine they have been associated with temperatures ranging from 0 – 11.1°C (Bigelow and Schroeder 1953). Bottom temperatures collected from NEFSC bottom trawl surveys where wolffish were encountered range from 0 – 10°C in spring and 0 – 14.3°C in fall. In Newfoundland wolffish thermal habitat ranged from -1.9 – 11.0 °C, Norway from -1.3 - 11 °C and in Iceland and Northern Europe -1.3 – 10.2 °C (Collete and Klein-MacPhee 2002; Falk-Petersen and Hansen 1991; Jonsson 1982). Laboratory studies indicate wolffish can survive a wide span of temperatures -1.7 – 17.0°C and that feeding is negatively correlated with the higher temperature extremes (Hagen and Mann 1992; King et al. 1989).

Reproduction

In general Atlantic wolffish are solitary in habit, except during mating season when bonded pairs form in spring/summer depending on geographic location (Collete, Klein-MacPhee 2002; Keats et al 1985; Pavlov and Novikov 1993). Spawning is believed to occur in September through October in the Gulf of Maine but is likely to depend on temperature and possibly photoperiod (Collete and Klein-MacPhee 2002; Pavlov and Moksness 1994). Spawning is reported to occur from August – September in Nova Scotia, during autumn in Newfoundland, September – October in Iceland, July – October in Norway, and late summer – early autumn in the White Sea (Keats et al. 1985; Templeman 1986; Jonsson 1982; Falk-Petersen, Hansen 1991; Pavlov, Novikov 1993). In the Gulf of Maine there is weak indication of a seasonal migration as wolffish may travel from shallow to deep in autumn and then deep to shallow in spring (Nelson and Ross 1992). Similar migrations occur in Iceland and the White Sea where wolffish migrate to colder temperatures before the spawning season (Pavlov and Novikov 1993; Jonsson 1982). Atlantic wolffish have the lowest fecundity compared to their relatives, the spotted wolffish (*Anarhichas minor*) and the northern wolffish (*Anarhichas denticulus*). Fecundity is related to fish size and body mass in this species and increases exponentially with length. Newfoundland mean fecundity estimates, combined from several NAFO statistical areas, range from 2,440 eggs at 40 cm to 35,320 eggs at 120 cm (Templeman 1986). In Norway a female at 60 cm produces approximately 5,000 eggs while a female 80-90 cm will lay 12,000 eggs (Falk-Petersen and Hansen 1991). Potential fecundity of wolffish in Iceland was measured between 400 and 16,000 eggs for fish at lengths of 25 and 83 cm respectively (Gunnarsson et al. 2006). Mature eggs are large measuring 5.5 – 6.8 mm in diameter (Colette and Klein-MacPhee 2002). Male Atlantic wolffish have small testes and produce small amounts of sperm peaking during late summer and autumn. These data along with morphological development of a papilla on the urogenital pore during spawning suggest internal fertilization (Pavlov and Novikov 1993; Pavlov and Moksness 1994, Johannessen et al 1993). Males have been observed guarding egg clusters for several months but it is not certain if they continue until hatching (Keats et al. 1985; Collete and Klein-MacPhee 2002). Hatching may take 3 to 9 months depending on temperature (Collete and Klein-MacPhee 2002).

Food Habits

The diet of Gulf of Maine and Georges Bank wolffish consist primarily of bivalves, gastropods, decapods and echinoderms (Nelson. Ross 1992). Wolffish possess specialized teeth, including protruding canine tusks (hence its name) and large rounded molars, which allow for removal of organisms from the sea floor and crushing of hard shelled prey (Collete and Klein-MacPhee 2002). Due to diet teeth are replaced annually (Albikovskaya 1983; Collete and Klein-MacPhee 2002). Fish have also been reported as an important food source in other regions along with amphipods and euphausiid shrimp for smaller individuals, 1 – 10 cm (Collete and Klein-MacPhee 2002; Albikovskaya 1983; Bowman et al. 2000). Travel between shelters and feeding grounds occurs during feeding periods as evidenced by crushed shells and debris observed in the vicinity of occupied shelters (Collete and Klein-MacPhee 2002; Pavlov and Novikov 1993). Fasting does occur for several months while replacing teeth, spawning and nest guarding occurs (Collete and Klein-MacPhee 2002).

Size

In the Gulf of Maine and Georges Bank regions individuals may attain lengths of 150 cm and weights of 18 kg (Goode 1884; Idoine 1998). Northeast Fishery Science Center bottom trawl surveys have captured animals ranging in size from 3 – 137 cm in spring and 4 – 120 cm in fall and with a maximum weight of 11.77 kg.

Age and Growth

Mean length at age for Atlantic wolffish in the Gulf of Maine was determined to be 22 years at 98 cm and 0 years at 4 cm (Nelson, Ross 1992). Fish over 100 cm were not sampled extensively in this study, 10 fish from 100-118 cm. Ages in the Gulf of Maine are comparable to wolffish ages in other regions, such as 21 years in east Iceland and 23 years in Norway (Gunnarsson et al. 2006; Falk-Petersen and Hansen 1991). Age 0 fish grow quickly in Icelandic waters and may reach 10.5 cm in the first year (Jonsson 1982). Gulf of Maine wolffish growth rates are faster than wolffish in Iceland, but grow fastest in the North Sea region (Nelson and Ross 1992; Liao and Lucas 2000). Growth in the Gulf of Maine for both male and female wolffish was best estimated using a Gompertz growth function, $L\infty = 98.9$ cm, $K = 0.22$ and $t_0 = 4.74$ (Nelson and Ross 1992). Female growth from Iceland has been modeled using a logistic growth function and coefficients estimated using non-linear optimization (Gauss-Newton method), results from the east and west regions were: $L\infty = 90.919$, $K = 0.230$ and $t_0 = 8.837$ and $L\infty = 70.046$, $K = 0.378$ and $t_0 = 4.691$, respectively (Gunnarsson et al. 2006). Von Bertalanffy growth parameters for the North Sea population of wolffish were $L\infty = 111.2$, $K = 0.12$ and $t_0 = -0.43$ and $L\infty = 115.1$, $K = 0.11$ and $t_0 = -0.39$, for males and females respectively (Liao and Lucas 2000).

Maturity

In the Gulf of Maine individuals are believed to reach maturity by age 5-6 when they reach approximately 47 cm total length (Nelson, Ross 1992; Templeman 1986). Size at fifty percent maturity (L_{50}) of females varies latitudinally which is likely due to the effects of temperature. Templeman (1986) showed that northern fish mature at smaller sizes than faster growing southern fish in Newfoundland. L_{50} was reported as 51.4 cm in the northern area, 61.0 cm in the intermediate region and 68.2 cm in the south. In a study somewhat contradictory to Templeman 1986, Atlantic wolffish in east Iceland, where water temperatures are colder, had larger L_{50} values than fish in the relatively warmer waters of east Iceland (Gunnarsson et al. 2006). Authors indicate that maturity may be difficult to determine using visual methods in females because of large eggs size in this species. Second generation eggs are visible in young, immature fish when the reach the cortical alveolus stage but they may not be able to spawn for several more years (Gunnarsson et al. 2006; Templeman 1986).

The US Fishery

Landings and Total Catch

NMFS Commercial Fishery Databases contain historical and current catch and effort information of Atlantic wolffish, 1963 - 2007. Data presented here are only from fishery statistical reporting areas that are completely or almost entirely within US territorial waters throughout the time series (Figure 2). The International Court of Justice in 1984 established the maritime boundary in the Gulf of Maine, known as the Hague Line, which divided US and

Canadian Exclusive Economic Zones (ICJ 1984). In 1985 fishery statistical areas 523 and 524, which overlapped the US/Canada boundary in the Georges Bank region, were separated into distinct areas 551, 552, 561 and 562 Figure 2). Disaggregating United States and Canadian landings data in areas 523 and 524 prior to 1985 was not possible so they are not reported here. Also not reported are landings in the newly created areas in US waters because they do not span the entire time frame.

US landings increased until it peaking in 1983 at 498.1 metric tons (mt) and then decline steadily until 2007, the latest complete year available, where landings were 28.7 mt (Figure 3 and Table 1). In the US, Atlantic wolffish are taken primarily as bycatch in the otter trawl fishery. Over all years, percent commercial landings of wolffish were dominated by otter trawl gear (92.24%), followed by fixed gillnets (3.76%) and bottom tending longlines (2.83%) (Figure 4). However, otter trawls have decreased in importance over time as evidenced by increased reported landings of gillnets and longlines (Appendix 1). Otter trawl gear accounted for a minimum of 74% to a maximum of 99% of the wolffish landings from 1964 to 2007 (Appendix 1). Fixed gill nets and bottom tending longline fisheries account for the majority of remaining landings.

Reported US commercial wolffish landings come primarily from fishery statistical areas 513, 514, 515, 521 and 522 (Figure 5 and Table 2). Landings have fluctuated between statistical areas over time and spatial differences may be difficult to interpret due to management actions, such as permanent closures and rolling time closures, in the Gulf of Maine.

Commercial fishery discards from the Northeast Fisheries Observer Program database were estimated for the period 1989-2007 from US only statistical areas based on the Standardized Bycatch Reporting Methodology combined ratio estimation (Wigley et al 2007). Discards appear to be a small component of the overall catch of Atlantic wolffish (Figure 7 and Table 1). The maximum estimated discards in any one year are 26.98 mt, 1989 (Table 3). Otter trawls account for 98.3% of the total discarded wolffish from all years. Discards appear to be increasing in the gillnet sector, which reported approximately 17% of the total wolffish discarded for 2007 (Table 3).

Recreational catch data was retrieved from the MRFSS database (Figure 6 and Table 4). Landings are reported in total number of fish and total weight per year. Landings include both A and B1 fish, these are fish permanently removed from the population. B2 fish are discarded live and are assumed to have survived. Adjusted landings were developed because average weight of an individual wolffish was highly variable. Average weight (kg) was calculated based on the reported numbers of landed fish (A + B1) divided by the reported landed weight (kg). A grand mean was calculated from average weights and used in the new adjusted landings values. Adjusted landing are less variable than the original reported values and are likely to describe the recreational portion of total catch. Recreational catches have become more significant in recent years as commercial landings have steadily declined (Figure 7 and Table 1). Recreational catch makes up 30% of the total catch and is almost half a large as commercial landings for 2007 (Table 1).

Total Catch is comprised of reported landings, estimates of commercial discards from the primary fishery sectors and recreational catch from US waters as previously described (Figure 7 and Table 1). Recreational catches begin in 1981 and discard estimates begin in 1989. Total US catch peaked in 1983 with 510.82 mt and has decreased steadily reaching a low of 42.43 mt in 2007.

Commercial Lengths Data and CPUE

Fishery observers collect length samples at sea opportunistically providing information on the size structure of the population. Observer lengths have been collected since 1989. Sample sizes from early in the time series are low but have exceeded 100 samples per year during 2003-2007 (Table 5). Median length has been variable over time but increased slightly during the 2003-2007 period indicating that larger fish are being harvested (Figure 8). Differences in length composition by commercial gear types were also plotted (Figure 9). Sample sizes are small in all gears except for otter trawl and gillnet, where size distributions and median values are similar (Table 6).

Commercial lengths from port samples have been taken irregularly during the span of the commercial fishery. A significant amount of samples were collected during 1982 – 1985 and have also been taken consistently since 2001. Commercial port sample length distributions were plotted by year (Figure 10). An increase in median length can be seen during the 2001 – 2007 time period. The median has increased from 75 cm in 2001 to 84 cm in 2007 (Table 7). This data suggests that size in the commercial fishery may be increasing as the 95% confidence intervals from the 2001-2003 period do not overlap with the 2004-2007 period. Differences were then examined to see if the increase could be explained by major gear type since longlines, and gill nets have become a larger component of the fishery (Figure11). Slight differences were observed in the size compositions of the various gears but this may be an artifact of low sample size of commercial gears other than otter trawls (Table 8). Commercial length samples were also plotted by statistical area to determine if any geographic trend in size could be seen (Figure 12). The primary fishery areas, 512-522, show similar length distributions. Areas 526 and 537 had anomalous length distributions but also had low sample sizes (Table 9).

Indices of catch per unit of effort (CPUE) were calculated from fishery observer trips and self reported Vessel Trip Reports (VTRs) in party and charter boat sectors for Atlantic wolffish. Observer CPUE was estimated for 1989-2007 in the longline, gillnet and otter trawl fisheries for US statistical areas 512-515, 521-522, 525-526 and 537 (Table 10). CPUE was calculated based on the ratio: sum of kept wolffish per year / sum of days fished per year. Observer CPUE has declined in the 3 fishing sectors reviewed (Figure 13). Atlantic wolffish CPUE for the longline fishery is plotted on the second y-axis as it is significantly higher than the otter trawl and gillnet sectors.

Party and Charter boat CPUE have also declined (Figure 14; Table 11). These indices were calculated from the number wolffish reported landed on VTRs and angler days fished. Angler days fished was estimated by number anglers * hours fished / 24 per year for all party and charter trips in areas 514 and 515.

Research Vessel Survey Data

Survey Length, Weight and Maturity

Atlantic wolffish catches were grouped by decade to reduce data gaps in length frequency plots. Distributions were plotted using proportion at length and number at length (Figures 15 and 16). The numbers at length graphs show an overall reduction in numbers by decade across the length range of Atlantic wolffish. The proportion at length graphs indicate that different size fish are available to the bottom trawl gear in spring and fall. In general, spring survey encounters larger individuals (>= 50 cm) and the fall survey captures smaller individuals ranging from 10-30 cm.

The spring survey also captures a unique distribution of small individuals, less than or equal to 7 cm, and may be used as a juvenile index.

Length weight relationships were developed for Atlantic wolffish from NEFSC bottom trawl survey data. Spring and fall survey data were combined to create one relationship for both male and female fish as no differences were found between seasons or sexes (Figure 17). Linear regression of log transformed data provided a good fit, $R^2 = 0.996$.

A logistic maturity ogive was developed for female Atlantic wolffish based on spring and fall survey vessel data (Figure 18). L_{50} was estimated at approximately 35 cm from these data. This L_{50} for female wolffish is lower than estimates reported in Newfoundland and Iceland where females containing second generation eggs were considered immature (Templeman 1986; Gunnarsson et al. 2006). NEFSC maturity data is based on visual inspection of the reproductive organs. Fish are classified into 1 of 7 stages of maturity (Burnett et al 1989). Fish classifications for females include immature, developing, ripe, eyed (unique for redfish), ripe and running, spent and resting. This analysis considered fish that were in the developing through resting stages as a mature and immature were those fish that contained no visible eggs. Size at maturity may be difficult to interpret for wolffish from these data as they may have an additional developing stage, or a set of second generation eggs which may last for several years, where fish are reproductively immature (Gunnarsson et al. 2006). These immature fish would likely be classified as developing in NEFSC surveys and were considered mature in the ogive thereby reducing the size at 50% mature.

Biomass and Abundance

Atlantic wolffish are encountered infrequently on NEFSC bottom trawl surveys. Strata used in wolffish analyses were limited to offshore areas completely or almost completely within US waters (Figure 19). Some historically important strata were excluded from this analysis, specifically on the Canadian portion of Georges Bank, but due to the sedentary nature of this fish it is believed to have not affected the estimation of the indices or overall trends in US waters (Figures 20 &21). Sampling effort per survey stratum in the Gulf of Maine has remained relatively consistent over most of the time series (Figure 22). The timing of the surveys in the Gulf of Maine has also been consistent during the spring and fall. Inshore sampling did not commence until the mid 1970's and was therefore not used. Higher sampling intensity did occur in portions of the 1970's and 1980's in select survey stratum but elevated abundance and biomass are not likely due to increased sampling effort (Figure 23).

In general the NEFSC spring and fall bottom trawl survey indices show abundance and biomass of Atlantic wolffish has declined over the last two to three decades (Figure 24.). The spring survey typically encounters higher abundance and biomass than the fall survey and was considered by the Data Poor Working Group to be optimal for assessing resource trends (Table 1). Survey differences may be attributed to wolffish being less available to the sampling gear while nest guarding in the fall (Colette and Klein-MacPhee 2002). Inter-annual variability among both surveys is high.

The spring biomass index averaged 0.786 kg/tow and ranged between 0.38 and 1.44 kg/tow from 1968 to 1988. Since the mid to late 1980's the resource has steadily declined. The average spring biomass index for 1989-2007 was 0.143 kg/tow, only 18% of the 1968-1988 average, and ranged from 0.0 kg/tow to 0.42 kg/tow. The fall biomass index shows little trend over time and is relatively low over most of the time series (Figure 24). A large anomalous peak in biomass appears in 1982 but is not seen again in subsequent years. Since the mid 1990's wolffish biomass has fluctuated with a slightly declining trend.

Abundance indices in both surveys show a decline in stratified mean number per tow since the mid 1990's. 3 year centered moving average plots of abundance and biomass removes the inter-annual variability within the indices and depicts an overall declining trend in the resource (Figure 25).

Spring and fall percent positive Atlantic wolffish catch was plotted by year (Figure 26). This type of index for species rarely captured can be a good indicator of how frequently rare events occur over time. These indices indicate that the number of survey tows catching at least one wolffish has decreased with time in both the spring and fall. The spring index shows an almost continuous declining trend since the late 1970's/early 1980's, averaging around 12% and dropping to approximately 2%. The fall index appears relatively stable from the mid 1960's through the early 1990's, fluctuating around 6 %. It then declines quickly from 1993 to 1996 and becomes relatively stable again near 2 % until 2007 where it reaches zero.

The spatial distribution of Atlantic wolffish has contracted according to the spring and fall bottom trawl surveys. Data were grouped by decade and survey catch in numbers were displayed using GIS (Figures 27 and 28). The spring survey shows high catch along Jefferies Ledge, Stellwagen Bank National Marine Sanctuary and off outer Cape Cod through the Great South Channel during the 1970's and 1980's. Catches in the 1990's extend across a similar area but appear with less abundance and frequency. Highest catches during the 2000's are limited to Stellwagen Bank region. A similar pattern emerges from fall survey catches and the resource appears to be more concentrated within the Jefferies Ledge and Stellwagen Bank regions. During the 1990's and 2000's catches are smaller and appear less frequently in the fall.

Modeling Results

SCALE Model

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) 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 (NOAA Fisheries Toolbox 2008a). 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 mean length at age are essential for reliable results. The model assumes static growth and therefore population mean length/weight at age are assumed constant over time. A depiction of model assumed population growth at age using the input mean lengths at age and variation can be seen in table 12 and Figure 29).

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 can not 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 $\sum(\text{Vrec})^2$ is than 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:

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

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

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

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

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

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

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.

Wolffish SCALE Model Configuration and results

Mean lengths at age and variation in mean length at age were based on fish collected during the 1980s from Nelson and Ross (1992). A Gompertz relationship had the best fit using all ages. We have re-estimated a von Bertalanffy relationship using data limited to fish older than 4 with L-infinity fixed at 110 cm (Figure 30). The mean lengths from Nelson and Ross's Gompertz relationship for fish younger than age 5 were also used in the SCALE model. The mean lengths from the younger fish do not have a large effect on the SCALE model results. In the final growth model we fixed L-infinity (110) at a slightly higher value than what was estimated by the Gompertz (98.9) model because few larger and older fish exist in Nelson and Ross's study and the SCALE model had difficultly predicting larger fish that are in seen in the catch length frequency distributions. A North Sea wolffish growth study estimated L-infinity at 111 for males and 115 for females (Liao and Lucas, 2000). Figure 31 shows the predicted catch length distribution under low Fs (F=0.001) assuming different L-infinities. A standard deviation of 6 was used for fish older then age-7. The assumed variation around the mean lengths at age can be seen in Table 12 and Figure 29. Nelson and Ross's oldest fish was 22 years. The age matrix was dimensioned from ages 1 to 30 with an assumed natural mortality of 0.15.

Only one recruitment index exists in the SCALE model (Figure 32). The spring NEFSC survey shows a distinct mode between 1 and 7 cm. This index was tuned to age-1. The recruitment index suffers from zero catches in many years and at times in blocks of several years. A 40+ cm index was developed from the NEFSC spring, NEFSC fall and the MDMF spring survey (Figure 33). All three surveys show declining trends in abundance with the indices also suffering from zero catches at the end of the time series. The survey length frequency distributions are limited due to the low numbers of wolffish caught in the surveys. There is concern that biomass may have fallen below detection in the surveys. Preliminary evidence suggests the Bigelow survey may also suffer from the same low catchablility issue. Survey indices were scaled using the approximate area of survey coverage divided by the average coverage of a survey tow (Table 13). The area swept estimates can provide some insight from estimated survey efficiencies using the estimated Qs in the SCALE model.

Zero catches were set to missing in the SCALE model. Setting zeros to the smallest value in the time series appears to have a large unsubstantiated influence on the model results. The age-1 recruitment series was given a relatively low weight (Table 14). Setting the weight to high on the recruitment index will force SCALE to fit the recruitment index very closely but the model is less constrained in estimating recruitment for years where recruitment information is missing which can produce unrealistic results. The age-1 index was used more as a guide with setting the penalty on recruitment variation. The penalty on recruitment variation was set high enough to produce recruitment variation within the bounds of what was observed in the recruitment index. The model has to estimate a declining trend in recruitment to fit the decline in the 40+ cm indices and the declining trend in the catch since 1983. The recruitment index was used as guidance on whether recruitment failure has occurred for the wolffish stock. Sensitivity of the model to the weighting on the recruitment index and the penalty on variation in recruitment can be seen in Figures 34 through 37.

The catch length frequency distributions are an important component of the SCALE model. Observer trawl kept length sampling and port samples where combined to characterize the catch size distributions. Catch length frequency information exists from 1982 to 1985 and from 2001 to 2007. A single selectivity block over the time series was used due to the lack of a distinct shift in the size distribution and due to the lack of size information in many years. There is no indication of size truncation in the catch length frequency distributions over time.
The lack of data prevents the SCALE model from estimating a reliable logistic selectivity curve. The SCALE model estimates a very flat selectivity curve that produces a L-50 at very large sizes. There is a tradeoff in the SCALE model between the estimated selectivity and fishing mortality rates. Two different selectivity regimes were chosen to determine its influence of stock status determination (Figure 38). Run one had a relativity flat selectivity curve which was allowed to hit the L-50 bound of 90 cm. Run two was setup to hit the slope parameter bound of 0.15 which produces a steeper selectivity function with a lower L-50 estimate. Results of the two selectivity runs are summarized in Figures 39-42 and Table 14.

The SCALE model time series starts in 1968 with the beginning of the NEFSC spring index. The SCALE model estimates virgin conditions at the beginning of the time series with a low Fstart estimate (0.001) in 1968 when the catch was low. A strong retrospective pattern did not exist with the Slope = 0.15 run (Figure 43). The sensitivity of the assumed L-infinity for growth on the model estimated Fs and recruitment can be seen in Figure 44.

Non-parametric biological reference points (BRP) were developed for both the selectivity L-50 = 90 run (Run 1) and the slope = 0.15 run (Run 2) within the SCALE model using $F_{40\%}$ as a Proxy for F_{MSY} (Table 15). A range of knife edge maturities values were used in estimating the BRPs. Maturity as 40+ cm fish was used to correspond to NEFSC survey maturity results, a 65+

cm and 75+ cm cutoffs were used as bounds taken from the Gunnarsson et al (2006) and Templeman (1986). Templeman found maturation occurring at larger sizes in lower latitudes. However Gunnarsson et al (2006) found maturation occurring at larger sizes in the colder waters on the eastern side of Iceland compared to the western side. The Data Poor Stocks Working Group suggested that $F_{50\%}$ may be a better proxy of F_{MSY} for a species that is long lived, late maturing, and has low fecundity. $F_{50\%}$ BRPs were developed for the Slope = 0.15 run (Table 15 and Figure 45). The $F_{50\%}$ BRPs are based on run 3 incorporating some minor fixes to the catch and catch length frequency (1986) data which were found after the working group meeting (Figures 46-48). Based on all SCALE model runs, the wolfish stock in 2007 is at a low biomass (23% to 45% of B_{MSY}) and is overfished (*assuming a $B_{THRESHOLD}$ of ½ B_{MSY}). The overfishing status determination was more uncertain with F_{2007} to F_{MSY} ratios ranging from 56% to 158%. The Peer Review Panel concluded that $F_{40\%}$ is reasonable and justifiable and that the F_{MSY} proxy < 0.35 is most probable. Therefore, MSY is likely in the range of 138-149 mt and SSB_{MSY} are likely between 794-1,011 mt.
(*This assumption was confirmed by the Chairman of the Peer Review Panel after the December meeting.)

Exploitation Ratios

Exploitation indices were created from reported wolffish catch and spring and fall biomass estimates (Figures 49; Table 1). Exploitation appears to have increased and could indicate this species is being over harvested even at low level commercial catches. Due to low survey catches some values cannot be shown on the chart. The spring exploitation index peaks at a value of 2,135.2 in 2004 and fall exploitation index contains 2 high points at approximately 20.1 in 1998 and 35.2 in 2006. Exploitation ratios were informative to the Review Panel but were considered to be highly variable.

DCAC Model

The DCAC model input consists of summed annual catch, an estimate of *M*, an estimate of the F_{MSY} to *M* ratio, the ratio of catch depletion over time and the number of years being analyzed (NOAA Fisheries Toolbox 2008b). It calculates a sustainable yield of a population after accounting for the “windfall” which occurs at the beginning of a fishery. When natural mortality is high, the DCAC model is the same as calculating the average landings. We conducted a sensitivity analysis of the delta depletion parameter over several time blocks to look at potential sustainable yields (Figure 50; Table 16). All of the time blocks cover the majority of the fishery and include high, moderate and low catch levels. The depletion-corrected average catch was significantly lower than the uncorrected average catch in each time block. Time block did not affect the DCAC but the delta depletion ratio has strong influence. DCAC results ranged from 138.8 mt to 176.6 mt and the Data Poor Stocks Review Panel believed were comparable to and supportive of the MSY values derived from the SCALE model.

AIM – An Index Method

The relationship between total catch of Atlantic wolffish and the spring biomass was explored using the An Index Method (AIM) model (NEFSC 2002 and NOAA Fisheries Toolbox 2008c). Both catch and the survey index have been declining over time with little response of the spring index to declining catches (Figure 51). The linear regression between the $\log_e$ replacement ratio and $\log_e$ relative F was not significant in a randomization test, critical value -0.385 and a significance level of 0.134 (Figure 52). This model was considered insufficient for providing results on Atlantic wolffish by the Review Panel.

Section 7. Provide advice about scientific uncertainty and risk for Scientific and Statistical Committees (SSCs) to consider when they develop fishing level recommendations for these stocks.

Major sources of uncertainty include:

1. Life history – size at maturity, age composition, $L\infty$ within the Gulf of Maine
2. Catchability in NEFSC bottom trawl surveys
3. Commercial length compositions and impacts to SCALE Model
4. Interpretation of 0 catches in recent years – modeling implications
5. Discard information from commercial fisheries
6. Habitat association is poorly known

The Data Poor Stocks Review Panel expanded upon this list of uncertainties. They included natural mortality, maximum age, fecundity and the connectivity of populations on Georges Bank and in the Gulf of Maine for important biological uncertainties. They included scientific uncertainty of the survey indices because populations are at the southern extent of the species range and may exhibit wide changes in distribution. Uncertainties from fisheries data include unknown harvest by foreign fleets and the extent of unreported catches and discards. The Review Panel believed that process uncertainty resulted from the lack of size truncation in commercially harvested fish, which indicated that fishing effort alone may not be responsible for changes in abundance. They suggest lack of preferable habitat may be considered as a viable alternative hypothesis. Model uncertainties include high survey catchability coefficients for pre and fully recruited sizes and the sensitivity of BRPs to maturity ogives and fishery selectivity curves. The Review Panel concluded that stock projections would be unreliable and should not be conducted because of the interpretation of zero catches in the survey data.

Section 8. If applicable, consider developing BRPs for species groups

NA

Section 9. Comment on what can be done to improve the information, proxies or assessments for each species.

Much work could be done to improve information on the basic biology of Atlantic wolffish in the Gulf of Maine. Age and growth data from both commercial and fishery independent sources needs to be collected to improve life history information, specifically L infinity. Conduct a maturity study based on egg size or first generation eggs in female wolffish to improve size at maturity estimates. Estimate fecundity for Gulf of Maine wolffish. Conduct tagging studies to confirm populations are sedentary and localized. Collect fishery observer data from more fishery sectors including the offshore lobster fishery. Comparative studies on wolffish catchability in multiple habitats, including complex rock habitat, with NEFSC survey gear and commercial gear types. A fishery independent index for wolffish should be developed for assessing potential biomass located in rocky habitats.

The Review Panel prioritized a list of research recommendations, including those mentioned above, to reduce uncertainty surrounding the biology, population dynamics and biological reference points of Atlantic wolffish.

1. Exploration of the relationship between survey catch per tow and habitat complexity and environmental signals should continue. These studies will aid understanding of the relationship between survey estimates and population abundance.
2. Age and growth studies for wolffish in the NE/GOM region should be conducted to refine estimates of $L\infty$.
3. Maturity ogive data are currently based on simple presence of eggs in females, and do not account for functional maturity which requires presence of larger eggs. The review team believed the current approach is inadequate. Regional maturity ogives should be developed.
4. The review team recommended that a fixed gear survey be considered to assess abundance in non trawlable habitats.
5. Tagging studies should be conducted to explore and quantify the vagility of wolffish to help improve understanding of population structure and connectivity.

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