A. GULF OF MAINE COD

EXECUTIVE SUMMARY

The status of the Gulf of Maine cod (*Gadus morhua*) stock is reviewed, and terminal year VPA estimates of 2000 fishing mortality and spawning stock biomass and the survivors in 2001 are presented. Precision estimates of the 2000 fishing mortality and spawning stock biomass estimates for Gulf of Maine cod are also provided. Short-term projections of 2002 catches and resulting 2003 spawning stock biomass at various levels of 2002 fishing mortality are also given. Long-term (25-yr) projections were conducted to evaluate relative trajectories of stock biomass and catch under various fishing mortality scenarios, and an age-structured production model was applied to estimate MSY-based reference points.

The 2001 assessment is based on several sources of information including: the age composition of USA commercial and recreational landings, commercial fishing vessel trip reports (VTR), NEFSC sea sample data, MRFSS estimates of recreational harvest, Northeast Fisheries Science Center (NEFSC) and Massachusetts Division of Marine Fisheries (DMF) spring and autumn research vessel survey data, and standardized USA commercial fishing effort data. This assessment updates the analyses presented in the 1998 assessment of the Gulf of Maine cod stock (Mayo *et al.* 1998) as well as those prepared in 1999 and 2000 by the Northern Demersal Working Group (NEFSC 2000, 2001).

Total landings of Gulf of Maine cod equaled 4,156 metric tons (mt) in 1998, declined to 1,636 mt in 1999, and increased to 3,730 mt in 2000. The sharp decline in landings between 1998 and 1999 and the subsequent increase in 2000 likely reflects the imposition of very low trip limits during 1999 and the subsequent relaxation of these limits in early 2000. It is probable that the extent of discarding increased sharply in 1999 in response to these reduced trip limits.

Commercial landings per unit of standardized effort declined steadily between 1982 and 1987, increased during 1988-1990 but declined sharply in 1992 and remained low in 1993. Fishery-independent spring and autumn bottom trawl surveys conducted by the NEFSC have documented a steady decline in total stock biomass since the 1960s; the largest decreases occurred during the 1980s. Although the most recent indices suggest a slight increase, overall, the Gulf of Maine cod stock biomass remains low relative to the 1960s and 1970s. Except for the 1998 year class, recent recruitment has been well below average.

Fully recruited fishing mortality appears to have declined slightly during 1998 - 2000 compared to pre-1998 fishing mortality rates although F in 2000 (0.73) remained very high relative to fully recruited F reference points ($F_{0.1}$ = 0.15; F_{max} = 0.27). Spawning stock biomass (SSB) declined from over 24,200 mt in 1990 to a low of 9,900 mt in 1998, but increased to 13,100 mt in 2000.

Total stock biomass (ages 1+) declined from a maximum of 41,900 mt in 1990 to 14,800 mt in 1998, but has since increased to 20,400 mt in 2000. Mean biomass for ages 1+ declined from a maximum of 42,700 mt in 1989 to 14,800 mt in 1997 and 1998, but increased sharply between 1999 and 2000 to 25,900 mt, due, in part, to the impact of the 1998 year class. B_{msy} is now estimated to be 90,300 mt (total stock biomass, ages 1+) with a corresponding F_{msy} of 0.23, (fully recruited, ages 4+). With respect to the age-structured MSY-based reference points, total stock biomass is slightly above 1/4 B_{msy} and F is over 3 times F_{msy}.

TERMS OF REFERENCE

The following Terms of Reference were provided by the Stock Assessment Workshop (SAW) Steering Committee as the context for this assessment of Gulf of Maine Cod reviewed by the Stock Assessment Review Committee (SARC) 33 in June, 2001.

(A) Update the status of the Gulf of Maine cod stock, providing, to the extent practicable, estimates of fishing mortality and stock size. Characterize uncertainty in estimates.

(B) Provide updated estimates of biological reference points (biomass and fishing mortality targets/thresholds), or appropriate proxies, based on available population data.

(C) Provide projections of biomass in 2002 and 2003 and catch in 2002 under various fishing mortality rate options.

INTRODUCTION

Atlantic cod (*Gadus morhua*) in the Gulf of Maine region have been commercially exploited since the 17th century, and reliable landings statistics are available since 1893. Historically, the Gulf of Maine fishery can be separated into four periods (Figure 1): (1) an early era from 1893-1915 in which record-high landings (> 17,000 mt) in 1895 and 1906 were followed by about 10 years of sharply-reduced catches; (2) a later period from 1916-1940 in which annual landings were relatively stable, fluctuating between 5,000 and 11,500 mt, and averaging 8,300 mt per year; (3) a period from 1941-1963 when landings sharply increased (1945: 14,500 mt) and then rapidly decreased, reaching a record-low of 2,600 mt in 1957; and (4) the most recent period from 1964 onward during which Gulf of Maine landings have generally increased but have declined steadily since the early 1990s. Total landings doubled between 1964 and 1968, doubled again between 1968 and 1977, and averaged 12,200 mt per year during 1976-1985. Gulf of Maine cod landings subsequently increased, reaching 17,800 mt in 1991, the highest level since the early 1900s. Total landings declined sharply in 1992 to 10,891 mt, and have since decreased steadily to 1,636 mt in 1999 before increasing to 3,730 mt in 2000.

This report presents an updated and revised analytical assessment of the Gulf of Maine cod stock (NAFO Division 5Y) for the period 1982-2000 based on analyses of commercial, recreational and and research vessel survey data through 2000. From the early 1960s through 1993, information on the catch quantity by market category was derived from reports of landings transactions submitted voluntarily by processors and dealers. More detailed data on fishing effort and location of fishing activity were obtained for a subset of trips from personal interviews of fishing captains conducted by port agents in the major ports of the Northeast. Information acquired during the course of these interviews was used to augment the total catch information obtained from the dealer. Procedures for collecting and processing commercial fishery data in the Northeast were revised after 1993.

Beginning in 1994, data on number of hauls, average haul time, and catch locale were obtained from logbooks submitted to National Marine Fisheries Service (NMFS) by operators fishing for groundfish in the Northeast under a mandatory reporting program. Estimates of total catch by species and market category were derived from mandatory dealer reports submitted on a trip basis to NMFS. Catches (landed and discarded portions) by market category were allocated to stock based on a matched subset of trips between the dealer and logbook databases. Data in both databases were stratified by calendar quarter, port group, and gear group to form a pool of observations from which proportions of catch by stock could be allocated to market category within the matched subset. The cross-products of the market category by stock proportions derived from the matched subset were employed to compute the total catch by stock, market category, calendar quarter, port group, and gear group in the full dealer database. A full description of the proration methodology and an evaluation of the 1994-1996 logbook data is given in Wigley *et al.* (1998) and DeLong *et al.* (MS 1997).

An initial analytical assessment of this stock was presented at the Seventh NEFSC Stock Assessment Workshop in November 1988 (NEFSC 1989) and subsequent revisions were presented at the 12th, 15th, 19th, 24th and 27th Northeast Regional Stock Assessment Workshops in June 1991, December 1992, December 1994, June 1997 and December 1998 (NEFSC 1991, 1993, 1995, 1997, 1998; Mayo 1995, 1998; Mayo *et al.* 1993, 1998). Interim assessments were reviewed by the Northern Demersal Working Group in 1999 (NEFSC 2000) and 2000 (NEFSC 2001).

THE FISHERY

Management History

Fishing for Gulf of Maine cod had been managed under international treaty prior to 1977 and by domestic management authority since 1977 (Table A1). Annual Total Allowable Catches (TACs) were first established under the International Commission for the Northwest Atlantic Fisheries (ICNAF) for Division 5Y (i.e., the Gulf of Maine) cod in 1973. The TAC remained at 10,000 mt from 1973-1975; the 1976 TAC was reduced to 8,000 mt and the TAC proposed for 1977 was reduced further to 5,000 mt.

Following implementation of the Magnuson Fishery Conservation and Management Act (FCMA) in 1977, management of this stock fell under the auspices of the New England Fishery Management Council. TACs were carried forward for the first few years under the Fishery Management Plan for Atlantic Groundfish, and were distributed among vessel tonnage classes and quarters of the years until 1982 when the “Interim” Plan for Atlantic groundfish was implemented. This plan eliminated all direct catch controls (quotas) and established mesh size and minimum landing size regulations as the primary regulatory measures for cod, haddock and yellowtail flounder.

Management of the Gulf of Maine cod fishery has been carried out since 1985 under the Northeast Multi-species Fishery Management Plan (FMP). This plan and its Amendments 1 through 4 essentially carried forward the regulatory measures originally implemented in 1982 under the "Interim" Plan. Beginning in 1994, with the implementation of Amendment 5, the primary goal of the FMP became a reduction in fishing mortality for 5 key monitoring stocks. This was to be achieved through a combination of reductions in days at sea (DAS) usage and, under Amendment 7, an additional series of seasonal and year-round area closures oriented primarily towards Gulf of Maine stocks.

Commercial Fishery Landings

Annual commercial landings data for Gulf of Maine cod in years prior to 1994 were obtained from trip-level detailed landings records contained in master data files maintained by the Northeast Fisheries Science Center, Woods Hole, Massachusetts (1963-1993) and from summary reports of the Bureau of Commercial Fisheries and its predecessor the U.S. Fish Commission (1895-1962). Beginning in 1994, landings estimates were derived from dealer reports prorated to stock based on the distribution of reported landed catch contained in fishing vessel logbooks as described above.

Total commercial landings in 2000 were 3,730 mt, approximately 130% greater than in 1999 but 10% less than in 1998 (Table A2, Figure A1). Since 1977, the USA fishery has accounted for all of the commercial catch. Canadian landings reported as Gulf of Maine catch during 1977-1990 are believed by Canadian scientists to be misreported catches from the Scotian Shelf stock (Campana and Simon 1985; Campana and Hamel 1990). Although otter trawl catches account for most of the landings (54% by weight in 2000), the otter trawl percentage has declined considerably compared to the period prior to 1993. Most of this change can be attributed to an increase in the percentage of cod taken by sink gillnets since 1993, although the percentage from combined handline and line trawls also increased substantially during the 1990s (Table A3).

Commercial Fishery Discards

Discard rates have been routinely calculated for Gulf of Maine cod by quarter and gear from NEFSC sea sampling data collected since 1989 (Table A4). Discard and kept components of the catch were summed for all observed tows, within each gear type, occurring in Division 5Y, and the ratio of the discarded- to-kept quantity was applied to landings for the corresponding quarter and gear type within each year. Data were available for otter trawls, shrimp trawls, and sink gillnets.

For otter trawl gear, discard-to-kept ratios (D/K) and absolute quantities of discarded cod declined from relatively high values in 1989 and 1990 to relatively low levels from 1991 through1998 as D/K ratios generally fluctuated between 0.002 and 0.155.. In the shrimp trawl fishery, D/K ratios remained high throughout 1989-1991, but declined substantially in 1992 and remained negligible in 1993. Sea sampling data for 1994-2000 were minimal; therefore, landings by this gear component were not distinguished from all other otter trawls in the proration scheme employed to derive the landings by stock for the present assessment. Consequently, discard estimates from both otter trawl and shrimp trawl gear were combined for the 1994-2000 period. D/K ratios from the sink gill net fishery remained relatively low between 1989 and 1998, generally in the range of 0.05 or so. In 1999, discard ratios increased sharply for otter trawl and sink gill nets during the second and third quarters, declined from these peak levels in the fourth quarter, but continued to remain relatively high through all of 2000 compared to pre-1999 rates.

Discards of Gulf of Maine cod ranged from 139 mt in 1998 to 3,598 mt in 1990 (Table A4). Discards exceeded 1,000 mt in each year between 1989 and 1991 before declining steadily since 1992. The relatively high discard rates calculated for otter trawl and shrimp trawl gear during 1989-1991 coincide with recruitment of the strong 1987 year class to the small mesh shrimp trawl gear and then the large mesh general otter trawl gear. Available length composition data for these gear types suggest that most of the discarded cod were about 30-50 cm with a mode around 40 cm. Discards emanating from these two gears are the likely result of minimum size regulations. In contrast, the relatively low, but persistent, discards of cod in the gillnet fishery comprised fish of all lengths, up to 125 cm. The larger size range reflects discarding resulting from minimum size regulations as well as poor fish quality (in the case of the larger, marketable cod). Discards in 1999 were estimated to be 2,630 mt, one of the highest in the data series, due to the imposition of low trip limits. Estimated discards declined to 1,170 mt in 2000 as trip limits were relaxed to 400 lbs/day in early 2000.

To further evaluate discarding in 1999 and 2000 when low trip limits were imposed, all available vessel trip report (VTR) records were examined from trips fishing in the Gulf of Maine and reporting some catch of cod. In addition, all trips from vessels which never reported any discard were excluded from the discard analysis. The VTR data were treated in the same manner as the sea sample data except that the discard-to-kept ratios and subsequent estimates of absolute discard were derived on a monthly basis instead of a quarterly basis. This increased temporal resolution, available due to the greater quantity of VTR records, afforded a means of comparing the seasonal progression of discarding with the evolution of trip limits in 1999 and 2000. Analysis of the VTR data (Figure A2) generally confirms the seasonal patterns as well as the magnitude of the discard estimates derived from the sea sample data in 1999 and 2000 (Appendix 1: Figures 1-3). The estimated total discards of Gulf of Maine cod derived from the monthly VTR discard-to-kept ratios equaled 2,822 mt in 1999 (Table A5a) and 2,246 mt in 2000 (Table A5b).

A third approach to estimating the magnitude of 1999 and 2000 discards of Gulf of Maine cod was based on a predictive model by imposing 1999 and 2000 trip limits on 1996 and 1997 VTR data at the appropriate times of the year. Given the manner in which fishery conditions change from year to year (number of trips taken and catch rates) as well as regulatory changes over time, the primary objective was to estimate a discard-to-keep ratio rather than a direct estimate of discards. The resulting discard-to-kept ratios were then applied to observed 1999 and 2000 calendar year Gulf of Maine cod landings to provide an estimate of total discards in those years.

The predictive model incorporated information about total trip income and fishing costs including operating costs and payments to labor to determine which trips may no longer be profitable as a result of the trip limit (a detailed description of the model, data, and assumptions is included in an appendix). Trips that were no longer profitable were assumed to be abandoned while the remaining trips were assumed to occur while incurring discards of all cod in excess of the trip limit. That is, if the cod value (P_{cod}*Q_{cod}) plus income earned from all component catch (ΣPiQi) exceeds the cost of paying crew (C_{crew}) plus operating the vessel ($C_{operating}$):

$$(1)\ (P_{cod} * Q_{cod} + \sum_i P_i Q_i) - (C_{crew} + C_{operating}) > 0$$

then the trip was assumed to be taken as observed. Otherwise the trip was assumed to be abandoned. Given that prices and landings are generally known, the economic relationship described in (1) will be sensitive to assumptions about crew and operating costs. Estimated operating costs for principal gear types (otter trawl, gillnet, and hook) were based on cost surveys (Georgianna and Cass, 1998; Lallemand et. al., 1998; Lallemand et. al., 1999). Since payments to crew are based on a share system, crew income will be affected by trip limits. Thus, some minimum return to crew was assumed to be required to enable a vessel to make a trip.

The minimum crew payment was estimated using two different methods; a minimum share and a minimum payment. The minimum share methods is consistent with the manner in which crew are remunerated which reflects some risk sharing between the crew and owner but could result in unrealistically low residual payments to labor. By contrast, the minimum payment approach provides an income floor below which the vessel owner may be assumed to be unable to recruit crew because they could earn more income by taking a job elsewhere. This income floor was assumed to be equal to the average wage rate for blue-collar occupations in New England ($13 per hour). Three sensitivity trials were used for the minimum share (50%, 25%, and 10%) and one minimum payment trial ($13 per hour x 8 hours or $104 per crew per day) was conducted to test the sensitivity of the discard-to-kept ratios to crew payment assumptions.

The predictive model was applied to VTR records for calendar years 1996 and 1997 to infer what landings and discards would have been had the trip limits been implemented in those calendar years. Since these data come from observed trips the trip limit model provides an estimate of landings and total discards (discards due to the trip limit plus recorded VTR discards for other reasons). The 1996 and 1997 calendar years were selected for analysis because they represent a time period over which the Gulf of Maine cod fishery was least affected by trip limits (there were no trip limits in 1996 and the trip limits for 1997 were not binding on most occasions). By contrast, the 1998 trip limits, as well as the rolling closures, make use of data from that calendar year problematic.

The trip limit model was run separately for each of the 1996 and 1997 calendar year data and the four different sensitivity runs yielding 8 estimates for each of the 1999 and 2000 discard-to-keep ratios (Table A6a). Note that as the assumed payment necessary to attract labor to the fishery declines, formerly marginal trips become profitable resulting in higher estimated landings and discarding hence the increasing discard-to-keep ratios. Overall, the minimum payment trial results in an intermediate discard-to-kept estimate. The estimated Gulf of Maine cod discard-to-kept ratios ranged from 1.80 to 2.47 with a median value of 2.15 for calendar year 1999. Due to higher trip limits, the discard-to-kept ratios ranged between 0.72 and 0.99 with a median value of 0.83 for calendar year 2000. Applying the estimated discard-to-kept ratios to the observed landings results in a median estimate of 3,524 metric tons of discards of

Gulf of Maine cod in 1999. Similarly, the median estimate of calendar year 2000 Gulf of Maine cod discards was 3,081 metric tons (Table A6b).

The estimates of discard of Gulf of Maine cod derived by each of the 3 methods are reasonably close to each other, within the range of 2,600-3,500 mt for 1999 and 1,200-3,100 mt for 2000. Each method has advantages and limitations. The sea sample data are less subjective since they are based on consistent interpretation by a small group of individuals. But these data are rather sparse, leading to considerable imprecision. The 1999 VTR data provide considerably more observations, which may increase precision, but these data may have been influenced by possible reporting bias in response to severe management actions in 1999. The third method uses VTR data from years prior to the imposition of severe trip limits, and presumably is less affected by reporting bias. However, this method relies on several assumptions regarding constancy of effort and catch rates.

While there is, at present, no objective basis to select one method over any other, all 3 suggest that total discards were in the range of approximately 2,500 mt in 1999 and 1,000 mt in 2000. When these discards are added to the reported landings, the resulting total commercial catch is estimated to be 4,136 mt in 1999 (1,636 mt + 2,500 mt) and 4,730 mt in 2000 (3,730 mt + 1,000 mt). These results provide expansion factors of 2.53 in 1999 (4,136 mt/1,636 mt) and 1.27 in 2000 (4,730 mt/3,730 mt). To convert commercial landings to commercial catch.

Commercial Fishery Sampling Intensity

A summary of USA length frequency and age sampling of Gulf of Maine cod landings during 1982-2000 is presented in Table A7. USA length frequency sampling averaged one sample per 155-200 mt landed during 1983-1987 but the sampling intensity was reduced in 1990 (1 sample per 387 mt) and 1993 (1 sample per 360 mt), and the absolute level of sampling was extremely low in 1993. Overall sampling improved slightly in 1994 and 1995, but the seasonal distribution was uneven and poorly matched to the landings. Sampling improved substantially in 1996 and remained equally high in 1997, reaching all-time highs in terms of both absolute number of samples and samples per ton landed in both years.

Most of the USA samples have been taken from otter trawl landings, but sampling and the estimation of length composition is stratified by market category (scrod, market, and large). Although the length composition of cod differs among gear types (primarily between otter trawl and gillnet), the length composition of cod landings within each market category is virtually identical among gear types.

Beginning in 1998, the quality of commercial port sampling for Gulf of Maine cod has declined considerably. The total number of samples taken declined sharply in 1998 and again in 1999, a possible outcome of the very low trip limits imposed in 1999. Although the number samples collected increased in 2000, the distribution by market category has been out of phase with actual landings. In particular, the number of 'Large' market category cod samples has diminished to the point that the representation of the older age groups may be somewhat compromised in recent years.

Of the 61 samples collected in 2000, 24 were scrod samples (39%), 36 were market (59%), and 1 was large (2%). Compared with the 2000 market category landings distribution by weight (scrod: 9%; market: 59%; large: 30%) (Table A8), sampling in 2000 over-represented the scrod category and severely under-represented the large category.

As well, the seasonal distribution of samples has become skewed such that, although there appears to have been sufficient numbers of samples taken, there has been insufficient sampling in some quarters and half-years, requiring pooling of samples on an annual basis. This approach was necessary in 1999 and 2000.

Commercial Landings Age Composition

The age composition of landings during 1982-1993 was estimated, by market category, from monthly length frequency and age samples, pooled by calendar quarter. Quarterly mean weights, by market category, were obtained by applying the NEFSC research vessel survey length-weight equation for cod:

$$\ln Weight_{(kg,live)} = -11.7231 + 3.0521 \ln Length_{(cm)}$$

to the quarterly market category sample length frequencies. Computed mean weights were then divided into quarterly market category landed weight to derive estimated numbers landed by quarter, by market category. Quarterly age/length keys were applied to the quarterly market category numbers at length distributions to provide numbers at age. These results were summed over market categories and quarters to derive the annual landings-at-age matrix (Table A9a).

Age composition of landings from 1994 through 2000 was estimated in a manner similar to that employed for the 1982-1993 estimates except that samples and landings were, at times, pooled to semi-annual or annual resolution because of the uneven distribution of length and age samples by quarter (Table A7). Semi-annual pooling was required for the 1st and 2nd quarters of 1994 because of incomplete sampling coverage of scrod and large cod landings; in 1995, samples were pooled in both semi-annual periods due to the absence of large cod samples and the sparse coverage of market cod in quarters 1 and 3. Quarterly allocation of samples to landings was achieved for all market categories in 1996 and 1997, but semi-annual and annual pooling was required in 1998 and annual pooling was required in 1999 and 2000.

Biological sampling in 2000 was especially problematic for 'Large' category cod. As only one sample was taken throughout the year, the entire representation of older age groups depended on this sample with a maximum length at just over 100 cm. To achieve greater representation of larger fish, the 'Large' category commercial port sample was augmented with length measurements of > 100 cm cod obtained from Gulf of Maine sea sample trips. The resulting 2000 age compositions obtained from the original and the augmented length data are presented in Tables A9 and A10. It was the consensus of the SARC that the 2000 age composition based on the original port sample data be used for further analyses.

Gulf of Maine cod landings have been generally dominated by age 3 and 4 fish in numbers and by ages 3, 4, and 5 in weight. Cod from the strong 1987 year class predominated from 1990 through 1992 but, by 1993, fish from the 1990 year class accounted for the greatest proportion of the total number landed. In terms of weight, the 1993 landings were equally distributed between the 1987 and

1990 year classes. In 1993, these two year classes accounted for approximately 70% of the total number and weight landed. From 1994 through 1996, landings were dominated by age 4 cod in both number and weight. In 1997, age 5 fish were dominant in terms of both number and weight, reflecting the higher abundance of the 1992 year class. Although traditionally low in terms of their contribution to the total landings, age 10 and 11+ fish were completely absent in 1993 and 1996, and numbers of age 8 and 9 fish have also been unusually low (Table A9a). Although this pattern may be partly a result of the poor sampling of 'Large' category cod, especially in recent years, a trend towards fewer older fish in the landings has been apparent since 1991. As well, the contribution of age 2 fish to the landings has decreased in recent years.

Adjustment of the 1999 and 2000 Commercial Landings at Age

The fishery for Gulf of Maine cod was affected in many ways by management actions which occurred in 1999 and have continued into 2000. Primarily, the imposition of extremely low trip limits in 1999 are likely to have precipitated a substantial increase in the amount of cod discarded compared to previous years, as noted above. Consequently, the 1999 and 2000 estimated commercial landings at age presented in Tables A9 and A10 do not reflect the full extent of removals from the stock by the fishery. Therefore, prior to inclusion in the VPA, the 1999 and 2000 landings estimates must be adjusted upwards at each age by the ratio of total estimated catch biomass (landings+discard) to the landed catch biomass.

This approach assumes that the age composition of the discarded component of the catch is the same as the landed component. In most discarding cases, where discards generally occur in response to mesh selectivity which is out of phase with minimum landing size regulations, it is necessary to estimate the size and age composition of the discarded component separate from the landed component. In general, the discards comprise the smaller, younger fish compared to those that are landed. However, in this case , where regulatory discards were generated as a result of extremely low trip limits, it is presumed that cod of all sizes and ages were discarded without prejudice. An examination of the 1998, 1999 and 2000 kept and discarded length composition samples from the NEFSC Sea Sample database supports this assumption. The sizes of discarded cod in 1998, when trip limits were considerably higher, were primarily below the 48 cm minimum landing size and the sizes of retained cod were approximately the same as those observed in the commercial port samples. In 1999 and 2000, however, the sizes of discarded and retained cod were generally the same, well above the minimum landing size and similar to those observed in the 1999 commercial port samples. Therefore the 1999 and 2000 commercial landings at age estimates from Table A10 were multiplied by discard adjustment factors of 2.53 and 1.27, respectively, before inclusion in the VPA catch at age matrix (see page 13).

Commercial Landings Mean Weights at Age

Mean weights at age in the catch for ages 1-11+ during 1982-2000 are given in Table A9b and, based on landings patterns, are considered mid-year values. Mean weights of age 2 and 3 cod have risen since about 1992, reflecting decreased partial recruitment of younger fish to the fishery, while those for intermediate aged fish have fluctuated without any particular trend. Mean weights for ages 9 and older fluctuate considerably and are particularly sensitive to sampling variability.

Thus, it is unlikely that the apparent increases in mean weight at age for ages 10 and 11+ since the late 1980s would indicate a shift in growth or an increase in older fish in the plus group.

In 1990, mean weights at age for ages 2 and 4 were the lowest in the 9-year time series, while mean weights for ages 6, 7, and 9 were among the highest. These changes, however, may be artifacts of low sampling levels in 1990. Mean weights at ages 8 and 9 in 1993 and at ages 5 and 6 in 1995 were the highest in the series, but these anomalies are also the likely result of poor sampling. However, the generally higher mean weights at ages 2 through 4 since 1996 may be related to the required use of 152 mm (6 in.) mesh in the otter trawl fishery. Catch at age and recalculated mean weights at age for the 7+ group which are used in the VPA are given in Tables A10a and A10b.

Recreational Fishery Catches

Estimates of the recreational cod catch were derived from the Marine Recreational Fishery Statistics Survey (MRFSS) conducted annually since 1979. The Gulf of Maine cod catch was estimated assuming that catches of cod recorded by that portion of the intercept survey were removed from the ocean in statistical areas adjacent to the state or county of landing. The MRFSS database has been recently revised, resulting in adjusted catch estimates for the years 1981 through 1997. Estimates of the total Gulf of Maine cod recreational catch as well as the portion of the catch excluding those caught and released through 2000 are provided in Table A11. Information on the catch prior to 1981, which has not been revised, is included in Table A11 to provide a longer-term perspective. Further information on the details of the allocation scheme and sampling intensity are given in NEFSC (1992).

The quantity of cod retained generally exceeded 75% of the total recreational catch from 1979 through 1991, but has averaged less than 50% since 1993. The estimated total cod catch (including those caught and released) declined from over 5,000 mt in 1980 and 1981 to less than 2,000 mt between 1983 and 1986, increased to over 3,500 mt in 1990 and 1991, then fluctuated between 1,100 and 2,600 mt between 1992 and 1996 before declining sharply to 671 mt in 1997. The total catch has since increased to 2,853 mt in 2000 of which 1,147 mt was retained. The proportion of the total landings (commercial and recreational) taken by the recreational sector increased to 34 and 24 percent in 1999 and 2000, respectively. The reported total catch and retained cod from party/charter vessel VTR reports is also provided in Table A11 since 1995.

Recreational Fishery Sampling Intensity

Information on the length frequency sampling levels of Gulf of Maine cod taken in the recreational fishery is provided in Table A11. An examination of the available length frequency sampling coverage was conducted to evaluate the potential utility of these data in estimating the overall length composition of the removals from the stock which could be attributed to this gear type. Overall, sampling for cod taken by recreational gear is poor, averaging less than 1 sample per 1,000 mt removed (Table A11). Sampling of the recreational fishery improved in 1994-1996, but has been relatively low in recent years. The age composition of the 1982-1996 recreational landings was derived for the 1997 assessment (Mayo 1998) but, given the highly variable sampling, these data were not formally included in the VPA conducted in 1997 (NEFSC 1997; Mayo 1998). However, given the recent increase in the proportion of the total landings accounted by the retained recreational catch, the 1997-2000 age composition of the recreational landings was estimated for the current assessment and the 1982-2000 estimates were incorporated into the total catch at age.

Recreational Fishery Landings Age Composition

Given the limited sampling coverage in this sector of the fishery, estimation of numbers caught by length and age required samples to be pooled on an annual basis. The low inter-seasonal variability displayed by the sample length composition data supports this approach. Differences between fishing modes 6 and 7 are also minimal. Therefore, estimates of the age composition of cod retained by the recreational sector were derived from the length composition data applied to the retained numbers of cod based on pooled annual length frequency samples from Gulf of Maine trips. Only the retained numbers of cod were included because the intercept sampling may not accurately reflect the size composition of the released cod. Age-length keys obtained from sampling the commercial landings, augmented by age samples from NEFSC bottom trawl surveys for cod less than 40 cm, were applied to the numbers retained at length on an annual basis to derive the numbers retained at age (Table A12a).

During the 1980s, Gulf of Maine cod recreational landings in numbers were dominated by age 3 fish with age 2 fish next in importance. Following the increases in minimum retention size in 1989 and again in 1996, the proportion of age 2 cod declined, and the age composition of the landings from this sector now resembles that from the commercial fishery with ages 3, 4 and 5 predominant (Tables A10a and A12a). The strong 1987 year class dominated the recreational catch in 1990, 1991 and 1992, and the 1992 year class can also be tracked in the estimated catch at age between 1995 and 1999. Ages 3 and 4 cod generally predominate in terms of weight caught, although the 1987 and 1992 year classes predominated at age 5 in 1992 and 1997, respectively.

Recreational Landings Mean Weights at Age

Mean weights at age were obtained by applying the NEFSC research vessel survey length-weight equation for cod to the numbers retained at age on an annual basis:

$$\ln Weight_{(kg,live)} = -11.7231 + 3.0521 \ln Length_{(cm)}$$

Mean lengths and weights at age of cod landed by the recreational sector (Table A12b) are consistently lower than those taken in the commercial fishery. This pattern persists through age 5, but for ages 6 and older, mean weights are highly variable due to the relatively poor sampling of fish at the larger sizes combined with the lack of market category stratification. Despite this variability, patterns present in the commercial landings mean weights are also evident in the recreational landings, ie,. low mean weights in 1990 and higher mean weights at age 2 in 1995 and 1996.

Total Landings Age Composition

Estimates of the age composition of total cod landings (Table A13a) were derived by combining the separate age composition estimates obtained for the commercial (Table A10a) and recreational sectors (Table A12a). Given the general similarities between the age compositions estimated for the commercial and recreational sectors, the total age composition reflects the same dominant year classes and age structure over time. In general, ages 3, 4 and 5 have predominated; the 1987 year class dominated the total landings in 1990, 1991 and 1992, and the 1992 year class can also be tracked between 1995 and 1999.

Total Landings Mean Weights at Age

Mean lengths and weights at age of cod landed by the combined commercial and recreational sectors (Table A13b) are intermediate to those obtained from the individual sectors. Mean weights at age are highly variable for the older ages due to the relatively poor sampling of fish at the larger sizes. Mean weights at age for calculating stock biomass at the beginning of the year are provided in Table A14. These values were derived from the landings mean weight at age data (Tables A9b and A13b) using procedures described by Rivard (1980).

STOCK ABUNDANCE and BIOMASS INDICES

Commercial Catch Rates

Trends in commercial landings per unit effort (LPUE) and fishing effort for the period 1965-1993 and 1994-1996 have been recently reported by Mayo (1998). Given the uncertainty in reported fishing effort since 1994, the 1994-1997 LPUE data were not formally included in the VPA conducted in 1998 (NEFSC 1998; Mayo *et al.*1998). Recent management actions, including imposition of trip limits and rolling closures also make interpretation of 1997-2000 LPUE inconsistent with previous years. Until effort units are resolved in the commercial fishery database, no further treatment of the LPUE series after 1993 will be performed. Trends in commercial LPUE through 1996 are illustrated in Figure A3.

The 1982-1993 age composition of the landings corresponding to the effort sub-fleet as presented by Mayo *et al.* (1994) was used with the updated standardized effort estimates to calculate a revised LPUE-at-age index. Numbers landed at age were estimated by applying quarterly commercial age-length keys to quarterly commercial numbers landed at length by market category. The LPUE-at-age indices were derived by dividing the estimated numbers landed at age by corresponding 1982 through 1993 standardized fishing effort. Further details regarding data selection, preparation and estimation procedures are provided in Mayo *et al.* (1994).

Research Vessel Survey Indices

Indices of cod abundance (stratified mean catch per tow in numbers) and biomass (stratified mean weight per tow in kilograms), developed from NEFSC and Commonwealth of Massachusetts Division of Marine Fisheries (MADMF) research vessel bottom trawl survey data, have been used to monitor changes and assess trends in population size and recruitment of cod populations off New England. Offshore (> 27 m) stratified random NEFSC surveys have been conducted annually in the Gulf of Maine in autumn since 1963 and in spring since 1968. Inshore areas of the Gulf of Maine (< 27 m) have been sampled during spring and autumn NEFSC and MADMF inshore bottom trawl surveys since 1978. For the NEFSC surveys, a "36 Yankee" trawl has been the standard sampling gear except during spring 1973-1981 when a modified "41 Yankee" trawl was used.

Prior to 1985, BMV oval doors (550 kg) were used in all NEFSC surveys; since 1985, Portuguese polyvalent doors (450 kg) have been used. Details on NEFSC survey sampling design and procedures are provided in Azarovitz (1981) and Clark (1981). The MADMF inshore bottom trawl sampling program is described in Howe *et al*. (1981). No adjustments in the survey catch-per-tow data for cod have been made for any of the trawl differences, but vessel and door coefficients have been applied to adjust the stratified means (number and weight per tow) as described in Table A15. Standardized catch-per-tow-at-age (number) indices are listed in Table A16. Catch-per-tow-at-age (number) indices from DMF spring and autumn surveys are listed in Table A17.

NEFSC spring and autumn offshore catch per tow indices for Gulf of Maine cod have generally exhibited similar trends throughout the survey time series (Table A15, Figure A4). Number-per-tow indices declined during the mid- and late 1960s, but since 1972-73 have fluctuated as a result of a series of recruitment pulses. Sharp increases in the number per tow indices reflect above-average recruitment of the 1971, 1973, 1977-1980, 1983, and 1985-1987 year classes at ages 1 and 2 (Table A16, Figure A5). The sequential dominance of these cohorts at older ages can be discerned from number-per-tow-at-age values in both spring and autumn NEFSC surveys (Table A16). The recent increases in the autumn 1994-1995 and spring 1996-1997 biomass indices may be attributed to somatic growth of fish from the 1992 year class which was the largest within the recent series of poor year classes.

Spring NEFSC number-per-tow indices have remained relatively low since 1985, below the 1981-1984 average (Table A15); spring weight-per-tow indices have also remained relatively low through 1991, but the index increased substantially in 1992, and remained relatively high in 1993, due to a large contribution from the 1987 year class (Table A16). The index declined markedly in 1994, remained low in 1995, increased moderately in 1996 and remained essentially unchanged in 1997. Spring weight-per-tow indices have since declined through 2000 (Figure A4).

Autumn number- and weight-per-tow indices declined sharply in 1991 to unprecedented low abundance; weight-per-tow indices continued to decline to record low levels through 1993 and remained extremely low through 1998 (Figure A4) but increases were evident in 1999 and 2000. The higher abundance in 1988 and 1989, resulting from recruitment of the 1986 and 1987 year classes, became depleted by 1991, resulting in the sharp declines in the overall index. This reduction, combined with a general paucity of large fish in the surveys in recent years (Table A16), resulted in the decline in the weight-per-tow indices after 1991. The recent increase in the autumn abundance and biomass indices in 1994 and 1995 reflected recruitment of the 1992 year class, but these indices had already begun to decline by 1996. Although the autumn biomass indices increased in 1999 and 2000, they still remain relatively low compared to earlier periods (Figure A4).

Overall, the 1987 year class appears to have been one of the strongest ever produced; catch-per-tow indices of this cohort at ages 1-3 in the NEFSC autumn surveys and at ages 0 and 1 in the MADMF autumn inshore surveys were nearly all record-high values (Tables A16 and A17). Based on MADMF and NEFSC survey catch per tow indices, the 1992 and 1998 year classes appear to have been of moderate strength; the intervening year classes of Gulf of Maine cod, particularly the 1993, 1994, 1995, and 1996 year classes have been well below average (Figures A5 and A6).

Inshore/Offshore Biomass Comparisons

To examine changes in the distribution of cod biomass in the Gulf of Maine, the NEFSC autumn survey data were partitioned into an inshore strata set (strata: 26 and 27; area: 1,734 square miles) and an offshore strata set (strata: 28-30, 36-40; area: 16,158 square miles). The inshore strata set approximates the area in the vicinity of Massachusetts Bay up to Jeffreys Ledge which represents the core area where cod presently occur in greatest concentrations. When two or more strata sets of unequal area are compared in this manner, the stratified mean catch per tow indices must be considered to represent the density of fish (index of number per unit area) rather than actual abundance or biomass (index of population size).

To compare trends in actual abundance and biomass between regions, the indices must be weighted by the area of each strata set. This provides an index of population size within each strata set which can be directly compared on the same basis by taking account of the area of the two regions (in this case, the inshore and offshore strata sets). Trends in the autumn NEFSC survey stratified mean weight-per-tow indices are illustrated in Figure A7 for each region and for the combined strata set (as in Figure A4). Stratified mean biomass indices from the inshore Gulf of Maine are considerably higher (generally between 20 and 60 kg/tow) than those for the offshore region (generally less than 20 kg/tow), simply indicating greater densities of cod in the two inshore strata. When area is taken into account, an opposite pattern is evident (Figure A8). When compared in this manner, it is more readily apparent that, while biomass has declined since the 1960s and 1970s in both the inshore and the offshore regions of the Gulf of Maine, the decline has been most severe in the offshore region. This trend is also evident when trends in the proportion of total biomass from each region are compared (Figure A9). During the 1960s and 1970s, between 70 and 80 percent of the cod biomass in the Gulf of Maine was distributed in the offshore region. The offshore proportion began to decline during the early 1980s, culminating in an approximately 50:50 split during the 1990s. Since then, the proportion of cod in the offshore region appears to have increased slightly.

Concentration Indices

The Lorenz curve is an econometrics method developed to study the distribution of income among individuals (Lorenz 1905, Dagum 1985). Thompson (1976) applied the Lorenz curve in a study of the distribution of fish caught by a population of fishermen (i.e., was it true that 90 percent of the fish were caught by 10 percent of the fishermen?). Myers and Cadigan (1995) applied this method to northern cod biomass off Newfoundland using 76 strata from a 12 year research survey time series. When the technique is applied to fish distributions, the Lorenz curve simultaneously takes into account biomass and area and puts them on a comparable basis. The Lorenz curve method used by Myers and Cadigan does not fully account for strata of unequal size. Since the NEFSC survey has a wide range of strata sizes, Wigley (1996) modified the method to account for strata of unequal size.

A Lorenz curve is calculated as follows: for a set of n strata, let x_i be the biomass and a_i be the area of stratum i, i=1,2...n, ranked by mean weight per tow. The Lorenz curve is the polygon joining the points (A_h/A_n, L_h/L_n), h=(0,1,2 ... n) where $L_0 = 0$ and $L_h = \sum^h_{i=1} x_i$ is the total biomass in the h strata with the lowest biomass, and $A_0 = 0$ and $A_h = \sum^h_{i=1} a_i$ is the total area of the h strata with the lowest biomass. The x-axis of the Lorenz curve represents the cumulative percentage of area, while the y-axis depicts the cumulative percentage of biomass. If fish are evenly distributed among strata the Lorenz curve would be an identity function. If fish are unevenly distributed (i.e., concentrated) the Lorenz curve bows downward and to the right. The concentration index is derived by doubling the area between the identity function and the Lorenz curve (Dagum 1985).

The Lorenz curve method was applied to Northeast Fisheries Science Center (NEFSC) research vessel survey data to examined the distribution of cod biomass as estimated from NEFSC autumn bottom trawl surveys in the Gulf of Maine region over a 38 year period. Lorenz curves were calculated for each NEFSC autumn bottom trawl survey between 1963 and 2000. The strata set used corresponded to that used in the stock assessment, strata 26-30, 36-40. Biomass values used in the analysis were estimates of minimum swept area biomass (kg) calculated for each stratum in each year. Cod biomass values were adjusted for differences in fishing power of the *Albatross IV* and the *Delaware II*, and for differences in the catchability of BMV doors and the polyvalent doors introduced to the survey in 1985.

Annual Lorenz curve plots (Figure A10) indicate that cod distribution in the Gulf of Maine became increasingly more evenly distributed between 1963 and the early 1980's, as indicated by the general declining trend in the concentration indices (Figure A11). However, in the second half of the time series, the concentration indices generally increase, indicating that cod biomass has become more concentrated in recent years. The 1982 concentration index is highly influenced by a one tow of cod in stratum 26.

Overall, patterns in cod distribution and concentration are consistent with the notion that, in recent years, the Gulf of Maine cod population has been primarily distributed in the inner, western regions of the Gulf of Maine. Thus, a higher proportion of the stock is now found within a relatively small area compared to earlier periods. This contraction in the overall distribution of the stock may have implications on catchability in the fishery.

MORTALITY

Total Mortality Estimates

Pooled estimates of instantaneous total mortality (Z) were calculated for 7 time periods encompassed by the NEFSC spring and autumn offshore surveys: 1964-1967, 1968-1976, 1977-1982, 1983-1987, 1988-1992, 1993-1997, and 1998-1999 (Table A18). Total mortality was calculated from NEFSC survey catch per tow at age data (Table A16) for fully recruited age groups (ages 4+) by the $\log_e$ ratio of the pooled age 3+/age 4+ indices in the autumn surveys, and the pooled age 4+/age 5+ indices in the spring surveys. For example, the 1983-1987 values were derived from:

Spring: ln (Σ age 4+ for 1983-87/ Σ age 5+ for 1984-88)

Autumn: ln (Σ age 3+ for 1982-86/ Σ age 4+ for 1983-87)

Different age groups were used in the spring and autumn analyses so that Z could be evaluated over the same year classes within each time period.

Values of Z derived from the spring surveys are generally comparable to those calculated from the autumn data. Rather than selecting one survey series over the other, total mortality was calculated by taking a geometric mean of the spring and autumn estimates in each time period. The pooled estimates indicate that total mortality was relatively low (Z <= 0.50) between 1964 and 1982, but increased significantly thereafter to approximately 1.0 during 1983-1997, with an indication of a slight decline after 1997.

Estimates of total mortality were also derived on an annual basis from the spring and autumn survey data (Figure A12). These values of Z exhibit considerable inter-annual variability due primarily to year effects in the surveys. When smoothed, however, the annual estimates suggest the same pattern of increasing mortality during the1980s as indicated by the pooled analysis presented in Table A18.

Natural Mortality

Instantaneous natural mortality (M) for Gulf of Maine cod is assumed to be 0.20, the conventional value of M used for all Northwest Atlantic cod stocks (Paloheimo and Koehler 1968; Pinhorn 1975; Minet 1978).

ESTIMATION of FISHING MORTALITY RATES and STOCK SIZE

Virtual Population Analysis Calibration

The ADAPT calibration method (Parrack 1986, Gavaris 1988, Conser and Powers 1990) was used to derive estimates of terminal fishing mortality (F) in 2000. As in previous assessments, age-disaggregated analyses were performed. Several comparative ADAPT calibrations were performed, each using the same NEFSC spring and autumn (ages 2-6) and MADMF spring (ages 2-4) and autumn (age 2) survey series. Due to uncertainty in the interpretation of effort units in the 1994-1997 VTR data, USA commercial LPUE abundance indices for ages 2-6 were included only through 1993. This change effectively removed the influence of the LPUE indices on the terminal year outcome of the calibration, while preserving the historic relationship employed in the previous assessment. As in the previous assessments (see Mayo *et al.* 1998), the USA commercial LPUE indices from 1982 through 1993 were derived from the catch at age corresponding to the effort sub-fleet used in the estimation of standardized fishing effort as described by Mayo *et al.* (1994). The NEFSC and MADMF autumn indices were lagged forward by one age and one year whereby age 1-6 indices were related to age 2-7 stock sizes in the subsequent year for corresponding cohorts. All NEFSC and MADMF indices were related to January 1 stock sizes, and USA commercial LPUE indices were related to mid-year stock sizes.

The 1982-2000 commercial landings at age as provided in Table A9a include true ages 2-10 as well as the 11+ group. In recent years, however, fish beyond age 7 have been poorly represented. As reported by Mayo (1995), a calibration run employing an extended age complement (true ages 2-9) produced high coefficients of variation (CV) on the terminal year stock size estimates and variable estimates of F on ages 7-9 in most years prior to the terminal year. Therefore, as in previous assessments of this stock (Mayo *et al.* 1993; Mayo 1995, Mayo 1998, Mayo *et al.* 1998, NEFSC 2000, NEFSC 2001), all VPA formulations employed a reduced age range (ages 2-6 and 7+).

Impact of 1999 and 2000 Discards

The VPA for the current assessment includes commercial landings from1982-2000 (Table A10), commercial discards from 1999 and 2000, and recreational landings from 1982-2000 (Table A12). The final catch at age used in the VPA is listed in Table A13, including the discard adjustment to the 1999 and 2000 commercial landings at age. Comparative ADAPT calibrations were performed to evaluate the impact of a range of discard estimates in 1999 and 2000 on terminal year fishing mortality. A summary of each of three VPA runs (lower, middle, and upper range of discard estimates in 1999 and 2000) is provided in Table A19.

Very little difference in the overall model fit is evident. The total sums of squares and the mean square residuals are almost identical under all scenarios, although there is a slight degradation in the coefficients of variation (CV) of the stock size estimates (2001 Ns) under the upper end discards scenario (Table A19). The major impact of the various discard scenarios occurs in the estimation of terminal year F. The effects on stock size estimates is relatively minor. Differences in fishing mortality between the lower and middle range scenarios are minor, but the estimate of the 2000 fully recruited fishing mortality is substantially greater under the upper end discards scenario.

Impact of Including Recreational Landings

The VPA formulation presented above was employed in an additional analysis to evaluate the specific impact of including (or excluding) recreational landings in the VPA. In general, inclusion of the recreational landings served to marginally increase the estimates of fully recruited F, and to substantially revise upwards the estimates of stock size. The CVs on estimates of stock size in 2001 were almost identical to those obtained from the commercial-only base formulation. The retrospective pattern, evident in the commercial-only run, remains in the commercial/recreational run. Overall, inclusion of recreational landings does not alter our perception of current stock status.

Final VPA Formulation

The ADAPT formulation employed in the final VPA calibration was the same as that used in the previous assessments (Mayo *et al.* 1998, NEFSC 2000, NEFSC 2001) except for the inclusion of 1982-2000 recreational landings at age. This analysis provided direct stock size estimates for ages 2 through 6 in 2001 and corresponding estimates of F on ages 1 through 5 in 2000. Since the age at full recruitment was defined as 4 years in the input partial recruitment vector, the terminal year F on age 6 was estimated as the mean of the age 4 and 5 Fs; age 6 is also the oldest true age in the terminal year. In all years prior to the terminal year, F on the oldest true age (age 6) was determined from weighted estimates of Z for ages 4 through 6. In all years, the age 6 F was applied to the 7+ group. Spawning stock biomass (SSB) was calculated at spawning time (March 1) by applying a series of period-specific maturity ogives. The present analysis used a maturity schedule which reflected earlier maturation beginning in 1994.

Residuals of the observed and predicted indices derived from the final VPA formulation (Figure A13) do not indicate any consistent trends over the period of the VPA, except for the MADMF age 2 autumn index.

Virtual Population Analysis Results

Summary results from the final VPA calibration, including age-specific estimates of instantaneous fishing mortality (F), stock size, mean biomass and spawning stock biomass, are presented in Table A20. All parameter estimates were significant. Coefficients of variation on the stock size estimates ranged from 0.29 (age 4) to 0.53 (age 6), while CVs on the estimates of q were between 0.15 and 0.20. Slopes of the abundance index-stock size relationships increased with age through age 6 for the NEFSC spring and autumn surveys and the USA commercial LPUE indices. The MADMF spring indices exhibited an increasing trend in q between ages 2 and 4.

Average (ages 4-5, unweighted) fishing mortality in 2000 was estimated to be 0.73 (Table A20, Figure A14), a slight decrease from 1999. The spawning stock biomass of age 1 and older cod declined from 23,900 mt in 1982 to 15,300 mt in 1987. Following the recruitment and maturation of the strong 1987 year class, SSB increased to 24,200 mt in 1990 but declined to 11,400 mt in 1993, a 3-year reduction of 53% (Table A20, Figure A15). SSB increased to 14,600 mt in 1995 due to the growth and maturation of the 1992 year class, but declined again in 1996 and reached a record-low of 9,900 mt in 1998. SSB is estimated to have increased gradually between 1998 and 2000 (Table A20). Total stock size (ages 1+) has also declined sharply in recent years from 44.6 million fish in 1988 to an average of 12.4 million fish during 1996-1998 (Table A20), a decrease of 72% but is estimated to have increased to about 18-19 million fish in 1999 and 2000 due in large part to recruitment of the 1998 year class.

Since 1982, recruitment at age 1 has ranged from less than 3.5 million fish (1993, 1994, and 1995 year classes) to 25.2 million fish (1987 year class). Over the 1982-2000 period, geometric mean recruitment for the 1981-1999 year classes was 6.6 million fish. The 1987 year class is the highest in the 1982-2000 series and about twice the size of the next strongest year class. The1992 year class was of moderate strength, and the 1998 year class appears to be comparable (Table A20, Figure A15).

Precision of F and SSB

A bootstrap procedure (Efron 1982) was used to evaluate the precision of terminal year estimates, by generating 600 estimates of the 2000 fully recruited fishing mortality rate and spawning stock biomass. The distributions of the bootstrap estimates and the corresponding cumulative probability curves are shown in Figures A16 and A17. The cumulative probability expresses the likelihood that the fishing mortality rate was greater than a given level (Figure A16) or the likelihood that spawning stock biomass was less than a given level (Figure A17), when measurement error is considered.

Coefficients of variation for the 2001 stock size (numbers) estimates ranged from 0.29 (age 4) to 0.51 (age 2), and CVs for qs among all indices ranged from 0.14 to 0.18. The fully-recruited fishing mortality in 2000 for ages 4+ was reasonably well estimated (CV = 0.30). The mean bootstrap estimate of F (0.76) was slightly higher than the point estimate (0.73) from the VPA, and ranged from 0.41 to 2.36. The 80% probability interval ranges from 0.58 to 0.96 (Figure A16).

Although the abundance estimates for individual ages in 2001 had wide variances (CV = 0.29 to 0.51), the estimates of 2000 spawning stock biomass and mean biomass were robust (CV = 0.17 and 0.13, respectively). The bootstrap means were 2.9 - 4.6% higher than the VPA point estimates. The 80% probability interval for SSB ranges from 11,200 mt to 15,600 mt (Figure A17). Despite this variability, current spawning stock biomass is estimated to have increased substantially from recent record lows. In general, estimates of stock size and fishing mortality in the present assessment are estimated with about the same precision as in the previous assessment of this stock (Mayo *et al.*1998).

Retrospective Analysis

The previous retrospective analysis for this stock was reported by Mayo *et al.* (1998). Although the formulation used in the present assessment is the same as in the previous assessment, changes in management measures for this stock during 1997-2000 may have imposed additional uncertainty in the interpretation of current stock status. Therefore, the retrospective analyses were conducted again. Retrospective patterns with respect to terminal F are evident for Gulf of Maine cod in the most recent years (Figure A18). Mean F (ages 4-5, unweighted) in the terminal year had been generally under-estimated between 1994 and 1997 by the ADAPT calibration. The previous retrospective analysis by Mayo *et al.* (1998) indicated the same pattern, but was able to detect the opposite pattern (slight over-estimate of F) prior to 1994. Convergence of estimates is generally evident within 3 years, and often within 2 years, prior to any given terminal year. The retrospective analysis provides additional evidence that current fishing mortality on this stock, although somewhat lower than in previous years, remains relatively high. The retrospective pattern for age 1 recruits suggests that recruitment has generally been under-estimated over the past 6 years. The estimates of SSB have been relatively stable, although there was a slight tendency to under-estimate spawning biomass.

Spawning Stock and Recruitment

The relationship between spawning stock biomass and recruitment for Gulf of Maine cod was examined from two perspectives. First, a traditional spawning stock-recruitment scatterplot (Figure A19a) was constructed over the period covering the 1982-1999 year classes. In addition, a survival ratio, expressed as recruits per unit of SSB (R/SSB) was also calculated for each year class (Figure A19b). The stock-recruitment trajectory indicates the position of the most recent levels of SSB and recruitment in the lower left corner of the plot. The 1993-1997 year classes are all below average and the 1993-1995 year classes are the lowest in the series.

Survival ratios of pre-recruits up to age 1 are highest for the 1987, 1992 and 1998 year classes, the first two emerging from about average SSB and the 1998 year class from low SSB. Survival ratios were generally higher during the early-to-mid 1980s prior to the emergence of the large 1987 year class. Survival declined after the 1992 year class appeared, but increased in 1997 and 1998.

Hind-cast VPA Total Biomass Estimates

The 1982-2000 total stock biomass estimates derived from the VPA were extended back through time to 1963 utilizing NEFSC autumn research vessel survey biomass (kg/tow) indices. Estimates of the catchability coefficient (q), defined as the ratio between the survey index of total biomass and the VPA estimate of age 1+ stock biomass, were computed annually from 1982-2000. The average of these ratios was then applied to the entire 1963-2000 series of survey biomass indices to derive scaled estimates of total stock biomass. Results suggest that the total biomass of Gulf of Maine cod was likely to have been well over 100,000 mt during the 1960s and 1970s (Figure A20), and that VPA estimates beginning in 1982 may represent the condition of the stock following sharp declines in the late 1970s and early 1980s.

BIOLOGICAL REFERENCE POINTS

Yield and Spawning Stock Biomass per Recruit

Yield, total stock biomass, and spawning stock biomass per recruit analyses were performed using the method of Thompson and Bell (1934). Mean weights at age for application to yield per recruit were computed as a 17-year arithmetic average of total catch mean weights at age (Table A13b) over the 1982-1998 period. Mean weights at age for application to SSB per recruit were computed as a 17-year arithmetic average of stock mean weights at age (Table A14) over the 1982-1998 period. The 1999 and 2000 mean weights at age were excluded due to poor sampling of commercial landings during these years. The maturation ogive was the same as used in computing SSB during the 1994-2000 period in the VPA. To obtain the exploitation pattern for these analyses, a two-year geometric mean F at age was first computed over 1999 and 2000 from the final converged VPA results. These years were chosen specifically to encompass the period since enactment of the most recent increase in the minimum allowable mesh (165 mm). A smoothed exploitation pattern was then obtained by dividing the F at age by the mean unweighted F for ages 4-5, adjusted to the average partial recruitment for ages 4 and 5. The final exploitation pattern is as follows:

Age 1 0.000, Age 2 0.0134,
Age 3 0.2867, Age 4 0.9889,
Ages 5+ 1.000

This pattern is similar to that used in the 1998 assessment (Mayo *et al.*1998) for ages 1 through 3, but indicates increased selection of age 4 fish (from about 80% to 100%) compared to the 1998 assessment, possibly reflecting the inclusion of recreational data in the catch at age employed in the VPA. This partial recruitment pattern was used in yield and SSB per recruit calculations. Input data and results of the yield and SSB per recruit calculations are listed in Table A21 and are illustrated in Figure A21. The yield per recruit analyses indicate that $F_{0.1}$ = 0.15 and F_{max} = 0.27, and SSB per recruit calculations indicate that $F_{20\%}$ = 0.36. The yield per recruit reference points ($F_{0.1}$ and F_{max}), and the SSB per recruit reference point ($F_{20\%}$) are slightly lower than those reported in the 1998 assessment (Mayo *et al.*1998).

MSY-Based Reference Points

The existing estimates of B_{msy} and F_{msy} for Gulf of Maine cod were derived in 1998 from a biomass dynamics model (ASPIC; Prager 1994, 1995) integrating landings and relative biomass indices over the period 1963-1997 (Anon.1998). The biomass dynamics model analysis was conditioned on the relationship between age 1+ mean biomass derived from the 1997 VPA and biomass indices from the NEFSC spring and autumn surveys and the MADMF spring survey. Estimates of q, expressed as the ratio of the survey index to the age 1+ mean biomass, were fixed for each of the 3 surveys used to calibrate the production model. The analysis conditioned on age 1+ VPA mean biomass suggested that B_{msy} for Gulf of Maine cod was in the range of 33,000 mt and that the corresponding age 1+ F_{msy} was 0.31 (Fwb).

Because Gulf of Maine cod do not recruit to the fishery until age 2, the biomass dynamics model was re-run, conditioned on the relationship between age 2+ mean biomass derived from the current VPA and the same survey biomass indices updated through 2000. The revised analysis suggests that age 2+ B_{msy} for Gulf of Maine cod is in the range of 26,000 mt and that the corresponding age 2+ F_{msy} is 0.41 (Fwb). The modeling results indicate that stock biomass was above B_{msy} from the 1960s to the early 1980s but, as F exceeded F_{msy} in the early 1980s, stock biomass declined to low levels in the 1990s. The model further suggests that stock biomass increased sharply in 1999 and 2000, approaching B_{msy} as F declined below F_{msy}.

The rapid increase in biomass estimated by the biomass dynamics model is consistent with the recent increase in mean biomass derived from the VPA. However, the age-structured information provided by the VPA suggests that a considerable portion of the recent increase in mean biomass can be attributable to the recruitment of the 1998 year class. This effect is also reflected in the survey biomass indices which were incorporated into the production model analysis.

Age-Structured Production Model

As an alternative to the ASPIC biomass dynamics model, an age-structured production model (Sissenwine and Shepherd 1987) was developed using stock and recruitment observations from VPA and yield and biomass per recruit results. Age-structured production models are more informative than biomass dynamics models and can determine F_{msy} in the form of fully-recruited F, and can estimate SSB_{msy} as an alternative to B_{msy}. As concluded by the SAW Methods Working Group (Section D of this report), fully-recruited F_{msy} and SSB_{msy} are less sensitive to transient conditions and are directly comparable to VPA estimates of fully-recruited F and SSB. Comparison of current VPA results with reference points derived from the biomass dynamics model in Anon. (1998) is no longer appropriate, because the revised VPA includes recreational catch (1982-2000), and historical recreational catch is not available for a revised ASPIC analysis.

Age-Structured Production Model Results

A Beverton-Holt (1957) stock- recruit function was fit to the VPA estimates of SSB (in thousand mt) and age-1 recruitment (in millions) assuming lognormal error structure as:

(1) $R=(9.87 \cdot SSB)/(7.55+SSB)$

Estimates of yield, total biomass, and spawning biomass per recruit (YPR, BPR, and SPR) were derived from the Thompson-Bell (1934) dynamic pool model over a range of fully-recruited fishing mortality rates (Table A21, Figure A21). Equilibrium SSB (SSB*) was then calculated at various levels of fully-recruited fishing mortality to scale the dynamic pool estimates of SSB per recruit to absolute values as:

(2) $SSB^*=(9.87 \cdot SSB\ per\ recruit)-7.55$

Equilibrium recruitment (R*) was calculated as a function of SSB*, using equation 1, and equilibrium yield was calculated as the product of yield per recruit and R*.

F_{msy} was determined as the F that produced the maximum equilibrium yield (MSY), SSB_{msy} was the SSB* at F_{msy}, and B_{msy} was calculated as the product of yield per recruit and R* at F_{msy}. F on total biomass was also approximated as YPR/BPR for comparison to biomass dynamics results. Estimates of yield, F, SSB, and B from VPA were plotted with equilibrium calculations for comparison (Figure A22**).**

Results indicate that MSY=16,100 mt, fully-recruited F_{msy}=0.23, B_{msy}=90,300 mt, and that SSB_{msy}=78,000 mt (Figure A22). Alternative stock recruit decisions were considered for sensitivity analyses, including the use of hindcasted SSB and R observations (Brodziak et al. 2001) and assuming geometric mean recruitment. Estimates of F_{MSY} appeared to be robust to stock-recruit decisions, ranging from 0.23-0.27. However, MSY and B_{msy} were more sensitive to alternative stock recruit assumptions and were proportional to the estimate of maximum R. For comparison, F_{msy} on biomass (0.18) is substantially less than the estimate from the ASPIC biomass dynamics model, and B_{msy} is substantially greater than that from ASPIC. However, fully-recruited F_{msy} is only slightly less than F_{max}, which was the previous overfishing definition.

Differences between the existing F_{msy} and B_{msy} reference points derived from the biomass dynamics model and those derived from the present analysis based on the age-structured production model are due to many factors. First, the age structured approach better accounts for the productivity of the stock by specifically incorporating past and present information on the relationship between spawning stock and recruitment. In addition, the age structured approach is predicated on the yield and biomass per recruit analyses which incorporate age-specific growth and maturity information and the most appropriate exploitation pattern from the fishery. The age-aggregated approach employed in the biomass dynamics model subsumes all of the age-specific information into an estimate of a single parameter (r), the intrinsic rate of growth of the stock. This rate of increase may not always reflect the current growth potential of the stock. As noted above, the age-structured model is consistent with the assessment model because it is based on the SSB and recruitment from the current VPA, which includes recreational catch and recent discards. It is not currently possible to develop a long time series of recreational catch for a revised ASPIC analysis that could be comparable to the VPA.

The ASPIC approach was adopted by the Overfishing Definition Review Panel (Anon. 1998) as a means of applying a consistent method across as many stocks as possible, including those for which information on age structure was not yet available. In the case of the Gulf of Maine cod analysis, it was necessary to condition the biomass dynamics model (i.e., fix the estimates of q) based on the relationship between the NEFSC survey biomass indices and the corresponding VPA estimates of mean biomass in order to obtain a significant fit. This may have imposed constraints on the subsequent estimates of B_{msy} and F_{msy}.

Long-term projections, reported below, confirmed the results from the age-structured production model. The projection results indicate that long-term yield at the revised estimate of F_{MSY} (0.23) is significantly greater than the previous estimate of MSY (10,000 mt, Anon.1998) and is near the revised estimate of MSY (16,100 mt). Similarly, projected total stock biomass is significantly greater than the previous estimate of B_{msy} (33,000 mt) and close to the revised estimate of B_{msy} (90,300 mt). Furthermore, historical survey observations indicate that stock biomass exceeded the revised estimate of B_{MSY} during most of the 1960s and 1970s (Figure A20). Therefore, it appears that the previous estimates of MSY and B_{msy} were greatly underestimated (conversely it appears that F_{msy} was over-estimated), and revised reference point estimates are more consistent with long-term projections and historical observations.

CATCH and STOCK BIOMASS PROJECTIONS

Stochastic age-based projections (Brodziak and Rago MS1994) were performed over a 25-year time horizon to evaluate relative trajectories of stock biomass and catch under various fishing mortality scenarios. Recruitment was derived from the Beverton-Holt spawning stock-recruitment relationship employed in the age structured production model. Stock and catch mean weights at age, the maturity at age schedule, and the partial recruitment at age vector are the same as those employed in the yield and SSB per recruit analyses presented above. The 2001 survivors derived from 600 bootstrap iterations of the final VPA formulation were employed as the initial population vector. The projection was performed at four fishing mortality rates: $F_{0.1}$ (0.15), F_{msy} (0.23), F_{max} (0.27) and F_{sq} (0.73). Fully recruited fishing mortality in 2001 was assumed equal to that in 2000 (0.73) under all F scenarios. Short-term forecasts of 2002 catch and corresponding 2003 SSB were derived from the first two years of the long-term projections. All input data are provided in Table A22.

Short-Term Projection Results

The forecast for 2002 and 2003 is summarized in Table A22 and Figure A23. The results suggest that if the current fishing mortality rate is reduced to F_{max} or less in 2002, SSB will continue to increase in 2003. However, if F in 2002 remains at or near the 2000 F, SSB in 2003 will not increase beyond that projected for 2002.

Long-Term Projection Results

The long-term projections (Table A23; Figures A24 and A25) suggest that fishing at F_{msy} (0.23) will result in the total stock biomass stabilizing at about 92,000 mt providing total catches of about 15,000 mt per year. If F is not reduced from the current level (0.73), neither total stock biomass nor spawning stock biomass are likely to increase appreciably above the existing level. Because the spawning stock-recruit relationship for this stock is relatively flat across most observed levels of SSB (Figure A22), recruitment is estimated to be only slightly impaired at this high fishing mortality rate. Given the recent trends in observed recruitment at low SSB, this is an unlikely optimistic outcome of these projections.

CONCLUSIONS

The Gulf of Maine cod stock remains at a low biomass level, although there are indications of a recent increase in total biomass and spawning stock biomass in 1999 and 2000.

Fully recruited fishing mortality appears to have declined only slightly in 2000 (0.73), indicating that F continues to remain very high relative to fully recruited F reference points ($F_{0.1}$ = 0.15; F_{msy} = 0.23; F_{max} = 0.27). Spawning stock biomass (SSB) declined from over 24,000 mt in 1990 to a low of 9,900 mt in 1998, but increased to 13,100 mt in 2000.

Biomass weighted F on ages 1+ generally fluctuated between 0.4 and 0.6 during 1982-1997, except for the period 1988-1989 when the strong 1987 year class influenced the calculation significantly. Biomass weighted F on ages 1+ declined to 0.30 in 1999 and to 0.23 in 2000, but these estimates are influenced to a large extent by the entry of the 1998 year class. Mean biomass (ages 1+) declined from a maximum of 42,700 mt in 1989 to 14,800 mt in 1997 and 1998, but has since increased to 26,000 mt in 2000, primarily on the strength of the 1998 year class.

Total (age 1+) stock biomass in 2001 is slightly above 1/4 of the revised B_{msy} reference point (90,300 mt) and fully recruited F in 2000 is about 3 times greater than the revised F_{msy} reference point (0.23).

A substantial retrospective pattern has existed in the VPA results for this stock whereby fully recruited F has generally been underestimated in the terminal year since 1994. In the retrospective analysis of the present assessment, F_{1998} and F_{1999} appear to have been slightly overestimated, while terminal Fs from 1994-1997 were underestimated.

SARC COMMENTS

Discards

Three methods for calculating discards were presented. The first method computes discards on a quarterly basis using sea sample data. The SARC agreed that this method does not have enough resolution to track discards accurately when trip limits are changing on a monthly basis. Further, the sampling level is low and the rate of discarding is likely to be very different depending on whether or not an observer is on board. The second method uses VTR data. These data allow discarding to be computed on a monthly basis, thus providing the resolution required to track trip limit changes. However, serious questions were raised with regard to the quantity and quality of the data and the approach of using the discard-to-kept ratio when it was revealed that the data are highly skewed. Coding problems, which did not distinguish between zero discards and null data, were an added concern. The SARC concluded the calculation of discards from the VTR data could not be accepted in the present form. The third method provided a calculation of discards for 1999 and 2000 based on a model of trip level economics applied to the 1996 and 1997 VTR data. This approach has the advantage of being independent of the suspect 1999 and 2000 VTR data. While considered to be very promising, sensitivity to assumptions needs to be evaluated and predictions need to be compared with data.

The SARC agreed that it was not appropriate to use discards calculated from any of the three approaches or to derive a value from some combination of these data. Instead, the decision was made to carry out three VPA runs with zero discard values for the period prior to 1999 and "ballpark" values for 1999 and 2000 which bracketed the possible range as well as a "middle" run. The terminal F's were fairly robust to changes in assumed discards and survivors in the final year changed only slightly. In addition to the problem of the magnitude of the discards, it was noted that "high-grading" was likely to be occurring when severe trip limits were imposed, and consequently the sizes and ages of discarded fish are also uncertain**.**

The SARC noted that the sampling of the large cod category in recent years, particularly in 2000, was poor, making it difficult to derive a catch at age matrix, even when quarterly estimates were pooled. Evidence of the problem can be seen by the low weights of the 7+ age group in 1999 and 2000. An approach of augmenting the port sample data for 2000 with length frequencies from sea sampling until the mean weight in the 7+ category appeared reasonable was considered; however, the approach is subjective and masks the problem of inadequate sampling. The SARC decided to proceed based on the port sampling data.

Recreational catches

Recreational catches have not previously been included in the VPA for this stock; however, the magnitude has been increasing and it now represents between 24% and 34% of the catches and cannot be ignored. Although the sampling of these catches is less than adequate, the SARC felt that the data should be included in the analysis because it represents a significant part of the catch and its inclusion will result in a more accurately estimated q for scaling population size in the unconverged portion of the time series. It was noted that the total number of cod caught in 2000 is nearly double the 1999 value and it was thought that this apparent change may in part be a consequence of inadequate sampling.

Geographical changes in distribution

It was noted that there is a geographical component to the abundance of cod over time. In recent years the Gulf of Maine cod population has been concentrated in the inner, western regions of the Gulf of Maine It is not apparent what factors have caused the increased concentration, and it was suggested by SARC that the weighted cumulative probability distribution approach of Smith and Page (1996) might be useful for examining the possible role of physical factors. While the size of the stock had declined considerably overall, this will be less apparent to those only looking at the inner Gulf of Maine. These changes may also influence the CPUE index. The SARC felt that it would be very useful to include the stock abundance trends in the different areas as part of the public presentations to clear up misconceptions that might exist.

Model calibration

The SARC evaluated the low, middle and high discarding VPA runs and noted that while the estimates of survivors are very similar there is some difference in the estimates of F. The diagnostics provided no support for favoring one discarding scenario over another. The middle run was accepted as the final model for projection purposes. It was noted that zeros for any survey at age index values are treated as missing in the minimization. Although there are not many instances in the age ranges used, this could potentially bias the VPA estimates. It was also noted that the VPA estimates are scaled by the assumed value for M and consequently caution should be applied in interpreting these estimates in absolute terms.

Biological reference points
It was necessary to recompute the biological reference points in the current assessment because of the inclusion of the recreational catch. The SARC felt that as a general principle, reference points should be recomputed in each assessment based on the updated information.

In contrast to previous assessments, the SARC decided that it was more appropriate to compute reference points from the age structured model rather than from the age-aggregated biomass dynamics model. The age structured model uses more of the available information related to the stock and there was no reason to think that reference points derived from the biomass dynamics model would be more robust with respect to uncertainties. It was agreed that the results from the age structured model would be compared qualitatively with those from the biomass dynamics model.

The SARC agreed that reference points should be computed using the Sissenwine and Shepherd (1987) approach. The SARC evaluated the sensitivity of reference point estimates to decisions regarding recruitment models. It was determined that F_{msy} estimates are relatively robust to alternative recruitment decisions but that MSY and B_{msy} were more sensitive. The SARC concluded that long term projections should be based on the same Beverton-Holt stock-recruitment model used in the age-structured production model which was fitted to the values estimated by the VPA with no hind-casting.

The SARC debated the relative merits of using total biomass vs spawning stock biomass as the basis for computing reference points. The former includes information about recruits, but is more likely to vary through time. Spawning biomass is more stable over time, but does not contain information about recruitment. Focusing on spawning biomass may be preferable if the primary management goal is to monitor and maintain the spawning stock.

Projections
The SARC emphasized that long term projections using age structured models provided a valuable tool for evaluating rebuilding scenarios. Current limitations of the software are for a 25 year time horizon which may not be long enough for the stock to reach equilibrium conditions.

Long term projections were done using the status quo F (0.73) as well as lower F's corresponding to biological reference points ($F_{0.1}$, F_{msy}, F_{max}). The annual landings (yield) did not differ very much between these runs, although fishing at the higher F resulted in a much lower stock biomass after 25 years. Fishing at the higher F is risky because the resulting stock biomass is low which makes it vulnerable to stochastic perturbations. The long term yield and spawning stock biomass predicted by the age-based production model and the long term projections were similar.

RESEARCH RECOMMENDATIONS

- Improve information on discards through increased observer coverage, further evaluation of VTR data and statistical analysis appropriate to the data.

  Examine the predicted distribution of trips from the economic trip limit model with actual distribution of trips.

- Conduct a more thorough comparison of party/charter boat catch estimates from VTR and MRFSS sampling.

- Increase the sampling of lengths and ages from both the commercial and the recreational catches, including the Maine DMR party boat survey

- Evaluate the uncertainty associated with the estimates of reference points from age-structured models and further develop methods to compare the uncertainty in projected biomass and fishing mortality with the uncertainty in the reference points.

- Evaluate physical factors that may be associated with increased cod concentration within the stock area using the weighted cumulative probability approach of Smith and Page (1996).

- Evaluate alternative approaches for fitting the Beverton and Holt stock recruitment model. See Myers, R.A. Bridson, J. and Barrownan, N. J. 1995. Summary of worldwide stock and recruit data. Can. Tech. Rept. Fish. Aquat. Sci. No. 2024.

- Develop approaches within the VPA calibration for distinguishing between zero's and null data. Consider adding computer code to track and list additional diagnostics about population state through time during simulation.

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