C. GULF OF MAINE/GEORGES BANK ACADIAN REDFISH

EXECUTIVE SUMMARY

The status of the Gulf of Maine/Georges Bank redfish (*Sebastes fasciatus*) stock through 2000 is reviewed, and the current status of the stock is compared on a relative basis to revised estimates MSY-based reference points. The 2001 assessment is based on several sources of information including: the age composition of USA commercial landings, Northeast Fisheries Science Center (NEFSC) spring and autumn research vessel survey data, and standardized USA commercial fishing effort data. This assessment updates the analyses presented in the 1993 assessment of the Gulf of Maine/Georges Bank redfish stock (Mayo 1993) as well as that prepared in 2000 by the Northern Demersal Working Group (NEFSC 2001).

Information on the size and age structure of the redfish stock is presented including: age composition of the commercial landings (1969-1985), length composition of inshore and offshore components of the stock based on NEFSC spring (1968-2000) and autumn (1963-2000) research vessel surveys, and age composition of the stock based on NEFSC spring and autumn research vessel surveys (1975-2000). Several aspects of the biology of the redfish stock are also presented including: patterns in diurnal catchability, length-weight relationships, analyses of maturity at length, and inshore/offshore biomass comparisons.

The assessment of current status is based on several analyses including: trends in catch/survey biomass exploitation ratios; a yield and biomass per recruit analysis; an age-structured dynamics model which incorporates information on the age composition of the landings, size and age composition of the population, and trends in relative abundance derived from commercial CPUE and research vessel survey biomass indices; and an age-aggregated biomass dynamics model. Surplus production estimates were derived from the age-structured production model, and information on current status of biomass and fishing mortality relative to MSY-based reference points is also provided by the biomass dynamics model.

The fishery on this stock developed during the 1930s. Landings rose rapidly from less than 100 mt in the early 1930s to over 20,000 mt in 1939, peaking at 56,000 mt in 1942, then declined throughout the 1940s and 1950s. Redfish have been harvested primarily by domestic vessels, although distant water fleets took considerable quantities for a brief period during the early 1970s. The distant water fleet effort, combined with increased domestic fishing effort, resulted in a brief increase in total catch to about 20,000 mt during the early 1970s. Landings declined throughout the 1980s and have averaged less than 500 mt per year during the 1990s.

Exploitation ratios (catch/survey biomass) suggest that fishing mortality has been very low since the mid-1980s compared to previous periods. Estimates of fishing mortality derived from the age-structured dynamics model and the age-aggregated biomass model are similar, both indicating that current fishing mortality is low relative to past decades and with respect to Fmsy (<5%). Stock biomass has increased since the mid-1990s, and is presently estimated to be about 33% of Bmsy due, in

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large part, to recruitment of one or more strong year classes from the early 1990s.

TERMS OF REFERENCE

(A) Update the status of the redfish 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 updated indices of relative abundance and biomass, based on appropriate research vessel survey series.

INTRODUCTION

Redfish, *Sebastes fasciatus* Storer, have supported a substantial domestic fishery in the Gulf of Maine and the Georges Bank (Great South Channel) regions off the northeast coast of the U.S. (Northwest Atlantic Fisheries Organization [NAFO] Subarea 5) since the late 1930s when the development of freezing techniques enabled a widespread distribution of the frozen product throughout the country. Landings by domestic vessels rose rapidly, peaking at 56,000 t in 1942 in Subarea 5, then declined throughout the 1940s and 1950s (Table C1, Figure C1). As landings declined in local waters, U.S. fishing effort began to expand to the Scotian Shelf and the Gulf of St. Lawrence (NAFO Subarea 4), and finally to the Grand Bank of Newfoundland (NAFO Subarea 3). This expansion continued throughout the 1940s and early 1950s, culminating with a peak U.S catch of 130,000 t in 1952 (Figure C1). By the mid-1950s,

redfish stocks throughout the Northwest Atlantic were heavily exploited by U.S and Canadian fleets (Atkinson 1987), and total landings began to decline in all Subareas.

During the 1960s and early to mid-1970s, catches by distant water fleets were substantial, at times accounting for 25-30% of the total Subarea 5 redfish catch (Table C1). With the declaration of exclusive economic zones by the U.S. and Canada in 1977, U.S. vessels were prohibited from fishing in all but a small portion of Subarea 4 off Southwest Nova Scotia. Landings from the Gulf of Maine subsequently increased temporarily during the late 1970s, but have been declining throughout the 1980s, and have remained below 1,000 t per year throughout the 1990s. Recent landings from this stock are at their lowest level since the directed fishery commenced in 1934.

The status of this stock has been assessed since the 1970s with a variety of techniques including production models (Schaefer 1954, 1957; Pella and Tomlinson 1969; Fox 1975), yield per recruit (Thompson and Bell 1934; Beverton and Holt 1957) and virtual population analysis (VPA). A preliminary production model estimate suggested a long-term potential yield of 20,000 t from this stock (Mayo 1975) but this was revised to 14,000 t when non-equilibrium conditions were taken into account (Walter 1976), irrespective of the growth model (exponential or logistic) employed (Mayo 1980). A yield per recruit analysis performed with M=0.05 and partial recruitment of 50% at age 6 and full recruitment at age 9, indicated Fmax at 0.13 and F0.1 at 0.06 (Mayo 1993).

Virtual population analysis, which was first performed on this stock using catch at age data from 1969-1980, indicated that age 9+

fishing mortality rates, in the range of 0.18 to 0.28 throughout most of the 1970s, were accompanied by a 62% decline in exploitable (age 5+) biomass between 1969 and 1980 (Mayo et al. 1983). A subsequent analysis which included additional catch at age data through 1983 indicated that, although F had begun to decline from a maximum value of 0.28 in 1979 to 0.17 in 1983, exploitable biomass had been reduced by 75% from the 1969 level by 1984 (NEFC 1986). The VPA was discontinued after 1986, but further declines in redfish landings since then suggest that F is now likely to be rather low (at or below M), rendering the convergence of VPAs somewhat unlikely.

The potential for this stock to return to conditions observed in the 1960s is limited, in part, by the combination of slow growth and low fecundity of redfish. Even at relatively low levels of F, ranging from 0.03 to 0.05, restoration of the 1969 age structure is not likely to occur except under extremely favorable recruitment conditions over the next 30-40 years (Mayo 1987).

COMMERCIAL FISHERY

Commercial Catch and Effort
Landings of redfish from Subarea 5 from 1934 through 2000 are given in Table C1 and Figure C1. Landings by domestic vessels rose rapidly from less than 100 t in the early 1930s to over 20,000 t in 1939, peaking at 56,000 t in 1942, then declined throughout the 1940s and 1950s. Redfish have been harvested primarily by domestic vessels, although distant water fleets took considerable quantities for a brief period during the early 1970s (Table C1). The distant water fleet effort, combined with increased domestic fishing effort, resulted in a brief increase in

total catch to about 20,000 t during the early 1970s. Landings declined throughout the 1980s and have averaged less than 500 t per year during the 1990s. Landings in 2000 (319 t) remain close to an historic low. Redfish have been harvested almost exclusively by otter trawlers fishing out of Maine and Massachusetts ports.

Commercial catch per unit effort (CPUE) indices for directed redfish trips, standardized by vessel tonnage class as described by Mayo et al. (1979), are listed in Table C1 and illustrated in Figure C2a. The resulting calculated fishing effort values were derived by dividing total annual landings by the directed CPUE index. Directed CPUE has declined steadily from over 10 tons per day fished during the late 1960s to less than 2 tons per day fished since 1984 (Table C1, Figure C2a). This 70-80% decline is consistent with the 60-70% decline in exploitable biomass estimated by previous VPAs (Mayo et al. 1983; NEFC 1986). Total fishing effort, after peaking during the late 1970s (coincident with the highest estimates of fishing mortality [NEFC 1986]), appeared to stabilize during the mid-1980s before declining precipitously through 1989.

A depiction of the available effort data is presented in Figure C2b. Historically, 80-90% of the total redfish catch and 20-40% of the total number of trips on which redfish were taken were accounted for in the directed CPUE calculation (50% redfish trips). These percentages declined sharply between 1979 and 1982, and are now at levels which preclude any definitive interpretation of the CPUE and effort trends.

Commercial Length Composition
The available commercial length and age sample data are summarized in Table C2.

Commercial length sampling for redfish has generally been sufficient to allow quarterly pooling until the 1990s. Sampling during most years since 1994 has been insufficient to characterize the length composition of the landings. The apparent improvement in sampling intensity in recent years is an artifact of the rapid decline in landings. Even with very low landings, sampling must be maintained at relatively high levels in order to reflect the age structure of the population. Age samples have been routinely collected since the 1960s but production ageing ceased after 1985 (Table C2).

Estimates of numbers landed at length were derived from 1969 through 2000 when sample data permitted. In most years prior to 1991, sampling was sufficient to allow pooling of length data on a quarterly, and in a few cases, semi-annual basis. However, from 1991 to 2000, pooling of samples was required on a semi-annual, and in several cases, an annual basis. Due to the differences in growth between males and females, sampling for redfish is conducted separately by sex, and estimates of numbers landed are also derived separately for males and females. The overall length composition is then obtained by addition of the estimates by sex.

Changes in the length composition of the landings between 1969 and 2000 are illustrated in Figure C3. In 1978, the landings still reflected a fairly broad age structure in the population of both males and females with the 1971 year class accounting for the mode between 20 and 30 cm. With the decline in subsequent recruitment, modes shifted toward larger sizes until fish from the 1978 year class appeared in 1983 and 1984. As landings continued to decrease throughout the 1980s, modal lengths shifted further until few fish

between 20 and 25 cm could be seen recruiting to the fishery.

Shifts in modal lengths are reflected in annual changes in mean length of the landings as illustrated in Figure C4. Increases in mean length occur during periods of poor recruitment (such as 1965-1976) while sharp decreases generally signify the appearance of a strong year class entering the fishery. The declines which began in 1976 and 1983 indicate recruitment of the 1971 and 1978 year classes entering the fishery at age 5. The subsequent overall increasing trend indicates a gradual ageing of the population as recruitment has declined over the past 30 years. Mean lengths of the landings have become extremely variable in recent years as landings have become extremely low and sampling has deteriorated.

Commercial Age Composition
Estimates of numbers landed at age were also derived from the biological sampling data for the period 1969 through 1985. With the sharp decline in landings evident during the 1980s, ageing of commercial samples was discontinued after 1985. For the period 1969-1985, however, estimates of numbers landed at age were derived by applying quarterly age/length keys, separately by sex, to the estimated numbers landed at length by sex. The overall age composition was then obtained by addition of the estimates by sex.

Catch at age and mean weight at age matrices based on all available commercial length and age data from 1969 through 1985 are given in Table C3, and trends in the age composition of the landings are illustrated in Figure C5 . The sharp discontinuity in the age structure of the population created by poor recruitment since the 1960s can be inferred from the age

composition of the landings. The most striking feature is the singular presence of the 1971 year class advancing through the fishery since 1976, followed by the entrance of the 1978 year class during 1983-1985. By the early 1980s, the fishery had become dependent on a few relatively strong year classes and recruitment appeared to have collapsed.

RESEARCH VESSEL SURVEYS

Bottom trawl surveys have been conducted by the Northeast Fisheries Science Center in the Gulf of Maine - Georges Bank region since autumn 1963 and spring 1968 (Azarovitz 1981). The NEFSC spring and autumn bottom trawl survey data were analyzed to evaluate trends in total abundance and biomass of redfish, diurnal effects on catchability, differences in density between inshore and offshore regions of the Gulf of Maine, trends in the size and age composition of the population, total mortality, relationships between length and weight, and changes in maturation at length.

Trends in Total Abundance and Biomass
Abundance (stratified mean number per tow) and biomass (stratified mean weight per tow) indices have been calculated from NEFSC spring and autumn surveys based on strata encompassing the Gulf of Maine and the portions of the Great South Channel (strata 24, 26-30, 36-40; Tables C4 and C5; Figures C6a and C6b). Trends in total abundance and biomass are similar in both spring and autumn surveys. Relative abundance of redfish has declined sharply in both survey series, from peak levels over of 100 fish per tow in the late 1960s and early 1970s to generally less than 10 fish per tow during the mid-1980s through mid-1990s. The decline in biomass has been

of the same order (Figures C6a and C6b). Both series suggest a slight increase in abundance and biomass between the mid-1980s and 1990s followed by a sharp increase in autumn 1996 and spring 1997.

Day/Night Comparisons
Redfish have been observed to exhibit consistent diurnal patterns in their vertical distribution. Although Kelly and Barker (1961) concluded that there is little evidence of diurnal movement of planktonic larvae, they also noted a significant decrease in catches of larval redfish by an Isaacs-Kidd midwater trawl during daylight. This was attributed to possible gear avoidance by larval redfish. Adult redfish, however, are thought to exhibit very pronounced diurnal movement patterns. Templeman (1959) noted that, off Newfoundland, redfish catches from sets made more than one hour before sunrise or after sunset were negligible compared to those from daytime sets. Catches were also related to the season, with good catches extending over a longer part of the day in the brightest months with the longest period of daylight. This pattern was well known in the commercial redfish fishery as vessels would often lay to during the night.

In an earlier paper on redfish biology, Steele (1957) noted the same overall diurnal pattern in redfish catches. In this study, Steele provided evidence of a 2-3 fold difference in average catch rates over a 24-hour period. This pattern was correlated, in part, with the vertical movement of the euphausiid, *Meganyctiphanes norvegica*, a major prey item of redfish in the North Atlantic. Steele (1957) also observed seasonal departures from the general pattern, and speculated that these differences may be related to the sexual maturation cycle of males and females. The

diurnal response of males and females differed among seasons.

The presence of a diurnal pattern in redfish activity in the Gulf of Maine was examined over the period 1992-2000. NEFSC spring and autumn survey catch data were partitioned into six 4-hour time blocks as follows: 0001-0400 hr (night2), 0401-0800 hr (dawn), 0801-1200 hr (day1), 1201-1600 hr (day2), 1601-2000 hr (dusk), and 2001-2400 hr (night1). Catch data for valid survey tows within the total Gulf of Maine strata set as above were selected from the spring, summer, and autumn surveys. Summer surveys were conducted only in 1992, 1993 and 1994 and the number of tows in the Gulf of Maine which contained redfish (n=85) was relatively small.

The catch data were analyzed for seasonal and diurnal effects by ANOVA using PROC GLM (SAS, 1990). Initial analyses indicated that seasonal effects were not significant; however, based on the observations of Steele (1957) regarding different seasonal responses by males and females, further analyses were conducted separately for spring and autumn data, with summer excluded. In the analyses of diurnal effects, the last time block (2001-2400 hr) was elected to represent unity and each of the 5 remaining blocks were related to the last block. The factors for each time block were re-transformed from log scale to linear scale.

In the overall analysis, catch rates from periods 2 (0401-0800 hr), 3 (0801-1200 hr) and 4 (1201-1600 hr) were significantly different ($p < 0.05$) from period 6 (2001-2400 hr). These represent dawn and the 2 daytime periods. Catch rates from the remaining periods (1 and 5), representing dusk (1601-

2000 hr) and night (2001-2400 hr) were not significantly different from period 6. Analyses of the spring and autumn data revealed possible seasonal differences (Figure C7). During spring, catch rates from time periods 2, 3, and 4 were significantly different ($p < 0.05$) from those of period 6, but during autumn, none of the time periods exhibited statistically significant differences in catch rates, although the general pattern was similar to spring. These differences between spring and autumn were not due to any pronounced bias in survey station coverage by time period as the number of stations in both spring and autumn were almost evenly distributed (Figures C8a and C8b).

In fact, the seasonal differences obtained for the Gulf of Maine are consistent with the observations of Steele (1957) and Templeman (1959). When the timing of the NEFSC survey in the Gulf of Maine is taken into account, (spring survey in late April, autumn survey in late October), it can be seen that this portion of the spring survey occurs during a period of considerably longer daylight compared to autumn. There is a 2-month absolute difference in the timing of the spring and autumn surveys with respect to the corresponding vernal and autumnal equinoxes. These results are consistent with Templeman's (1959) observation that good catches occur over a longer part of the day in the brightest months. The results also seem to corroborate Steele's (1957) observation that seasonal differences may be related to the reproductive cycle where females may be more pelagic during the larval extrusion stage in spring whereas both sexes may occupy bottom during a greater period of time during the copulation stage in autumn.

Despite the large diurnal differences in catch rates derived from these analyses, abundance and biomass indices are not likely to exhibit any substantial bias given the even distribution of occupied stations over time. It is likely, however, that annual departures from an even distribution among the six time periods may impart a degree of inter-annual variability which may partially explain some of the large year effects exhibited in these data. However, if the redfish survey indices were to form the basis of an estimate of absolute biomass, the diurnal differences noted herein must be taken into account before any estimation is made.

Inshore/Offshore Comparisons
Indices were also computed for inshore (strata 26, 27, 39, and 40; area: 3,042 square miles) and offshore (strata 24, 28-30, 36-38; area: 17,419 square miles) subsets of the data (Figures C9a and C9b). 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 or biomass per unit area) rather than actual abundance or biomass (index of population size). The inshore Gulf of Maine area from Massachusetts Bay to the eastern coast of Maine has generally contained higher densities of redfish compared to the offshore regions, particularly in terms of numbers (Figure C9a). These fish are generally smaller than those in the offshore regions, and the index from the inshore area may be used as a measure of recruitment (Mayo 1980). Trends in these indices have been consistent with trends in the overall combined indices (Figures C6a and C6b).

Trends in mean length and weight of redfish from inshore and offshore strata sets during autumn are illustrated in Figures C10a and

C10b. As with commercial mean lengths, sharp declines indicate the appearance of a relatively strong year class. This is most evident in the autumn series of inshore data which has provided the most consistent indicator of recruitment patterns over time. The sharp declines which occur immediately after 1971, 1978, and 1984 reflect the initial appearance and subsequent increased influence of these year classes in the inshore bottom trawl survey indices. The 1991 year class is reflected in the offshore mean length and weight patterns.

To compare trends in actual abundance and biomass between regions, the indices must be weighted by the area of each strata set. This approach provides indices of population size within each strata set which can be directly compared on the same basis. When viewed in this manner, it is clear that the greatest fraction of the redfish population has historically been found in the offshore region of the Gulf of Maine (Figures C11a and C11b).

Size Composition
Length composition data from spring, autumn and shrimp surveys (Figures C12 and C12a) simultaneously illustrate the changes in relative abundance and size structure of the population which resulted from the decline in recruitment over time. The redfish population was composed of a relatively broad range of sizes in the 1960s resulting from consistent recruitment of year classes from the 1950s and 1960s. By the mid-1970s, however, abundance of large fish had declined substantially and only the 1971 year class remained a dominant feature in the demographics of the population. The consistency of the survey indices had begun to erode by the beginning of the 1980s and, throughout this decade, only sporadic

indications of the 1978 and subsequent year classes were evident.

During the 1990s, however, substantial numbers of redfish, generally between 20 and 25 cm, began to appear, first in spring 1992, then in autumn 1995 and 1996. These data likely reflect the strength of one or more year classes from the mid-1980s and early 1990s. In autumn 1999, a mode at 5 cm could indicate a potentially strong 1999 year class. By 1997, large numbers of redfish up to 30 cm and larger were appearing consistently. However, the size structure of the population remains truncated compared to the 1960s and early 1970s. The same pattern appears in the shrimp survey.

Age Composition
Age composition estimates are available from NEFSC autumn surveys from 1975 through 2000 and from NEFSC spring surveys from 1975 through 1990 with some exceptions. The survey otolith collection is routinely aged to the maximum possible age. For this analysis and the subsequent analysis of mortality rates, all ages greater than 50 years were binned at 50+. As the autumn survey has provided the most consistent set of abundance and biomass indices, priority was given to ageing of the autumn survey otolith collection. Annual trends are illustrated in Figure C13. The age composition data clearly illustrate recruitment patterns and changes in age structure of the population that are suggested by the length composition data. In 1975 the population still appeared to exhibit a relatively broad age structure. The 1971 year class is prominently featured in 1975 followed by the 1978 year class in the early 1980s; these two year classes continued to dominate the demographics of the population through the 1980s.

More recently, the 1985 and 1991 year classes appear most prominent. As indicated by the length composition estimates, the age structure of the population during the late 1990s remains truncated compared to the 1975 and earlier period.

Total Mortality Estimates
Estimates of instantaneous total mortality were computed from the age composition data derived from NEFSC autumn surveys from 1975-1996. Annual Z estimates, based on the annual survival rate from ages 6 and older to ages 7 and older, were highly variable, ranging between -1.6 to +1.6. These estimates reflect the high degree of variability in year class strength evident in the survey abundance indices at age presented in Figure C13. Therefore, an alternate approach was attempted.

The 1975-1996 autumn survey age composition data contain information on cohorts spanning 1925 to as recently as 1995. To minimize the variability induced by variation in year class strength, separate catch curves were constructed for each cohort. Since the time span represented in the age composition data covers the years 1975-1996, cohorts from years prior to the mid-1970s become truncated at the younger ages whereas cohorts from years after 1975 become progressively truncated at the older ages. When combined in a single plot, the mortality on by various ages spanning the period 1925-1995 is visually represented (Figure C14). This provides a general indication of the average mortality sustained by the population over this 70 year period. It is evident that, in most cases, redfish are incompletely recruited until ages 5 or 6. However, mortality rates appear to be relatively consistent for most cohorts after age 6. No attempt was made at

this stage to derive mortality estimates for individual cohorts.

Length-Weight Analyses

The relationship between length (cm) and weight (kg) of redfish was examined by season and sex using linear regression (PROC REG; SAS 1990) of the form:

Ln Weight = a + b* Ln Length.

The analysis is based on 8,567 individual length and weight measurements collected during NEFSC spring and autumn surveys since 1992. There are no significant differences (p=0.800) in the length-weight relationship between spring and autumn. However, differences between males and females are highly significant (P< 0.01) (Figure C15), with females considerably heavier at a given length.

Maturation Analyses

Redfish are relatively long-lived, slow growing fish with an extremely low natural mortality rate compared to most highly exploited species. Growth studies have indicated maximum ages ranging from 50-60 years at lengths of 45-50 cm (Mayo et al. 1990). Perlmutter and Clark (1949) provided early evidence that immature redfish in the Gulf of Maine exhibited extremely slow growth and that maturation was delayed until about age 9. Kelly and Wolf (1959) further demonstrated the extremely slow growth of adult redfish up to age 20. More recently, Mayo et al. (1981) provided further validation of the slow growth rates for redfish up to age 7 based on length mode progression and otolith edge formation. Consequently, an instantaneous natural mortality rate of 0.05 has been employed in age-structured models, consistent with the longevity of this species. Moreover, growth and maturation appear to be linked. The most recent estimates of redfish

maturation suggest a median age of about 5.5 years (Mayo et al. 1990; O'Brien et al. 1993) compared to the 9-10 years indicated by Perlmutter and Clark (1949).

In this analysis, the relationship between maturation and length is examined within 3 time periods using logistic regression (PROC LOGISTIC; SAS 1990) of the form:

$$Pm = e^{(a + b*Len)} / (1 + e^{(a + b*Len)}).$$

The analysis is based on 3,728 individual maturity stage observations from 1975 through 2000 within the following periods: 1975-1981, 1982-1991, and 1992-2000. There are 6 maturation stages for male redfish and 7 stages (including eyed larvae) for females. The development and present basis for the NEFSC maturity stages are described by Burnett et al. (1989).

In general, redfish maturation at length remained relatively constant over the 25 year period analyzed. A slight trend towards decreasing size at maturity is evident in both the spring and autumn results (Figure C16). Estimates of median length at maturation (L50) for females varied between 20.3 cm and 22.6 cm. The slightly higher values occurred in the earliest period. Estimates of L50 for males ranged from 20.2 to 21.3 cm and the higher values also correspond to the 1975-1981 period Figure C17).

ASSESSMENT OF CURRENT STATUS

Yield and SSB per Recruit

Yield and spawning stock biomass (SSB) per recruit were calculated according to the methods described by Thompson and Bell (1934) and Gabriel et al. (1989). Natural mortality was assumed to be 0.05. Mean weights at age for the yield per recruit

calculations were taken as the 1969-1984 mean of the commercial mean weights at age (Table C3). Partial recruitment was based on the fishery selectivity pattern derived from the age-structured model presented below. This pattern was similar to that employed in the previously published VPA (Mayo 1993) which was taken from the most recently published VPA (NEFC 1986) which reflects the recruitment of the 1971 year class. Growth and maturation data for SSB/R analysis were taken from the female data presented by Mayo et al. (1990).

Estimates of $F_{0.1}$ (0.06) and F_{max} (0.13) (Table C6, Figure C18) are identical to those derived by Mayo (1993); these estimates were similar to those reported by Mayo (1980) using the Beverton-Holt approach with the same value of M (0.05) for 89mm mesh (males) and 102 mm mesh (females). F at 30% of Maximum Spawning Potential was estimated as 0.07, slightly above the estimate of $F_{0.1}$.

Index of Exploitation
An index of exploitation (Table C7; Figure C19) was derived for the period 1963-2000, expressed as the ratio of the autumn NEFSC biomass index (Table C5) to total fishery removals (Table C1). The index fluctuated considerably during the 1960s and 1970s, but generally increased until the 1982, then declined sharply during the 1980s. Since 1990, the index of exploitation has remained at an extremely low level as landings remained low despite the recent increase in the survey biomass index. However, in contrast to the 1960s and 1970s, where a substantial portion of the stock persisted in the 30-40 cm range (Figure C12), during the 1990s, almost all of the redfish were less than 25 cm, and almost none were larger than 30 cm. This suggests that, given the present demographics

of the stock, only a small fraction of the biomass would be considered exploitable. Thus, the exploitation ratio based on the total biomass index, tends to under-estimate current exploitation relative to the earlier period in the series.

Age-structured Dynamics Model
In this section, an age-structured assessment model is developed for redfish. Age-structured population dynamics of redfish are modeled in a standard manner using forward-projection methods for statistical catch-at-age analyses (Fournier and Archibald 1982, Methot 1990, Ianelli and Fournier 1998, Restrepo and Legault 1998). The population dynamics model, statistical estimation approach, model diagnostics, and model results are described in sequence below.

Population dynamics model
The age-structured model is based on forward projection of population numbers at age. This modeling approach is based on the principle that population numbers through time are determined by recruitment and total mortality at age through time. The population numbers at age matrix $N=(N_{y,a})_{Y \times A}$ has dimensions Y by A, where Y is the number of years in the assessment time horizon and A is the number of age classes modeled. The oldest age (A) comprises a plus-group consisting of all fish age-A and older. The time horizon for redfish is 1934-2000 (Y=67). The number of age classes is 26, representing ages 1 through 26+.

Recruitment (numbers of age-1 fish) in year y (R_y) is modeled as a lognormal deviation from average recruitment (μ_R), where V_y are iid normal random variables with zero mean and constant variance.

$$R_y = \mu_R e^{V_y}$$

For all years y from 1935-2000, $R_y = N_{y1}$ is estimated from the recruitment deviation and average recruitment.

Initial population abundance at age in 1934 is based on recruitment deviations from average recruitment for 1909-1934 and natural mortality. For all ages a < A, the numbers at age in the first year (ystart=1) are estimated as a lognormal deviations from average recruitment as reduced by natural mortality

$$N_{1,a} = \mu_R e^{V_{ystart-a+1}} e^{-(a-1)M}$$

For the plus group, the initial numbers at age is the sum of numbers at ages 26 and older based on an equilibrium recruitment deviation for ages 26 and older and natural mortality.

$$N_{1,A} = \frac{\mu_R e^{V_{ystart-A+1}} e^{-(A-1)M}}{1 - e^{-M}}$$

The total instantaneous mortality at age matrix $Z=(Z_{y,a})_{YxA}$ and the instantaneous fishing mortality at age matrix $F=(F_{y,a})_{YxA}$ both have dimensions Y by A. Instantaneous natural mortality at age is assumed to be constant (M) and for all years y and ages a

$$Z_{y,a} = F_{y,a} + M$$

Population numbers at age through time are computed from the initial population numbers at age, recruitment through time, and total mortality at age through time. For all ages a younger than the plus group (a < A), the number at age are sequentially determined using

$$N_{y,a} = N_{y-1,a-1} e^{-Z_{y-1,a-1}}$$

For the plus group, numbers at age are the sum of survivors at age A-1 and plus group survivors

$$N_{y,A} = N_{y-1,A-1} e^{-Z_{y-1,A-1}} + N_{y-1,A} e^{-Z_{y-1,A}}$$

Fishing mortality at age a in year y is modeled as a separable process, where S_a is selectivity at age a and F_y is fully-recruited fishing mortality in year y

$$F_{y,a} = S_a F_y$$

Fully-recruited fishing mortality in each year is modeled as a lognormal deviation from average fishing mortality (μ_F),where U_y are iid normal random variables with zero mean and constant variance

$$F_y = \mu_F e^{U_y}$$

Fishery selectivity at age is modeled as being time-invariant throughout the assessment time horizon. This approach was chosen for parsimony. In particular, redfish catch-at-age data to estimate fishery selectivity are limited to 1969-1985, a period when the fishery practices are believed to have been relatively stable. Fishery selectivity at age is estimated for ages 1 through 9. For ages older than 9 years, fishery selectivity is assumed to be equal to the age-9 selectivity value. This approach was chosen to reflect the asymptotic selectivity pattern from previous VPA-based assessments of redfish, wherein age 9 was the age of full selectivity. Two constraints are applied to the estimated selectivity at age coefficients. First, the selectivities are constrained to average 1 for estimated ages. This forces the scale of each coefficient to be near unity. Second, a constraint is applied to ensure that estimated selectivities change smoothly between adjacent ages. Details of the implementation of both constraints are described in the section on statistical estimation approach. Last, for each year the selectivity at age values are scaled so that the maximum selectivity at age value is unity. This ensures that estimated fully-recruited fishing mortality rates are directly comparable to biological reference points such as $F_{0.1}$.

The fishery catch numbers at age matrix $C=(C_{y,a})_{YxA}$ and the fishery catch biomass at age (yield) matrix $Y=(Y_{y,a})_{YxA}$ both have dimensions Y by A. Fishery catch at age in each year is computed from Baranov's catch equation using population numbers, fishing mortality, and total mortality at age

$$C_{y,a} = \frac{N_{y,a} F_{y,a} \left(1 - e^{-Z_{y,a}}\right)}{Z_{y,a}}$$

Catch biomass at age in each year is the product of catch numbers at age and mean weight at age, where W_a is the mean weight at age computed as the average of mean redfish weights at age from fishery sampling during 1969-1985

$$Y_{y,a} = C_{y,a} W_a$$

Total fishery catch biomass in year y (Y_y) is the sum of yields by age class

$$Y_y = \sum_{a=1}^{A} Y_{y,a}$$

The total fishery catch biomass time series is compared to observed values using a lognormal probability model.

The proportion of fishery catch at age a in year y ($P_{y,a}$) is computed from estimated catch numbers

$$P_{y,a} = \frac{C_{y,a}}{\sum_a C_{y,a}}$$

The time series of fishery proportions at age are fitted to observed fishery values using a multinomial probability model.

Fishery catch-per-unit effort in year y ($CPUE_y$) is modeled as a catchability coefficient (Q_{CPUE}) times exploitable biomass raised to a power (β_{CPUE}), where exploitable biomass is computed at the midpoint of the year

$$CPUE_y = Q_{CPUE} \left(\sum_a S_a W_a N_{y,a} e^{-Z_{y,a}} \right)^{\beta_{CPUE}}$$

This model for CPUE coincides with the proportionality model when $\beta_{CPUE} = 1$. The estimated CPUE time series is fitted to observed values using a lognormal probability model.

The survey biomass index in year y (I_y) for either the NEFSC autumn or spring survey is modeled as a catchability coefficient (Q_{SURVEY}) times the population biomass that is vulnerable to the survey, where $S_{SURVEY,a}$ is survey selectivity at age a and p_{SURVEY} is the fraction of annual total mortality that occurs prior to the survey

$$I_y = Q_{SURVEY} \sum_a S_{SURVEY,a} W_a N_{y,a} e^{-p_{SURVEY} Z_{y,a}}$$

The survey biomass index time series are fitted to observed values using a lognormal probability model.

Survey selectivity at age is modeled using Thompson's exponential-logistic model (Thompson 1994), where α, β, and γ are parameters and survey selectivity for redfish is assumed to be time invariant.

$$S_{SURVEY,a} = \frac{1}{1-\gamma} \left(\frac{1-\gamma}{\gamma} \right)^\gamma \left(\frac{e^{\alpha\gamma(\beta-a)}}{1+e^{\alpha(\beta-a)}} \right)$$

This model has the useful property that the maximum selectivity value is unity. For values of $\gamma>0$ survey selectivity is dome-shaped, and survey selectivity is flat-topped when $\gamma=0$.

Survey catch proportion at age a in year y ($P_{SURVEY, y, a}$) is computed from survey selectivity, the fraction of mortality occurring prior to the survey, and population numbers at age

$$P_{SURVEY,y,a} = \frac{S_{SURVEY,a} N_{y,a} e^{-p_{SURVEY} Z_{y,a}}}{\sum_a S_{SURVEY,a} N_{y,a} e^{-p_{SURVEY} Z_{y,a}}}$$

The time series of survey proportions at age are fitted to observed fishery values using a multinomial probability model.

Statistical estimation approach

The population dynamics model is fit to observed data using an iterative maximum likelihood estimation approach. The statistical model consists of nine likelihood components (L_j) and two penalty terms (P_k). The model objective function (Λ) is the weighted sum of the likelihood components and penalties where each summand is multiplied by an emphasis coefficient (λ_j) that reflects the relative importance of the data.

$$\Lambda = \sum_j \lambda_j L_j + \sum_k \lambda_k P_k$$

Each likelihood component is written as a negative log-likelihood so that the maximum likelihood estimates of model parameters are obtained by minimizing the objective function. The Automatic Differentiation Model Builder software is used to estimate a total of 179 model parameters. The likelihood components and penalty terms are described below.

1. Recruitment

Recruitment strength is modeled by lognormal deviations from average recruitment for the period 1909-2000. A total of 92 recruitment deviation parameters (V_y) and one average recruitment parameter (μ_R) are estimated based on the objective function minimization.

The recruitment likelihood component (L_1) is $\qquad L_1 = \sum_y V_y^2$

where

$$V_y = \ln(R_y) - \ln(\mu_R)$$

2. Fishery CPUE

Fishery CPUE is modeled by lognormal deviations of predicted values from observed values, denoted with a superscript "OBS" for all variables, during 1942-1989, where W_y are iid normal random variables with zero mean and constant variance

$$CPUE_y^{OBS} = CPUE_y e^{W_y}$$

A total of 2 parameters (Q_{CPUE} and β_{CPUE}) are estimated based on the objective function minimization. The fishery CPUE likelihood component (L_2) is

$$L_2 = \sum_y V_y^2$$

3. Fishery age composition

Fishery age composition is modeled as a multinomial distribution for sampling catch numbers at age. The constant $N_{E,FISHERY,y}$ denotes the effective sample size for the multinomial distribution for year

y and is assumed to be constant across time for the years 1969-1985 when redfish catch-at-age data are available. The observed number of fish at age in the fishery samples is computed as the effective sample size times the observed proportion at age. The effective sample size was assumed to be 200 fish in each year during 1969-1985. The negative log-likelihood of the multinomial sampling model for the fishery ages (L_3) is

$$L_3 = -\sum_y N_{E,FISHERY,y} \sum_a \left(P_{y,a}^{OBS} \ln P_{y,a} - P_{y,a}^{OBS} \ln P_{y,a}^{OBS} \right)$$

The second term in summation over a is a constant that scales L_3 to be zero if observed and predicted proportions were identical. Nine fishery selectivity coefficients (S_1 through S_9) are estimated based on the objective function minimization.

4. Autumn survey age composition
Autumn survey age composition is also modeled as a multinomial distribution for sampling survey catch numbers at age. The constant $N_{E,AUTUMN,y}$ denotes the effective sample size for the multinomial distribution for year y and is assumed to be constant across time for the years 1975-2000 when redfish autumn survey catch-at-age data are available. The observed number of fish at age in the survey samples is computed as the effective sample size times the observed proportion at age. The effective sample size was assumed to be 100 fish in each year during each year. The negative log-likelihood of the multinomial sampling model for the autumn survey ages (L_4) is

$$L_4 = -\sum_y N_{E,AUTUMN,y} \sum_a \left(P_{AUTUMN,y,a}^{OBS} \ln P_{AUTUMN,y,a} - P_{AUTUMN,y,a}^{OBS} \ln P_{AUTUMN,y,a}^{OBS} \right)$$

As with the fishery age composition, the second term in the summation over a is a constant that scales L_4 to be zero if observed and predicted proportions were identical. Three autumn survey selectivity coefficients (α_{AUTUMN}, β_{AUTUMN}, γ_{AUTUMN}) are estimated based on the objective function minimization.

5. Autumn survey biomass index
The autumn survey biomass index is modeled by lognormal deviations of predicted values from observed values during 1963-2000, where $D_{AUTUMN,y}$ are iid normal random variables with zero mean and constant variance

$$I_{AUTUMN,y}^{OBS} = I_{AUTUMN,y} e^{D_{AUTUMN,y}}$$

The autumn survey biomass likelihood component (L_5) is

$$L_5 = \sum_y D_{AUTUMN,y}^2$$

One autumn survey catchability ($_{AUTUMN}$) coefficient is estimated based on the objective function minimization.

6. Spring survey age composition

Spring survey age composition is also modeled as a multinomial distribution for sampling survey catch numbers at age. The constant $N_{E,SPRING\,y}$ denotes the effective sample size for the multinomial distribution for year y and is assumed to be constant across time for the years 1975-1980 and 1984-1990 when redfish spring survey catch-at-age data are available. The observed number of fish at age in the survey samples is computed as the effective sample size times the observed proportion at age. The effective sample size was assumed to be 100 fish in each year during each year. The negative log-likelihood of the multinomial sampling model for the autumn survey ages (L_6) is

$$L_6 = -\sum_y N_{E,SPRING,y} \sum_a \left(P^{OBS}_{SPRING,y,a} \ln P_{SPRING,y,a} - P^{OBS}_{SPRING,y,a} \ln P^{OBS}_{SPRING,y,a} \right)$$

Three spring survey selectivity coefficients (α_{SPRING}, β_{SPRING}, γ_{SPRING}) are estimated based on the objective function minimization.

7. Spring survey biomass index

The spring survey biomass index is also modeled by lognormal deviations of predicted values from observed values during 1968-2000, where $D_{SPRING,y}$ are iid normal random variables with zero mean and constant variance

$$I^{OBS}_{SPRING,y} = I_{SPRING,y} e^{D_{SPRING,y}}$$

The spring survey biomass likelihood component (L_7) is

$$L_7 = \sum_y D^2_{SPRING,y}$$

One spring survey catchability (Q_{SPRING}) coefficient is estimated based on the objective function minimization.

8. Catch biomass

Catch biomass is modeled by lognormal deviations of predicted values from observed values during 1934-1999, where T_y are iid normal random variables with zero mean and constant variance

$$Y^{OBS}_y = Y_y e^{T_y}$$

The catch biomass likelihood component (L_8) is

$$L_8 = \sum_y T^2_y$$

9. Fishing mortality
Fishing mortality on fully-selected ages is modeled by lognormal deviations from average fishing mortality for the period 1934-1999. A total of 66 recruitment deviation parameters (U_y) and one average fishing mortality parameter (μ_F) are estimated based on the objective function minimization. The fishing mortality likelihood component (L_9) is

$$L_9 = \sum_y U_y^2$$

where

$$U_y = \ln(F_y) - \ln(\mu_F)$$

10. Fishery selectivity
Two constraints on fishery selectivity are included in a penalty function. The fishery selectivity penalty function (P_1) is

$$P_1 = \left(\frac{1}{9} \sum_{a=1}^{9} S_a - 1 \right)^2 + \sum_{a=1}^{7} \left(S_a - 2S_{a+1} + S_{a+2} \right)^2$$

The first term constrains the fishery selectivity coefficients to scale to an average of 1. The second term constrains the fishery selectivity coefficient of age a+1 to be near to the linear prediction of this value interpolated from age a and age a+2 selectivities over the range of estimated selectivity coefficients.

11. Fishing mortality penalty
One constraint on fishing mortality is imposed to ensure that during the early phases of the iterative estimation process that the observed catch is not generated by an extremely small F on an extremely large population size. The fishing mortality penalty function (P_2) is

$$P_2 = 10 \sum_y \left(F_y - 0.1 \right)^2 \Leftrightarrow phase < 3$$

$$P_2 = \frac{1}{1000} \sum_y \left(F_y - 0.1 \right)^2 \Leftrightarrow phase \geq 3$$

The constraint is weighted with a value of 10 for the initial estimation phases and is weighted with a value of 0.001 for the latter and final estimation phases. The value of 0.1 was used because this is near the maximum computed in previous VPA-based analyses of the redfish stock. Sensitivity analyses that changed 0.1 to either 0.05 or 0.2 showed virtually no difference in parameter estimates.

Initial values are input for all parameters before the estimation phases are conducted. A total of seven estimation phases were used for the iterative minimization of the objective function. The first phase estimates average recruitment. The second phase estimates average fishing mortality and fishing mortality deviations. The third phase estimates recruitment deviations. The fourth phase estimates fishery and survey selectivity coefficients. The fifth and sixth phases are placeholders left open for additional parameters, if needed, while the seventh phase estimates the fishery CPUE catchability and beta parameters.

The eleven emphasis values used for the baseline analysis were: 10 (recruitment), 10 (fishery CPUE), 1 (fishery age composition), 1 (autumn survey age composition), 1000 (autumn survey biomass index), 1 (spring survey age composition), 1000 (spring survey biomass index), 1000 (catch biomass), 1 (fishing mortality), 100 (fishery selectivity penalty), 1 (fishing mortality penalty).

Model diagnostics
Model diagnostics were the discrepancies between observed data and predicted values for the catch biomass series (Figure C20), the autumn survey biomass series (Figure C21), the spring survey biomass series (Figure C22), the fishery CPUE series (Figure C23), fishery age composition series (Figure C24), autumn survey age composition series (Figure C25), and spring survey age composition series (Figure C26).

Model results
Key model results of spawning biomass, fishing mortality, recruitment, and population biomass for the period 1963-2000 are listed in Table C8.

Fishery and survey selectivity estimates at age are shown in Figure C27. Fishery selectivity was flat-topped with full selectivity at age 9. While it was assumed that selectivity for ages 10 and older was equal to age-9 selectivity, this did not mean that the age-9 fish had to be fully-selected. The autumn survey selectivity pattern was moderately dome-shaped with full selection at age 5. In contrast, spring survey selectivity was dome-shaped with full selection at age 9. The NDWG noted that the spring survey selectivity pattern was robust but the autumn survey selectivity pattern was sensitive to the inclusion of recent autumn survey age composition data. In particular, autumn survey selectivity was flat-topped in an initial model run that included the 1996-1998 and 1981-1983 autumn survey age composition data but did not include the 1999-2000 data.

Recruitment estimates are shown in Figure C28 (see also Table C8). Strong year classes have been sporadic in recent years with the 1971 and 1992 year classes being very large. Recruitment was higher, on average, in the 1950s-1960s than in recent years. Overall, the model's ability to resolve which year class(es) in the early 1990s were strong was dependent on the recent autumn survey age composition data, in part due to the lack of commercial fishery age composition data since 1985. The NDWG noted that the earliest recruitment values in the time series (1934-1962) were not reliable as absolute measures of recruitment strength by year because these values were sensitive to assumptions about how to estimate the initial population size at age in 1934. This sensitivity was a natural consequence of having little information on annual recruitment variation at the beginning of the time series. In particular, the extremely large recruitment estimate in 1942 was sensitive to model assumptions about initial population size.

Population biomass estimates are shown in Figure C29 (see also Table C8). Population biomass declined from the 1950s to the late-1980s and has increased since then. The NDWG noted that the early portion of the population biomass time series (1934-1951) was less reliable because there was no relative abundance information during that time period, i.e., the model was only tuned to catch biomass in the 1930s-1940s. The NDWG also noted that population biomass estimates in the 1970s-1980s were very similar to those obtained with an untuned VPA conducted for SAW 2.

Spawning biomass estimates (at start of the spawning season) are shown in Figure C30 (see also Table C8). Spawning biomass declined from the 1950s to the late-1980s and has increased throughout the 1990s. The NDWG noted that the current population biomass estimate was sensitive to the size of the strong year class(es) of the early-1990s which could start to appear in fishery catches, if a directed redfish fishery was started again.

Fishing mortality estimates are shown in Figure C31 (see also Table C8). Annual estimates of fishing mortality early in the time series (1934-62) were not considered to be reliable because they were sensitive to assumptions about initial population size. Instead, the early estimates of F provide information on the average fishing mortality that was experienced by the redfish population as the fishery began. Fishing mortality increased from 0.05-0.1 in the early 1960s to over 0.20 in the late-1970s to early-1980s. Since then, fishing mortality has declined and is currently below 0.01 in 2000.

Stock-recruitment data are shown in Figure C32. Recruitment was below-average throughout 1963-2000, with the exception of a few strong year classes, for example, the 1971 and 1992 year classes.

Surplus production implied by the age-structured estimates of exploitable biomass and observed catches are shown in Figure C33.

Surplus production was above 10 kt per year during the 1960s and then declined to very low levels in the 1980s because recruitment was very low. The recent increase in surplus production is due to strong recruitment in the early 1990s. The trajectory of surplus production shows the decline from 1963 to 1990 followed by a sharp increase in recent years.

Model sensitivity to the assumption that natural mortality is 0.05 is shown in Figure C34. The likelihood profile for natural mortality shows that there are values of M from 0.025 to 0.045 that produce a higher value of the total model likelihood than M=0.05. The biomass time series shows the consequence of higher or lower values of M on estimated population biomasses.

Model sensitivity to the assumption that each of the relative abundance indices (autumn and spring survey biomass indices and CPUE) provides useful information on population trend is shown in Figure C35. The delete one index sensitivity analysis shows that the model is robust to the exclusion of one index. The delete two indices sensitivity analysis shows that the model is robust to the use of only the autumn or the spring survey series. However, use of only the CPUE series would produce a substantially different population biomass trajectory.

Biomass Dynamics Model

MSY-based reference points
The current overfishing definition and targets for redfish are based on an MSY estimate from surplus production analysis (MSY=14,000 mt, Mayo 1980), supplemented with an F_{MSY} proxy from a dynamic pool model ($F_{20\%}$=0.12), to derive a proxy B_{MSY} (14,000/0.12=60,500 mt, Applegate et al. 1998). As calculated, the current B_{MSY} proxy is in units of exploitable biomass.

The age-structured model provides some information on the likely range of MSY based on average recruitment and yield-per-recruit values. If $F_{0.1}$=0.06 is assumed to be a suitable proxy for F_{MSY}, then the average recruitment of 27,954

thousand age-1 recruits would produce an MSY of roughly 4,562 mt. Based on the 95% confidence interval for the point estimate of average recruitment and a fixed yield-per-recruit value of 0.1632 at $F_{0.1}$=0.06, the 95% confidence interval for MSY would be (4,401 mt, 4,729 mt). In contrast, if one assumed that F_{MAX}=0.13 was a suitable proxy for F_{MSY}, the point estimate of MSY would be 5,048 mt with a 95% confidence interval of (4,870 mt, 5,234 mt). Thus, the age-structured model suggests that MSY may be on the order of 4,400-5,200 mt, a much lower value than that suggested by surplus production analyses. However, these estimates of recruitment depend considerably on the average recruitment applied to the yield per recruit estimates. Since the mid-1960s, recruitment has been extremely low in most years with the exception of a few very large year classes. Thus, an average value which captures the observed recruitment pattern is difficult to calculate for this stock. For similar reasons, these data provide little evidence of a stock-recruitment relationship. Therefore, an age-disaggregated approach, in which natural mortality, growth and recruitment are subsumed into a single parameter, the intrinsic rate of growth (r), may provide additional insight into the past trajectory of biomass and fishing mortality for this stock.

A biomass dynamics model (ASPIC, Prager 1994) was developed to revise the MSY estimate and replace proxies with direct estimates of MSY reference points that include all available information on trends in biomass and catch. The analysis includes the entire time series of catch since the beginning of the fishery (1934-2000), NEFSC spring and fall survey biomass indices (1968-2000 and 1963-2000, respectively), and the standardized CPUE series (1952-1990; Figure C36). The three biomass indices are moderately correlated (correlation ranged from 0.42-0.63). Initial attempts to fit ASPIC had problems with convergence and sensitivity to starting values and random number seeds. In order to reduce the number of estimated parameters, biomass in 1934 was set equal to K and therefore removed from estimation. Initial trials that estimated B1R indicated that biomass in 1934 was near K. The assumption that the stock was at virgin biomass in 1934 is justified, because there was no fishery prior to 1934 and incidental catch of redfish in other fisheries was negligible. Furthermore, life history characteristics of redfish such as long lifespan, slow growth, slow maturity, and internal fertilization suggest that the population is "K-selected" and will maintain a relatively stable stock size near its carrying capacity in the absence of fishing.

Model results
The model fit the biomass indices well (R^2=0.71 for CPUE, 0.59 for fall, and 0.37 for spring; Figures C37-C39). Although the observed data represents a large dynamic range (Figure C40), biomass dynamics parameters (r: intrinsic rate of increase and K: carrying capacity) are largely influenced by a few observations. For example, r is largely influenced by the large rate of increase in recent years from strong recruitment, and K is largely determined by estimates from the early years in the time series, which are not calibrated with biomass indices (Figure C40).

The estimate of MSY is 20,000 mt (Figure C41) with an 80% confidence limit of 19,000-22,000 mt, which is similar to a previous estimate from production modeling (Mayo 1975). The estimate of F_{MSY} (0.09 on total biomass, with an 80% CI of 0.08-0.10) is consistent with life history and relatively low productivity of redfish. The estimate of B_{MSY} is 226,000 with an 80% CI of 211,000-244,000 mt. However, estimates of absolute biomass from ASPIC are commonly misleading, and ratios of biomass or F to MSY conditions are more reliable (Prager 1994). Comparisons of biomass estimates from ASPIC, the historical VPA (NEFSC 1986) and the present age-based dynamics model suggest that ASPIC underestimates redfish biomass (Figure C42). Therefore, only relative biomass and F estimates from ASPIC (Figures C43 and C44) should be considered to be reliable. The estimate of biomass in 2001 is 33% of B_{MSY} with an 80% CI

of 27-40%, and the estimate of F on biomass in 2000 is estimated as 5% of Fmsy with an 80% CI of 4-7% (Table C9, "REDFISH3" in Table C10).

Sensitivity of ASPIC results to excluding the CPUE series and estimating biomass in 1934 was assessed with alternative analyses. Results from sensitivity analyses suggest that estimates are relatively robust to both decisions (Table C10). Estimates of MSY, F_{MSY}, and B_{MSY} and B_{2001}/B_{MSY} had less than 3% difference in estimates among alternative runs, but estimates of F_{2000}/F_{MSY} had slightly greater sensitivity (9% difference). However, alternative runs that estimated B1R had problems converging on a solution. No solution could be found when CPUE was included and B1R was estimated. Many bootstrap trials could not converge when B1R was estimated without including CPUE ("REDFISH2"), and results were sensitive to random number seeds. Including CPUE in the analysis appears to reduce variance of parameter estimates, and therefore "REDFISH3" was chosen as the best run.

An additional analysis was performed to assess sensitivity of model parameter estimates to the recently observed strong recruitment by truncating the analysis to 1934-1995 ("REDFISHT" in Table C10). Results indicate that the stock is less productive (i.e., a 34% decrease in Fmsy) when recent observations are excluded from the model. Therefore, when the entire time series is included in the model, there is an explicit assumption that the recently observed high recruitment is consistent with the long-term reproductive capacity of the stock.

The capacity of the redfish stock to rebuild to B_{MSY} was assessed using ten-year stochastic projections from "REDFISH3" assuming F=0 from 2001 to 2010. Results indicate that the stock can rebuild to B_{MSY} in 2010 in the absence of fishing (Figure C45). However, the projection implicitly assumes the higher productivity indicated by analysis of the entire time series (i.e., including the recently observed

strong recruitment). As demonstrated in the sensitivity analyses, the estimate of intrinsic growth rate (r) is sensitive to recent recruitment observations.

SUMMARY

- Landings have remained at historic low levels (< 1,000 t) since 1989 after declining from an average 14,000 t during 1977-1979.

- Commercial CPUE had declined by the late 1980s by over 80% from levels observed during the 1960s.

- Exploitable (age 5+) biomass estimates derived by VPA declined by 75% between 1969 and 1984.

- Fully recruited (age 9+) instantaneous fishing mortality (F) ranged from 0.18 to 0.26 between 1969 and 1983, but has declined in recent years as landings have declined sharply from mid-1980s levels.

- Relative abundance and biomass indices from NEFSC bottom trawl surveys declined by over 90% between the mid-to-late 1960s and late 1980s. Recent indices have increased to levels observed during the early 1970s.

- As a consequence of extremely poor recruitment between the mid-1960s and the mid-1980s, the age structure of the population has narrowed considerably and is now represented by one or two significant year classes. The population is now dominated by relatively young (less than 15 yrs) fish compared to the 1970s.

SARC COMMENTS

The SARC noted that the NEFSC spring and autumn survey indices of abundance, after falling to their lowest recorded levels in the mid-1980s, had gradually increased until the mid-1990s, then

increased rapidly in 1996 and 1997 to levels similar to those observed in the late 1960s. The age compositions of the NEFSC survey data revealed relatively strong 1991 and 1992 year classes, supported by recruitment of reasonable magnitude in the surrounding years. The strong 1991-1992 year classes that emerged as age 4 and 5 fish in 1995-1996 were not detected in any numbers at younger ages in either the shrimp or the bottom trawl surveys. It was suggested that these year classes may not have been available to the gear at the younger ages or that the year class may possibly have immigrated from the Scotian shelf. There is an indication from examination of otoliths that size at age of these recent cohorts appears to be slowing down in contrast to previous cohorts.

Currently, the stock is comprised primarily of young fish with few older mature fish. The SARC also noted that the average total mortality (Z) determined from the combined autumn survey age composition data for all cohorts over the period from 1925 to 1995 was in the range of 0.15-0.20.

The SARC considered that the large pulse of recruitment of the 1942 year class in the age-structured dynamics model may be a mathematical artifact of 26 year old fish caught in the first year of catch-at-age data (1969) in the model. The SARC concluded that the age-structured results prior to 1963, when the autumn survey data became available as a relative abundance index, are less reliable and should not be used as they lie beyond the range of the tuning data. In particular, the estimated biomass in 1934 should not be used as an estimate of virgin biomass. Absolute biomass from the age-structured model prior to 1963 is important for a historical perspective of the stock; however, uncertainty exists in the proportion of biomass by age before the survey was conducted.

The SARC expressed concern that F may be higher in recent years than that estimated by the age-structured model due to an unknown and possibly significant discard mortality, from both discarded catch and through encounter of uncaught redfish with the fishing gear, noting that the large mesh trawl fishery effort has recently shifted to the Gulf of Maine from Georges Bank. It was noted that size classes currently present in the population are not yet fully recruited to the 6 inch mesh regulation in the large mesh trawl fishery. The SARC concluded that research is needed to quantify the significance of this non-landed fishing mortality.

The SARC noted that, in the analysis based on the biomass dynamics model (ASPIC), the estimation of 'r', the intrinsic rate of increase, may be unduly influenced by the most recent estimates of recruitment and therefore affect estimation of biological reference points. An alternative ASPIC analysis was requested with the most recent years (1996-2000) of survey indices deleted from the input data. The results indicated that the estimate of 'r' was sensitive to the more recent strong year classes. Reliable information on relative biomass prior to 1952 is not available, since the CPUE was not standardized prior to 1952. As a result the SARC agreed that the early CPUE data be excluded as a relative abundance measure and only the 1952- present data be applied in the analyses.

The SARC discussed the appropriateness of the surplus production model for estimating biological reference points for a slow growing, long lived species such as redfish. Although biomass dynamics models assume an instantaneous response to change in population size, they have been used by the International Whaling Commission in studies of marine mammals, and for other long-lived species such as swordfish, where similar lags might be expected.

The SARC noted that estimates of model parameters will change as the models are improved and as new data are added. The absolute magnitude of selected reference points will change, sometimes considerably, as they must be updated when new parameter estimates become available. Estimates of B_{msy} and F_{msy} from the ASPIC results are not reliable as absolute estimates; however, the ratios of B_{2001}/B_{msy} and F_{2000}/F_{msy} are informative. Rather than specifying absolute values for the threshold and target reference points, it is equally effective and more consistent to express the current status as a ratio of the reference point. The statement that the current biomass is estimated to be 33% of B_{Target} where $B_{Target} = B_{MSY}$ clearly identifies the current status with respect to the reference point.

The values of existing reference points were considered to be inappropriate and the SARC advised that they be replaced with values determined from the curent assessment. Using the ratio derived from the biomass dynamics model, $B_{2001}/B_{MSY} = 0.33$ and the current fishing mortality status is estimated as $F_{2000}/F_{MSY} = 0.05$. The absolute estimate of F_{MSY} from the surplus production model exceeds the assumed M used in the age-based model, highlighting the difficulty of expressing estimates from two types of models in comparable terms. For long-lived species, it is considered inappropriate to use a value such as $F_{20\%}$ as a limit or threshold reference point, and a value such as $F_{40\%}$ or $F_{50\%}$ is required to ensure sustainability. For rockfish, $F_{50\%}$ is considered necessary (Ralston et al. 1998, Dorn 2001).

The SARC concluded that the stock is being rebuilt from the collapsed state it reached in the 1970s. It is unlikely to recover quickly. The current stock is comprised primarily of young fish, and its growth and reproductive potential may differ from that of a similar sized population with a greater representation of older, mature fish.

Sources of Uncertainty

The source of recent large year classes is not as certain as previous large year classes, and the possibility exists that these year classes immigrated into the Gulf of Maine region.

Characterization of the length composition of the landings is uncertain due to insufficient sampling since 1994.

The difference between the spring and autumn selectivity pattern in the age-structured model can not be explained by differences in the time series and may be due to other causes such as differences in the spatial distribution of the stock during the two seasons.

Reliable information on relative biomass prior to 1952 is not available, since the CPUE was not standardized prior to 1952.

Estimates of B_{msy} and F_{msy} from the ASPIC results are not reliable as absolute estimates, however, the ratios of B_{2001}/B_{msy} and F_{2000}/F_{msy} are informative.

RESEARCH RECOMMENDATIONS

- Further examination of the mortality estimates from catch curve for the individual cohorts should be undertaken. Maturation, growth, yield per recruit, etc., should be calculated for each cohort to examine density dependence of parameters.

- Investigate the growth rate of recent year classes and the implications on the rate of maturation.

- Investigate the option of starting the age-structured model in 1963, and applying the resulting parameters to hindcast the population in 1934.

- Further investigation of the magnitudes of the biomass and fishing mortality estimated by

the age-structured dynamic model is required.

- Determine the discard mortality and undertake research to assess the mortality resulting from encounter with fishing gear.

- Examine Canadian surveys to determine if strong year classes were also produced in Division 4X or other regions of the Scotian Shelf area in the early 1990's.

- Investigate whether the increase in the redfish stock might be due to immigration rather than recruitment.

- Explore the possible use of alternative reference points, such as $F_{50\%}$ or F=M, as status determination criteria for redfish.

- Ensure that the intensity of sea sampling is adequate to provide details of the age composition of commercial catches and quantities of discards.

- Incorporate length frequency data into the age-structured model.

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