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AN ASSESSMENT OF THE STATUS OF STOCKS OF SWORDFISH IN THE NORTHWEST ATLANTIC OCEAN

R. Conser, P. L. Phares, J. J. Hoey, M. I. Farber
NMFS, Southeast Fisheries Center
75 Virginia Beach Drive, Miami, Florida, U.S.A.

SUMMARY

Catch and size frequency data from the U.S., Canadian, Japanese, and Taiwanese fisheries are used to assess the status of stocks of swordfish (Xiphias gladius) in the northwest Atlantic Ocean.

Algorithms are developed for estimating catch at age from catch-at-size data, incorporating the sexually dimorphic growth characteristic of swordfish. Virtual population analysis (VPA) is conducted to estimate age-specific fishing mortality rates (F) and stock size trends. Mark-recapture data are used in estimating terminal F's for the VPA. Ricker yield-per-recruit analysis is conducted using an F schedule derived from the VPA. The Ricker model is also employed to evaluate the effect of fishing on spawning stock biomass per recruit.

Results indicate that the fishery has experienced substantial increased in the fishing mortality rate since 1978 and has approached the fully exploited level.

Improvements in the precision of parameter estimates and the determination of the status of stocks will require the routine collection of fishing effort data and data on the sex ratio of the catch, in addition to those data presently being obtained from the fishery.

RESUME

Les données de taille et des prises des pêcheries américains, canadiennes, japonaises et taiwanaises sont utilisées pour évaluer l'état des stocks d'espadon (Xiphias gladius) du nord-ouest de l'Atlantique.

Des algorithmes sont effectués pour estimer la prise à un âge donné à partir des données de prise à une taille donnée, en y incorporant le dimorphisme sexuelle de croissance propre à l'espadon. Des analyses des populations virtuelles (VPA) sont menées à bien pour estimer les taux de mortalité spécifique de l'âge (F) et les tendances de la taille du stock. Les données de recapturation de marques sont utilisées pour estimer les F terminaux à partir des VPA. Le modèle de Ricker est également utilisé pour évaluer l'effet de la pêche sur la biomasse du stock reproducteur par recrue.

Les résultats indiquent que depuis 1978, la pêcherie a subi des accroissements substantiels du taux de mortalité par pêche et a atteint le niveau exploité le plus haut.

Des améliorations sur la précision des estimations des paramètres et de la détermination de l'état des stocks demandera une collecte de routine des données de l'effort de pêche et des données sur le sex ratio des prises, en plus des données actuellement obtenues sur la pêcherie.

RESUMEN

Se emplean los datos de captura y frecuencias de talla de las pesquerías de Estados Unidos de América, Canadá, Japón y Taiwan para evaluar la situación de las poblaciones de pez espada (Xiphias gladius) en el Océano Atlántico Noroeste.

Se desarrollan los algoritmos para estimar la captura por edad a partir de los datos de captura por talla, y se incorporan las características sexuales dimórficas del pez espada. Se lleva a cabo el VPA para calcular las tasas de mortalidad por pesca específico de la edad (F) y tendencias de tamaño de la población. Se utilizan los datos de marcado-recaptura para calcular las F terminales del VPA. Se efectúan los análisis de rendimiento por recluta de Ricker empleando un programa F deducido del VPA. El modelo de Ricker se emplea, asimismo, para evaluar el efecto de la pesca sobre la biomasa de la población reproductora por recluta.

Los resultados indican que la pesquería ha experimentado importantes aumentos en la tasa de mortalidad por pesca desde 1978 y que se encuentra próxima al nivel de explotación total.

Para lograr una mayor precisión de los cálculos por parámetros, y una mejor definición de la situación de las poblaciones, se precisará la recopilación rutinaria de datos de esfuerzo y de la proporción por sexos de la captura, además de aquellos que actualmente se obtienen de la pesquería.

INTRODUCTION

Broadbill swordfish (Xiphias gladius) are distributed widely throughout the Atlantic Ocean, from 45°S to 45°N latitude. They are the most widely distributed of the billfishes and occur in tropical, subtropical, and temperate waters (Palko et al. 1981). Swordfish have pronounced seasonal variations in abundance and distribution over most of their range. Catch rates indicate that the densest areas of concentration occur in the northwest Atlantic along the east coast of the United States and Canada; in the south Atlantic along the South American coast from Brazil to Argentina; and in the eastern Atlantic off the west coast of Spain and in the Mediterranean Sea (Beardsley 1979). Analysis of spawning information indicates that ripe females and larvae occur in each of these three areas (Beardsley 1977; Arfelli and Amorim 1983; Grall et al. 1983). Although the number of swordfish tag recaptures is limited (approximately 60 recaptures) and most of the tagging has been done in the northwest Atlantic, no movement among the three areas has been documented. However, swordfish are taken in almost all areas of the Atlantic Ocean and there does not appear to be any clear-cut dividing line between the three well-defined concentrations (Wise and Davis 1973). This suggests that interchange is possible, both across the north Atlantic as well as between the north and south Atlantic.

Two working hypotheses regarding swordfish stock structure have been suggested: (1) that there are three stocks, i.e., northwest Atlantic, south Atlantic, and east Atlantic; and (2) that there is a single stock throughout the Atlantic (Beardsley 1979). The weight of available evidence appears to favor the first hypothesis but swordfish stock structure in the Atlantic Ocean remains an open question. In this paper, we have employed the first working hypothesis for the purpose of evaluating the status of stocks of swordfish in the northwest Atlantic.

In the northwest Atlantic, swordfish have been exploited mainly by the longline fisheries of the United States and Canada and secondarily by the U.S. and Canadian harpoon fisheries and the high-seas tuna longline fisheries of Japan and Taiwan. Prior to 1963, swordfish were predominantly harvested by a seasonal Canadian and U.S. harpoon fishery centered off the coast of southern New England and Nova Scotia (Figure 1). In the early 1960's, incidental catches of swordfish by research vessels and by Norwegian and Japanese longliners prompted Canadian and U.S. fishermen to use pelagic longline gear for swordfish (Beckett 1971). Longlining rapidly replaced harpooning as the dominant U.S. and Canadian fishing method and when coupled with the Japanese tuna longline efforts, accounted for the vast majority of effort expended throughout the northwest Atlantic fishery. Landings increased dramatically as longlining enabled the fishery to operate throughout the year with a greatly expanded geographical range.

In 1971, the U.S. Food and Drug Administration (FDA) instituted regulations prohibiting interstate transportation and importation of swordfish containing tissue mercury in excess of 0.5 parts per million (ppm). These regulations reduced effort substantially in both the U.S. and Canadian fisheries since the primary market for swordfish was in the U.S. However, a clandestine fishery did continue throughout the regulated period but landings and other fisheries data were not reported. In the mid-1970's a new swordfish fishery developed, primarily among Cuban-American fishermen in south Florida. Gear modifications, influenced by traditional Cuban creole drifting gear (Guitart-Mandy 1964; Berkeley et al. 1981), improved catch rates and allowed a small boat (less than 15m) fishery to develop. In 1978, the U.S. FDA increased the allowable level of mercury to 1.0 ppm. During the late 1970's Canada, Mexico and the U.S. adopted extended jurisdiction laws that displaced many foreign and domestic fishermen from their traditional fishing grounds. These events led collectively to a dramatic increase in the number of vessels participating in the U.S. swordfish fishery. Most of the increased effort occurred in the southern areas of the U.S. fishery. U.S. landings have constituted the majority of northwest Atlantic landings since 1978 (Table 1). Although the Japanese and Taiwanese continue to take small amounts of swordfish in their tuna longline fisheries, the U.S. and Canadian fisheries generally account for some 80 to 90 percent of landings.

Due to the lack of continuous, historical data from the fishery and the uncertainty associated with many important biological parameters and vital rates, formal stock assessment studies on swordfish have not been conducted on a routine basis, as is common for other species under the auspices of ICCAT (e.g., tunas). However, studies on local and national fisheries have been conducted that collectively contribute to our understanding of the status of stocks of swordfish in the northwest Atlantic. Beckett and Tibbo (1968) examined the changes in size composition following the first years of Canadian longline fishing. Beckett (1974), Caddy (1976), and Caddy (1977) reviewed available population parameters needed for stock assessment and suggested management options. Beardsley (1979) and Kikawa and Honma (1981) estimated swordfish indices of abundance from Japanese longline data, assuming a single Atlantic-wide stock. Hurley and Iles (1982) and Farber and Conser (1983) developed similar indices for the northwest Atlantic stock area. Berkeley and Houde (1980 and 1981) estimated size at age from hardparts and conducted yield per recruit analysis, using data from the Florida fishery. Hoey et al. (1985) constructed a historical size frequency database for the U.S. fishery that documented much of the data that had been missed in routine sampling during 1978-84.

In this paper we take advantage of these previous studies, in particular the improvement in U.S. fisheries statistics, to assess the status of stocks of swordfish in the northwest Atlantic Ocean. Catch and size frequency data from the period 1978-84 were used in conjunction with mark-recapture data to conduct virtual population analysis (VPA) and equilibrium yield per recruit analysis (Y/R).

DATA AND METHODS

Stock Structure

Figure 1 depicts the major swordfish fishing grounds within the northwest Atlantic Ocean. For the purposes of this assessment, the northwest Atlantic stock area was taken to be the area north of 10°N latitude and west of 35°W longitude. The meridian used to separate the east and west Atlantic is somewhat arbitrary in that no clear-cut division was apparent from examination of Japanese longline catch rates. The 35°W meridian was selected because it encompassed all of the catches from the U.S. and Canadian fisheries.

Landings Data

Swordfish are taken by the U.S., Canada, Japan, and Taiwan in the northwest Atlantic stock area (Table 1). Because of the lower level of fishing activity and the clandestine nature of the fishery during the years prior to 1978 (due to the regulations concerning tissue mercury levels), no attempt was made to compile U.S. and Canadian landings for this period. U.S. landings for 1978-83 were taken as compiled from state landings records (SAFMC 1985). The 1984 landings were obtained from the U.S. National Marine Fisheries Service landings statistics (Newlin and Schween, pers. comm.). Canadian landings were obtained from ICCAT (1984) and Peacock (pers. comm.). Japanese and Taiwanese landings (in numbers of fish), 1978-82, were obtained from the ICCAT Secretariat (Nordstrom, pers. comm.) on computer tape. Landings (in number) for 1983 and 1984 (for Japan and Taiwan) were taken to be the same as the 1982 landings. Landings (in number) were converted to weight using average weights of the catch by area, month, and year from the U.S. fishery (U.S. fishery areas are listed in Table 1 and their locations are shown in Figure 1).

Size Frequency Data

Size frequency information for the U.S. fishery was taken from the data provided by cooperating fishermen and dealers. This extensive and newly available database is described more fully by Hoey et al. (1985). Size frequency data for Japan and Taiwan were also received on computer tape from the ICCAT Secretariat. No Canadian size data are available for the 1978-84 period.

Mark-Recapture Data

Swordfish mark-recapture data were compiled from two sources within the U.S. National Marine Fisheries Service: (1) the Southeast Fisheries Center Cooperative Game Fish Tagging Program (E. Scott, pers. comm.) and (2) the Northeast Fisheries Center Shark Tagging Program (J. Casey, pers. comm.). All releases and recaptures occurred within the northwest Atlantic stock area. The combined data set for the period 1977-83 included 1241 releases and 59 recaptures.

Growth Models

Swordfish are thought to exhibit sexually dimorphic growth (Berkeley and Houde 1981) but because the fish are dressed at sea, it is not possible, in general, to sample the sex ratio of the catch. Consequently, the vast majority of the landings as well as the size frequency samples have no sex data associated with them. It was necessary, therefore, to construct a combined growth curve that could be used in conjunction with the size samples to assign the landings to the proper cohort. Several age and growth studies have been conducted recently on swordfish in the northwest Atlantic (Berkeley and Houde 1983; Radtke and Hurley 1983; Wilson and Dean 1983a). Based primarily on sample size considerations and verification of annuli, the Berkeley and Houde estimates of mean size at age, for ages 1 through 8, were selected for use in fitting the combined growth curves (see Farber and Prince (1985) for a more detailed discussion of the various swordfish age and growth studies).

Both the Gompertz and von Bertalanffy growth models were fitted to the Berkeley and Houde mean length at age estimates for males and females using weighted nonlinear regression (Figure 2). The male and female observations at each age were weighted by the proportion of males and females, respectively, found in the catch. The Berkeley and Houde (1981) estimates of sex ratio at age were used to calculate these proportions (see Appendix). The resulting fitted curves follow the male lengths at age more closely than the female at young ages and approach the female lengths at age for the older ages (Figure 2). The Gompertz and von Bertalanffy fitted curves are nearly identical through the data. However, when the fitted curves are extrapolated beyond the data (i.e., for ages older than 8) and converted to age-weight relationships (Figure 3), the weighted von Bertalanffy curve approaches a much larger W_∞ than the weighted Gompertz curve (1348 vs. 430 lbs, dressed weight). In addition, the weighted von Bertalanffy curve crosses the female curve and approaches a larger W_∞ than the female curve (Figure 3). The weighted Gompertz curve also appears to be more consistent with the sample size frequency data from the fishery (Figure 4). Based on these comparisons, the weighted Gompertz curve was selected for use in assigning the landings to cohorts. All of the fitted parameters for the various growth curves are provided in the Appendix.

Assigning The Landings To Cohorts

The sample size frequencies were combined by year, month, and area of fishing (Gulf of Mexico; Florida East Coast; South Carolina; North Carolina and North). The age of each sample was estimated from its dressed weight using the weighted Gompertz curve shown in Figure 4. Given the date of sampling and the estimated age of the sample, an estimate of the birth date could be made. All samples "born" in the same calendar year were assigned to the same cohort. Then for each year-month-area strata, all samples assigned to cohorts were raised by the ratio of total landings to sampled landings. The assignment procedure assumes that due to the large sample size involved, individual errors in ageing will average out and the cumulative catch at age will be unbiased. Simulation studies need to be undertaken to verify this assumption.

The reported landings for the U.S., Canada, Japan, and Taiwan for 1978-84 were aged to give catch-at-age by country, year, month, and area of fishing. The landings of other countries were negligible in these years and were ignored. When there was no corresponding sample for reported landings, a sample from a month and area (in the same year or a different year) likely to have similar sizes was substituted. In subsequent analyses, the catch-at-age was summed over countries, months, and areas as needed. The total catch-at-age for all countries is given in Table 2.

Natural Mortality

The instantaneous natural mortality rate (M) is one of the most difficult parameters to estimate for fish populations. Caddy (1977) estimated M for fish taken in the Canadian fishery to be in the range 0.21 to 0.43 per year. Using Tanaka's (1960) relationship between M and maximum age, Berkeley and Houde (1980) suggested that the best estimate of natural mortality was M = 0.20 per yr. Using Pauly's (1980) multiple linear regression method, Berkeley and Houde (1981) estimated M to be 0.16 per yr. Using Pauly's method and different von Bertalanffy parameters, Conser et al. (1985) estimated M to be 0.21 per yr. Applying the Murphy and Sakagawa (1976) relationship between K and M in tunas, the Berkeley and Houde (1981) K estimate (i.e., K = 0.1054) yield an M estimate of 0.19 per yr. Similarly, the Conser et al. (1985) K estimate (i.e., K = 0.1380) yields an M estimate of 0.25 per yr.

Yoshida (1979) and Au (1983) have reviewed the natural mortality rates used in tuna population dynamics throughout the world. Although there are biological and ecological differences between the tunas and swordfish, the tunas (especially the more temperate species) are the species most closely related to swordfish for which natural mortality estimates have been developed. The Yoshida and Au natural mortality estimates along with several added herein are displayed in Figure 5. The tunas are ordered from the most temperate (i.e., southern bluefin) to the most tropical (skipjack). In terms of average life expectancy and location on the temperate-tropical scale, swordfish are probably most similar to albacore or bigeye tuna. The vast majority of the M estimates that have been used for these species are greater than or equal to 0.20 per yr.

Given the M estimates that have been used in previous swordfish studies and the estimates that have been used for the more temperate tunas, M = 0.21 was selected as the best natural mortality estimate. This value was the lower extreme of Caddy's range but otherwise appears to be in the middle of the range of the swordfish estimates discussed above. It is near the low end of the range of estimates that have been used for albacore and bigeye but at the high end of the bluefin and southern bluefin range. It is also consistent with the average life expectancy of swordfish (probably 10 to 12 years).

For the purpose of sensitivity analysis, an alternate hypothesis that swordfish have a much longer average life expectancy than generally believed (perhaps similar to bluefin or southern bluefin) was explored. A natural mortality of M = 0.16 was used for the sensitivity cases. This was the lowest value that had been used in previous swordfish studies and about in the middle of the bluefin and southern bluefin range.

Virtual Population Analysis

The virtual population analysis (VPA) method of Gulland (1965) was used to estimate stock size and fishing mortality rates (F) at age over the period 1978-84. Average weights at age from the fishery were used in conjunction with the VPA results to estimate stock biomass, surplus production, and female spawning stock biomass. For the spawning stock biomass calculations, mean age at first spawning for females was estimated to be age 6 from data reported by Wilson and Dean (1983b). The calculations were carried out under two assumptions concerning the proportion of females in the age 6+ population. It was assumed that (1) the sex ratios (by age) of the age 6+ population were 1:1 and alternatively that (2) the sex ratios (by age) of the age 6+ population were the same as those reported in the catch of the Florida fishery during 1979-80 (Berkeley and Houde 1981) for ages 6 to 8 and 0:1 (male to female) for age 9 and older. The Berkeley and Houde sex ratios are provided in the Appendix.

Fishing mortality rates in the terminal year (1984) were estimated using Farber's (1985) total mortality (Z) estimates from mark-recapture data. Farber estimated Z, the variance of Z, and approximate 95% confidence intervals using the methods of Chapman and Robson (1960) and Robson and Chapman (1961). No attempt was made to adjust the Z estimates for the possible upward bias due to tag shedding. The estimates (Table 3) were based on 1241 releases and 59 subsequent recaptures over the period 1977-83. Estimated sizes at release and/or recapture indicated that most of the fish were age 3 or older when released.

A constant terminal (1984) Z for ages 3 and older was estimated using Farber's Z estimates over 1980-83. Although it would have been desirable to estimate the terminal Z with the most recently available data (e.g., 1982 or 1983), the size of the standard errors for the 1982 and 1983 Z estimates (Table 3) indicated a high degree of uncertainty in those estimates. Thus, a weighted average of the Farber Z estimates over 1980-83 was used with the number of recaptures per year serving as the weights. The resultant estimate was Z = 0.463. This estimate along with the natural mortality estimate, discussed earlier, provided a terminal F vector to apply against the catch at age table (Table 2) using VPA. The backcalculated fishing mortality rates (using M = 0.21) are given in Table 4.

The average F's over 1979-81 indicated that full recruitment occurs at age 6. The average F's for ages 0-5 were normalized to the age 6 value to provide partial recruitment estimates (Figure 6). The cumulative logistic distribution was fitted to these partial recruitment estimates, as suggested by Jensen (1982). However, the fitted curve did not fit the data well (Figure 6), so rather than use the logistic curve for partial recruitment, the normalized average F's were used instead. The mean age at recruitment from the logistic curve was 2.6 years which did not differ greatly from the mean age of 2.7 years estimated from a piecewise linear function through the normalized average F's. In comparison, Berkeley and Houde (1981) used 2.1 years for knife-edge recruitment in the Beverton-Holt Y/R model. Because their data were taken solely from the Florida fishery and the data used here come from a much broader area (including the more northerly fisheries), our slightly older mean age at recruitment appears to be reasonable.

These partial recruitment estimates were used in conjunction with the age 6+ F estimate (from mark-recapture data) to estimate more realistic F's for the less than fully recruited ages. VPA backcalculations were then carried out using a terminal F vector consisting of constant F's for the fully recruited ages (i.e., ages 6+) and F's constructed from the partial recruitment estimates for the less than fully recruited ages (i.e., ages 0-5).

The degree to which the VPA stock size estimates are sensitive to variation in the terminal F vector was examined by estimating the partial derivatives of stock size with respect to terminal F. Rivard's (1982) procedure was used to estimate the partial derivatives numerically. The sensitivity of the VPA results to the natural mortality rate was examined by carrying out all VPA calculations for the M = 0.16 estimate as well as the M = 0.21 estimate.

Equilibrium Yield Per Recruit Analysis

The incremental method of Ricker (1975) was used for estimating equilibrium yield per recruit (Y/R) and equilibrium female spawning stock biomass per recruit (SSB/R). The model is well suited for swordfish since it allows for the use of the Gompertz growth model, an allometric length-weight relationship, and models partial recruitment more accurately than the Beverton-Holt Y/R model. It is also amenable to estimating SSB/R (while allowing for various assumptions concerning the proportion of females in the age 6+ population).

Calculations were carried out using quarter year intervals from age 0 to age 20. Mean biomass within a time interval was calculated exponentially. Weight at the beginning of each time interval was estimated from the combined, weighted Gompertz growth curve (Figure 4 and Appendix).

The current F vector, used in calculating Y/R and SSB/R, was constructed by smoothing the 1983 F's (ages 6+) with a moving average of four to reduce noise that would contribute to the uncertainty in the Y/R and SSB/R estimates. F's for ages 0-5 were estimated using the partial recruitment vector (discussed earlier) and the age 6 F estimate (after smoothing). The resulting vector (ages 0-19) was taken as being representative of the current fishery.

The number of years needed for the fishery to achieve an equilibrium state, given the current F vector, was estimated by calculating the cumulative Y/R as a function of age and then estimating the number of years needed for a cohort to achieve 95% of its potential Y/R.

As with the VPA runs, the sensitivity of the results to alternative natural mortality estimates and the two assumptions concerning the proportion of females in the age 6+ population were examined.

RESULTS

Due to the convergence properties of VPA backcalculations, estimates from the earlier years in VPA generated tables will generally be more reliable than those near the terminal year. Because the time series of available data from the swordfish fishery is relatively short, this general property of the VPA method should be kept in mind in the following discussion of the VPA results.

VPA stock size estimates by age and year for M = 0.21 and M = 0.16 are given in Tables 5 and 6, respectively. Stock size trends for selected age groups are displayed in Figure 7. Assuming a natural mortality estimate of M = 0.21, total stock size has increased 15% from 1978 to 1984. This has occurred largely due to improved recruitment over the period. The age 3-5 stock size has also increased (+7%) but the number of older fish (ages 6+) has declined appreciably (-35%). Although the magnitude of all of the stock size estimates is smaller when the lower natural mortality rate is assumed (i.e., M = 0.16), the trends over the 1978-84 period are nearly identical.

Fishing mortality rate (F) estimates by age and year for M = 0.21 and M = 0.16 are given in Tables 7 and 8, respectively. Average F's (weighted by stock size) for selected age groups are displayed in Figure 8. Assuming M = 0.21, fishing mortality rates have increased substantially from the 1978 level, especially on the younger (ages 0-2) and older (ages 6+) age groups. Average F on the younger fish peaked in 1980 and then declined, generally, due to improved recruitment. However, the 1984 level is still more than twice the 1978 level. The average F on the older fish increased rapidly through 1983 (where it was 66% greater than 1978) and then declined in 1984. The 1984 level was still 30% greater than the 1978 level. Declines from 1983 to 1984 occurred in all age groups. Although the magnitude of the F estimates is greater when M = 0.16 is assumed, the trends are nearly identical.

Mid-year estimates of stock biomass for selected age groups are displayed in Figure 9. Assuming M = 0.21, stock biomass of the age 0-2 fish declined through 1981 and then increased due to improved recruitment. The 1984 estimate is 19% greater than the 1978 estimate. Biomass of the age 3-5 fish declined slightly through 1983 and then increased in 1984 to approximately the same level as 1978. However, the biomass of the older fish (ages 6+) has declined steadily throughout the period. The 1984 estimate is 42% lower than the 1978 estimate. As with the stock size and F results, the stock biomass trends are nearly identical when M = 0.16 is assumed.

Annual estimates of surplus production are compared to the reported landings over 1978-84 in Figure 10. Surplus production is defined as the excess of recruitment and growth over the loss of biomass due to natural deaths. Surplus production has increased steadily throughout the period. Landings were greater than surplus production through 1983, causing total stock biomass to decline (Figure 9). The 1984 landings were less than the surplus production, causing stock biomass to increase accordingly. Surplus production has increased mainly due to a shift in the population age structure from an older, slower growing population to a younger, faster growing one. This is an expected response when a population experiences an increase in exploitation from relatively low levels.

Female spawning stock biomass has declined appreciably over 1978-84 (Figure 11). Only small differences in the estimates occur depending on the assumptions involved concerning natural mortality and the proportion of females in the age 6+ population. The overall decline in female spawning stock biomass is estimated to have been between 41 and 46%.

The partial derivatives of total stock size with respect to terminal F are given in Table 9 for the two natural mortality rate estimates. The derivatives provide a measure of the sensitivity of the stock size estimates to errors in the terminal F vector. The VPA results (Figure 7) indicate that total stock size has increased over 1978-84 by 15% (assuming M = 0.21) or 14% (assuming M = 0.16). The partial derivatives indicate that if the terminal F had been approximately 18% greater, there would not have been an increasing trend in stock size between 1978 and 1984. However, if the terminal F had been 18% lower, then the increase in total stock size from 1978 to 1984 would be 28% instead of 15%.

Table 10 provides the age specific fishing mortality rates (F vectors) used in the Ricker equilibrium Y/R analysis for the two estimates of M. These F vectors characterize the current fishery (i.e., F MULTIPLIER = 1.00) in the yield per recruit (Figure 12) and spawning stock biomass per recruit (Figure 13) analyses. Figure 12 provides the Y/R estimates as a function of F multiplier for the two M estimates. Assuming M = 0.21, $F_{0.1}$ occurs at an F multiplier of 0.55 and F_{max} occurs at 1.10. Assuming M = 0.16, $F_{0.1}$ occurs at an F multiplier of 0.40 and F_{max} occurs at 0.65. The long-term (10-15 years) equilibrium Y/R, that would be expected if the current F vector (1983) is maintained consistently in the future, is 99% of the maximum Y/R for this F pattern (assuming M = 0.21) or 97% of maximum Y/R (assuming M = 0.16). However, it should be noted that changes in the F pattern (e.g., increasing the size at first capture) would result in significantly larger Y/R (see Conser et al. 1985).

Equilibrium female spawning stock biomass per recruit (SSB/R) as a function of F multiplier is shown in Figure 13. Assuming M = 0.21, the long term SSB/R, that would be expected if the current F vector is maintained in the future, is 44% of the SSB/R that would be expected if fishing had been at the $F_{0.1}$ level (under the assumption of a 1:1 sex ratio); or 39% of the SSB/R that would be expected if fishing had been at $F_{0.1}$ (using the Berkeley and Houde sex ratios). Assuming M = 0.16, the analogous percentages are 25% and 21%. In general, the 1:1 sex ratio assumption will result in slightly higher estimates than the Berkeley and Houde sex ratio assumption.

The length of time needed for the swordfish fishery to reach equilibrium, given a constant F vector, is approximately 9 to 12 years, assuming M = 0.21, or 12 to 15 years, assuming M = 0.16 (Figure 14).

DISCUSSION

Although caution needs to be exercised in interpreting some of the results inferred from the mathematical models (as discussed in the Results section), it should be noted that independent information from the fishery is available to corroborate certain key aspects of the VPA results. However, in general, results of equilibrium models (such as Y/R) cannot be corroborated with information or data from the present fishery unless the population is in equilibrium at the present time (which is not the case for swordfish in the northwest Atlantic).

The VPA results indicate that the age 6+ stock size (in numbers of fish) has declined 35% since 1978 and that the corresponding biomass has declined 42%. The U.S. harpoon fishery takes mostly large fish and consequently, relies heavily on the age 6+ population. The general landings pattern and overall success of the harpoon fishery over 1978-84 closely parallels the VPA trends for ages 6+.

Fishing mortality rate estimates indicate that F's were generally increasing over 1978-83, especially for the younger (ages 0-2) and older (ages 6+) fish (Figure 8). This is consistent with general information from the fishery that indicates nominal effort has increased and that the effectiveness of the gear has also improved. However, the 1984 F estimates (for all age groups) show a decline in fishing mortality from 1983, especially for the older fish (Figure 8 and Tables 7 and 8). Information from the fishery tends to corroborate the decline. The Canadian fishery, which takes mostly large fish, reported a 62% decline in landings from 1983 to 1984 (Table 1). Information from the fishery (G. Peacock, pers. comm.) indicates that effort on swordfish during 1984 was greatly reduced because halibut were in great abundance and most fishermen fished for halibut rather than swordfish. Effort is also thought to have declined in the U.S. fishery. With relatively stable sampling effort within major areas between 1983 and 1984, participating vessels and total trips represented in the SEFC sample declined approximately 25%. In the U.S. fishery two factors contributed to lower swordfish effort in 1984: (1) longline fisheries developed for yellowfin and bigeye tunas and many swordfish fishermen, especially in the Gulf of Mexico and the mid-Atlantic area, fished during the daytime hours for tunas; and (2) financial difficulties and lower catch rates increased the rate at which vessels exited the fishery (B. Phillips, pers. comm.).

This estimated decline in F, if accurate, is also important in interpreting the equilibrium Y/R and SSB/R results. The 1983 F vector was used to characterize the current fishery in the equilibrium model primarily because it was felt that it should be more reliable than the 1984 F vector (since it resulted from at least one VPA backcalculation). If F in 1984 is lower than in 1983 and representative of F in 1985 and beyond, then the Y/R and SSB/R results presented here may be somewhat pessimistic in their characterization of the future direction of the fishery.

It may appear, at least initially, that the results of the VPA and Y/R analyses imply somewhat different conclusions concerning the status of stocks of swordfish in the northwest Atlantic Ocean. However, when examined more closely it becomes apparent that the two models are providing consistent information concerning the status of stocks. The key to interpreting the models' results is in the realization that the Y/R model is an equilibrium model while the VPA model requires no assumptions regarding population equilibrium. An equilibrium model applied to the swordfish fishery assumes that recruitment, fishing effort, population size and age structure have all remained constant over a 10 to 15 year period (depending on natural mortality rate assumed). Considering the rather dramatic changes in the swordfish fishery over the last 15 years, it is highly unlikely that these assumptions would hold and the population would be in equilibrium at the present time. Consequently, the Y/R model provides little or no information concerning the current status of stocks. On the other hand because the VPA model does not rely on the equilibrium assumptions, it does provide useful information on the present status of stocks. The value in the results of the Y/R model is in the information it provides concerning the direction that the population (and the fishery upon it) is heading in future years. Although the population will probably never reach equilibrium (with a dynamic fishery exploiting it), the Y/R results (as developed in this paper) provide information on the expected magnitude of future yield per recruit relative to the maximum Y/R and the relative magnitude of the spawning stock biomass should the current F level be maintained consistently into the future. From these results general inferences regarding the future of the fishery can be drawn. For example, future reductions in fishing mortality from the current F will result in a new F level that will be closer to $F_{0.1}$ with a concomitant increase in spawning stock biomass (per recruit).

CONCLUSIONS

The VPA provides the best information available concerning the current condition of the swordfish population in the northwest Atlantic Ocean. Subject to the inherent uncertainties involved in recent year VPA estimates and the other assumptions involved, it can be concluded that fishing mortality has increased substantially from the 1978 level, especially on the younger (ages 0-2) and older (ages 6+) age groups. Total stock size has increased as a result of improved recruitment over the same period. However, the number of older fish in the stock has declined appreciably. Total stock biomass has also declined, mainly due to declining biomass of the older age group. Recent spawning stock biomass appears to be about one half of the 1978 level. However, the change in population age structure (due to increased fishing) has resulted in a more productive population, causing surplus production to increase appreciably over the period. Landings in recent years are probably near the MSY level and the population appears to be at or near the fully exploited level.

If fishing mortality rates in the future are maintained at the current level (i.e., the 1983 F vector), then future yield per recruit (i.e., 10 to 15 years hence) will be either near the maximum level for the current F pattern or slightly below it (depending on the natural mortality rate assumed). However, future spawning stock biomass per recruit will be considerably smaller than the biomass that would be expected when fishing at $F_{0.1}$ (generally considered a safe level of fishing). Although there is some evidence that F in 1984 and 1985 was lower than the 1983 level, this relatively low biomass level may be cause for concern and, when coupled with the uncertainties inherent in these analyses, warrants careful monitoring of fishing mortality rates in future years to ensure that spawning potential is not affected adversely.

It is recommended that the fishery be monitored closely so that management measures can be implemented quickly should fishing mortality increase beyond the 1983 level in future years. However, it should be noted that in order to monitor fishing mortality rates on a real-time basis and to refine the present understanding of the status of stocks, the following data (that are not currently available) are required:

(1) Fishing effort data are needed to tune VPAs to real-time fishery conditions. Such tuning will provide timely estimates of fishing mortality and better appraisals of the status of stocks. In this paper, historical mark-recapture data were used to estimate terminal Z for the VPA. While this provided reasonable values for backcalculations, the estimate was derived from averaging over years and will not be sensitive to annual changes in the future fishery. Effort data need to be collected in a systematic fashion by all nations fishing for swordfish and these data need to be reported to ICCAT in a timely manner.

(2) Because of the sexually dimorphic growth characteristic of swordfish, data on the sex ratio of the catch by size, time, and area need to be collected routinely in order to assign the catch to the proper cohort. In this paper, the catch was assigned to cohorts using the combined, weighted Gompertz growth curve. In doing so it was necessary to assume that the sex ratios of the catch in all time-area strata were the same as the ratios (by age) reported by Berkeley and Houde (1981). To provide timely and accurate advice, sex ratio data are needed annualy for all nations. At sea sampling is generally needed to acquire these data.

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APPENDIX

A. Sex ratios (Berkeley and Houde 1981)

Age	I	II	III	IV	V	VI	VII	VIII
males: females	2.1:1	1.5:1	3.6:1	2.6:1	1.9:1	1.2:1	1.1:1	0.4:1

B. Growth curves

The Gompertz curve has the form

(1a) $(\text{LJFL in cm}) = L_\infty e^{-be^{-k\,(\text{age in years})}}$

where LJFL = lower jaw fork length, and L_∞, b and k are equation parameters.

The Gompertz parameter values used for various groups of data are:

Group	L_∞	b	k	source
sexes combined, weighted	262.46	1.1754	0.1912	this ms.
females only	262.65	1.2360	0.2236	Zweifel &
males only	206.96	0.9679	0.2746	Slater (1982)

The von Bertalanffy curve has the form

(1b) $(\text{LJFL in cm}) = L_\infty(1-e^{-k\,(\text{age in years}\,-\,a_0)})$

where LJFL in lower jaw fork length, and L_∞, k and a_0 are equation parameters. The von Bertalanffy parameter values used for various groups of data are:

Group	L_∞	k	a_0	source
sexes combined, weighted	371.24	0.07042	-3.4311	this ms.
females only	335.36	0.09762	-2.5227	Berkeley &
males only	219.43	0.1838	-2.2512	Houde (1983)

C. Size conversion formulae used

(2) $(\text{RD kg}) = (2.7108 \times 10^{-6}) \times (\text{LJFL cm})^{3.2994}$ (Beardsley et al. 1979)

(3) pounds = kilograms/.4536

(4) DW = (.75) x RD (Berkeley and Houde 1981)

where RD = round weight
DW = dressed weight
LJFL = lower jaw fork length

APPENDIX (continued)

D. Conversion from dressed weight to age

(5) (age in years) = ln (1.1754/ ln (262.46/LJFL)) / 0.1912

where

$\text{LJFL} = ((\text{DW in pounds}) \times 0.4536 / (2.7108 \times 10^{-6} \times .75))^{1./3.2994}$
and ln is the natural logarithm.

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Table 2. Catch of swordfish (in number of fish) from the northwest Atlantic by age and by year, 1978-84.

	YEAR							
AGE (yrs)	78	79	80	81	82	83	84	
0	751.	1618.	3114.	2418.	4443.	3505.	3760.	0
1	4243.	5289.	13114.	5823.	13872.	15195.	10866.	1
2	7673.	10062.	19922.	11498.	14965.	20663.	19262.	2
3	12943.	11431.	21861.	17745.	17641.	17311.	18942.	3
4	16524.	10640.	17326.	16062.	10093.	15479.	15474.	4
5	13406.	9500.	13440.	11792.	14161.	12961.	10814.	5
6	9943.	7746.	9588.	8817.	9325.	9588.	7554.	6
7	6074.	5530.	6188.	6301.	5908.	6485.	5038.	7
8	3603.	4267.	3911.	4619.	3706.	4273.	3084.	8
9	2190.	2831.	2573.	3234.	2588.	2748.	1797.	9
10	1327.	2029.	1557.	2265.	1717.	1838.	1109.	10
11	725.	1671.	1072.	1489.	1094.	1117.	694.	11
12	507.	1101.	639.	1153.	752.	766.	512.	12
13	347.	672.	490.	736.	565.	507.	324.	13
14	301.	524.	315.	569.	477.	451.	301.	14
15	121.	334.	250.	406.	312.	280.	250.	15
16	69.	212.	153.	422.	271.	230.	123.	16
17	141.	206.	107.	250.	154.	181.	124.	17
18	59.	172.	109.	183.	103.	115.	81.	18
19	57.	103.	64.	96.	87.	93.	73.	19
20	42.	101.	50.	67.	79.	56.	41.	20
21	42.	74.	29.	112.	74.	45.	29.	21
22	17.	20.	28.	47.	41.	37.	31.	22
23	14.	20.	24.	23.	32.	24.	44.	23
24	1.	28.	15.	24.	30.	30.	23.	24
25	19.	47.	6.	16.	16.	18.	24.	25
26	3.	7.	9.	28.	20.	16.	8.	26
27	1.	3.	1.	5.	8.	17.	9.	27
28	0.	1.	11.	21.	19.	8.	6.	28
29	0.	0.	10.	1.	12.	5.	6.	29
30	1.	10.	6.	2.	8.	7.	2.	30

Table 1. Swordfish landings (1000's lbs, round weight) from the northwest Atlantic (see Fig. 1). U.S. landings are given by area: Gulf of Mexico (Gulf), Florida East Coast (FEC), South Carolina (SC), or North Carolina and north (NC & N). Landings may not sum to totals due to rounding.

	Years						
	1978	1979	1980	1981	1982	1983	1984
U.S.							
Gulf	53	378	1,726	1,159	1,256	717	666
FEC	536	1,391	2,308	2,719	2,947	2,818	2,577
SC	584	823	845	688	1,158	1,181	676
NC & N	5,972	4,926	3,557	3,124	3,671	4,548	4,475
Total USA	7,145	7,518	8,436	7,690	9,032	9,264	8,394
Canada	2,205	2,205	2,646	2,205	2,205	2,205	833
Japan & Taiwan	1,606	1,381	1,770	3,266	1,390	1,415	1,275
TOTAL	10,956	11,103	12,851	13,160	12,625	12,883	10,502
% U.S.	65%	68%	66%	58%	72%	72%	80% U. S.

Table 4. Instantaneous fishing mortality rates (per yr) for swordfish in the northwest Atlantic. The natural mortality rate is M = 0.21 and the terminal F vector is estimated from mark-recapture data (see text for details).

AGE (yrs)	YEAR 78	79	80	81	82	83	84	
0	0.0028	0.0067	0.0139	0.0116				0
1	0.0196	0.0247	0.0697	0.0329	0.0862			1
2	0.0496	0.0595	0.1234	0.0813	0.1119	0.1806		2
3	0.1172	0.0980	0.1791	0.1557	0.1744	0.1848	0.2530	3
4	0.2066	0.1347	0.2135	0.1957	0.2378	0.2307	0.2530	4
5	0.2384	0.1778	0.2539	0.2229	0.2677	0.2706	0.2530	5
6	0.2568	0.2132	0.2769	0.2665	0.2788	0.2961	0.2530	6
7	0.2322	0.2235	0.2665	0.2991	0.2908	0.3225	0.2530	7
8	0.1966	0.2567	0.2465	0.3297	0.2917	0.3577	0.2530	8
9	0.1577	0.2364	0.2455	0.3350	0.3148	0.3702	0.2530	9
10	0.1493	0.2170	0.1997	0.3590	0.3022	0.3912	0.2530	10
11	0.1059	0.2870	0.1720	0.3015	0.2980	0.3327	0.2530	11
12	0.1072	0.2341	0.1710	0.2858	0.2478	0.3560	0.2530	12
13	0.0909	0.2042	0.1567	0.3070	0.2234	0.2663	0.2530	13
14	0.1250	0.1948	0.1405	0.2778	0.3385	0.2827	0.2530	14
15	0.0737	0.2010	0.1355	0.2736	0.2443	0.3449	0.2530	15
16	0.0482	0.1804	0.1346	0.3581	0.2998	0.2896	0.2530	16
17	0.0957	0.2003	0.1314	0.3417	0.2161	0.3395	0.2530	17
18	0.0611	0.1637	0.1565	0.3499	0.2325	0.2511	0.2530	18
19	0.0594	0.1455	0.0853	0.2032	0.2824	0.3438	0.2530	19
20	0.0947	0.1705	0.0986	0.1220	0.2595	0.2998	0.2530	20
21	0.1196	0.2424	0.0682	0.3357	0.1943	0.2336	0.2530	21
22	0.0619	0.0777	0.1373	0.1520	0.1991	0.1421	0.2530	22
23	0.0587	0.0972	0.1272	0.1614	0.1484	0.1734	0.2530	23
24	0.0059	0.1612	0.0992	0.1829	0.3300	0.2043	0.2530	24
25	0.1081	0.4143	0.0475	0.1475	0.1805	0.3415	0.2530	25
26	0.0282	0.0533	0.1300	0.3263	0.2804	0.2791	0.2530	26
27	0.0298	0.0359	0.0097	0.1000	0.1467	0.4134	0.2530	27
28	0.0000	0.0381	0.1804	0.2897	0.6699	0.2165	0.2530	28
29	0.0000	0.0000	0.6418	0.0225	0.2704	0.3730	0.2530	29
30	0.0510	0.2120	0.2530	0.2530	0.2530	0.2530	0.2530	30

Table 3. Estimates of annual survival and total instantaneous mortality, along with their respective estimated variance, standard error and approximate 95% confidence intervals using mark-recapture data. Table taken from Farber (1985).

YEAR	S	VARS	SES	LCBS	UCBS	Z1	VARZ1	SEZ1	LCBZ1	UCBZ1
1977	0.833	0.028	0.167	0.500	1.167	0.166	0.017	0.129	-0.093	0.424
1978	0.766	0.004	0.062	0.641	0.891	0.261	0.006	0.077	0.106	0.415
1979	0.600	0.060	0.245	0.110	1.090	0.422	0.089	0.298	-0.174	1.018
1980	0.659	0.005	0.072	0.515	0.804	0.405	0.011	0.105	0.196	0.616
1981	0.604	0.005	0.071	0.462	0.747	0.491	0.013	0.114	0.263	0.719
1982	0.500	0.083	0.289	-0.077	1.077	0.526	0.167	0.408	-0.290	1.343
1983	0.500	0.083	0.289	-0.077	1.077	0.526	0.167	0.408	-0.290	1.343

$\bar{S}$ = Average S = 0.638
$\bar{Z1}$ = Average Z1 = 0.400
Approximate 95% Confidence Interval about $\bar{Z1}$ = (0.272,0.528)

S = Estimate of annual survival rate.
VARS = Variance of S
SES = Standard Error of S
LCBS/UCBS = Lower Confidence Bound on S and Upper Confidence Bound on S; i.e., approximate 95% confidence interval about S
Z1 = Estimate of total instantaneous mortality calculated from S.
VARZ1 = Variance of Z1
SEZ1 = Standard Error of Z1
LCBZ1/UCBZ1 = Lower Confidence Bound on Z1 and Upper Confidence Bound on Z1; i.e., approximate 95% confidence interval about Z1.

Table 5. Stock size estimates (in number of fish) by age and by year, 1978-84. Annual totals for selected age groups are provided at the bottom of the table. The natural mortality estimate is M = 0.21 per yr.

	YEAR							
AGE (yrs)	78	79	80	81	82	83	84	
0	297090.	288992.	310750.	348384.	409670.	360795.	384456.	0
1	242665.	240141.	232798.	249091.	280222.	328080.	289306.	1
2	175635.	192889.	189904.	176931.	196679.	214689.	252294.	2
3	129517.	135477.	147319.	136068.	133098.	145997.	155491.	3
4	97781.	93377.	99561.	99830.	94391.	92077.	102824.	4
5	69784.	64464.	66151.	65190.	66536.	60320.	60776.	5
6	48590.	44568.	43742.	41596.	42286.	41266.	37301.	6
7	32373.	30491.	29191.	26882.	25830.	25937.	24877.	7
8	22300.	20804.	19765.	18127.	16157.	15655.	15229.	8
9	16597.	14849.	13046.	12522.	10566.	9783.	8873.	9
10	10581.	11490.	9503.	8273.	7260.	6252.	5476.	10
11	7987.	7388.	7497.	6309.	4683.	4350.	3427.	11
12	5521.	5824.	4494.	5117.	3782.	2818.	2528.	12
13	4420.	4020.	3735.	3070.	3117.	2393.	1600.	13
14	2833.	3271.	2657.	2589.	1831.	2021.	1486.	14
15	1885.	2027.	2182.	1871.	1589.	1058.	1234.	15
16	1623.	1420.	1344.	1545.	1154.	1009.	607.	16
17	1710.	1254.	961.	952.	875.	693.	612.	17
18	1103.	1260.	832.	683.	548.	572.	400.	18
19	942.	841.	867.	577.	390.	352.	368.	19
20	515.	712.	589.	645.	381.	238.	202.	20
21	412.	380.	487.	433.	463.	239.	143.	21
22	314.	296.	241.	369.	251.	309.	153.	22
23	272.	239.	222.	171.	257.	167.	217.	23
24	189.	208.	176.	159.	118.	179.	114.	24
25	205.	153.	143.	129.	107.	69.	119.	25
26	120.	149.	82.	111.	90.	72.	40.	26
27	38.	94.	115.	58.	65.	55.	44.	27
28	45.	30.	74.	92.	43.	45.	30.	28
29	71.	37.	23.	50.	56.	18.	30.	29
30	22.	58.	30.	10.	40.	35.	10.	30
0-30	1173139.	1167201.	1188481.	1207830.	1302534.	1317542.	1350260.	
0- 2	715390.	722022.	733452.	774406.	886571.	903565.	926056.	
3- 5	297082.	293318.	313031.	301088.	294025.	298394.	391091.	
6-30	160667.	151861.	141998.	132336.	121938.	115583.	105113.	

Table 6. Stock size estimates (in number of fish) by age and by year, 1978-84. Annual totals for selected age groups are provided at the bottom of the table. The natural mortality rate is M = 0.16 per yr.

	YEAR							
AGE (yrs)	78	79	80	81	82	83	84	
0	217525.	209708.	222402.	252896.	296438.	260996.	282593.	0
1	184014.	184670.	177210.	185648.	213275.	248511.	219174.	1
2	136873.	152895.	152490.	139929.	153684.	168961.	197768.	2
3	104419.	109565.	121019.	111610.	107798.	117181.	124961.	3
4	81140.	77068.	82841.	83025.	78786.	75634.	83929.	4
5	58635.	53956.	55883.	54670.	55984.	50515.	50225.	5
6	40843.	37649.	37242.	35276.	35751.	34703.	31146.	6
7	27263.	25672.	24964.	22933.	21963.	21904.	20772.	7
8	18357.	17651.	16795.	15590.	13759.	13293.	12716.	8
9	13461.	12339.	11122.	10719.	9047.	8322.	7409.	9
10	8745.	9456.	7914.	7114.	6167.	5335.	4573.	10
11	6420.	6231.	6193.	5313.	3985.	3680.	2861.	11
12	4433.	4803.	3776.	4292.	3161.	2392.	2111.	12
13	3521.	3311.	3081.	2630.	2599.	2003.	1336.	13
14	2285.	2681.	2204.	2175.	1566.	1695.	1241.	14
15	1501.	1670.	1803.	1588.	1331.	896.	1031.	15
16	1268.	1168.	1116.	1306.	980.	848.	507.	16
17	1296.	1017.	800.	810.	726.	587.	511.	17
18	853.	975.	677.	583.	461.	477.	334.	16
19	711.	672.	673.	477.	329.	298.	301.	19
20	411.	553.	478.	514.	318.	201.	169.	20
21	316.	312.	378.	361.	377.	199.	120.	21
22	240.	231.	198.	296.	205.	253.	128.	22
23	208.	189.	178.	143.	209.	137.	181.	23
24	155.	165.	143.	130.	100.	148.	95.	24
25	156.	131.	115.	108.	89.	58.	99.	25
26	88.	116.	68.	92.	77.	61.	33.	26
27	30.	72.	92.	50.	53.	47.	37.	27
28	34.	25.	59.	78.	38.	38.	25.	28
29	55.	29.	20.	40.	47.	15.	25.	29
30	11.	47.	25.	8.	33.	29.	8.	30
0-30	915275.	915827.	931960.	940404.	1009335.	1019418.	1046419.	
0- 2	538412.	547273.	552102.	578473.	663397.	678468.	699535.	
3- 5	244194.	240589.	259743.	249305.	242568.	243330.	259115.	
6-30	132669.	127165.	120115.	112626.	103370.	97620.	87769.	

Table 7. Instantaneous fishing mortality rates (per yr) for swordfish in the northwest Atlantic. The natural mortality rate is M = 0.21. The terminal F vector is estimated from mark-recapture data for ages 6-30 and by applying the partial recruitment vector (Fig. 6) to estimate F's for ages 0-5. Average F's (weighted by stock size) for selected age groups are provided at the bottom of the table.

	YEAR						
AGE (yrs)	78	79	80	81	82	83	84
0	0.0028	0.0062	0.0112	0.0077	0.0121	0.0108	0.0109
1	0.0196	0.0247	0.0644	0.0262	0.0564	0.0527	0.0425
2	0.0496	0.0595	0.1234	0.0747	0.0880	0.1126	0.0883
3	0.1172	0.0980	0.1791	0.1557	0.1585	0.1406	0.1447
4	0.2066	0.1347	0.2135	0.1957	0.2378	0.2054	0.1819
5	0.2384	0.1778	0.2539	0.2229	0.2677	0.2706	0.2188
6	0.2560	0.2132	0.2769	0.2665	0.2788	0.2961	0.2530
7	0.2322	0.2235	0.2665	0.2991	0.2900	0.3225	0.2530
8	0.1966	0.2567	0.2465	0.3297	0.2917	0.3577	0.2530
9	0.1577	0.2364	0.2455	0.3350	0.3148	0.3702	0.2530
10	0.1493	0.2170	0.1997	0.3590	0.3022	0.3912	0.2530
11	0.1059	0.2870	0.1720	0.3015	0.2980	0.3327	0.2530
12	0.1072	0.2341	0.1710	0.2858	0.2478	0.3560	0.2530
13	0.0909	0.2042	0.1567	0.3070	0.2234	0.2663	0.2530
14	0.1250	0.1948	0.1405	0.2778	0.3385	0.2827	0.2530
15	0.0737	0.2010	0.1355	0.2736	0.2443	0.3449	0.2530
16	0.0482	0.1804	0.1346	0.3581	0.2998	0.2896	0.2530
17	0.0957	0.2003	0.1314	0.3417	0.2161	0.3395	0.2530
18	0.0611	0.1637	0.1565	0.3499	0.2325	0.2511	0.2530
19	0.0694	0.1455	0.0853	0.2032	0.2824	0.3438	0.2530
20	0.0947	0.1705	0.0986	0.1220	0.2595	0.2998	0.2530
21	0.1196	0.2424	0.0682	0.3357	0.1943	0.2336	0.2530
22	0.0619	0.0777	0.1373	0.1520	0.1991	0.1421	0.2530
23	0.0587	0.0972	0.1272	0.1614	0.1484	0.1734	0.2530
24	0.0059	0.1612	0.0992	0.1829	0.3300	0.2043	0.2530
25	0.1081	0.4143	0.0475	0.1475	0.1805	0.3415	0.2530
26	0.0282	0.0533	0.1300	0.3263	0.2004	0.2791	0.2530
27	0.0298	0.0359	0.0097	0.1000	0.1467	0.4134	0.2530
28	0.0000	0.0381	0.1004	0.2897	0.6599	0.2165	0.2530
29	0.0000	0.0000	0.6416	0.0225	0.2704	0.3730	0.2530
30	0.0510	0.2120	0.2530	0.2530	0.2530	0.2530	0.2530
0 - 30	0.0833	0.0778	0.1180	0.0970	0.1030	0.1051	0.0888
0 - 2	0.0200	0.0266	0.0571	0.0290	0.0429	0.0502	0.0419
3 - 5	0.1751	0.1272	0.2059	0.1835	0.2086	0.1869	0.1708
6 - 30	0.1950	0.2250	0.2390	0.2980	0.2850	0.3240	0.2530

Table 8. Instantaneous fishing mortality rates (per yr) for swordfish in the northwest Atlantic. The natural mortality rate is M = 0.16. The terminal F vector is estimated from mark-recapture data for ages 6-30 and F's for ages 0-5 are estimated using a partial recruitment vector developed in a parallel fashion to the vector used in the M = 0.21 case. Average F's (weighted by stock size) for selected age groups are provided at the bottom of table.

	YEAR							
AGE (yrs)	78	79	80	81	82	83	84	
0	0.0037	0.0084	0.0153	0.0104	0.0163	0.0146	0.0145	0
1	0.0253	0.0315	0.0834	0.0343	0.0729	0.0684	0.0551	1
2	0.0625	0.0738	0.1521	0.0937	0.1112	0.1417	0.1112	2
3	0.1437	0.1196	0.2168	0.1883	0.1944	0.1737	0.1787	3
4	0.2480	0.1614	0.2556	0.2341	0.2845	0.2494	0.2218	4
5	0.2830	0.2107	0.3001	0.2647	0.3182	0.3236	0.2642	5
6	0.3043	0.2509	0.3249	0.3138	0.3299	0.3532	0.3030	6
7	0.2747	0.2643	0.3108	0.3509	0.3422	0.3838	0.3030	7
8	0.2378	0.3018	0.2891	0.3842	0.3427	0.4245	0.3030	8
9	0.1931	0.2841	0.2869	0.3927	0.3682	0.4389	0.3030	9
10	0.1789	0.2632	0.2385	0.4195	0.3564	0.4629	0.3030	10
11	0.1301	0.3409	0.2068	0.3593	0.3505	0.3957	0.3030	11
12	0.1319	0.2839	0.2017	0.3416	0.2963	0.4225	0.3030	12
13	0.1126	0.2471	0.1883	0.3587	0.2671	0.3185	0.3030	13
14	0.1534	0.2368	0.1676	0.3311	0.3975	0.3377	0.3030	14
15	0.0912	0.2430	0.1622	0.3222	0.2912	0.4697	0.3030	15
16	0.0606	0.2181	0.1602	0.4272	0.3534	0.3457	0.3030	16
17	0.1250	0.2465	0.1560	0.4035	0.2597	0.4035	0.3030	17
18	0.0777	0.2112	0.1908	0.4120	0.2754	0.3808	0.3030	18
19	0.0907	0.1808	0.1085	0.2448	0.3351	0.4085	0.3030	19
20	0.1169	0.2195	0.1199	0.1516	0.3115	0.3576	0.3030	20
21	0.1548	0.2955	0.0865	0.4058	0.2383	0.2802	0.3030	21
22	0.0796	0.0903	0.1660	0.1882	0.2427	0.1720	0.3030	22
23	0.0754	0.1214	0.1571	0.1911	0.1809	0.2092	0.3030	23
24	0.0070	0.2027	0.1206	0.2224	0.3879	0.2458	0.3030	24
25	0.1408	0.4882	0.0583	0.1748	0.2167	0.4058	0.3030	25
26	0.0377	0.0677	0.1532	0.3962	0.3280	0.3335	0.3030	26
27	0.0362	0.0461	0.0118	0.1143	0.1785	0.4883	0.3030	27
28	0.0000	0.0442	0.2265	0.3449	0.7664	0.2602	0.3030	28
29	0.0000	0.0000	0.7454	0.0276	0.3234	0.4420	0.3030	29
30	0.1010	0.2620	0.3030	0.3030	0.3030	0.3030	0.3030	30
0-30	0.1060	0.0982	0.1495	0.1239	0.1322	0.1353	0.1137	
0- 2	0.0260	0.0345	0.0749	0.0381	0.0565	0.0660	0.0546	
3- 5	0.2118	0.1534	0.2471	0.2203	0.2522	0.2284	0.2092	
6-30	0.2358	0.2683	0.2814	0.3509	0.3365	0.3852	0.3030	

Table 9. Partial derivatives of total population size with respect to the terminal F vector for two natural mortality (M) estimates. The table entries represent the percentage change in the total population size estimate (in number of fish) that would result from a one percent increase in each of the age-specific F's of the terminal F vector. Increasing the magnitude of the F vector (i.e., a positive change) results in lower population size estimates (i.e., negative table entries). Analogously, the percentage increase in population size estimates due to a one percent decrease in the terminal F vector can be seen by reversing the signs of the table entries.

Natural Mortality Rate (yr^{-1})	1978	1979	1980	1981	1982	1983	1984
M = 0.21	-0.280	-0.362	-0.471	-0.601	-0.734	-0.853	-0.957
M = 0.16	-0.217	-0.292	-0.397	-0.532	-0.677	-0.817	-0.946

Table 10. Age specific fishing mortality rates (F vectors) used in the Ricker equilibrium yield per recruit analysis for two estimates of the natural mortality rate (M). These F vectors characterize the current fishery (i.e., F MULTIPLIER = 1.0) in the yield and spawning stock biomass per recruit estimates displayed in Figures 12 and 13, respectively.

Age	M = 0.21	M = 0.16
0	0.0145	0.0192
1	0.0566	0.0728
2	0.1175	0.1468
3	0.1926	0.2360
4	0.2420	0.2928
5	0.2912	0.3488
6	0.3366	0.4001
7	0.3604	0.4275
8	0.3630	0.4305
9	0.3625	0.4300
10	0.3365	0.3999
11	0.3094	0.3686
12	0.3125	0.3721
13	0.2959	0.3529
14	0.3142	0.3741
15	0.3063	0.3649
16	0.3060	0.3646
17	0.3086	0.3676
18	0.2821	0.3368
19	0.2548	0.3046

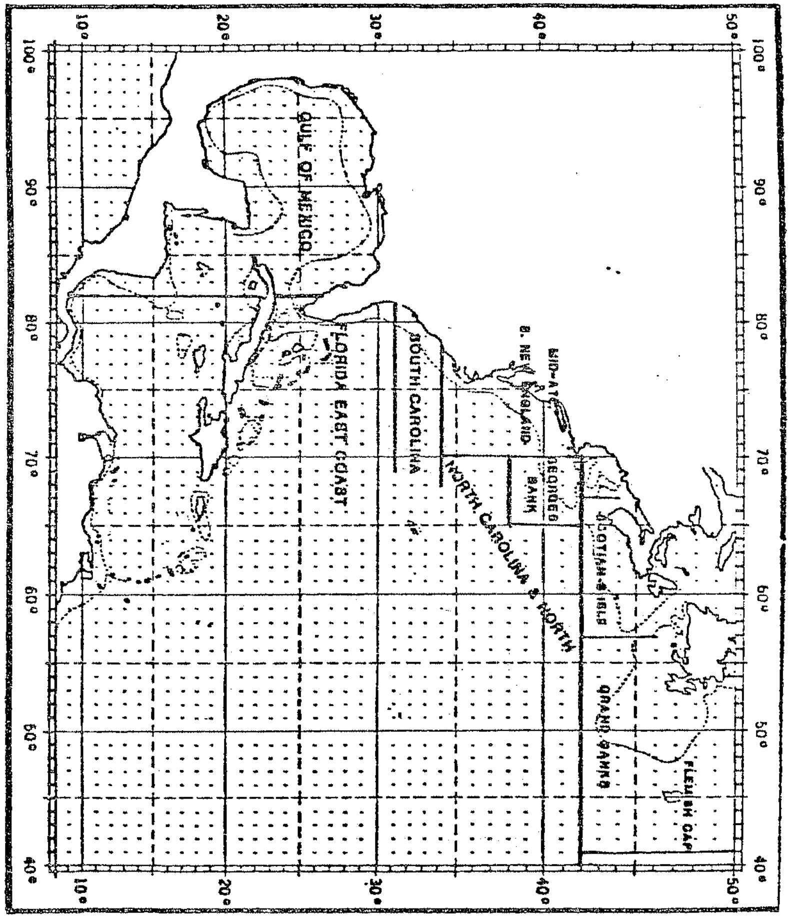

Figure 1. The major swordfish fishing grounds within the northwest Atlantic Ocean. For stock assessment purposes, the northwest Atlantic stock area was taken to be the area north of 10°N latitude and west of 35°W longitude.

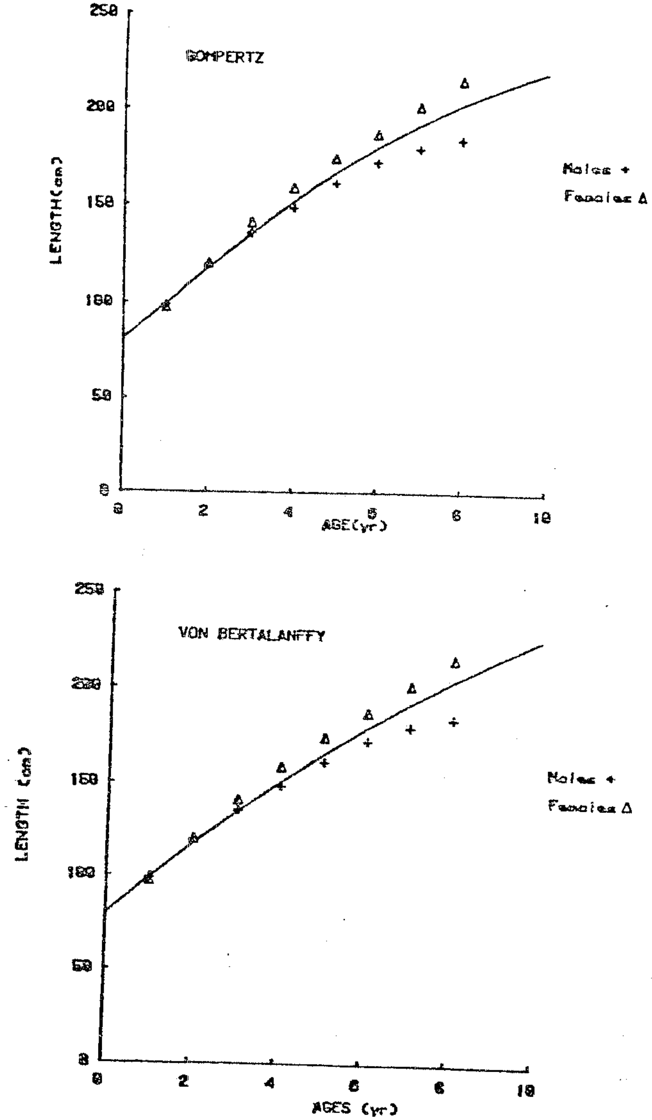

Figure 2. The Gompertz and von Bertalanffy growth models fitted to the Berkeley and Houde (1981) mean length at age estimates using weighted nonlinear regression. The male and female observations at each age were weighted by the proportion of males and females, respectively, found in the catch. The Berkeley and Houde (1981) estimates of sex ratio at age were used to calculate these proportions.

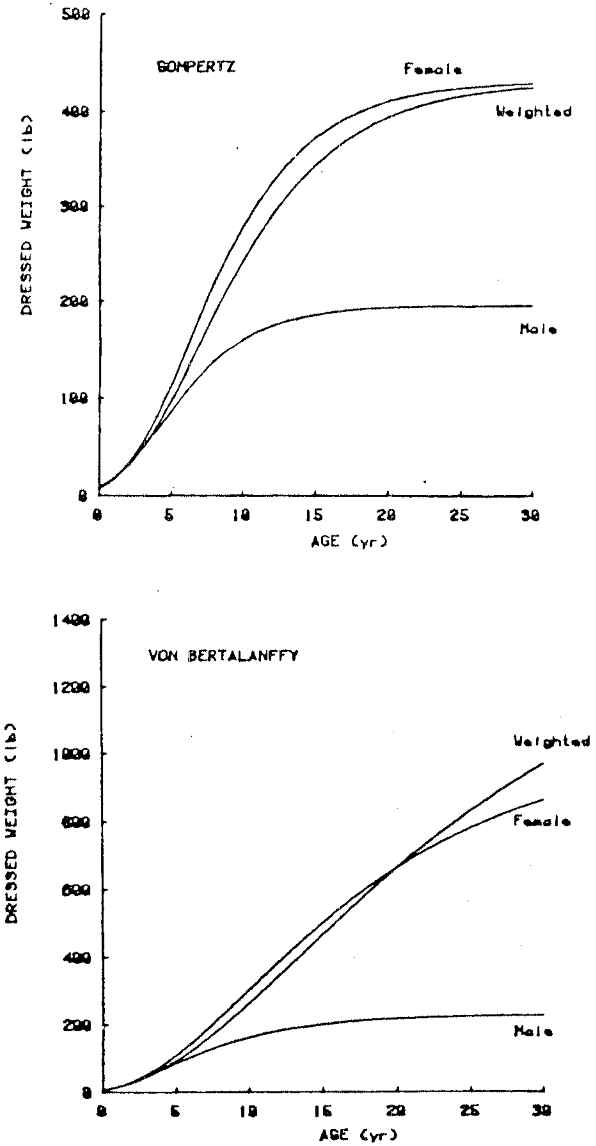

Figure 3. The Gompertz male and female growth curves from Zweifel and Slater (1982) and the von Bertalanffy male and female curves from Berkeley and Houde (1981) along with the weighted curves from Figure 2. All curves were fitted to the Berkeley and Houde length at age data (ages 1-8), extrapolated to age 30, and converted to weight at age using the Beardsley et al. (1979) length-weight relationship.

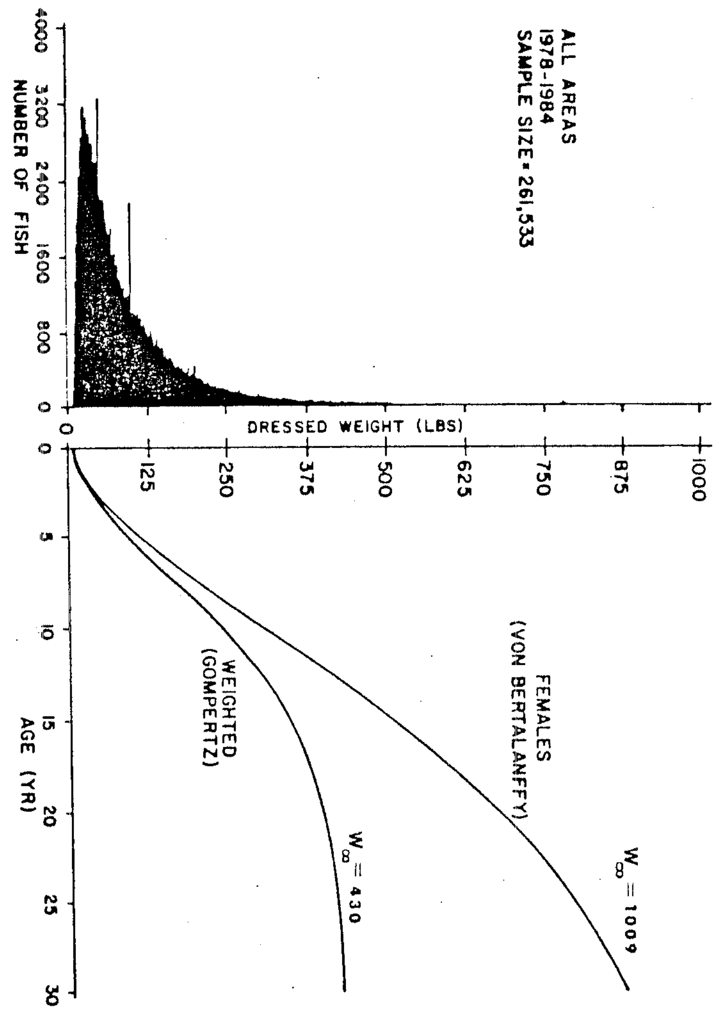

Figure 4. Size frequency distribution of swordfish samples from the U.S. fishery over 1978-84 compared to the weighted Gompertz and the female von Bertalanffy growth curves (from Figure 3). Growth curves were fitted to size at age data for ages 1 to 8 and extrapolated to age 30. W infinity estimates for the growth curves are also provided.

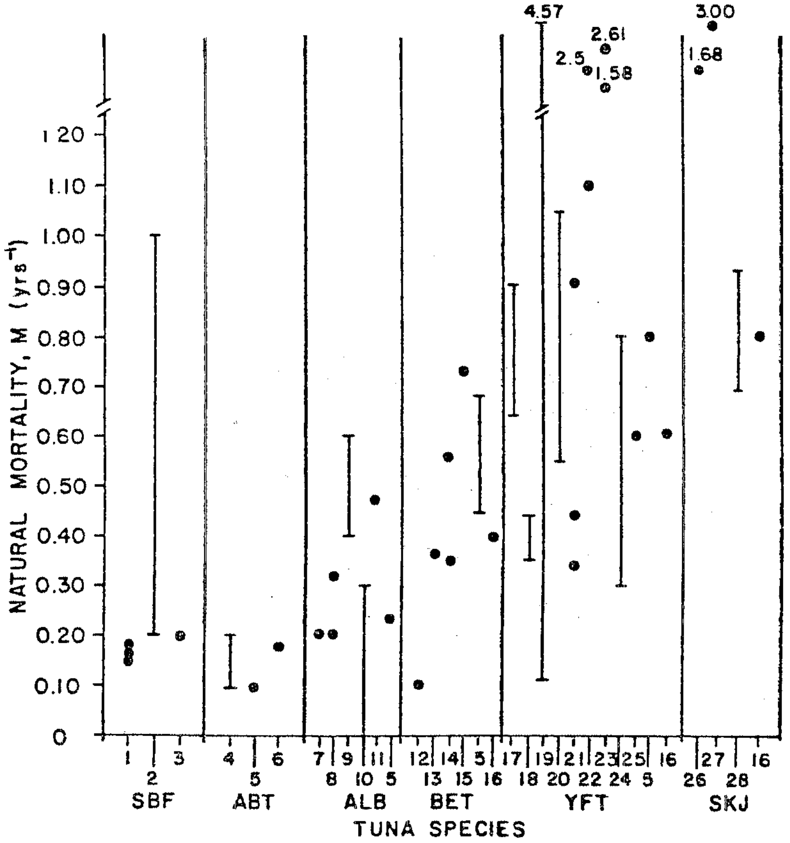

Figure 5a. Estimates of the instantaneous natural mortality rate (M) from literature reviews for southern bluefin tuna (SBF), Atlantic bluefin tuna (ABT), albacore (ALB), bigeye tuna (BET), yellowfin tuna (YFT), and skipjack (SKJ). Numbered references are specified in Figure 5b.

Figure 5b: Numbered references from Figure 5a.

1. Suda (1971) cited in Yoshida (1979)
2. Hayasi et al. (1972) cited in Yoshida (1979)
3. Murphy (1977) cited in Yoshida (1979)
4. Sakagawa and Coan (1974) and Mather et al. (1974) cited in Yoshida (1979)
5. Murphy and Sakagawa (1977) cited in Yoshida (1979)
6. Rodriguez-Roda (1977) cited in Parrack (1980)
7. Suda (1966) cited in Yoshida (1979)
8. Beardsley (1971) cited in Yoshida (1979)
9. Suda (1974) cited in Yoshida (1979)
10. Bard (1974) cited in Yoshida (1979)
11. Marita (1977) cited in Yoshida (1979)
12. Silliman (1966) cited in Yoshida (1979)
13. Suda and Kume (1967) cited in Yoshida (1979)
14. Ishii (1968) cited in Yoshida (1979)
15. Suda (1970) cited in Yoshida (1979)
16. ICCAT (1980)
17. Hennemuth (1961) cited in Yoshida (1979)
18. Kawakami and Kitahara (1964) as cited by Suda (1971), cited in Yoshida (1979)
19. Fink (1965) cited in Yoshida (1979)
20. Schaefer (1967) cited in Yoshida (1979)
21. Ishii (1969) cited in Yoshida (1979)
22. Honma et al. (1971) cited in Yoshida (1979)
23. Pianet and LeHir (1971) cited in Yoshida (1979)
24. Hayasi and Honma (1971) cited in Yoshida (1979)
25. Francis (1977) cited in Au (1983)
26. Joseph and Calkins (1969) cited in Au (1983)
27. Bayliff (1977) cited in Au (1983)
28. Murphy and Sakagawa (1977) cited in Au (1983)

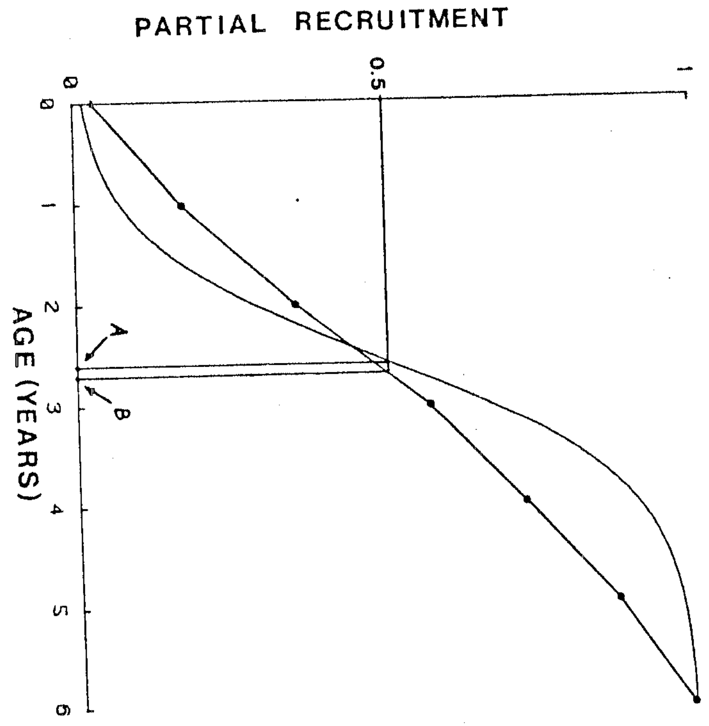

Figure 6. Partial recruitment estimates for ages 0 through 6, the cumulative logistic function fitted to the partial recruitment estimates, and a piecewise linear function through the estimates. Mean age at recruitment is estimated from the logistic function (A) to be 2.6 yr and from the piecewise linear function (B) to be 2.7 yr.

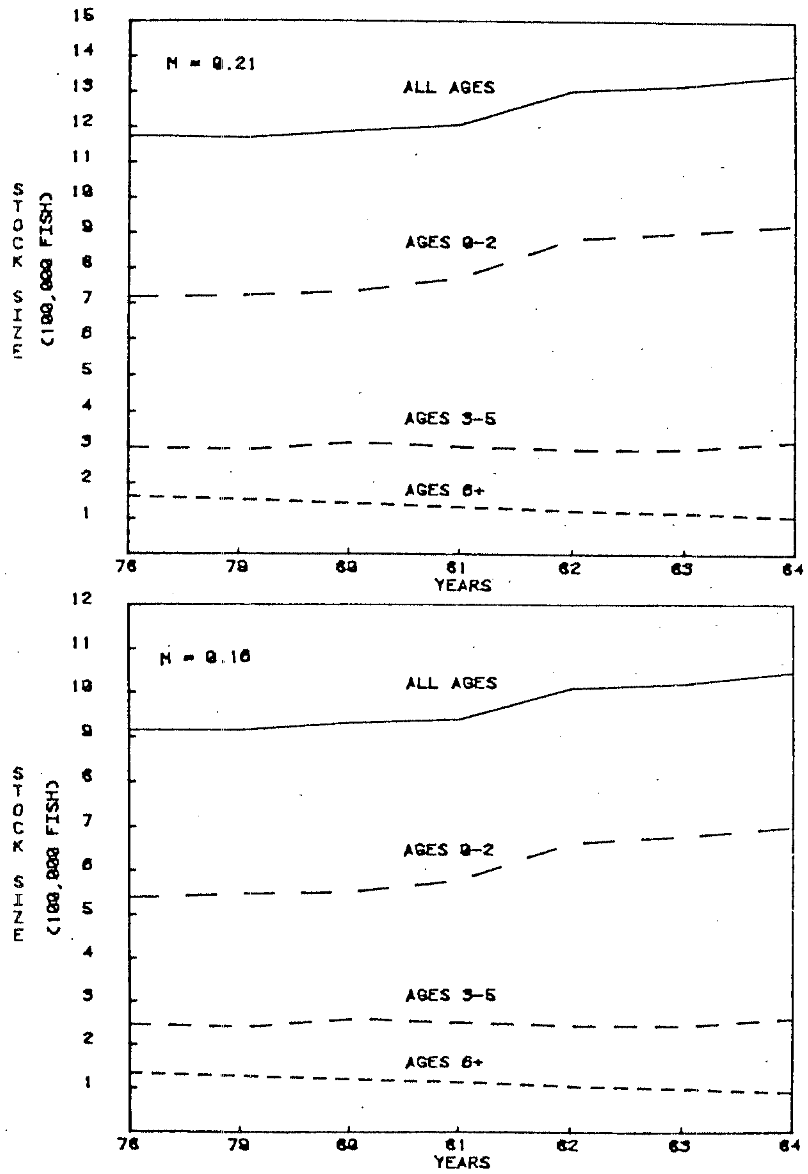

Figure 7. VPA stock size estimates for selected age groups and two natural mortality rates.

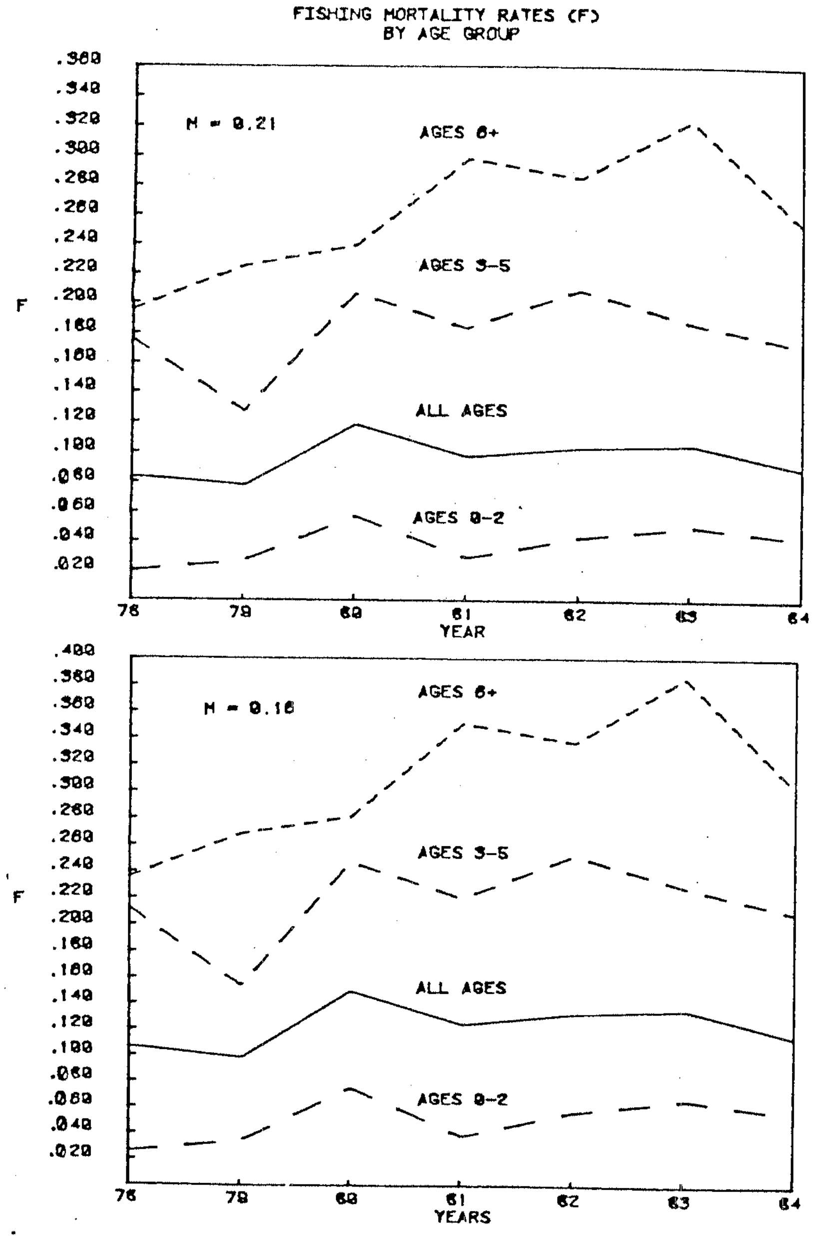

Figure 8. Average fishing mortality rates (weighted by stock size) for selected age groups and two natural mortality rates.

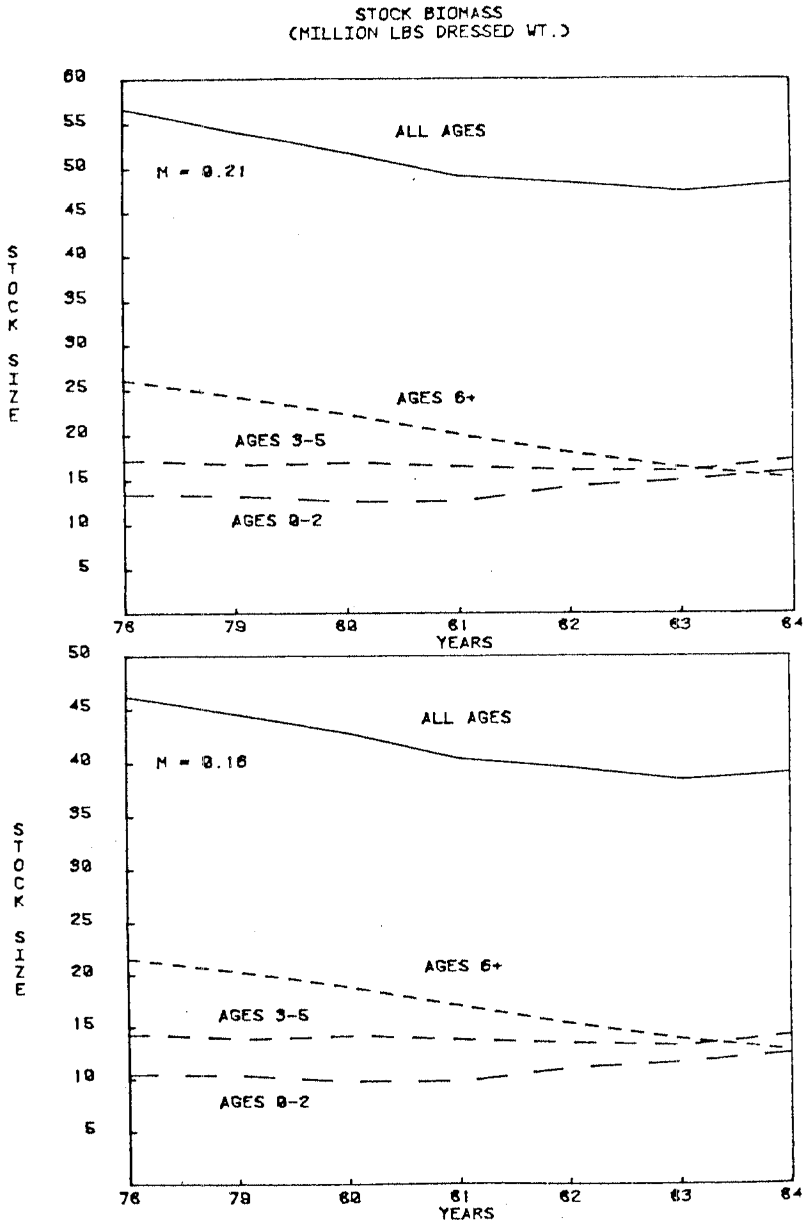

Figure 9. Mid-year estimates of stock biomass (millions of pounds, dressed weight) for selected age groups and two natural mortality rates.

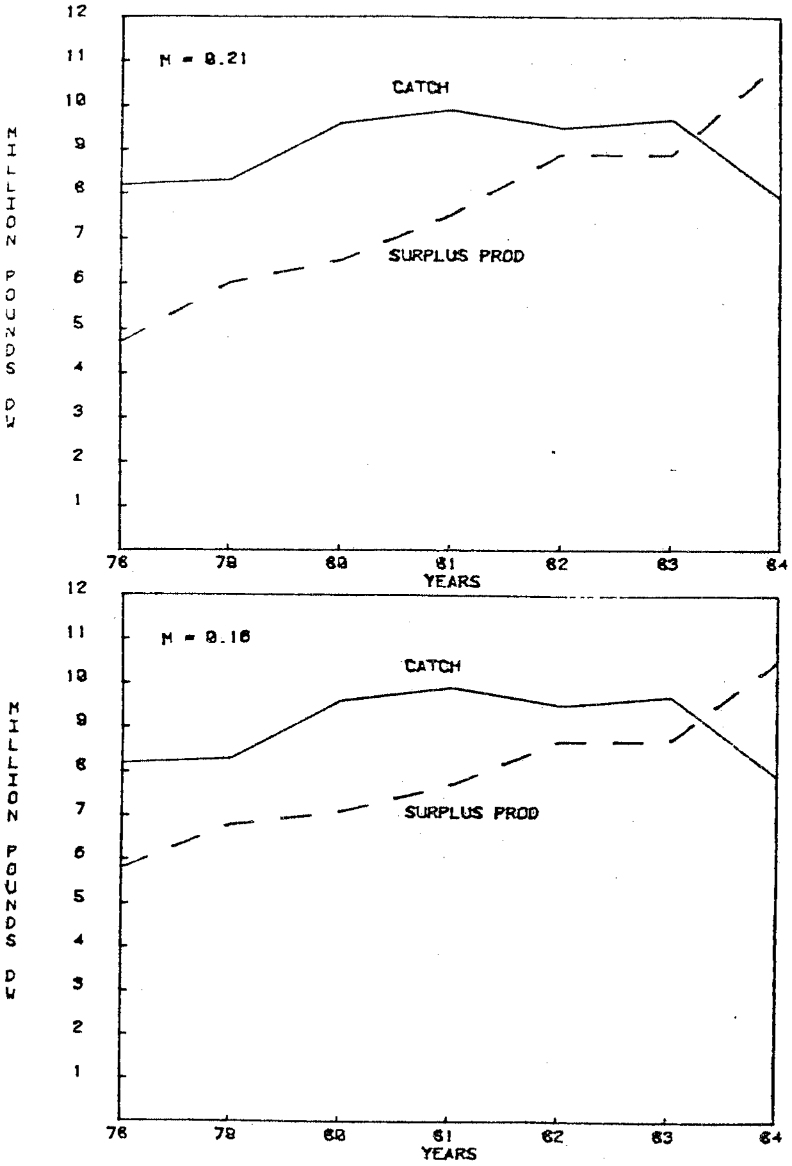

Figure 10. Annual estimates of surplus production compared to reported landings (millions of pounds, dressed weight) for two natural mortality rates. Surplus production is defined as the excess of recruitment and growth over the loss of biomass due to natural deaths.

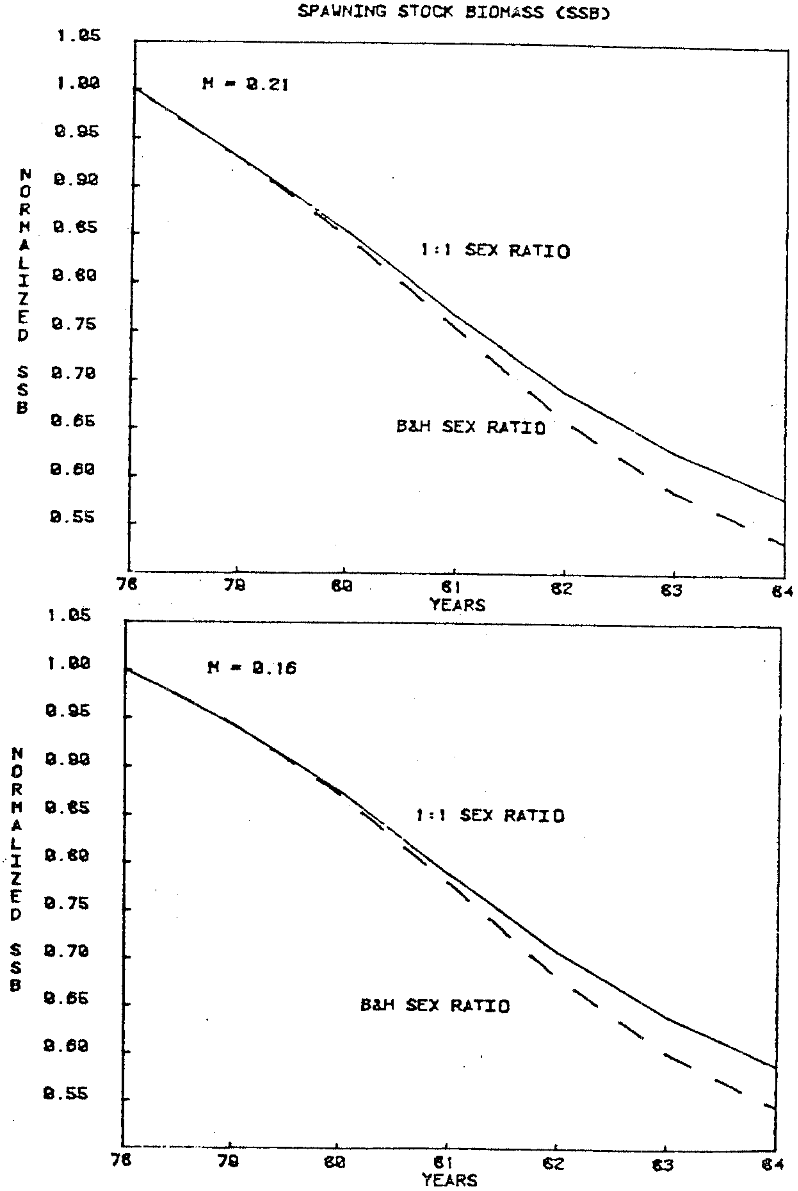

Figure 11. Female spawning stock biomass (normalized to the 1978 value) for two natural mortality rate estimates and two assumptions concerning the proportion of females in the age 6+ population. The first assumption is that there are an equal number of males and females at each age in the age 6+ population (1:1 SEX RATIO). The alternative assumption is that the age 6+ population reflects the Berkeley and Houde (1981) sex ratios at age (B&H SEX RATIO).

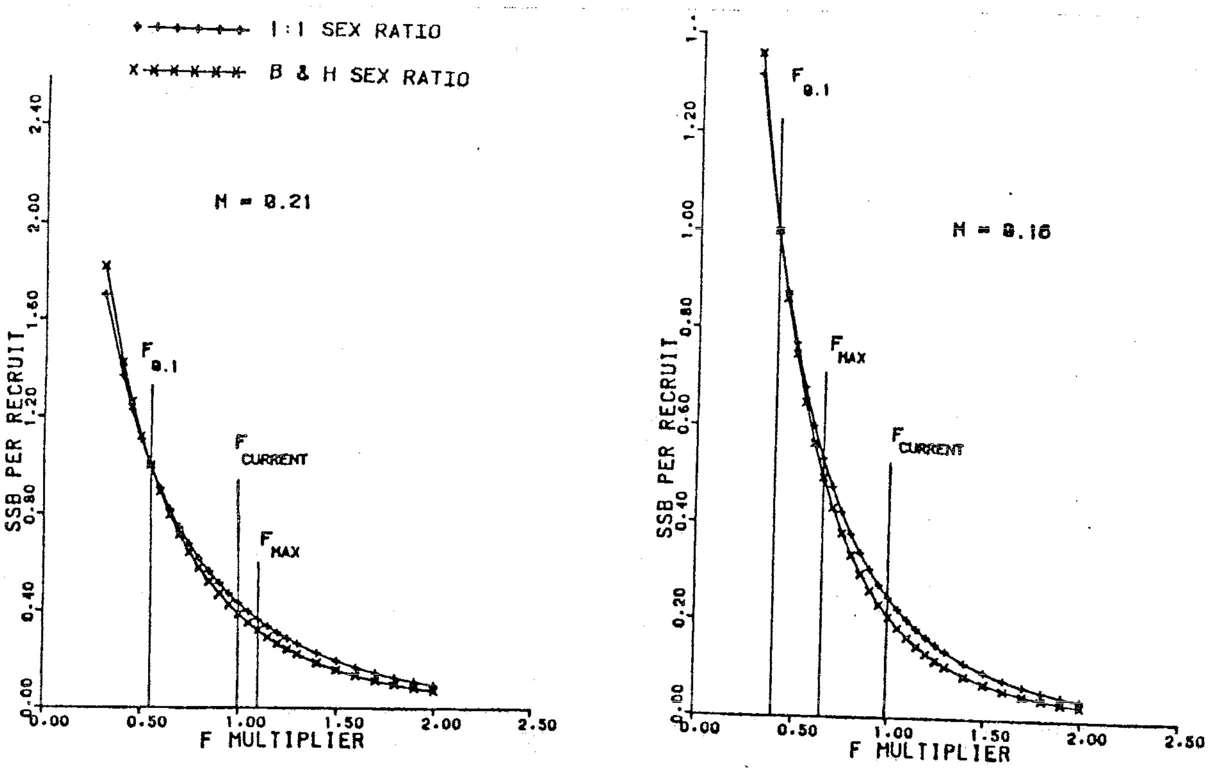

Figure 13. Equilibrium female spawning stock biomass per recruit (SSB/R) for two natural mortality rates and two assumptions concerning the proportion of females in the age 6+ population. The first assumption is that there are an equal number of males and females at each age in the age 6+ population (1:1 SEX RATIO). The alternative assumption is that the age 6+ population reflects the Berkeley and Houde (1981) sex ratios at age (B&H SEX RATIO). All SSB/R values were normalized to the respective SSB/R value at F(0.1).

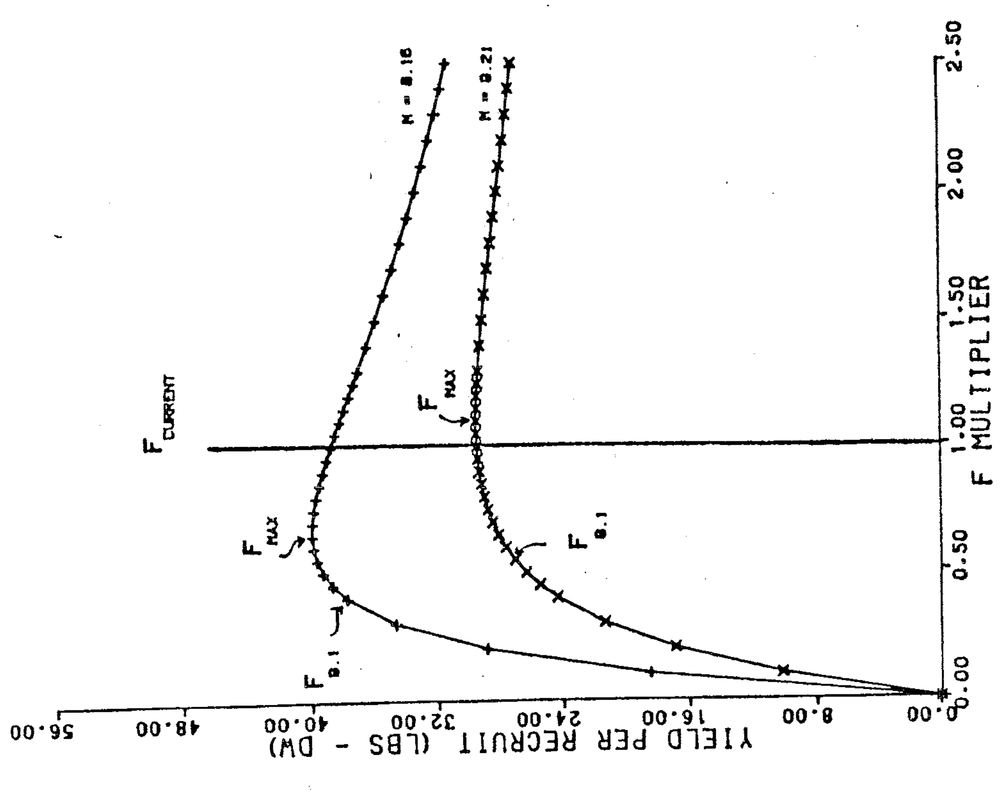

Figure 12. Equilibrium yield per recruit (pounds, dressed weight) for various multipliers of the current F vector and two estimates of natural mortality.

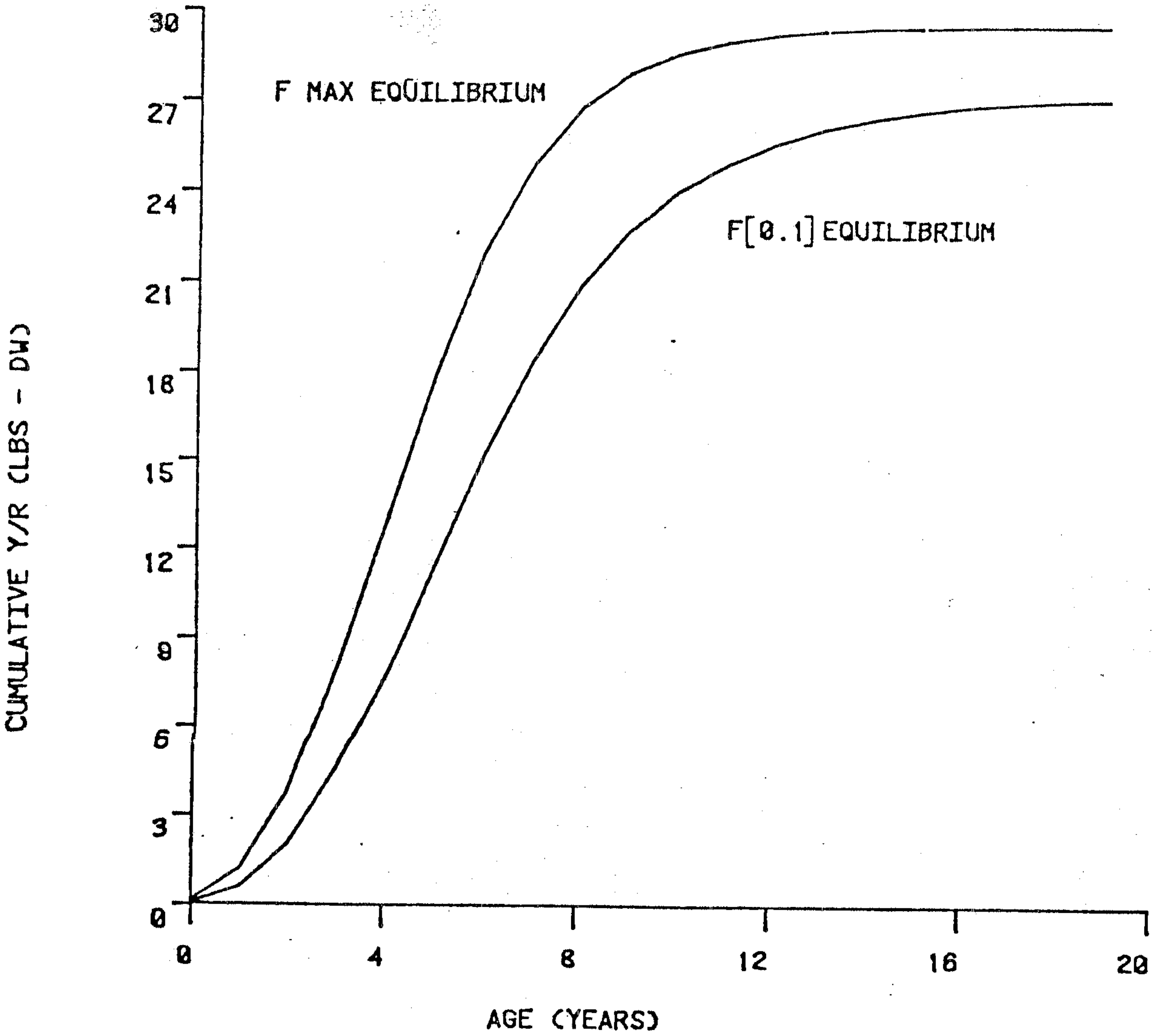

Figure 14. Cumulative equilibrium yield per recruit (Y/R) from the current fishery at $F_{0.1}$ and F_{max}. Under equilibrium conditions, 95% of a cohort's potential Y/R will be achieved by age 9 (when fishing is at F_{max}) or by age 12 (when fishing is at $F_{0.1}$). These calculations assume a natural mortality rate of M = 0.21/yr. The corresponding ages for M = 0.16 are 12 and 15, respectively. These ages (in years) can be used to approximate the time needed to reach equilibrium.