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A Population Assessment of Butterfish, *Peprilus triacanthus*, in the Northwest Atlantic Ocean

by

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ABSTRACT

Reported landings of butterfish, *Peprilus triacanthus* (Peck), in the Northwest Atlantic Ocean increased from 3,209 metric tons (t) in 1964 to a peak of 19,454 in 1973. Most of the catch during the period was taken by vessels from Japan, the United States, Russia, and Poland. Unreported butterfish by-catch in the long-finned squid, *Loligo pealei*, fisheries of several nations, particularly Spain and Italy, were probably significant additional sources of butterfish mortality. Available scientific evidence indicates that during 1968-1976, fishing mortality rates increased, while the mean weight of individuals in the exploitable population and average age at capture generally declined. Exploitation rate (E) during 1968-1975 averaged 0.31. Yield per recruit studies conducted assuming an instantaneous rate of natural mortality (M) of 0.8 suggest E_{max} (exploitation rate resulting in maximum yield per recruit) and $E_{0.1}$ (exploitation rate generating a marginal increase in yield per recruit of 0.1 of that from a lightly exploited fishery) are, respectively, 0.37 and 0.27 for a 30-mm mesh net, and 0.55 and 0.36 for a 60-mm one. Mean weights of fish in the catch, fishing at $E_{0.1}$, would be 57% greater for the larger net (66 g) than for the smaller mesh (42 g). Equilibrium yields resulting from an average annual recruitment of $1,138.5 \times 10^6$ fish (1968-1975) are about 14,500 t (30-mm mesh) and 19,000 t (60-mm mesh), if $E_{0.1}$ is assumed. The maximum long term yield from the stock given annual recruitment fluctuation about the 1968-1975 mean, is approximately 21,500 t,

if $\bar{E}_{0.1}$ is the maximum exploitation rate that will not adversely effect recruitment.

INTRODUCTION

Landings of butterfish, *Peprilus triacanthus* (Peck), increased significantly off the northwestern Atlantic coast of the United States with the advent of distant-water fleet fishing activity in 1963. Catches reported to the International Commission for the Northwest Atlantic Fisheries (ICNAF) increased from 3,207 metric tons (t) in 1964 to 19,454 t by 1973. Reported landings during this period were primarily by vessels from Japan, USSR, Poland, and the USA. A considerable unreported by-catch of butterfish was evident in squid fisheries pursued by several countries, with much of the catch discarded at sea (López-Veiga and Labarta 1975; Nagasaki 1976; Waring 1975). Concern for the status of butterfish in the ICNAF convention area was demonstrated by the recommendation of a total allowable catch (TAC) for 1977 of 18,000 t (ICNAF 1977; Department of Commerce 1976). This figure was judged to be precautionary in nature, since a detailed assessment was not available at the time. Responsibility for the management of the butterfish resource, virtually throughout its fishable range, reverted to United States jurisdiction with the passage of the Fishery Conservation and Management Act of 1976 (FCMA, Public Law 94-265). A management plan for the species is presently being developed by the Mid-Atlantic Fishery Management Council.

In this study we review information concerning the population dynamics and exploitation of the butterfish resource collected prior to and during the period of intensive fishing. Available biological data, research vessel survey results, and commercial catch statistics are integrated with varying assumptions of population parameters to quantitatively describe the system and to predict the impacts of removals given various harvesting strategies.

BIOLOGY

Meristic and morphometric studies by Caldwell (1961), Collette (1963), and Horn (1970) identified depth-isolated butterfish populations in the Atlantic. Caldwell found one population in coastal waters north of Cape Hatteras and deep waters (deeper than 22 m) south of Hatteras, and a second population in shallow waters (less than 22 m) south of Cape Hatteras. Collette and Horn confirmed Caldwell's finding of distinct butterfish populations in shallow and deep waters south of Cape Hatteras For the purposes of this study all reported distant water fleet (offshore) catches, and US landings north of Cape Hatteras are considered to be derived from a single unit stock. Southern inshore landings are excluded from these analyses.

Butterfish north of Cape Hatteras display definite seasonal migratory patterns associated with water temperature (Colton 1972) and exhibit seasonal movements similar to those of Atlantic mackerel, *Scomber scombrus*, weakfish, *Cynoscion regalis*, and long-finned squid, *Loligo pealei*, (Horn 1970; Waring 1975). North of Cape Hatteras summer movements are inshore and northward. To the south there appears to be no strong inshore-offshore translocation (Fritz 1965; Caldwell 1961; Horn 1970). The range extends northward to Nova Scotia and Prince Edward Island, although commercial concentrations generally do not occur north of Georges Bank (Colton 1972). Butterfish retreat to the edge of the continental shelf in late autumn as northern inshore waters cool. The winter distribution, in the Middle Atlantic area, appears to be at the edge of the continental shelf in waters about 200 m deep (Heald 1968; Horn 1970).

Spawning occurs once per year, usually from May to July (Hildebrand and Schroeder 1928; Pearson 1941; Bigelow and Schroeder 1953). Seasonal gonadosomatic indices are unimodal, peaking in June (Wilk et al. 1975; Kawahara 1977). Spent individuals migrate inshore, after spawning a few km seaward of the coast (Bigelow and Schroeder 1953). Hildebrand and Schroeder (1928) reported butterfish as small as 14.5 cm (type of length measurement not given) contained well developed ovaries in May. Thus butterfish are partially recruited to the spawning population at the end of their first year, and essentially fully recruited at the end of their second, if Kawahara's (1977) second-quarter age-length key is applied. DuPaul and McEachran (1973) implied butterfish in Chesapeake Bay are only partially recruited to the spawning population at the end of their second year as 37 of 56 age I+ fish examined from samples taken in September were maturing. Wilk et al. (1975) indicated that from March to June immature or sexually indeterminate specimens comprised 13-36% of samples in the New York Bight.

Age and growth studies of butterfish, based on examination of otoliths, have been conducted by Draganik and Zukowski (1966), DuPaul and McEachran (1973), Waring (1975), and Kawahara (1977). In the latter three investigations the samples were composed of four age groups (0+-III+); Draganik and Zukowski reported the maximum age as six. Back-calculated mean lengths at age were significantly smaller within Chesapeake Bay (DuPaul and McEachran 1973) than further offshore (Kawahara 1977). The von Bertalanffy equation describing growth in length for both sexes combined, given by Kawahara, is $\ell_t = 210.2 \{1-\exp[-0.8618\ (t+0.0699)]\}$, where ℓ is fork length in mm, and t is age in years. The corresponding length-weight equation is $W = 1.635 \times 10^{-6} L^{3.4920}$, where L is fork length in mm and W is total weight in g. According to the von Bertalanffy equation, growth is fastest during the first year and incremental increases in length are smaller as fish age. The value of K, the growth coefficient, is quite high, characteristic of fast-growing, short-lived fishes. Age data presented by Kawahara (1977) suggest annulus formation occurs from May-July, and we have adopted this convention in assigning age class designations to cohorts in our analyses.

Butterfish feed on a variety of invertebrates including tunicates, crustaceans, chaetognaths, polychaetes, ctenophores, and cnidarians (Maurer and Bowman 1975; Haedrich 1967; Mansueti 1963; Oviatt and Kremer 1977). In turn they provide a substantial portion of the diet of a number of fishes including haddock, *Melanogrammus aeglefinus*, silver hake, *Merluccius bilinearis*, swordfish, *Xiphias gladius*, bluefish, *Pomatomus saltatrix*, and weakfish (Horn 1970; Bigelow and Schroeder 1953).

DEVELOPMENT OF THE FISHERY

Butterfish off the northeast coast of the United States were landed entirely by domestic fishermen from the inception of formal record keeping (late 1800's) until 1962. Catches from 1920-1962 averaged about 3,500 t per year (Waring 1975). From 1963-1967 yearly landings fluctuated around 5,000 t. During 1968-1976 annual reported landings averaged 11,655 t, peaking in 1969 (17,511 t) and again in 1973 (19,454 t) (Table 1). Vessels from Japan, the United States, Russia and Poland accounted for most of the landings, respectively, during the period 1963-1976.

Catches by United States fishermen have been derived with a variety of fishing methods including fixed gear (pound nets, trap nets, gill nets) and mobile gear (otter trawls, haul seines). Seasonal domestic landings were greatest from late spring (Hildebrand and Schroeder 1928, p. 21) through autumn (Waring 1975), when the butterfish resource was available to the inshore fishermen. In contrast, catches by distant water fleets were derived primarily during late autumn - early spring when the butterfish resource was concentrated in offshore waters. Landings by the Japanese, coincident with the offshore *Loligo* squid fishery, were taken from November to April (Kawahara 1977).

By-catch of butterfish during the offshore *Loligo* fishery was considered to be significant. López-Veiga and Labarta (1975) stated that butterfish was the main species in the by-catch of both the Spanish *Loligo* and *Illex illecebrosus* fisheries, although Spain had never reported any butterfish catches (Waring 1975). Data presented by López-Veiga and Labarta indicate that the monthly by-catch ranged from 3% (February) to 38% (September) of the entire catch in the directed squid fisheries during 1973 and early 1974. Italy landed significant quantities of squid in the convention area from 1972 to 1976; however, their butterfish catches have not been documented (Tibbetts 1977; Waring 1975).

Nagasaki (1976) reported the ability of Japanese fleets to direct effort at either *Loligo* or butterfish when these species inhabit the same grounds. However, the following evidence suggests that the ratio of *Loligo* to butterfish in Japanese catches was generally similar to the annual relative species abundances as determined from research survey information during 1969-1975.

The average ratio of *Loligo* to butterfish (based on kg/tow) was calculated for spring and autumn research vessel bottom trawl surveys from

1969-1975 for the area between Cape Hatteras and Cape Cod and depths between 27 and 366 m (Grosslein 1969). Butterfish catches from the spring surveys (in weight) from 1973 through 1976 were divided by a factor of 1.35 to account for the larger survey net used; however, *Loligo* catches required no adjustment based on results of gear mensuration studies involving the two survey nets (Sissenwine and Bowman 1977). Spring and autumn survey ratios for the same year were averaged to derive single ratios applicable to the entire year. The ratio of *Loligo*/butterfish landings reported by Japan was plotted agains the survey ratio, indicating a general linear correlation (Figure 1). In 1972 there was a much higher ratio of *Loligo* to butterfish in the Japanese commercial catch than in the surveys. However, commercial catch ratios for other countries landing significant amounts of *Loligo* and butterfish in 1972 (e.g. USA, USSR, Bulgaria) more closely approximated the survey data than the Japanese catches. Interestingly, Japanese *Loligo* catches in 1972 were greater than any other year from 1963-1976 suggesting some butterfish may have been discarded to accommodate the large squid catch. The implication of the close agreement of survey and commercial landings ratios is that catches (including discards) of butterfish can be approximately determined by knowing the total landings of *Loligo*, and the relative survey abundance of both species. Assuming countries reporting *Loligo* but not butterfish landings did not discard squid, butterfish by-catch was approximated from the survey ratios by multiplying nominal *Loligo* catches by survey ratios to account for butterfish discards of those countries reporting only *Loligo*. If fishing patterns of countries not reporting butterfish were non-random with respect to relative availability of *Loligo* and butterfish then these estimates may be inflated. The resulting total catches are listed in Table 1. The most significant change was in 1973, when the total catch was adjusted 71% to 33,236 t. The adjusted figures must also be regarded as under-estimates of total catch, since there are no data on discards by those countries reporting butterfish landings.

DYNAMICS OF THE POPULATION

Age Composition of the Catch

Length frequency sampling of butterfish catches by ICNAF member countries has been quite limited. Frequencies have been supplied by Japan, USSR, and the USA. Japan provided January-March length data from 1970-1976; however, data reported for other annual quarters, and by the other countries was intermittent. Although a significant portion of the USA landings were derived with fixed gear and seines, trawl catches (bottom and mid-water) accounted for more than 90% of the total butterfish caught from 1968-1976. Thus, even though length frequency samples represent only trawl catches, they probably adequately reflect the fishery. Since at least one length sample was reported for each quarter, beginning in 1970, all samples within a quarter were combined and weighted by individual sample size to yield an overall quarterly frequency distribution. The length compositions of catches in 1968 and 1969 were derived from semi-annual bottom trawl survey samples collected by the National Marine Fisheries Service (NMFS). Age frequencies were then calculated by applying the quarterly age-length keys of Kawahara (1977) to the length frequencies.

Japanese first quarter length and age frequencies from 1970 through 1976 are presented in Figure 2. The age distribution of the catch remained stable during 1970-1972, with I+ individuals dominating the catch. A considerable proportion of the landings in 1973 were of those fish spawned the previous summer. During 1974-1976 age group 0+ and I+ fish were predominant in the samples.

The quarterly catch in numbers at age was computed by:

$$N_{ijk} = \left(\frac{P_{ijk} \cdot \overline{W}_{ij}}{\sum_{i=1}^{n} P_{ijk} \cdot \overline{W}_{ij}} \cdot C_{jk} \right) / \overline{W}_{ij}$$

where; N = the number of fish of age i, caught during calendar quarter j of year k,

P = the proportion (in numbers) of age i, in commercial samples during the quarter,

$\overline{W}$ = mean fish weight of age i, in quarter j,

C = total commercial butterfish catch (weight) in quarter j of year k.

The mean weights of fish in each age group, during each calendar quarter are given in Table 2. The annual catch in numbers, by year class, was calculated by summing appropriate quarterly catches of each cohort (Table 3). Total catches in numbers were greatest in 1973, followed by 1974, 1969, and 1976. The mean weights of all fish caught calculated by dividing total landings in weight by total numbers were largest in 1970 and 1974, and relatively small in 1968 and 1973.

Abundance Indices

The relative annual abundance of butterfish in offshore areas was calculated from bottom trawl surveys conducted between Cape Hatteras and Nova Scotia by the National Marine Fisheries Service (Grosslein 1969). Survey catches from the Georges Bank and Gulf of Maine areas were not included in the analyses because butterfish catches in those areas were relatively smaller and less consistent that those from Southern New England and the Middle Atlantic (Cape Cod to Cape Hatteras). Sampling procedures during the surveys are detailed in Grosslein (1969) and Clark and Brown (1977). A standard sample consisted of a 30-minute bottom trawl tow at predetermined locations in a stratified random survey design. The stratified mean catches per tow in numbers and weight were calculated with observed (linear), and transformed ($\log_e$ Number + 1, $\log_e$ Weight + 1) data, since serious violations of the assumptions of normal statistics can occur when populations being sampled are highly aggregated. Autumn survey abundance indices, which tended to be greater than corresponding spring indices, are presented in Table 4. Variations in numbers per tow parallel corresponding calculations in weight, and relative indices between years are similar for linear and transformed data. Largest transformed catches (in weight) were in 1976, followed by 1973, while butterfish catches were smallest in 1970 and 1972. Numbers per tow ($\log_e$) were greatest in 1973 and 1976, and also relatively low in 1970 and 1972. Autumn survey indices (in weight) generally correlate well with fluctuations in annual catch (Table 1) with the exception of 1976.

The mean weight of individuals caught during the surveys is expressed in Figure 3. Both spring and autumn data exhibit a general trend of declining average weights during the study period. This decrease may be attributable to two factors: (1) large year classes dominating the survey catches as juveniles, and (2) a decrease in mean weight as fishing became more intense and larger individuals were removed. Although differential recruitment between cohorts may have played an important role in causing large fluctuations in mean weight, the long-term trend to smaller fish is probably due to increased fishing pressure. The persistent decline in the catch per tow indices of age I+ and II+ individuals in spring surveys between 1973 and 1976 (Table 5), notwithstanding the presence of several strong year classes since 1971, clearly demonstrates the importance of increased fishing pressure to the decline in mean weights. The autumn mean weight averaged 41 g between 1972 and 1976, a figure quite close to the average weight of 0+ individuals in the fourth calendar quarter (Table 2). Estimates of average weight in spring and autumn 1976 samples were identical (42 g).

The total instantaneous mortality coefficient (Z) was estimated for each year class from 1968 through 1975, based on numbers per tow at age from the spring surveys. Autumn data were not useful in this analysis because at this time juveniles are not fully recruited to the offshore survey areas. Spring length frequencies of catch per tow (linear scale) were partitioned into age classes by means of the appropriate age-length key of Kawahara (1977). Total mortality coefficients of each year class were computed by regressing $\log_e$ (number at age) on coded age (Table 5). The approximate doubling of total mortality between 1968 and the mid-1970's coincided with the tremendous increase in landings associated with the advent of distant water fleet activity.

Population Size Estimates

Estimates of stock size at the beginning of each year (1968-1976) were computed by virtual population analysis (VPA, Pope 1972). Calculations of stock size for short-lived fishes by this technique are particularly sensitive to variations in the assumed natural mortality coefficient (M) and associated estimates of fishing mortality of the oldest age group in the fishery ("starting" or "terminal" F's). Since no studies of the natural mortality rate of butterfish have been conducted, we deduced a reasonable estimate of M by comparing total stock size estimates generated by various M values with the VPA, and biomass calculations based on areal expansion of survey catch-per-tow data for 1969-1973 (Waring 1975). Areal expansion estimates were calculated by:

$$\hat{B} = \frac{\overline{y}_{st} \cdot A}{\alpha}$$

where;

$\hat{B}$ = estimated biomass of butterfish in the sampled area,

$\overline{y}_{st}$ = stratified mean weight per tow of butterfish in the survey,

A = total area (Km^2) of all strata considered in the analysis,

α = area swept (Km^2) by the gear during a standard survey tow.

Butterfish apparently undergo vertical migrations, staying relatively close to the bottom during daylight and dispersing upward at night. Therefore, correction factors based on relative day/night catch ratios were also appilied. Thus diel changes in vulnerability to bottom trawl gear probably did not bias the calculations (Waring 1975).

Virtual population analyses were conducted with M values of 0.6, 0.8, 1.0, and 1.2, and starting F's for each year class scaled according to Z values from survey data (Table 5).

Biomass estimates from areal expansions of autumn catch-per-tow data averaged 61,630 t from 1969 through 1973 (Waring 1975). Mean stock sizes from the VPA corresponding to the period of areal expansion estimates (1969-1973) were 40,483 t, 61,762 t, 113,162 t, and 190,571 t for M's of 0.6, 0.8, 1.0, and 1.2 respectively. Thus, M is apparently at least 0.8, since areal expansion results in a minimum biomass estimate due to the assumption of 100% capture efficiency of the gear. The estimates from expanded catch-per-tow are also minimum to the extent that a portion of the resource was inshore and/or north of the Southern New England and Middle Atlantic offshore survey strata.

Stock size estimates (numbers), based on M=0.8, are presented in Table 6. Corresponding stock biomass was derived by multiplying numbers at age by the first quarter mean weight (Table 2), to calculate population mass at the beginning of the year. A total stock weight estimate for year n was determined by summing stock sizes in weight only for year classes n-1, n-2, n-3, and n-4, since year class n is not spawned until July. Overall stock size (1968-1976) varied from 31,896 (1976) to 70,631 t (1973), and averaged 53,571 t.

Fishing mortality rates derived from the VPA with M = 0.8 are listed in Table 7. Mean mortality rates increased substantially from 1968 (0.213) to 1974 (0.872). Relatively large variations in F's occur among fully recruited cohorts within years, perhaps due to the sensitivity of the analysis to starting F's and/or a violation of the assumption of constant natural mortality for all ages.

The apparent discrepancy in the estimates of relative stock size in 1976 between the survey data and the VPA (Tables 4 and 6) is due to a large 1976 cohort that was not reflected in virtual population size calculations or the fishery at the beginning of the year. The larger year classes indicated by the VPA were 1972, 1968, 1971, and 1973, while smaller cohorts were 1975, 1969, 1970, and 1974. These data are generaly consistent with survey results. A large year class may not be evident in the autumn survey of the year it was spawned since juvenile fish are concentrated inshore during the early autumn. Depending on the timing of the cruise relative to climatic changes, juvenile fish may not be fully available to the offshore survey.

Annual landings during the period 1968-1976 averaged 31% of the initial yearly stock size (Table 6), with the proportion harvested (P_h) ranging from 18% (1968) to 50% (1976). Annual exploitation rates (E, calculated with mean F's from the VPA and M = 0.8) parallel the calculations of the portion of initial biomass harvested, even though computations of P_h and E are based on weights and numbers of fish, respecitvely.

YIELD ANALYSIS

Yield Per Recruit

Yield per recruit (Y/R) analyses were conducted for butterfish with the model of Paulik and Gales (1964), since an isometric length-weight relation could not be assumed. Fork lengths at 50% selection (L_c) were calculated with Meyer and Merriner's (1976) empirical selection factor (L_c = selection factor · mesh size) of 1.8. Evaluations were conducted for stretched mesh sizes of 30 mm (L_c = 54 mm), 60 mm (L_c = 108 mm), 80 mm (L_c = 144 mm), and 100 mm (L_c = 180 mm). Various values of M, ranging from 0.6 to 1.2, were also included. The following data were used as input parameters to the model: asymptotic length (L_∞) = 210.2 mm, asymptotic weight (W_∞) = 210.9 g, growth coefficient (K) = 0.8618, age at zero length (t_0) =-0.0699 years, age at recruitment to the fishable population (t_r) = 0.25 years, exponent of the length-weight equation (δ) = 3.4920, M = 0.6-1.2, F = 0.01-2.50, maximum age (t_λ) = 6.0 years, and age at selection to the fishery (t_c) = 0.275, 0.767, 1.271, 2.182 years. Values of $F_{0.1}$ (fishing mortality rate generating a marginal increase in Y/R of 10% of that from a lightly exploited fishery, Gulland and Boerema (1973)) were determined to be the point at which marginal Y/R was 10% of the yield at F = 0.01. Exploitation rates corresponding to F_{max} (fishing mortality rate generating maximum Y/R for a given age at entry) and $F_{0.1}$ were computed from: $E = F\ [1-\exp(-Z)]/Z$.

Calculations of yields, fishing mortalities, and exploitation rates for various combinations of mesh size and natural mortality rate are listed in Table 8. Transverse isopleth sections for M = 0.8 are presented in Figure 4. If M = 0.8, maximum Y/R (>26.48 g) occurs with the 80 mm mesh, and F>2.50. If a 60-mm mesh net is used, a maximum yield of 22.07 g could be harvested with an F of 1.33. From $F_{0.1}$ computations, 23.04 g can be derived with F = 0.96 and a mesh of 80 mm; however, with a 60 mm mesh, 20.32 g can be taken with an F of only 0.69 (Figure 4, Table 8). Yields derived with the 100 mm net are less than corresponding values for the 60 mm and 80 mm mesh sizes, except at extreme fishing mortality rates, because natural mortality removes more biomass than can be generated after selection to the fishery when age at entry is delayed.

Exploitation rates (E_{max}, $E_{0.1}$) are only slightly different among M values within mesh size categories (Table 8). Thus, these calculations are not highly sensitive to the absolute value of the natural mortality coefficient. Figure 5 summarizes the relations between stretched mesh size (mm) and $E_{0.1}$. The calculated regression equations describe more than 99% of the variation about the lines for all M values. Therefore, $E_{0.1}$ for a particular mesh size within the range 30 to 100 mm (and a selection factor of 1.8) can be accurately computed.

The theoretical mean weight of individuals in the catch was estimated for several exploitation rates by dividing yield (in weight) for a given number of recruits by the number of fish harvested from that cohort over it's life span. Curves of mean weight versus exploitation rate for the 30 mm and 60-mm mesh sizes are presented in Figure 6. If the average exploitation rate from 1968-1976 were 0.31 (Table 6), then average weight in the catch should have equalled 39 g if a 30 mm mesh were used, and 70 g if the mesh were 60 mm. The Japanese predominantly used a 30 mm mesh inside a 60 mm one in their squid-butterfish fisheries. Other distant water fleets used mesh sizes approximating those of the Japanese; however, trawl nets of United States fishermen averaged 66 mm in the industrial (reduction) fishery and 114 mm for the food fishery (Waring 1975). Bottom trawl surveys employed nets with a 13 mm mesh liner. Mean weights of fish in the survey catches (1968-1976 autumn average = 47 g) were close to predicted values for the 30 mm mesh. However, mean weights in the fishery (Table 3, 1968-1976 average = 93 g) more closely approximate values predicted for the 60 mm net. The apparent discrepancy may reflect non-uniformity of gear in the fishery, culling of small fish (<15 cm) taken with small mesh nets, and seasonal variations in exploitation rate since the model used assumes equal distribution of fishing effort throughout the year. The relative proximity of estimates of mean weight from Y/R analyses to data from the fishery and surveys tends to validate assumptions of population parameters.

Equilibrium Yield

The total harvest of butterfish is a function of the number of recruits entering the population, fishing mortality, and age at entry to the fishery. If the 30 mm mesh is used (L_c = 54 mm) in conjunction with an intensive offshore fishery during late autumn and winter months, a considerable portion of the stock will be harvested prior to initial spawning because fish will be selected to the fishery as 0+ individuals, but are only partially recruited to the spawning population at the end of their first year. However, if age at selection is delayed, harvest rates resulting in maximum yield increase to the point that very little of the adult stock survives the fishery, even though large increases in fishing mortality result in only marginal gains in yield (Figure 4). Thus, although arbitrary, values of $F_{0.1}$ are preferable to those resulting in maximum Y/R (F_{max}) when stock-recruitment relationships are considered. The reduction in fishing mortality rate from F_{max} to $F_{0.1}$ (Table 8) results in only minor declines in corresponding values of Y/R, while preserving a much larger portion of the spawning stock, since exploitation rates are reduced 8 to 43% depending on mesh size and natural mortality rate. A positive stock-recruitment relationship has not been demonstrated for butterfish but it is clear that more progeny will be generated at $F_{0.1}$ than at F_{max} due to the increased survival of spawners.

The effects of various management scenarios on total yield from a given number of recruits can be simulated with the Y/R model. Yield from a cohort over it's life span is the product of the number of recruits alive at the age of selection by the fishery (with knife-edged selectivity) and Y/R calculated for the desired F level. Long-term yields from a population are probably approximated by the simplistic model of applying Y/R to average recruitment even though substantial variation in juvenile production can occur.

The mean number of butterfish entering the population from 1968 through 1975 was $1,138.5 \times 10^6$ (Table 6). If the ages at selection for the 30 mm and 60 mm meshes are 0.275 and 0.767 years, respectively, then the average numbers of recruits alive at t_c, for each mesh are: $1,138.5 \times 10^6 \cdot \exp-(0.8)(0.275) = 913.7 \times 10^6$, and $1,138.5 \times 10^6 \cdot \exp-(0.8)(0.767) = 616.4 \times 10^6$. Yields associated with $E_{0.1}$ ($F_{0.1}$(30 mm) = 0.47; $F_{0.1}$ (60 mm) = 0.69) are then: 30 mm mesh ≈ 14,500 t; 60-mm mesh = 19,000 t. Thus, yields at $E_{0.1}$ from the average recruitment for 1968-1975 range from 14,500 to 19,000 t, depending on which mesh size was in use. Average recorded landings during the period were 11,685 t, with an adjusted mean catch of 16,123 t. Because most of the catch during the period (by distant water fleets) was taken with nets between 30 and 60 mm, a total adjusted catch between yield calculations for the two mesh sizes indicates the population was utilized near $E_{0.1}$. These findings are consistent with computations of annual exploitation rates derived from VPA (Tables 6 and 7). The mean exploitation rate from 1968-1975 (Table 6) was 0.29. Values of $E_{0.1}$ for 30 and 60 mm mesh nets (M = 0.8) are 0.27 and 0.36 respectively (Table 8). Maximum potential yield was computed by iterating Y/R calculations with respect to mesh size (1-mm increments). Maximum catch at $F_{0.1}$, given constant annual recruitment, was about 21,500 t with a mesh size of 82 mm and $F_{0.1}$ = 1.01.

CONCLUSIONS

Total mortality rates derived from survey numbers-per-tow at age, fishing mortality rates from virtual population analysis, and mean weights in bottom trawl surveys and commercial catches indicate that exploitation of the northern unit stock of butterfish occupying the northwest Atlantic increased rapidly from 1968-1976. Juvenile fish (age 0+) comprised a considerable portion of the catch between 1973 and 1976. Calculated exploitation rates from 1968-1976 ranged from 0.13 to 0.46, averaging 0.31. Values of $E_{0.1}$ for 30 and 60-mm mesh sizes are 0.27 and 0.36 respectively. Equilibrium catches associated with $E_{0.1}$ range from 14,500-19,000 t, if average mesh size in the fishery ranges from 30 to 60 mm. Predicted mean weights of fish in the commercial catch are 57% greater for the 60 mm mesh net (66 g) than for the 30 mm net (42 g). If $E_{0.1}$ is assumed to be the maximum exploitation rate that will not adversely effect recruitment and annual recruit is assumed to vary about the 1968-1975 mean, maximum long-term yield from the stock will be about 21,500 t.

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Table 1. Reported landings and adjusted[a] catches of butterfish between Cape Hatteras and Nova Scotia. Data are in metric tons.

Year	USA	USSR	Japan	Bulgaria	Poland	GDR	Romania	Ireland	Reported Total	Adjusted Total
1963	4,513	2,285							6,798	6,798
1964	2,461	748							3,209	3,209
1965	3,340	749							4,089	4,089
1966	2,615	3,865							6,480	6,480
1967	2,452	2,170	146						4,768	4,768
1968	1,804	1,911	3,526						7,241	7,241
1969	2,438	11,107	3,930	36					17,511	17,816
1970	1,869	404	8,624						10,897	14,319
1971	1,570	486	5,771	26					7,853	10,483
1972	819	1,848	3,675	114		34			6,490	13,040
1973	1,557	2,334	12,172	239	2,804	196	152		19,454	33,236
1974	2,528	1,372	5,457		3,508				12,865	17,993
1975	2,088	789	3,624	298	3,754	1		612	11,166	14,852
1976	1,528	420	7,884	4	1,518	3	62		11,419	15,837

[a]Adjusted to account for discards of countries not reporting butterfish catches from the Loligo squid fishery.

Table 2. Mean butterfish weight (g) by age class and calendar quarter. Data are adapted from Kawahara (1977).

Age	July-Sept	Oct-Dec	Jan-Mar	Apr-Jun
0+	--	40	47	55
I+	56	101	104	104
II+	99	153	163	152
III+	150[a]	222	219	183

[a]Value adjusted from original source due to small sample size

Table 3. Annual butterfish catch (millions of fish) between Cape Hatteras and Nova Scotia, 1968-1976.

Year class	Year of Catch								
	1968	1969	1970	1971	1972	1973	1974	1975	1976
1964	0.02								
1965	3.94	0.03							
1966	19.80	8.05	1.45						
1967	68.11	51.03	23.97	2.31					
1968	10.90	109.81	58.95	19.45	4.47				
1969		9.51	39.86	43.88	25.30	0.21			
1970			13.89	27.27	44.57	7.06	3.03		
1971				10.55	25.60	87.90	30.87	1.43	
1972					39.09	309.84	74.87	18.35	3.26
1973						55.04	65.76	67.67	17.49
1974							21.66	63.32	74.08
1975								5.30	75.09
1976									0.71
Total	102.77	178.43	138.12	103.46	139.03	460.05	196.19	156.07	170.63
Mean fish weight (g)	71	100	104	101	94	72	103	95	93

Table 4. Autumn survey abundance indices for butterfish in offshore waters from Cape Hatteras to Cape Cod. Values are stratified mean catch per 30-minute bottom trawl tow.

Year	Numbers		Weight (kg)	
	Linear[a]	Transformed[b]	Linear[a]	Transformed[b]
1968	121.09	1.99	10.44	0.66
1969	76.93	2.16	5.32	0.66
1970	48.29	1.13	3.07	0.34
1971	242.17	2.19	5.45	0.58
1972	86.67	1.36	3.21	0.36
1973	178.03	2.35	8.39	0.75
1974	116.32	1.95	5.12	0.66
1975	52.47	1.69	2.94	0.58
1976	160.31	2.32	6.71	0.86

[a]Stratified mean of original catches in numbers and weight.

[b]Original observation transformed by: $\log_e$ number +1; $\log_e$ weight+1.

Table 5. Calculation of total instantaneous mortality (Z) of butterfish, from numbers per tow at age for spring bottom trawl surveys, 1968-1977. Coefficient of variation is r^2, intercept is a, slope is b.

Year class	Stratified mean number per tow at age				Regression statistics for $\log_e$ N/tow versus age [a]		
	0+	I+	II+	III+	r^2	a	b(=-Z)
1968	11.66	2.96	1.30	0.01[b]	0.980	3.462	-1.097
1969	10.04	2.36	1.24	0.31	0.981	3.322	-1.108
1970	26.36	4.22	8.00[b]	0.33[b]	0.768	4.546	-1.250
1971	313.31	40.17	3.68[b]	0.17[b]	1.000	7.801	-2.054
1972	44.09	9.05	1.89	0.18	0.989	5.745	-1.807
1973	22.12	6.88	1.82	0.18	0.972	4.918	-1.576
1974	162.24	5.12	1.04		0.957	7.304	-2.524
1975	36.40	4.39			1.000	5.710	-2.115
1976	4.21						

[a]Coded ages A_i = 1,2,3, ... n for ages 0+, I+, II+, ... N+

[b]Not included in regression

Table 6. Butterfish stock size (millions of fish), calculated from virtual population analysis (instantaneous mortality, M=0.8).

Year class	Year of Catch 1968	1969	1970	1971	1972	1973	1974	1975	1976	Mean
1964	1.9[a]									
1965	5.6	0.2								
1966	92.7	29.0	8.0							
1967	562.1	208.7	61.4	12.7						
1968	1,684.2	750.3	266.6	82.2	24.6					
1969		823.3	363.7	137.7	34.3	1.2				
1970			847.5	371.8	149.4	39.0	13.0			
1971				1,215.3	539.4	225.7	46.8	3.1		
1972					1,976.8	862.5	194.1	40.7	7.0	
1973						1,168.8	489.4	177.6	37.7	
1974							1,024.0	446.1	159.7	
1975								368.1	161.9	
1976										
Stock biomass (S,t) at beginning of year	41,022	61,740	56,580	67,976	51,884	70,631	53,663	46,750	31,896	53,571
Total catch (C,t)	7,241	17,816	14,319	10,483	13,040	33,236	17,993	14,852	15,837	16,091
Portion of initial stock harvested (P_h)	0.18	0.29	0.25	0.22	0.25	0.47	0.34	0.32	0.50	0.31
Exploitation rate (E)[b]	0.13	0.17	0.18	0.28	0.35	0.36	0.42	0.40	0.46[c]	0.31

[a]Calculated from 5.57 x exp(-1.1).

[b]E=F[1-exp(-Z)]/Z, where F is instantaneous fishing mortality, Z is total mortality.

[c]Assumed.

Table 7. Fishing mortality rates (F) for butterfish, calculated from virtual population analysis (natural mortality, M =0.8).

Year class	Year of Catch							
	1968	1969	1970	1971	1972	1973	1974	1975
1966	0.361	0.494	0.300					
1967	0.191	0.424	0.776	0.300				
1968	0.009	0.235	0.376	0.407	0.300			
1969		0.017	0.171	0.590	2.582	0.300		
1970			0.024	0.112	0.542	0.298	0.400	
1971				0.013	0.071	0.773	1.920	1.000
1972					0.029	0.691	0.762	0.957
1973						0.071	0.214	0.750
1974							0.031	0.227
1975								0.021
Mean F[a]	0.213	0.279	0.290	0.504	0.660	0.690	0.872	0.788
Year class[b]	'66-'67	'66-'68	'66-'69	'67-'69	'68-'70	'69-'72	'70-'72	'71-'73

[a]Mean F for fully recruited ages, calculated from corresponding survival rates weighted by stock size in numbers (Table 6).

[b]Year classes included in the calculation of Mean F.

Table 8. Yield per recruit calculations for butterfish. Y/R is yield per recruit, M is instantaneous natural mortality coefficient, F is instantaneous fishing mortality coefficient, E is annual exploitation rate. Values and rates correspond to maximum yield per recruit (max) and marginal increase in yield per recruit equal to 10% of that from a lightly exploited fishery (0.1).

Mesh size	M	Y/R_{max} (g)	F_{max}	E_{max}	$Y/R_{0.1}$ (g)	$F_{0.1}$	$E_{0.1}$
30 mm	0.6	22.45	0.59	0.35	21.38	0.39	0.25
	0.8	16.44	0.71	0.37	15.60	0.47	0.27
	1.0	12.65	0.84	0.38	11.99	0.55	0.28
	1.2	10.11	0.98	0.40	9.55	0.63	0.29
60 mm	0.6	29.14	0.99	0.50	27.08	0.55	0.33
	0.8	22.07	1.33	0.55	20.32	0.69	0.36
	1.0	17.48	1.78	0.60	15.95	0.84	0.38
	1.2	14.29	2.35	0.64	12.92	1.03	0.41
80 mm	0.6	35.25	2.05	0.72	31.39	0.75	0.41
	0.8	>26.48	>2.50	>0.73	23.04	0.96	0.45
	1.0	>20.04	>2.50	>0.69	17.56	1.22	0.49
	1.2	>15.24	>2.50	>0.66	13.62	1.49	0.52
100 mm	0.6	>35.32	>2.50	>0.77	30.23	1.09	0.53
	0.8	>22.41	>2.50	>0.73	19.57	1.38	0.56
	1.0	>14.28	>2.50	>0.69	13.01	1.74	0.59
	1.2	> 9.13	>2.50	>0.66	8.67	2.08	0.61

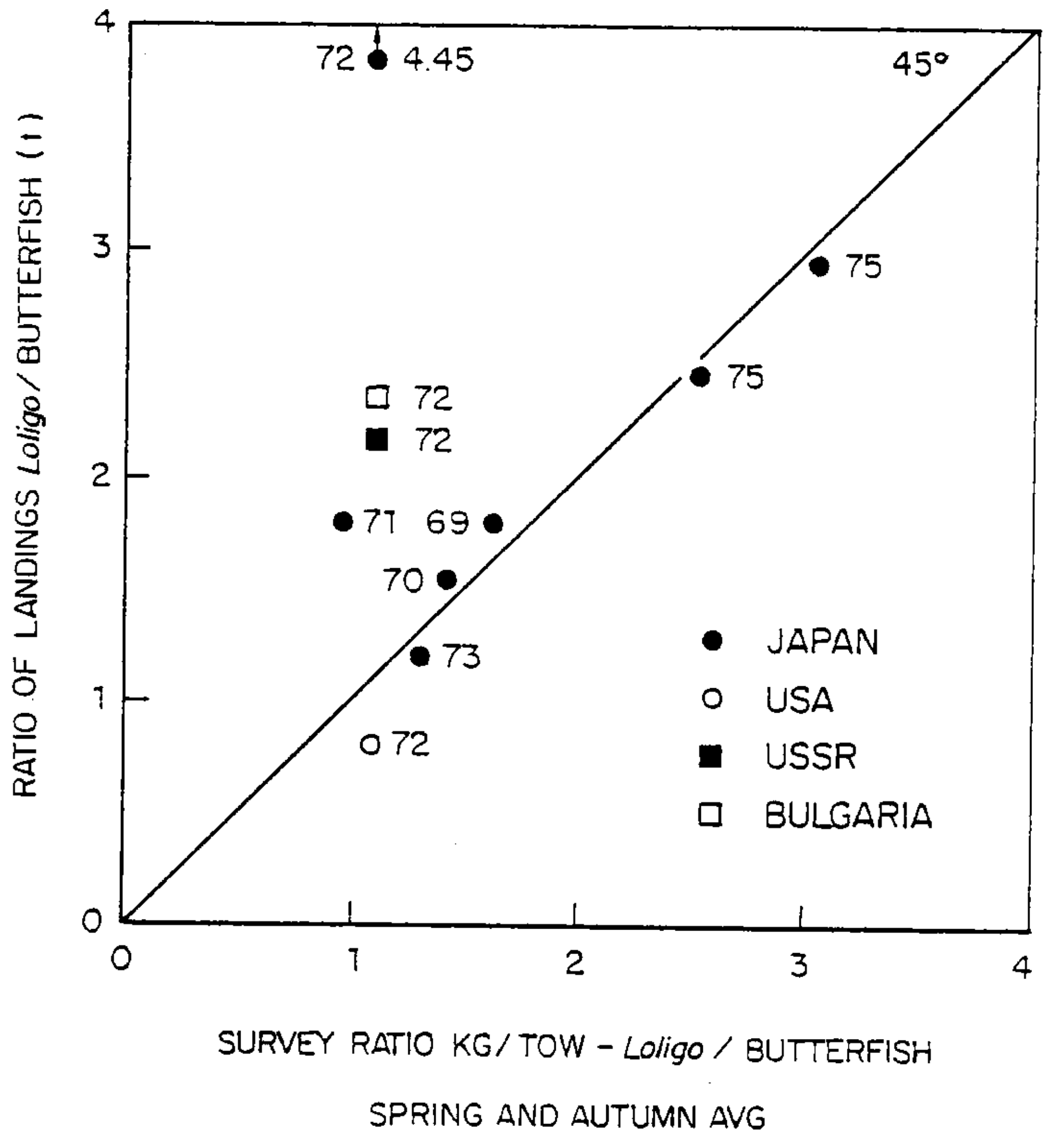

Figure 1. Ratio of *Loligo* to butterfish in research vessel surveys versus Japanese landings, 1969-1975, and 1972 catch ratios for the United States, Russia, and Bulgaria.

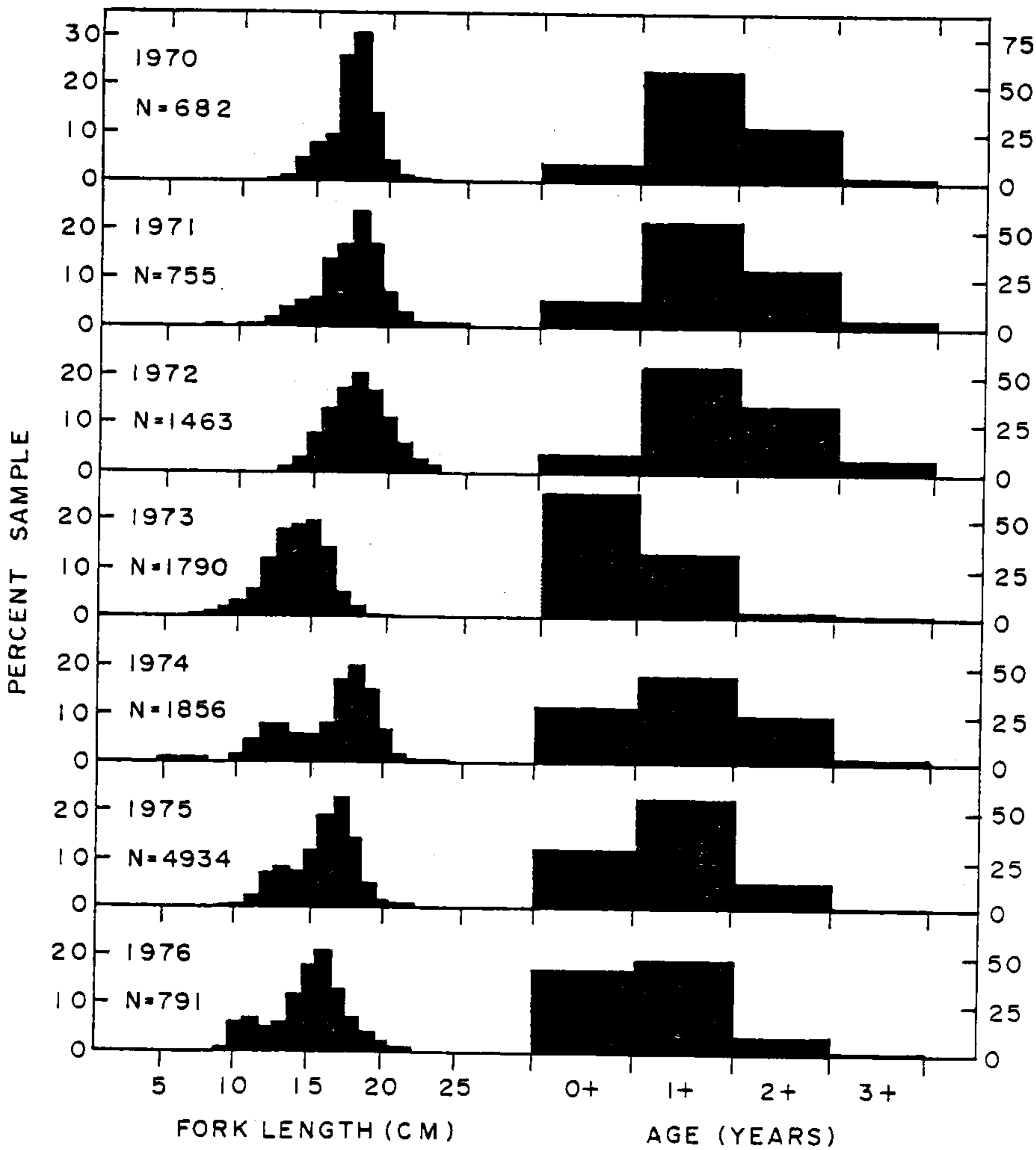

Figure 2. Length (fork length, cm) and age composition of Japanese commercial butterfish samples, January - March, 1970-1976.

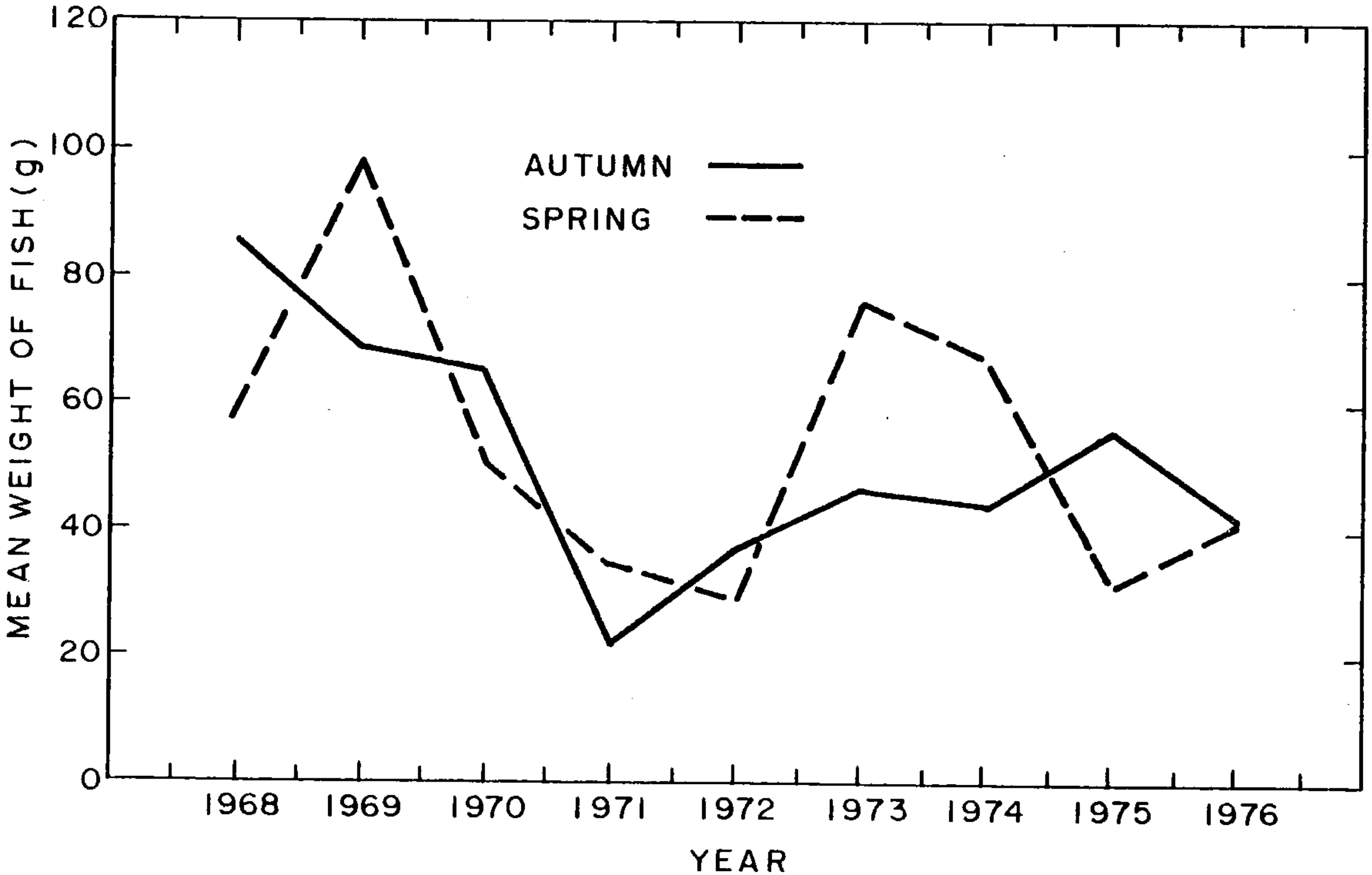

Fig. 3. Mean weight (g) of butterfish taken from Southern New England and Middle Atlantic waters, 27-366 m deep, during research vessel surveys, 1968-1976.

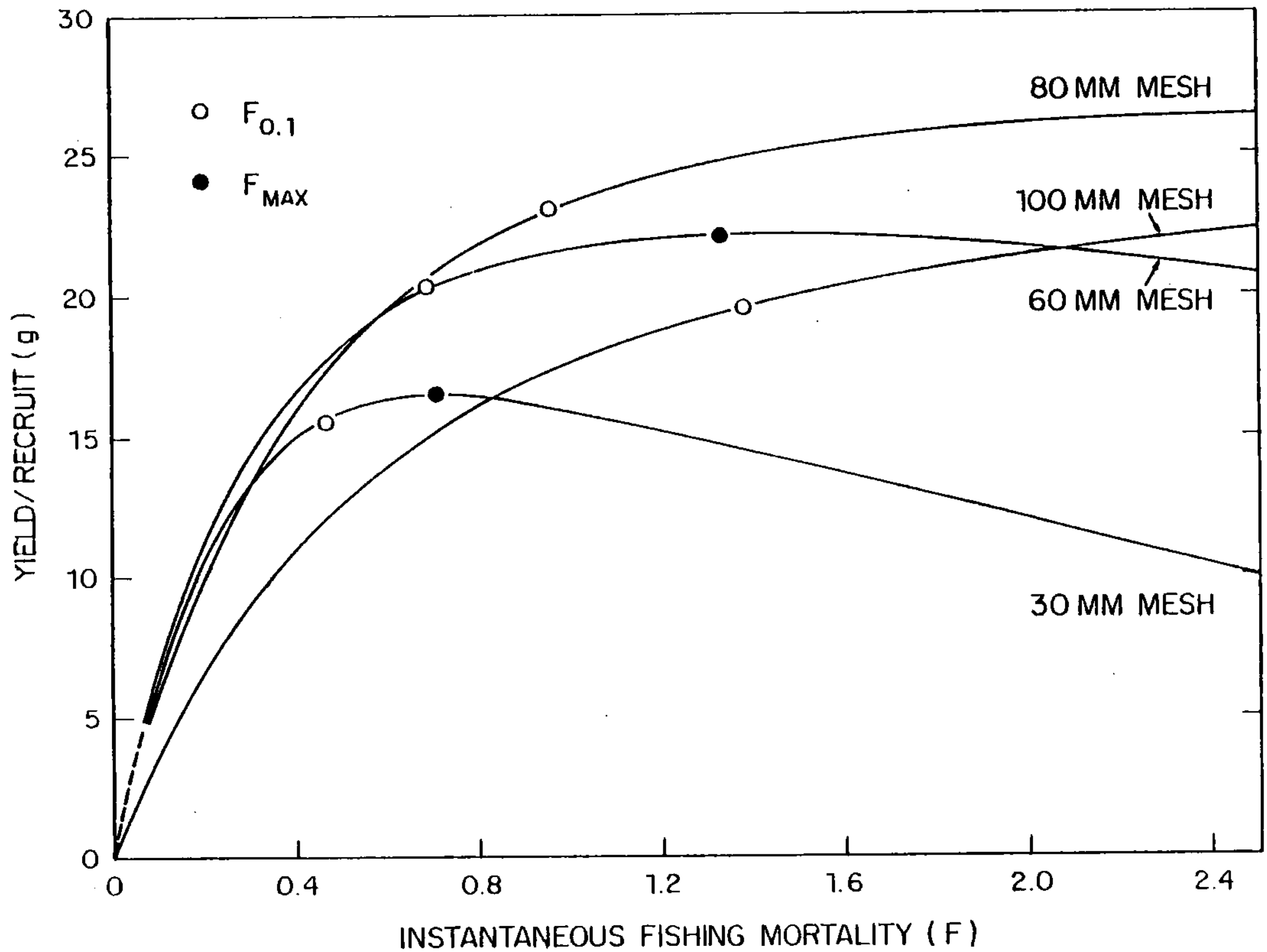

Fig. 4. Yield per recruit of butterfish with various mesh sizes, natural mortality (M) = 0.8.

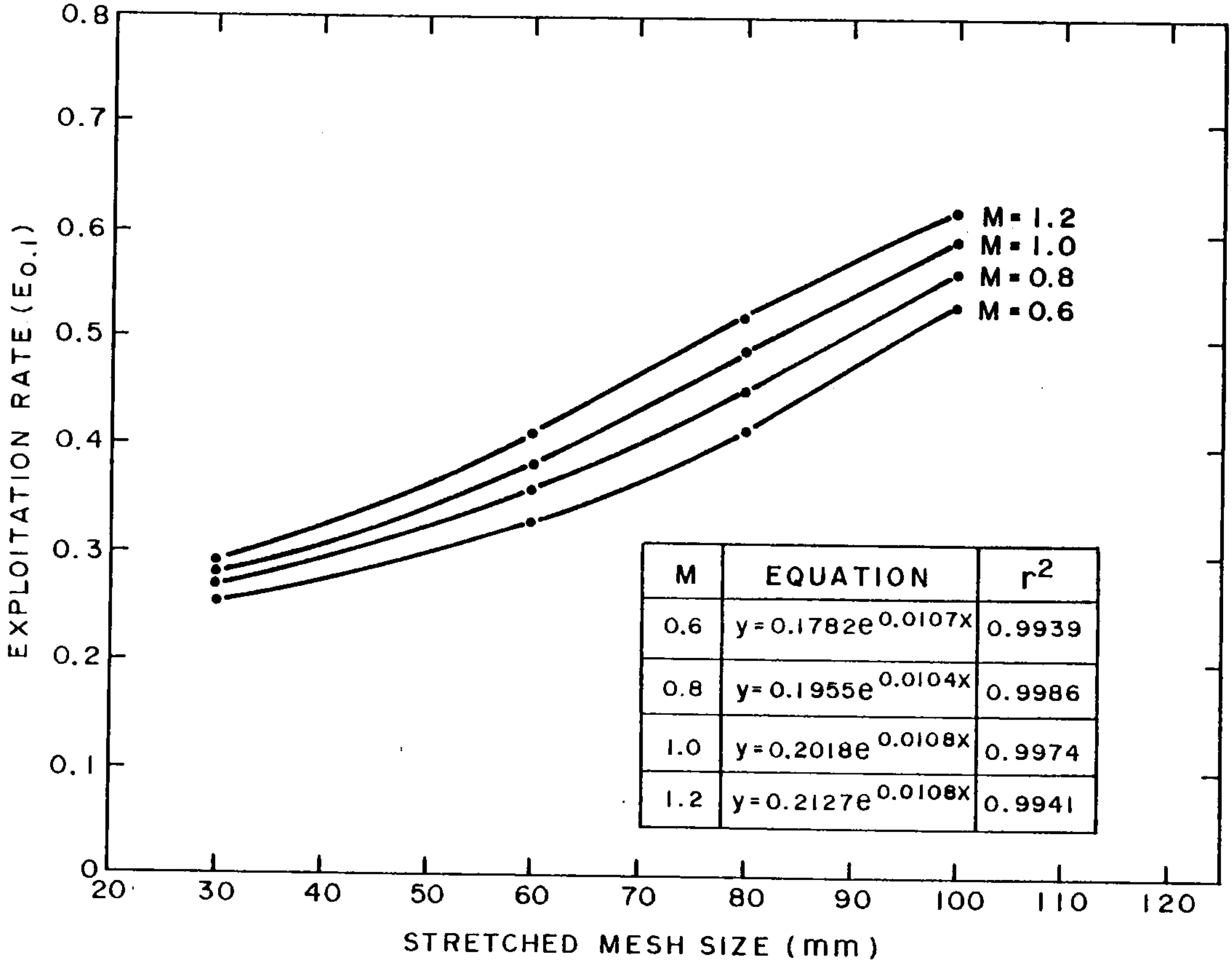

Fig. 5. Relations between stretched mesh size (mm) and exploitation rate ($E_{0.1}$) for several assumptions of the natural mortality rate (M). Coefficient of determination is r^2.

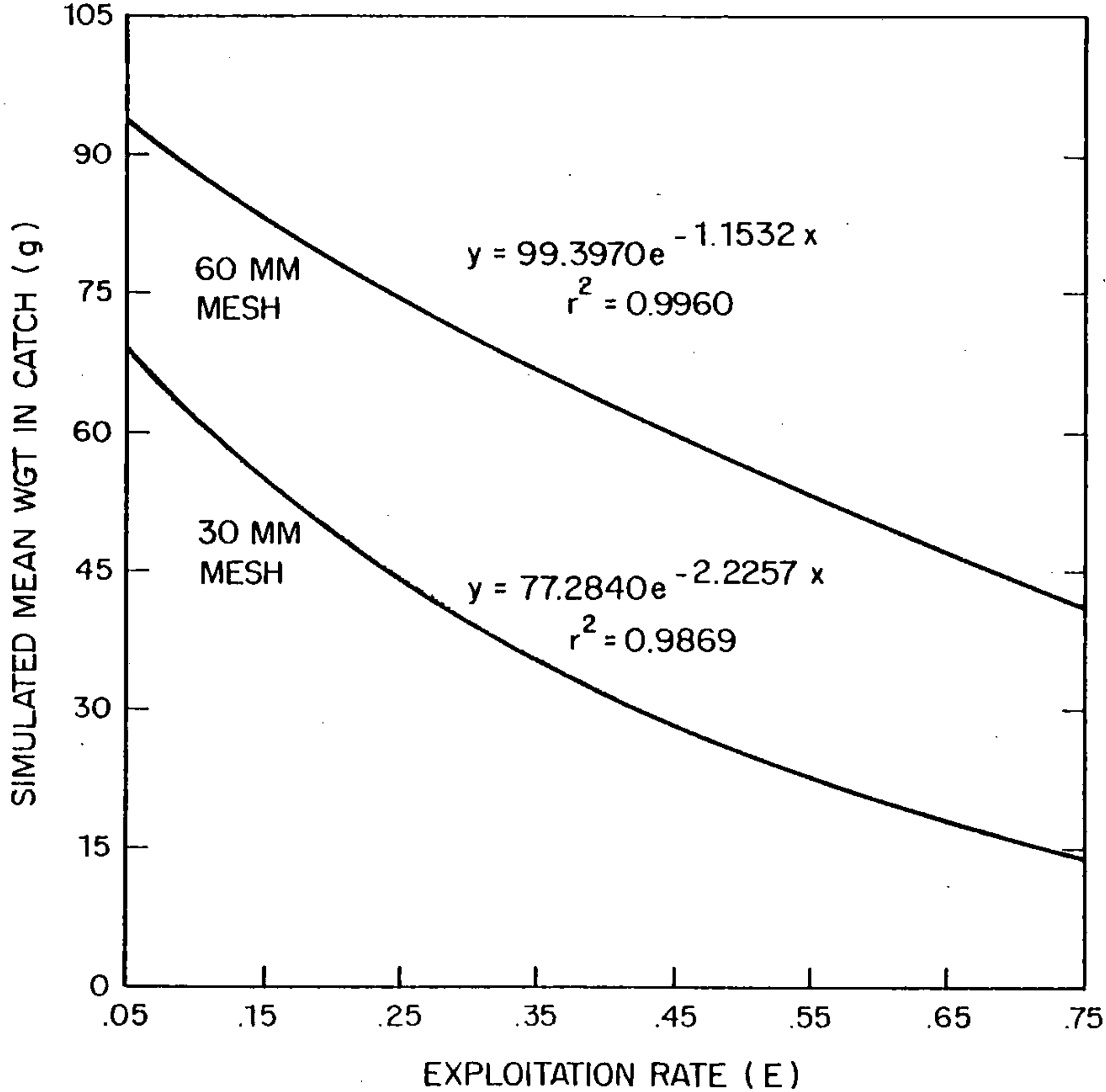

Fig. 6. Relations between exploitation rate and simulated mean weights of butterfish in commercial catches with 30 mm and 60 mm mesh nets. Coefficient of determination is r^2.