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YIELD AND RECRUITMENT SIMULATIONS FOR ATLANTIC HERRING

by

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INTRODUCTION

Atlantic herring (Clupea harengus) resources were regulated off the northeastern coast of the United States during 1972-75 under a catch quota-based management system by the International Commission for Northwest Atlantic Fisheries (ICNAF). Since 1978, herring within the Fishery Conservation Zone (3-200 miles) have been regulated under catch quotas prescribed under the Fishery Management Plan (FMP) for Atlantic Sea Herring.

Efficient management by this strategy requires definition of an optimum fishing mortality rate and relatively accurate estimates of stock size. Target fishing mortality (F) rates have typically been defined in terms of the level of F required to maximize yield per recruit (F_{max}) for or, more conservatively, as the fishing mortality rate at which marginal increases in yield equal 10% of that in the lightly exploited fishery ($F_{0.1}$; Gulland and Boerema 1973). The $F_{0.1}$ concept was designed to address, in part, recruitment overfishing and economic efficiency. Reliable yield-per-recruit estimates are therefore requisite for calculation of appropriate target levels of fishing mortality. Coupled with long term average expected recruitment, yield per recruit values at target F levels may provide estimates of average equilibrium yield.

An Ad Hoc Herring Assessment Working Group, comprised of representatives of New England state fisheries organization, New England Regional Fishery Management Council staff, and the National Marine Fisheries Service currently provides management advice on herring to the New England Fishery Management Council. The following analyses were undertaken at the request of the Working Group in order to identify the effects of (1) competing mortalities between juvenile and adult components of the fishery on yield per recruit and (2) effect of random recruitment on long term management strategies.

Yield Analyses

Equilibrium yield per recruit for Atlantic herring was evaluated by the method of Ricker (1958) for three exploitation patterns: (1) a combined juvenile and adult fishery (representing the historical fishing pattern), (2) a predominately offshore fishery on age groups 3 and older and (3) a predomately inshore fishery on ages 1-3. The Ricker method, an extremely flexible numerical integration of the yield curve allows utilization of vectors of weight-at-age and age specific natural and fishing mortality rates.

Partial recruitment factors for the combined fishery option were determined from geometric mean fishing mortality rates for the years 1965-76 derived by virtual population analysis of pooled Gulf of Maine, Nova Scotia and New Brunswick fisheries. The Georges Bank fishery, which collapsed in 1977 was not included in this analysis and catches of juveniles in the coastal fisheries were adjusted to account for the contribution of juveniles from the Georges Bank spawning stock (see Anthony et al. 1981 for complete description of the rationale and methods used in the adjustment). Partial recruitment factors utilized were 0.090, 1.00, 0.774, and 0.772 for ages 1-4; ages 5 and older were considered to be fully recruited.

To determine recruitment factors for the offshore fishery option, the ratio of catches of age 3 and 4 herring in the offshore fishery to the total catch of age 3 and 4 fish was used to adjust mortality rates derived in the pooled VPA discounted for Georges Bank. Recruitment factors used for the offshore fishery option were 0 for age groups 1 and 2, 0.329 and 0.639 for ages 3 and 4, and 1.00 for ages 5 and older. Recruitment factors for the juvenile fishery analysis were identical to those used for age 1-3 in the combined fishery option and mortality rates on ages 4 and older were set at zero.

The vector of mean weight at age values used in this analysis as determined from long term monitoring of the commercial catch were 15, 50, 120, 180, 220, 240, 275, 300, 315, 326, 334, 340, 344, 348 and 350 grams for ages 1-15 respectively.

Several studies suggest that the natural mortality rate (M) for herring increases with age. Convex catch curves were noted for herring populations for the Atlanto Scandian (Lea 1930), East Anglian (Hodgson 1932), southern North Sea (Jensen 1939) British Columbian (Tester 1955) and Gulf of Maine (Anthony 1972) stocks. It is difficult, however to separate the effects of natural mortality and immigration in these analyses (Anthony 1972). Prior assessments (before 1972) of herring stocks have been done with several levels of constant M and with M increasing with age; the rationale for using a constant M of 0.2 in recent assessments (since 1972) is provided in Schumacher and Anthony (1972).

Since the actual pattern of age specific natural mortality is unknown, three vectors of M were employed in an initial analysis of the combined fishery option. These were then compared with results obtained with an assumed constant natural mortality rate of M = 0.2. The natural mortality vectors employed are provided in Table 1.

These mortality vectors examine the effect of (a) M increasing for age groups 5 and older, (b) M increasing for ages 3 and older (c) an initial high level of M on age 1 and a subsequent increase in M for age groups 4 and older (d) a constant M (0.2). Anthony (1972) applied a constant M of 0.15 on ages 2-4 and increasing M on ages 5 and older and Schumacher and Anthony (1972) examined the effect on yield of natural mortality of 0.2, 0.3, and M increasing with age.

Yield per recruit was particularly sensitive to the natural mortality rates applied to younger age groups (Figure 1). Sharp reductions in yield per recruit were noted with higher M on age 1 fish and a subsequent increase in natural mortality on age groups 4 and older (option c). Application of increasing natural mortality rates on herring of ages 3 and older (option b) resulted in reduced yield per recruit only at lower levels of F (Figure 1). Increased natural mortality on age 5 and older fish provided increased yield per recruit over estimated values assuming constant M, reflecting the lower value of M placed on age groups 1-4 in the variable M analysis.

Variation in age specific natural mortality rates resulted in marked differences in $F_{0.1}$ levels, a result of considerable interest to management since annual total allowable catches may depend directly on specification of target levels of fishing mortality. Calculated $F_{0.1}$ values ranged from 0.24-0.36 with varying natural mortality vectors (Figure 1).

The assumption of constant natural mortality resulted in the lowest estimates of $F_{0.1}$ while application of increasing natural mortality on age 3 and older herring produced higher estimates of $F_{0.1}$. In the following analyses, both constant M and increasing M for age 5 and older herring were employed.

Yield per recruit as a function of fishing mortality on fully recruited ages ($F_{100\%}$) for the combined, offshore, and juvenile fishery options is given in Figures 2 and 3 for the variable and constant M cases respectively.

Clearly, the maintenance of a juvenile-only fishery would result in a substantial loss in potential yield per recruit (Figures 2 and 3); relatively high rates of $F_{0.1}$ are estimated for both the constant and variable M options.

An increase in yield per recruit would result from maintenance of an offshore-only fishery relative to a combined offshore and inshore fishery. The increase in yield per recruit is very small, however, over the range of $F_{0.1}$ (0.24-0.36) estimated in this document. Differences in yield per recruit between the offshore fishery only and combined fishery options at F=0.3 were only 6.4% and 7.1% for the constant M and variable M cases. Considering fishing mortality rates of 0.2 or less, for both natural mortality options yield per recruit is slightly increased when a juvenile fishery is operating in combination with the offshore fishery (Figures 2 and 3). Only at high levels of fishing mortality is the yield per recruit appreciably greater in an offshore-only fishery relative to the combined fishery option. In this situation, however, the probability of recruitment and stock declines increases.

Equilibrium Yield

Given estimates of long term mean recruitment, equilibrium yield corresponding to a target fishing mortality rate may be determined. Recruitment at age 1 derived from the pooled VPA discounted for Georges Bank ranged from 1.2×10^9 to 8.1×10^9 individuals during 1965-76; the geometric mean recruitment level during this period was 2.7×10^9 individuals. Equilibrium yields assuming target fishing mortality rates corresponding to $F_{0.1}$ levels for the constant and variable natural mortality options are provided in Table 2. Increased yields were noted for the variable M option. As expected, the offshore-only fishery option resulted in increased yield relative to the juvenile only and combined fishery options. Although higher yields and $F_{0.1}$ levels were predicted for the offshore fishery option relative to the combined fishery, it should be noted that spawning stock biomass is reduced at higher levels of fishing mortality.

Recruitment Simulations

The highly variable nature of recruitment in herring stocks necessitates a flexible short-term management strategy which may be adapted to the current status of the resource (Anthony 1972). Analysis of long term recruitment patterns may be useful in evaluating expectation of yield and stock size under varying levels of fishing mortality assuming environmental factors remain relatively constant.

Recruitment (age 3) estimates derived from the pooled VPA discounted for Georges Bank were used to determine parameters of a log-normal distribution function following Hennemuth et al. (1980). The estimated mean and variance of log-transformed recruitment values were used in conjunction with a random number generator to develop random recruitment estimates. Preliminary analysis provided no indication of autocorrelation in recruitment and therefore, independent random recruitment values were generated for each time inverval. Twenty year simulations of projected catch and stock size were replicated twenty times at three levels of applied fishing mortality: 0.25, 0.35, and 0.45 on fully recruited age groups (5+). Partial recruitment factors derived earlier were used in this analysis. A constant natural mortality rate of 0.20 was applied over all age groups. Initial stock size (age 4 and older) estimates for the base year 1981 were determined from the relationship $N_{i+1} = N_i (\exp(-Z_i))$. Catch (numbers at age) in 1981 were then determined from stock size at the start of 1981 according to Baranov's catch equation. Frequency distributions of projected yield (catch at age multiplied by a vector of mean weights) and stock size over the twenty time periods and twenty replicates were then constructed.

High levels of fishing mortality result in a marked decline in predicted stock size and stock levels are more tightly constrained about modal values (Figure 4). Modes in stock levels declined from 550,000 mt at an $F_{100\%}$ of .25 to 350,000 mt at an $F_{100\%}$ of 0.45 (Figure 4). A fishing mortality rate on fully recruited ages of 0.45 produced a projected modal yield of 160,000 mt; reduction in $F_{100\%}$ to 0.25 resulted in a modal yield of 140,000 mt (Figures 4 and 5).

The relative risk of reducing stock size to a specified level in any one year with increasing F may be evaluated by reference to Figure 6. For example, if a hypothetical minimum stock size constraint of 350,000 mt were established, the probability of driving the stock size down to this level or lower with an $F_{100\%}$ of 0.25 is 7.5%; this probability increases to 25.5% and 51.3% at $F_{100\%}$ levels of 0.35 and 0.45 respectively.

Examples of twenty year simulation runs for an F at full recruitment of 0.45 are provided in Figure 7. Although individual stochastic projections of this type do not provide predictions for any given year, they do illustrate the range of annual variability and long term average expectation of herring yield and stock size. It should be noted that for the catch and stock size projections presented in this analysis, it is implicitly assumed that the environmental or ecological variables which affect recruitment are
It should also be noted that initial projections of stock size and yield for each simulation run are sensitive to the chosen starting stock size conditions and the full effect of the variable recruitment function is not attained until the initial cohorts have effectively passed through the fishery.

Summary

Yield per recruit and $F_{0.1}$ levels determined for Atlantic herring were sensitive to natural mortality rates applied to younger age (1-5) groups due to the importance of younger age groups to standing stock biomass. Increasing natural mortality rates on age 3 and older herring resulted in reduced yield per recruit relative to that observed under assumptions of increasing M on ages 5 and older and a constant natural mortality rate of 0.2. Further reductions in yield per recruit were noted with an assumed natural mortality rate of 0.25 placed on age 1 herring, a decrease in M on ages 2 or 3 to 0.2, and a subsequent increase in M on ages 4 and older (Figure 1).

Variation in natural mortality vectors also resulted in marked differences in $F_{0.1}$ levels, ranging from 0.24 for the constant M option to 0.36 for M increasing on age groups 3 and older. There is evidence that natural mortality rates for Atlantic herring increase with age (Anthony 1972) although actual age-specific natural mortality rates are difficult to determine. Due to this difficulty, constant natural mortality has been assumed in previous assessments (however, see Anthony 1972 and Schumacher and Anthony 1972 for comparisons of constant M and variable M options). For the purposes of the present analysis two options, constant M and M increasing on age groups 5 and older are considered in further comparisons between juvenile, offshore and combined fishery options. Maintenance of a juvenile only fishery results in a loss in yield per recruit. At levels of F between 0.2 and 0.4 for fully recruited individuals, little loss in potential yield per recruit accrues with application of fishing mortality on juvenile herring.

Simulations of yield and stock size for Atlantic herring assuming random recruitment indicated declines in stock size with increasing fishing mortality.

Although increasing levels of $F_{100\%}$ from 0.25 to 0.45 increase yield 7%-14% the accompanying decline in stock size 18%-36% indicate that reduced levels of F should be considered.

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Table 1. Age specific natural mortality vectors used in yield-per-recruit analyses.

	AGE													
Option	1	2	3	4	5	6	7	8	9	10	11	12	13	14
a	.15	.15	.15	.15	.20	.25	.30	.35	.40	.45	.50	.55	.60	.65
b	.15	.15	.20	.25	.30	.35	.40	.45	.50	.55	.60	.65	.70	.75
c	.25	.20	.20	.25	.30	.35	.40	.45	.50	.55	.60	.65	.70	.75
d	.20	.20	.20	.20	.20	.20	.20	.20	.20	.20	.20	.20	.20	.20

Table 2. Equilibrium yield (10^3 MT) for juvenile, offshore and combined fishery options assuming constant natural mortality and variable M assuming geometric mean recruitment during 1965-76.

	Juvenile		Offshore		Combined	
	Constant M	Variable M	Constant M	Variable M	Constant M	Variable M
	0.85	0.99	0.36	0.46	0.24	0.29
Yield	131.00	148.00	213.00	262.00	183.00	209.00

a) assuming geometric mean recruitment during 1965-76
b) deleting extremes in recruitment

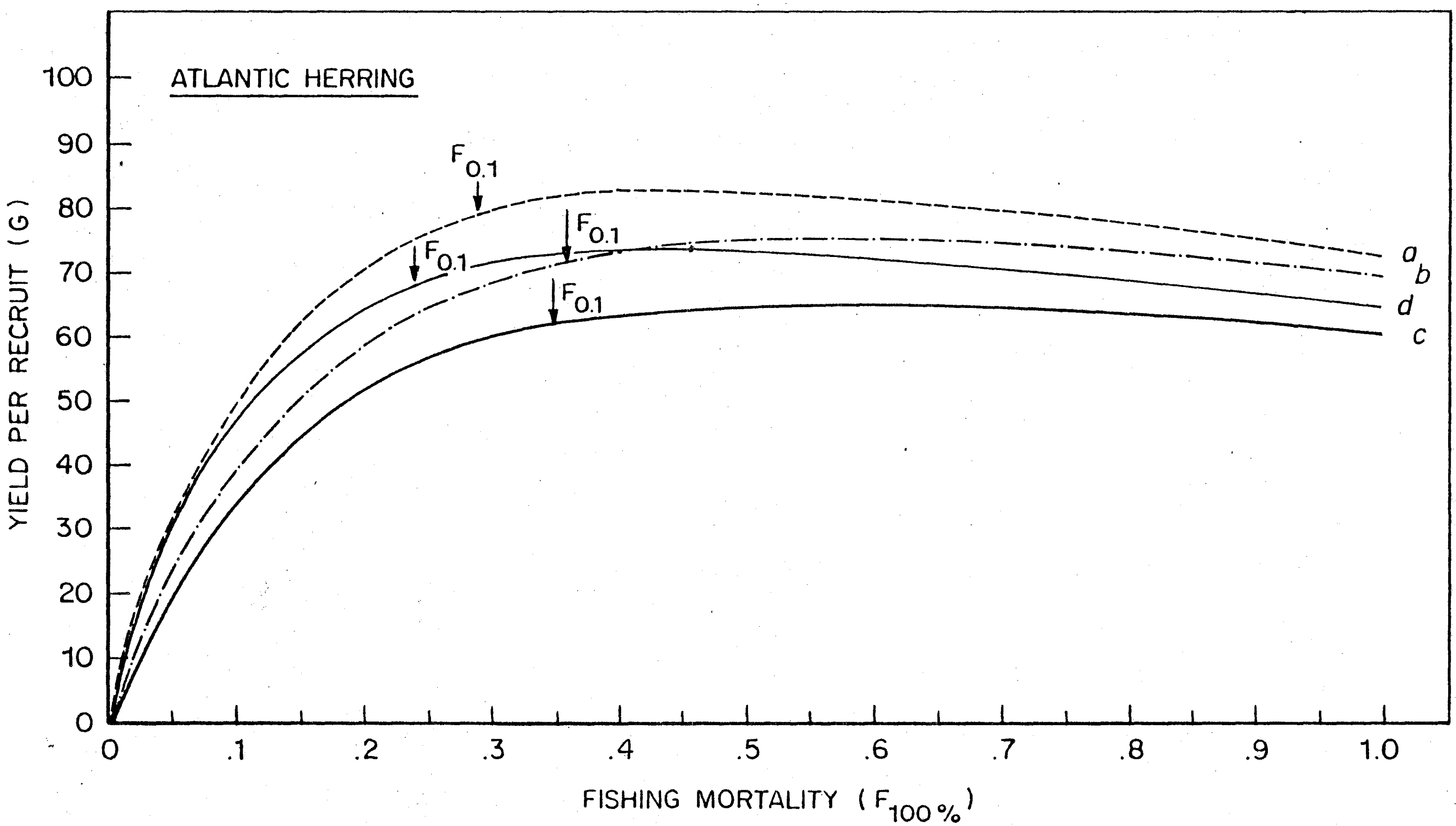

Figure 1. Yield per recruit as a function of fishing mortality of Atlantic herring for four options of natural mortality.

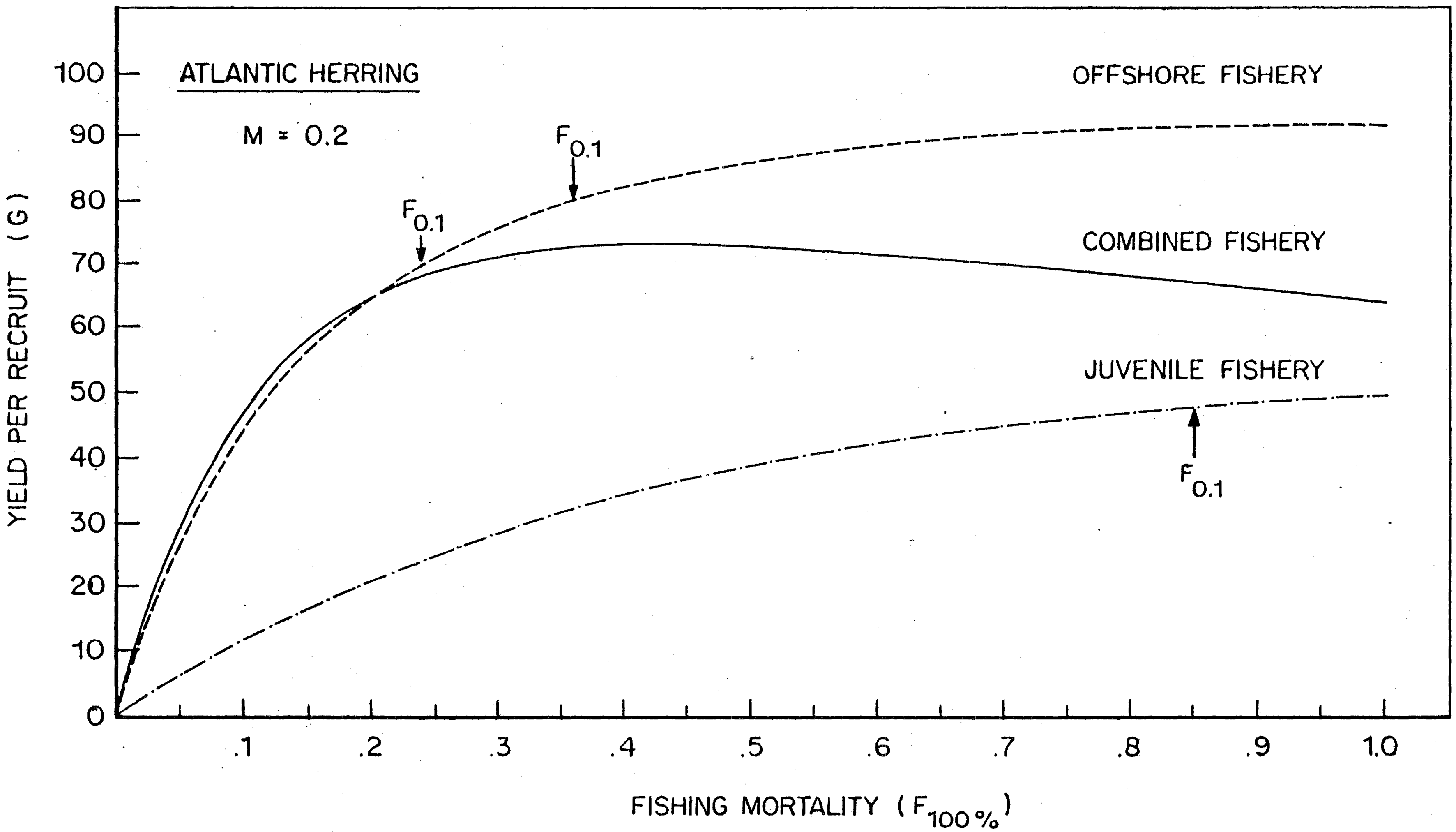

Figure 2. Yield per recruit as a function of fishing mortality of Atlantic herring by fishery with natural mortality constant over ages.

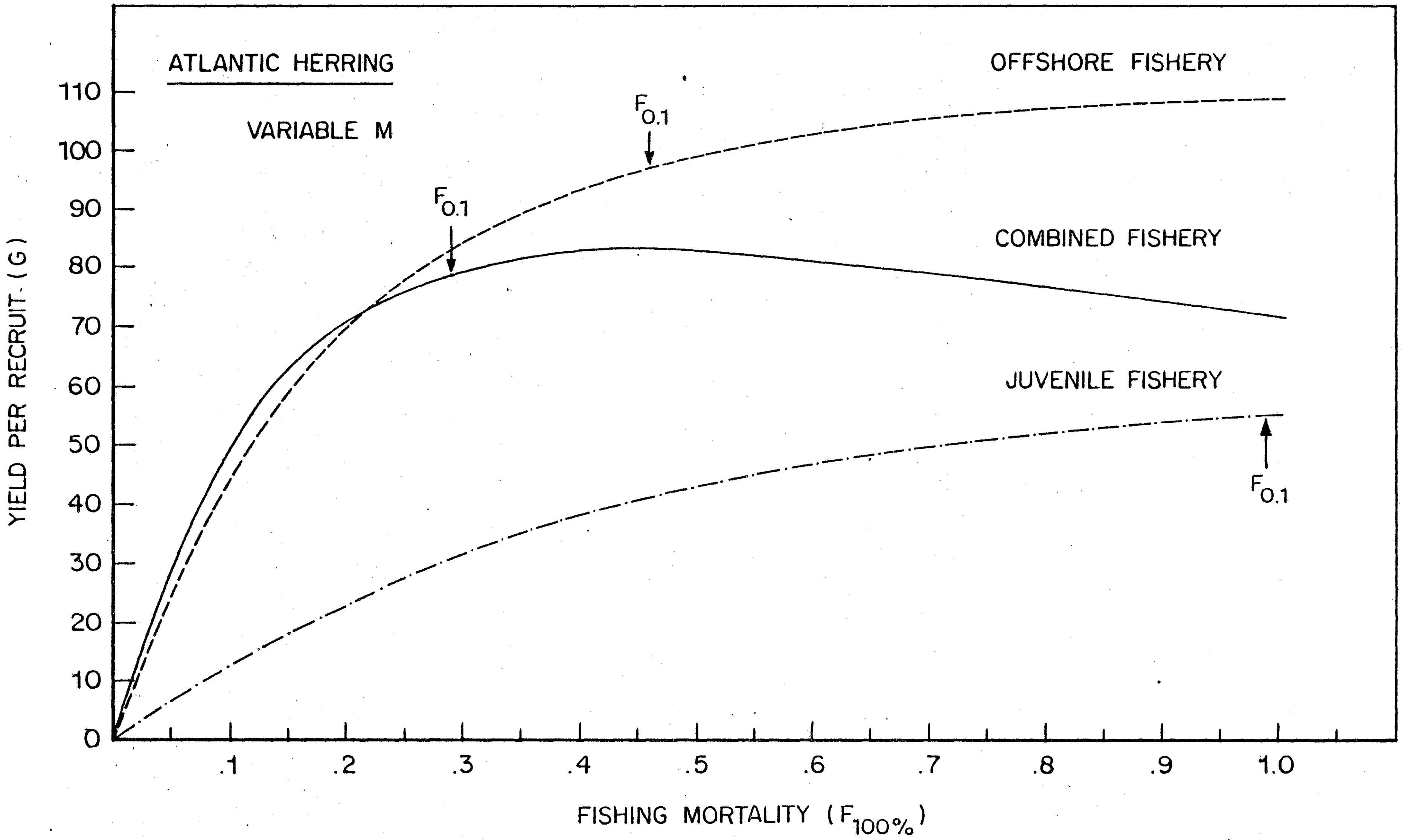

Figure 3. Yield per recruit as a function of fishing mortality of Atlantic herring with natural mortality variable over ages.

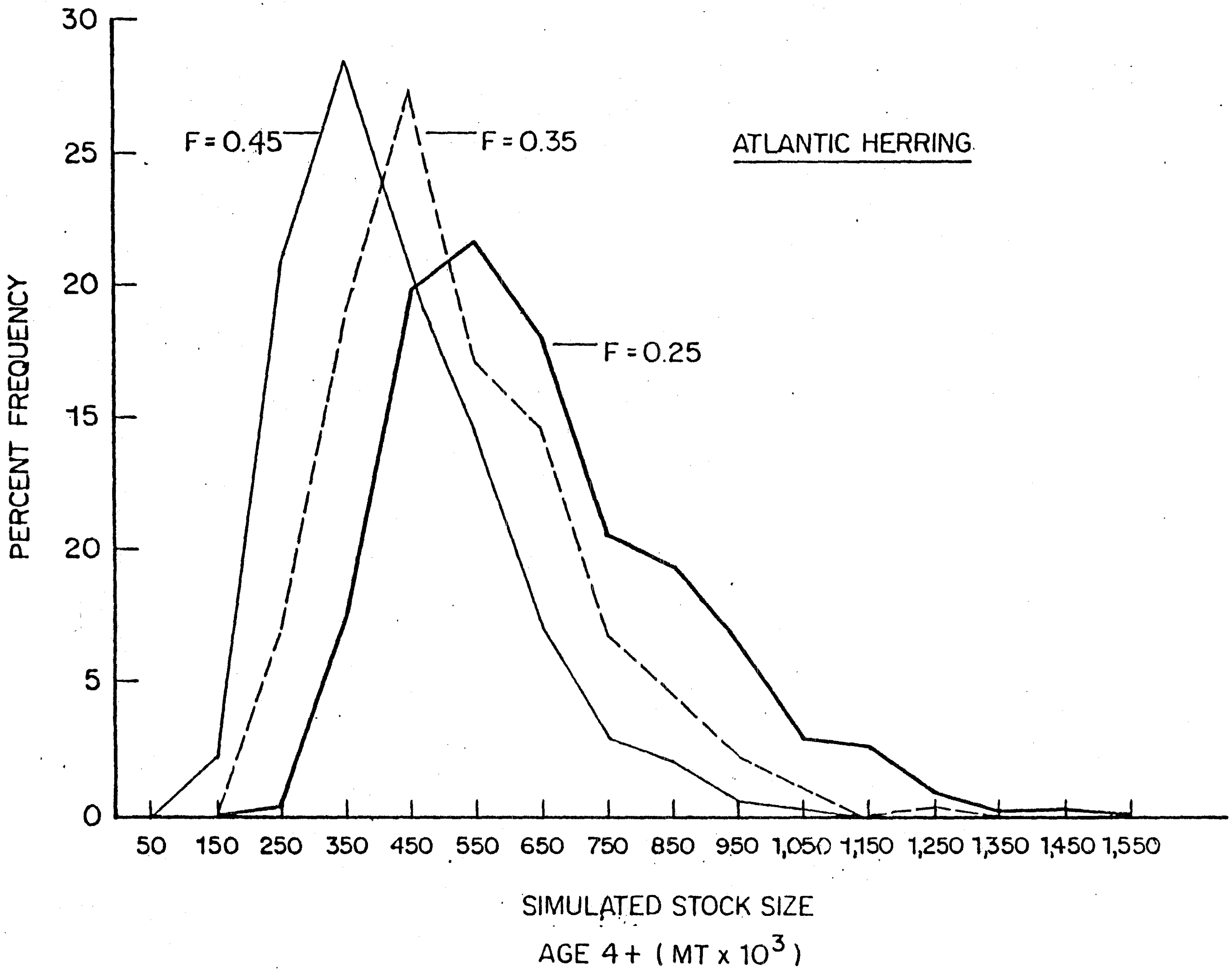

Figure 4. Simulated stock size under three levels of fishing mortality and assuming an empirically derived log-normal recruitment function.

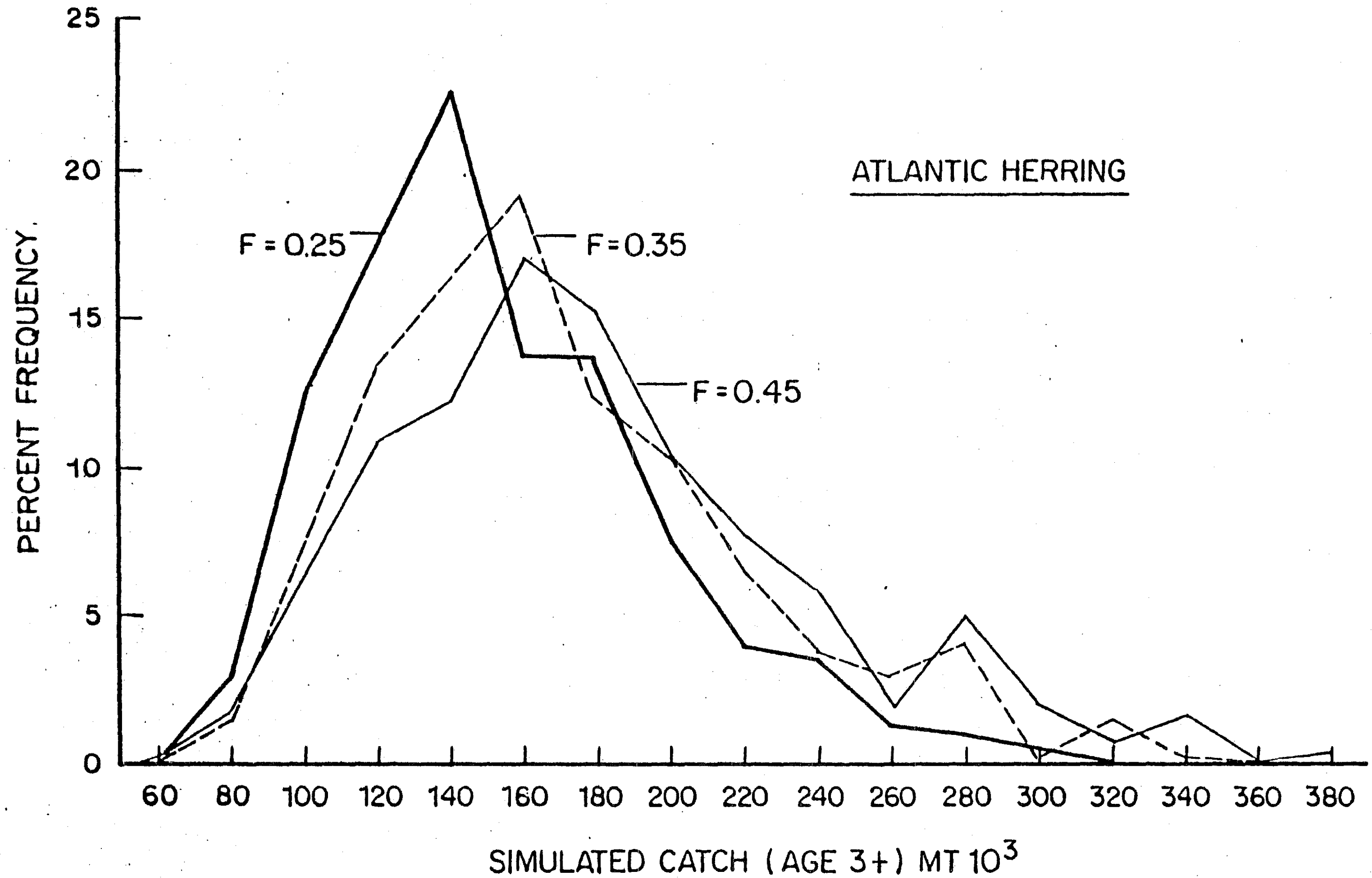

Figure 5. Simulated catch rates under three levels of fishing mortality and and empirically derived log-normal recruitment function.

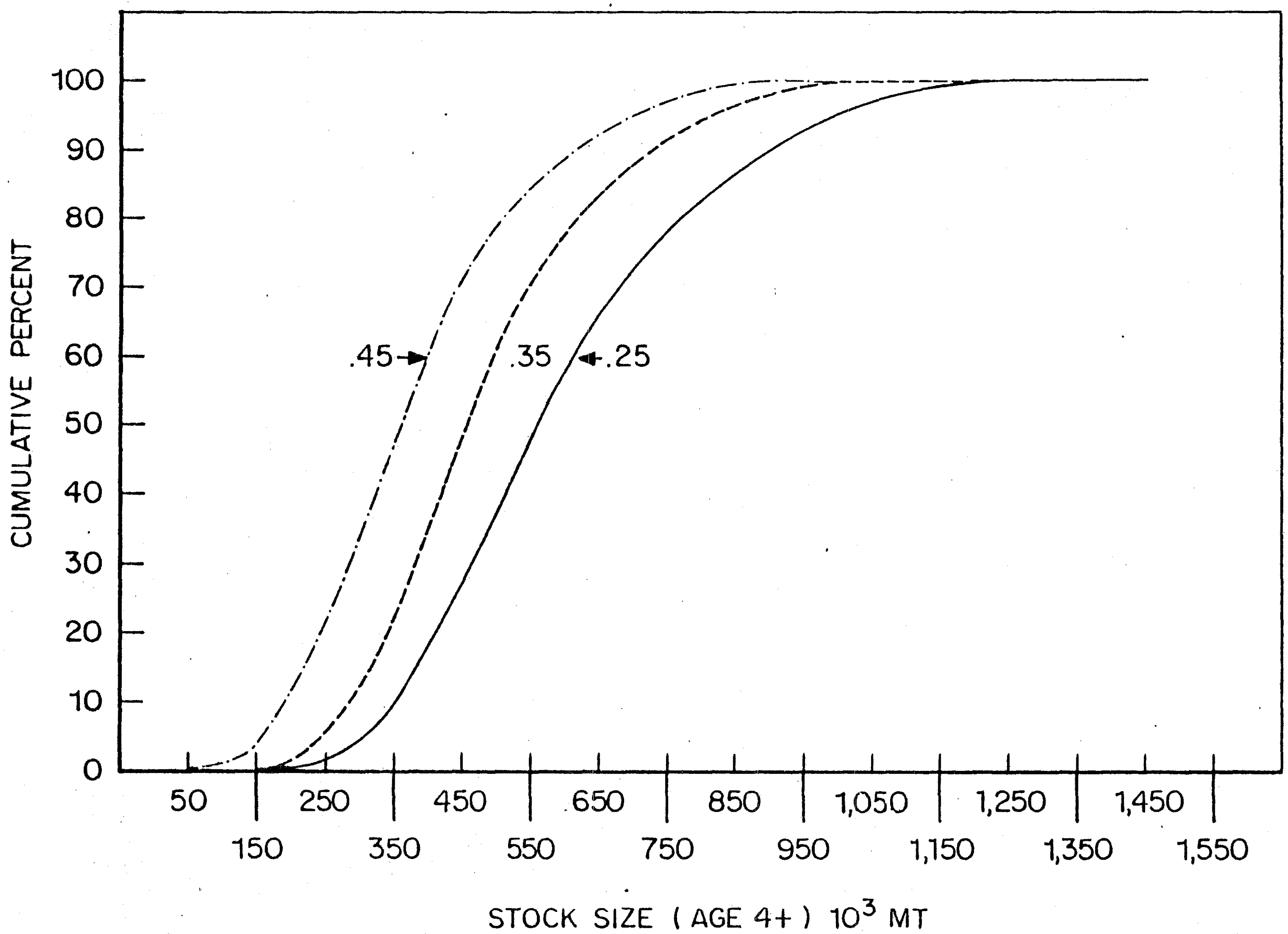

Figure 6. Cumulative percent probability of stock reduction below specific stock size under three levels of fishing mortality.

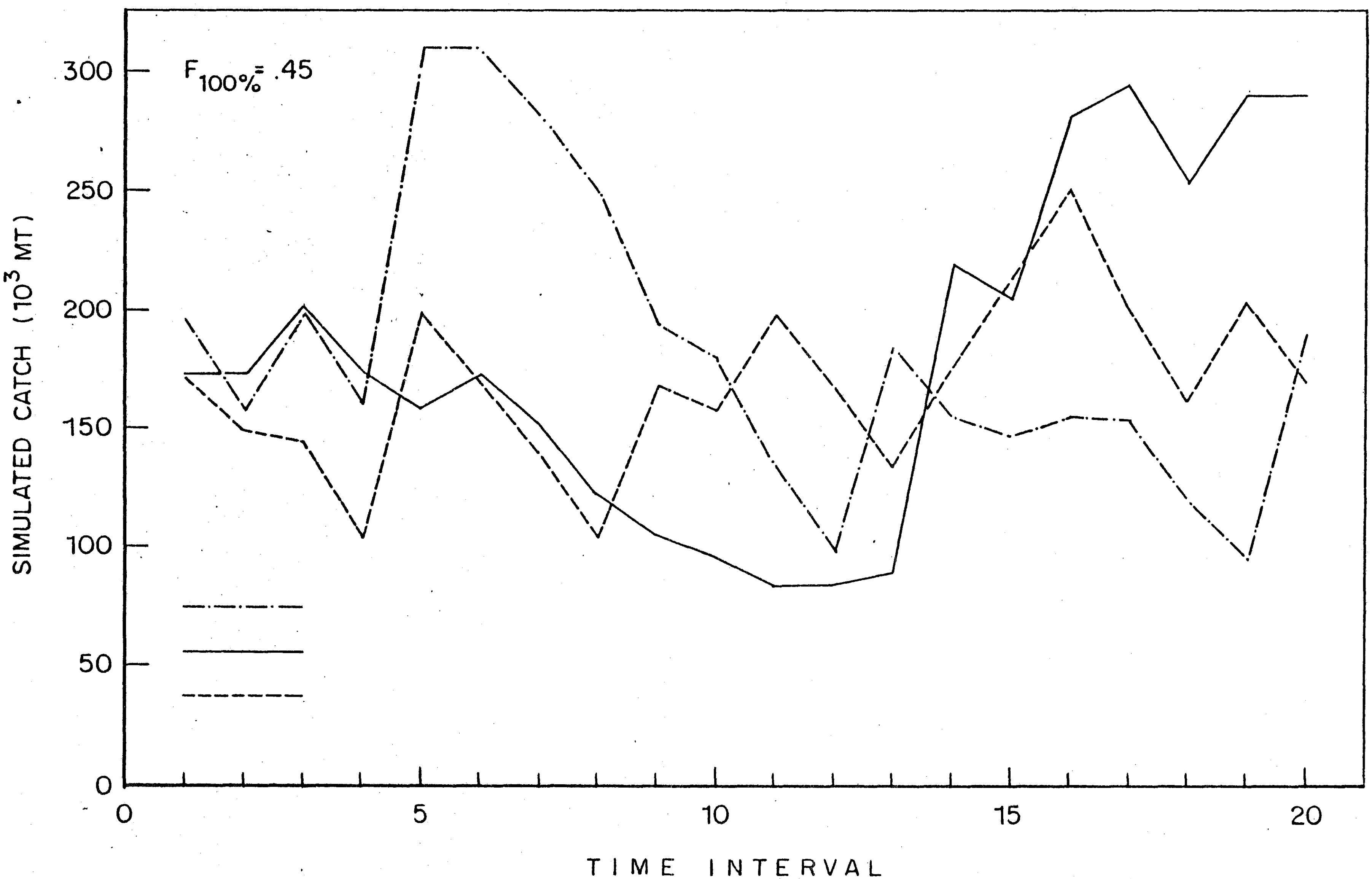

Figure 7. Twenty year catch simulations for Atlantic herring for three randomly selected recruitment patterns and constant fishing mortality at 100% selection.