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Effect of Size Selection Within and Between Fishing Gear Types of the Yield and Spawning Stock Biomass Per Recruit and Catch Per Unit Effect for A Cohort of an Idealized Groundfish

by

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ABSTRACT

A discrete time model was developed to evaluate yield and spawning stock biomass per recruit and catch per unit effort for a cohort of an idealized groundfish. The size selection characteristics of trawls and hooks were described with a logistic distribution function with a range of L_{50}s and steepnesses; and the size selection characteristics of gillnets and traps were described with a normal distribution function with a range of L_{opt}s and standard deviations.

Analysis of isopleth diagrams for yield and spawning stock biomass per 1000 recruits for both types of selection functions indicate that yield is maximized for both types of selection functions when harvesting is concentrated on a fish length slightly larger than that at which biomass for the cohort of the unfished population is maximized, and at fishing mortality levels of 2 and greater. Spawning stock biomass under these harvesting conditions is between 24 and 36 percent of the unfished condition. The steepness of the logistic distribution function as related differences in trawl codend mesh shape or hook style does not affect the cohort yield, but significantly affects the spawning stock biomass, at a specified level of fishing mortality and L_{50}. The standard deviation of the normal distribution

selection function as related to differences in gillnet and trap design also does not affect the cohort yield, but significantly affects the spawning stock biomass at a specified level of fishing mortality and L_{opt}. Thus, the sharper the selection process, the greater the spawning stock biomass available for production of future cohorts.

In contrast, catch per unit effort is maximized at fishing mortality values of less than 1.0, when the age at entry or length of susceptability to fishing gear is set at the age or length of maximum biomass for the unfished cohort.

These conflicting results present a dilemma for the fishery resource manager: maximize cohort yield at a substantially reduced catch per unit effort or maximize catch per unit effort at a reduced yield.

INTRODUCTION

Statement of the Problem and Objective

In the last three decades, considerable progress has been made defining the selection characteristic of various fish harvesting gears. Fishery managers and fishing gear technologists have investigated the subtle characteristics of species-specific, size selection as a function of mesh size and shape in trawls, mesh size and hanging ratio in gill nets, hook size and style in longlines, and mesh size and funnel opening size in traps, so as to provide improved management of fishery stocks harvested with these gear types. In contrast, models of yield and spawning stock biomass per recruit used in the analysis of fish population dynamics have assumed knife-edge selection at the length or age of recruitment to the fishery. Given the detailed understanding of size selection in the harvesting technology, the purpose of the research reported in the sequel was to integrate gear-specific, size selection into a yield and spawning stock biomass per recruit model. The specific objectives were to investigate the question: Is there a preferred gear type that uniquely provides the maximum biological yield and spawning stock biomass per recruit and, maximum catch per unit effort based on an *inherent* pattern of age-specific fishing mortality?

Literature Review

Yield per recruit models are useful to fishery resource managers for predicting the effects of alterations in harvesting activity on the yield available from a given year-class or cohort (Gulland, 1983). Two parameters that define the model and are easily regulated by resource managers are: fishing mortality (F) and the pattern of harvesting activity on different sizes of fish. Traditionally, this has been simplified to the age of first entry to the fishery. Knife edge selection (100% vulnerability at age of first capture) has been assumed so that the Beverton-Holt analytical solution to the yield equation could be applied (Beverton and Holt, 1957; Gulland, 1969 and 1983; Pauley, 1984; Ricker, 1975; Saila et al. 1988; Sparre et al., 1989). While this assumption may be appropriate for size selection according to a logistic distribution function, as is found in a trawl codend, the Beverton-Holt yield equation does not incorporate recent advances in the detailed understanding of size selection processes of the principal gear types used on groundfish (trawls, traps, gillnets, and longlines).

The study of size selection characteristics of fish harvesting gear began in the early 1900's with an application toward fishery management (Baranov, 1918 in Baranov, 1976). In the late 1950's, the International Commission for the Northwest Atlantic Fisheries (ICNAF) co-sponsored a special scientific meeting on the selectivity of fishing gear (Anonymous, 1963), and research summarized in the proceedings of that meeting were the basis for three decades of progress. The size selectivity of all fish harvesting gear can be broadly classified into two types of probability distributions (Clark, 1960; Holt, 1963; Pope et al., 1975:

1. A sigmoid-shaped curve describes a probability distribution increasing from 0 to 1 with increasing fish size. This curve can be represented by a logistic probability distribution function. The selection characteristics of this curve are, that all fish smaller than a particular size are not captured (P = 0), that all fish larger than a particular size are captured (P = 1); and that fish of a certain size (L_{50}) have a 50 percent probability of capture (P = 0.5) if encountering the gear.

2. A dome shaped curve describes the probability distribution increasing from 0 to 1, then decreasing to 0 again, with increasing fish size. This curve can be represented by a normal probability distribution function. The characteristics of this curve are that all fish smaller than a particular size (L_1) and larger than another particular (L_2) are not captured, and that fish of a certain size (L_{opt}) between L_1 and L_2 have a 100 percent probability (P = 1.0) of capture if encountering the gear.

Groundfish size selection by a trawl codend follows a logistic probability distribution function. Early work by Clark (1963) established sigmoid-shaped selection curves for groundfish species in the Northwest Atlantic. In the 1970's and 1980's additional research provided species and mesh size specific selection curves (Smolowitz, 1983). In the late 1980's and 1990's, recent work has attempted to further define codend selectivity as a function of mesh shape, square versus diamond, and relate that to codend escape survival (DeAlteris & Reifsteck, 1993). For groundfish selection by trawl codends, the following generalizations are supported by the literature: (1) larger meshes retain larger fish, shifting the selection curve to the right; (2) square mesh shape codends provide a steeper selection curve, that is shifted slightly to the right, as compared to a codend of similar mesh size, but diamond mesh shape.

Groundfish size selection by a gillnet follows a normal probability distribution function (Hamley, 1975). Early work by Regier and Robson (1966) established an experimental methodology to define the parameters of a normal distribution used to define the selection character of the gillnet. Later work by Borgstrom (1989), and Hamley and Regier (1973) further defined the application of the normal distribution function to gillnet selection. More recently, Lazar and DeAlteris (1993), presenting the results of an analysis of gillnet selection in Gulf of Maine groundfish fishery, used a truncated two-term gram Charlier series model to define in greater detail the shape of the selection curve.

Groundfish size selection by a longline with hooks has been documented to follow a sigmoid shaped curve (McCraken, 1963 and Saetersdal, 1963). However, more recent work on hook selectivity is equivocal. Ralston (1982) investigating the Hawaiian deep-sea handline fishery concluded that a sigmoid-shaped curve most accurately described the selective properties of the gear in that fishery. Similar results were reported by Bertrand (1988) in his analysis of hook selectivity in the handline fishery of the Saya de Malha Banks (Indian Ocean). In contrast, Ralston (1988) investigating the size selection of snappers by hook and line gear concluded that neither model in its simplest form depicted hook selectivity in this situation. Similarly, Otway and Craig (1993) studied the effects of hook size in catches of undersize snapper and also determined that neither normal or logistic curves were directly applicable.

Groundfish size selection by traps has not been investigated previously, so it must be inferred from the few trap selectivity experiments conducted in other fisheries. Stevenson and Stuart-Sharkey (1980) tested the effect of three different mesh sizes and found that increasing the mesh size led to a significant reduction in the number of smaller fish caught. Ward (1988) reporting on the results of mesh size experiments in the Bermuda trap fisheries, developed selection curves for the dominant species, with a sigmoid-shape. However, as noted by Ward, the traps had very large funnel openings relative to fish size in the population and therefore there was nothing to prevent the entrance of the largest fish in the population. Bohnsack et al. (1989) investigated the effect of fish trap mesh size on reef fish off southeastern Florida, and also found that larger meshes retained less small fish. It is clear that the mesh covering a trap will effect the retention of the smaller fish that enter the trap. If there is no restriction to the entry of the larger fish in the population into the trap, then the selection curve will be sigmoidal shaped. However, the traps with the highest catch efficiency will have smaller openings in the funnels so as to minimize the exit of captured fish, that would otherwise be retained by the mesh size. Therefore these traps would have a dome-shaped selection curve.

METHODS

A discrete time model was developed using a LOTUS spreadsheet. To minimize errors associated with the model, the time step was set at 0.1 years, over the range of 0 to 30 years.

The length of the fish (L) at age (t) was calculated using a simplified von Bertlanffy growth equation:

$$L_t = L_{max} (1-e^{Kt}) \tag{1}$$

where, L_{max} = maximum length

K = instantaneous growth rate.

The weight of the fish (W) at age (t) was determined using a length-weight relationship:

$$W_t = a L_t^{\ b} \tag{2}$$

where, a = L-W conversion coefficient

b = L-W growth factor

The percent maturity (P_t) of individuals in the cohort at age was expressed using a logistic function:

$$P_t = (1+e^{(-\alpha 1 \ * \ (t-\beta 1))})^{-1}$$

where, $\alpha 1$ = steepness of the curve (3)

$\beta 1$ = age at 50% maturity

The numbers of individuals (N_t) remaining in the fished cohort at age (t) was determined using an instantaneous exponential decay function incremented at the time step of 0.1 years:

$$N = N_{(t-1)} * e^{-0.1M}$$

where, M = instantaneous natural mortality

The biomass (B_t) of the individuals in the unfished cohort at age (t) was calculated using:

$$B_t = N_t * W_t \qquad (5)$$

and the spawning stock biomass (SSB_t) of the individuals in the cohort at age (t) was determined using:

$$SSB_t = P_t * B_t \qquad (6)$$

Based on the previously reviewed gear selection literature, trawls and hooks were determined to possess similar size selection characteristics and that these could be represented with a logistic probability distribution as a function of the length of an individual fish (PL_L):

$$PL_{(t,L)} = (1+e^{(-\ \alpha 2 \ * \ (L-\ L_{50}))})^{-1} \qquad (7)$$

where, $\alpha 2$ = steepness of the curve

L_{50} = length at 50% selection.

Gillnets and traps were determined to possess similar size selection characteristics and these could be represented with a normal probability distribution as a function of the length of an individual fish (PN_L):

$$PN_{(t,L)} = e^{-(L_t - L_{opt})^2 / (2 * SD^2)} \qquad (8)$$

where, SD = standard deviation

L_{opt} = length of optimum selection.

Applying length specific susceptibility to fishing (PN_L or PL_L) at a specified level of fishing mortality (F) and including naturality mortality (M), the number of individuals remaining in the fished cohort (NF_t) at each time step (t) was calculated:

$$NF_t = NF_{(t-1)} * e^{-((PN_L \text{ or } PL_L)(F) + M)(0.1)} \qquad (9)$$

Thus, the yield of the fished cohort (Y_t) from each time-step was:

$$Y_t = (PN_L \text{ or } Pl_1 \ (F)/((PN_L \text{ or } PL_L)(F) + M) * (NF_{(t-1)} - NF_t) * (W_t) \qquad (10)$$

and the spawning stock biomass of the fished cohort (SSB_t) at each time step is simply:

$$SSB_t = (NF_t) * (W_t) * (P_t) \qquad (11)$$

Based on these equations, and specification of L max, K, a, b, $\alpha 1$, $\beta 1$, and M , the total biomass and spawning stock biomass of the unfished cohort were determined, and with the specification of fishing conditions of F, $\alpha 2$, L_{50}, SD and L_{opt}, the total yield of spawning stock biomass of the fished cohort were determined. By evaluating a wide range of L_{50}, L_{opt} and F values, the resulting matrix of data was contoured to produce isopleth diagrams of yield spawning stock biomass per recruit.

The effect of the shape of the distribution function on the size selection, and the resulting yield and spawning stock biomass value was evaluated by specifying a range of steepness and standard deviations for the logistic and normal distribution curves while holding other factors constant.

An estimate of catch per unit effort was determined for a specified L_{opt}/L_{50} by dividing the yield produced by a certain level of fishing mortality by the value of fishing mortality.

The model was checked for accuracy by comparing the results of the yield calculation from this LOTUS program to the result of the analytical solution of the Beverton-Holt yield equations that assumes knife edge selection at a specific age of recruitment to the fishery (Saila et al., 1988). Identical specifications were input to each model, except that for this LOTUS model, the steepness of the logistic distribution selection curve was set so as to approximate knife-edge selection. Yield per recruit was determined for increasing whole unit values of F from 0 to 7. The resulting curves of yield versus fishing mortality were identical in shape but offset by less than 4 percent. This error is attributed to the difference between the analytical solution to the equation (the higher values) and the discrete time model (the lower values). As the time-step was decreased from 1.0 to 0.1 years in the model development, the error diminished considerably.

RESULTS

The specifications for the idealized groundfish used in this analysis were: L max = 100 cm, K = 0.1, a = 0.00001, b = 3, $\alpha 1 = 1$, $\beta 1 = 3$, and M = 0.2.

Based on these values, the characteristics of the individuals and the cohort of idealized groundfish are shown in Figures 1 and 2. An individual idealized groundfish reaches an assympotic maximum length and weight of 100 cm and 10kg, respectively. Maturation occurs rapidly, with 50 percent of the cohort mature at an age of 3 years and a length of 45 cm. The number of individuals in the cohort reduce to 5 percent of the initial condition by an age of 16, although the model is extended to an age of 30 years and a single fish remaining. Biomass of the cohort peaks at an age of 6.3 years and an individual fish length of 75 cm. Total biomass of the unfished cohort over it's lifetime expressed as the sum of the average annual biomass was 12,378 kg. The total spawning stock biomass of the unfished cohort was 11,758 kg.

The logistic and normal probability distribution functions for size selection are shown in Figures 3A and 3B, respectively. The L_{50}s for logistic function range from 50 to 100 cm, and a representative steepness of 0.33 was specified. The L_{opt}s for the normal function range from 50 to 100 cm and a representative standard deviation of 5 was specified.

The program was run for a range of fishing mortality values from 0.5 to 7.0 at 0.5 intervals, calculating yield and spawning stock biomass values for both types of selection functions, at the six L_{50} and L_{opt} values. The resulting isopleth diagrams for yield and spawning stock biomass are shown in Figures 4 and 5 for size selection by the logistic distribution function and the normal distribution function, respectively.

Evaluating the isopleth diagrams for the logistic distribution function, it is clear that maximum yield will be realized at a L_{50} of 80 cm and at fishing mortalities of 3.0 and greater. Operating the fishery in this range will provide a spawning stock biomass of 35 percent at F = 3.0, decreasing to 30 percent at F = 7.0.

Evaluating the isopleth diagrams of the normal distribution function, it is clear that again maximum yield will be realized at a L_{opt} of 80 cm and at fishing mortalities of 2.0 and greater. Operating the fishery in this range will provide a spawning stock biomass of 30 percent at F = 2.0, decreasing to 24 percent at F = 7.0.

The effect of the shape of the selection curve on the yield and spawning stock biomass was evaluated at a L_{50}/L_{opt} of 80 cm and a F value of 3.0. Steepness values ranging from 0.13 to 2.00 were specified for the logistic distribution function (Figure 6). The steepness of the selection curve had virtually no effect on the yield per recruit, but clearly affected the spawning stock biomass per recruit. Lower values for the steepness value resulted in a 50 percent reduction of the spawning stock biomass per recruit. Standard deviation values ranging from 2 to 10 were specified for the normal distribution function (Figure 7. The standard deviation of the selection curve had again no effect on the yield per recruit, but again affected the spawning stock biomass per recruit. Higher values for the standard deviation resulted in a 50 percent reduction in the spawning stock biomass per recruit.

Catch per unit effort at a specified L_{50}/L_{opt} of 80 cm was evaluated over a range of values of fishing mortality for selection by both logistic and normal distribution functions (Figure 8). While there is little difference in the shape or values of the curves, it is evident that maximum catch per unit effort occurs at fishing mortality values less than 1.0, and that catch per unit effort decreases markedly from that point on.

DISCUSSION SUMMARY AND CONCLUSIONS

The objective of this research was to investigate the question: Is there a preferred gear type that uniquely provides the maximum biological yield and spawning stock biomass per recruit and maximum catch per unit effort based on an inherent pattern of age-specific fishing mortality? Based on the results presented herein, the answer is no.

The selection characteristic of trawls and hooks have been represented by a logistic distribution function of varying L_{50} and steepness values; and the selection characteristics of gillnets and traps have been represented by a normal distribution function of varying L_{opt} and standard deviation values. The isopleth diagrams for yield for both the logistic and normal distribution selection functions indicate maximum yields of approximately 1075 kg per 1000 recruits at fishing mortality values of 3.0 and greater, and L_{50}/L_{opt} values of 80 cm. The instantaneous maximum biomass of the unfished cohort is also approximately 1075 kg per 1000 recruits. That is, both types of selection have the capacity to harvest the maximum potential biomass of a cohort at moderate levels of fishing mortality, if the fish age at entry or length of susceptibility to the fishery is set at the age or length of maximum biomass for the unfished cohort. At these relatively high levels of fishing mortality (3.0 and greater), the specific shape of the distribution function for the size selection has no effect on the yield per recruit, but significantly affects the spawning stock biomass per recruit. The sharper the selection process, the greater the spawning stock biomass available for production of future cohorts.

In contrast, catch per unit effort is maximized at fishing mortality values of less than 1.0, when the age at entry or length of susceptibility is set at the age or length of maximum biomass for the unfished cohort.

These results present a dilemma for the fishery resource manager: Maximize cohort yield at a substantially reduced catch per unit effort or maximize catch per unit effort at a reduced yield, that is, maximize production or profit.

Future research using this model will include an application to the groundfish species of Northwest Atlantic Ocean, evaluating the present status of the fishery relative to the maximum potential of the fishery. This information will be useful to resource managers to set targets for fishing harvesting activity in terms of gear selectivity and fishing mortality.

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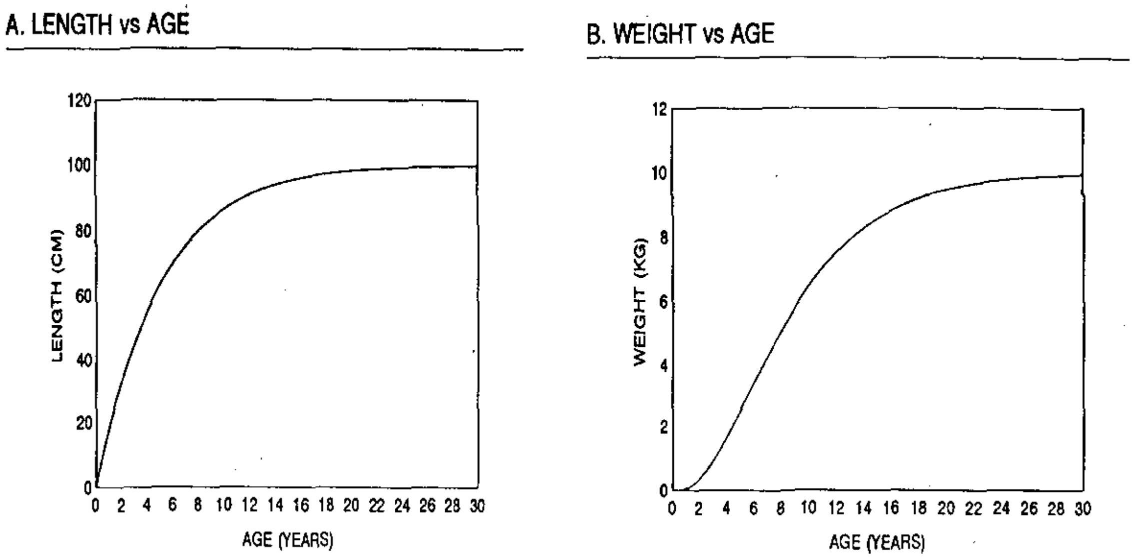
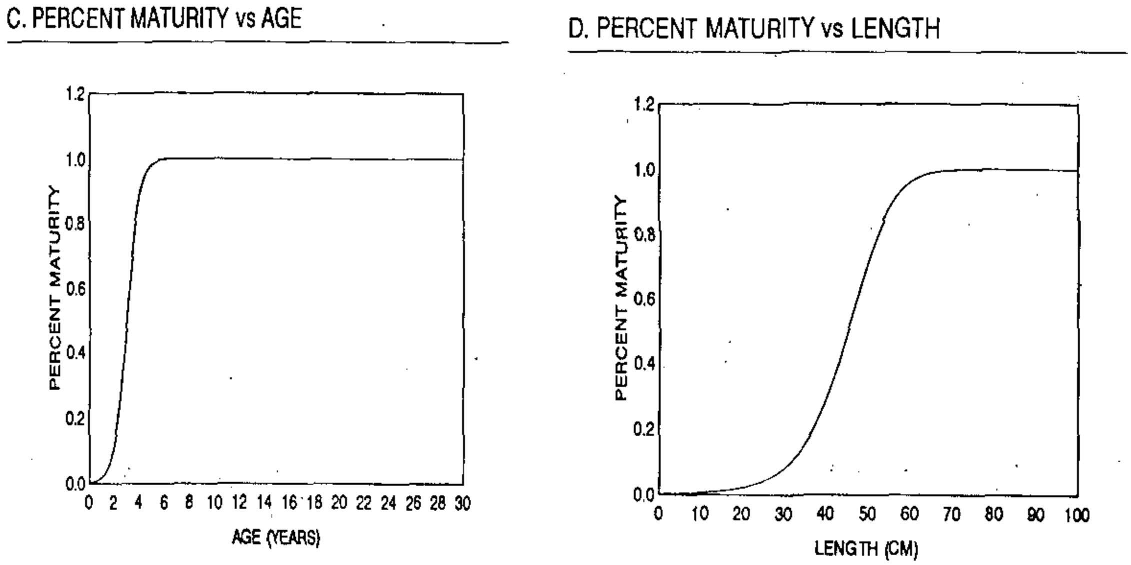


A. LENGTH vs AGE

B. WEIGHT vs AGE



C. PERCENT MATURITY vs AGE

D. PERCENT MATURITY vs LENGTH

Figure 1. Functional characteristics of a unfished cohort of an idealized groundfish.
A. Length vs Age
B. Weight vs Age
C. Percent Maturity vs Age
D. Percent Maturity vs Length

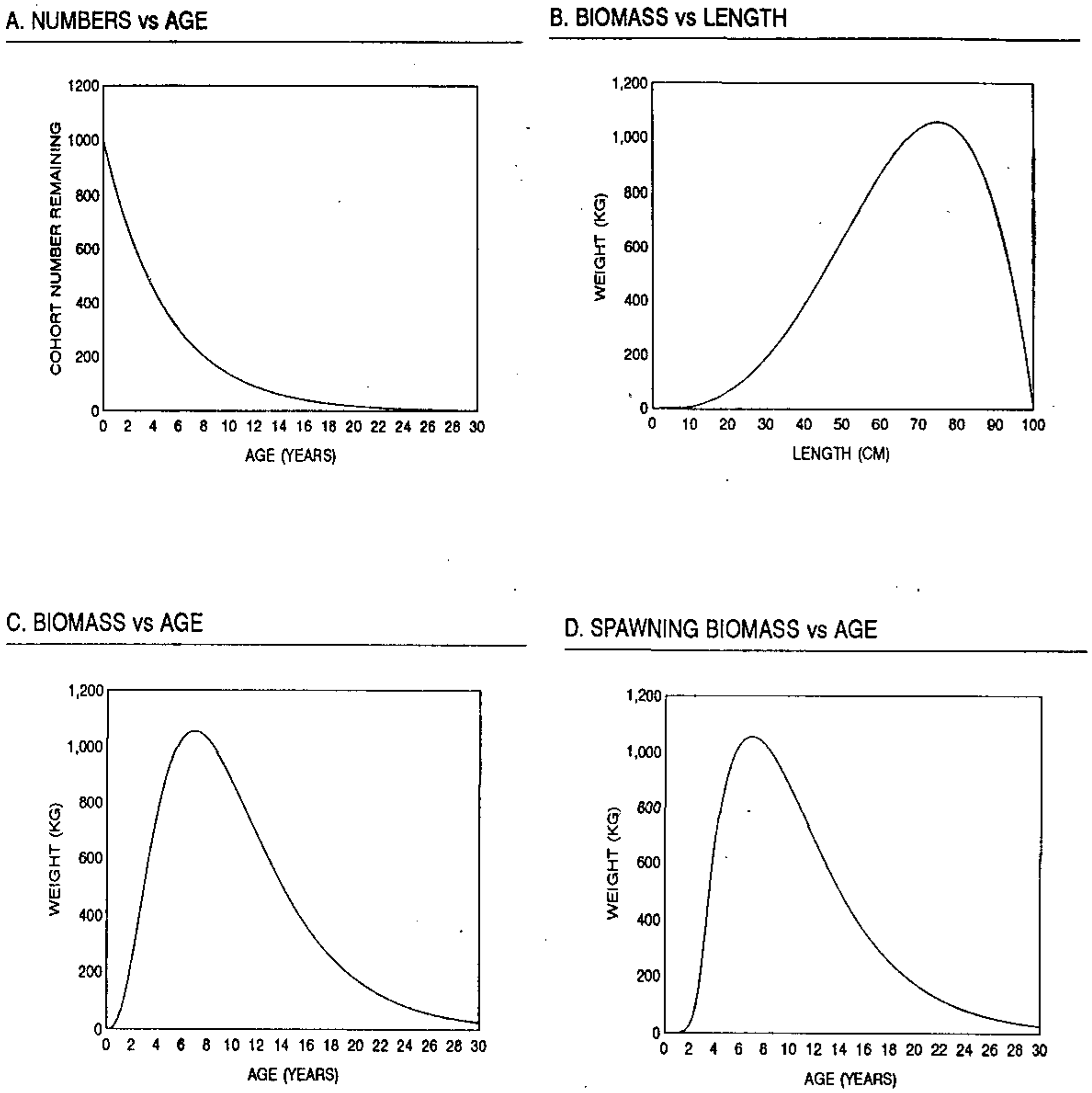
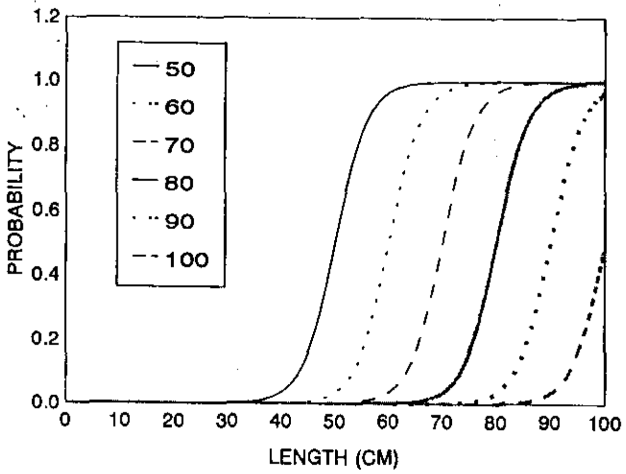


Figure 2. Functional characteristics of a unfished cohort of an idealized groundfish.
A. Numbers vs Age
B. Biomass vs Length
C. Biomass vs Age
D. Spawning Biomass vs Age

A. LOGISTIC DISTRIBUTION SELECTION CURVES



B. NORMAL DISTRIBUTION SELECTION CURVES

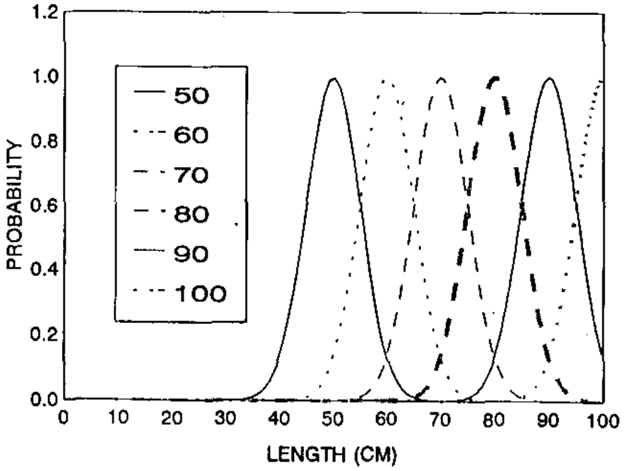
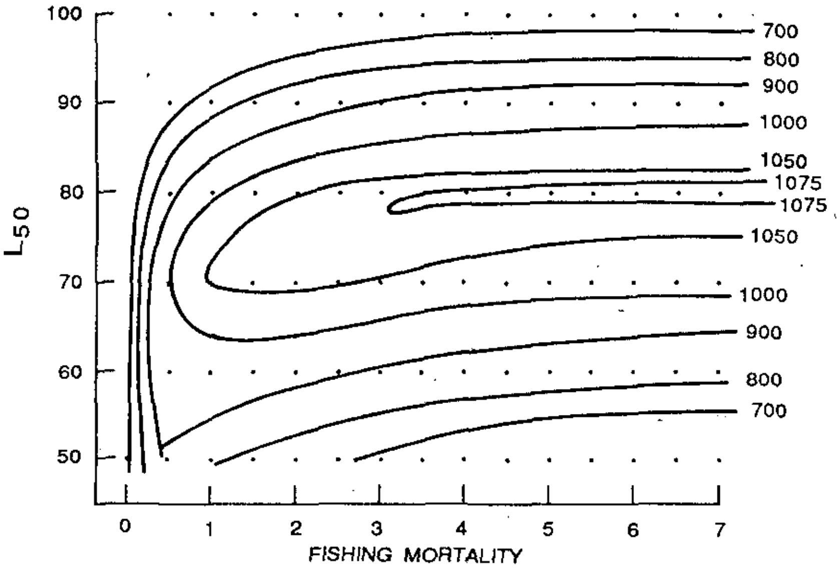


Figure 3. Selection characteristics of harvesting gears used on the cohort of idealized groundfish.
(1) Logistic Distribution Selection Curve.
(2) Normal Distribution Selection Curve.

LOGISTIC DISTRIBUTION FUNCTION SELECTION: YIELD PER 1000 RECRUITS



LOGISTIC DISTRIBUTION FUNCTION SELECTION: SSB PER 1000 RECRUITS

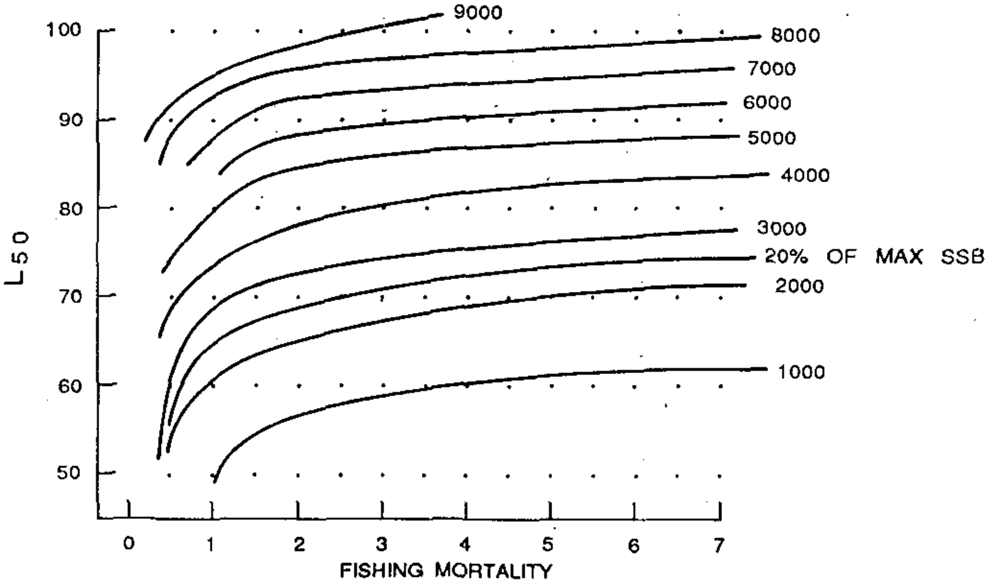
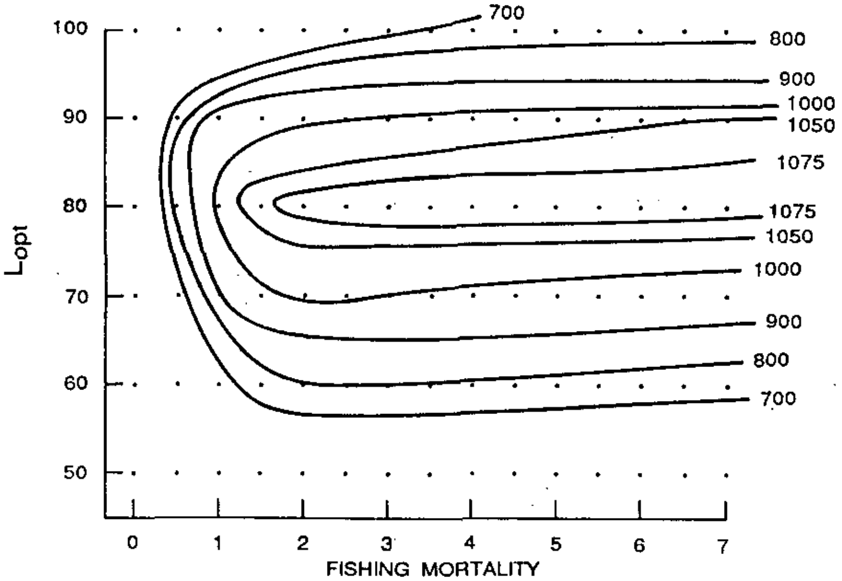
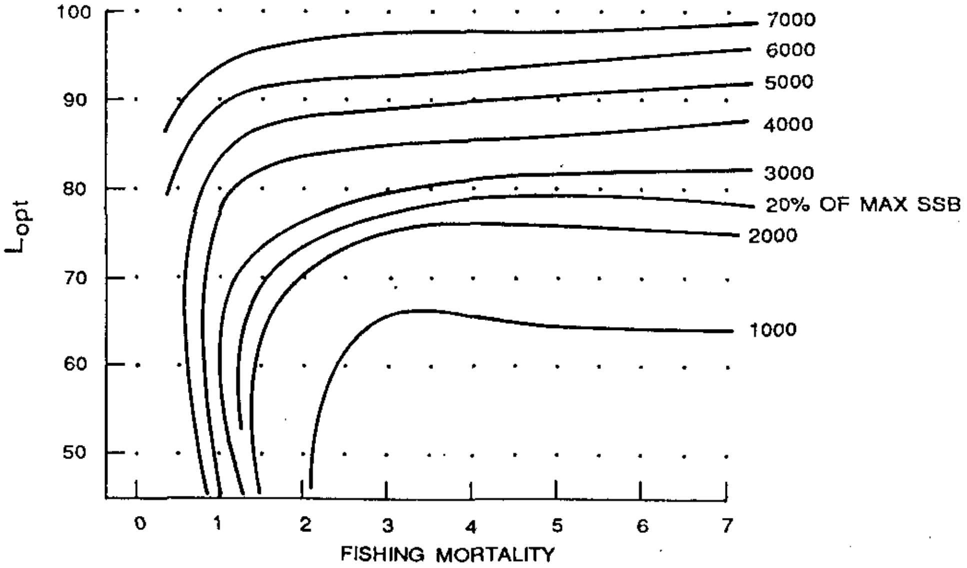


Figure 4. Isopleth diagrams of yield and spawning stock biomass per 1000 recruits for size selection based on a logistic distribution function.



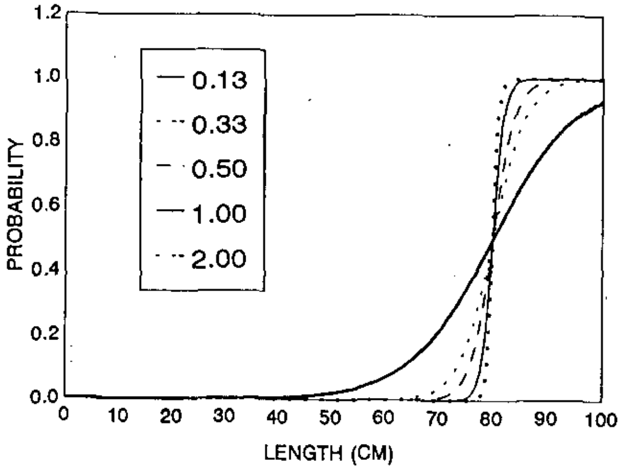
NORMAL DISTRIBUTION FUNCTION SELECTION: YIELD PER 1000 RECRUITS



NORMAL DISTRIBUTION FUNCTION SELECTION: SSB PER 1000 RECRUITS

Figure 5. Isopleth diagrams of yield and spawning stock biomass per 1000 recruits for size selection based on a normal distribution function.

A. LOGISTIC DISTRIBUTION SELECTION CURVES



B. WEIGHT vs STEEPNESS

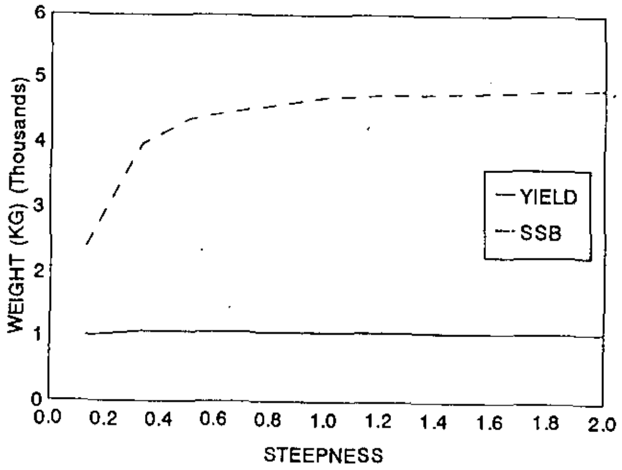
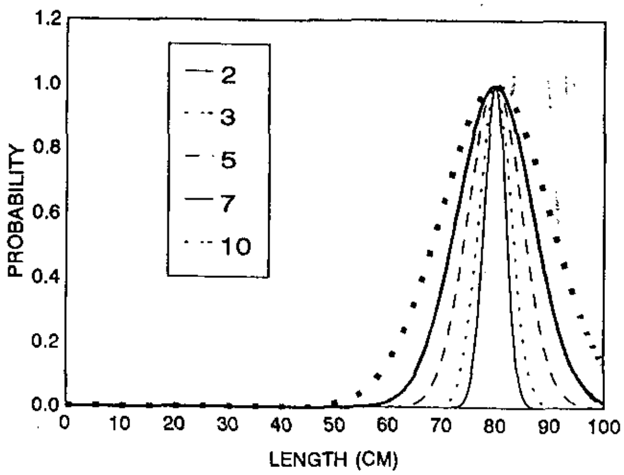


Figure 6. Effect of the steepness of the logistic distribution function on the size selection curve, and yield and spawning biomass per 1000 recruits at L_{50} = 80 cm and F = 3.0 for the cohort of an idealized groundfish.

A. NORMAL DISTRIBUTION SELECTION CURVES



B. WEIGHT vs STANDARD DEVIATION

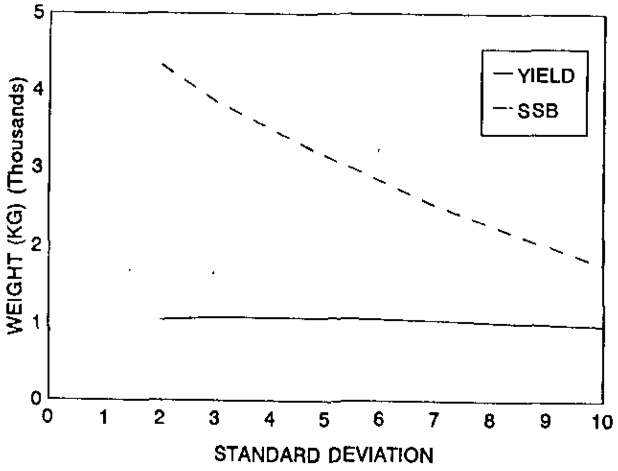
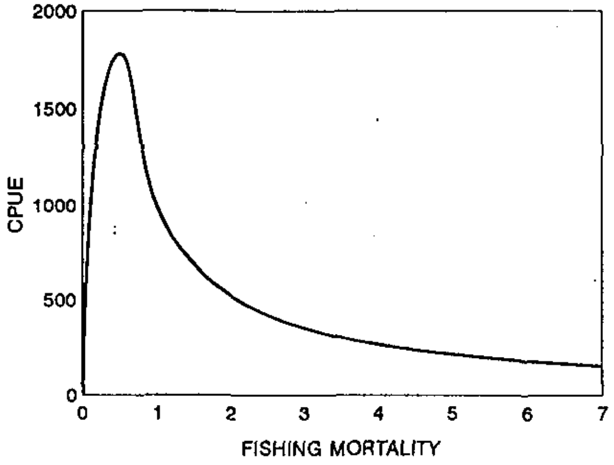


Figure 7. Effect of the standard deviation of the normal distribution function on the size selection curve, and yield and spawning biomass per 1000 recruits at L_{opt} = 80 cm and F = 3.0 for the cohort of an idealized groundfish.

A. LOGISTIC DISTRIBUTION FUNCTION SELECTION



B. NORMAL DISTRIBUTION FUNCTION SELECTION

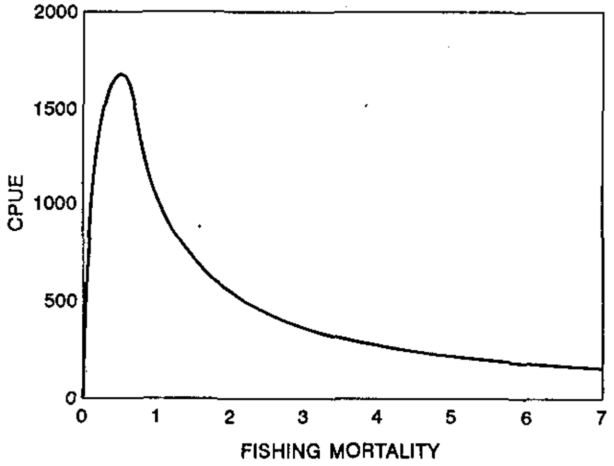


Figure 8. Catch per unit effort as a function of fishing mortality for selection by the logistic and normal distribution functions for an L_{50}/L_{opt} of 80 cm.