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Biological Reference Points Relevant to a Precautionary Approach to Fisheries Management: an Example for Southern Gulf of St. Lawrence Cod

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Abstract

An age-structured production model is used to estimate biological reference points relevant to recent international agreements on fisheries management. These new agreements require the estimation of stock biomass and fishing mortality levels required to achieve maximum sustainable yield. The traditional yield-per-recruit models used for groundfish and herring management on the Canadian east coast do not provide the necessary information. Instead, analyses which explicitly account of relationships between stock size, recruitment and fishing mortality, such as the one illustrated here, are needed.

Introduction

Recent international agreements call for biological reference points which are related to maximum sustainable yield. The ICES Comprehensive Fisheries Evaluation Working Group reviewed the management implications of two agreements, which Canada has signed; The Code of Conduct for Responsible Fisheries adopted by the FAO Committee on Fisheries in November 1995, and the agreement on the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks adopted by the United Nations General Assembly in August 1995 (Anon 1996a). The working group concluded that these conventions require that fisheries management systems have the following qualities:

- Fishing should be limited to sustainable levels
- Uncertainty should not be a reason to maintain high fishing mortality
- Stock biomass should be kept above that which will produce maximum sustainable yield (B_{MSY})
- Fishing mortality should be kept below that which will produce MSY (F_{MSY})
- There should be only low probability that biomass might fall below B_{MSY} and that fishing mortality should rise above F_{MSY}.

In the absence of other information, reference points related to MSY would be limit reference points which set boundaries intended to constrain harvesting within safe biological limits. Fisheries management strategies shall ensure that the risk of exceeding limit reference points is very low. If a stock falls below a limit reference point, management action should be initiated to facilitate stock recovery. A second class of reference points called target reference points are intended to meet management objectives which are not only related to conservation. Fisheries management strategies shall ensure that target reference points are not exceeded on average and that limit reference points are rarely exceeded.

The current eastern Canadian groundfish and herring management strategy does not explicitly recognize MSY and further research is required to implement these agreements. The eastern

Canadian groundfish and herring management strategy has been to maintain fishing mortalities constant at reference levels defined by yield-per-recruit analyses which consider only fish growth and mortality and not the relationship between stock size, recruitment and fishing mortality. Stock production models have been used to estimate MSY. Traditional models of this type implicitly assume a relationship between stock and recruitment. Age-structured production models, which are described here, explicitly fit stock recruitment relationships and apply them along with yield per recruit and spawning stock biomass (S) per recruit considerations.

This paper presents an example of age-structured production modeling using data from the southern Gulf of St. Lawrence (NAFO 4TVn (N-A)) cod stock as a case study. It is meant as an illustration only. There is currently considerable uncertainty about natural mortality of this stock, and it is possible that the population estimates used in this study are biased. However, I hope the example promote discussion of the appropriate use of this type of modeling for defining fisheries management strategies.

A Comment on Stock/Recruitment Relationships

It is tempting to discount possible relationships between stock size and recruitment given the scatter of data points in lengthy time series. However, an important underlying relationship may be masked by intrinsic variation in the system and by a reduced range of observations (Walters and Ludwig 1981, Hilborn and Walters 1992 chap. 7). If environmental factors influence the survival rate of fish during the pre-recruit life history (eggs, larvae, juveniles), then a higher initial number of eggs will produce a higher number of recruits for any level of environmental mortality. If the environmental effect is strong, one would not expect to see a strong relationship between stock size and recruitment. Secondly, most assessment time series begin after stocks had already been reduced by fishing. The population age structure was already truncated and the biomass was already reduced relative to the potential range over which the stock/recruitment relationship could operate. Finally, the precision of stock size and recruitment estimates is relatively poor. All of these factors could potentially mask a relationship between stock size and recruitment.

These characteristics are shown with a simulation using a southern Gulf cod-like population (same age range, weights at age, and partial recruitment) over a 40 year time period. A Ricker stock/recruitment relationship with multiplicative process error was used to generate simulated year-classes

$$R = aSe^{\sigma - bS}$$

where R is the number of recruits
S is the spawning stock size
a and b are the stock/recruitment parameters
σ is a normal variant with mean 0 and standard deviations of 0.1, 0.3, and 0.5

Natural mortality was assumed constant at 0.2 for all ages and years. Fully recruited fishing mortality was held constant for the projection period, and 3 levels were used, 0.2, 0.6, and 1.0. Spawning biomass was calculated assuming knife edged maturity at age 5. The simulation period covered 41 years and the initial population abundance was that given for the stock in 1950 by Lett (1978). Mean weight at age was held constant at average values observed for the stock during 1993-95. No sampling error was included in the simulation. Ten replicates of each process error and F combination were run. The same set of random variates was used for each process error and F combination in each replicate.

The effect of process error and the simulated level of fishing mortality on the perceived stock/recruitment relationship is shown for one replicate of the simulation in Fig. 1. The initial spawning biomass was about 175,000 t. When the fishing mortality was 1.0 throughout the simulation, S declined considerably providing observations of stock size and recruitment on the lower end of their respective ranges. When the process error was low (0.1), there was a clear relationship between S and R, but when the process error was high (0.5), the relationship was not readily apparent (upper panels in Fig. 1). When F was 0.2 throughout the simulation, S remained above 150,000 t, in the upper part of the possible range. When the process error was low (0.1), there was little variation in either S or R, and the simulated data provided little information about the S/R relationship (lower left panel in Fig. 1). When the process error was high (0.5), there was a wide scatter of S and R. Only when F was high (1.0), which resulted in a large decline in S during the simulation period, and the process error was low (0.1) was there a clear stock recruitment relationship.

Stock size and yield were more variable when there was a high level of process error in the stock/recruitment relationship (Fig. 2). When the process error was 0.1, and F was 1.0, the stock declined steadily throughout the simulation period, eventually being reduced to 0 if the simulation period was extended indefinitely. With the same process error but F = 0.2, the stock tended toward an equilibrium position, yielding in the order of 30,000 t annually. However, when the process error was high (e.g. 0.5), the increased variation in recruitment resulted in considerable variation in yield. When F was 1.0, the stock size declined but not as far as when the process error was low, and the stock was able to withstand higher levels of F. When F was 0.2, yield also varied and the population did not reach a steady equilibrium.

The incorrect rejection of stock/recruitment relationships could result in non-optimal yields. In these simulations, average annual yields were highest for an F of 0.2 (Fig. 3). The average yields also increased with the magnitude of the process error. The latter effect resulted from the form of process error used in the simulations. The mean recruitment for a given S increased as the process error increased because of the multiplicative nature of the error function.

This analysis was not meant to provide evidence that such relationships exist, this is done elsewhere (e.g. Hilborn and Walters 1992 chap. 7). These are simply scenarios of what might happen if stock/recruitment relationships exist but are masked by system error and the fishing regime. The point is that one should not reject such relationships simply because the basic data are scattered. There are many reasons why this may happen and the consequences of falsely rejecting stock/recruitment are potentially severe.

Age-Structured Production Models

Age-structured production analysis is a straightforward extension of yield per recruit (Y/R) and spawning biomass per recruit (S/R) analysis. Yield per recruit analysis is used to estimate the amount of yield expected from a unit of recruitment as a function of fishing mortality, partial recruitment, and weight at age (details in Rivard 1982, section 5). One can also calculate S/R under the same conditions using a maturity-at-age ogive. The results are typically displayed as curves relating Y/R and S/R to F (step 1 in Fig. 4). Where production modeling begins is by fitting a stock recruitment curve to the respective stock data (step 2 in Fig. 4). It is then possible to estimate equilibrium conditions from the estimated parameters (Anon 1996a, Ricker 1975 Appendix III). For a Ricker relationship

$$R = aSe^{-bS}$$

the equilibrium stock biomass (S_e) is

$$S_e = \frac{\ln(a(S/R))}{b}$$

Substituting S/R from spawning stock biomass per recruit analysis, one may estimate S_e for any F and use this to estimate R_e (step 3 in Fig. 4). Equilibrium yield is then estimated using R_e * Y/R for that F (step 4 in Fig. 4). Equilibrium yield may also be plotted against S_e. Reference points include B_{MSY}, the biomass corresponding to maximum sustainable yield; F_{MSY}, the fishing mortality rate corresponding to MSY; and F_{crash}, the fishing mortality beyond which yield is 0.

Effects of Changes in Size at Age on Stock Production

Size at age and stock production of southern Gulf of St. Lawrence cod declined from the late 1970s to the 1990s. The effect of this change on yield per recruit and stock production reference points were investigated by conduction age-structured production analyses using input average weights at age and F at age from 4 time periods, 75-79, 80-84, 85-89, 90-95 (Table 1). Maturity was assumed to be knife edged at age 5 and M was assumed to be 0.2 on all ages and years. A Ricker stock recruitment curve was fit to the data from 1950-1995 assuming lognormal error distribution (Sinclair et al. (1996) ,Table 2, Fig. 5). The fitted parameters are given below and were used in all analyses.

$$R = 0.7891Se^{-0.003442S}$$

There were important differences in reference points from the yield per recruit and age-structured production analyses. $F_{0.1}$ remained relatively stable in these periods, varying between 0.17 and 0.21 (Table 3). F_{max} varied little over the first three periods, then increased dramatically in the final time period as the Y/R curve became asymptotic (Fig. 6). F_{msy} declined from 0.40 to 0.23, F_{crash} declined from 1.33 to 0.79, and MSY declined from 78,000 t to 31,000 t.

The differences in the type of information available from the two models is shown clearly by comparing the yield and yield per recruit vs. F curves (Fig. 6). The yield curves were strongly dome-shaped with clear maxima. Both MSY and F_{crash} declined over the period 1975-95. Thus, one can see that reduced production may affect both total yield and the level of maximum sustainable F. This is contrasted with yield per recruit curves which are distinctly flat-topped, and which do not decline at high Fs. Ignoring the yield curve and concentrating only on the yield per recruit implications of declining size at age may mask potential danger of high F on a stock with reduced production.

This point is further emphasized by plotting the observed annual values of F and yield along with the equilibrium curves (Fig. 6, upper panel). Most of the observed points between 1950 and 1985 lie between the equilibrium curves for the 1975-79 and 1980-84 time periods. Eventhough the Fs were generally above F_{msy}, the stock appeared to be close to equilibrium. However, as the size at age of the stock and its production declined, F increased. There was little increase in yield initially, followed by a decline at higher F. More importantly, the F in the final years before the fishery was closed was well above sustainable levels.

Effects of Changes in Age of Recruitment on Stock Production

The effects of changes in partial recruitment (PR) on reference points from age-structured production analysis and yield per recruit analysis are compared in this section. There has been little variation in PR for the southern Gulf cod stock, except that fish recruited somewhat earlier during the late 1970s than in subsequent years. Instead of using observed PR patterns, I used a knife edged PR and varied the age of full recruitment from 4 to 8. This level of variation far exceeds what has been observed for this stock and it is used here purely as a comparison of the type of information available from these two models. I also used the weights at age from the 1990-95 period.

There were marked differences in Y and Y/R as a function of F between the two models (Fig. 7). Both F_{msy} and F_{crash} declined significantly as the age of full recruitment declined in the age-structured production analyses. The curves changed shape from being nearly flat-topped when full recruitment was at age 8 to very dome shaped when age 4 fish were fully recruited. MSY was about 25% less with age 4 fully recruited than with age 8 fully recruited. The Y/R curves were relatively insensitive to changes in the age of full recruitment (Fig. 7). The main difference was that the curves were flat-topped for full recruitment at ages 5, 6, 7, and 8, and slightly domed at age 4.

Uncertainty in the Stock/Recruitment Relationship

There is considerable uncertainty regarding the stock recruitment relationship in several stocks (Fig. 5 for example) and, ideally, this would be taken into account when estimating reference points. I used bootstrapping in a attempt to illustrate these uncertainties. Weights at age and F at age from the 1990-95 time period were used and the stock recruitment data were from 1950-1995. The Ricker stock recruitment relationship was fitted using the solver add-in in MS Excel 5.0. Residuals from the initial fit were resampled, with replacement, and added to the initial predicted values to form psuedo-replicates of the observed recruitment values. The stock/recruitment parameters were then estimated for the psuedo dataset, and the associated stock production parameters were estimated. A total of 300 replicates was used.

The point estimates and median bootstrap estimates of B_{MSY} and F_{MSY} were virtually identical (207,000 t and 0.23 respectively) indicating that the bootstrapping was reliable. Ninety-five percent of the B_{MSY} estimates were between 160,000 t and 325,000 t, while 95% of the F_{MSY} estimates were between 0.153 and 0.359.

Cumulative frequency distributions of B_{MSY} and F_{MSY} were calculated and displayed in the form of risk curves (Fig. 8). Curves like these could be used to select limit reference points relevant to a precautionary approach to fisheries management. A risk averse approach would choose a limit B_{MSY} with a relatively low probability of being greater than the true B_{MSY}. In this case, if a 20% risk was acceptable, the corresponding B_{MSY} would be about 240,000 t. For F, one would choose a limit reference point with a relatively low probability that it would exceed the true value. Using the same 20% rule, the limit F would be about 0.20.

Discussion

Implementation of recent international agreements which describe a precautionary approach to fisheries management will require estimating biological reference points relevant to stock production. These agreements refer to B_{msy} and F_{msy} as limit reference points, and these may only be estimated if one accounts for mechanisms which control population size and production including relationships between stock size and recruitment. Yield per recruit models traditionally used for groundfish and herring management in eastern Canada are not adequate for this requirement. Attempts to relate yield per recruit to total yield by multiplying Y/R by average recruitment make a strong and unlikely implicit assumption that R/S increases as F increases (Pereiro 1992).

There is a tendency to reject the existence of stock recruitment relationships by simple examination of scatterplots of the two variables. However, several factors may mask the important underlying relationship, including environmental influences on pre-recruit survival rates, reduced range of stock size induced by high Fs, and sampling variability. The consequences of falsely rejecting stock recruitment relationships may be severe.

Age-structured production analysis is a simple extension of yield per recruit analysis and may be used to estimate reference points relevant to a precautionary approach to fisheries management. Additional information on S and R are required. Simple approaches of estimating S, as used here, have drawbacks however. I used a constant knife edged maturity ogive where maturation is more likely to be spread over several ages and it is likely that the maturity schedule has changed over time. There is also evidence that fecundity is not a simple function of weight, but that larger fish produce more eggs per unit weight than smaller fish. The viability of eggs and larvae produced by multi-year spawners may also be higher than that of first-time spawners. Additional work on defining suitable maturity ogives is warranted.

Management actions implied by changes in size at age of this stock would be quite different if production models or yield per recruit models were being used. Under a yield per recruit management strategy where $F_{0.1}$ would be used to set TACs, there would have been little difference in the target Fs during these time periods. However, if a stock production management strategy was used, the target Fs would have declined over the period 1975-95. This would have been consistent with the decline is stock production. It is interesting to note that F_{msy} was less than F_{max} in the last 2 time periods and F_{crash} was less than F_{max} in the most recent time period. Some management organizations have treated yield per recruit and production biological reference points as equivalents (e.g. F_{max} and F_{msy}, $F_{0.1}$ and 2/3 F_{msy}) eventhough there is no direct link between the two. Indeed, it is only when recruitment and stock size are independent that F_{max} and F_{msy} would be equal. If that were the case, survival from spawners to recruits would have to be inversely proportional to F, an unlikely scenario. Furthermore, these results indicate that, in certain circumstances, F_{max} could be unsustainable.

Management actions implied by changes in age of recruitment to the fishery would also be quite different if production models or yield per recruit models were being used. Yield as a function of F as estimated with the age-structured model generally declined as the age of recruitment declined. In this example, if fish did not recruit until age 8, well after they matured, it would be virtually impossible to collapse the stock by fishing alone. However, if the fish recruited at age 4, one year prior to maturing, an F above 0.3 would be unsustainable. Y/R, on the other hand, was surprisingly insensitive to changes in the age of recruitment. If one considered only Y/R, there would be no apparent danger in Fs above 1.0 regardless of the age of recruitment to the fishery. Clearly, it would not be prudent to accept high levels of F based on yield per recruit analysis.

I have attempted to account for the uncertainties in the stock recruitment relationship here. While this is a rather simplistic approach, it does raise the question of how the uncertainties should be translated into limit reference points. Is it appropriate to use the upper X^{th} percentile of the B_{msy} distribution and the lower Y^{th} percentile of the F_{msy} distribution?

Adoption of B_{MSY} as a limit reference point has important implications on criteria for reopening the southern Gulf of St. Lawrence cod fishery. The Fisheries Resource Conservation Council suggested a set of criteria for fishery reopening, one of which called for a spawning stock biomass half way between the value at the time the fishery closed and the long term average (Anon 1996b). The criterion was 115,000 t for southern Gulf cod. This is well below the limit reference point suggested by age-structured production analysis.

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Table 1: Mean weight and F at age for southern Gulf of St. Lawrence cod during 4 time periods. These data were used as input to *yield per recruit* and age-structured production analysis.

	Weight at age (kg)				F at age			
Age	75-79	80-84	85-89	90-95	75-79	80-84	85-89	90-95
3	0.299	0.292	0.284	0.276	0.008	0.000	0.000	0.005
4	0.691	0.540	0.480	0.458	0.112	0.024	0.032	0.047
5	1.214	0.818	0.669	0.675	0.292	0.126	0.126	0.167
6	1.833	1.141	0.835	0.887	0.408	0.262	0.304	0.283
7	2.448	1.430	1.024	1.080	0.522	0.396	0.394	0.403
8	3.336	1.898	1.271	1.269	0.510	0.446	0.446	0.470
9	3.841	2.585	1.609	1.484	0.518	0.530	0.522	0.535
10	5.448	3.340	1.874	1.876	0.606	0.686	0.694	0.605
11	6.374	4.775	2.506	1.966	0.698	0.616	0.700	0.603
12	6.343	8.365	3.845	2.357	0.662	0.650	0.910	0.765
13	9.432	9.701	6.715	2.495	0.590	0.952	0.666	0.815
14	7.114	9.680	9.797	4.640	0.516	0.296	0.536	0.547
15	11.193	9.077	13.015	11.996	0.570	0.610	0.614	0.575

Table 2: Spawning stock biomass (S, '000 t) and recruitment (R, millions, age 3), fully recruited fishing mortality (F) and landings (Y, '000 t) for southern Gulf of St. Lawrence cod. The dates indicate year for S, F, and Y, and year-class for R.

Year/Year-class	S	R	F	Y
1950	227.823	106.459	0.316	44.023
1951	261.133	76.949	0.210	34.827
1952	311.792	68.245	0.250	41.956
1953	341.442	80.668	0.289	58.911
1954	365.380	105.924	0.396	63.901
1955	402.066	109.718	0.313	65.227
1956	426.508	142.174	0.407	104.469
1957	364.178	133.065	0.380	89.131
1958	310.551	45.519	0.638	86.582
1959	256.520	58.515	1.103	70.720
1960	216.038	40.797	0.440	66.013
1961	236.424	59.397	0.485	65.583
1962	260.468	50.732	0.299	66.664
1963	215.737	57.658	0.415	70.202
1964	162.959	96.920	0.392	60.547
1965	134.680	87.217	0.589	65.104
1966	118.029	50.803	0.472	57.081
1967	110.061	47.251	0.372	43.412
1968	111.898	89.952	0.383	48.991
1969	133.154	35.518	0.378	50.261
1970	153.760	49.013	0.687	65.988
1971	151.897	56.994	0.578	57.931
1972	130.997	47.400	0.547	69.317
1973	106.376	123.021	0.515	51.943
1974	85.012	170.269	0.698	50.579
1975	76.731	165.316	0.845	43.266
1976	73.230	116.753	0.599	37.343
1977	75.062	116.617	0.350	26.884
1978	134.234	86.373	0.439	39.020
1979	198.152	153.079	0.702	57.696
1980	240.275	206.524	0.495	57.226
1981	237.839	110.274	0.660	67.147
1982	235.992	104.996	0.513	61.669
1983	222.458	85.907	0.497	63.990
1984	221.735	70.346	0.599	57.564
1985	264.682	57.993	0.521	63.973
1986	252.650	66.579	0.646	68.682
1987	221.046	72.267	0.486	54.592
1988	182.728	47.811	0.620	55.719
1989	155.537	36.969	0.782	57.269
1990	122.885	32.507	0.958	57.877
1991	101.586	27.741	1.065	49.460
1992	85.019	15.937	1.210	41.127
1993	67.218	20.000	0.161	5.239
1994	82.699		0.025	1.334
1995	96.169		0.012	1.075

Table 3: Comparison of yield per recruit and age-structured production reference points and the associated S/R and Y/R for southern Gulf of St. Lawrence cod over four time periods 1975-79, 1980-84, 1985-89, and 1990-95

	$F_{0.1}$			F_{max}			F_{MSY}				
Years	F	S/R	Y/R	F	S/R	Y/R	F	S/R	Y/R	MSY	F_{crash}
75-79	0.21	5.69	0.87	0.36	3.87	0.93	0.40	3.60	0.93	78053	1.33
80-84	0.18	4.96	0.65	0.29	3.73	0.69	0.30	3.59	0.69	58041	1.47
85-89	0.17	3.58	0.43	0.30	2.59	0.45	0.23	3.01	0.45	37460	0.92
90-95	0.21	2.74	0.37	0.90	1.17	0.42	0.23	2.58	0.38	30653	0.79

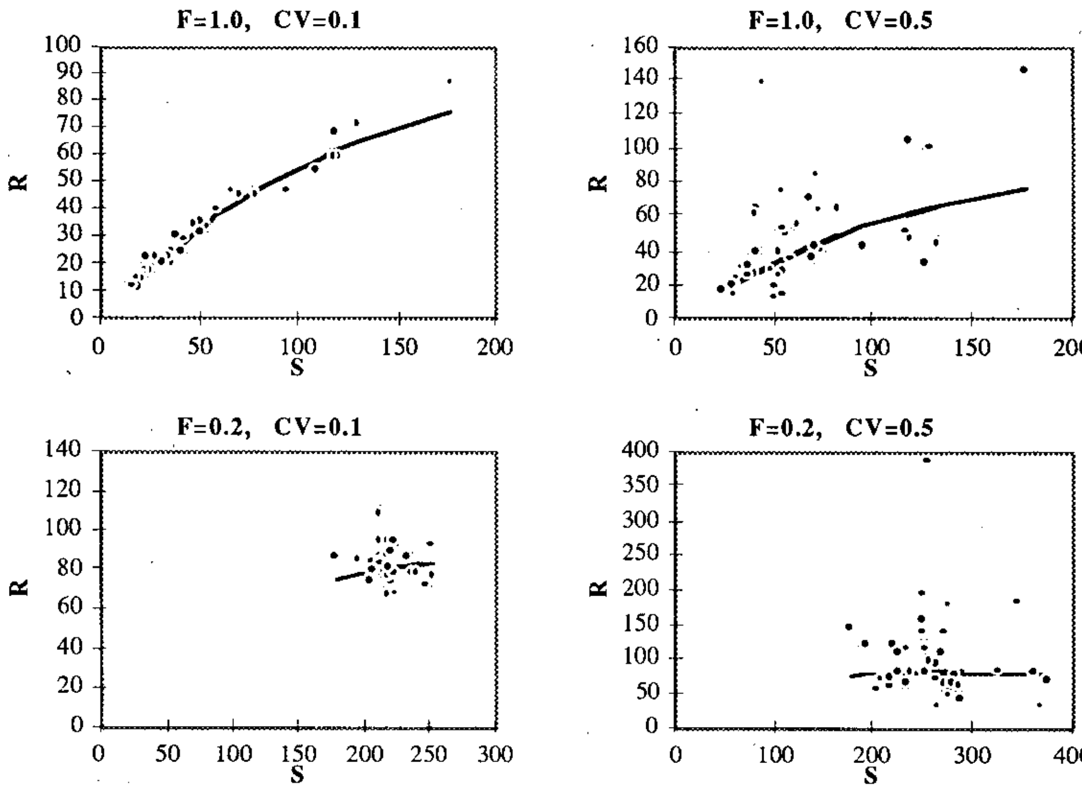

Fig. 1: Scatter plots of stock (S) and recruitment (R) from simulations with different levels of process error in the stock/recruitment relationship (CV) and F. The underlying stock/recruitment relationship (shown as a solid line) is masked by high process error and low range in stock size.

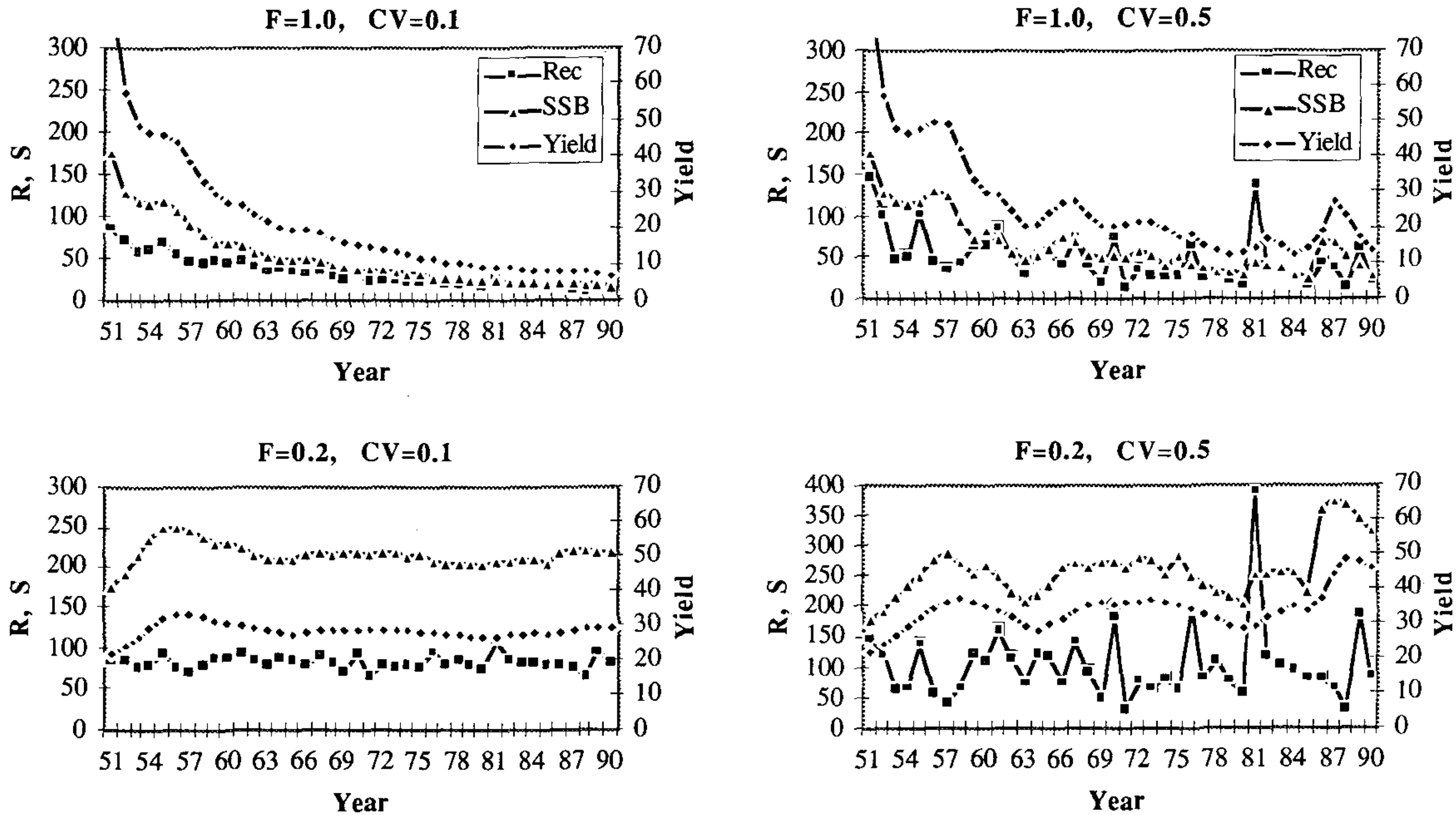

Fig. 2: Example trajectories of recruitment, spawning biomass (S), and yield from one replicate simulation of the effect of F and recruitment process error (CV) on stock production.

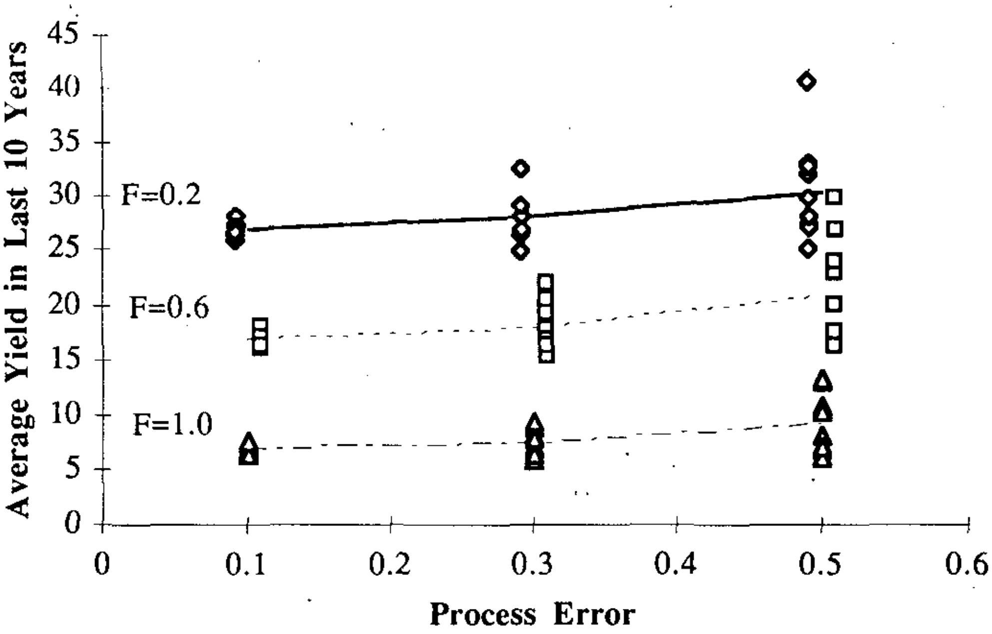

Fig. 3: Average annual yields from the last 10 years of simulations with different process errors and fishing mortalities. Yields were higher at lower Fs. Yields increased with the level of process error.

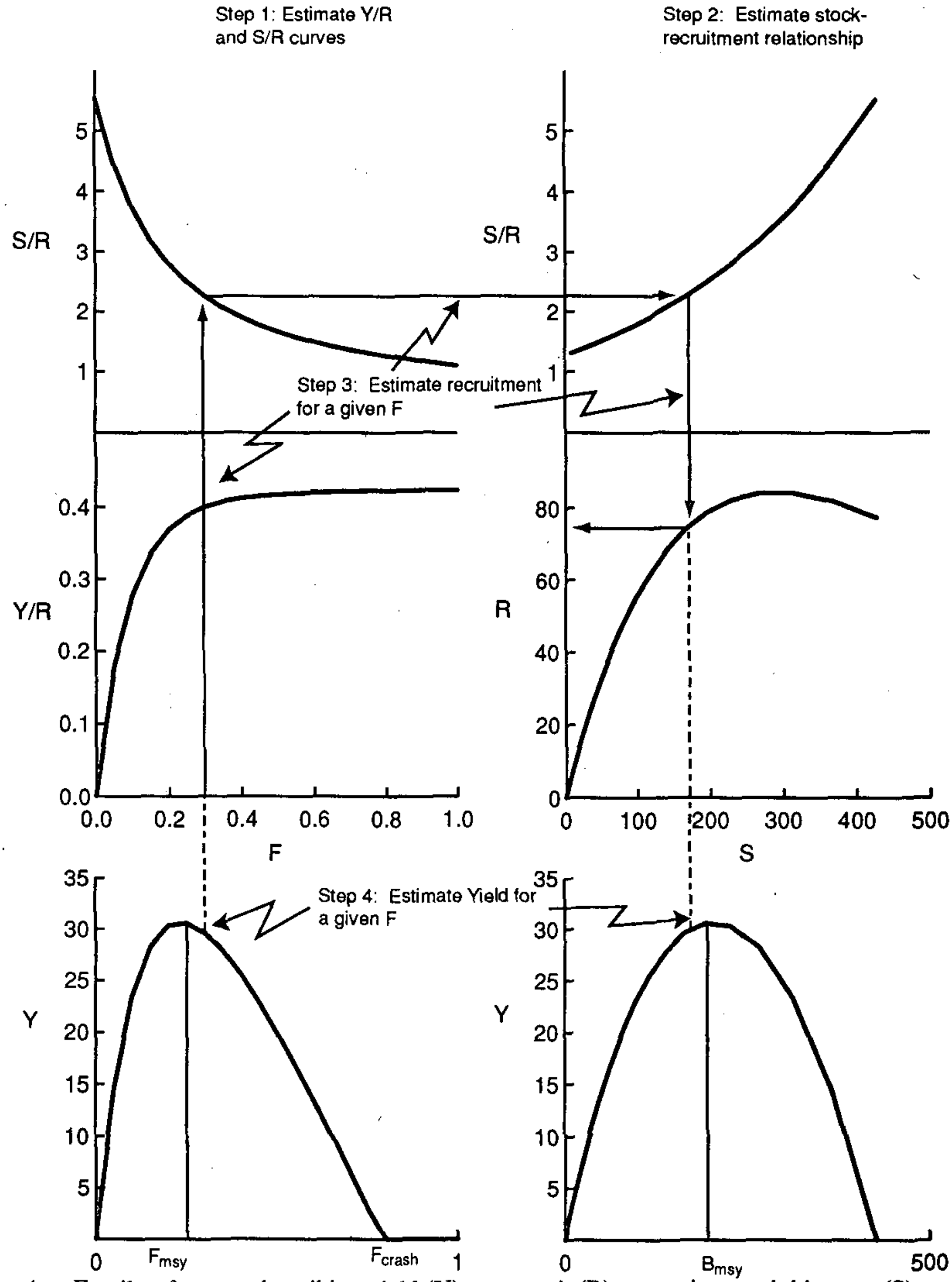

Fig. 4: Family of curves describing yield (Y) per recruit (R), spawning stock biomass (S) per recruit, and yield as a function of fishing mortality (F). The steps to relate the curves are described in the text (based on Fig. 1 of Sissenwine and Shepherd (1987)).

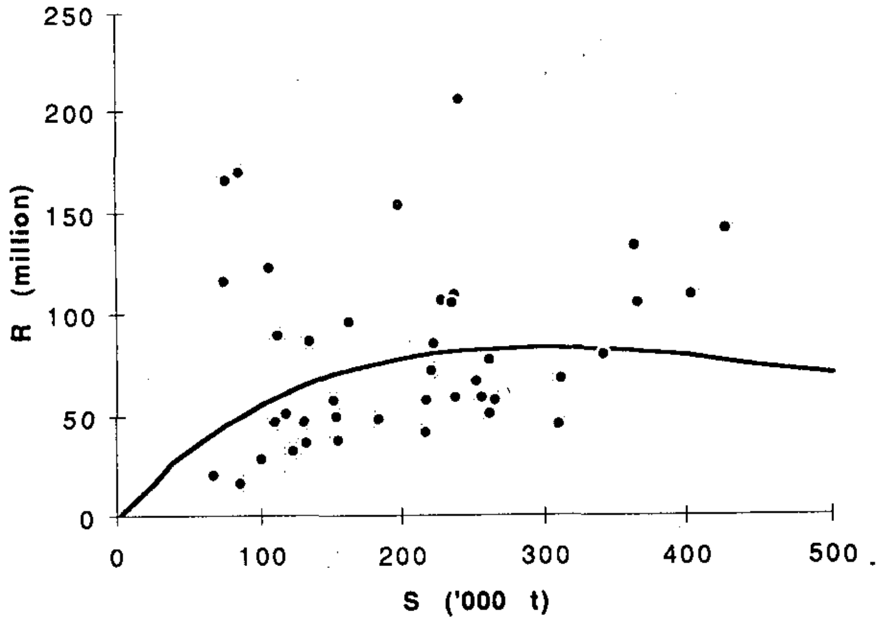

Fig. 5: Ricker stock/recruitment curve for southern Gulf of St. Lawrence cod. Data come from the period 1950-95. Recruitment (R) is year-class abundance estimated at age 3, and spawning biomass (S) includes ages 5+.

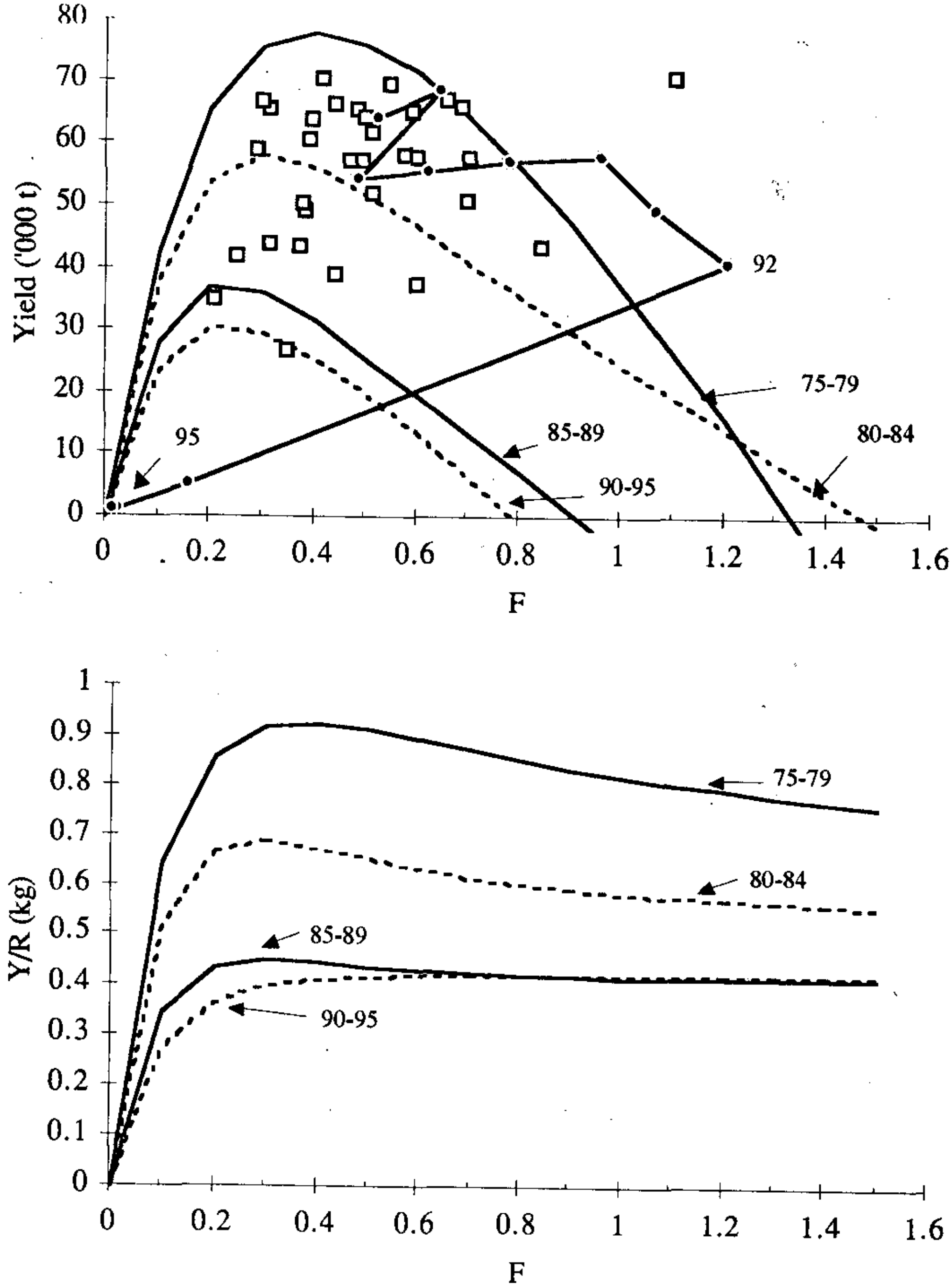

Fig. 6: Comparison of equilibrium curves of yield vs. F from age-structured production analysis (upper panel) and yield per recruit vs. F from yield per recruit analysis (lower panel) estimated for 4 separate time periods for southern Gulf of St. Lawrence cod. Observed annual values of Y and F are plotted on the upper panel. The points from 1950-1984 are plotted individually while those from 1985-95 are joined to indicate recent trends.

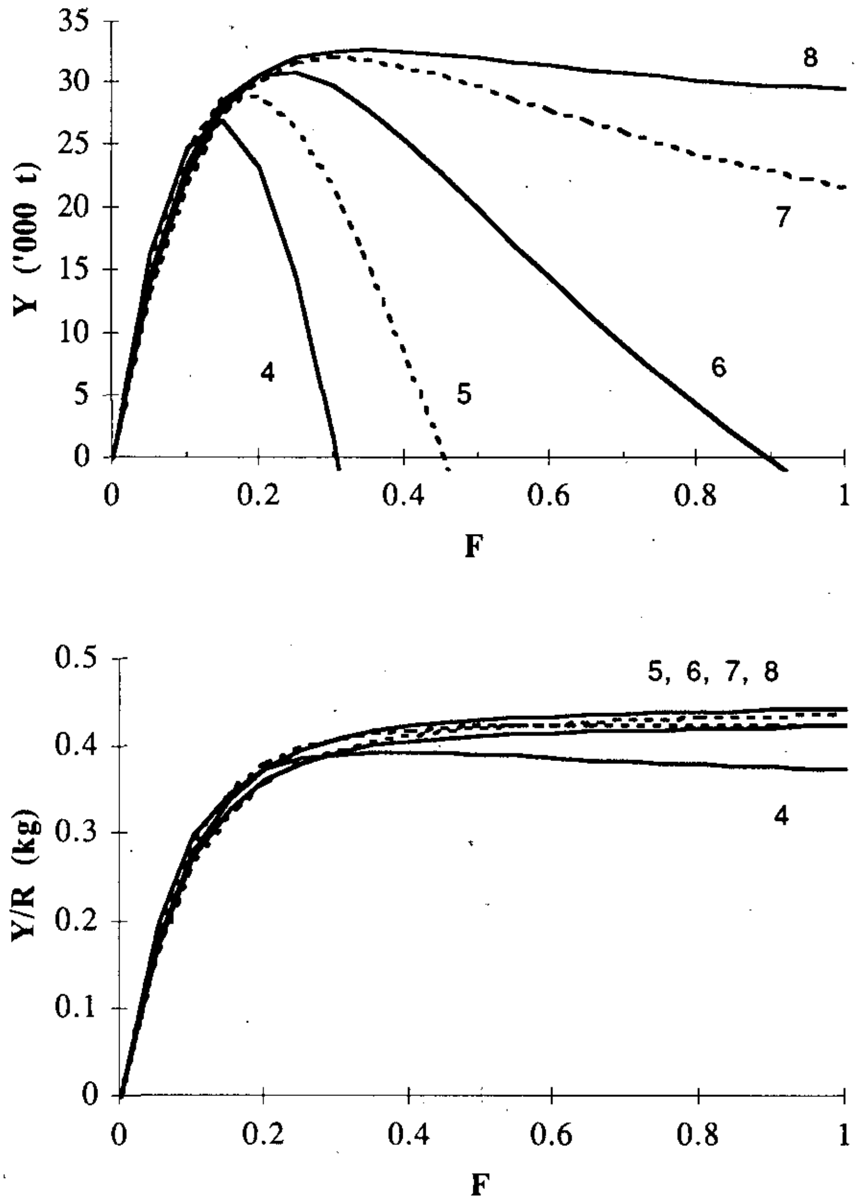

Fig. 7: Comparison of equilibrium curves of yield vs. F from age-structured production analysis (upper panel) and yield per recruit vs. F from yield per recruit analysis (lower panel) estimated for different ages of knife-edged full recruitment for southern Gulf of St. Lawrence cod. Weights at age from the 1990-95 period were used in all cases. Yield was much more sensitive than yield per recruit to changes in age of recruitment.

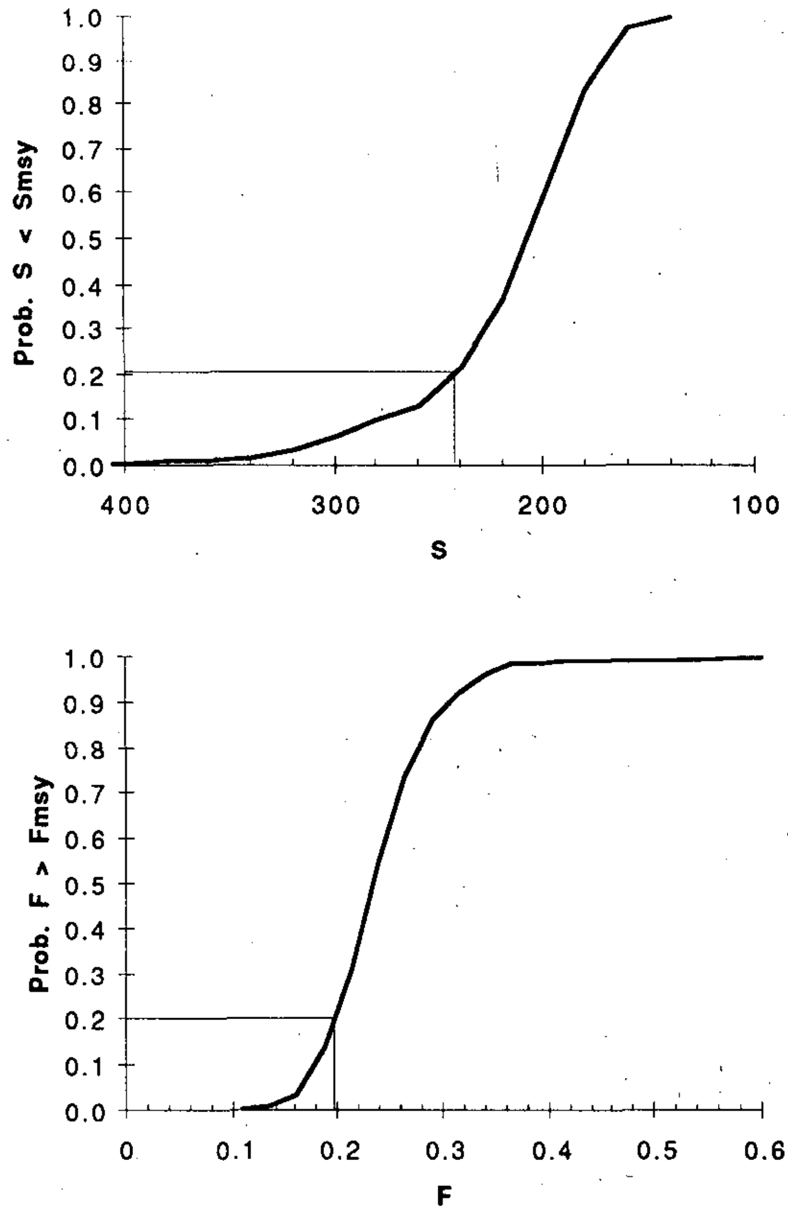

Fig. 8: Cumulative distributions of bootstrap estimates of B_{MSY} (upper panel) and F_{MSY} (lower panel) presented as risk curves. Note that the x-axis on the upper panel is reversed.