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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 which form the basis of a Precautionary Approach to 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 in the Northwest Atlantic may not be suitable for a Precautionary Approach if stock size and recruitment are related. It is shown that under these conditions, yield-per-recruit reference points such as $F_{0.1}$ and $F_{max}$ may result in sub-optimal yields and may even be unsustainable. Analyses which explicitly account for relationships between stock size, recruitment and fishing mortality, such as the one illustrated here, may be needed to implement the Precautionary Approach.

*Key words*: cod, Gulf of St. Lawrence, precautionary approach, management, yield

## Introduction

Recent international agreements call for biological reference points which are related to maximum sustainable yield. The ICES Comprehensive Fisheries Evaluation Working Group (Anon., MS 1996) reviewed the management implications of two agreements; The Code of Conduct for Responsible Fisheries adopted by the FAO Committee on Fisheries in November 1995 (FAO, 1996), 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 (UN, 1995). 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, $F_{msy}$ would be a limit reference point and fisheries management strategies should insure that the risk of exceeding $F_{msy}$ is very low. $B_{msy}$ could be interpreted as a stock rebuilding target. If a stock falls below $B_{msy}$, steps should be taken to promote stock rebuilding (e.g. reduce fishing). If a stock is assessed to be above $B_{msy}$, fishing mortality should not exceed $F_{msy}$.

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

This paper presents an example of age-structured production modeling using data from the

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southern Gulf of St. Lawrence (NAFO Div. 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, it is hoped the example promotes discussion of the appropriate use of this type of modeling for defining fisheries management strategies.

## Methods

### 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, see chapter 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 and variable, one would not expect to see a strong relationship between stock size and recruitment. Most assessment time series begin after stocks had already been reduced by fishing, the population age structure had already truncated and the biomass had already been reduced relative to the potential range over which the stock/recruitment relationship could operate. Also, 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 of St. Lawrence cod-like population (same age range, weights-at-age, and partial recruitment) over a 41-year time period. A Ricker type 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, and $\sigma$ is a normal variate 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

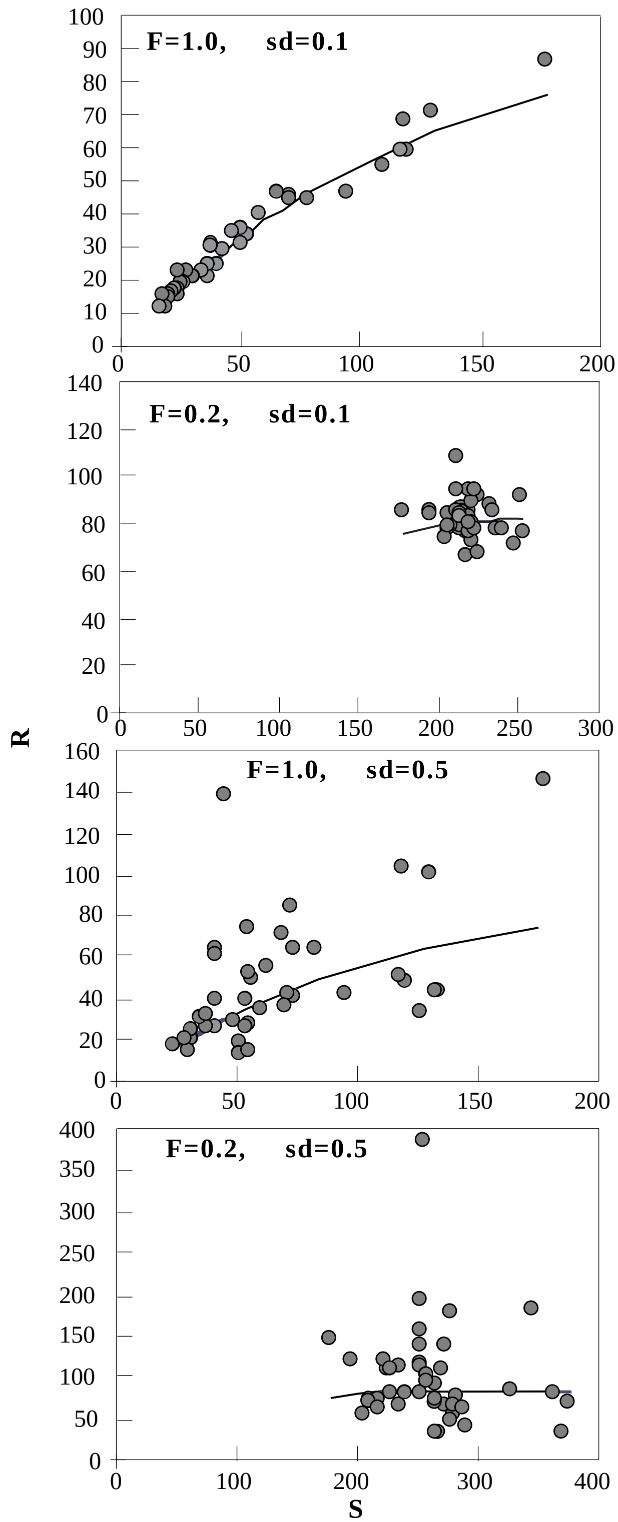


Fig. 1. Scatter plots of stock ($S$) and recruitment ($R$) from simulations with different levels of process error in the stock-recruitment relationship ($sd$) and $F$. The underlying stock-recruitment relationship (shown as a solid line) is masked by high process error and low range in stock size.

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 (MS 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. These simulations are meant to illustrate the point that a stock/recruitment relationship may be masked by reasonable levels of process error and a restricted range of observations. They are not meant to illustrate the southern Gulf cod stock *per se*.

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 tons. When the fishing mortality was 1.0 throughout the simulation, *S* declined considerably providing a range of observations of stock size and recruitment from the upper to 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 tons, 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* was 0.2, the stock tended toward an equilibrium position, yielding in the order of 30 000 tons annually. However, when the process error was high

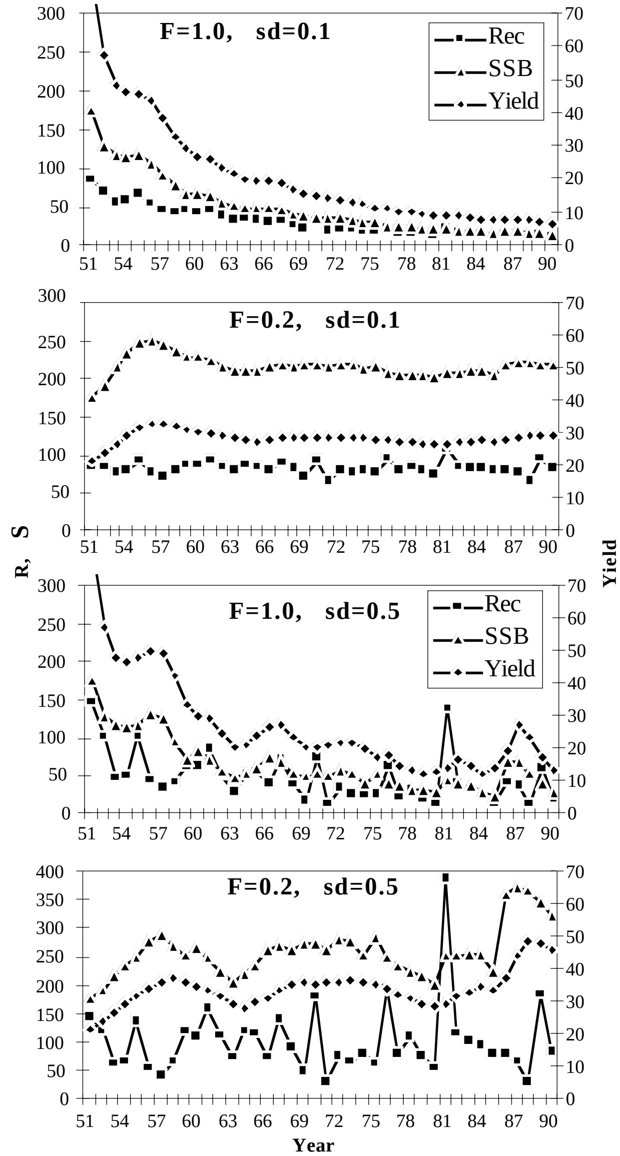


Fig. 2. Example trajectories of recruitment (*R*), spawning biomass (*S*), and yield from one replicate simulation of the effect of *F* and recruitment process error (*sd*) on stock production.

(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

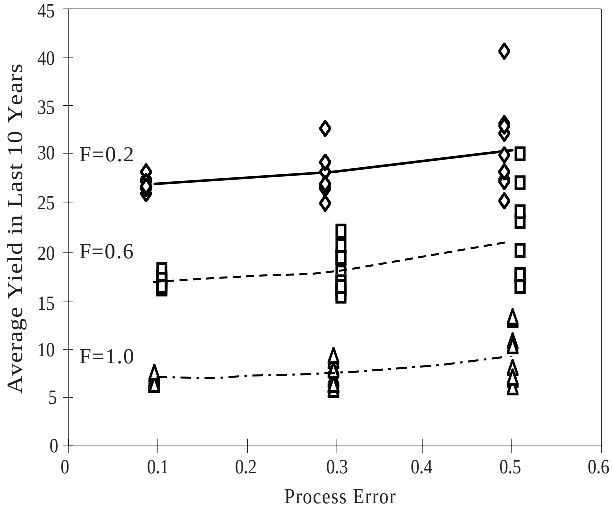


Fig. 3. Average annual yields from the last 10 years of simulations with different process errors and fishing mortalities. Yields were higher at lower *F*s. Yields increased with the level of process error.

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. However, examination of the stock-recruitment plots may lead an investigator to the false conclusion that there is no relationship. An $F_{msy}$, or high *F* strategy, may be adopted with corresponding low yields and the potential of stock collapse.

This analysis was not meant to provide evidence that stock-recruitment relationships exist (this is done elsewhere, e.g. Chapter 7 in Hilborn and Walters, 1992). 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 (e.g. stock collapse).

## 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. *Y*/*R* 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 (see details in Section 5, Rivard, 1982). 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). A Ricker type stock-recruitment relationship is as follows:

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

It is then possible to estimate equilibrium conditions from the estimated parameters (Anon., MS 1996; Ricker, 1975, Appendix III). 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 *MSY*; $F_{msy}$, the fishing mortality rate corresponding to *MSY*; and $F_{crash}$, the unsustainable fishing mortality, 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 *Y*/*R* and stock production reference points were investigated by conducting 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 to 1995 assuming lognormal error distribution (Sinclair *et al*., (MS 1996), Table 2, Fig. 5). The fitted parameters are given below and were used in all analyses.

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

There were important differences in estimated reference points from the *Y*/*R* and age-structured production analyses. $F_{0.1}$ remained relatively stable in these periods, varying between 0.17 and 0.21

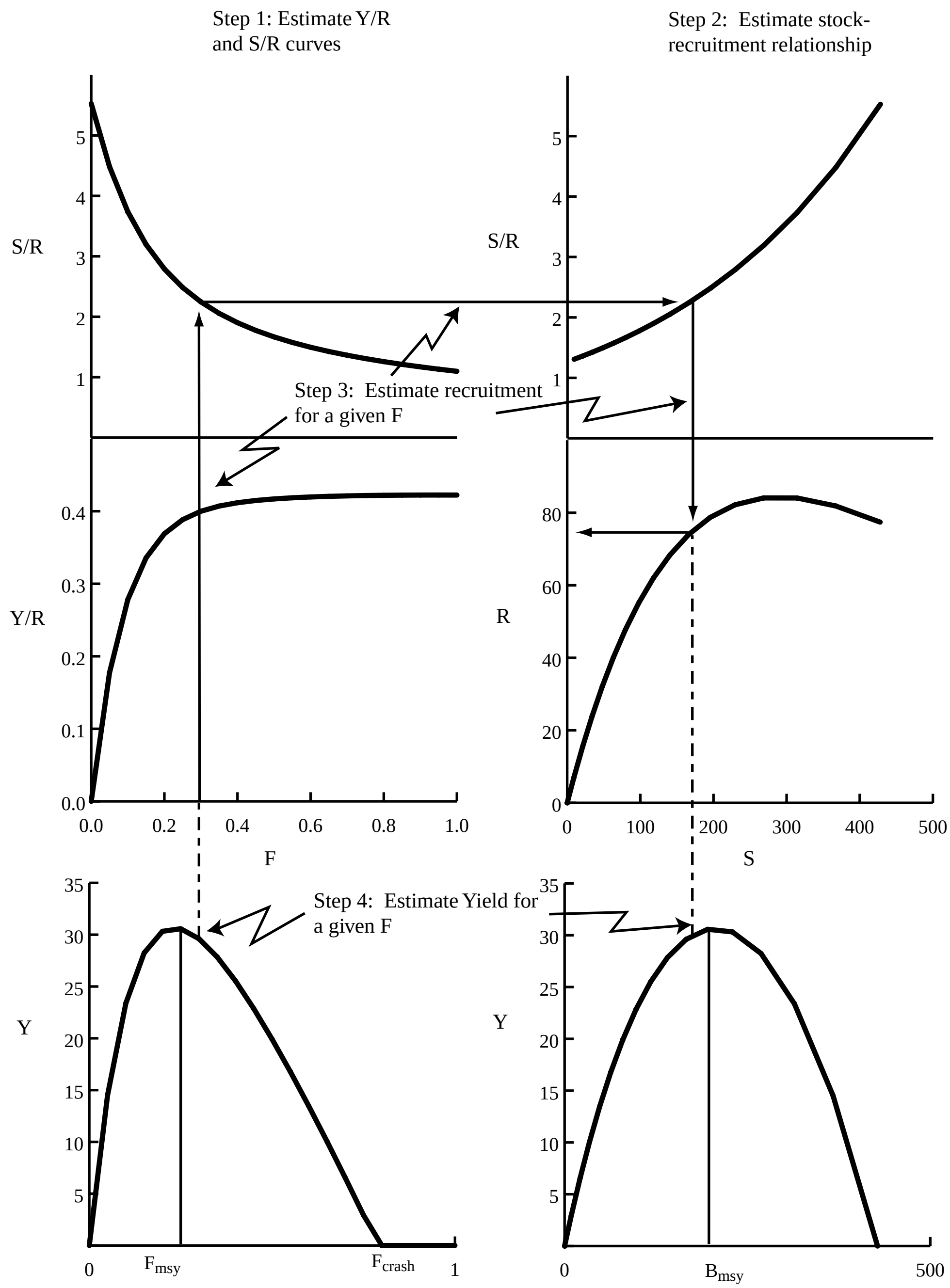


Fig. 4. Family of curves describing yield ($Y$) per recruit ($R$), spawning stock biomass ($S$) per recruit, and yield as a function of fishing mortality ($F$). The steps to relate the curves are described in the text (based on Fig. 1 of Sissenwine and Shepherd (1987)).

(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 tons to 31 000 tons.

The differences in the type of information available from the two models is shown clearly by comparing the yield and $Y/R$ *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

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 (*Y*/*R*) 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 |

production resulting from reduced weights-at-age may affect both total yield and $F_{msy}$. This is contrasted with *Y*/*R* curves which are distinctly flat-topped, and which do not decline at high *F*s. Ignoring the yield curve and concentrating only on the *Y*/*R* 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. Even though the *F*s 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 *Y*/*R* 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, a knife edged *PR* was used and the age of full recruitment was varied 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. The weights-at-age from the 1990–95 period were also used.

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 distinctly 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. Bootstrapping of the stock-recruitment relationship was used in a attempt to illustrate these uncertainties. The Ricker stock-recruitment rela-

TABLE 2. Spawning stock biomass (*S*, '000 tons) and recruitment (*R*, millions, age 3), fully recruited fishing mortality (*F*) and landings (*Y*, '000 tons) 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 |

tionship was fit to the base data (1950–95) assuming lognormal errors. Residuals from the initial fit were re-sampled, with replacement, and added to the initial predicted values to form pseudo-replicates of the observed recruitment values. The stock-recruitment parameters were then estimated for the pseudo dataset, and the associated stock production parameters were estimated using fixed weight- and *F*-at-age (average for the 1990–95 time period). It was assumed that all the error was in the estimated recruitment, that stock size was known without error, and that weight- and *F*-at-age was fixed. It is suggested that other formulations which allow for errors in all the inputs should be investigated. A total of 300 replicates were used, all calculations were done in MS Excel 5.0, and the Solver add-in was used to estimate the stock recruitment parameters.

Cumulative frequency distributions of $B_{msy}$ and $F_{msy}$ were used to calculate risk curves of the biomass and fishing mortality reference points (Fig. 8). A risk averse approach would choose a rebuilding target biomass with a relatively low probability of being less than the true Bmsy. In this case, if a 20% risk was acceptable, the corresponding target would be about 240 000 tons. For *F*, one would choose a limit reference point with a relatively low probability that it would exceed $F_{msy}$. Using the same 20% rule, the limit *F* would be about 0.20.

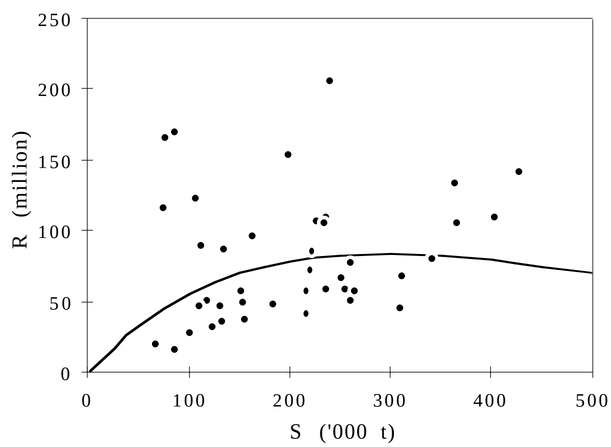


Fig. 5. Ricker stock-recruitment curve for southern Gulf of St. Lawrence cod (1950–95). Recruitment (*R*) is year-class abundance estimated at age 3, and spawning biomass (*S*) includes ages 5+.

## 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 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.

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 *F*s, and sampling variability. The consequences of falsely rejecting stock-recruitment relationships may be severe (e.g. reduced yield, stock collapse).

Age-structured production analysis is a simple extension of *Y*/*R* 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. Here a constant knife edged matu-

TABLE 3. Comparison of yield-per-recruit (*Y*/*R*) 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 | 78 053 | 1.33 |
| 80–84 | 0.18 | 4.96 | 0.65 | 0.29 | 3.73 | 0.69 | 0.30 | 3.59 | 0.69 | 58 041 | 1.47 |
| 85–89 | 0.17 | 3.58 | 0.43 | 0.30 | 2.59 | 0.45 | 0.23 | 3.01 | 0.45 | 37 460 | 0.92 |
| 90–95 | 0.21 | 2.74 | 0.37 | 0.90 | 1.17 | 0.42 | 0.23 | 2.58 | 0.38 | 30 653 | 0.79 |

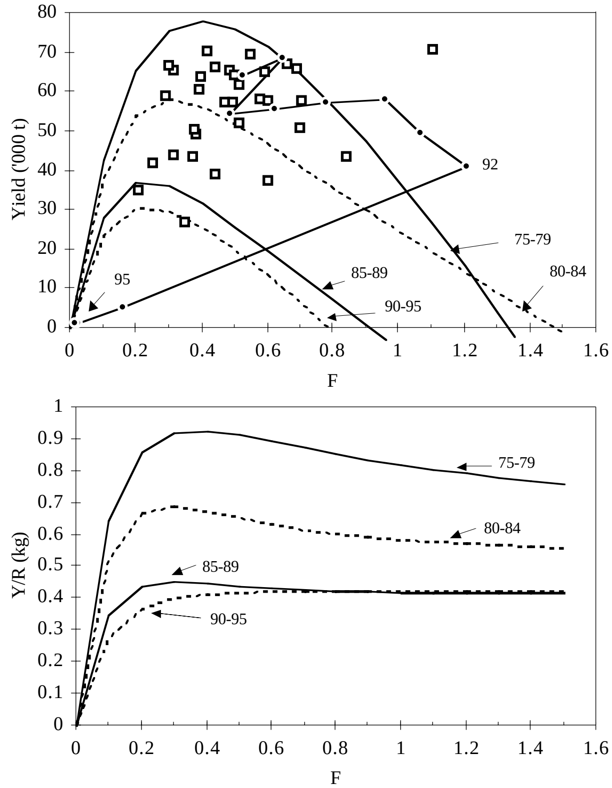


Fig. 6. Comparison of equilibrium curves of yield *vs F* from age-structured production analysis (upper panel) and yield per recruit *vs F* from yield-per-recruit analysis (lower panel) estimated for 4 separate time periods for southern Gulf of St. Lawrence cod. Observed annual values of *Y* and *F* are plotted on the upper panel. The points from 1950–84 are plotted individually while those from 1985–95 are joined to indicate recent trends.

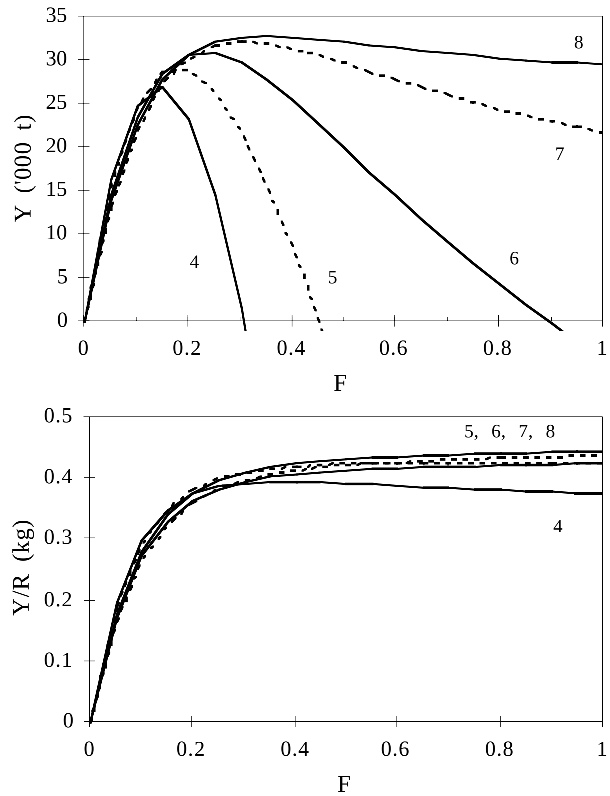


Fig. 7. Comparison of equilibrium curves of yield *vs F* from age-structured production analysis (upper panel) and yield-per-recruit *vs F* from yield-per-recruit analysis (lower panel) estimated for different ages of knife-edged full recruitment for southern Gulf of St. Lawrence cod. Weights-at-age 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.

rity ogive was used ,where as 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.

Production models and *Y*/*R* models suggest different management actions in response to changes in size-at-age of the southern Gulf of St. Lawrence cod stock. Under a *Y*/*R* management strategy where $F_{0.1}$ would be used to set TACs, there would have been little difference in the target *F*s during the period 1975–95. However, if a stock production management strategy were used, the target *F*s would have declined. This would have been consistent with the decline in 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 *Y*/*R* and production biological reference points as equivalents (e.g. $F_{max}$ and $F_{msy}$, $F_{0.1}$ and 2/3 $F_{msy}$) even though 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 this was the case, sur-

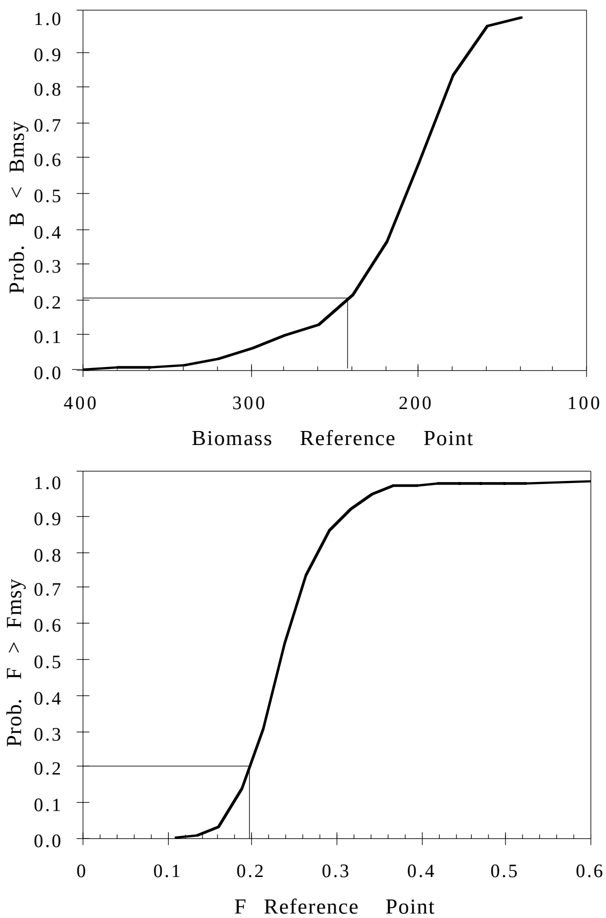


Fig. 8. Risk curves for the selection of a biomass reference point related to $B_{msy}$ (upper panel) and a fishing mortality reference point related to $F_{msy}$ (lower panel). These were estimated using cumulative distributions of bootstrap estimates of $B_{\text{msy}}$ and $F_{msy}$. **Note**. the x-axis on the upper panel is reversed.

vival from spawners to recruits would have to be inversely proportional to *F*, an unlikely scenario (Pereiro, 1992). 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 *Y*/*R* 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 *F*s 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 *Y*/*R* analysis alone.

In this study, an attempt is made to account for the uncertainties in the stock recruitment relationship. 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?

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