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Stability and Sustainability of Harvesting Strategies in a Modelled Fishery

by

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Abstract.

A bio-economic model based on the Scotian Shelf groundfish mobile-gear fleet is used to explore the effects of various harvesting strategies. The model emphasizes the feedback control nature of the fisheries system, specifically the biological, economic and management controls. Uncertainty is expressed in the biological controls via environmental influences on recruitment. Also, the effect of uncertainty in the management actions will be assessed. The criteria for evaluation are levels of productivity, sensitivity to errors, and the stability of the strategy. Excursions from the average values of productivity are examined in terms of recoverable and non-recoverable deviations which we denote as stability and sustainability.

SPECIAL SESSION ON MANAGEMENT UNDER UNCERTAINTIES
RELATED TO BIOLOGY AND ASSESSMENTS.

Introduction.

The author apologizes to the reader who is expecting a document which is consistent with the usual standards of the NAFO SCR document series. This document is little more than a series of captions to the figures that were presented at the Special Session. However, the aim is to give some record of the presentation.

Recently, fishermen have been asking for quotas that are fixed over a period of years to "stabilize" the fishery. The practice in most Canadian groundfish stocks is to annually re-assess the resource, apply a target fishing mortality and update the quota. This should allow the industry to follow booms in the resource and similarly to protect it during busts. There appears to be a sort of trade-off between stability, in the sense of constant quotas over a period of time, and optimizing the catch annually. The term stability is also misleading. If constant quotas are in effect while the resource is varying, then effort will have to vary to meet the quota. Fixing one aspect of the fishery (catch, effort or escapement) means that the others will vary. In general, stability with respect to one of these elements means variation in the others. The question is then which sorts of variability are the least disruptive to the industry.

A traditional age-structured catch projection model has been expanded to include coarse economic considerations and quota setting. It also uses a stock-recruitment function with a environmental effect , which may be periodic or random, superimposed. The economic factors are costs of fishing and the effect of fleet revenue on fleet capacity. The model emphasizes the feedback control nature of an exploited resource. A schematic for a general feedback control system is shown in Figure 1. There is a reference target level, a process and an output. The output is measured and compared to the target. Biological density dependent feedback is explicit in the stock-recruit function. The capacity of the fleet depends upon profits. And finally, the quotas that are set represent formal feedback controls. The three feedback loops of this model are shown in Figure 2. The fishery is a common element of all three control loops. It is the output of the fleet and biological loops and the input for the management loop.

Results are presented in the form of equilibrium plots, sensitivity analysis, risk analysis and power spectra. The equilibrium plots form a link to traditional analyses such as yield per recruit or stock-recruit relationships. The sensitivity plots help reveal the interconnectedness of the modeled system. Risk analysis emphasizes the repercussions of various harvesting strategies and helps define overfishing. Feedback control systems tend to oscillate with a natural or resonant frequency and spectral analysis are an accepted tool for the investigation of oscillating systems.

Methods.

The basic model is developed from an age structured description of a fish stock. The model is based on cod and 15 years ages are included. A Shepherd (1982) stock recruitment curve is operant and has been fitted to 4VXX cod data and is mildly domed. The numbers at age, $N_{a,y}$, have subscripts of age and year and B_{SS} is spawning stock biomass which is defined with a maturity ogive Mat_a and weight at age W_a (Table 1).

$$B_{SS} = \Sigma \, Mat_a \, W_a \, N_{a,y}$$

$$N_{1,y+1} = a_1 \, B_{SS} \, (1 + (1 + (B_{SS}+a_3)^{a_2})$$

where the parameters a_1, a_2 and a_3 are respectively 3.33, 2.5 and 70 with recruitment in millions of animals and biomass in thousands of tons. Recruitment is also mediated by an environmental signal which is user supplied. The environment acts serially and is random (log-normal) with a range of approximately an order of magnitude and a coefficient of variation of 40%. Catch is modeled with Baranov's catch equation and selectivity is taken from a recent assessment. (see Table 1)

We define fleet capacity as the potential effort that the fleet may exert. The actual effort exerted in a year is the lesser of the capacity and the effort limits imposed by the management regime (if any). Three types of management regimes have been used with the model: i) target fishing mortality, ii) target catch and iii) target escapement. Results using target escapement strategies are not reported as in general they were much less stable than the other tow types. The target fishing mortality is mediated through a catch level as is the practice for many Canadian groundfisheries. The profit is defined for the fleet with a fixed cost of 25000 and a variable cost of 65000 per boat and a labor cost of 40% of the gross revenue. The response to profit is that the capacity can go up or down by a maximum of 5% per year. The capacity responds weakly to the profit with a sigmoid function with a standard deviation of a 10% profit rate. That is a 10% profit will cause a 3.4% increase in capacity , a 20% profit a 4.8% increase, etc. One should note that this is a negative feedback in that more boats will tend to have lower profit rates and the system will stabilize. Neither opportunity costs nor net present values (discounted future returns) have been used in these calculations.

Results.

Figure 3 shows equilibrium values for the fishery model when the feedback controls are not operating. The upper plot is analogous to a standard yield and biomass per recruit calculation. It is a production model with the recruitment constrained to a fixed level. $F_{0.1}$ and F_{Max} are approximately .2 and .4 respectively. The lower plot in Figure 3 contains the economic variables, revenue, cost and profit for the fleet. The maximum profit point is about midway between $F_{0.1}$ and F_{Max}. The effort units on the x axes are 1000 times F, or equivalently the q is .001.

Figure 4 plots the same variables as figure 3, but in this case only the biological feedback control is operant. The feedback control is applied to the recruitment level and is a production model. As expected the biomass does not vary as much as figure 3 which is unregulated. The yield and profit curves decrease slower a high effort levels than Figure 3.

Figure 5 displays the results when only the economic feedback control is active. The upper plot of biological variables is identical to Figure 3. Because the fleet fishes less when it is uneconomic to do so, the profit as a function of effort does no go so negative at low fishing levels. Nor does it go negative at high efforts as was seen in Figure 3.

Figure 6 has both biological and economic feedback control operating. The maximum profit point is now about 0.6, much higher than F_{Max} from yield per recruit.. The profits at very low fishing levels are worse than in Figure 5 because the biological regulation implies much lower biomasses, and hence catch rates, for the 'near virgin' fishery.

Figure 7 is a sensitivity plot which looks at the effects of the variables on the x axis to a 10% change in the natural mortality (m), the gear efficiency (q), the effect of profits on future effort (Effort profit) and the target F. The system is first run with the variable at their standard levels, in this case $m = 0.2$, $q = 0.001$, the effort profit is as described above and the target F is $F_{0.1}$ which is 0.2. Profits are seen to be the most sensitive variable of those tested. For example and 10% increase in the natural mortality shows a 30% negative effect on profits. As is consistent with Figures 3-6 an increase in the target F to 10% above $F_{0.1}$ has about a 5% increase in profits while it has only about a 2% negative impact on the biomass.

We earlier stated that if the effort were constrained to a fixed level the catch would vary up and down with the biomass and conversely if the catch were constrained the effort would vary in the opposite way to the biomass fluctuations. Figure 8 shows this effect. The upper plot has catches constrained at 10, 20, 40 60 and 70 thousand tons. Higher levels of catch were not sustainable. The horizontal bands show the extent of the effort variation. The lower plot has fishing mortality at various levels up to an F of 1.2 and the vertical bands show the variation in yield. The means of these distributions are shown in Figure 9a with the constant F curve being slightly higher than the constant catch. The implications of these strategies on profits are given in Figure 9b. Again the constant F strategy curve is higher. However, at F's beneath 0.5, the variation in profits is much lower for the constant catch strategy.

Figures 10 and 11 are risk analyses for constant catch strategies. Figure 10 shows the fishing mortality of the last 30 years of simulations with TAC's set at various constant levels. For reference, $F_{0.1}$ and F_{Max} are also shown. At higher levels of TAC's the distributions of points are seen to trial off to the left. This reflects high effort and low catches and is an indication of the stock being considerably depleted. This occurs at above twice F_{Max}. Figure 11 shows the effects on biomass of the same simulations. Only the highest level of catch, nominal 100 thousand tons and denoted by x's, shows the skewing to the left which indicates stock collapse.

Figure 12a shows annual catch and effort values when the TAC is updated only every 5 years. Even at a relatively low effort of 400, which correspond to an F of 0.4, a large scatter is seen in both catch and effort. Locking the TAC for 5 year periods destabilizes the feedback control. An over-estimated TAC for one five year period is followed by an underestimate for the next. The lower plot again has the TAC's fit for 5 years but in this case the TAC is set by using the geometric mean recruitment for the first three age classes. This is seen to stabilize the excursions, particularly in catch, compared to Figure 12a.

Conclusions.

The addition of feedback controls into fishery models is seen to dramatically effect management strategies. Biological feedbacks have been included in production models for many years. Less commonly have they not been combined with economic and management controls. When these controls are added, the target F levels analogous to $F_{0.1}$ and F_{Max} have much higher values than the yield per recruit derived values. $F_{0.1}$ moved from .2 for yield per recruit to about .6 when both biological and economic controls were operating. The choice of model has an effect of at least similar magnitude to the precision of the model. This may be thought of in accuracy versus precision terms. Doubling the precision of a traditional yield per model will not help if biological control of recruitment and growth are important factors.

The constant catch strategy is least disruptive in terms of annual variation in profits. A hybrid strategy where catch is constant for 5 years and then re-assessed to a target F showed a higher variation in catch/effort than either 'pure' catch or effort strategies, especially at higher F's. Our results suggest that such a method would perform much better if it incorporated some damping. In Figure 12 the damping was included by using the GM average recruitment for three years in setting the TAC's.

These results are not meant to be definitive. Rather, they are meant to engender more interest in the develop of models which are more closely related to the real situation. If the effects incorporated above can be quantified, they should be included. Even if they cannot, estimates can be derived to demonstrate the magnitude of the potential impacts and in which directions biases might be expected.

Bibliography.

Shepherd,J.G. 1982. A versatile new stock-recruitment relationship for fisheries, and the construction of sustainable yield curves. J.Cons.int.Explor.Mer, 40(1):67-75.

Table 1 Descriptive parameters used in simulation. They are based on Fanning 1989

Age	Weight	Maturity	Selectivity
1	.07	.00	.000
2	.33	.06	.000
3	.60	.35	.086
4	.96	.59	.379
5	1.48	.81	.759
6	2.10	.91	.845
7	2.81	.96	1.000
8	3.66	.97	1.000
9	4.39	.98	1.000
10	5.40	1.00	1.000
11	6.20	1.00	1.000
12	7.11	1.00	1.000
13	8.05	1.00	1.000
14	8.44	1.00	1.000
15	9.49	1.00	1.000

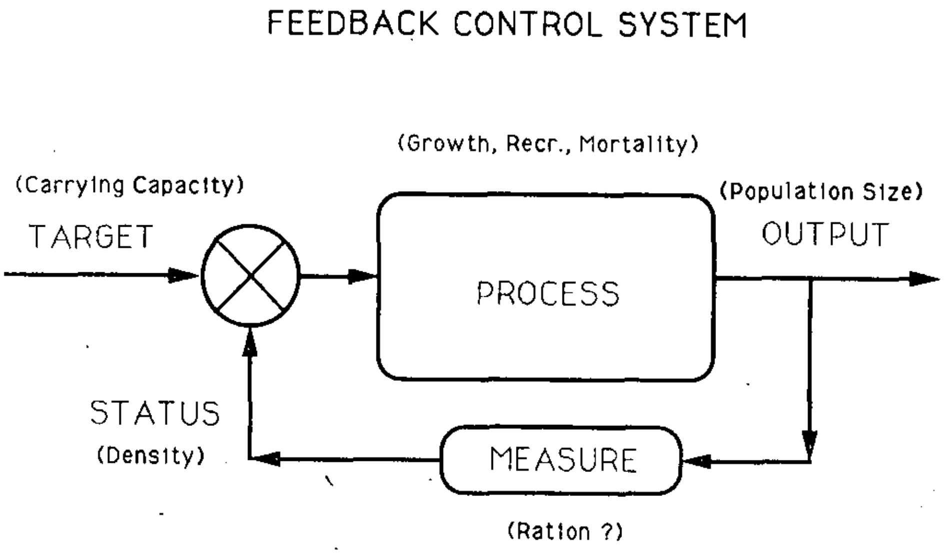

Figure 1. Schematic of feedback control. Biological based parameters are in brackets.

Fishery System Model

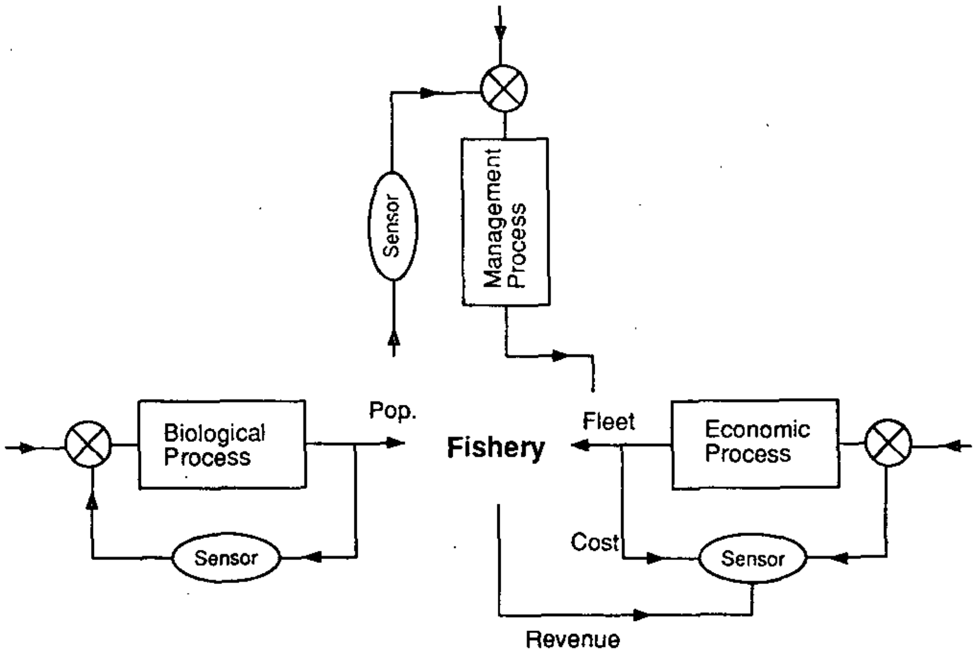

Figure 2. Fishery system model incoporating three feedback control loops.

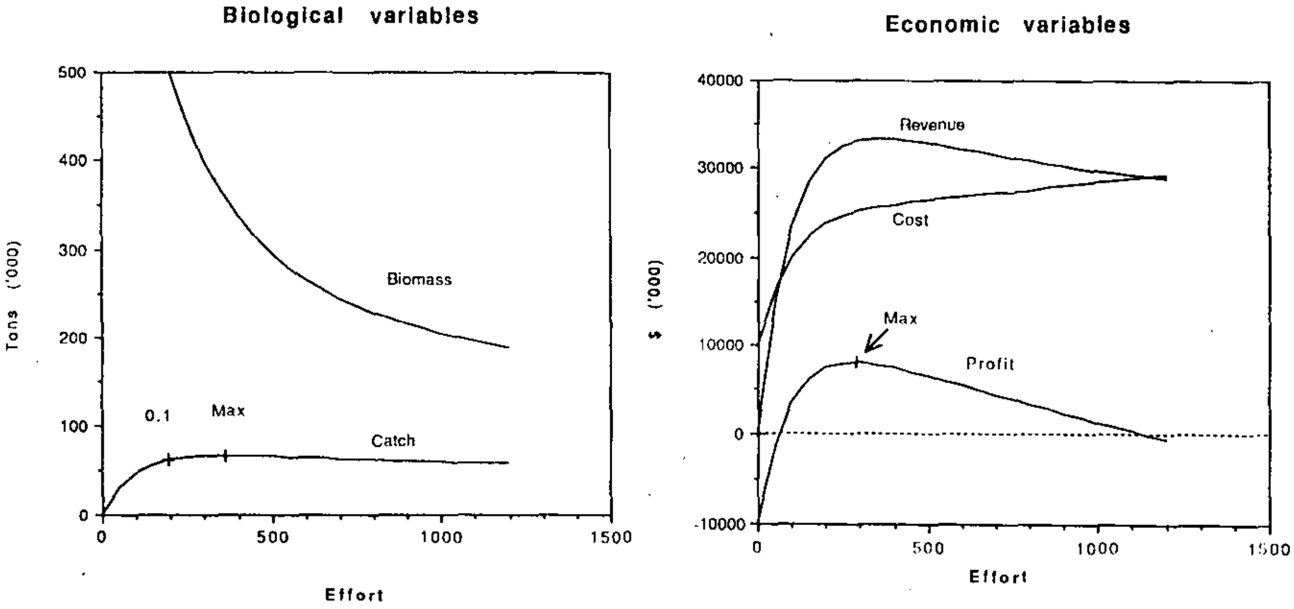

Figure 3. Equilibrium results with no feedback controls.

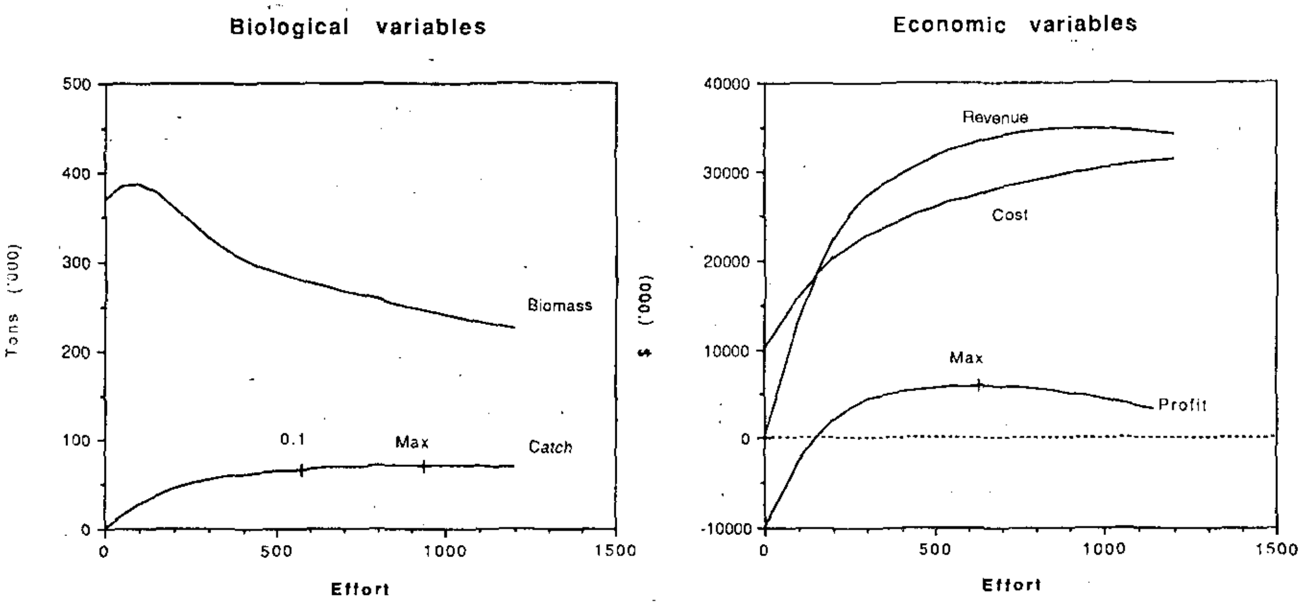

Figure 4. Equilibrium results with biological feedback control.

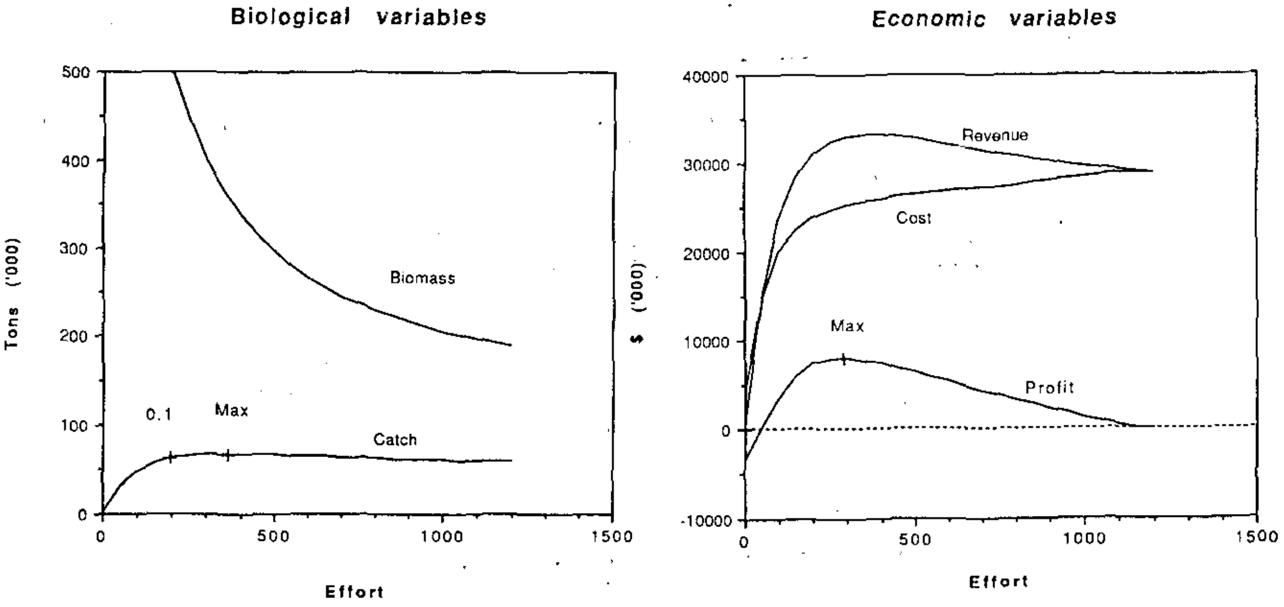

Figure 5. Equilibrium results with economic feedback control.

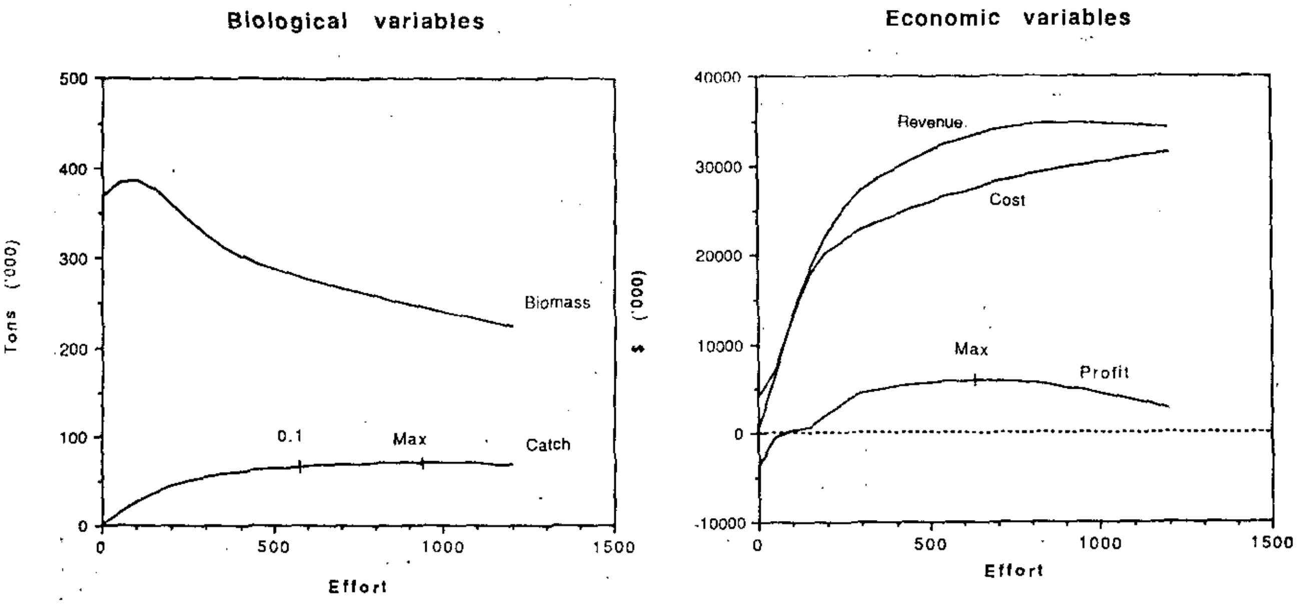

Figure 6. Equilibrium results with biological and economic controls.

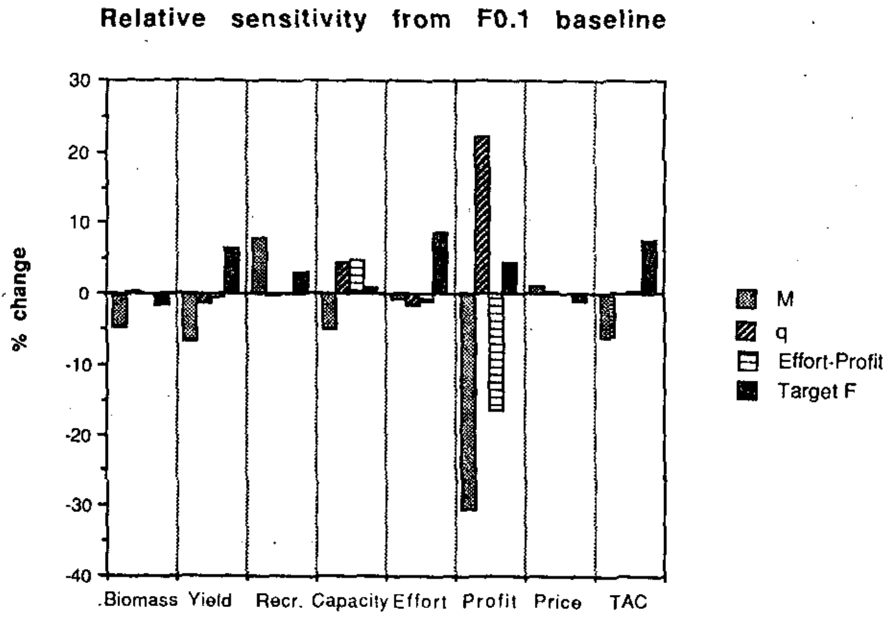

Figure 7. Relative sensitivity to 10% changes in natural mortality, efficiency, economic feedback and target F.

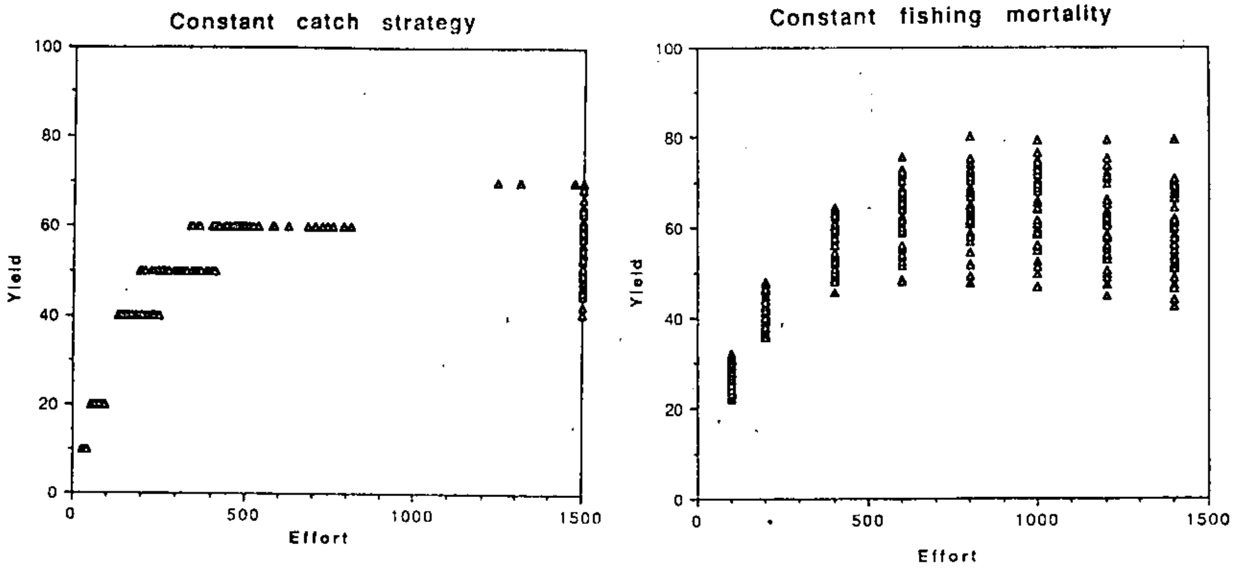

Figure 8. Comparison of constant catch and F strategies.

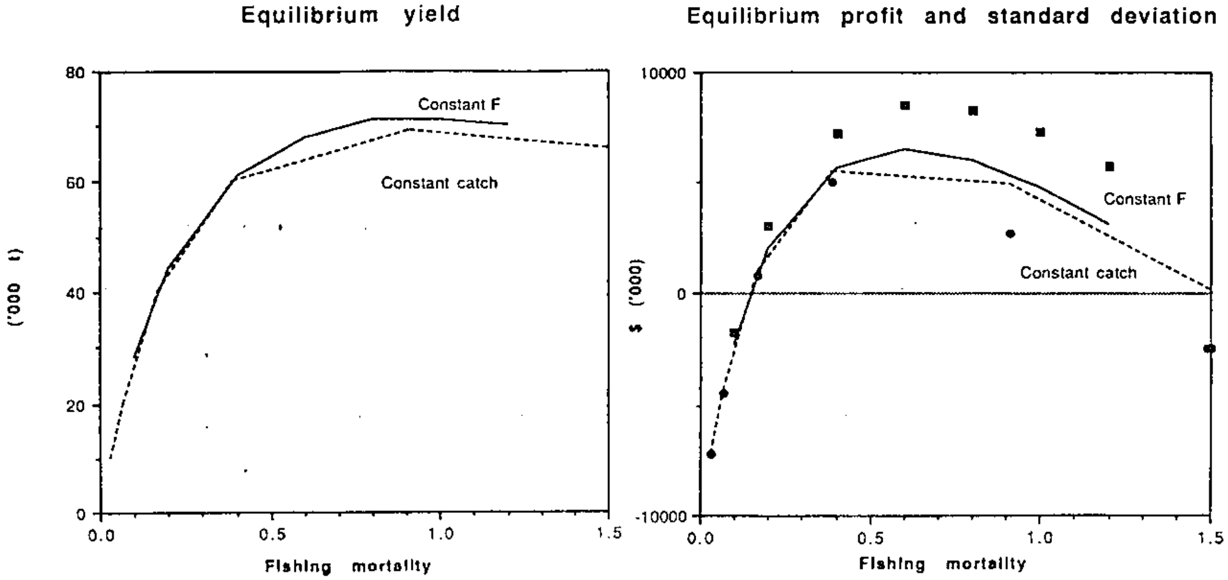

Figure 9. Comparison of constant catch and F strategies.

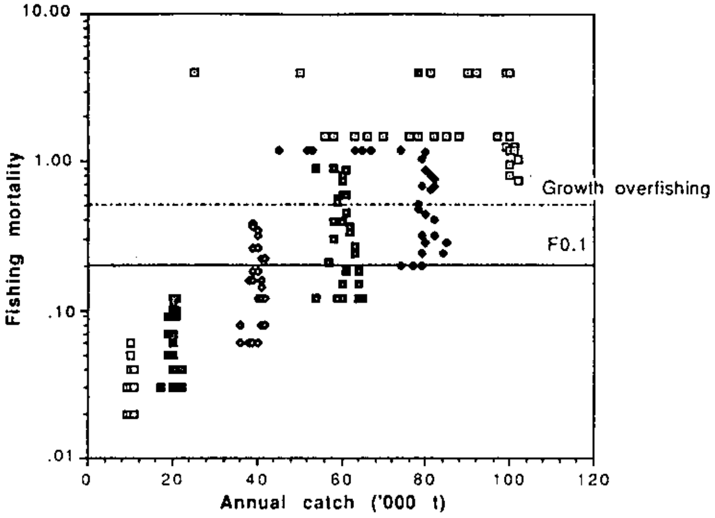

Figure 10. Response of fishing mortality to constant catch strategies.

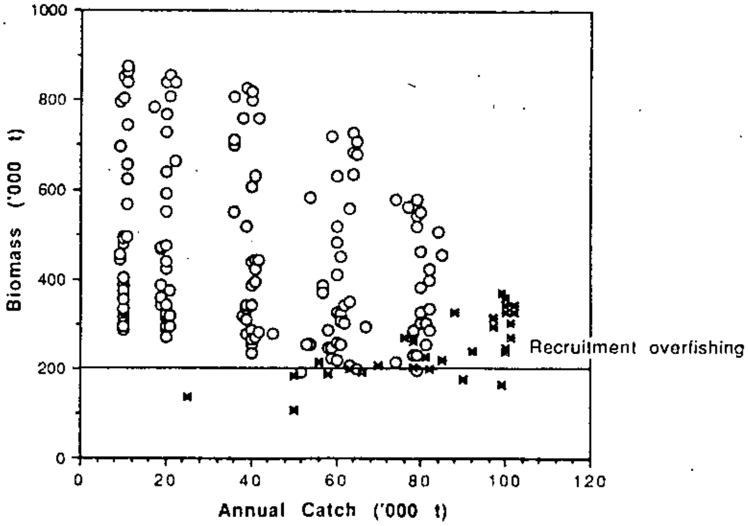

Figure 11. Response of biomass to constant catch strategies.

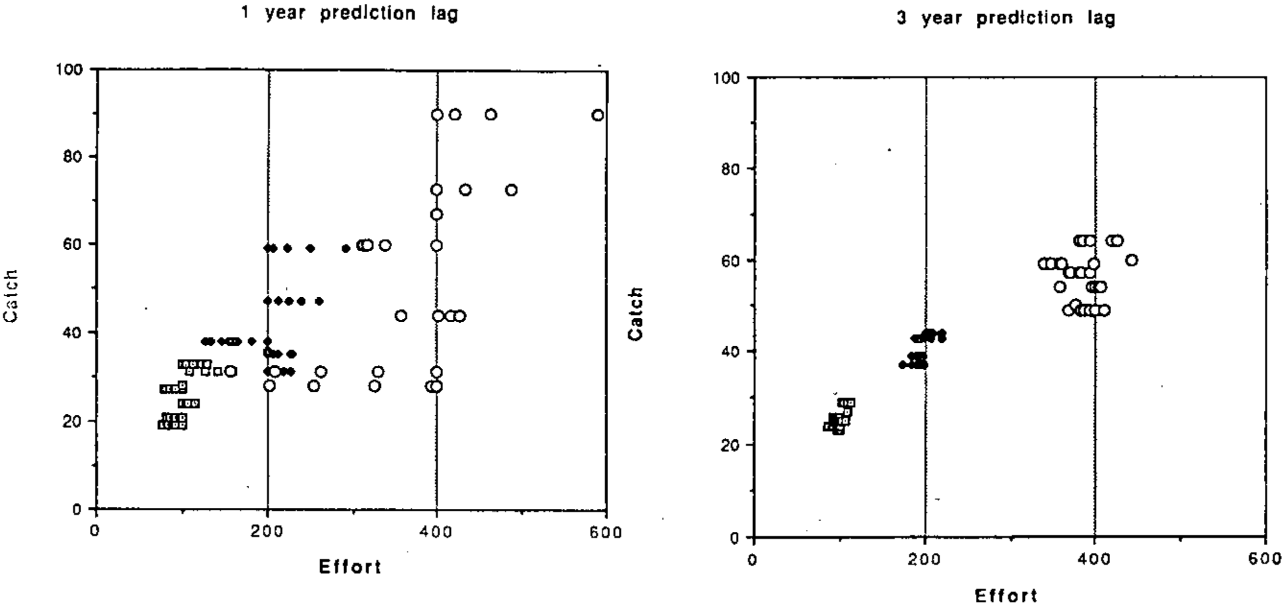

Figure 12. Prediction lags of 1 and 3 years with TAC's fixed for 5 years.