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Environmental Fluctuations and Fisheries Management

by

W. G. Doubleday
Department of the Environment
Fisheries and Marine Service
Biological Station
St. Andrews, N. B.
Canada

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Abstract:

The effect of random fluctuations in production on the success of fisheries management schemes is examined using a discrete version of Schaefer's (1954) model. Control of stock biomass, catch, and effort are considered. The average yield taken is shown to be inversely related to yearly fluctuations in yield. Control of stock biomass maximizes the average yield at the cost of large fluctuations in catch. Control of catch requires a large reduction in average yield to obtain stability. The effects of controlling effort lie between those of controlling biomass and controlling catch.

The restoring force of an exploited stock to deviations from equilibrium is examined and the presence of a critical zone of biomass less than one fourth of the virgin biomass in which further displacement weakens the restoring force and from which recovery of stock biomass is slow is noted. It is shown that control of effort at a level corresponding to an equilibrium biomass of two thirds the virgin stock instead of one half as is commonly recommended achieves a reduction in catch variance of from 60% to 75% and an increase of catch per unit effort of 33 1/3% with a loss in yield of 11%. The biomass buffer between equilibrium biomass and the critical zone is increased 133% making the stock more resilient to depletion by a succession of weak year classes.

Introduction:

"The preceding analysis assumes that the only variable factor affecting the fish stocks is the amount of fishing, but other, environmental, factors can have big effects. One of these is the variation in recruitment, ..." (Gulland 1969). This caveat can be appended to almost any stock assessment. In this paper, the theoretical consequences of recruitment-induced fluctuations in production on fisheries management are examined and shown to be serious. The fisheries manager must balance stability and yield and cannot ignore one in search of the other.

MSY and Yield per Recruit:

Various definitions of maximum sustainable yield (MSY) are possible. One possibility is to define the MSY of a stock as the maximum long term yield in weight which may be removed from a stock. Implicit in this definition is a range of management strategies over which the yield is optimized, and the conservation of the stock (extinction implies a long term average yield of zero). A more restrictive definition would require that the same yield be taken each year.

In the absence of recruitment fluctuations, there is no difference between the two yields, but, if fluctuations are present, the latter yield is considerably smaller than the former, as will be shown below, due to the inevitable drift of the spawning stock biomass into a zone of low recruitment.

Many stock assessments for the ICNAF area are based on the concept of maximizing the yield per recruit. Managing on this basis ensures a maximal catch for a given mesh selection curve from year classes which have recruited, but ignores the conservation of the spawning stock. Sustainability of the maximum yield per recruit depends entirely on the wisdom of the scientists who determined mesh size regulations years ago and is not, in any sense, guaranteed.

Stock and Recruitment:

The problem of relating the state of a fish stock to its recruitment is the object of much recent research. The assumption that recruitment is independent of stock size for a wide range of stock sizes, which formed the basis of Beverton and Holt's (1957) manual is no longer considered tenable. Recent analysis of the North Sea plaice stock, for example, indicates a clear relationship between stock biomass and recruitment (Lett, personal communication). Two recent ICES symposia (1970, 1975) have dealt with this problem.

The function of stock size used to predict recruitment has evolved from abundance indices (Beverton and Holt 1957) to numbers of adults (Ricker 1958) to biomass in conjunction with temperature (Lett *et al*. 1975). It appears that spawning stock biomass can be manipulated to maximize average recruitment although fluctuations due to environmental variables and species interactions remain.

It is easy to show that if production, i.e., recruited biomass plus biomass gained by growth less biomass lost by natural mortality, is distributed about a mean which is a function of spawning stock biomass, then the long term average yield is maximized by controlling the spawning stock biomass at the appropriate level. This has been demonstrated in papers by Ricker (1958) and Larkin and Ricker (1964) by simulating a model relating stock numbers to recruitment. Unfortunately, as Allen (1973) pointed out, this strategy transmits all variations in production to variations in catch which could cause economic chaos.

In this paper, attention is focused on a model derived from that of Schaefer (1954) by imposing discrete time units of one year. This modification facilitates analysis and is in better agreement with the yearly recruitments which comprise most of the production of stocks in the ICNAF area. It is assumed that the relation between biomass and production is quadratic. Although this model can profitably be refined to include the peculiarities of particular stocks, it is simple and robust and gives a good approximation, for example, to the stock and recruit relations of Gulf of St. Lawrence mackerel (fig. 1).

For analytical convenience, a one year lag time is employed and most of the analysis assumes a constant variance in production with statistically independent deviations from year to year. Unless successive deviations are negatively correlated, these assumptions tend to result in underestimates of the influence of fluctuations. The alternative of log-normal fluctuations was examined in some simulations with similar results.

Notation:

B	stock biomass relative to virgin stock biomass $0 \leq B \leq 1$
B_{eq}	equilibrium stock biomass
P	yearly production
A	constant defining production/biomass (P/B) ratio at $B = 1/2$
F	effort scaled so that $0 \leq F \leq 1$ and $F = 1/2$ corresponds to equilibrium biomass $B = 1/2$
Y	yield
ε	normally distributed random variable with mean 0 and variance σ^2

The Model:

The yearly production at a stock biomass of B is

$P = AB(1-B)$ and the yield taken is

$Y = FAB$,

The restoring force at biomass B towards the point where $Y = P$ is $P-Y = AB(1-B-F)$.

$$B_{eq} = 1-F$$

The relation of P-Y to B together with the variance σ^2 determines the magnitude of fluctuations in production and hence the size of random displacements from equilibrium. P-Y is the net change in biomass toward equilibrium in one year.

Constant Catch and Constant Effort:

Figs. 2 and 3 illustrate the expected restoring force to displacement of biomass when a fishery is managed by constant catch and by constant effort when $A = 1$ corresponding to a P/B ratio of 1/2 when $B = 1/2$. Attempting to take the MSY catch each year results in extreme instability with a negative restoring force to displacement below $B = 1/2$. A small displacement would be followed by successively larger displacements until the stock biomass becomes zero. By comparison, management of effort at $F = 1/2$ which would give the same yield in the absence of fluctuations allows a positive restoring force to displacement below equilibrium. This is due to reduction in Y so that P-Y is positive. The results of various attempts to increase stability at the cost of yield are also illustrated. A much greater loss in yield is required when holding catch fixed to produce the same maximum restoring force as when effort is fixed.

When the stock is exploited at $F = 1/2$, the restoring force increases with increasing deviations below $B = 1/2$ until the point $B = 1/4$ is reached. Further deviation of B below 1/4 results in a decrease in the restoring force. Thus, the region $0 \leq B \leq 1/4$ is a critical zone from which the ability of the stock to recover is impaired. If the biomass enters this zone, yield is reduced for several years and a complete collapse is risked.

Observe that setting $F = 1/3$ giving an equilibrium biomass of 2/3 considerably increases the maximum restoring force and increases the biomass buffer separating equilibrium biomass from the critical zone by 133%. This strategy makes the stock much more robust in response to environmental fluctuations while losing only 11% of yield.

As F decreases from 1/2 the average yield at B_{eq} decreases slowly at first and then more rapidly. If $F = 1/2-\delta$,

$$\begin{aligned} Y &= A(1/2-\delta)(1/2+\delta) \\ &= A(1/4-\delta^2) \end{aligned}$$

The effects of changes in F on variation of yield and on the biomass buffer also change continuously. The value of $F = 1/3$ was chosen for close examination because the loss in yield is modest while the benefits are considerable. In practice, a level of F could be chosen to correspond to the size of A and σ^2 so that an acceptable level of catch variation and of biomass buffer size is obtained.

If practically possible (the three year lag time between collection of data and change in quotas at ICNAF is a serious difficulty), regulating the biomass at B = 1/2 produces the maximum sustainable yield. Slobodkin (1973) remarked that MSY seems to be obtained with biomass 40-60% of the virgin biomass for a wide range of models. If σ^2 is large, the resulting fluctuations in yield may be unacceptable. Thus, there is an incentive to examine how regulation of effort affects fluctuations in yield.

Linear Approximation:

In the neighbourhood of B_{eq}, the restoring force for fixed effort may be approximated by the line

$$P-Y = (B_{eq}-B)AB_{eq}$$

with slope AB_{eq}. This approximation has an error term $A(B-B_{eq})^2$ proportional to the squared displacement of B from B_{eq}. The % error is

$$\frac{100(B_{eq}-B)}{B}$$

Thus, the restoring force is consistently overestimated and the variance of B and Y will be underestimated.

Using the linear approximation and writing B(t) for the biomass at time t and E for mathematical expectation,

$$E[B(t)]= B_{eq} \quad = \quad 1-F \qquad \text{if } E[B(t-1)] = B_{eq}.$$

Thus, B_{eq} is a first order approximation to the mean biomass when the fishery is in statistical equilibrium.

Writing Σ^2 for the variance of B at statistical equilibrium, we have:

$$B(t+1) = B(t) + (B_{eq}-B)AB_{eq} + \varepsilon$$

so that $\mathrm{Var}\ B(t+1) = \mathrm{Var}\ (B(t))\ (1+(AB_{eq})^2) + \sigma^2$

and at equilibrium $\mathrm{Var}\ B(t+1) = \mathrm{Var}\ B(t) = \Sigma^2$

Therefore $$\Sigma^2 = \frac{\sigma^2}{2AB_{eq}-(AB_{eq})^2}$$

Fig. 4 shows Σ^2/σ^2 as a function of AB_{eq}.

As F approaches 1, AB_{eq} approaches 0 and Σ^2 increases without limit. Reducing F reduces Σ^2/σ^2 until $AB_{eq} = 1$ when the variance ratio begins to increase.

The high variance ratios for AB_{eq} near 0 are due to removing nearly all the standing stock each year. The high variance ratios for AB_{eq} near 2 are due to overcorrection for displacements so that biomass oscillates from side to side.

Simulations indicate that the approximation underestimates Σ^2/σ^2 by 10-20% for $A = 1$ $\sigma = 0.1$ with a higher % error for $\sigma = 0.05$ and is unreliable if $\sigma = 0.15$. The approximation does, however, show trends in the variance ratio correctly.

Increasing B_{eq} from 1/2 to 2/3 reduces Σ^2 if A is less than 1.6. To calculate the variance of Y, Σ^2 is multiplied by $(AF)^2$ thus Var(B) is reduced by a factor of 1/4 for $F = 1/2A$ and 1/9 for $F = 1/3A$. Thus, environmental fluctuations are partly absorbed by changes in biomass and partly by changes in yield. Increasing B_{eq} from 1/2 to 2/3 reduces the variance in yield by more than 50%, and an increase to 3/4 reduces the variance in yield by 75%. Simulations indicate a reduction in variance of yield by about 60% for the change of B_{eq} from 1/2 to 2/3.

Shift of Equilibrium:

Because the slope of the restoring force decreases for negative deviations and increases for positive ones,

σ^2 affects the equilibrium biomass for a given effort F.

Thus $E[B(t+1)] = E[B(t)] + E[AB(1-B-F)]$

So that at equilibrium $E[AB(1-B-E)] = 0$

Let this equilibrium biomass be B*.

$$E[AB] - E[AB^2] - E[ABF] = 0$$

$$B^{*2} - B^*B_{eq} + \Sigma^2 = 0$$

or $B^*(B_{eq} - B^*) = \Sigma^2$ so that $B^* < B_{eq}$

$$\frac{B_{eq} - B^*}{B_{eq}} = \frac{\Sigma^2}{B^*B_{eq}}$$

Thus, the relative loss in equilibrium biomass due to fluctuations in biomass for a fixed level of effort is approximately the squared coefficient of variation of biomass. Because of this, the average yield for a given effort F is less than AFB_{eq} and the loss is smaller for larger values of B_{eq}. The loss in yield from this factor is less than 10% and, in most cases, less than 5%.

Simulations:

Simulations were carried out to examine the effect of reduction of F from 1/2 to 1/3 and 1/4 for various values of A and σ^2. The results are shown in table 1. Examples of 50 year simulations are shown in figs. 5, 6, 7 and 8.

In the simulations, variance in catch was reduced 60% by setting F = 1/3 and almost 80% by F = 1/4. The loss in average yield was about 11% for F = 1/3 and 25% for F = 1/4. The loss in yield with F = 1/3 consisted of missed large catches while small catches were not affected. Thus, the economic loss due to the reduced average yield is minimized and is more than compensated for by the 33% increase in average catch per unit effort. In some simulations with F = 1/2, the stock biomass entered the critical zone and for several consecutive years produced lower yields than the same stock with the same environmental fluctuations regulated at F = 1/3.

Some simulations were carried out with $\ln(\varepsilon)$ normally distributed with mean 0 and variance σ^2. In these, the reduction of F from 1/2 to 1/3 resulted in a 14% loss of yield and a 70% reduction in variance.

Sources of Error:

There are many possible sources of bias and sampling error in estimating biomass and yield. In view of the asymmetry of the restoring force of a stock to displacement above and below B_{eq} and the lag time of years involved in recognizing and correcting errors in estimates, it is wise to err on the size of setting B_{eq} too high rather than too low.

Fitting a Schaefer model by a regression of catch per unit effort on effort in a declining fishery is likely to overestimate the MSY although it should produce better estimates of the appropriate effort level.

Multispecies Fisheries:

When catching groundfish with an otter trawl, it is impossible to direct fishing effort accurately at one species. Even if the production vs., biomass and effort vs., yield relationships for a number of species were such that the same level of effort resulted in the MSY for all, there is a serious danger in treating the fluctuations in combined yields as if they were from a single stock.

The difficulty is that, with a high level of exploitation, individual stocks are likely to fluctuate into the critical zone of less than 1/4 the virgin stock biomass from which they recover slowly. These stocks would be held down, as is the case with North Atlantic haddock stocks, by the removals as bycatch in fisheries aimed at other groundfish. Thus, the spectre of stock after stock fluctuating into the critical zone with a steady decrease in overall yield arises. In the presence of multispecies fisheries, it is essential to maintain a sufficient buffer of biomass for each component stock to ensure that it stays in the region where restoring force increases with displacement from equilibrium.

Conclusion:

In the presence of fluctuations in production, attempting to remove the MSY yield each year from a stock leads to disaster. Management of the stock biomass within narrow limits enables the MSY to be taken on the average but passes on environmental fluctuations to the catch. Management of a stock by fixing effort allows some of the fluctuations to be absorbed by the stock and some by changes in yield.

An excellent compromise between yield, stability, and conservation is to fix fishing effort at a level corresponding to an equilibrium biomass two thirds the virgin stock biomass. The loss in yield is 11% with a reduction in variance of yield of 60-70% an increase in catch per unit effort of 33% and an increase of the biomass buffer between equilibrium and the critical zone of 1/4 or less of the virgin biomass of 133%.

In the context of the groundfish fishery on the Scotian Shelf, following the analysis of Halliday and Doubleday (1975), a 60% reduction in fishing effort is required to achieve an equilibrium biomass of 2/3 the virgin biomass. This could be carried out in phased reductions.

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Table 1. Simulation Results

$\varepsilon \sim N(0, \sigma^2)$

A	σ	F	Years	Mean Yield	%	Variance	%
1	0.1	1/2	1000	0.244	100	0.00374	100
1	0.1	1/3	1000	0.221	90.6	0.00153	40.9
1	0.1	1/4	1000	0.187	76.6	0.00081	21.7
1	0.05	1/2	1000	0.252	100	0.001020	100
1	0.05	1/3	1000	0.223	88.5	0.000379	37.2
1	0.05	1/4	1000	0.188	74.6	0.000200	19.6
1	0.2	1/2	61	Extinct			
1	0.2	1/3	461	Extinct			
1	0.2	1/4	464	Extinct			
1.5	.1	1/2	100	0.370	100	.00846	100
1.5	.1	1/3	100	0.332	89.7	.00329	38.9
1.5	.1	1/4	100	0.280	75.7	0.00181	21.4
1.5	.15	1/2	100	0.338	100	.0227	100
1.5	.15	1/3	100	0.323	95.6	0.00769	33.9
1.5	.05	1/2	100	.378	100	.00207	100
1.5	.09	1/3	100	.335	88.6	.000806	38.9
1.5	.05	1/4	100	.282	74.6	.000442	21.4
.5	.1	1/2	100	.122	100	.00259	100
.5	.1	1/3	100	.113	92.6	.000766	29.6
.5	.1	1/4	100	.0955	78.3	.00387	14.9
.5	.15	1/2		Extinct			
.5	.15	1/3	100	.105		.00205	

$\ln(\varepsilon) \sim N(0, \sigma^2)$

A	σ	F	Years	Mean Yield	%	Variance	%
1	.1	1/2	100	.255	100	.000326	100
1	.1	1/3	100	.224	87.0	.000090	27.6
1	.4	1/2	100	.268	100	.004832	100
1	.4	1/3	100	.231	86.2	.00144	29.8
.5	.4	1/2	100	.140	100	.000619	100
.5	.4	1/3	100	.118	84.3	.000158	25.5

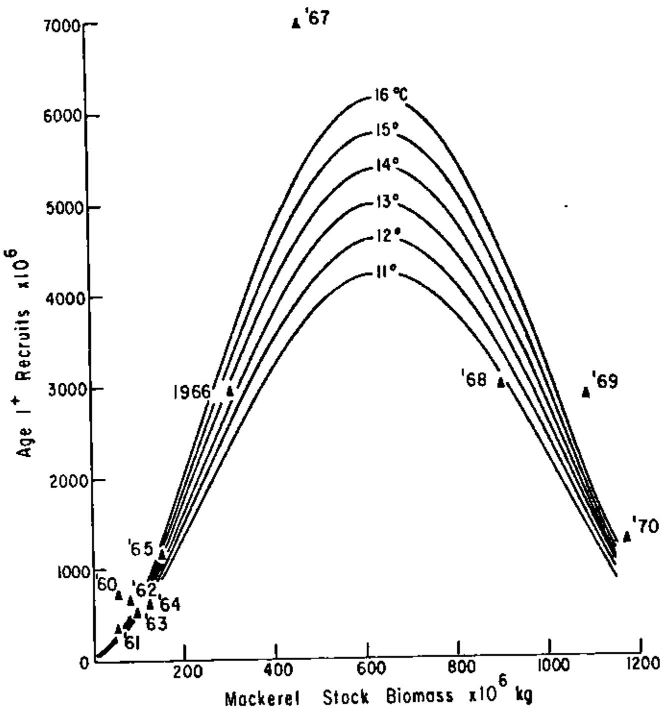
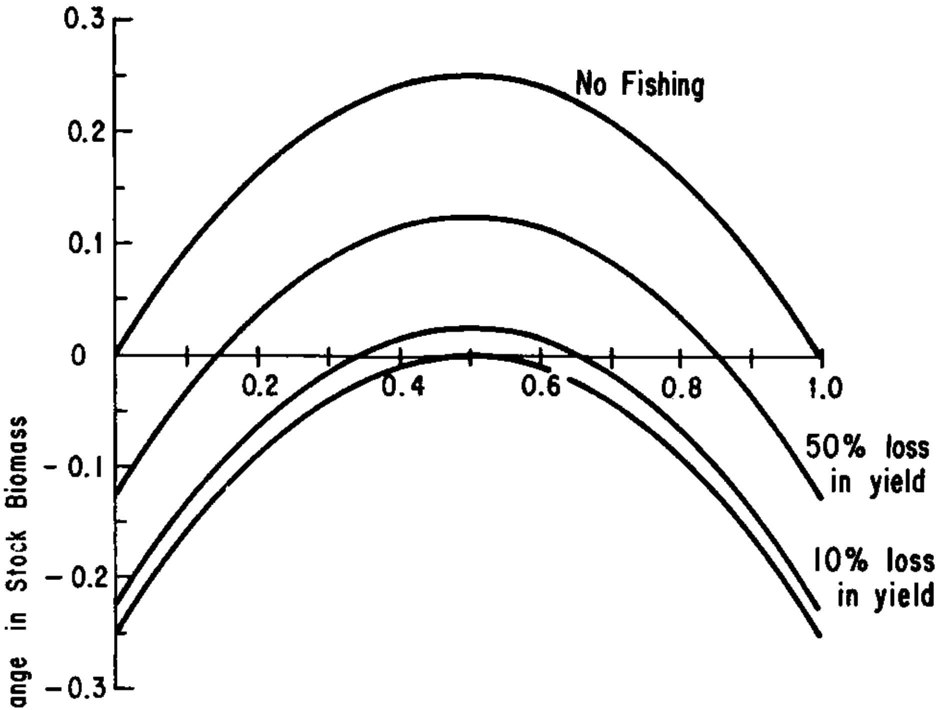


Fig. 1. Biomass and recruitment relation for mackerel in the Gulf of St. Lawrence from Lett, P. F., A. C. Kohler, and D. N. Fitzgerald. The influence of temperature on the interaction of the recruitment mechanisms of Atlantic herring and mackerel in the Gulf of St. Lawrence. ICNAF Res. Doc. 75/33: (16pages).



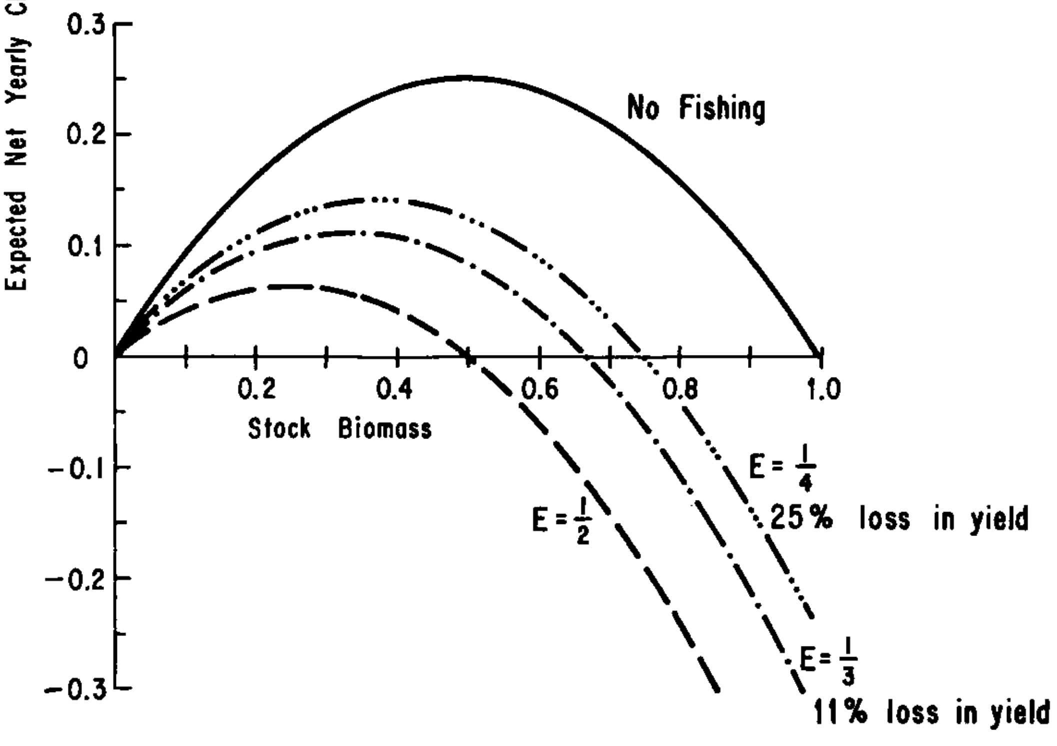


Fig. 2. (top) Expected restoring force to displacements from equilibrium under a strategy of constant catch quotas.

Fig. 3. (bottom) Expected restoring force to displacements from quilibrium under a strategy of constant fishing effort.

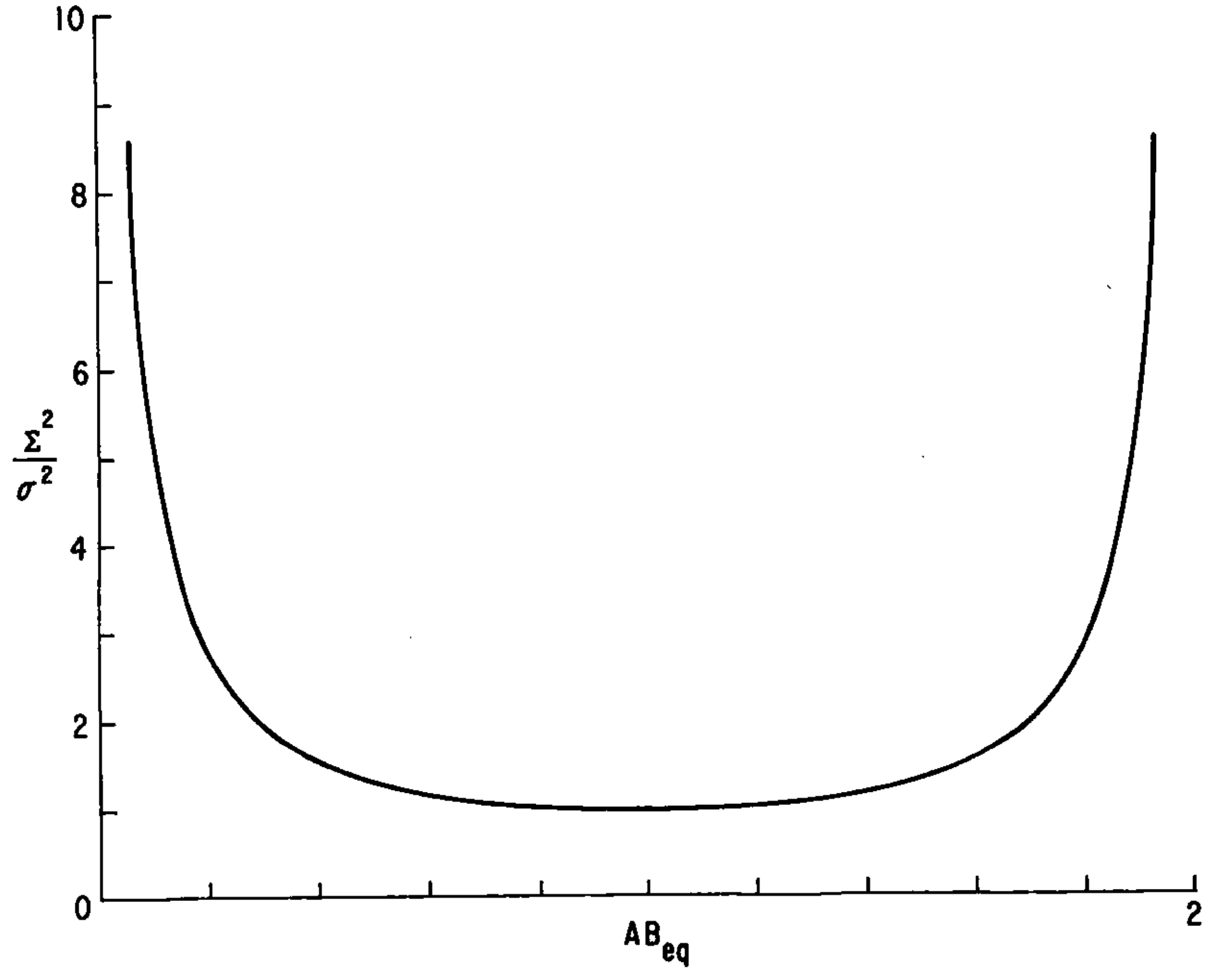
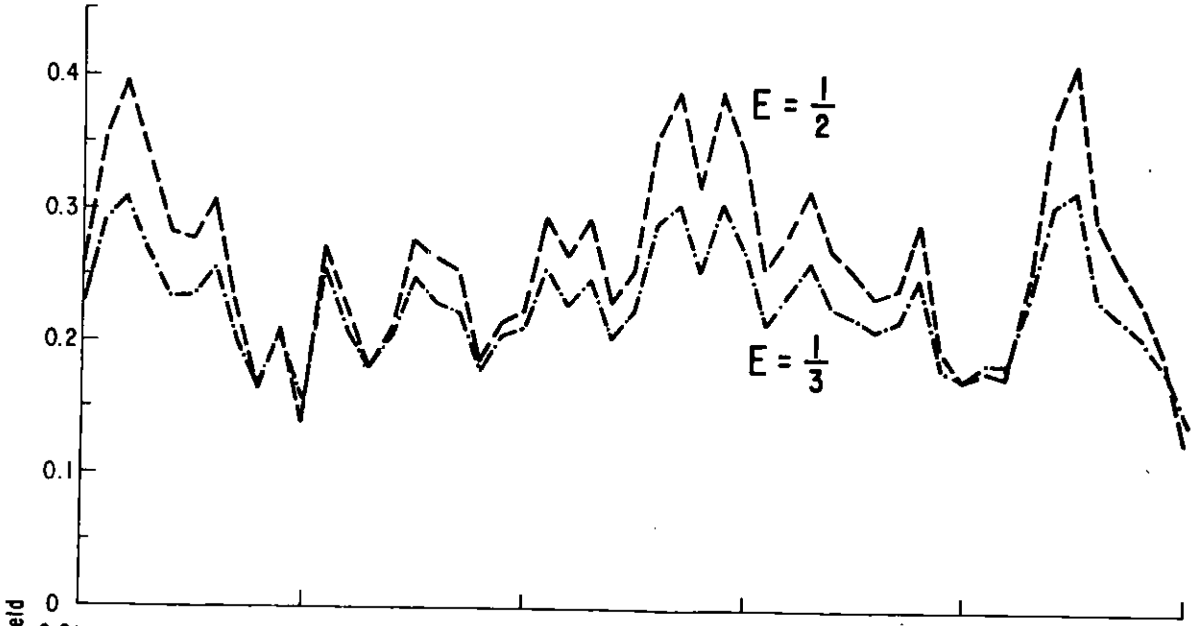


Fig. 4. Approximate relation of the variance ratio of stock biomass (Σ^2) to yearly production (σ^2) for a range of model parameters (see text).



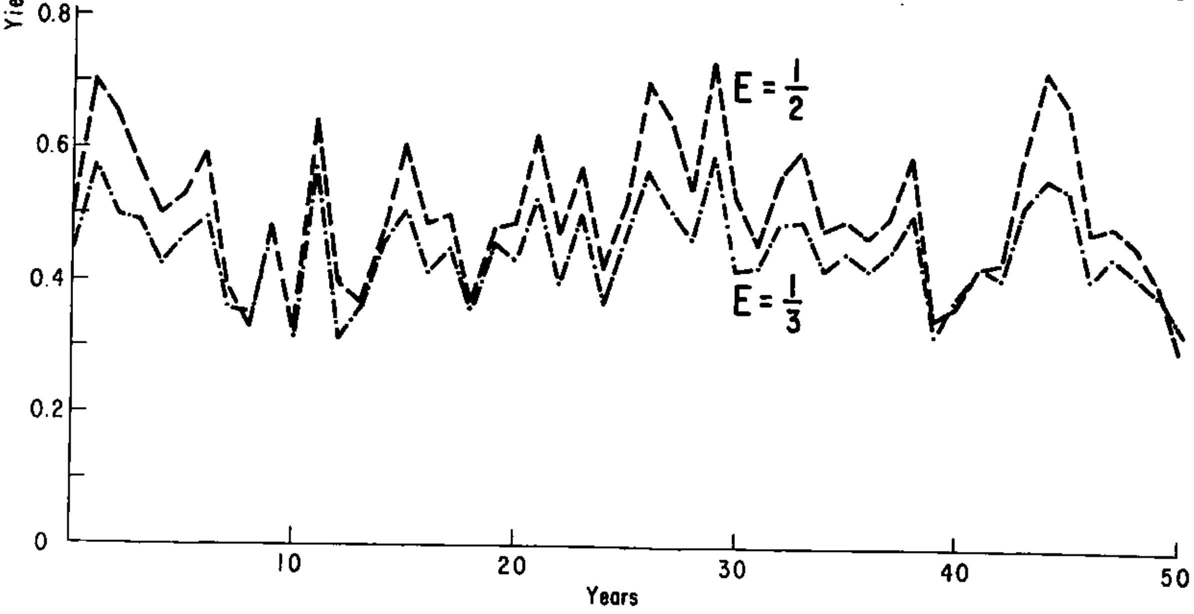
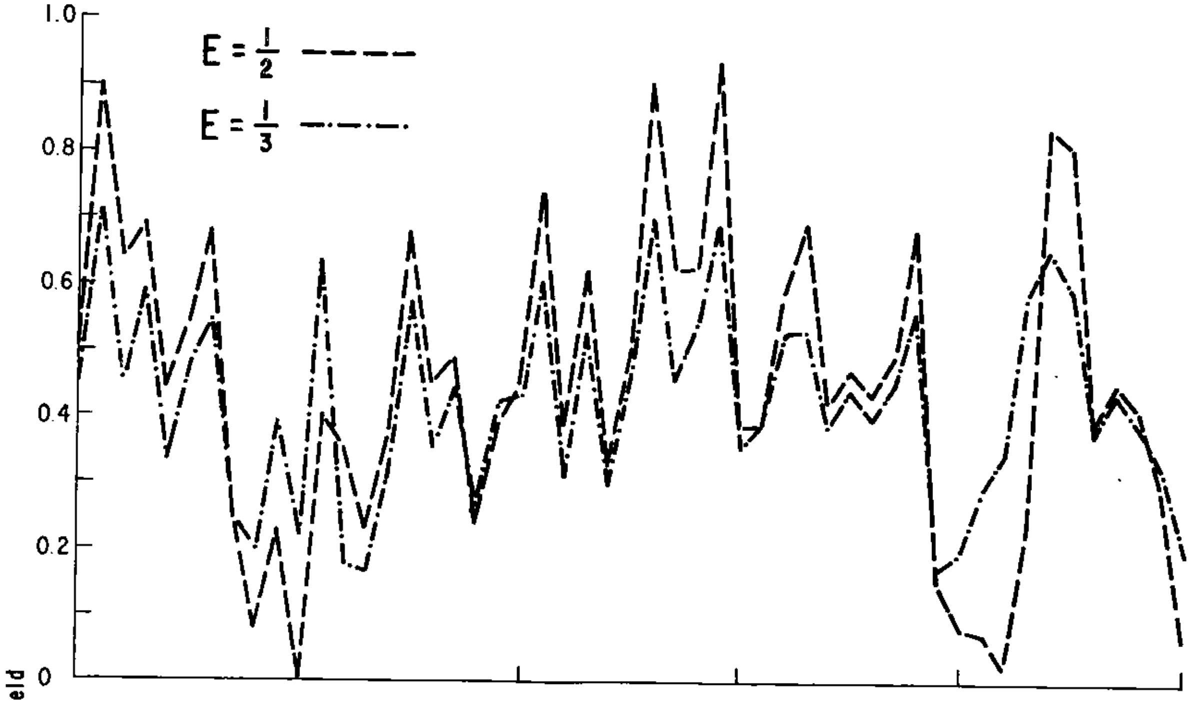


Fig. 5. (top) Simulated catches for normally distributed ϵ with $\sigma = 0.1$ and $A = 1$.

Fig. 6. (bottom) Simulated catches for normally distributed ϵ with $\sigma = 0.1$ and $A = 2$



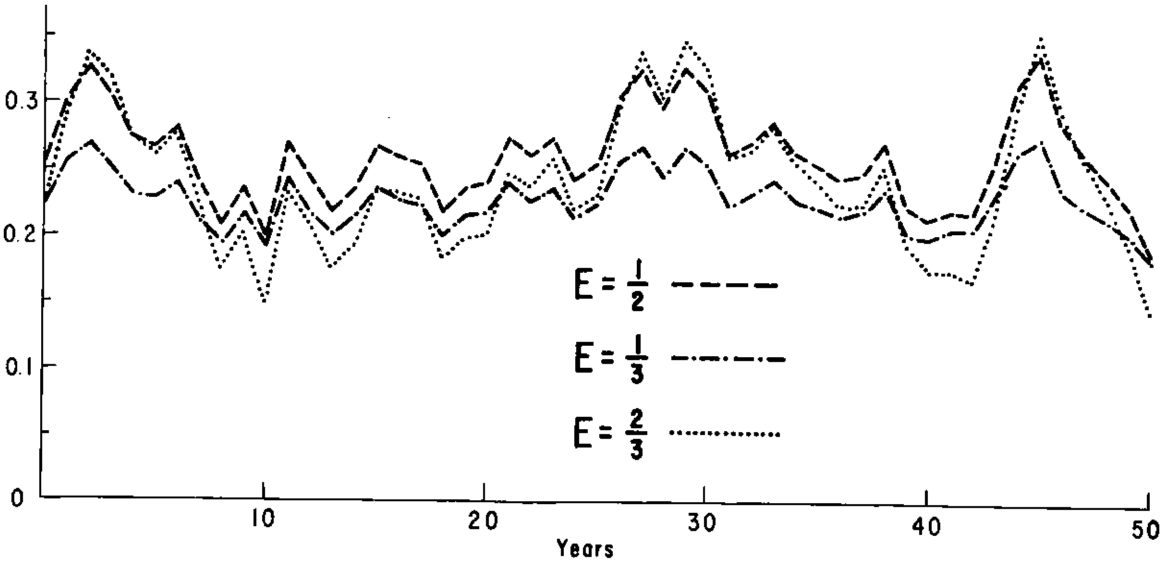


Fig. 7. (top) Simulated catches with normally distributed ϵ with $\sigma = 0.2$ and $A = 2$.

Fig. 8. (bottom) Simulated catches with log normally distributed ϵ with $\sigma = 0.1$ and $A = 1$.