The Monitoring of Biological Effects: The Separation of Natural Changes from Those Induced by Pollution [and Discussion]

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The monitoring of biological effects: the separation of natural changes from those induced by pollution

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An added mortality rate of eggs, larvae and juveniles of fish populations, or impact, is assumed to be density independent. The total mortality from hatching to recruitment is represented by the fecundity, and any increment in density independent mortality implies a decrement in density dependent mortality. At high stock the consequence is an increase in stock towards a position of less resilience: at low stock less resilience is found with a decrease in stock. In general impact generates a shift of *K*-strategy, the self-stabilizing strategy, to *r*-strategy, an opportunistic one. In a fish population very little impact should be tolerated at low stock because it would prevent recovery to a management objective such as maximum sustainable yield. At high stock, impact may generate more stock at an unknown risk.

1. Introduction

Fish lay many eggs: 3×10^3 in salmon, 4 or 7×10^4 in herring, 10^5 in plaice and 4×10^6 in cod. Such figures represent considerable mortality between spawning and recruitment. The death rates of eggs are high, 0.05 %/day in herring and 5 %/day in plaice, as are death rates of larvae, 4 %/day in herring, 5 %/day in plaice and 10 %/day in cod. The death rates of yearling fish are much lower, 0.02 %/day. Because the death rates of the juvenile fish are high, it is sometimes thought that additional mortality can be imposed without damaging the stock, or that a predatory mortality might be replaced. A pollutant or a power station might kill eggs or larvae in large numbers, for at the earliest stages in the life history they are particularly vulnerable.

However, the high death rates of fish larvae and juveniles may play a particular rôle in the stabilization of their populations. Fish grow during their lives by from three to six orders of magnitude, to the same degree as the loss by death between spawning and replacement of the stock. It is possible that the food resources of the environment are exploited by the recruiting year-class as the little fish grow, for their death rates may be controlled by there being enough food for the survivors. Such a density dependent mechanism is needed to stabilize the stock. We cannot determine the effect of an additional mortality on this process. It is assumed, however, that an additional mortality which is density independent must reduce the density dependent mortality because the total loss from spawning to recruitment is determined in the fecundity, which is a constant proportion of mass. This assumption stems from the fact that density dependent growth is not observed in adult marine fishes; in fresh water, fecundity may be density dependent as a consequence of adult density dependent growth, as for example in perch in Windermere.

2. A MODEL OF IMPACT

The word 'impact' has been used to mean the loss of eggs, larvae or juveniles to the recruitment of a fish stock (see van Winkle 1977). A convenient equation relating recruitment to parent stock is

$$R = \alpha P \exp(-\beta P), \tag{1}$$

where R is recruitment in numbers, P is stock in eggs, α is a constant which expresses density independent mortality (or more strictly, a survival), and β is the coefficient of density dependent mortality (Ricker 1954, 1958).

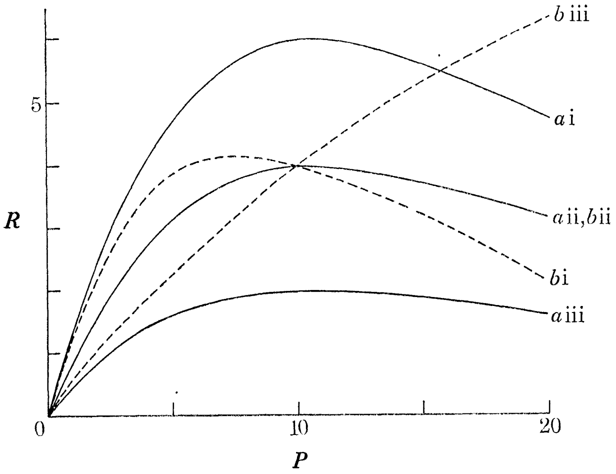

FIGURE 1. Two families of Ricker stock–recruitment curves: (*a*) $\beta = 0.0921$; $\alpha = 1.5$ (i), 1·0 (ii), 0.5 (iii); (*b*) $\alpha = 1.51$, $\beta = 0.1328$ (i); $\alpha = 1.0$, $\beta = 0.0921$ (ii); $\alpha = 0.5$, $\beta = 0.0228$ (iii).

The equation was developed to describe the generation of recruitment from the parent stock and in particular the effect of reduced stock upon recruitment. It describes the process in general terms and can accommodate the biological hypotheses, aggregation of predators, mortality due to food lack and cannibalism. (Cushing & Horwood (1977) give an account of these hypotheses.) It is used in the following treatment, partly because it has already been used in studies of this problem and partly because it has broad biological application.

Figure 1 shows two families of Ricker curves. Three curves are presented in full line with decreasing values of α, but the same value of β; they have the same shape but differ in the slope at the origin, which is α and have a maximum at $P = 1/\beta$. With no density dependent mortality, $R = \alpha P$ and the density independent effect of impact may be expressed as a reduction in α. Any reduction in α reduces recruitment and, by implication, stock in later generations.

It seems unlikely, however, that a small persistent reduction in the number of eggs, larvae or juveniles would reduce the stock permanently. The fixed fecundity implies a mortality between stock and subsequent recruitment which is determined in evolutionary terms. Therefore if density independent mortality is increased, density dependent mortality must be reduced; here we assume that the two forms of mortality can really be distinguished in biological terms. Let us assume that a decrement in α leads to a decrement in β; $\beta = -(1/P) \ln (R/P\alpha)$ and assuming constant values of R at a middle level of stock, β was calculated for a range of reduced values of α. The family of curves obtained in this way are shown as dotted lines in figure 1.

The central curve ($\alpha = 1.0$, $\beta = 0.0921$) is common to both families, but in the second the changes in shape are immediately obvious; when α is high, so is β, and vice versa.

Any family of curves, such as the second, has been constrained to pass through the common value of recruitment at $P = 10$, $R = 4$ and all would have the property that they cross there. At lower stock values, the lower curve lies below the high one and the reverse is true at higher stock values. The crossover point is arbitrary and could be set at any value of stock. At a crossover point in low stock, the curves would be steeper and at high stock shallower. As a rough rule, the maximum sustainable yield occurs at about one-half (or somewhat less) of the unexploited stock, so a value of $P = 10$ was chosen. At low stock ($P < 10$) a reduction in α will lead to reduced recruitment and then reduced stock, whereas at high stock ($P > 10$) the reduced α will be compensated for by increased recruitment. In other words, impact may endanger a stock that is exploited too much anyway, but it may enhance recruitment in an unexploited or lightly exploited stock.

Table 1

α	β	peak $= 1/\beta$
1.50	0.1328	7.56
1.25	0.1146	8.78
1.00	0.0921	10.92
0.75	0.0663	15.90
0.50	0.0228	44.80

We are more interested in the effect on stock than upon recruitment. A model was used to investigate changes in stock over an extended time period, as recruitment changes with differences in α and β as described above. Components of recruitment of random origin are added, which must be fed through the stock individually:

$$P' = R'_1 + R'_2 \exp(-Z) + R'_3 \exp(-2Z) \ldots R'_\lambda \exp[-(\lambda - 1)\, Z] \tag{2}$$

$$[\alpha' P' \exp(-\beta' P')] + e = R', \tag{3}$$

where R' is recruitment under impact P' is stock under impact, λ is the number of age groups in the adult stock, and e is the random component of recruitment.

The number of age groups in the model depends upon the total mortality, as the last age group was defined as one-tenth of its abundance at recruitment. The model was designed to iterate through many generations, new recruitments being added each year, i.e. the random component was generated by random numbers, randomly positive and negative, the mean of which was zero. It was assumed that part of the variations in year-class strength was independent of the two constants in the Ricker equation. Of course the same variability might be expressed as variation in these constants.

Figure 1 shows that recruitment is reduced as α is reduced, i.e. as density independent mortality increases; $R = \alpha P$ and as $\alpha' < \alpha$, $R' < R$. A reduction of $\alpha = 1.5$ to $\alpha = 0.5$ represents a considerable impact; the corresponding reductions in β are shown in table 1.

Figure 2 shows how stock and recruitment respond to a change in stock value of $\pm 11\,\%$ at high stock ($\alpha = 1.5$; $\beta = 0.1328$; $Z = 0.3$), i.e. with no impact. Recruitment reaches $5\,\%$ of the original equilibrium in 5 years and stock in about 15 years. Hence a run of fifty years should have reached equilibrium for changes in the stock and recruitment components alone. Figure 3 shows variability of stock and recruitment values for 50 years with no impact using the model; the figure indicates merely the degree of variability introduced by the random component of recruitment. The points are spread from top left to bottom right which reflects the sum of the slope of the curve and the random components of variability. The order of variation of recruitment is that of any marine fish population (see below).

Figure 4 shows the results of the procedure carried out with the model for the five values of α or the four levels of impact. The standard errors of the mean for 50 years are shown as vertical bars. At high stock, an impact of 0.5 (0.75/1.50 in terms of α) generates an increase in stock after fifty years which is not significantly different from lack of impact (i.e. $\alpha = 1.50$). A

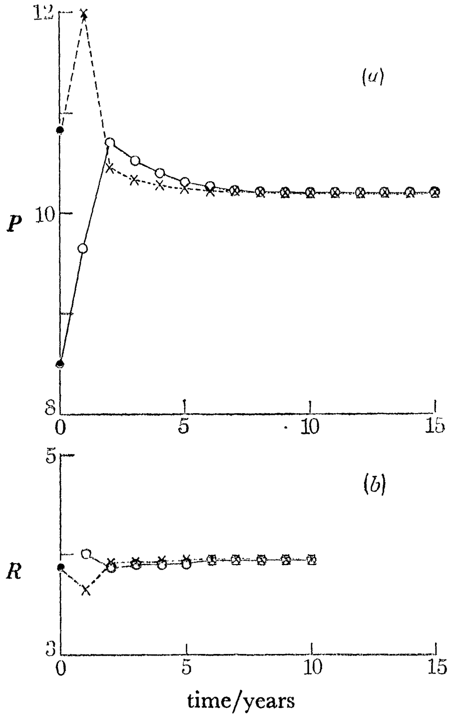

Figure 2. The resilience of stock in the model without the random component: (*a*) stabilization of stock after positive and negative perturbations of 11%; (*b*) stabilization of recruitment after the same perturbations of stock.

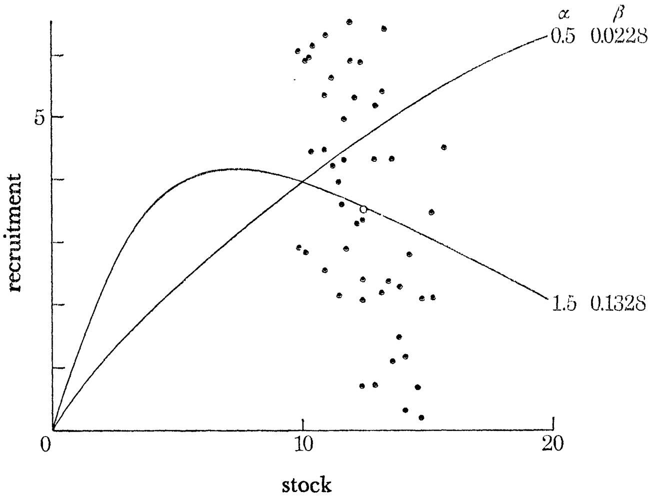

Figure 3. The variability about the initial stock (o) due to the random component for fifty years.

greater impact might generate a considerable increase in stock. At low stock the argument is statistically the same, that the decrease of stock is not significantly different from no impact until impact reaches about 0.5. However, both statistical conclusions are rather dangerous. At low stock, it is obvious that no stock reduction due to any impact can be allowed if the object of conservation is to bring the stock to about the maximum sustainable yield (at $P \approx 10$, in this example). Even a relatively low impact of 0.83 (1.25/1.50 in terms of α) causes a reduction in the mean recruitment, even if it is not statistically different after 50 years (because of the variability in recruitment). At high stock, a different danger arises because the shape of the stock/recruitment curve has been changed, i.e. the stock has lost some of its resilience with which it has been endowed in evolutionary terms.

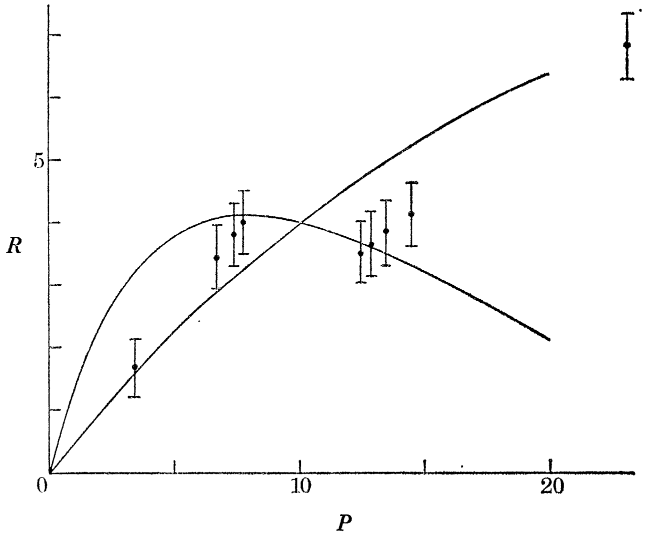

FIGURE 4. The effect of impact (as a reduction in α) at high and low stock. The vertical bars represent the standard errors of the means of 50 years' model observations. The effect of impact is to move from the stock–recruitment curve ($\alpha = 1.5$, $\beta = 0.1328$) to the curve ($\alpha = 0.5$, $\beta = 0.0228$).

The practical conclusion from this analysis might be as follows. If the stock is overexploited (i.e. at low stock in figure 1), any impact must be treated with great care partly for the reasons given above and partly because the observations about any stock recruitment curve are variable, even with decades of observations. The death rate of eggs or larvae due to impact may be expressed as a proportion of fecundity. Any impact greater than 10% might be considered too great for somewhat arbitrary reasons. The first is that against the variability of recruitment, a significant reduction in recruitment can only be detected when it is too late and in any case it is too large. Hence the statistical judgement should not be relied on. However, with an impact of 0.90, the reduction in recruitment will be low (< 5% in the example illustrated in figure 4) which does not matter much in face of the high variability of recruitment.

If the stock is underexploited, it gains from impact and at first sight impact should therefore be encouraged. But perhaps greater insight is needed into the density dependent mechanisms. If we believe the simple model portrayed here, density dependence is reduced with increasing impact and stock increases. If the density dependent mortality had two components, (*a*) food control in larval life or on juveniles near the beaches and (*b*) cannibalism in later life, stock might not increase quite so simply. Hence there might be a case for again ignoring the statistical judgement; perhaps the judgement might be made progressively in time as the effect of impact was assessed in terms of its effect on the biological mechanisms.

An analogous approach may be made using Ricker's expression for an exploited equilibrium stock:

$$P_e = (1/\beta) \ln [\alpha(1-E)], \tag{4}$$

where E is the exploitation rate, as proportion of recruits fished. The reduction of stock due to impact S.D. (stock reduction, in the terms of Christensen *et al.* 1977) is:

$$\text{S.D.} = (P_e - P'_e)/P_e = 1 - P'_e/P_e. \tag{5}$$

From (5) and (4),

$$\text{S.D.} = 1.0 - (\beta/\beta') \ln [\alpha'(1-E)]/\ln[\alpha(1-E)], \tag{6}$$

where α' and β' are the constants in the Ricker equation under impact (as formulated above).

At any stock $P' < P_e$, stock will be reduced in much the same way as in figure 4 and if $P > P_e$, stock will be increased. It should be pointed out that the formulation for the exploited equilibrium stock applies to a single age stock such as the Pacific salmon; it does not apply quite as readily to a multi-age stock. The reason for this is that the expression is based on Ricker's replacement stock (at which P_r (replacement stock) $= R_r$ (replacement recruitment)); in a multi-aged stock, such estimates are inaccessible unless the trend of natural mortality with age is known.

The same approach can be used with the logistic curve which is that used in general ecology and recently in theoretical elaboration (see May 1976). It is conveniently expressed in the form of a difference equation.

$$N_{t+1} = N_t \exp[r(1-N_t/K)], \tag{7}$$

where N_t is the number in the first generation and N_{t+1} that in the second, r is the intrinsic reproductive rate, and K is the 'carrying capacity' of the environment. The relation of numbers to carrying capacity is given by $(1-N_t/K)$ and the exponent $(-rN_t/K)$ expresses density dependence.

The Ricker equation describes the generation of the number of recruits from the stock of eggs under the influence of density dependent and density independent mortalities. In the logistic derivation a daughter population is generated from a parent one by a reproductive rate modified by the ratio of parent numbers to the carrying capacity of the environment. Provided r is positive, the two equations yield rather similar results, which is not surprising as my colleague J. W. Horwood has noted that they are formally identical; the biological interpretation of the constants differs.

A pollutant might be expected to affect the intrinsic reproductive rate, r, but not the carrying capacity, K, at least in the first place. This resembles the treatment of the Ricker equation in that α is reduced by impact with a consequential reduction in β; the carrying capacity, K, in the logistic equation is analogous to the degree of exploitation of the stock in the Ricker equation.

With the same scale of parent stock numbers as used in figures 1 and 4, $K = 10$, which implies a dome-shaped curve with a high r, analogous to that in figures 1 and 4. Figure 5 shows population curves about $K = 10$ for three values of r; the figure resembles figure 1 in that a dome-shaped curve is changed to a near-linear one as r is reduced from 1.5 to 0.21. For the Ricker curve, a similar result is obtained with a reduction of α from 1.5 to 0.5 (and consequential reductions in β). It may appear perverse to extend the curves beyond the carrying capacity of the environment. If impact were to affect the biological structure, but leave the total carrying capacity the same, one might imagine that a stock could increase under impact, as for example with eutrophication. Carrying capacity of an adult fish stock is perhaps defined fairly easily, e.g. there are so many tonnes of worms available for plaice. But during the life history from larva to recruitment many different foods are used and differences in ecosystem structure may be as important as differences in quantities of food.

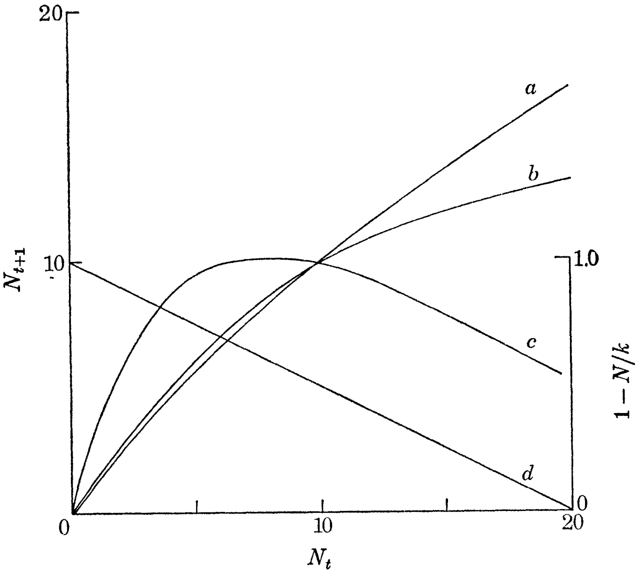

FIGURE 5. The effect of impact as illustrated by the logistic curve about $K = 10$: (*a*) $r = 0.22$; (*b*) $r = 0.41$; (*c*) $r = 1.3$. (*d*) Variation in $(1-N/k)$. The effect of impact is to reduce the intrinsic reproductive rate, r.

The analogy between the two approaches may be pressed a little further. If $N > K$ for structural reasons, a reduction in r will usually lead to an increase in the filial population much as recruitment might be increased under impact in an underexploited fish stock. Similarly if $N < K$, a reduction in r must lead to a decrease in the filial population, just as recruitment is decreased under impact in an overexploited fish stock. Then subsequent generations might be expected to increase steadily when $N > K$ and to decrease when $N < K$. The reason for this result is that smaller populations are restrained as (r/K) is reduced and larger populations are given hazardous opportunities under the same conditions. This is expressed in the characteristic return time, T_R, which estimates the capacity of the population to return to equilibrium. $T_R = 1/r$ and the return times for the populations described in figure 5 are shown in table 2.

TABLE 2

r	T_R
1.5	0.67
0.41	2.44
0.22	4.55

The return time increases as r is reduced; as impact increases the capacity of the population in a steady state to return to equilibrium is reduced. This implies a shift from a K-strategy to an r-strategy under impact, a change from a highly adapted self-stabilizing system to an opportunistic one. Such a change may be disadvantageous in the face of environmental variability.

It is possible that a pollutant may affect the carrying capacity of the environment, K; in pictorial terms, the crossover point at $N = 10$ $(= K)$ shifts to the left or right in figure 5, or impact decreases or increases the carrying capacity of the environment. Broadly, one would imagine that pollution should decrease the carrying capacity, but if the carrying capacity remained constant but the ecosystem structure was changed, the population might be increased merely by increasing opportunities for expansion as, for example, in eutrophication.

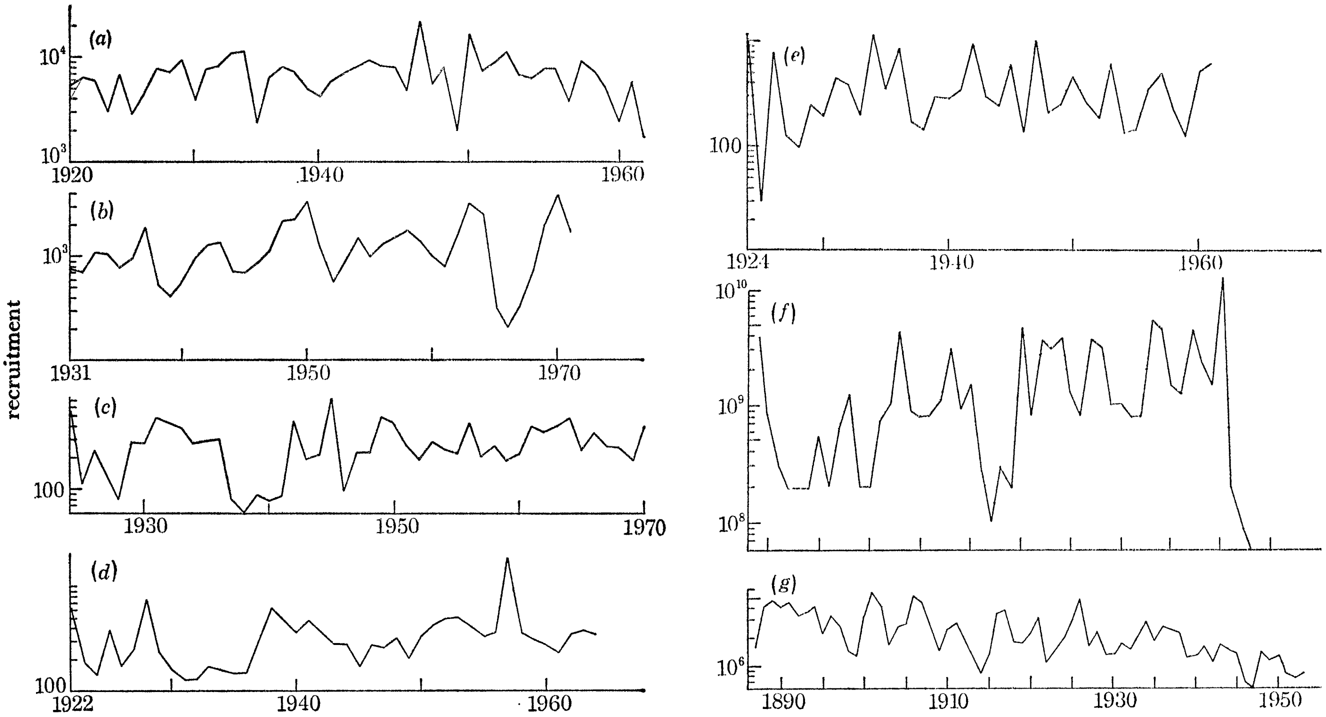

Figure 6. Variability of recruitment in some fish populations: (*a*) North Sea herring; (*b*) Arcto-Norwegian cod; (*c*) Iceland cod; (*d*) North Sea plaice; (*e*) West Greenland cod; (*f*) Norwegian herring; (*g*) Karluk river sockeye salmon.

The difference between the Ricker equation and the logistic in practical terms is that in the Ricker the constants are those of a simple population. For the exploited fish stock it can be said outright that any impact on an overexploited one should not be allowed and that in an underexploited stock the potential increase should be regarded with suspicion. The analogous arguments about the carrying capacity are very similar, but we do not know how to define carrying capacity more precisely for it is rarely known which food in the life cycle is critical in the stabilization of the population.

3. Discussion

The variability of recruitment in marine and anadromous fish stocks is high, in the Karluk River by a factor of three, in the Downs herring of the southern North Sea by a factor of five, in the North Atlantic cod stocks by an order of magnitude, in the North Sea sole by a factor of

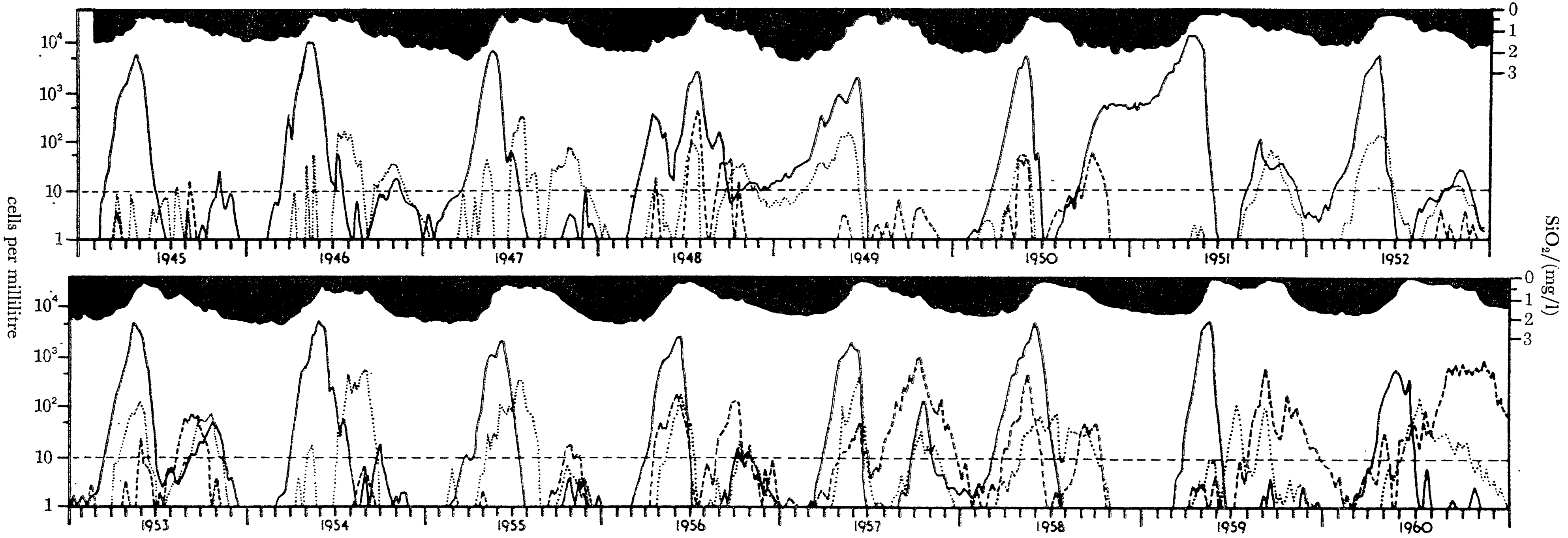

Figure 7. The variability of algal production in Windermere for a period of 15 years (from Lund 1964).
——, *Asterionella*; ---, *Fragilaria*; ···, *Tabellaria*.

sixty, and in the North Sea haddock by two orders of magnitude. That in the model described above is quite typical, being of about one order of magnitude. The stock in the model has eight year-classes in the lightly exploited phase. Cod and Norwegian herring live for two decades or so and plaice as old as 36 years have been recorded in the southern North Sea and the model stock represents many stocks in the sea.

Figure 6 shows the variability in recruitment for a number of fish stocks extending for some decades. The gadoid stocks are variable about a steady mean level. The herring and salmon stocks rise or decline slowly through the decades. Clupeid stocks in general are subject to sudden rises and collapses as they respond to environmental changes; for example, the

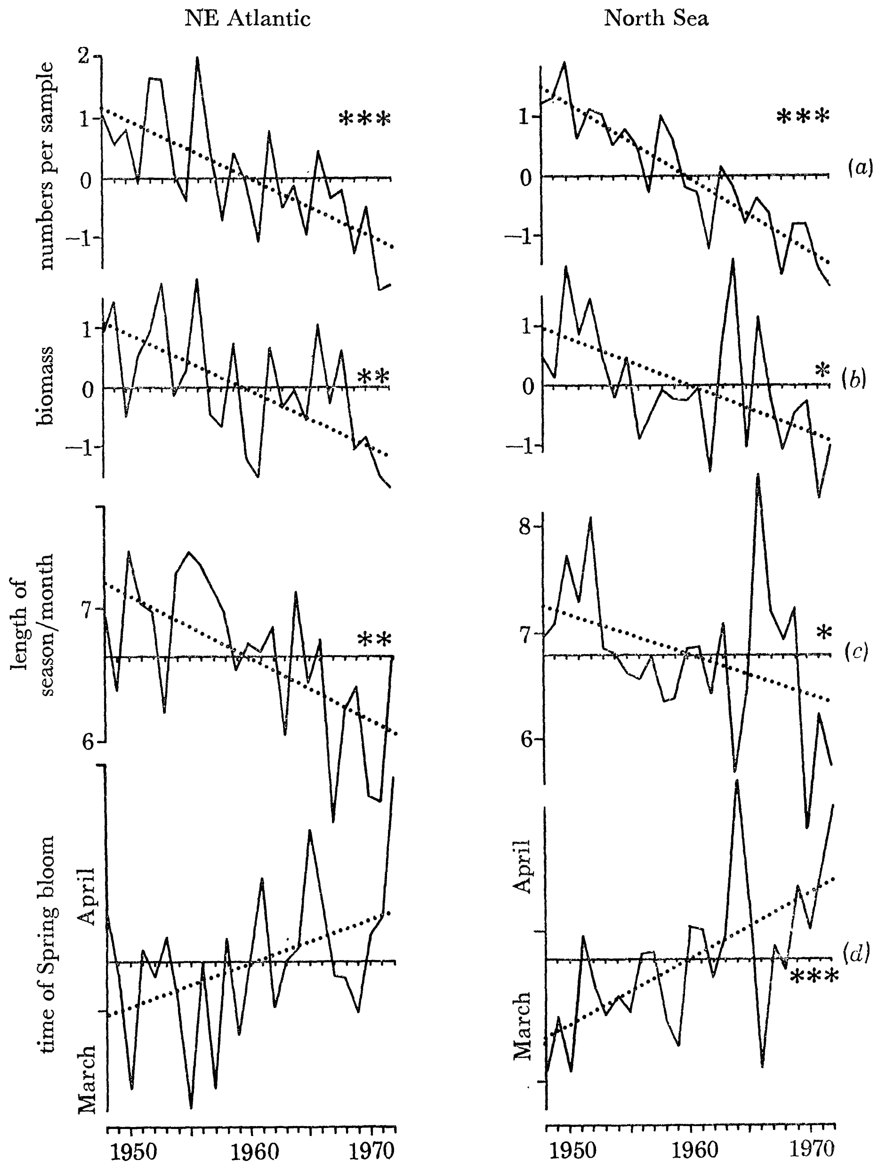

FIGURE 8. The variability of copepod numbers (*a*), zooplankton biomass (*b*), and zooplankton (*c*), and phytoplankton (*d*), growing seasons in the North Sea and North Atlantic for 24 years. Calculated trend times are shown, the significance of the fit being denoted by one, two or three asterisks for $p < 5.0\%$, $p < 1.0\%$ and $p < 0.1\%$ respectively (from Glover, Robinson & Colebrook 1974).

Norwegian herring appeared in abundance with the 1904 year-class and collapsed under heavy fishing with that of 1959. The variability is high and an impact due to pollution would be difficult to detect as suggested earlier.

Figure 7 shows the variability of algal production in Windermere for a period of sixteen years (Lund 1964). There is considerable variation in the magnitude and duration of production and in the relative variation between species. Figure 8 illustrates the changes in the plankton in the North Sea and North Atlantic between 1948 and 1972 (Glover, Robinson & Colebrook 1974). There is a significant delay in the time of onset of the spring outburst of nearly a month which may have started in 1961. The decline of other components in numbers of copepods and in the biomass of zooplankton was probably consequential. Both figures illustrate the high variability of natural changes in the plankton and figure 8 in particular may show the response of the plankton in the North Atlantic to climatic change.

The judgements on impact were based on the increments at high stock with impact or the decrements at low stock despite the variability of recruitment. But the variability used was a little bogus because we can expect no stock to remain at a constant rate of exploitation for fifty years, unless of course stocks were in the end exploited optimally. In the present world we might expect exploitation to vary considerably and even at optimal exploitation it must, and therefore impact would generate increment and decrement as exploitation shifts above and below the optimal exploitation. If they were randomly distributed, such increments and decrements would not matter practically.

Judgement of the effect of impact on a fish stock depends on the degree of exploitation. At low stock under heavy exploitation, it is simply that no impact can be tolerated until the stock has been returned to the desired objective, the maximum sustainable yield or any lesser quantity that might be optimal. At high stock under little or no exploitation, the judgement is harder because its resilience to environmental change has been reduced. The shape of the stock/recruitment curve is changed from a dome with a quick return time to a near-linear one with a slow return time, i.e. from a cod-like one to a herring-like one. The Arcto-Norwegian cod stock has survived seven centuries of environmental change with not much difference to the fishery in the Vestfjord in northern Norway; the Norwegian herring fishery has become extinct on five occasions at least during that period. If the climate changes with a period of about 100 years, impact at low stock may well make resilient fish stocks into opportunistic ones.

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Discussion

R. J. Morris (*C.U.E.P., Department of the Environment, London, U.K.*).

1. To quote from the Gesamp report no. 6 (1977): 'The use of existing fishery statistics to demonstrate the deleterious, beneficial or null effects of (pollutants) is fraught with dangers, due to the quality of the data and the potentially great number of unknown factors...Caution must be exercised in this type of approach. Landings may not relate in the short term to abundance and all fisheries statistics are no better than the system used to collect them.' Many of Dr Cushing's data appear to be based on fish-catch data. Does he accept the reservations concerning such data which was expressed in the Gesamp report?

2. Dr Cushing equates the potential stress effects on fish populations of overfishing with those of pollutants. Is this a valid comparison? Overfishing simply causes a reduction in numbers of a species in specific areas resulting in a loss of recruitment potential for those populations. Species have several ways of combating such a lowering in population numbers, one being a reduction of the age of maturity (e.g. in certain species of whales). Sublethal pollution stress may result in a general loss of biochemical physiological efficiency throughout whole populations with a gradual lowering of reproduction potential.

D. H. Cushing.

1. In general, statistics of landings are well recorded. With the use of age determinations from otoliths, and length measurements, landings are converted to catches at age in numbers. With virtual population analysis, catches at age for an array of years are converted to estimates of stock. The Gesamp report is quite right when it says that landings are not related to abundance, but with these methods we convert them to abundance or stock. The first sentence quoted probably refers to the direct use of catches; however, the quality of the material is often good, particularly in the U.K.

2. Recruitment may be reduced by fishing despite any responses by the population. In that sense pollutants might also reduce recruitment.

M. Waldichuk (*Pacific Environment Institute, West Vancouver, B.C., Canada*). From what Dr Cushing has said, I should judge that the greatest potential threat of pollution on commercial fisheries could occur during a severe decline of a fishery due to severe fishing pressure or natural climatic changes. Conceivably severe pollution of vital spawning grounds could hasten the decline of a fishery under heavy exploitation.

Would Dr Cushing be able to offer an approach towards establishing a critical level in a fishery when the stress of pollution could have a serious effect in leading to a drastic decline or collapse in a fishery? Is there a statistical technique that could provide this predictive capability?

D. H. Cushing. A stock is vulnerable to recruitment failure if it is fished too heavily, i.e. at a fishing mortality greater than that at the maximum sustainable yield (m.s.y.). The m.s.y. is determined by methods based on virtual population analysis or cohort analysis.

G. J. Smith (*Imperial Cancer Research Fund, Lincoln's Inn Fields, London, U.K.*). With respect to Dr Cushing's introductory statement concerning the addition of 'beneficial' chemicals to the environment, I have two queries: (i) How will one overcome the danger of adding chemicals that are themselves not harmful to organisms but which potentiate the harmful effects of other chemicals i.e. the classical 'co-carcinogen' argument of cancer research? (ii) With respect to adding pesticides to the sea in order to decrease predatory populations and so increase fish yields, how will one avoid the vicious circle of adding more pesticides as the predatory species develops more resistance to the pesticides?

D. H. Cushing. The addition of any chemical to the environment is almost certain to induce some change in the local ecosystem. There will always be some degree of risk which should not be overlooked. But in my view there is as yet not sufficient justification to assume the addition of any chemical will always induce a deleterious effect. To be sure, any addition would need to be preceded by appropriate screening, and accompanied by the necessary monitoring, but in principle it seems to me that we should not at this stage close our minds to the possibility that beneficial effects might be achieved in particular circumstances. It would appear unwise, and certainly impracticable, to attempt manipulation over the wide geographical area of a particular stock without very full appreciation of the consequences, but local modifications seem as conceivable as the local deleterious pollution incidents currently being reported and one might envisage a constructive development borne of the same knowledge that is being accumulated in the framework of environmental protection.