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The effect of biological interactions on the theory of mixed fisheries

by

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INTRODUCTION

In order to examine in detail any fishery situation it is necessary to postulate a model of how the fishery behaves. Single species management has been attempted by a variety of models. The most important of these to ICNAF assessments have been the dynamic pool model and the Schaefer model. For the study of mixed fishery problems, however, the Schaefer model has the great advantage of simplicity and consequently the further development of ideas on mixed fisheries in this paper will follow that approach. Pope (1975a) has shown that a mixed fishery for two stocks can be represented in two dimensions as contours of equal total yield plotted against the fishing mortality for each species. If the two stocks have yield curves of a parabolic Schaefer form, then the resulting contours of equal yield have the form of ellipses when plotted against the fishing mortality on each species. Furthermore, by-catch rates for the second species as a result of a directed fishery for the first species can be taken into account and vice versa: the maximization of physical yield then becomes an exercise in quadratic programming.

This approach indicated that if a multiple species fishery conformed to this model and if the development of fishing effort on the system occurred as some constant ratio between species, then the form of the yield curve for total catch would be a parabolic function of total effort. Pope (1975a) pointed out, however, that unless the ratio of effort on species 1 to that on species 2 passed through the maximum attainable yield the resulting yield curve obtained would neither indicate the true MSY catch from the system nor indicate the level of effort at which maximum yield would be attained. Another fact to emerge from this approach was that a total effort quota designed to obtain the MSY when applied in the right proportion could destroy one of the stocks if it were wrongly applied. This approach was unable to comment on the validity or otherwise of total yield curves based on fishing effort that had not developed on two species in a constant ratio. It was felt that most real fisheries would have developed in a less well-defined manner and that therefore the resulting yield curves based on total effort versus total catch per effort, for example those developed by Pinhorn (1975) and by Halliday and Doubleday (1975), might not necessarily indicate the true maximum yield from the various stocks. This mixed fisheries theory was open to criticism in that it did not take account of possible interactions between species and because it only indicated the stationary (equilibrium) behaviour of the system. In order to meet the first of these criticisms the current work in this paper attempts to consider the effect of biological interactions between stocks.

BIOLOGICAL INTERACTIONS BETWEEN SPECIES

Walter (1975) gives the non-steady state condition form of the Schaefer model as

$$\frac{1}{P} \frac{dp}{dt} = b - ap - qf$$

where p is population biomass of the stock, t is time, f is fishing effort and b and a are parameters which characterize the stock. This can be extended in an obvious fashion to consider the effect of the interactions of a second population with biomass r. This results in the two equations

$$\frac{1}{P} \frac{dp}{dt} = b - ap \pm cr - qf \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

$$\frac{1}{r} \frac{dr}{dt} = \hat{b} - \hat{a}r \pm \hat{c}r - \hat{q}\hat{f} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

where the plain constants indicate the parameters and fishing effort of stock 'p' and the hatted parameters those of stock 'r'. When the two stocks are in equilibrium then

$\frac{dp}{dt} = \frac{dr}{dt} = 0$ and it follows that

$$b - ap \pm cr - qf = 0 \qquad \text{.....................} \; (4)$$

$$\hat{b} - \hat{a}r \pm \hat{c}p - \hat{q}\hat{f} = 0 \qquad \text{.....................} \; (5)$$

where the sign of c and $\hat{c}$ are either both negative in the case of a competition model or - and + respectively in the case of a prey-predator model. The South African pilchard and anchovy fisheries reported on by Pope and Harris elsewhere in this meeting form a possible example of the competition type of model. The interactions of, for example, the Newfoundland cod and the capelin of Divisions 2J-3KL would possibly furnish an example of the prey-predator model.

Some general conclusion can be drawn from the form of equations 4 and 5. Assuming the sign of c and $\hat{c}$ to be negative and by multiplying 4 by p and 5 by r, we obtain

$$bp - ap^2 - crp = \text{yield } (p) \qquad \text{.....................} \; (6)$$

$$\hat{b}r - \hat{a}r^2 - \hat{c}rp = \text{yield } (r). \qquad \text{.....................} \; (7)$$

Therefore, if Y = yield (p) + yield (r)

that is the total yield, then

$$Y = -ap^2 - \hat{a}r^2 - (c + \hat{c})\, rp + bp + \hat{b}r \qquad \text{..................} \; (8)$$

Thus within the area of validity of the model the yield curves would take the form of ellipses with their major axis inclined to the axis of population sizes. Also it follows from equations 4 and 5 that

$$p = \frac{\hat{a}\,(b - qf) - c\,(\hat{b} - \hat{q}\hat{f})}{\hat{a}a - c\hat{c}} \qquad \text{..................} \; (9)$$

$$r = \frac{a\,(\hat{b} - \hat{q}\hat{f}) - \hat{c}\,(b - qf)}{\hat{a}a - c\hat{c}} \qquad \text{...................} \; (10)$$

and total yield

$$Y = Af^2 + \hat{A}\hat{f}^2 + (C + \hat{C})\, f\hat{f} + Bf + \hat{B}\hat{f} \qquad \text{..................} \; (11)$$

where A, $\hat{A}$, C, $\hat{C}$, B and $\hat{B}$ are functions of a, $\hat{a}$, b, $\hat{b}$, c, $\hat{c}$ respectively.

The total yield from such a system also has contours of constant equilibrium yield in the form of ellipses and similarly these do not now have their major axis parallel to the axes of the fishing effort on the two species. The above argument thus leads to a solution similar to that described for the non-interactive fisheries, except that (1) the ellipses are now inclined to the coordinate axis of the system (2) there are additional constraints on the system corresponding to the values of r and f at which p becomes zero and the values of p and $\hat{f}$ at which r becomes zero. These are respectively from equations 4 and 5

$$b - cr - qf \geq 0 \qquad \ldots\ldots\ldots\ldots\ldots\ldots (12)$$

$$\text{and} \quad \hat{b} - \hat{c}p - \hat{q}\hat{f} \geq 0. \qquad \ldots\ldots\ldots\ldots\ldots\ldots (13)$$

From equations 9 and 10 these may be rewritten as

$$\hat{a}a\ (b - qf) - ca\ (\hat{b} - \hat{q}\hat{f}) \geq 0 \qquad \ldots\ldots\ldots\ldots\ldots\ldots (14)$$

$$\text{and} \quad \hat{a}a\ (\hat{b} - \hat{q}\hat{f}) - \hat{c}\hat{a}\ (b - qf) \geq 0. \qquad \ldots\ldots\ldots\ldots\ldots\ldots (15)$$

EXAMPLES OF INTERACTIVE MIXED FISHERIES

The consequences of the equations in the previous section are best seen in practical examples.

Pope and Harris (1975) give an example of such an interactive fishery for the South African pilchard and anchovy. Figure 1 shows the form of the yield curves estimated for the total yield of these two stocks.

The equilibrium equations governing these yield functions are:

$$.43 - .000143\ P - .000143A - F\ (P) = 0 \qquad \ldots\ldots\ldots\ldots\ldots (16)$$

$$\text{and} \quad 1.10 - .001A \quad - .0005\ P \ - F\ (A) = 0 \qquad \ldots\ldots\ldots\ldots\ldots (17)$$

where P is the biomass of pilchard, A is the biomass of anchovy and F (P) and F (A) are their respective fishing mortalities. Pope and Harris' paper should be consulted for a detailed description of this system but the main features are fairly apparent. The plot of total yield (Figure 1) on the fishing mortality of the two species shows that the system has three modes of behaviour. In the first (Region A) the yield is composed entirely of pilchard, and the anchovy biomass is zero. In Region B a mixed fishery for both species exists and in Region C the pilchard biomass is zero and the yield is composed entirely of anchovy. The boundaries between these regions are the constraints mentioned in the previous section. It is noticeable that the region of mixed fishery is a fairly narrow wedge and that it would probably be difficult to control a fishery sufficiently closely to be sure that it will always lie inside this region. It is also noticeable that for this apparently highly interactive fishery the maximum yield attainable in the mixed fishery (340,000 tonnes) is only slightly larger than that which would be obtained in either of the pure fisheries (320,000 tonnes for pilchard and 302,000 tonnes for anchovy). Thus the effect of stock interactions is to reduce the total MSY of the system to below the sum of the individual species MSYs. The degree to which this occurs is a function of the degree of interaction between the stocks. This can be seen from the following modifications of equations 16 and 17 made in order to change the interaction terms. In all of the following illustrative examples the only changes made to equation 16 are to the coefficient of the A term and the only changes to equation 17 are to the coefficient of the P term. Consequently outside the mixed fishery region B the yield of the single stocks in all examples are unchanged. The region of the mixed fishery will however be modified. The first example reduces the interactions by an order of magnitude. Thus equations 16 and 17 become

$$.43 - .000143\ P - .0000143\ A - F\ (P) = 0 \quad \dots\dots\dots\dots\dots \quad (18)$$

$$1.10 - .001A \quad - .00005\ P \quad - F\ (A) = 0 \quad \dots\dots\dots\dots\dots \quad (19)$$

Figure 2 shows the resulting constraints and yield functions. It is apparent that the system is very similar to a non-interative fishery (c.f. Pope, 1975b on Cod and Redfish) with the area of the mixed fishery considerably extended and the contours of total yield being concentric ellipses with axes almost parallel to the coordinates. The maximum yield (576,000 tonnes) is far closer to the sum of the two individual pure fisheries than was the case in Figure 1. Figure 3 shows a situation halfway between Figure 2 and Figure 1. The equations governing this are

$$.43 - .000143\ P - .000118A - F(A) = 0 \quad \dots\dots\dots\dots\dots \quad (20)$$

$$1.10 - .001A \quad - .000266P - F(A) = 0 \quad \dots\dots\dots\dots\dots \quad (21)$$

In this case the total yield has a value of 415,000 tonnes and the region of mixed fishery is of intermediate size. It is interesting to contrast this with Figure 4 which shows the yield when equation 20 is modified to

$$.43 - .000143\ P + .000118A - F\ (A) = 0 \quad \dots\dots\dots\dots\dots\dots \quad (22)$$

and equation 21 held the same.

The system thus described is a prey-predator model with the pilchard hypothetically preying on the anchovy. The general shape and size of the yield function in this case corresponds more nearly with the contours of Figure 2 than Figure 3, with the ellipses less inclined to the coordinate axis and rather fatter. The total yield in this case is 523,000 tonnes which is also closer to the less interactive case.

The examples thus show some of the effects of the interaction terms to the behaviour of the system. The chief features to note are that (a) for highly interactive fisheries the mixed fishery region is narrow (b) the phenomenon of the total biomass switching over from being mostly one species to mostly the other is likely to be observed if fishing is sufficiently intensive. Where interaction terms are lower or where they are of opposite sign (as in a prey-predator system) this is less likely to happen. When fisheries are highly interactive it is also possible that the total yield is very little greater than that which would be achieved for either component fishery, were the other component extinct. When they are not highly interactive the total yield approximates to the sum of the yields of the individual species, particularly when it is appreciated that in practice these individual yields would probably be assessed in the presence of the other species and not when it was extinct.

IMPLICATIONS OF THE THEORY TO THE MANAGEMENT OF MIXED FISHERIES

The effects of by-catch rates on the potential yield of the systems described by the models are the same as those described in Pope (1975a) (which should be consulted for a detailed description). That is to say whether the true maximum yield of the stock is attainable or not will depend on whether the levels of fishing mortality giving the maximum yield lie within or without the sector defined by the lines indicating the fishing mortalities which would be generated in the various directed fisheries. If this sector was narrow, that is to say the various fisheries had considerable overlap and by-catch rates were high, then the total effort imposed on the system would generate mortalities in the two stocks which were in a fairly constant proportion. In these circumstances a total effort quota could be expected to be quite effective because the model, whether interactive or non-interactive, would have a parabolic yield function in the mixed fisheries region with respect to the total effort generated. In effect the high by-catch rates would supply the individual stock management constraints. In these circumstances, however, it is improbable that the maximum attainable yield would be as high as the maximum sustainable yield.

If the by-catch rates in the various directed fisheries were not so large, then the sector in which effort would cause fishing mortalities to be generated would be wider and the fishing mortalities generated on the two stocks could differ in proportion to a greater extent. Under these circumstances a total effort quota would be less likely to generate a satisfactory management scheme unless it was backed up by individual stock catch quotas or effort quotas. If this were not done there would be no guarantee that the proportion of the effort going on the various stocks would in fact be that which generated the maximum yield. A study of Figures 1 through 4 reveals that the proportion of mortality going on each stock effects both the total yield that can be achieved and also the level of effort at which it can be taken. As an example of this in the system examined in Figure 2, if the proportion of F(P) to F(A) was 2 to 1 then the maximum yield would be about 400,000 tonnes at a fishing mortality of approximately (0.230, 0.115). If, on the other hand, the proportion were in the ratio of 1 to 2 then the maximum yield would be greater than 550,000 tonnes at fishing mortalities of approximately (0.25, 0.50). Thus the proportion in which the mortalities are generated crucially affects both the total yield and the level of fishing effort which generates it. The history of fishing in the ICNAF area does not lead one to suppose that fishermen could be relied upon to generate fishing efforts in the most advantageous proportion if the choice were left to them. If on the other hand individual stock catch or effort quotas are imposed, then they define a unique position of the yield functions of Figures 1 through 4, and consequently a total effort quota would only act as a safety net to prevent serious over-exploitation in the case of badly set stock quotas.

Similar criticisms to those made above also affect total catch quotas. A total catch quota might however be of some value in a highly interactive fishery such as that described in Figure 1. In this case a total catch quota might be expected to be successful but it would not guarantee that the species mixture in the catch was always the same. In fact, since presumably the most attractive species would sustain the highest mortality, it is possible that this would be overfished and the system move into a region where the total yield was similar but where it was composed of some less attractive species. In other words, if you want a fish meal fishery and you do not care what you catch, then an overall catch quota on a highly interactive fishery might be successful. If, however, you wish to continue to catch prime fish then individual stock constraints are necessary.

The above criticism of total quotas assumes however that we have detailed knowledge about the nature of the interaction in the fisheries. If we do not then a total effort quota or total catch quota would be a means of recognising that the overall MSY of the system would be less than the sum of the individual stock MSYs when either the fish stocks are interactive biologically or the by-catch rates in directed fisheries prevent the total MSY from being attached. In the former case biological considerations might suggest a likely level for the overall MSY and hence for the total catch quota. As a system of management it would however have no scientific advantage over reducing the TAC for each species to an appropriate proportion of the species MSY.

CONCLUSIONS

Considerations of mixed fishery models which include biological interactions lead to the conclusion that the total yield from an interactive system would be lower than the sum of the individual species MSY. They do not lend support to the adoption of total catch or total effort quotas as a means of managing such systems without individual stock constraints. Such total quotas might however be of some value in taking account of the fact that the total MSY of a system might be less than the sum of the individual stock MSYs. Thus they would be of greatest value where knowledge of the stocks was incomplete. However, the equivalent result could be achieved with greater safety and less complicated regulations by simply reducing the individual species TAC's by an appropriate proportion.

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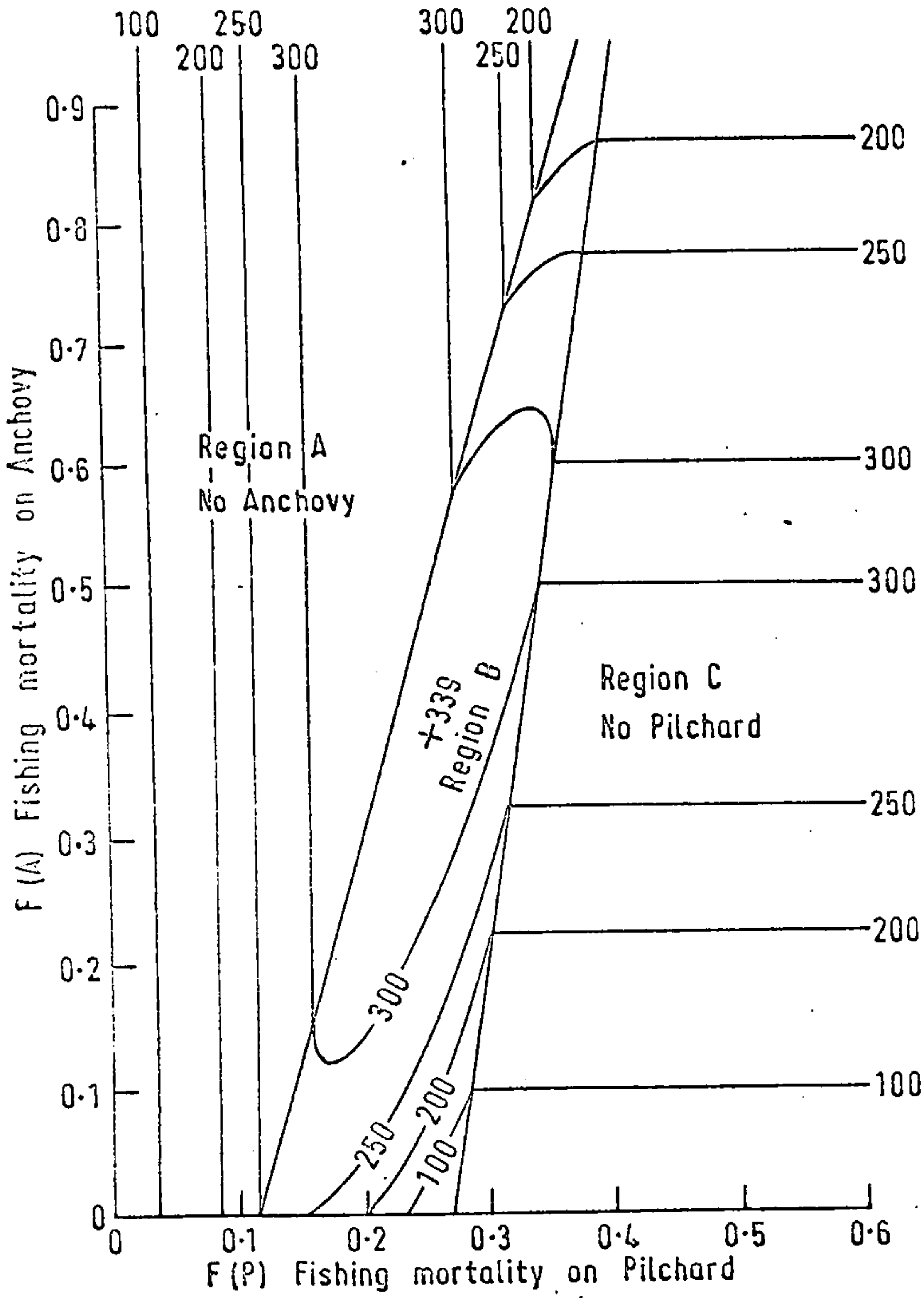

Figure 1 Contours of total yield drawn against the fishing mortality of South African anchovy and pilchard and the region of mixed fishery (Region B) and of pure fisheries for the two stocks (Regions A and C).

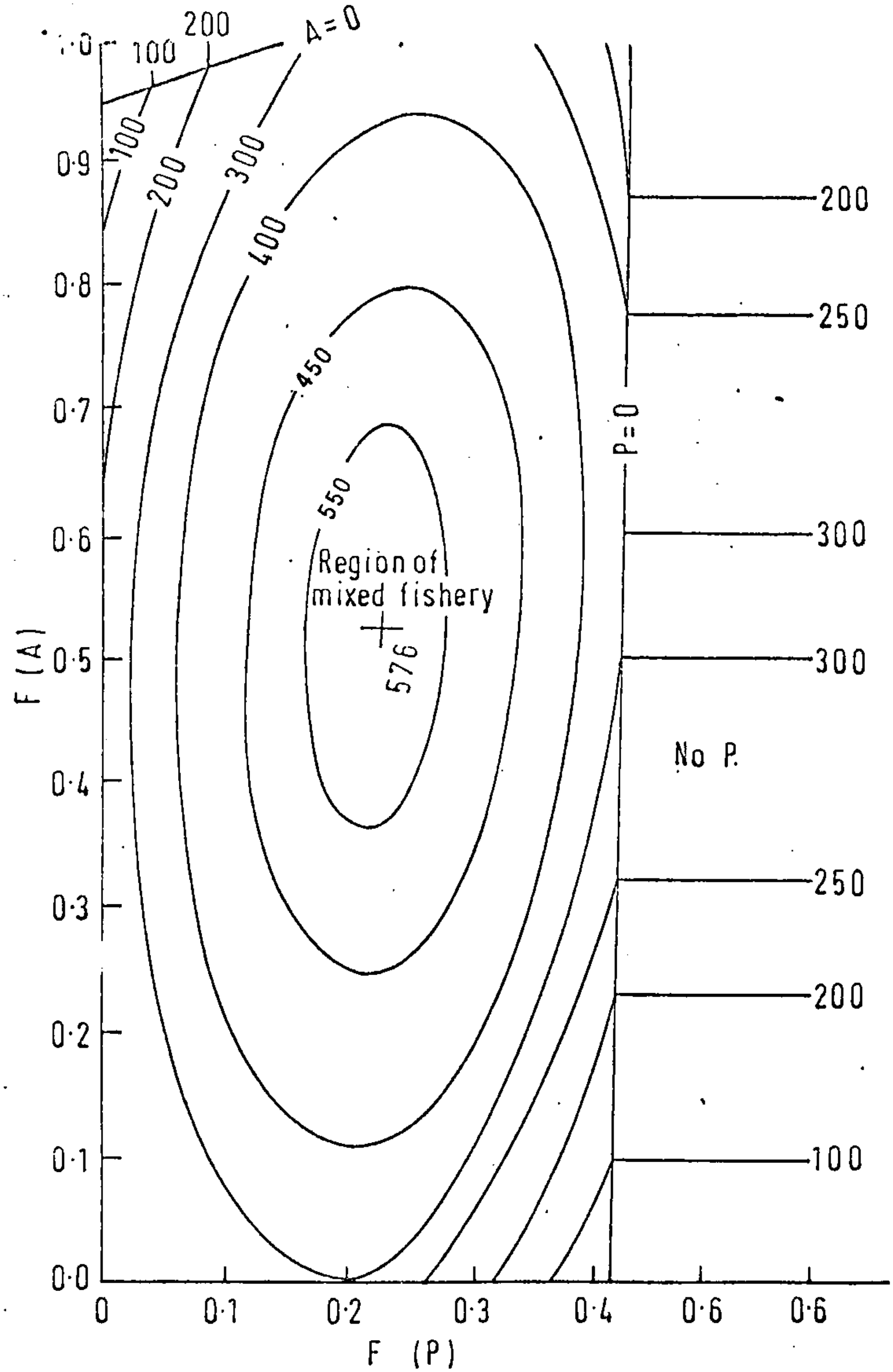

Figure 2 As Figure 1 with the interaction terms reduced arbitrarily by an

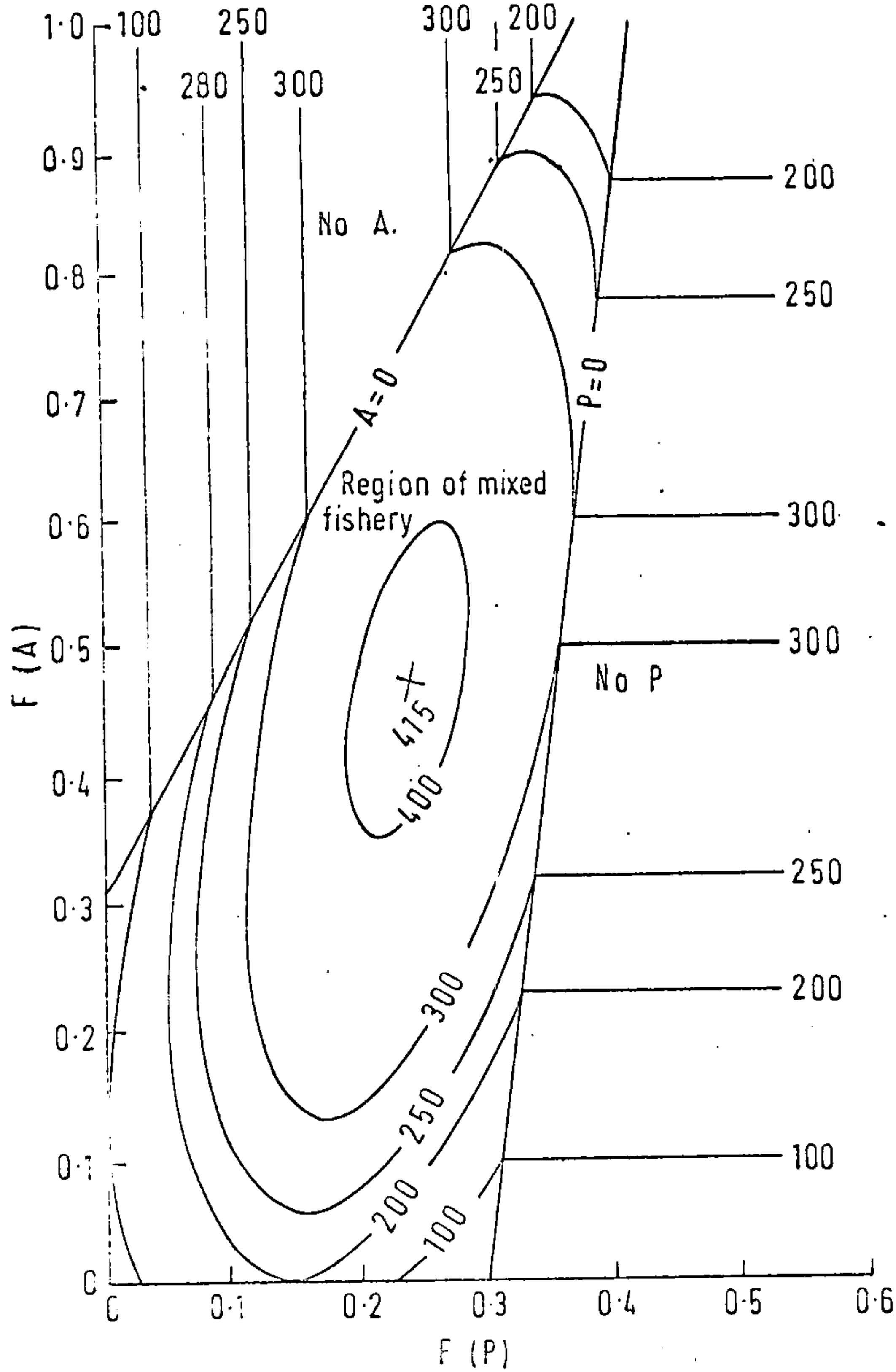

Figure 3 As Figure 1. A situation between the extremes of Figure 1 and Figure

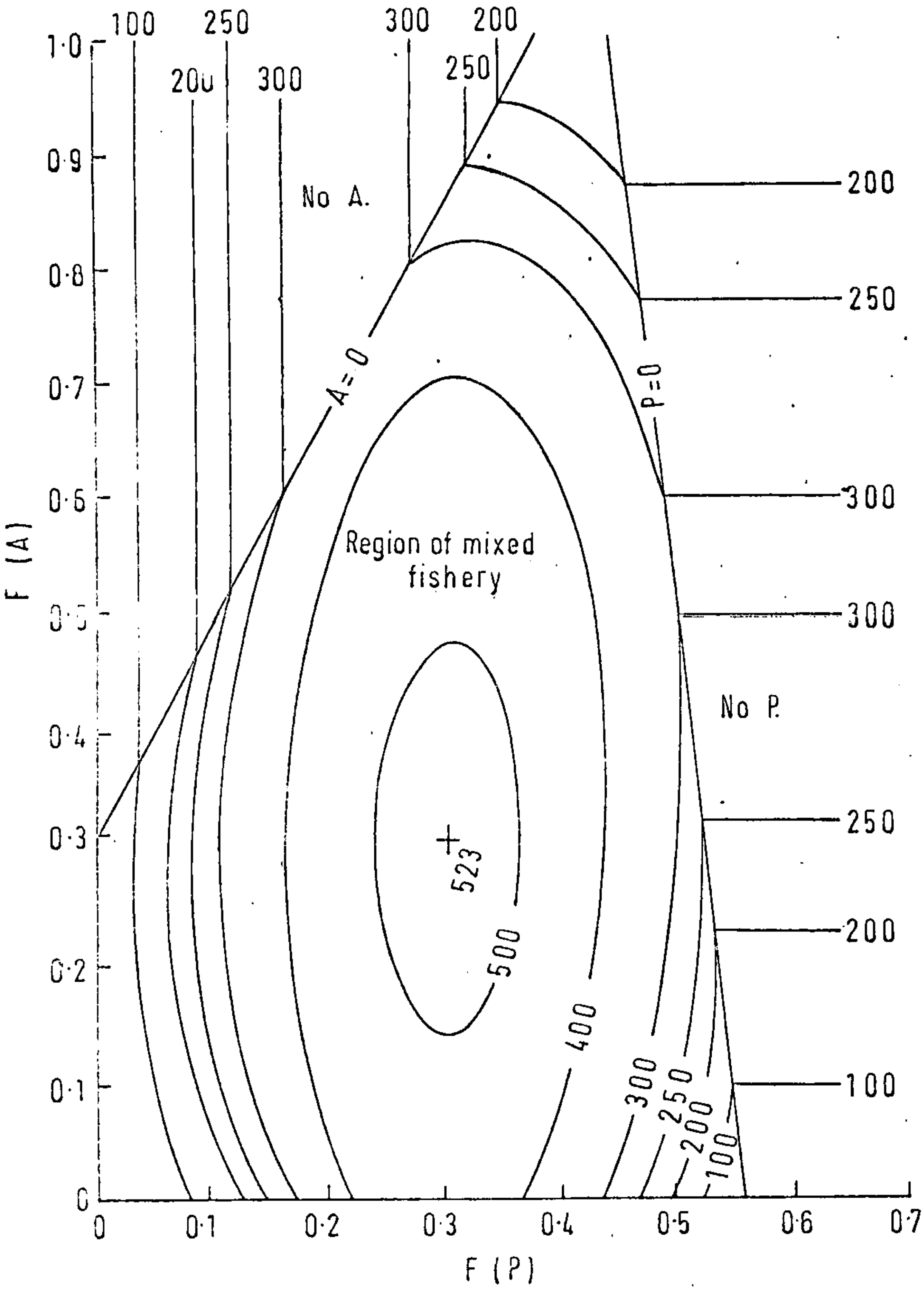

Figure 4 As Figure 1, but with the interaction terms numerically equivalent to those of Figure 3 but with the sign of the interaction of anchovy on pilchard reversed to examine a prey predator type system.