The stability of fish stocks

J. A. Gulland

Department of Fisheries

FAO, Via delle Terme di Caracalla, I-00100 Rome, Italy

In the common models of stock assessment, fish populations are stable and minor disturbing forces (e.g. small increments in fishing effort) cause only minor changes in the equilibrium position. Clark's (1974) conclusion, based on a "salmon" type of fish, that if there is a depensatory part of the stock/recruit relation, there will be an unstable situation, is extended to all types of population. A similar situation, in which a small increment in fishing effort can result in a collapse of the stock can also occur if (as seems to happen in some pelagic fisheries) the catchability coefficient, q, can increase with decrease in fish stock. This potential for collapse can be serious in fishery management unless there is adequate provision for monitoring the stocks, and for rapid implementation of control measures as they become necessary.

Clark, C. W. 1974. J. Cons. int. Explor. Mer, 36: 7-14.

In a recent paper Clark (1974) has drawn attention to one situation in which fish stocks may be highly unstable, and in which a small increase in fishing effort beyond a certain level can result in the complete collapse of the stock. In view of the importance of this situation to the study and management of fish stocks, it is worth examining the degree to which his conclusions hold good beyond the special case examined.

Clark considered a one generation species, harvested in a short period (i.e. short enough for natural mortality to be ignored) between recruitment and the single spawning – for example an idealized Pacific salmon. If the stock recruitment relation is given by

$$R = F(S), \quad \text{where } S = \text{spawning stock}$$

then, in a steady-state condition, a catch in numbers, C, can be taken, where

$$C = F(S) - S \tag{1}$$

Clark uses Y instead of C, but it is preferable, when the distinction may be important to reserve this symbol for yield in weight. Clark further determines the effort, f, (E in his notation) required to take this catch from the relation

$$f = \ln (F(S)/S) \tag{2}$$

which can also be deduced, in the familiar fisheries methods, from the equations

$$S = R\,e^{-FT} = F(S)e^{-FT} \tag{3}$$
and $\quad F = qf$
where T = duration of the fishery season.

The two equations are equivalent if the units of effort are chosen such that $qT = 1$. Given the form of $F(S)$ Equations (1) and (2) can be readily used as parametric equations to generate the yield-effort curve, giving C as a function of f.

The more general case, of a multi-generation species, exploited over a range of ages is slightly more difficult to present, but the main features can be shown to be similar. For a given pattern of fishing, a certain set of values of fishing mortality F_t at each age will be generated, and the yield, Y, and the spawning biomass, S, will be given by the equations

$$Y = \int_0^\infty F_t w_t N_t dt \tag{4}$$

$$S = \int_0^\infty S_t w_t N_t dt \tag{5}$$

where

w_t = mean weight of fish of age t

S_t = proportion of fish age t that are spawning.

If we can ignore, for the purposes of this analysis, changes in natural mortality and growth, then Equations (4) and (5) are essentially functions of the numbers of recruits, R, and the vector $\bar{F}$ giving the fishing mortality at each age. The latter in turn is some function of the fishing effort, f, so we can write

i.e. $Y = R\,a\,(f)$ (6)

                      $P = R\,b\,(f)$ (7)

The precise forms of (6) and (7) are complex, but it is clear that $b(f)$ steadily decreases with increasing f. The expression $a(f)$ is the familiar yield per recruit function. This rises from the origin, initially proportional to f. It may have a pronounced maximum if fishing starts on relatively small fish, but in many situations – including many fisheries on clupeoid stocks – the curve is relatively flat over a wide range of fishing mortalities, including the higher rates that are of primary interest in the present discussion. We will, therefore, when necessary for simplicity of discussion take $a(f)$ as constant. That is the yield per recruit in weight will be taken as approximately constant, the increase in numbers with increased fishing being balanced by a decrease in average weight.

Equation (7), and the basic stock-recruit relation $R = F(S)$ together determine the equilibrium values of S and R. These simultaneous equations are best solved graphically. The special case $f = 0$ corresponds to Figure 1 of Clark, but for any other value of f, Equation (7) determines another straight line through the origin, whose slope increases with f.

For Clark's purely compensatory case, i.e. a stock-recruit curve with no inflection, there is only one point where the line cuts the curve, and this equilibrium point steadily approaches the origin as fishing effort increases. The implications of this type of curve in which the downward-sloping left-hand

part of the stock-recruit curve is within the likely range of fishing effort have been examined on a number of occasions, for example by Garrod and Jones (1974).

If the stock-recruit curve is depensatory in some parts and has a point of inflection, then the line given by Equation (7) may cut it in two points. If the slope of the stock-recruit curve at the origin is less than the slope of the line for zero effort

i.e. $F'(0) < 1/b(0)$

then, corresponding to Clark's critical depensatory case, there will be two points of interaction for all values of f; otherwise there will be two equilibrium points only for those values of f above a certain level. In either case there is an upper limit to f – that given by the tangent to the stock-recruit curve which passes through the origin – above which there is no point of intersection. Any fishing effort greater than this limiting effort will lead, if maintained, to the collapse of the stock.

The case of two equilibrium points is illustrated in Figure 1. This figure can also be used, following the method of Moran (1950) to illustrate the stability of the two positions. The lines connecting one spawning stock to the subsequent recruitment (the point on the curve), to the resulting spawning stock (the point on the line) and so on, as shown by the arrows in the figure, show that the upper point [with higher stock and recruitment $(S_1 R_1)$] is stable, and the lower one $(S_2 R_2)$ is unstable. That is, if the fishing effort (or more strictly the fishing mortality) is maintained at
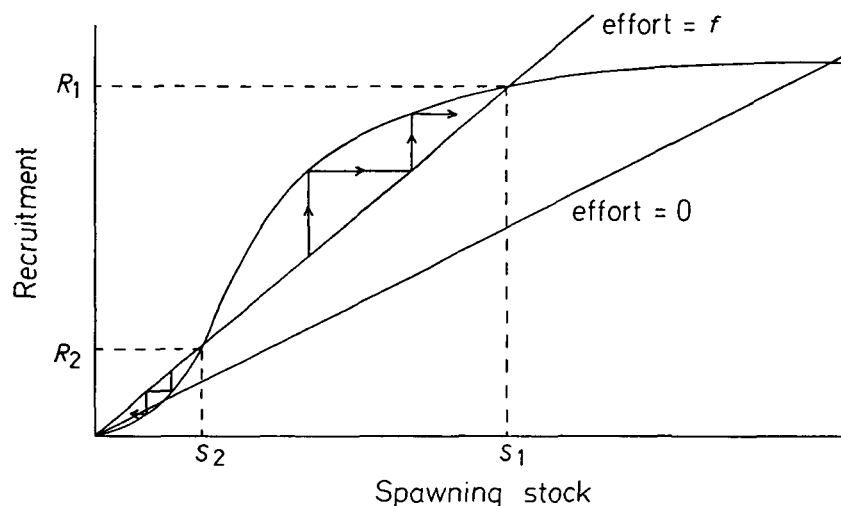

Figure 1. The relations between spawning stock and subsequent recruitment (curve), and between recruitment and resulting spawning stock under different levels of fishing effort (straight lines). The intersection $R_1 S_1$ is a point of stable equilibrium, but $R_2 S_2$ is unstable. Arrows denote trends in recruitment and stock if the population is disturbed from equilibrium.

the same value, then provided $S > S_2$, then the population will tend (in the absence of further disturbances) to the point S_1R_1. However, if $S < S_2$ then the stock will collapse to the origin (again in the absence of other disturbances) if the fishing effort is maintained. If $S = S_2$, then the stock will remain at this level for just so long as there is no disturbance; any disturbance will result either in a collapse, or an increase towards the stable position $S = S_1$.

These results can be used to deduce the yield/ effort relation. This is not quite so easy to express in quantitative terms as in the simple case used by Clark (1974) but the quantitative results are easily seen. For low values of effort, yield increases with effort, the shape of the curve being similar to that of the left-hand side of most yield-per-recruit curves. For high values of f the yield will be roughly proportional to the recruitment. Putting these together the shape of the yield/effort curves corresponding to possible stock-recruit curves are shown in Figure 2. When there is an inflection in the latter (curve 3 of Fig. 2b), then part of the yield curve will bend back. These curves are similar to those of Clark's Figure 2, showing that his results are quite general, and not restricted to the simple case of single-age spawners exploited during a very short period immediately before spawning.

However, the equilibrium points along the backward bending part are not stable, and thus do not represent values that will occur as averages over the period if effort is maintained. If the population were to be suddenly placed at one of the equilibrium positions on this part of the curve it would be an even chance – depending on the direction of the small disturbance needed – whether it collapsed or increased towards the stable position. In the real world the population size at any time will not be exactly equal to the equilibrium value (whether stable or unstable) corresponding to the current level of fishing mortality, but will depend to a large extent on the previous history of the stock, particularly of the fishing mortality. If this has been increasing, then the stock will most likely be greater than the equilibrium value corresponding to the (high) current fishing. Therefore, the stabilizing forces will be tending to bring the population to the stable positions on the upper part of the curve, rather than causing collapse. Thus, the backward bending part is not in practice likely to be observable, as is indicated by the broken line. (The similarity of these curves to the two-dimension projections of the surfaces described by Zeeman (1976) in relation to general catastrophes suggests interesting further lines of study.)
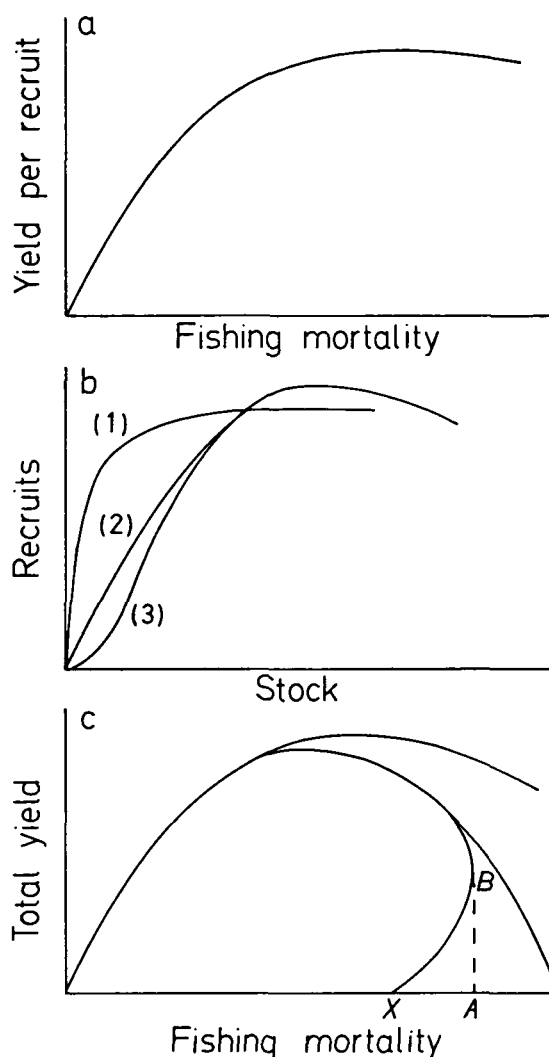

Figure 2. The effect on the yield/fishing mortality curve of different stock/recruitment relations.

a. A typical relation between fishing mortality and yield per recruit.

b. Possible stock/recruitment curves, showing a curve with almost constant recruitment (1), strong density-dependent recruitment (2), and a curve with negative density-dependence at low stocks (3).

c. The relations between total yield and fishing mortality obtained from the curves of Figures 2a and 2b.

These results, while interesting, do not appear likely to cause fishery managers undue anxiety. Clearly recruitment failures are serious, and recruitment over-fishing in the sense of Cushing (1972) is to be more carefully guarded against than growth over-fishing. However, provided the progress of the fishery along these curves can be accurately monitored

there will be no problem. Even if the monitoring is somewhat ineffective, or the reaction of the manager is slow, so that the fishing mortality overshoots the point of maximum yield or even the level which can be sustained, i.e. beyond the value AB in Figure 2c, the result need not be permanent disaster. Provided the stock has not fallen below the critical level R_2S_2 in Figure 1, below which it collapses even in the absence of fishing (and there is little evidence that such a critical level exists for many, or indeed any, important fish stocks) a sufficient reduction in fishing mortality will lead to a recovery of the stocks. The necessary reduction will, at the worst, be one that reduces the fishing mortality below the backward-bending part of the curve, i.e. to less than X in Figure 2c, but a less drastic reduction to somewhat between A and X will be sufficient, provided that the population has not fallen below the (unstable) equilibrium value corresponding to that level of fishing. Further, this recovery will tend to be along the upper part of the curve in Figure 2c. This somewhat cheerful scenario does, however, suppose that action is taken in time, otherwise there may have to be a long period of low catches to rebuild the stock. An essential need is therefore adequate monitoring, and willingness and ability to act when danger signs occur.

The difficulty is that the reduction must be in fishing mortality F. The fisherman or fishery manager is used to thinking in terms of catch or effort, and especially they often believe that any reduction in catch or effort will result in reduction in F, and is a positive conservation measure. This need not be the case. The fallacy as regards catch is best illustrated by Antarctic whaling. Just prior to a critical special meeting of the International Whaling Commission in 1965, which resolved the basic conflicts between short-term and long-term interests in favour of the latter, fin whale stocks were declining very fast (at around 20–30% per year). It took much scientific argument (and the failure of the industry to achieve their quota in the 1963/64 season) to persuade the Commission and the industry that the sizes of reduction in the quota being proposed (of around 10–15%) would in fact result in *increased* fishing mortality and an accelerated decline. The catch fallacy is now well recognized, at least by scientists, though many fishermen and administrators have a somewhat natural difficulty in accepting the magnitude of reduction in *catch* that is required to achieve a reduction in mortality (and have any real conservation effect) in a situation where the stock is rapidly declining.

The effort fallacy is similar, but more insidious. The fact that a reduction in effort need not result in a reduction in mortality has proved less dangerous

to date mainly because effort control has been less frequently used than catch limits. In addition to the difficulty that occurs when effort ceases to be proportional to mortality in relation to achieving a desired management policy by effort controls, the failure in proportionality can also change the whole form of the apparent yield-effort curve. Mathematically the failure in proportionality arises from changes in the catchability coefficient, q, in the equation

$$F = qf$$

The various ways in which the variations in q and their causes can be classified, have been widely discussed particularly at two ICES symposia (Gulland, 1964; Pope, 1975). These discussions mainly concerned seasonal or diurnal variations, or trends in time due to increasing power or efficiency of the fishing vessels. For the present purposes variations in q that are related to fish abundance – particularly when q increases with decreasing stock abundance – are more serious, especially at lower stock levels. The extent to which this happens depends on the gear. There seems little reason to expect the proportion of fish in the path of a trawl which are caught by it to vary appreciably with abundance. The efficiency of several types of gear (lines, traps, and possibly gill-nets) can be reduced at high fish densities by the occupation of the available space. This gear saturation is readily observed and appropriate corrections made (Gulland, 1956).

The serious problems relate to those fisheries in which searching and the success of searching is a major determinant of the catch. These include most of the fisheries on shoaling pelagic fish, particularly with purse seines, though pelagic trawling may also be affected. The question mainly relates to the measures of fishing time that are used in determining fishing effort. It is possible to break up a complete trip into a number of operations, e.g. steaming to the chosen fishing grounds, searching on these grounds, shooting and hauling the net, and returning to port. When adequate information on each of these operations is available it may be feasible to devise a measure of effort that will be proportional to the actual fishing mortality caused (Anon, 1974). Conceptually it may be easier to carry through the calculations with the immediate objective of determining an adjusted catch-per-unit-effort that provides a consistent index of abundance. For example, the number of hauls made per unit searching time (adjusted for the speed of the vessel, and searching power as evidenced by sonar or other equipment) may give an index of the number of schools per unit area. Multiplied by an index of the size of schools

(e.g. catch per haul corrected for the efficiency of the gear as evidenced by the size of the net, etc.) this should provide a reasonable index of density. A further adjustment, using some estimates of the areas of the stock may be necessary to provide an index of abundance.

This is fine provided sufficiently detailed information on the commercial operations are available from log books. Even in the more detailed log book systems, e.g. those of I-ATTC for tropical tunas, and in Peru for the anchoveta fishery, this may not be completely true. More generally the best effort information relates to numbers of landings, days at sea, or numbers of hauls. Any of these, if used to compute effort, can result in values of q that increase rapidly as the stock decreases.

A number of mechanisms can cause increases in q as the stock decreases. For example, the area inhabited can shrink, maintaining the density and indices of catch-per-unit-effort. Often the school size will remain the same, while the number of schools fall, so that catch per haul remains steady. Increases in q that do result in some fall in c.p.u.e. but not as great as the actual decrease in abundance, can be caused by a greater part of the unit fishing time (the trip, or the day at sea) being spent in searching. Mathematically these effects can be expressed as a relation $q = \alpha P^\beta$ where P = abundance of the fishable population.

It may be important to note that P, that part of the total population (from eggs to adults) which is exposed to fishing, i.e. the fishable or recruited part, will not in general be the same as the spawning stock. Many fisheries are based partly or predominantly on fish while they are immature. While the effects discussed below are not directly concerned with any specific relationship between the abundance of the adult stock and subsequent recruitment, the results could be made more serious if reductions in adult stock did affect recruitment.

The usual basic assumption that q, the catchability coefficient, is constant is given by $\beta = 0$ and increases in q with decreases in stock by $\beta < 0$. For the particular case of $\beta = -1$, c.p.u.e. remains constant despite changes in stock. Fox (in press) has found that data for the Californian sardine fishery is fitted by $\beta = -0\cdot3$.

Fox (in press) has examined the consequence of the above relation to the usual analyses of catch and efforts data. His extension of the GENPROD model (Pella and Tomlinson, 1969) becomes

$$-dP/dt = HP^m - KP - \alpha P^\beta f \cdot P$$

from which he derived the equilibrium value of effort, in terms of the catch-per-unit-effort, U, as,

$$f = aU^b + cU^d$$

where a, b, c, and d are functions of H, K, α, β and m.

From this the other relations between effort, catch, and catch-per-unit-effort (biomass) can be readily deduced. The important conclusion, as pointed out by Fox, is that for some values of m, including the traditional Schaefer (1954) value of $m = 2$, when $\beta < 0$, this can produce a backward bending yield curve. For example Fox's Figure 8 shows the fit to the data of the Californian sardine, which in terms of nominal fishing effort has a backward bending curve like Figure 2c, even though the equivalent relation between yield and fishing mortality is the typical parabolic Schaefer curve (or the GENPROD curve for $m = 2$). The backward curvature in this case has no connection with the basic biology of the fish, but is due wholly to the difficulty of getting a proper measure of fishing effort, i.e. one proportional to fishing mortality.

The stability of the equilibrium position in the backward bending part of the curve is clearly important. There are a number of different ways in which the system could be temporarily disturbed from a equilibrium position, including changes in fishing effort, e.g. diversion to or from another stock in which conditions are temporarily better or worse, in average stock size (e.g. the entry of a good or bad year class), or in the catchability coefficient, i.e. in the fishing mortality caused by a given fishing effort, (e.g. by unusual hydrographic conditions concentrating the fish). Though they may differ in detail in their effects, it would seem that these all tend again
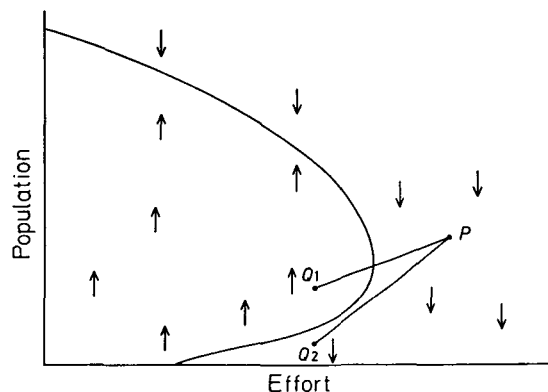

Figure 3. Possible relations between fishing effort and equilibrium population size if the catchability coefficient (q) varies with stock abundance. The arrows show the trends in population size if the population is not on the equilibrium line. Note that only the points on the upper part of the line are stable. Q_1, Q_2 denote successful and unsuccessful changes in a fishery on a too heavily fished stock originally at state P.

to make the lower, backward bending part of the curve unstable. Suppose for example the catchability increases then the fishing mortality resulting from the same nominal effort will increase, tending to further depress the stock. Conversely, if the catchability drops, then there will be some increase in population, therefore even after conditions return to normal, a drop in mortality and hence a further recovery in population. The likely stability may therefore correspond to that illustrated in Figure 3. This shows a possible equilibrium relation between population abundance and nominal fishing effort corresponding to the backward bending yield-effort curve in Figure 2c. The arrows indicate the changes in population likely to occur (other things being equal) away from the equilibrium line. They illustrate the lack of stability in the backward bending part. The figure also illustrates an important conclusion for management of fisheries in which the effort has increased beyond the level that can be maintained, e.g. to P. If the effort is reduced quickly enough within the sustainable range, i.e. so that there has not been much drop in population, e.g. to point Q_1 then the population will recover. However, if the cut in effort is not fast enough or far enough, e.g. to Q_2 the collapse can continue. That is, in fishery management, as in war, too little and too late can be fatal, and early but moderate action can be as effective as drastic but slow response to management needs. This in turn requires adequate response in all the links in the management chain, not least in the monitoring and scientific analysis.

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