New Policy Objectives and Management Procedures for EU Fisheries

A Commentary and Suggestions [1]

by

Sidney Holt [2]

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[2] Voc. Palazzetta 68, Paciano (PG), 06060 Italy. +39 075 830 7035. sidneyholt@libero.it

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Summary

This paper welcomes the proposal by the European Commission that the Common Fisheries Policy for managing fisheries within the Exclusive Economic Zone (EEZ) of the European Union (EU) be amended to provide explicitly for the core objective of management to be identified as the restoration of fish stocks to levels and conditions in which they are capable of providing maximum sustainable yields, and maintenance of those stocks at or above those levels. This welcome is extended despite the fact that the MSY as a valid management objective, or even as a real biological feature of exploitable wild populations, has for decades been strongly – and rightly – challenged by scientists and economists, including by the author. ***Accoedingly the welcome is conditional on a redefinition of the MSY concept, and of the notion of sustainability,*** in operational terms. The redefinitions offered follow the approach taken by scientists working within the International Whaling Commission (IWC) and subsequently taken up by other scientists concerned with fin- and shell-fisheries: that *sustainability* be treated as a state of finite, not infinite, duration: that a *predetermined management period* be more or less coincident with the period of 'sustainability' and that the '*maximum*' *sought is the cumulative catch from a stock during the finite management period*. Further conditions should be set that make operational a precautionary approach but which also as far as practicable ensure the possible continuity of the fishery in case of the need to drastically reduce the intensity of exploitation.

A procedure for implementing this policy would differ from the traditional practice of constructing the best model of the dynamics of the fish stock and then setting catch limits (TACs) calculated from that model. It would depend instead on the application of an *Allowable Catch and/or Effort Algorithm* (ACEA) for calculating and setting permissible levels of catch and/or fishing intensity, the performance of which has been rigorously and thoroughly tested using artificial 'data' generated by a range of plausible population models that describe what are thought to be the general dynamic characteristics of the exploited populations, modulated of course by the available real data. These models need to exhibit certain features that are described in the paper, and in particular provide for caution against possible irreversible changes when stocks are excessively depleted, and which recognize the possibility of recovery from such levels being slower than might be expected or hoped for. They need also to take account of the desirable changes in the age- and body-size compositions of the populations and the catches from them.

This approach is compatible with the idea of ecosystem-based management and can take proper account of the need for care in situations of external environmental change. It does not make impossible demands for intensive biological research but does require commitments to estimate stocks periodically by surveys independent of data from the industrial catches, to monitor closely the conduct of the fishery, and – once the management goals and corresponding algorithms have been agreed – consistency in implementing the procedure. Metaphorically, the horse must not be changed in mid-stream except in case of dire emergency.

After an exposition of the traditional approaches to management, focused on MSY or on various alternative 'reference points' based on the shapes of theoretical curves of sustainable yield against stock level or fishing intensity, the paper describes the experience of the IWC in its ultimately failed attempts to implement a traditional MSY management objective (1975-1985). This is followed by an account of its subsequent experience in finding a new way, and discussion of its application in principle to manage marine fisheries generally. The need is emphasized to model appropriately the transitions from one population state to another, eventually more productive one.

Preface
European fisheries management practices since the end of World War II have led to the depletion of most fisheries resources in what is now the EU EEZ, and even the endangerment of some of what were the biggest and most valuable of them. Some, such as the skate, have been reduced virtually to biological extinction, others such as the cod and herring, which were once enormously productive for centuries, have been so reduced that it has been found necessary to impose temporary moratoria on their commercial exploitation. Similar situations have developed elsewhere, with the same primary cause among several other secondary causes: excessive and inappropriate deployment of fishing power and effort.

Experience from the reductions in fishing effort during WWII showed conclusively that such reductions can usually lead to recoveries of depleted stocks.[1] At that time the effects of fishing, apart from substantially reducing the size of the stock, were mainly changes in the age and size compositions of the recruited sectors of the fish populations such that the average catches were lower than they could have been with less fishing effort in the long-term; and the stocks affected were mainly of demersal species such as flat-fishes and haddock. These phenomena were referred to as arising from ***growth over-fishing***. Later, technical and market developments, especially as a result of the expansion of industrial fishing for the production of meal and oil from some pelagic species, including from the young of those species, led to so-called ***recruitment over-fishing*** – in whih the stock reduction was such that reproduction was severely impeded, with even more devastating consequences.[2]

In efforts made - almost always belatedly - to 'save' fishing industries that have been harmed by such processes, fisheries management authorities, and scientific groups advising them, have sought to restrain fishing effort, usually indirectly by the imposition of limits on catches (TACs – *Total Allowable Catches*), accompanied by a variety of regulations regarding permitted fishing gears, minimum legal sizes of landed fish and restrictions on the seasons and geographical locations of fishing operations. TACs have sometimes in principle, or at least in theory, been set at or near to levels that are thought by scientists to be sustainable by the stocks in the condition in which they were at the time, and occasionally somewhat below those levels, with the intention of allowing stock recoveries and also introducing a measure of precaution. However, the current needs of the fishers – or, at least, their perception of such needs – and the consequent political pressures, have more often resulted in TACs being set higher, sometimes much higher, than those recommended by scientists, and, further, if some stock recoveries are noted after more drastic action has been taken, in TACs being prematurely increased again, with even more disastrous results. Weaknesses in the scientific procedures of stock assessment have compounded such problems in many cases.

Now the European Commission is beginning to think about radically new approaches to management to make long-term and sustainable improvements, with a focus on an over-arching objective of bringing fish stocks to levels of abundance that can support the taking of a *Maximum Sustainable Yields* (MSY) from them. This is in fact not very 'new', having been expounded and proposed in the early 1930s by Norwegian and British scientists. A version of that approach has been given respectability by being formally incorporated in Article 61 of the UN Convention on the Law of the Sea (UNCLOS), and reflected later in a series of less formal agreements under UN auspices, such as documents emanating from major international conferences in Rio de Janeiro and Johannesburg.[3] The MSY concept has however, over the years, also been the subject of deep criticism by many scientists, so much so, in fact, that the EU initiative could be misunderstood and even jeopardized.

The purpose of this document is to offer a critique of these hopes and fears and thus contribute to finding a generally acceptable way forward. It necessarily begins with a review of the basic principles of a theory of fishing, including comments on and some criticisms of the types of models that are often used in making fish stock assessments and providing management advice. This is to illustrate the problems of trying to manage fisheries based on a classical definition of MSY[4], including that the choice of the specific mathematical model has enormous consequences for management. However, there are rarely, if ever, sufficient data from nature to indicate which model is most appropriate. This section is followed by an example of the development of a management procedure that was invented to overcome this, and other, conceptual and practical difficulties - the one for the whale fishery for baleen whales developed by the International Whaling Commission. That included - indeed was based on an implicit re-definition of the concept of MSY. Finally, an explanation is offered of how that kind of procedure could in principle be followed for managing fisheries, and some of the difficulties that might arise.

1. Introduction

In two documents circulated by the European Commission to the Council and the European Parliament, and presented to an Experts meeting of the Commission's Advisory Committee on Fisheries and Aquaculture (ACFA), on 15 September 2006, it is proposed that sustainability in EU fisheries should be implemented through a new policy of seeking Maximum Sustainable Yield (MSY).[5] These provide, especially in the "Communication" Sections 1, 2 and 3, straightforward accounts of the scientific approach to management for sustainability that has evolved in the scientific community over the past 50 years.

In these documents the idea is anchored to the Implementation Plan adopted at the World Summit on Sustainable Development (WSSD), held in Johannesburg in 2002, with particular reference to its Section 31. This called, *inter alia*, for actions to *maintain or restore stocks to levels that can produce the maximum sustainable yield with the aim of achieving these goals for depleted stocks on an urgent basis and where possible not later than 2015*. That statement is derived from the principle enshrined in Chapter 17 of Agenda 21 from the UN Conference on Environment and Development (UNCED), held in Rio de Janeiro in 1992. States therein committed themselves "*to the conservation and sustainable use of marine resources and specifically to maintain or restore populations of marine species at **levels** that can produce the maximum sustainable yield… .*" [emphasis added]. That, in turn, was derived from provisions in the UN Convention on the Law of the Sea, 1982 (UNCLOS), but there the central objective - to maintain or restore populations of harvested species at levels which can produce MSY - was "qualified by environmental and economic factors" and further, by "taking into account … fishing patterns, the interdependence of stocks and any generally recommended international minimum standards." UNCED Agenda 21 and the WSSD Implementation Plan may reasonably be regarded as "soft" international law, but UNCLOS provides the more authoritative relevant "hard" law. The UNCLOS formulation provides a little more leeway in interpretation of the MSY imperative than do subsequent contractions of the rule.

It is important to note the repeated reference to stock "*level*" in all these formulations. Unfortunately, these conceal the fact that MSY, as classically defined, is a function also of properties of exploited populations other than their *size*, most relevantly their *composition* and particularly their compositions by age and body size, as well, in some circumstances, to the sex ratio. For the moment, however, let us focus on *level*, which might be expressed with reference to a number of animals or to the weight of the population - its *biomass*. The use of this term is significant in that, unlike population size itself, it generally implies a number or biomass relative to some *reference* number or biomass. Furthermore, that reference number is commonly taken to be the population size before exploitation began or, alternatively, to which it would eventually return if exploitation were to cease; this is variously referred to as the *pristine level* or *carrying capacity* .Additionally, the "*conservation status*" of a stock, or some such term, is commonly expressed with reference either to that level or to some other *reference point*, such as the level at which MSY may be generated (MSYL).[6] Again, most commonly, the conservation status of a stock may be judged to be "over-fished" if a sustained reduction in fishing effort or intensity would in the long run provide higher continuing yields. In the simplistic terms of "levels" this designation implies that fishing has reduced the stock to below the MSYL

I have reviewed elsewhere the history and theory of the notion of "sustainability", in the context of "sustainable use" of a renewable resource.[7] Here I recapitulate the essence of the standard theory as it applies to the question of MSY as a management target for marine commercial fisheries. We begin with the simple *logistic* curve of growth of a population in number, as proposed in 1838 by P.F. Verhulst,[8] re-invented by T.B. Robertson in 1908 and adapted by Raymond Pearl in 1920. This describes the growth of a biological population in which the *rate* of increase (strictly, the *proportional* increase rate, that is the numerical increase in a short period of time expressed as a fraction – percentage – of the population number during that time) [9]is continuously and progressively reduced as the population grows, this process being called ***density dependence*** (Fig. 1a). This equation predicts a smooth population growth up an S-shaped (“sigmoid” or "ogival") curve to a stable upper limit, usually designated as ***K*** [10]and called, variously, the *environmental carrying capacity* or *saturation level* (Fig. 1b). It is important to bear in mind that there is no empirical basis for such a simple and universal curve, although – surprisingly – it is still frequently used, misleadingly, by economists building econometric models that incorporate living (renewable) resources, and by some bio-mathematical modelers seeking to express inter-specific interactions in marine ecosystems.

Verhulst’s equation, as originally expressed, assumed the decrease in the growth rate was a constant value for a given increase in population, that is that the increase rate is a linear function of the population size, with negative slope. This can be regarded as a process of feedback, called *compensation.* The simple logistic can be generalized to take into account any growth function such that the proportional growth rate is a (continuously) decreasing function of the population size, not necessarily linear – most commonly a polynomial or a power function. Such are sometimes called *pure compensation* models.[11] The simple theory of fishing then says that if a population is reduced by fishing to less than its carrying capacity and held at a certain steady level, a sustainable catch will be taken, equal to the rate of population increase at that level multiplied by the population size. This produces a curve of sustainable yield as a function of population size that must have a peak somewhere (the MSY at MSYL). For the simple logistic this is at exactly half the carrying capacity but for the non-linear modifications it can be anywhere between a very small population and a population close to the carrying capacity (Fig. 2)[12]. A degree of non-linear compensation that has been used in assessments of whale populations gives an MSYL at about 60% of carrying capacity, while models used in some fish stock assessments imply an MSYL of about 30% of carrying capacity. It should, however, be borne in mind that there is essentially no empirical evidence that such properties actually occur in Nature, nor that the shapes of 'real' curves would be closely similar to the examples given.

The relative rate of population increase is the difference between a rate of reproduction, or *recruitment* (***R***), and a rate of natural mortality (***M***); call this difference the *net rate of reproduction* (*r*). In the theory of fishing ***R*** is usually expressed as a number related to an age and/or size at which the fish become, in principle, of commercial interest, although the size/age at which they begin to be caught depends on markets, regulations, seasons and locations of capture and the gear used. Thus ***R*** is actually determined by the population reproduction rate (numbers of eggs laid, etc.), and the subsequent cumulative natural mortality up to the age of recruitment (*pre-recruit mortality*). Similarly, the value of ***M*** used in fish stock assessments is that pertaining to the recruited population. But the corresponding value of the mortality rate caused by fishing, ***F***, is of course related to the age/size at which the fish first become liable to capture.

In principle the density-dependence by which ***r*** becomes greater than zero as a population is reduced below carrying capacity can come from changes in ***R*** or in ***M*** or in both. Most commonly, however, it is assumed that it originates essentially in changes in ***R***. Such changes could themselves originate in changes in reproduction and/or in pre-recruit mortality. In any case ***M*** is quite difficult to estimate (except perhaps by sampling an unexploited population)[13]; efforts to measure or even simply to detect density dependence of ***M*** have had scarce success. Changes in reproduction that could give rise to density-dependent changes in ***R***, and hence in ***r***, may come from changes in the fecundity of adult females and in the ages/sizes at which they become sexually mature and active (perhaps because of changes in the availability of food *per capita*) and perhaps by other biological processes. Changes in ***R*** can also, evidently, be caused by changes in the pattern of the pre-recruit mortality rate, and that can arise from competition among larvae and juveniles for food, but also from predation on them, including by larger individuals of the same species. The Atlantic cod is an example of such a cannibalistic species.

The value of ***r*** determines the sustainable yield (***SY***) from a stock of a given size, ***S*,** if that stock is in a *steady state*, *i.e.* at equilibrium. ***SY*** is equal to ***S*** multiplied by ***r*.** The value of ***r*** when the stock is in a steady state at ***S*** = MSYL is identified as r_{msy} . So MSY = MSYL times r_{msy} if MSYL is expressed in absolute terms (number or biomass) rather than as a fraction/percentage of the carrying capacity. Similarly the value of ***r*** when the stock is very small, close to extinction, is identified as r_0 . In the models described here the maximum value of ***r*,** identified as r_{max} is equal to r_0 , but this equality does not hold for all simple population models, as we shall see.

There are obviously some biological limits to the degree to which either ***R*** or ***M*** can change – in either direction - in response to changes in population abundance or density[14]. ***M*** cannot become less than zero. ***R*** may for certain types of animal have a limiting upper value determined by the biological limits of fecundity – for example whales, dolphins and other marine mammals can usually produce only one offspring per year or two, at most. Hence biological factors determine the possible upper limit to the range of ***r.*** In discussions about possible assumptions to make about this parameter when observational or experimental knowledge is lacking – as it usually is – it has been not uncommon to make erroneous assumptions, such as for example, that a biologically low value of the reproduction rate, ***R*** (as for example in the mammals and elasmobranches - sharks and rays), implies a population model with a relatively high MSYL. But in fact this level depends not at all on the rates of recruitment and mortality *as such* but solely on the specific way the *difference* between these, *i.e.* ***r*** , changes with population size. It is evident from this that determination of the MSYL from data will be very difficult, as has been found over the years of attempts to assess the state of fish stocks in the context of trying to implement an MSY-based management policy, or indeed any policy using other indicators of optimal or target state that are in any way linked to MSY and/or MSYL and the shape of the curve of sustainable yield against population size or fishing effort[15]. More usually the MSYL is merely assumed, or sometimes a population model is constructed that happens to exhibit, by accident,as one of its properties, a certain MSYL.

The simple models described above give curves of sustainable yield against population size, the shapes of which are quite arbitrary. Other models, mathematically equally simple, can give plausible curves with some of the same properties but much flatter topped (Fig. 3). For all curves of sustainable yield against recruited population size it is possible to obtain the same, but non-maximum, sustainable yield from two different levels of population, one above MSYL and one below it. For flatter-topped curves, however, sustainable yields quite close to MSY can be obtained from very different higher and lower population levels. Since the population level can be expressed as a function of ***F***, which is related to the intensity of fishing (fishing effort; roughly proportional to ***F*** if appropriately calibrated in terms of efficiency) it is evidently inefficient to seek the absolute MSYL; far better to aim at something slightly less than that but obtainable with very much less effort from a larger population and, naturally, with less risk of inadvertent stock depletion.. In this situation "the Best (really) is the Enemy of the Good".[16]

Since, for a population in steady state, ***SY*** is equal to ***S*** times ***F,*** all the curves of ***SY*** against population illustrated above can easily be re-plotted as ***SY*** against ***F*** or fishing effort (see Fig. 2). Another identity comes from the fact that, in a steady state, for any level of an exploited population $r - F = 0$, so that $r = F$. These curves of ***SY*** against fishing mortality or fishing effort look similar to the curves of ***SY*** against population, going to zero when there is no fishing, and again at a threshold level of fishing effort when the population is exterminated, that is when reproduction cannot overcome the combined (total) mortality rate $\boldsymbol{F + M}$. The value of $\boldsymbol{F}$ generated by that threshold level of fishing effort we shall call $\boldsymbol{F_{ext}}$ ("ext" for extinction). The curves have peaks – MSY – at an intermediate value of $\boldsymbol{F}$, which we shall call $\boldsymbol{F_{msy}}$ **.** This is sometimes referred to – misleadingly - as *optimum* $\boldsymbol{F}$.

The curves of $\boldsymbol{SY}$ against $\boldsymbol{F}$ point to two different approaches to managing fishing for sustainability. One is to regulate catches as some fraction of the expected sustainable yields, the other to regulate the intensity of fishing. In these simple models the two approaches seem to be equivalent, but if – as always in practice - there is both natural variability in the parameters of the model, and uncertainty as to their values, the consequences of the two approaches are very different. (We shall look at this matter later, noting that by far the greatest type of variability of which we are aware is that of annual recruitment and the setting of sensible catch limits involves the difficult and highly uncertain practice of predicting that variability from year to year.) At this point it should be emphasized that the simple models predict extermination of the population only if the threshold level of fishing is maintained over time. If fishing is relaxed before extermination occurs then the population would "bounce back", making a partial or complete recovery, depending on the level of fishing subsequently maintained. That is to say the system is entirely reversible. We have to examine the question of how realistic the idea of reversibility may be.

Biological processes can be identified that result in $\boldsymbol{r_{max}}$ being not equal to $\boldsymbol{r_0}$ but higher than that, occurring at some intermediate population level. This phenomenon is called *depensation*, or "the Allee Effect", after the ecologist who first studied it. To honour him we define the population level at which $\boldsymbol{r_{max}}$ occurs as $\boldsymbol{S_A}$ – usually assumed to be quite low; and the fishing mortality rate which, if maintained, will lead to a population steady state at that level, as $\boldsymbol{F_A}$. This phenomenon, if and when it exists, has important consequences for the management of fisheries exploiting reduced or depleted populations.[17] The most obvious of these is that if fishing intensity is reduced the "recovery" of the population may, at first, be slower than expected from models that do not include depensation; later, a "take off" period would be expected as recovery accelerates, followed by the expected slowing of population increase as compensatory processes "kick in".[183]

Even more important, however, is that depensatory processes can lead to *irreversibility*. The ***blue*** curve of sustainable yield against population size in Figure 3 illustrates depensation. Figure 4 also illustrates another yield curve (this one from yet another model family) and the corresponding curve of net reproductive rate against population size (corresponding with the three non-depensatory curves illustrated in Figure 1). These exhibit *simple* depensation. The special case of c*ritical depensation* is manifest by a left-hand limb touching and crossing the x-axis (population size) when the population is small but still finite, not zero. A population described by such a model is unstable when depleted to below a ***minimum viable population level***; it will not recover even if the fishing effort causing its depletion (or indeed other natural or human-caused processes) ceases.[19] This situation is not illustrated here because it elucidates no additional features of the dynamics that concern us and we have as yet no evidence for its existence in fishes

Depensation can be introduced into all the population models mentioned earlier simply by adding another parameter. This seems to have encouraged a particular approach to the statistical analysis of fisheries data (through the application of the principle of Occam's Razor, that a simple explanation is to be preferred to a more complicated one) in which the absence of depensation is treated as a null hypothesis, to be rejected if possible by the limited available data.[20] This has led to the conception – I think a *mis*-conception - that depensation is rare or in some way unusual. Myers *et al*, 1995 and 1999, analysed a compilation of data and could not, they said, "find convincing evidence that depensation occurred in exploited fish populations". However, Liermann and Hilborn, 1997, using a better statistical method *did* demonstrate that the data were consistent with moderate levels of depensation for several taxonomic groups.[21]

It is easy to postulate plausible models, with no extra parameters, that *do* manifest the phenomenon of depensation; one of them has been used to produce the blue curve in Figure 3.[22] These would suggest that in statistical tests the null hypothesis (perhaps to be rejected by data) should be that depensation *does* occur. The importance of this for management of fisheries on substantially reduced populations is that if it assumed that there is no depensation in any range of population level, when in fact there is, then continued fishing can lead to severe depletion and even virtual extermination, as well as slower than desired recovery after a correction is made, usually late in the day. If, on the other hand, it is assumed that depensation does occur, but in fact it does not, then no lasting harm will have been done, and there will be less temptation to allow higher catches in the short-term that would cause unnecessary depletion.[23]

2. Possibly more realistic models

In the Introduction we have rather casually mentioned that the discussion about population models in numerical terms can apply also to population biomass.

This is not strictly true although in some fisheries applications it has been assumed. The simple (symmetrical) logistic curve idea was first applied by Norwegian scientists in the 1930s to the *numbers* of blue whales in the Antarctic, but was soon after applied in several situations to *weights* of catches, for example the tunas in the Eastern Tropical Pacific and the cod in the North Sea. But, since the simple logistic, or the Pella and Tomlinson modification of it, were arbitrarily chosen, without an experiential basis, this did not disastrously affect the sorts of rough assessments being made, although it might have contributed to the eventual over-fishing of the tunas. Nevertheless, it is clear that the biomass and biological productivity of a steady-state population of a certain numerical size, and hence the sustainable yield expected from it, can vary greatly according to the distribution of fishes by age and hence body size comprising it; and, conversely, the productivity of a population having a certain biomass will depend greatly on the ages and sizes of the individuals in it.

There have been several approaches to dealing with this problem but the scientific literature and practice has come to be dominated by procedures elaborated by R. J. H. Beverton and S. J. Holt in the 1950s.[24] We first consider the fate of a cohort of recruits entering the "fishable stock" in a certain year. At first they will be relatively numerous and relatively small. As time passes some will die naturally or by being caught and the survivors will increase in size. Eventually, as natural deaths continue (and perhaps more rapidly with increasing age), but the individuals grow more slowly with increasing age, the total weight of the cohort will increase to a peak and then decrease until eventually its last member dies. The greatest catch that could be taken would be obtained by waiting for the peak to be reached and then catching the entire cohort. Provided the peak was reached a sufficient time after the animals had become sexually mature and spawned this catch might be regarded as a sort of 'MSY'. But in practice, of course, it is not feasible in sea fisheries to arrange to catch all the cohort at once at an optimal age so a more complicated calculation has to be made in which a fishing mortality rate is imposed throughout the fishable life-span of a given cohort, that is from the age/size at recruitment (or the later age at which fishing commences). This gives a catch somewhat less than that obtainable from catching all the cohort at the optimal age, and it is a function of the value of fishing mortality, $\boldsymbol{F}$, imposed. The next step is to pass from consideration of the catches from a cohort throughout its life, to the identical total catch in weight and age/size composition expected from the summed catches from several successive cohorts (formally of the same initial number) in a single year.

Such calculations have usually been expressed in terms of $\boldsymbol{SY}$ as a function of $\boldsymbol{F}$, but they can equally easily be graphed in the form $\boldsymbol{SY}$ as a function of population size (possibly number but more usually biomass). The resulting curves of sustainable or 'steady state 'Yield per Recruit' (***Y/R*** is the usual terminology, but ***R*** here means annual number of recruits, not a rate of recruitment) against ***F*** are commonly peaked but may also be asymptotic, that is reaching a plateau at very high fishing intensities; which form is taken depends on the relative age at which recruits begin to be exploited (the human element) and on the parameters in models describing on the one hand the natural mortality and on the other the pattern of growth in weight of the individuals (the biological element)[25] (Figure 7). Thus we can say there may or may not be an MSY on a per recruit basis, but also there *always* will be one if the recruitment is affected – detrimentally - by the diminution of population biomass and hence in numbers of sexually mature animals as a consequence of fishing.

Scientists have found it is very difficult to detect a clear relationship between population biomass or number of spawning fish and the resulting recruitment one or more years later. There is a voluminous literature about this, both in terms of theory and data from many stocks and species. (There are also very many speculative models of what the relationship might look like). Commonly, over quite a wide range of populations size, no correlation with subsequent recruitment is found, but this is at least partly because of the natural "noise" – specifically the enormous variability of recruitment that is found in fishes, especially in the small pelagic species.[26] Nevertheless it is obvious that at some low level of population – and it could be *very* low – the number of recruits must be adversely affected, and ultimately approach zero. If account is taken of this, by "marrying" the ***Y/R*** curve with a curve such as one of those illustrated in Figure 5 which relates mature population to subsequent number of recruits, we obtain yet another domed curve (Figure 6) in which the "stock-recruitment relationship" is that derived by Beverton and Holt, called by those authors a *self-regulating yield curve*, where, again, ***SY*** can be expressed as a function of either population size or of ***F***.[27] It can also conveniently be expressed, in the latter case, as a function of the exploitation rate, ***E*** , which is the ratio of ***F*** to the total mortality rate ***Z = F + M.*** (See the illustrative series, Figures 8a to f, and the '*Explanations*' given to this and preceding figures, and especially Figure 10.)

The compensatory density-dependence that theoretically generates the ***SY*** in such a *self-regulating* model is in the pre-recruit natural mortality rate underlying the stock-recruitment curves in Figure 5. There is no density-dependence assumed either in the reproduction rate itself or in the ***Y/R*** module of the "marriage". It is significant, however, that depensation emerges from the union, at least for some sets of parameter values. No additional parameters are necessary for this, though one would make it possible to express the phenomenon more flexibly, that is occurring within a broader range of population levels. A similar effect can come from the assumption of any of several other forms of stock-recruitment curves that have been proposed by numerous authors (some of which are inflected at low population levels and therefore explicitly generate depensation in the yield curves) but which need not concern us here.

*The next two sections of this paper and much of the subsequent discussion leading to the Conclusions and Recommendations, refer extensively to the history of attempts to regulate commercial whaling, first for sustainability and then for eventual maximization of yields. conditional on application of a strong and fully specified precautionary principle Readers might, understandably, wonder why so much attention should be given here to **whaling** when the problem before us is the regulation of **fishing**. There are two reasons for this. First, I have for a longer time, and more recently, been personally engaged in the whaling problem. And, second, although I think the IWC was the first forum in which the approach to management by simulation was taken seriously and developed, and there have been several subsequent fishery studies – that I have referenced as far as I know of them – along the same lines, the IWC study is the only one that has sought to arrive at solutions that do not at all depend on acceptance of a particular population model, a condition that I consider to be essential. This explains why I have here given so much attention to the existence of alternative population models.*

3. The IWC Experience: Part 1

Although some inter-governmental fisheries management organizations adopted MSY as a target long before its embodiment in more general hard and soft international law, the International Whaling Commission (IWC) embraced it eagerly in 1974-75 as it searched for a response to the call in 1972 by the United Nations General Assembly for a 10-year moratorium on commercial whaling, which would ameliorate the global concern about the extermination of whale resources without actually enacting a moratorium. The outcome was an arrangement called the New Management Procedure (NMP) that was formally adopted in 1975 and implemented from 1976 on.[28]

Under the NMP all stocks of whales were to be classified in accordance with assessments as to their status in relation to MSYL. Stocks thought to be "close" to MSYL (not more than 20% above it or 10% below it) were to be classified as *Sustained Management Stocks* (SMS) for which, if the stock was at or above MSYL the TAC would be set at 90% of MSY (in number); the 90% figure was supposed to provide a degree of caution against uncertainty of assessments. SMS stocks up to 10% below MSYL were assigned reduced TACs, which became zero when the stock was more than 10% below MSY, at which point becoming classified as *Protection Stocks* (PS). Stocks more than 20% bigger than MSYL were classified as *Initial Management Stocks* (IMS) for which the TAC would be "not more than 90% of MSY so far as this is known, or, where it will be more appropriate, catching effort shall be limited to that which will take 90% of MSY in a stock at MSYL." Furthermore, " In the absence of any positive evidence that a continuing higher percentage will not reduce the stock below the MSYL no more than 5% of the estimated initial exploitable stock level shall be taken in any one year." And, "Exploitation should not commence until an estimate of stock has been obtained which is satisfactory in the view of the (IWC's) Scientific Committee (SC)".

These formulae did serve the purpose of discontinuing exploitation of most of the severely depleted stocks of baleen whales (The NMP was originally put forward by the delegation of Australia as an "amended moratorium"). Through the late 1970s the scientists struggled to implement the provisions for SMS and IMS stocks, with decreasing success. The reasons for ultimate failure were several and are worth recounting for the benefit of the present fisheries exercise.

- To identify the MSYL the SC decided to adopt a modified logistic curve, *à la* Pella and Tomlinson, with parameter values to set MSYL plausibly but rather arbitrarily at 60% of carrying capacity.[29] Implementation of this involved estimating the latter as well as the current stock size, which at best could be done with difficulty and much uncertainty and in some cases not at all.
- The 90% rule was hopelessly inadequate to cover the real uncertainties in assessments.
- Virtually scholastic arguments arose as to whether a stock might be, say, 1% or 2% or 5% below MSYL Such fine tuning was far beyond the practical possibilities of reliable assessment, but the advice and ultimate decisions were contested vigorously both within the SC and at the level of political/administrative decision because they had unwelcome economic effects on the conduct of the whaling operations.
- The IMS rules were intended to result in bringing "stocks (down) to the MSYL and then optimum[30] level in an efficient manner without risk of reducing them below that level." This provision arose from the opinion of a few IWC Members that to permit any exploited whale population to remain above MSYL would be "a waste of renewable natural resources". The late introduction of the provision for zero TACs until a certain knowledge requirement had been met was an advance form of the application of what later came to be called "the precautionary principle"; it did however lead to considerable argument among scientists as to what constituted "a satisfactory estimate" of stock size.
- It was soon found that some stocks, the exploitation of which had only recently begun (the minke whale in the southern hemisphere was the main, though not the only case; its exploitation began only about 1969), could not be classified, nor did they fit the IMS zero-TAC rule. Within a few years the scientists were not only disagreeing among themselves but were offering advice for which there was no statutory provision – starting with "provisional classification" they moved to suggesting TACs be set at *replacement yield* (***RY***), that is the catch which, if taken one year would leave the population unchanged for next year. But ***RY***, while being

apparently easier to calculate than ***SY,*** was by definition not-sustainable because it related to a sock composition that was not in steady state, nor did it point to an ultimate management objective.

- Endorsement of the NMP did not resolve the problem the IWC had faced almost since its inception: that corrective actions to prevent further depletions were inadequate and could not be taken promptly enough. This was a result of several factors, apart from the inadequacy of the NMP itself: serious disagreements among the scientists as to the advice to be offered (which allowed the national delegations to try to pick and choose) and the fact that at the political level there still co-existed the contrasting aims of achieving sustainability and, where relevant, stock recovery, and meeting immediate short-term economic demands.

Eventually, the dying "Procedure" was put to rest (though not buried - it remains in the Schedule to the IWC's founding treaty until it is formally removed), a process urged on by a study by an Australian mathematician, William de la Mare. De la Mare carried out a computer simulation of the application of the NMP which showed that **even if the chosen population model** (Pella-Tomlinson modified logistic or BALEEN) **correctly represented the real world, and even if the parameters of the model were well estimated, if there was significant random variation in these the NMP would inevitably lead to further stock depletion in the long run.**[31] This opened the way to a serious and prolonged re-appraisal by the SC of the management of whaling,which was facilitated by the declaration by the IWC, in 1982, of a moratorium on all commercial whaling, of indefinite duration. The scientists were thereby relieved of the requirement to try to assess, classify and advise on TACs for every whale stock every year, and could give their complete attention to devising a workable, effective "procedure".

4. The IWC Experience: Part 2

The experience recounted here provides, I think, lessons for all efforts to manage fisheries on the basis of scientific approaches, and for that reason is described in some detail. The outcome of the SC's work over several years was a **Revised Management Procedure** (RMP). From a long, intense and highly organized competition between five scientific groups a version devised by J. G. Cooke was eventually adopted by consensus by the SC and accepted by the Commission. It has not yet been implemented for reasons that have nothing to do with the quality of the Procedure and the science behind it, but rather because it has not yet been possible to reach agreement on other elements of a Revised Management System (RMS), particularly compliance controls. [32]

The RMP has, as its core module, a Catch Limit Algorithm [33] (CLA). Its other module is a set of rules for applying the CLA in situations where there might be several separate and perhaps geographically over-lapping populations of a species the boundaries and movements of which are not well known – which is most situations. We need not discuss the details of the latter here because they too will be specific to each fishery situation. The RMP has in any case been well described in several publications, especially those by its originator.[34]

The CLA achieves its objectives through, in effect, redefining *MSY* and also *sustainability*, in operational terms. It seeks to maximize the *cumulative* catch (rather than the annual catch) over a *specified period* of time (instead of through a notionally infinite time. This objective is qualified by two restraints. Firstly, at no time should the stock be unintentionally reduced to below a certain specified level, with a certain very low, specified probability; this is one of the ways in which the principle of precaution is codified and quantified. The other restraint is that the stock would have had the opportunity, by the end of the specified period, to have recovered to, or towards, a specified level which is relatively high in relation to "carrying capacity". There is a third condition, of interest to fishermen as well as to whalers; it is that the permitted annual catches (TACs, or *Catch Limits*, in IWC terminology) shall as far as practicable not be changed much from one year to another, except if observations, new data and other important circumstance require otherwise, *i.e.* in emergency situations.[35]

The redefinitions make it feasible to devise a management procedure that does not rely on fitting a particular model to available data and then using the model to calculate advice regarding TACs. Instead, an *algorithm* is formulated and tested for its *performance*, *efficiency* and *robustness*,[36] with respect to the primary objective and, as far as possible, to the other objectives, by simulation, using as input artificial 'data' generated by plausible population models. The priority among conflicting objectives is to be decided *a priori* by the political/ administrative authorities and the stakeholders. In the IWC case first priority was given to the avoidance of unintended depletion, but in practice some kind of weighting formula might be adopted to balance the various objectives. The time period through which simulations are conducted, and which also must govern the applicability of the procedure in practice, is determined by several factors, including the generation time and natural life spans of the resource organism, the life-span of humans, and the likely time-frame of management institutions – in a sense a measure of social stability. In the IWC exercise it was determined also by computing capacity at the time and chosen to be 100-years, although few people would expect a management institution to endure as long as that. In practical terms the time-frame can have a considerable effect on the sequence of TACs generated. For example, the Norwegian fishery authorities and scientists have recently been advocating extending the IWC simulations to 200 or more years. The effect of this would be to allow much bigger catches now (which is of course the only purpose of the proposed changes!) and in the immediate future, resulting in further depletion of the stock – but not critically so – in the expectation that with reduced catching in the future the stock will still be given time to recover to the pre-determined level.[37] But it seems unreasonable to presume that a management system agreed today will endure for two centuries; a "limited sustainable" period of 50 years or even less would appear to be more appropriate. And the essence of this approach to managing resource use is that a procedure, once adopted and put into motion must be followed for the agreed and tested management/ 'sustainability' period. That does not preclude making adjustments from time to time as new information becomes available, but it is essential that such adjustments themselves be scrupulously tested by further simulations. Another change to the formerly agreed algorithm that Norwegian authorities and scientists have sought to make is the alteration of what are in modeling practice called the *tuning parameters* – which might be the ultimate target level for the stock at the end of the management period, the threshold below which the stock must not be driven and the various probabilities attached to these. While it is reasonable to examine the effects of such changes, if any of them were to be made the need for repeating the simulation process cannot be avoided.[38]

The main 'data'-generation model used by the IWC scientists (the "management development group") was the one that had been used in making the assessments for the application of the NMP: the Pella-Tomlinson modified logistic, with MSYL = 60%, followed by the more evolved BALEEN model with parameters giving the same basic characteristics of the yield curve and with random variables incorporated. When an algorithm had been invented that fulfilled, as well as possible, through the hundreds of simulations performed, the management objectives and conditions, other simulations were performed with the same model but a wide range of different parameter values, with the algorithm being adjusted so that it performed acceptably throughout that range. Thus the resulting TAC advice would not depend critically on assumptions made or uncertainties about the parameter values and hence the MSY-rate and MSYL.

The next step was to repeat this but by generating 'data' from other plausible population models, and *their* variety of sets of feasible parameter values. Adjustments were made to the algorithm, and in this way it was hoped to ensure that the advice[39] emerging from use of the algorithm would be independent of assumptions and uncertainties about both the population model and its parametric characteristics. Throughout this development process consideration was given to the likely availability of real data to which the algorithm could successfully be applied. The basic requirements were a series of historical catch data, and periodic estimates of the size of the stock. Historic catch data are subject to errors, sometimes substantial ones, from failure to keep old records, carelessness, and especially by past cheating on the part of operators.

Simulations were therefore conducted, with consequent adjustments to the algorithm, to ensure that the output would be robust to such "errors". As to the size of the population it was decided quite early on that indices derived from commercial operations, such as catch-per-unit-effort and sightings cruises carried out by commercial vessels in the course of whaling operations, could not be acceptable, and attention homed-in on estimates from properly planned and conducted, ***and cooperatively analysed,*** sightings (or in the case of the sperm whale, acoustic) surveys[40].

Application of the procedure, once management objectives are formally agreed in all necessary detail, and the algorithm adopted, is straightforward. Each year a Catch Limit is set, taking into account the catch in the preceding year and the results of any new estimate of stock abundance, and of it's statistical accuracy coming from a new survey. The necessary frequency of surveys is an important item to be decided on the basis of several considerations that need not occupy us here, but high among those considerations is the expected accuracy of the results.

Early in RMP-CLA development consideration was given to ways of dealing with possible environmental changes during the chosen management period, and with possible competitive interactions among the group of baleen ("whale-bone") whale species to which it was intended the procedure would apply. It was agreed that these could in practice be treated as two aspects of the same problem. Thus the feeding of a competitor, that might be changing in its abundance, on the same food resource could be regarded as an environmental change and tested as such. This is practicable because there are time-lags in the natural system and, provided that abundance surveys are subsequently conducted with appropriate frequency, significant interactions would be detected and taken into account more or less automatically in the next rounds of assessments. So simulations were carried out with assumed environmental changes in various patterns on a large scale and through time. (For example assume a sudden change from one year to the next of 50% in environmental productivity, up or down, and also changes on the same scale spread over many years, then as before make any necessary adjustments to the algorithm so that it continues to perform well and is still robust. Here it should be understood that this is a highly creative process involving deep logic and much imagination).

5. Application to other fisheries

The approach to management developed by the IWC's SC for application to commercial exploitation of baleen whales on their feeding grounds can in principle be applied to all fisheries based on wild stocks. The whaling situation is not special nor exceptional in this regard, although even within that narrower scope considerable adjustments would necessarily be made to deal with the exploitation of baleen whales throughout their migratory ranges, and with other marine mammals, such as the toothed whales, having quite different social structures, behavioural patterns and other biological characteristics. One big difference between the baleen whaling and fishing situations is that while the whaling industry and governmental administrations were content to regard the great whales merely as *numbers*, any application to other fisheries must at least deal with weights of catches, if not of economic values. But this is not a serious obstacle: the input 'data' for simulations would simply have to be generated by theoretical population models generally similar to the self-regenerating model briefly described in Section 2.

The IWC took as its objective regarding catching the cumulative catch through a period of 100 years (subject to various constraints specified among the other objectives). For fisheries the length of the management period which effectively defines "sustainability" would certainly be much shorter. But whatever it would be, the question could arise of whether in specifying the cumulative catch account should be taken of discounting the value of future catches as is common economic practice. Here we need only note that there would be no difficulty in principle in adopting a discounted target for the purpose of developing and testing an appropriate algorithm, but of course the choice of a particular discount rate would be crucial; mathematical economists showed long ago that a high discount rate virtually nullifies attempts at conservation, at least for slowly reproducing and growing species.[41]

In 1999 L. T. Kell *et al* published a study aimed at exploring a possible procedure for managing the exploitation of the stocks of plaice in the North Sea; they give references to other such efforts elsewhere in the world.[42] However, these efforts seem to me to be somewhat defective in at least two ways. First, the 'data'-generation models adopted do not explicitly nor implicitly provide for depensation and instead rely on an arbitrary definition of a "precautionary region" within the Yield-Spawning Stock-Biomass envelope. Second, calculation of TAC advice is still based on one model, chosen to be the best one available rather than developing a CLA/ACEA[43] that has been tested for robustness using a variety of plausible models.

At this point it is appropriate to note that one of the consequences of moving reduced populations towards levels of greater abundance that could provide higher yields is that the annual variability of the stock, and hence of the catches, will be less - even much less in the case of long-lived species. This is simply because the annual recruitment will have less effect on the total biomass of the population – a simple matter, pointed out long ago by scientists working in the 1940s. Furthermore, the average size of fish in the catch increases at lower exploitation rates, and if bigger fish are more valuable per unit weight than small ones this is an additional advantage. (See Fig. 8c)

There are certain respects in which the testing process followed by the IWC's SC was not entirely satisfactory and this is perhaps the place to mention them. *First*, the problem recognized and now being exploited by the Norwegian authorities, that the time-span chosen for the simulations and therefore determining the implied duration of the management scheme can have a critical effect on the TACs currently and in the short-term. Future implementations of the ACEA approach need to examine this. *Second*, the alternative models used to test the robustness of the ACEA candidates did not include any that manifested depensation. The potentially dangerous consequences of this omission were probably avoided in the IWC studies by choosing a relatively high lower-bound to the population size, in the hope that this would be well above the level below which depensation might kick-in (S_A). It was theoretically and hopefully avoided also in the earlier (failed) NMP approach to management by causing the TAC to become zero if it was assessed that the stock had been reduced to below 54% of its carrying capacity. It should be understood, however, that this threshold was not established merely to avoid risk of extreme depletion and possible extermination of the stock, but because the IWC was committed to maintain stocks at, or restore them to, relatively high MSY levels. If a fisheries policy does not include explicit provision for complete and immediate closure when a stock has been diagnosed as seriously depleted, and even reduced and strictly limited catching is permitted, then there is a continuing danger that the stock may be further reduced to, or held at, a level below the depensation threshold, S_A, and even into a region of *critical* depensation.

A third, possibly more serious, problem is perhaps not yet to have taken into account fundamental studies of population dynamics by a Danish mathematician-geneticist-ecologist working in Greenland, Lars Witting, an expert in population genetics. He has argued – I think convincingly – that, for evolutionary reasons the intrinsic (initial) rate of population increase, r_0 , cannot be an exponential function, as was assumed by Verlhurst and in all subsequent theoretical studies in population dynamics. The simple argument is that if we begin with a small population in which individuals have a range of values of reproductive and mortality potentials, (hence of exponential r_0's) in which there is some genetic element, then natural selection will lead to a population in which the resulting average r_0 is not exponential but takes what Witting termed a *hyper-exponential* form.[44]

Witting's study leads to an important practical conclusion: long-duration natural, intrinsically generated, population cycles, of long duration, are to be expected.[45] And his analytical method has provided the most plausible explanation of the fact that the grey whale population of the Northeast Pacific has recovered, under long protection from commercial whaling (and despite substantial continuing catches in Siberia), to a number much greater than it has been estimated to be even before commercial whaling began in the nineteenth century. Population assessments made by the IWC SC using "traditional" methods, which do not correctly fit the oscillatory trajectory of the population, led to a conclusion that the current ***SY*** of that species is several hundred whales per year, whereas Witting's assessment – which *does* explain the present super-abundance - gives the current ***SY*** as nearer to *zero, and becoming negative, hence with zero catch limit*, because the population, which is now close to the top of a two century-long intrinsically generated cycle, will soon begin to decline even if there is no whaling.[46]

In considering the ACEA-approach to devising a management procedure the choice of models to be used to generate 'data' for use in testing candidate algorithms is most important. For most fisheries, in which maximization of sustainable catch in weight or value is of prime interest the models must necessarily incorporate consideration and simulation of the age- and size-distributions of the catches. Further, they must be capable of allowing for for the fishing mortality rate not to be equal for all fish-ages, spanning premature and mature animals, especially. And, naturally, they must allow for recruitment to be dependent on the size of the spawning stock and possibly to manifest depensation. For this purpose the self-regulating model proposed by beverton and Holt could be suitable at least as a starting point; it has been used to generate the examples given in Figs. 8a, 8b and 8c..

6. Some Implications of Transients

It should be abundantly clear that if a stock has been depleted, and if catches are then held at a level that leads to the population stabilizing, tending towards a steady state maintained by sustainable catching, then it is advantageous to take steps to allow the population to grow to a larger and more productive size – towards, in fact, what might be presumed to be its MSYL. This means catching *less* than the current ***SY*** while population growth continues for a time. Similarly, because a previously unexploited or very lightly fished stock must be expected to decline once substantial commercial operations begin, it is desirable to try to ensure that such decline is controlled and precautionary measures taken in due time to prevent unintended depletion. Unfortunately, the history of fishing is, with very few exceptions, repeated failure to take appropriate, timely measures before the arrival of unpleasant economic and social consequences.[47] Exceptions are possibly the attempt by the Commission for Conservation of Antarctic Marine Living Resources (CCAMLR), which has tried to restrain the growth of commercial fishing for "krill" (euphausid crustaceans)[48], and the IWC, which disallows any exploitation of a previously unexploited whale stock until at least there is an acceptable estimate of the size of that stock. Even this is barely adequate because, once that criterion has been satisfied, what might be a safe initial intensity of exploitation *(i.e.* percentage of the stock) is always highly uncertain.

There have been some attempts to calculate the transitional states (as catch and population trajectories) from one supposed equilibrium to another one consequent to a regulatory change calling for reduced catches in the short term in the expectation of greater catches in the future.[49] Naturally they have involved further computations from the same model that was used to compute the TACs that are required by the prevailing management policy. Adoption of the new approach to management described above would call for more sophisticated and complex calculations. But, just as it is impossible to execute such a policy without precise specification, quantification and prioritization of management objectives related to cumulative catches and the critical stock levels, it would be necessary to specify unambiguously any restraints accorded to catches in the short-term. Questions to be answered include whether it's acceptable to close down a particular species or gear-type fishery? If so, for how long? If not what would be the minimal acceptable level(s) of catch – next year? In the next few years?[50] If reasonable answers could be given to these and related questions, then an extension of the ACEA-development process could be implemented. This would, however, add another dimension to the simulation procedure. Depending on the specific requirements set for managing the exploitation of reduced populations it would be necessary to devise and test ACEAs that would not cause annual catches to fall so low that fishing could not be continued profitably. Here we are entering virtually uncharted simulation territory, but it could be mapped and doing so would be a worthwhile scientific challenge. It would be even more of a challenge as one proceeded to try to model a complex, multinational, multi-species, multi-gear and vessel fishery. But that challenge must be faced if a modified-MSY policy is to be seriously implemented. It almost certainly would call for drastic revision and upgrading of the process by which scientific advice is provided to the EU, just as the IWC, in its small corner, had to create – and fund - a specialised sector of its Scientific Committee to develop the RMP for baleen whales. Additionally, the costs of direct estimation of the sizes of each population every few years, by whatever methods might be available, must be provided for.

Any attempt to lead to better fishing in future by reducing fishing effort now would not only bring with it a need for prediction of transient states but almost inevitably require some excursion into economics. In contrast with the IWC's focus on whale numbers, and the usual TAC approach that merely sets allowable weights of catches, any move towards an MSY-seeking policy will change to some degree the unit values of the catches, because the average sizes of the fish in the catches will change, and possibly for other reasons. These are predictable from the 'data'-generating models used in the simulations to test and refine ACEAs, and monitoring by sampling presents no conceptual or novel problems.

7. Recoveries of depleted stocks

The situation in which a stock has been so depleted by excessive fishing that it is decided to declare a moratorium on that particular fishery is, of course, a special case requiring the examination of transients. In this section we look at the important consequences of depensation processes possibly operating in the much reduced population. To simplify this, for illustrative purposes, we revert to the 'production' models of the logistic or similar families, without consideration of time lags and stock structure.

Depensation will cause the depleted stock to increase (provided there is no critical depensation that would lead inexorably to extinction), after fishing is suspended, more slowly - at least at first - than would be expected from the 'classical' models in which the relative rate of population growth is highest at stock levels close to zero. This could look like a simple error in the estimation of the parameters of a logistic model, but the pattern of subsequent recovery could be substantially different. The three Figures 9a, b and c , with their full legends, have been calculated to illustrate these features. Some mental effort will be necessary to shift from thinking about sustainable yields as functions of population size or of fishing effort and mortality, to think about sustainable yields in a time frame. And further, it must be remembered that such graphs do not express the real transition from one non-steady state situation to another or eventually to a new steady state through a period in which the stock composition is not in steady state.

8. The Ecosystem Idea

Rising evidence of the almost over-whelming and widespread destructiveness of human interactions with living systems, including the ocean, has brought with it an idea - now virtually a command - that management of these uses and interferences should take account of the nature of those systems and resources as a whole, so that "the ecosystem approach" or "Ecosystem-Based Management (EBM) is now favoured, and is almost mandatory in some realms of management, politics and science. But, as Mahatma Gandhi is reported to have replied when asked what he thought about Western Civilisation: "That would be a good idea"! The "good idea" is described in the referenced WWF publication.[51] in the following terms:

"**Principles**: EBM has objectives and targets that;

- Focus on maintaining the natural structure and function of ecosystems and their productivity.

• Incorporate human use and values of ecosystems in managing the resources.
• Recognize that ecosystems are dynamic and constantly changing.
• Are based on a shared vision of all stake-holders.
• Are based on scientific knowledge, adapted by continual learning and monitoring."

The WWF Policy statement affirms that " EBM aims to achieve 'sustainability' in exploiting the (fishery) resources " and that "in a fishery managed under EBM principles, the burden of proof for demonstrating that there are no major unacceptable impacts from fishing rests with the fishery." (Although it is not clear whether this means the industry or the management authorities or both). Further, because marine ecosystems are complex and our knowledge poor "the EBM approach to managing fisheries accepts that "…decisions will often be made in a climate of uncertainty. However, uncertainty should never be an excuse for inaction…. Some fisheries already use performance evaluation procedures that measure the populations and productivity of fish stocks, for example to determine TACs of target species. Evaluating the success of a fishery in meeting EBM principles will necessarily be more complex…However, the general evaluation methods and an approach to an EBM system will be familiar to many fisheries managers, including the familiar problems of data weakness and model uncertainty." The specific proposals here for the way in which an MSY-target management system should be applied are entirely consistent with the "Princoples" enumerated in the WWF document cited.

It should be noted that while this WWF publication, and many others in similar vein call for 'use' to be 'sustainable', the fisheries policy we are now contemplating goes much further than that – it is aimed higher. Comparison with the IWC history is relevant. In the 1960s scientists and some national governments sought to bring catches of whales down to sustainable levels; then, with the NMP, in the 1970s, the objective became sustainability at relatively high population levels, to yield MSY; then in the 1990s the more realistic and possibly obtainable objective was adopted: to get a reasonably high cumulative yield over a predetermined period while avoiding nasty happenings through unintentional depletion, and leaving the population at the end of that period at a relatively high level and with a biologically satisfactory age, size and sex composition (at least), that might be interpreted as "in good health". The ACEA-approach also recognizes the need for – indeed depends on – continual monitoring of the exploited stocks (as well as precautionary assessment of the as yet unexploited stocks). It is "adaptable" in that specific catch regulations depend on observing the changes in the regulated system. There is however a very important other side to this coin – the ACEA approach also depends on a ***continuity*** of management actions; one is not allowed to change course on a whim, to compromise beyond the boundaries of the prior agreed policy and management objectives, at least not without going back to the beginning and devising and testing revised algorithms.

It is highly questionable whether we yet know enough about, and have the ability usefully to model, the dynamics of any ecosystem and effectively predict the consequences of our uses of it.[52] We do know enough to understand that any significant change alters practically everything else, but the almost infinite ramifications of such impact, in both qualitative and quantitative terms, continue to mystify and surprise us. The now common but still very inadequately defined concept of the "health" of an ecosystem remains difficult to grasp and even more difficult to measure. For now the best we can do is to formulate some simple rules (simple to formulate, that is, not necessarily simple to apply) that concern the future of those elements of an ecosystem (population, species; habitat) that we impact directly – and usually purposely – and of those other elements that are directly and substantially related to the directly impacted elements; all this while keeping a sharp eye out for unexpected, unintended changes that might be caused by the direct impacts.

One such rule, widely espoused, is to try not to cause extinctions of any species, and preferably not of sub-populations of that species, either. Wit is hoped that by defining lower thresholds below which regulated exploitation will not cause a population to drop we shall lessen the probability of extinctions and at the same time ensure the continuing biological productivity of that population and hence our ability to profit from exploiting it. Other rules are to try not to destroy critical habitats of fishes, not to introduce alien species, to control and eliminate pollution, not to reduce species to such low levels that their "ecosystem function" is diminished and/or the biological productivity of the entire system is adversely affected (although those features are not yet well defined nor readily measurable), and so on. Beyond this, a policy directed to keeping or bringing fishing effort down to levels that result in leaving the fish populations relatively abundant, would have other beneficial consequence beyond obtaining good catches at much less cost. *First*, incidental catches of unwanted species – such as turtles, dolphins, unmarketable fishes – would surely be reduced, roughly in proportion to the reduction in effort. *Second*, for those small but commercially valuable fish species that contribute to the diets of sea birds and some marine mammals, as well as of bigger species of fish, it will be easier to honour the provisions in the UN Convention on the Law of the Sea, and related texts such as the Fish Stocks Agreement, that require that fishing be managed in such a way as not to impair the productivity of dependent (predatory) species.

So, in all these ways the adoption of an MSY objective, redefined as we have done here, following the ACEA approach pioneered by scientists working with the IWC, should be seen as a significant step towards ecosystem-based management.

It remains to consider briefly the matter of multi-species management, which some might regard as a sort of halfway house between single stock management and EBM. The term "multi-species fisheries" has been used in the literature in two quite different ways. One concerns the capture of several species in the same fishing operations – typically bottom-trawling – which may or not be interacting indirectly with each other through, for example, over-lapping diets. This situation could be dealt with, at least at a first cut, by assessing the target catches of each separately and regarding indirect interaction as an environmental externality and monitoring any consequential changes.

The other use of the term relates to the situation, in the simplest case, where two co-existing species are both of commercial interest but one is a predator on the other. This is certainly much more difficult to deal with. Seeking as a management goal the highest feasible cumulative catch in weight is clearly not reasonable, if only because the unit price of the predator is practically always substantially higher than that of the prey, so there must necessarily be an economic element in the simulations.[53] In addition the realistic modeling of the dynamics of the predator-prey system, even for only two species, is remarkably difficult.[54] Scientists, in building such models, have usually adopted one of the simple logistic-type models for each species, inserting linking parameters between them. This may serve the purpose of illustrating the general features of population and system change that might be expected – such as oscillations, near-extinctions, chaotic behaviour and so on - but is not appropriate for practical management purposes.[55] As a practical measure, permitting both predator and prey populations to recover or co-exist at relatively high abundances, through application of the modified MSY policy to each and all of them, is likely to give more stability to these fisheries, in contrast with the crises that constantly arise when both predators and prey are substantially reduced or depleted.

9. Regulatory methods

We have here given our attention mainly to management by the setting of TACs, because that is the way the EU now performs this function and because the new type of procedure has been elaborated first by the IWC which has always set Catch Limits as its principle form of regulation, backed up by minimum sizes (and sexes) of animals to be caught, protected areas ("Sanctuaries"), limited whaling seasons, protected species, protection of suckling females and their calves, and so on. However, the principle choice to be made in any effort to control the fishing mortality rate $\boldsymbol{F}$, remains between some form of TAC and fishing effort limitation. This is not the place for detailed consideration of that choice; both approaches have their advantages and disadvantages, and those are different for different kinds of fishes, the difference in that respect depending primarily on the variability of recruitment. The EU has long been committed to a TAC method, but the proposed transition to an MSY policy does present an opportunity to reconsider that commitment. Certainly the basic principle of creating alternative population models and using these to generate 'data' to test the performance of candidate ACEAs can equally well be applied to effort-based management, and the definitions of management objectives would be very similar if no identical.

In this connection the late R. J. H. Beverton demonstrated, in a paper published posthumously,[56] that since there is great uncertainty about the values of parameters of the stock-recruitment function used in any self-regenerating model, $\boldsymbol{F_{msy}}$ is very much more stable than $\boldsymbol{F_{ext}}$ and than the yield itself. (See Fig. 8 here and Fig. 5 of Beverton's paper) This was at least true of the peaked and domed curves of yield against $\boldsymbol{F}$ that he illustrated for the haddock in the northeast Atlantic. In his example a reduction of between 50 and 60% in the fishing effort pertaining to 'the present time' in his analysis (to bring the stock close to the estimated MSYL) would lead to increases in SY of between 10 and 60%, depending on the stock-recruitment function parameters for the three illustrated parameter sets, which were all plausible but far from sure despite the high quality and great length of the time-series of available data. But the intensities of fishing that would be expected, if continued, to exterminate this stock varied widely, from 70% higher than the 'present' level to only 10% higher than that level. Equally, the big differences in MSY at roughly the same MSYL illustrate the inefficiency of control by specifying maximum catches rather than maximum effort.[57]

10. Conclusions

Notwithstanding the many years of serious criticism, especially by scientists and economists, of the concept of MSY, both as a natural phenomenon and as a primary fisheries management objective,[58] it is now entrenched in the Law of the Sea and in numerous official and several less authoritative or binding unofficial global, regional and national policy documents. Some critics allow that the coordinates of MSY and MSYL as biological properties of wild populations might exist but are elusive, others that those coordinates are inappropriate in terms of economic efficiency, social consequences and effective conservation of renewable resources. Yet others argue that an approach to management through modeling the dynamics of single species and stocks is bound to fail and that management procedures must progress through the realm of multi-species modeling and thus to the dynamics of entire eco-systems or, as a compromise, sub-systems. Meanwhile many – perhaps most – sea fisheries and ancillary service industries are going from bad to worse in terms of total catches, catch rates, catch unpredictability, quality of catches, expectations of future employment, and prices to consumers. There is no doubt that the principle cause of these troubles is now, as it has long been, too much fishing effort chasing diminishing numbers of fish, enhanced by the drive towards catching smaller species and younger individuals. Other problems, such as that different fishes compete with or eat each other (true), that oceanographic conditions are changing (probably), that whales and other big predators are eating 'our' fish (it happens, but the effects, if any, are doubtful), that fishing is itself destroying other parts of marine ecosystems such as reefs, dolphins and turtles, and – indirectly – seabirds (partly true) are important in themselves but barely significant compared with the consequences of rapid and profound fish population depletions leading to over-fishing. What might be done to ameliorate this situation?

It is suggested here that adaptive management procedures[59] properly applied to single stocks, aimed at both sustainability and stock recoveries, could be a major step forward (even if not the ultimate solution) provided that the idea of MSY and also the notion of sustainability are redefined; that management objectives are precisely specified and accepted by stake-holders and management authorities; and that what I would call a computer-aided regime is instituted and adhered to. The essential redefinitions to apply to the real world rather than quasi-philosophical notions are, *first*, that ***sustainability*** is regarded as applying to an appropriate, specified, limited period which corresponds to the duration of computer simulations of the adopted procedure and of the commitment to a continuous robust management authority and, *second,* that ***maximum sustainable yield*** is identified as the *greatest possible cumulative catch* throughout that period subject to a number of important secondary conditions being met. These latter include that at no time must there be a significant risk of the stock being unintentionally driven down near to a predetermined level at which irreversible processes may begin, and that at the end of the management period the stock will have recovered to and be thereafter maintained at a pre-determined relatively high level. An additional, super-imposed condition might be that at no time is the catch to be reduced below a level at which the fishing industry is no longer economically viable, but the ability to define such a level is of course dependent on the state of the stock at the beginning of the management period. All this has to be achieved in the usual situations in which there is considerable uncertainty about the dynamics of the stock being exploited, and about the effects on it of other factors than the intensity of fishing.

This situation is to be attained by the consistent application of a Catch Limit Algorithm (CLA) that has been tested by simulations for its performance in meeting the declared management goals and conditions. These simulations would use 'data' for 'catch' and stock abundance (and composition) generated first by a preferred and plausible population model, but with the candidate ACEA being adjusted to perform adequately with 'data' generated by other, plausible models; in fact the object of such testing would be to try to "break the ACEA" – i.e. destroy its performance, while keeping the models and their parameter values within the realm of presumed reality. That is to say the result should be as far as possible independent of any particular favoured population model. Tests also have to be conducted to ensure that as far as possible the ACEA is robust to environmental changes, including those related to competition with other stocks and resources and other biological interactions among them.

This is not a trivial task. A beginning has been made in recent years in exploring the scientific aspects of it (and has now reached the point at which such an approach is technically feasible) but in adopting such an approach the Commission and its scientific advisors would need to increase substantially their capacities to support adaptive management. A certain requirement is also the conduct of periodic surveys to assess the size and the state of each stock, and to ensure that catches and the compositions of catches are fully and correctly recorded. However, in contrast with the current fisheries practice of treating such survey results as imply one more piece of information, the RMP approach requires that their results be used , with catch statistics, specifically, through application of the algorithm, for the calculation of allowable catches. Because of this the IWC scientists paid much attention to the question of how frequently surveys must be conducted, and to what standards, and what is to be done if the surveys fail for some reason or are not carried out with the designated frequency and in accordance with the prescribed rules. In such cases the penalties are considerable: the catch limits are automatically phased down, eventually to zero.

In the period of devising and testing a precautionary and adaptive management system of the kind proposed further consideration should be given to alternatives to setting TACs or at least to supplementary regulations aimed at limiting and regularly adjusting the intensity of fishing directly, as measured by the fishing effort exerted and/or the value of the fishing mortality rate it generates. There are considerable advantages, in terms particularly of stability of the fishery in the medium- and long-term, of moving away from a purely TAC-regulated system.

Careful and progressive reduction in fishing effort would bring with it advantages beyond simply increasing catches at much lower cost. In many cases the age- and size-compositions of the catches would change in such a way as to give greater stability of catch from year to year (as good and bad recruitments have less effect on the variability of catches when many cohorts are well-represented in the population) and an increase in unit value that may result from increases in the average size of fish caught. Additional benefits would be substantial reductions in the incidental kill of other species such as birds and small cetaceans, and in the volumes of discards, both of unmarketable fish species and of under-sized individuals of marketable species. These consequences of reduced effort would mark an important step towards the generally desired but still elusive ecosystem-based management.

11. Recommendations

1. The EU should be encouraged to adopt a fisheries management policy aimed at all exploited stocks in the EU EEZ recovering to, or maintained at levels and in states that are capable of providing maximum cumulative yields in weight (or value) over a specified time, subject to other specified objectives including at least a minimum likelihood of stocks being inadvertently and unintentionally depleted to substantially lower levels, and particularly to levels at which stocks may become unstable as a result of continued fishing.

2. The specified time-frame will be long enough to define the operational meaning of 'sustainability', and will also be the time during which an agreed Management Procedure should be consistently applied.

3. The Procedure should be capable of unambiguously specifying allowable catches and/or allowable fishing intensity (fishing effort, fishing power), using historic and current data that are known to be available, and including estimates of stock abundances and compositions that do not depend on information from the commercial fisheries.

4. The Procedure should be the application of an Allowable Catch and/or Effort Algorithm (ACEA) - together with ancillary algorithms as may be necessary to deal with problems of mixing etc of putative different stocks of the same species - that has been rigorously tested and found, by simulations using 'data' generated by appropriate population models, to perform well, and to be efficient, and robust.

5. In consideration of considerable uncertainties about fish population dynamics, the ACEA should so far as possible not depend for its adequate performance on the use of a *particular* population model or on the use of a particular set of parameter values in that model.

6. The ACEA should be tested for its performance under conditions of substantial external (environmental) changes, long- and shorter-term, including physical and biological changes of various kinds and scales.

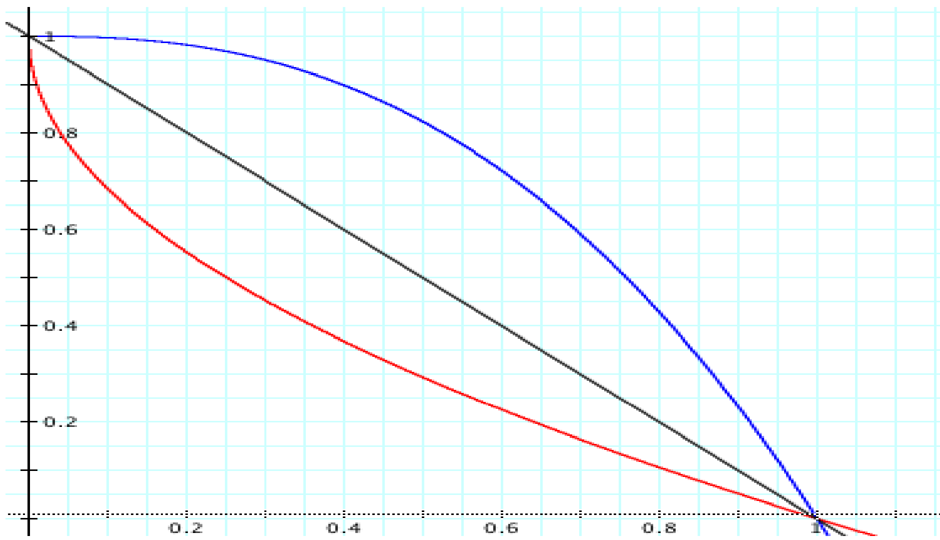
7. Serious consideration should be given to the possible benefits of limiting or otherwise regulating the intensity of fishing rather than setting Total Allowable catches, or at least an appropriate combination of those methods.

Thanks

To Jean Collins at the FAO Fisheries Library in Rome and her colleagues for helping me to obtain some of the referenced publications. To Tony Pitcher for re-awakening, some years ago, my interest in self-regenerating population models, and to Michael Earle for encouraging me to become engaged in the EU Common Fisheries Policy revision process and for contributing commentary that allowed me substantially to improve earlier drafts of this paper. To Drs Justin Cooke and William de la Mare for helping me, through the years, to understand the ramifications, snags and challenges of devising a new way of looking at the problems of managing fisheries on a scientific basis which is not limited to biological considerations but also incorporates elements of systems engineering. To Carol Phua for arranging WWF support for this study and to Tim Holt for reading successive drafts of this paper. The remaining errors are mine.

Finally a homage to my late colleague, Prof. Ray Beverton, who would, I think, be delighted that the European Union is now seriously considering substantive revision of its Common Fishery Policy.

Figure 1a   Simple density dependence – Compensation



Population size relative to carrying capacity → *K*

↑
Relative or specific growth rate

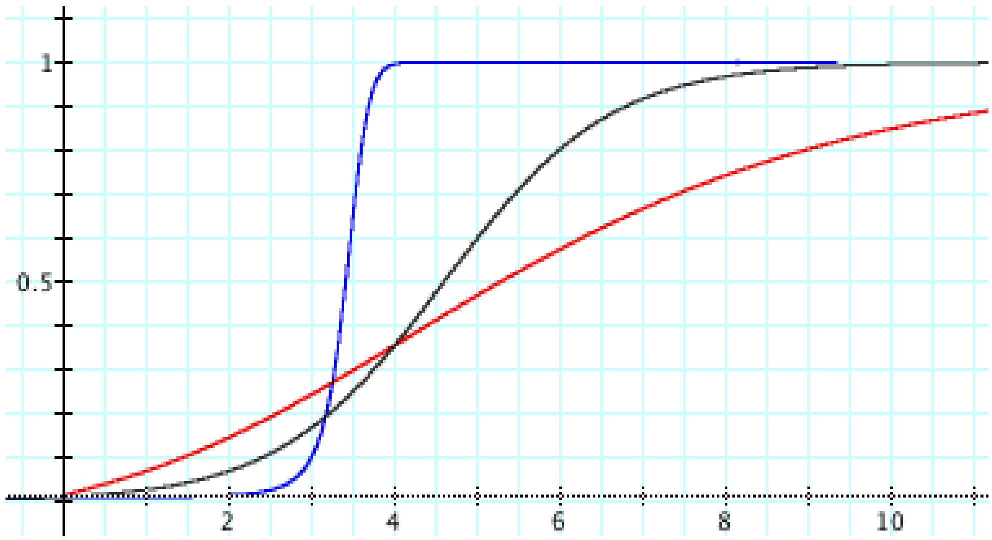
Explanation: The three graphs show samples of the relationship between the relative or specific rate of increase of a growing population (*i.e.* the rate of growth at a certain time as a proportion of the size of the population at that time) to the size of the population. (In the scientific literature this increase rate is usually referred to as the *instantaneous rate of increase* and expressed as an exponential coefficient. For our purposes here it can be understood as a fraction or as a percentage rate.)

The rate of increase is shown on the vertical (y) axis and is scaled to 1 at a diminishingly small population size. The population size itself is along the horizontal axis (x-axis) and is scaled from an initial number close to zero to a final number when it stabilizes at carrying capacity, scaled to 1.

The convex (***blue***) line illustrates a situation in which most of the force of density-dependence (compensation) is exerted when the population is large. The concave (***red***) line illustrates the opposite situation, when the force of compensation is manifest especially when the population is small. The straight (***black***) line illustrates a case where compensatory processes have the same effect throughout the whole range of population sizes.

These curves are samples of a family of curves based on algebraic functions called the logistic family, the straight line being the ubiquitous simple logistic.

Figure 1b Curves of population growth in generalized logistic family



Time ⇐

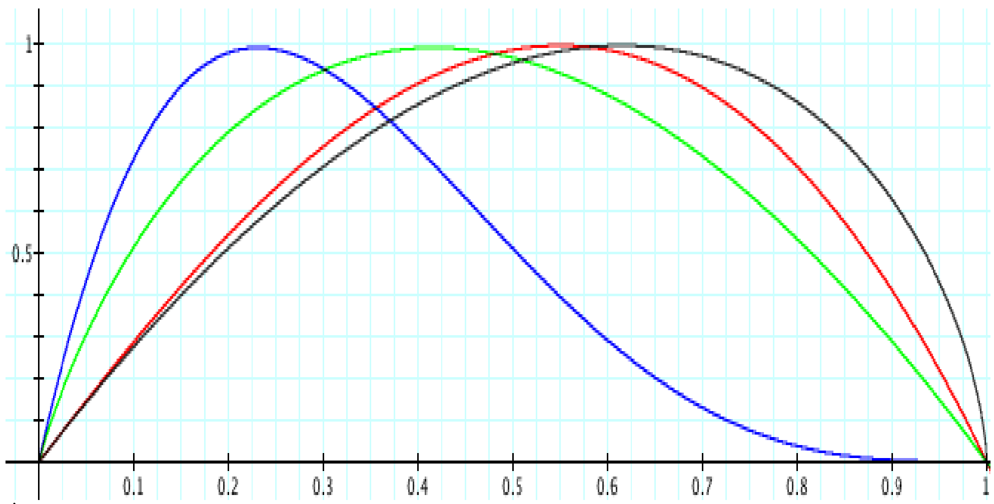
↑ **Population size**

Explanation: The three curves here, with the same ***colour*** codes as in Fig. 1a, are the integrals with respect to time of the absolute rates of population increase which are, in turn, derived from the relative rates of increase shown in the preceding Figure multiplied by the population size at the time. The population size, in terms of number of individuals are here scaled to the final size of the population (theoretically after infinite time) = 1.

The ***black*** line is the familiar simple logistic, a symmetrical sigmoid with an inflection at population size = 0.5. The ***blue*** shows asymmetric population growth which 'takes off more slowly thereafter accelerating and rather suddenly reaching its asymptote, that is the so-called 'carrying capacity'. The ***red*** line, on the other hand, shows a population taking off fast but thereafter taking a long time to approach the same asymptote. These curves have inflections, respectively, at population sizes less than, and more than 50% of the carrying capacity.

The original idea of a sustainable yield is that if the population can be exploited at such a rate as to hold it steady at, or reduce it to, a size ('level') less than the carrying capacity the sustainable yield obtained will be equal to the slope of the sigmoid curve at that stabilized point. The MSY will be obtained by holding the population steady at the level at which the inflection occurs.

Figure 2 Curves of sustainable yield, from the logistic family, against population (stock) size and fishing effort



↑ **Population size *or* fishing effort index**
<u>SY</u>

Explanation*:** *Two* pairs of curves are shown, for sustainable yield plotted against stock level and level of fishing effort. All are scaled on the y-axis to MSY=1. One pair – ***black and ***red*** lines – comes from the modified logistic model with parameter values such that MSYLevel is at 0.55 (55%) of the carrying capacity; the other – ***blue*** and ***green*** lines – comes from the same model but with MSYL at 0.40 (40%) of carrying capacity.

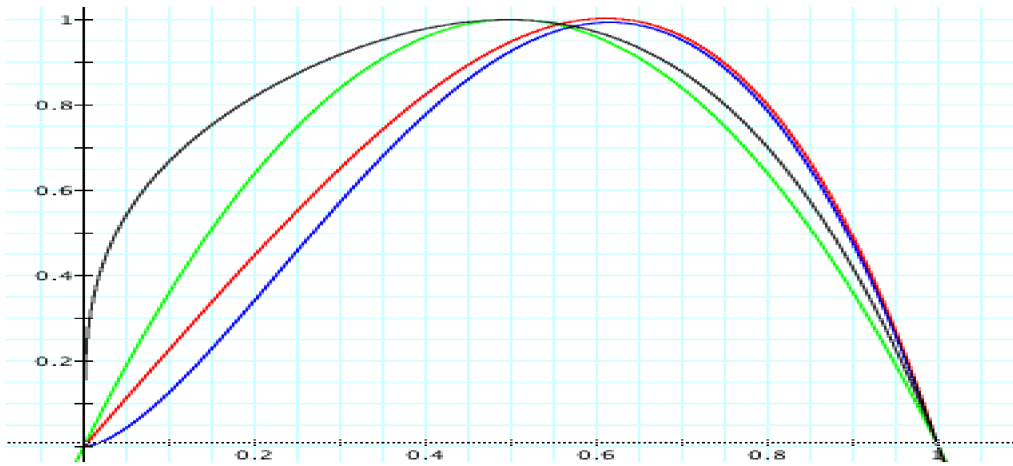
The ***red*** and ***green*** curves are of yield plotted against stock level relative to carrying capacity; the ***black*** and ***blue*** curves show yield plotted against an index of fishing effort relative to the level of effort that if maintained would result in extinction of the stock (This effort is assumed to be standardized to be proportional to the fishing mortality rate it causes).

Notice: that while the two curves of yield against stock level are similar in shape, those of yield against the fishing effort index are distinctly different from each other. The latter curve (***black***), in the case of MSYL=55%, has a peak at 63% of the extinction effort. It is also relatively flatter-topped than the corresponding curve (***blue***) for MSYL=40%. This last has, however, a peak of sustainable yield against fishing effort much lower – at 23% of extinction effort - than that of yield against stock level (green). This curve is also less 'domed', more 'peaky'.

These differences mean that if the MSYLevel is low (below 50% of carrying capacity) the 'optimal' fishing effort is far below the 'danger' level of extinction, but also that a relatively small error in estimating its location leads quickly to catches substantially less than the maximum. If, on the other hand, the MSYL is above 50% an error in estimating its location can readily lead to excessive depletion and even virtual extinction.

Note that these are features of the model, not necessarily of the real world.

Figure 3   Yield curves from logistic and non-logistic families



↑ **Population size relative to carrying capacity** ***K***

SY

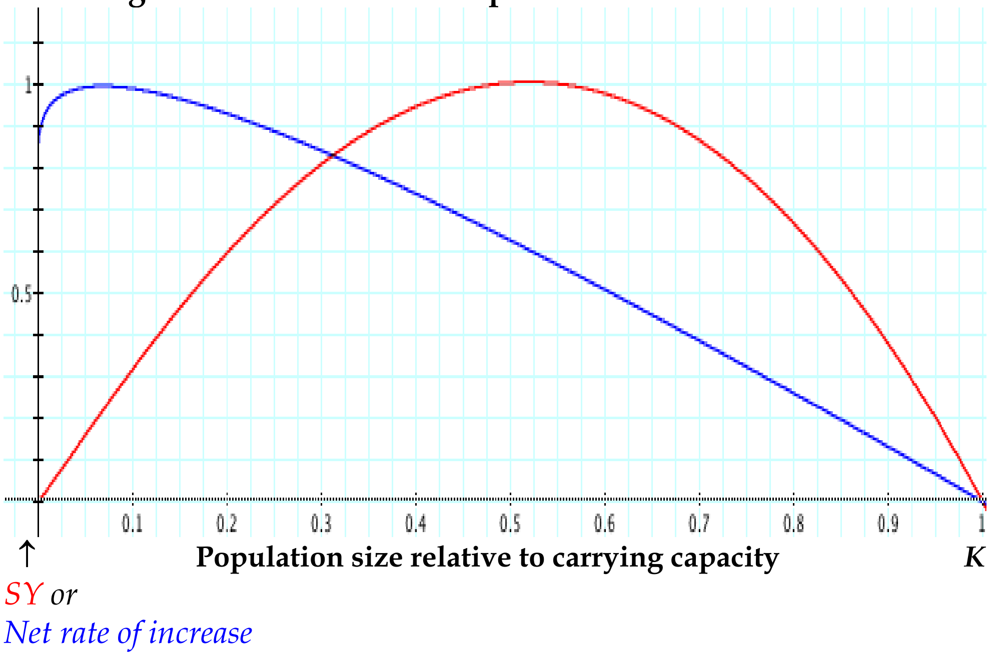
Explanation The ***red*** curve is the modified logistic with MSY=1 and MSYL=0.6, identical with the ***red*** curve in Figure 2. The ***blue*** curve, with the same MSY and MSYL comes from another algebraically simple, biologically equally plausible model family. The right-hand limbs are practically identical but the left-hand limbs are distinctly divergent, especially at low population levels. Consider a population that has been depleted to just 10% of its original level. A calculation of current sustainable yield from the logistic-family model (if the given MSY and MSYL were correct) would suggest a minimum TAC more than 80% higher than that from the exemplar non-logistic family.

The ***blue*** curve also exhibits on its left-hand limb, for population less than about 20% of carrying capacity, the phenomenon of *depensation* (see later) which would cause the population to move towards extinction if the fishing effort that had brought it to below about 25% of carrying capacity were to be sustained.

The ***black*** curve is from the same simple non-logistic model family as the ***blue*** curve, with the same MSY but MSYL=50%. It is flatter-topped but does not manifest depensation. In this case the calculated sustainable yields from which TACs might be proposed would be vastly different from the logistic-family conclusions unless the population was very close to the MSYL The simple logistic, with MSYL=50% is shown in ***green*** for comparison.

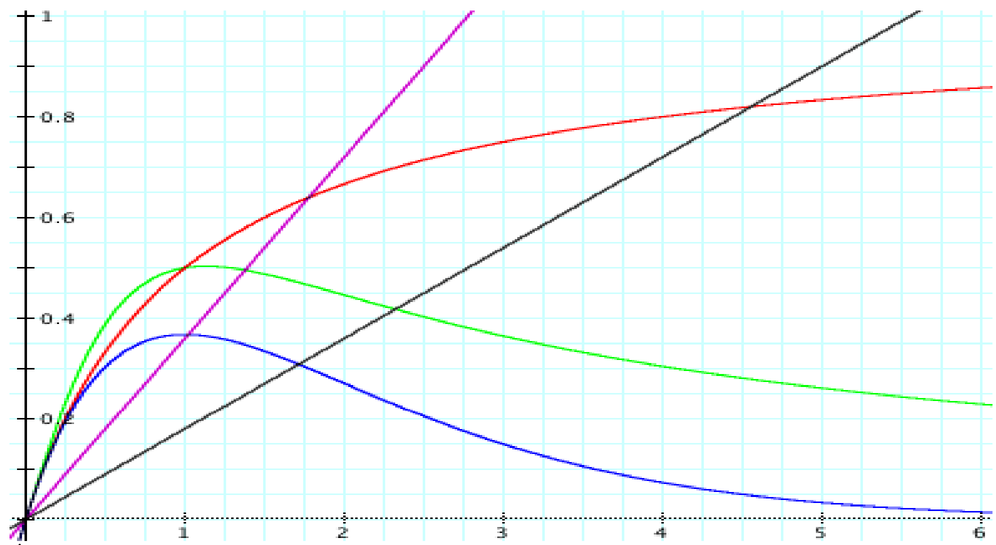
Note: the logistic family is described by the function $y = x - x^n$. The non-logistic family used here simply to illustrate model-dependence of scientific advice about sustainable yields and similar reference points is $y = x^n - x^m$.

Figure 4 Illustration of Depensation



Explanation: The ***red*** curve of sustainable yield (relative to MSY) against population size (relative to carrying capacity) looks very similar to the generalised logistic with MSYL=0.55, but it is actually one of *another* model-family, as can be seen by a close look at the lower part of the left-hand limb. The slight inflection is revealed clearly by the graph of the *net rate of increase* (***blue***). The maximum net rate of population growth does not happen when the population is practically at zero but already when it is at about 7% of carrying capacity. This is in contrast with the critical level in which depensation is manifest or dominant, at about 15%, as it happens, in the example given by the ***blue*** curve in Figure 3.

Figure 5 Relations between numbers of recruits and numbers or biomass of spawning fish



↑ **Index of recruitment**

Undex of **number or biomass of spawning fish** →

Explanation: This figure illustrates three of the functions most commonly used to express this relationship, out of the many that have been proposed. The ***red*** curve is that proposed by Beverton and Holt (1957), and is possibly the one most used, with that by W. E. Ricker (1975) a close second (***blue***). The ***green*** line is that of a more flexible function, due to J. G. Shepherd (1982); it has an additional parameter and can mimic the Beverton-Holt and the Ricker curves, that proposed by D. H. Cushing (1971, 1973) and some others.

The y-axis (vertical) is the number of recruits arising from a number (or sometimes a biomass) of spawning fish (x-axis, horizontal) In this graph the x-axis is arbitrary, but the y-axis is scaled such that the slopes of all three curves when close to the origin - (y ⇑ 0; x ⇑ 0) - have the same value: 1 in this illustration.

Interested readers should, for detailed analysis of, and comparisons between, the properties of these and other proposed stock-recruitment functions, consult Chapter 3 of "Quantitative Fish Dynamics" by T J. Quinn II and R. B. Deriso, 1999. O U. P, 542pp.

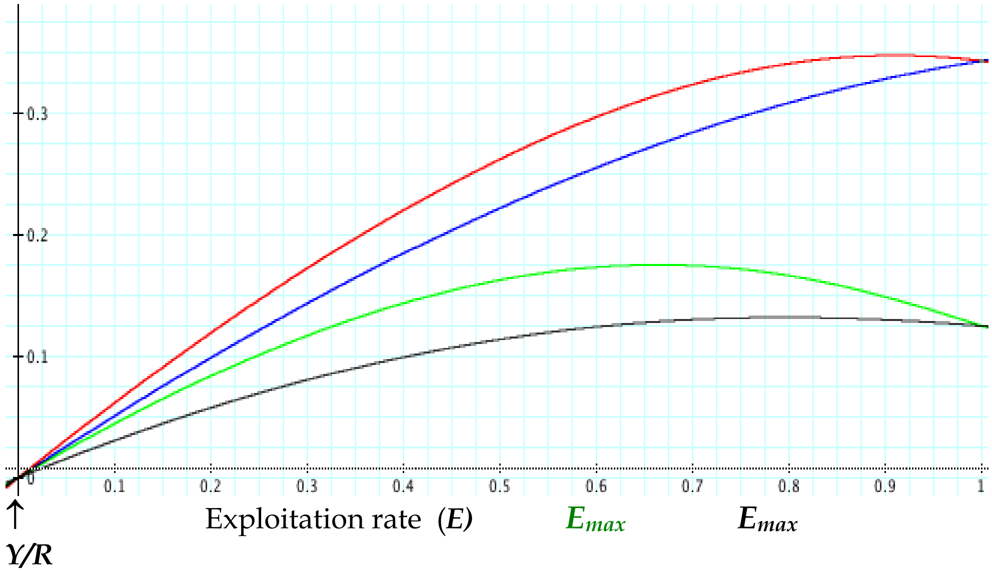
The ***red*** Beverton-Holt curve arrives at an asymptote = 1 when the spawning population is very large, theoretically infinite, and is based on similar assumptions to those of the logistic population model, *i.e.* that density dependence of mortality (in this case of pre-recruit fish from egg to recruitment) is linearly dependent on the size of the spawning population from which they came and thus on their own numbers in the larval and juvenile stages of life. The ***blue*** Ricker model applies to situations in which as the spawning population attains high numbers, the pre-recruit mortality rate increases. The Shepherd model can be adjusted to vary from a Ricker domed curve to an ever-increasing number of recruits, with no maximum or asymptote.

Three important features of these graphs should be noted. The first is that although the x-axis extends to the right forever, the number of spawners in a stock, in steady state (equilibrium) is ultimately limited by the number of spawners that can eventually be produced from a given number of recruits. This limit is indicated, crudely, by the intersection of each curve on this graph with a straight line (***black***) drawn from the origin (x=0; y=0). So, in the Beverton-Holt example (***red***), the unexploited population, at carrying capacity, has 4.6 spawners (remember, the scale is completely arbitrary here) at about 80% of the theoretically maximum – asymptotic – number.)

The second feature to note is that at very low spawner and recruit numbers the numbers of recruits are directly proportional to the numbers or biomass of spawners.

The third important feature is that when the number of spawners is lowered, as a result of fishing, a new steady state is reached, at the intersection of the stock-recruitment curve with the adjusted survival line (magenta). In this example, looking again at the ***red*** Beverton-Holt curve, the straight ***magenta*** line represents the consequences of a level of fishing effort or fishing mortality rate such as to halve the number of spawners, but the spawning number or biomass moves to a new steady state at about 1.8 (about 40% - *i.e*. less than half - of the 'pristine' number or biomass), with the annual number of recruits being about 66% of the theoretical maximum and so 66/80 = 83% of the number of recruits that used to enter the unexploited stock.

Figure 6 Graphs of sustainable Yield per Recruit against Rate of Exploitation



***Explanation*:** The four curves illustrate the Beverton-Holt simplified model of yield (in weight of fish) as a function of Exploitation rate, defined as the fraction of the total mortality of fish above the age/size of recruitment that is caused by fishing *i.e.* $E = F/Z = F/(F+M)$

[*To interpret the E-scale it might help to note that* $F = M \times E/(1-E)$]

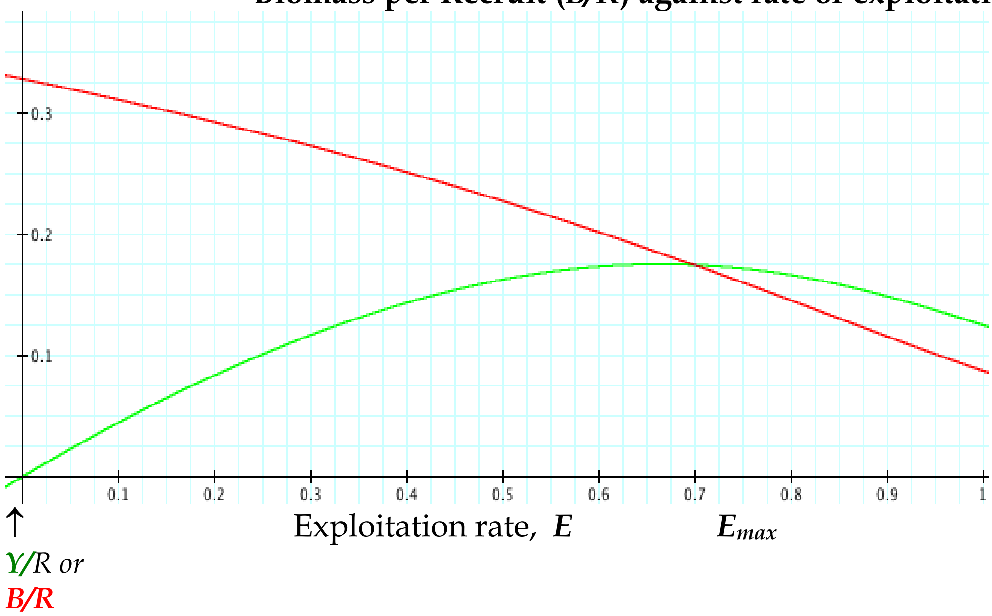
In this model there are two variable parameters: ***k*** and *c*. ***k*** scales the ratio of two opposing forces – the intrinsic rate of growth in weight of an individual fish (***K***), and the rate of natural mortality (***M***). c scales the ratio of the body weight at which a recruited fish is first liable to be captured (***w***) and the final, limited (asymptotic) weight to which it would grow if it lived forever (***W***). Such *range* of size is classically regarded as dependent on such human factors as the type of fishing gear and particularly the width of net meshes.

In these examples the ***red*** and ***blue*** curves show the situation in which the relative weights, ***w/W*** are 0.34 (*i.e.* fish first become liable to capture when they are already about one third of their theoretically final body weight), while the ***green*** and ***black*** curves illustrate the case where ***w/W*** is 0.125. If this were being applied to a bottom trawling one could think of ***red*** and ***blue*** representing use of a larger-meshed cod-end, and ***green*** and ***black*** as use of a smaller mesh.

The difference *within* each pair of curves is that they relate to species-stocks with different growth/natural mortality ratios, ***K/M.*** In the model version illustrated by the blue and ***black*** curves this ratio is 0.5, *i.e.* the 'force' of growth is one half of that of natural mortality. The parameter set providing the ***red*** and ***green*** curves has the growth and mortality 'forces' equal, i.e. ***K/M*** = 1. ***Note that***:
1. The large mesh (higher ***c***) provides more sustainable yield per recruit than the smaller one, and particularly at higher exploitation rates (*i.e.* fishing effort).

2 All curves except ***blue*** have a maximum. Any maximum is always at values of ***E*** above 0.5. Some curves are more flat-topped than others.
3. Curves with ***K/M*** larger have maxima further to the right (i.e. at higher ***E***) than those with smaller values of ***K/M.***

Figure 7. Curves of sustainable Yield per Recruit (*Y/R*) and Recruited Biomass per Recruit (*B/R*) against rate of exploitation (*E*).



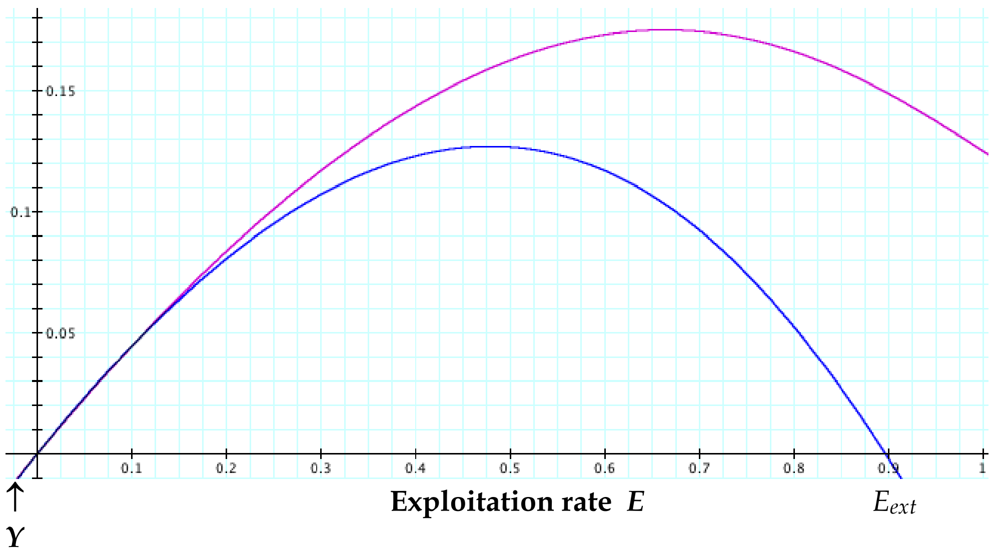
Explanation: The ***green*** curve of sustainable Yield per Recruit, ***Y/R,*** against ***E*** is the same as the ***green*** curve in Figure 6, with a maximum at about ***E*** = 0.7. The ***red*** line, which is not quite straight, is the corresponding biomass of the exploited Stock per Recruit, ***B/R***. The biomass graph is scaled, for convenience, to intersect the ***Y/R*** – curve at its maximum. For our purpose the scale of the vertical axis (x-axis) is of no significance; we are interested in *shapes* of curves on that scale.

In the unexploited stock (***E*** = 0) we begin with a biomass of the stock (above the age at which fish would become liable to capture if there were any fishing) at the arbitrarily-scaled value of about 0.32. What happens as we move to the right, with fishing beginning and increasing, depends upon the particular shape of the relationship between stock size and recruitment in the species-stock in question (refer back to Figure 5). At first, with fishing having a limited effect on the stock biomass per recruit the recruitment may change little, even imperceptibly. But at some point, as fishing intensifies, the biomass must begin to be reduced to a level at which the number of recruits itself begins to fall. Eventually, of course, it will fall to zero and the stock will have been exterminated; that can happen before fishing is so intense that ***E*** ⥣ 1.

If the ***green*** curve were to be adjusted to take such changes into account it would be distorted in two respects. One is that it would touch the horizontal axis (x-axis) at 1 or less than 1. The other is that it would reach a maximum at a lower value of E than 0.7, and possibly lower than 0.5.

By this sequence or arguments we arrive at an understanding of the structureof a ***self-regulating population model.*** **N**umerical solution of this model is generally by *iteratone* (a sort of sophisticated trial and error) in which account is taken of whether or whether only sexually mature animals are exploited or there is substantial exploitation of immature fish. It is beyond the scope of this paper to examine the general and various properties of such a model. Figure 8 gives one example.

Figure 8a A self-regenerating model, illustrating the relation between Yield, *Y*, and fishing mortality rate, *F*.



Explanation*:** The yield per recruit curve (magenta) is identical with the ***green curve in Figure 7 except for the arbitrary scale of the vertical axis (y-axis). The ***blue*** curve illustrates the self-regenerating model in which the number of recruits has been adjusted in relation to biomass of mature fish as it is changed by fishing. The scale of sustainable yield has been adjusted so that the two curves have the same slope at the origin and low exploitation rate, *i.e.* when the population size is at or close to the carrying capacity (pristine, or unexploited level).

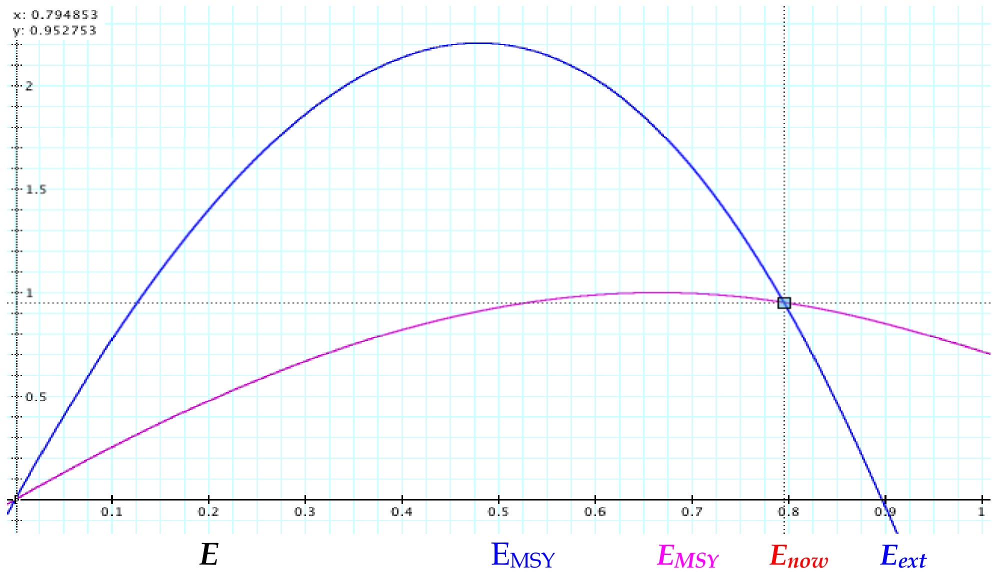
We point out three features of this illustrative example:

1. when the exploitation rate is low the sustainable yield is not much affected by the relationship between spawning stock and recruitment but at higher exploitation levels the yield is increasingly negatively affected by that relationship.
2. the maximum of the yield indicated by the self-regenerating model is at a lower value of ***E***, i.e. at 0.5 instead of 0.7. This difference is highly significant. An ***E*** value of 0.7 implies that the ratio ***F/M*** is 2.4, but if ***E*** = 0.5, then ***F/M*** = 1.0 . So the MSY would be obtained by a fishing effort 2.4-times less than (42% of) what might be targeted if the dependence of recruitment on spawning stock were not taken into account.
3. the stock is driven to extinction when the exploitation rate reaches 0.9, *i.e.* when the fishing mortality, ***F*,** becomes as high as 9 times the natural mortality rate, ***M***.

That the stock can be driven to extinction by a high but finite fishing effort implies that the self-regenerating model exhibits depensation, notwithstanding the fact that *neither* of its two components – the recruitment-spawning stock relationship used here as an example, and the yield-per-recruit model – have that feature explicitly built into them.

Beverton's exploration of this model, with feasible parameter values pertaining to the haddock in the North Sea, showed that while particular parameter values in the recruit-stock relationship could greatly affect the predicted MSY, they did not much affect the MSYL. From this he concluded – I think reasonably - that management seeking MSY is much 'safer' if effected by limiting fishing effort than if by setting TACs.

Figure 8b   Further illustration of a self-regenerating model

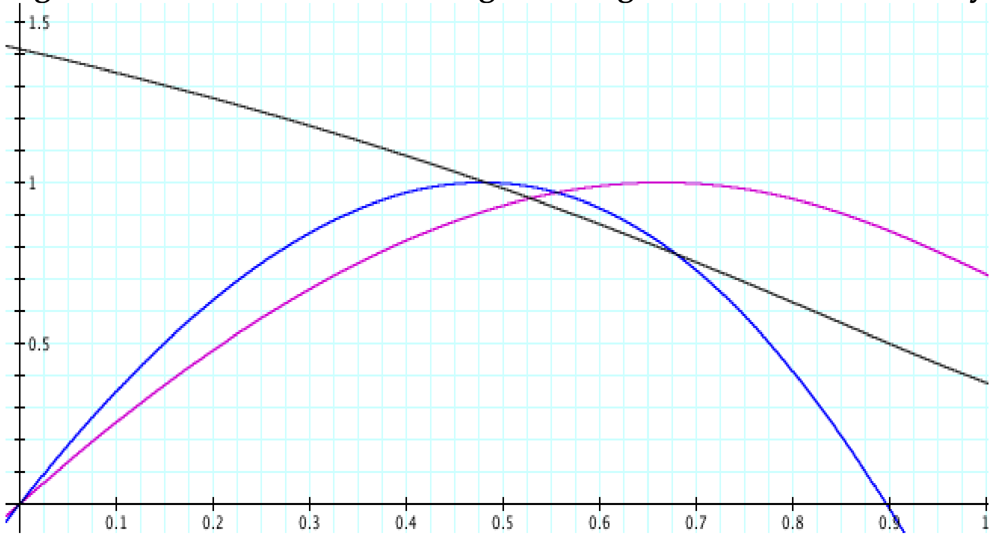


Explanation*:** In Figure 8 the Yield-axis was scaled so that the slopes of the curve of ***Y/R (*i.e.* constant ***R***) and of ***Y*** against ***E*** coincided when ***E*** was close to zero. This represents the situation when a new fishery is opening on a hitherto unexploited stock. As the fishery expands the sustainable yield (***blue***) at first increases just as it would if recruitment was not dependent on the biomass of spawners (***magenta***). However, as the stock is reduced, the number of recruits begins to fall, and eventually an MSY is reached long before expected on a constant recruitment assessment.

Here, in Figure 9, we look at the – unfortunately – more common case of an over-fished stock. The Yield-axis is now scaled so that the same two curves intersect at the hypothetical 'present' *now* (E_{now}). It would appear, from a ***Y/R***-assessment that a considerable reduction of the fishing effort, sufficient to bring E down from nearly 0.8 to the expected MSYL close to 0.7, would bring a small increase in sustainable catch, as this ***Y/R*** curve is rather flat-topped.

However, when dependence of recruit number on spawning biomass is taken into account it appears that a very large reduction in fishing effort would lead to a very great increase in sustainable yield (***blue***). But, note also that the stock is now perilously close to the extinction level (E_{ext}).

Figure 8c More about the self-regenerating model for sustainable yield



max 2   max 1

↑   Exploitation rate (*E*) →

SY

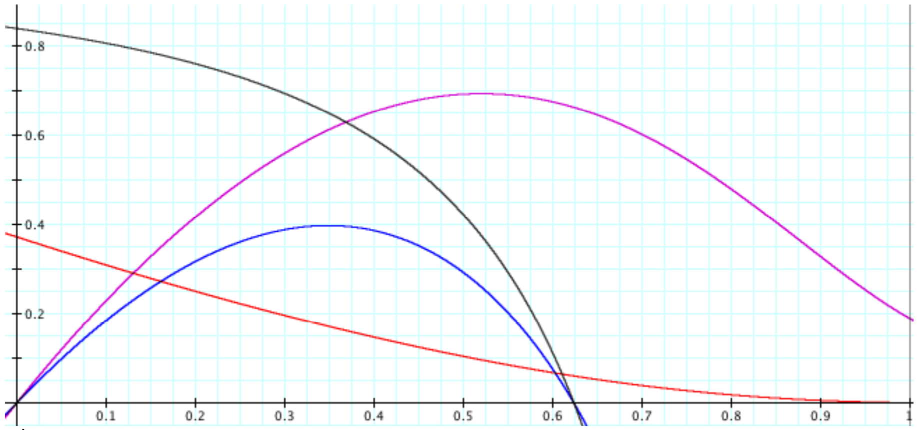
w ***kg***

Explanation: This is the same model with the same parameter values as in Figs. 8a and 8b, the magenta line is the Beverton-Holt yield per recruit (***Y/R***) model, he blue line is with recruitment dependent on spawning stock biomass according to the B-H stock-recruitment relationship. But here the vertical axis of sustainable yield (***SY***) is scaled so that MSY = 1 for both curves.

The black line shows the mean weight (***w***) of fish in the catch: it is scaled, simply for convenience, to have an indicative weight of 1 kg at max 2. If larger fish are more valuable per kg than smaller ones it is advantageous to reduce the exploitation rate even possibly to be a little lower than that that producing MSY. The magnitude of any benefit depends, of course, on the model parameter values; the choice made of parameter values for this example is such to make substantial changes in the average size of caught fish. Interpretation of such averages must be made with care; with high ***E*** most of the catch ill consist of fish little bigger than the size at recruitment, but with lower *E* there will be a wider range of sizes in the catch, from the small post-recruits up to significant numbers of much larger fishes. The parameters for this illustration were set such that the maximum weight to which the fish grows is about eight times the size at recruitment. The average weight of fish in the catch at very low exploitation rate is up to three and a half times the weight of recruits, or rather less than one third of the theoretical maximum weight. At the MSYL of the self-regenerating curve the average weight is about two and a half times the weight at recruitment.

If a fishery was assessed to be more-or-less stabilized at ***E*** = 0.55 it might be concluded, from a ***Y/R*** assessment that increased effort would bring increased total yield, though the average size of fish caught would be smaller. But assessment using a self-regenerating model would indicate that the same increase in sustainable yield would come from a roughly equivalent reduction in fishing effort, and the average size of fish caught would be bigger.

Figure 8d More features of a self-regenerating model.



Explanation: The model illustrated here is the same as in Figs. 8a, b and c but, for variety, different parameter values. Here the yield per recruit (***Y/R***) curve (magenta) has a maximum at ***E*** = 0.52, but the maximum of the self-regenerating curve (blue) has been pushed back to E = 0.40. The growth parameter, K, remains equal to the natural mortality rate M, but the latter is now M = 0.2 instead of 0.1 as before.. The ratio of the size of fish at recruitment to their final (asymptotic) weight is now only 0.03. The relation between spawning stock and recruitment is again that of Beverton and Holt (See Figure 8e below). With these parameter values the stock is exterminated when ***E*** is greater than 0.62. The red line illustrates the way that spawning biomass per recruit implied by the simple model changes with ***E***. The black line illustrates the number of recruits in the self-generating model, also as a function of ***E***

The various reference points illustrated can be related to the fishing mortality, ***F***, rather than to ***E***. ***F*** is an exponential coefficient but here is also 'translated' into a percentage annual mortality rate, ***f*** **.** Both may be regarded as roughly proportional to the fishing effort.

Maximum of the yield per recruit curve at ***F*** = 0.22   (***f*** = 20%)
Maximum of self-regenerating model at ***F*** = 0.13 (***f*** = 12%)
Extinction at ***F*** = 0.33 (***f*** = 28%)

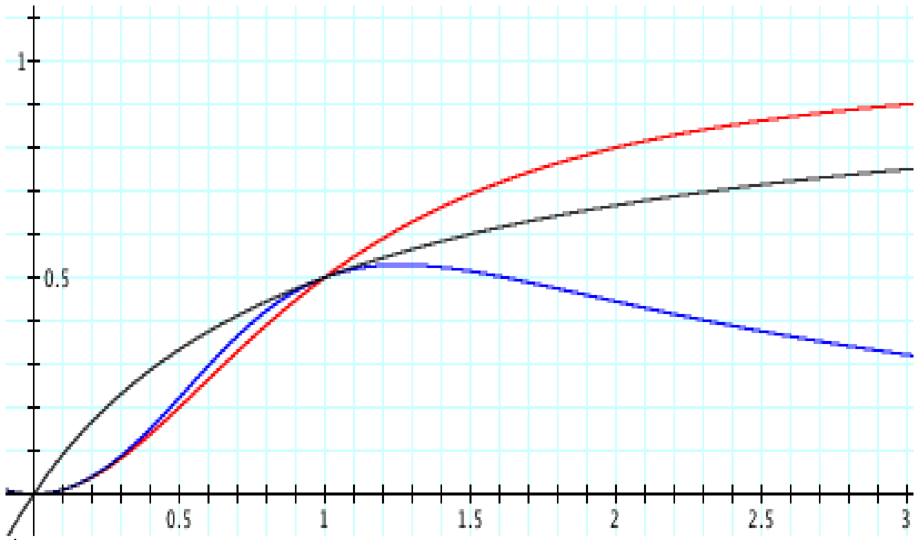
The equations for the models illustrated in Figs. 8 are
(1) ***Constant recruitment.*** y = ***Y/W.R***, x = ***E***, ***c*** = ***(w/W)*** ^{3}

$$y = x(1-c)^{k}\left(1 - \frac{3(1-c)}{1+k(1-x)} + \frac{3(1-c)^{2}}{1+2k(1-x)} - \frac{(1-c)^{3}}{1+3k(1-x)}\right)$$

(2) ***Self-regenerating.*** ***y*** = ***Y/W***, ***m*** and ***n*** are parameters of the stock-recruitment function given in the *Explanation* of Fig. 8e.

$$y = x(1-c)^k \left(1 - \frac{1}{\frac{(1-c)^k (1-x)}{m}\left(1 - \frac{3(1-c)}{1+k(1-x)} + \frac{3(1-c)^2}{1+2k(1-x)} - \frac{(1-c)^3}{1+3k(1-x)}\right)n}\right)\left(1 - \frac{3(1-c)}{1+k(1-x)} + \frac{3(1-c)^2}{1+2k(1-x)} - \frac{(1-c)^3}{1+3k(1-x)}\right)$$

Figure 8e Recruitment as a function of spawning stock size



↑ □□□□□□□□□□□ b□□□□□□□□□□□□□□□□□□□□□□□□□□□ (***B***)→
□□□□□□□ment (***R***)

Explanation: These graphs illustrate the properties of a very simple equation that can mimic many kinds of previously published relationships and is convenient to use in simulations using 'data' generated from self-regenerating models. It is

$$R = B^m/(1+B^n)$$

If ***m* = *n* = 1** this becomes the well-known Beverton-Holt stock-recruitment function. (black line). The recruitment scale is that the asymptote approached when the spawning stock is very large is 1.
If *m* = *n* > 1 the recruitment still approaches an asymptote of 1 but the curve has an inflection at a low stock level and thus incorporates depensation. The illustration here (red) is for **m = n = 3**. It has an inflection at ***R*** = 0.25, i.e. about one quarter of the asymptotic number.
If ***m* <*n*** then the curve retains its inflection but the number of recruits declines from a maximum at intermediate spawning biomass (blue), eventually to zero. This is similar to another well-known function, due to W. Ricker. In the example ***m*** = 2 and *n* = 3. This has an inflection close to that of the blue curve and stays quite close to it until the spawning biomass index reaches 1.

Figure 8f   Characteristics of some simple stock-recruitment functions

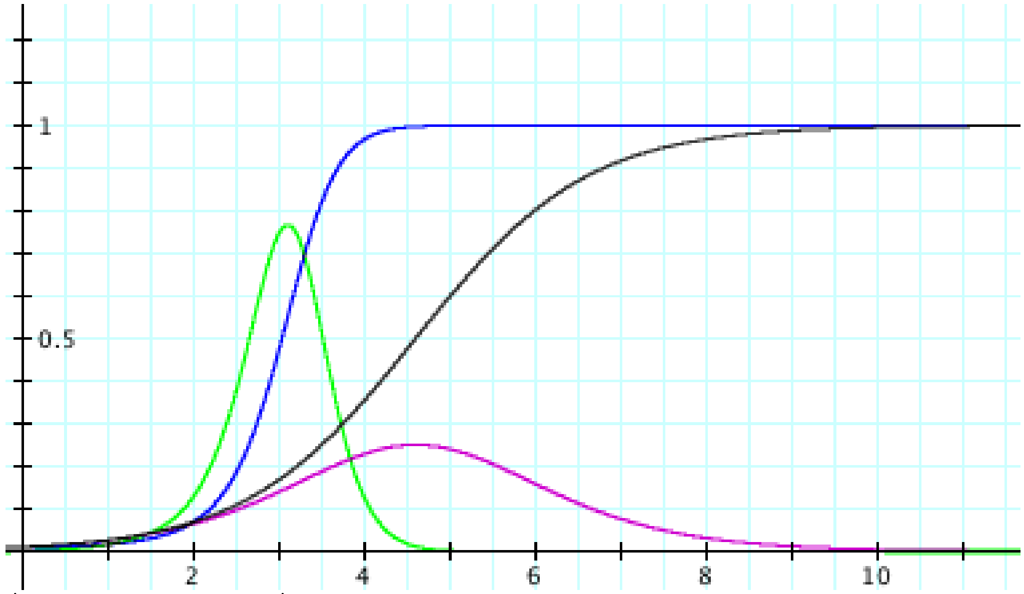
↑ →

(black; blue)
and slope (red; magenta)

Explanation: These graphs illustrate the sharp differences that are possible between superficially very similar functions. By comparing their first derivatives, *i.e*. the slopes of theoretical graphs of recruitment plotted against spawning stock biomass. The graphs illustrated are two of the three shown in Fig. 8e. The black curve is the uninflected Beverton-Holt form, and the graph of its slope (first derivative) is shown in red, a modified hyperbola. The depensatory blue curve is nearly the same as the blue curve in Fig. 8e but with different parameter values: $\boldsymbol{m}$ = 1.5 and $\boldsymbol{n}$ = 2.5. Its first derivative (magenta) is strikingly different, showing the inflection at about $\boldsymbol{R}$ = 0.4, $\boldsymbol{B}$ = 0.55 and a peak at $\boldsymbol{R}$ = 0.5, $\boldsymbol{B}$ = 1.25.

Over quite a wide range of recruitment (0 to 0.6) and spawning stock (0 to 1.4) the black and blue curves would be difficult if not impossible to distinguish from each other from field data. Nevertheless the behaviours of a depleted population, as would be predicted by the two functions, would differ dramatically. This diagram illustrates how important it could be, in seeking to develop a management procedure – especially any to be applied to management of depleted stocks - to test candidate ACEAs for their robustness using as wide a range as possible of plausible models to generate 'data' for use in simulations.

Figure 9a Depensation and stock recovery: growth and yield

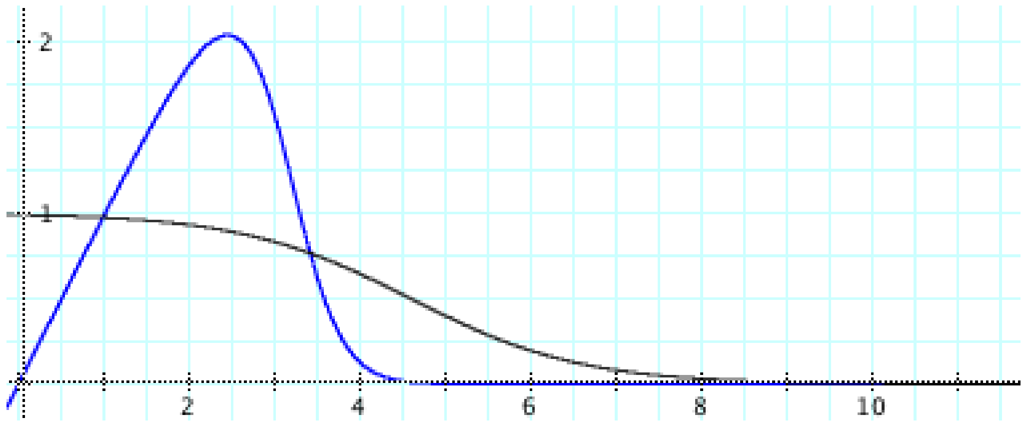


⇑ Time ⇑

Stock

Explanation :The black curve illustrates simple logistic population growth (black, in Figure 1b). The blue curve shows the corresponding growth curve of the model with depensation illustrated in blue in Figure 1b. Parameter values are set, for illustrative purposes such that MSYL = 0.5 (50%) of carrying capacity for both models, but the MSY in the blue model is about three times the MSY in the black model. This can be seen from the green and magenta curves. These plot the ***slopes*** of the growth curves, that is the sustainable yield as it changes over time because the population is growing.. Notice that, for the logistic (black and magenta), the curve of SY against time is bell-shaped, in contrast with the parabolic shape of the SY against stock size. The non-logistic model with depensation (blue, green) is similarly bell-shaped, though more peaked and less spread. So although the two growth curves seem to be of similar shapes their patterns are distinctly different, over and above the difference in the scales of MSY.

Figure 9b Depensation and stock recovery: relative growth rates

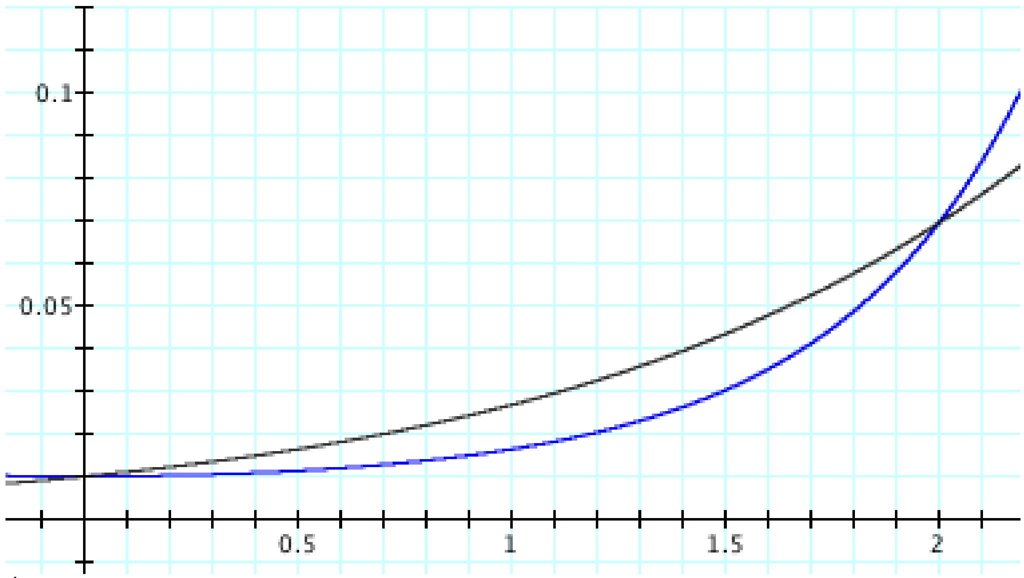


↑ Time □→

Relative
Growth rate

These two graphs are from the same models and same parameter values as Figures 3a and 3b but show the ***relative*** rate of growth, i.e the slope (sustainable yield) divided by the population size as a function of elapsed time. If plotted against population size rather than time the simple logistic (black) would be a straight line from 1unity near zero population to zero near carrying capacity. The superficially very similar non-logistic model (blue) has a completely different pattern of relative growth rate against time. The rate of increase is close to zero at very small population sizes. As the population slowly increases the rate of increase accelerates, reaching a peak after an elapse of about 2.5 arbitrary time units., but declines rapidly thereafter., approaching zero, of course as the population approaches carrying capacity.

Figure 9c Pattern of stock recovery at low population levels.



↑ Stock size

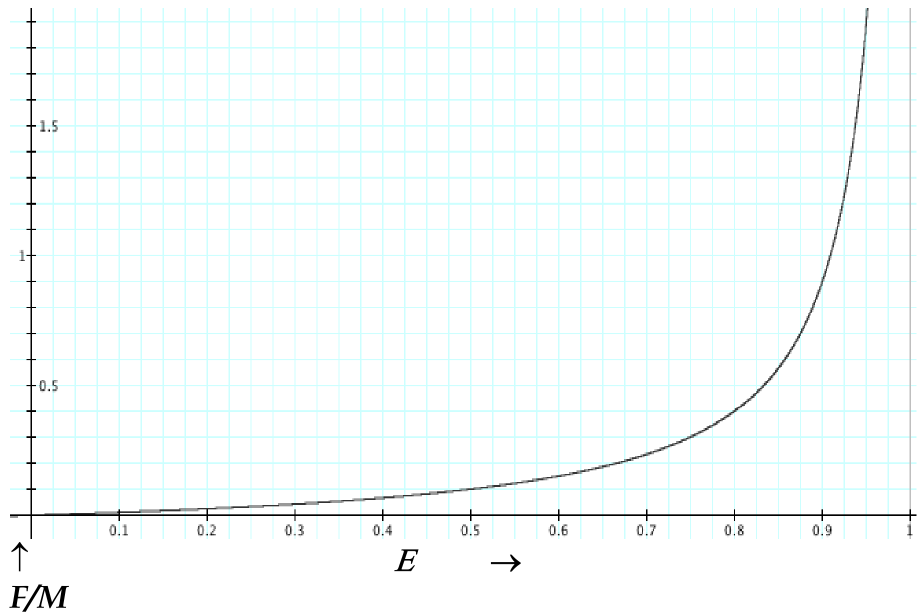
Time →

Explanation: Here we look closely at the lower ends of the two population growth curves of Figure 9a but with the stock size scale adjusted so that the figure represents the situation in which the stock barely survives, having been reduced by fishing to only 1% of its original size (carrying capacity). The logistic (black) shows the usual, 'classical' feature of expected recovery, after the cessation of fishing,, with relative growth rate highest when the population is extremely small. By contrast the non-logistic with depensation (blue) shows a very slow beginning of recovery, but accelerating, though not reaching the same level as the logistic until two arbitrary time units have passed and the stock has recovered to about 7% of carrying capacity; this might be regarded as the limit of the preponderance of depensatory processes. Thereafter it continues steeply upward until it reaches the much higher MSY-slope, and then approaches carrying capacity more rapidly than does the logistic model.

This particular graph shows the general features of these alternative models, but naturally both the logistic and non-logistic parameters can be adjusted so that, for example, non-logistic MSY is no higher than that of the logistic model. Both can be generalized to have MSYL higher or lower than 0.5 (50% of carrying capacity).

In recent stock assessments the logistic model and its generalized family have rarely been used in this simplistic way; normally now there would at least be an effort to incorporate age and size distributions, time lags to sexual maturity, and specific functions relating stock to recruitment. But the consequences of ignoring possible depensation when predicting recovery trajectories of greatly depleted stocks remain essentially the same.

Figure 10 Relation between exploitation rate (***E***) and fishing mortality rate (F).



Explanation: This graph has been included to assist in interpretation of the preceding figures. It is convenient to plot graphs of Sustainable Yield, etc against intensity of fishing on a scale of the exploitation rate, ***E***, which has a limited range of zero to one. ***E*** does not, however, vary linearly with the fishing mortality rate, ***F*,** although it does so very approximately over the range from zero to about 0.5.* The relationship is that the ratio of the *variable* fishing mortality rate to the *constant* natural mortality rate, ***M*,** is

F/M = E/(1-E)

M can be regarded as a scaling constant, and in the graph illustrated here it is put equal to 0.1 (About 9.5%per annum). The *shape* of this graph is not, of course, affected by the value of ***M***.

F and hence ***F/M***, may be, to a first approximation, considered as proportional to the *fishing effort* exerted, appropriately measured and calibrated. Hence, for example, when we have shown graphs in which, say, extermination of the stock occurs at a value of ***E*** not very much higher than the value giving MSY, in the range roughly from about 0.6 to 0.9 or more, the difference between the fishing effort for MSY and that for extermination will be distinctly wider than it would seem from looking at the ***E***-scale.

* A linear form is, however: (1/F) = (1/M).((1/E) – 1)

Calculations illustrated here were made with ***Graphing Calculator*** **v3.5** ***for Apple Mac****.* *Copies of the illustrative models and parameter values are available from the author on request.*

References and Endnotes

[1] See for example Margetts, A. R. & Holt, S. J., 1948 "The Effect of the 1938-1945 War on the English North Sea Trawl Fisheries" *Cons. Int. Explor. Mer, Rapp. et Proc.-Verb.* **122**: 28-46, and other papers in the same Special Volume.

[2] Although to be found in many text-books and popular expositions of the theory of fishing, and long in use, these two terms are not really appropriate for modern discussion, since the two phenomena are not independent of each other. For example, if a stock has been depleted to the extent that future recruitment is significantly affected, then its age- and size- composition will certainly also have been changed for the worse.

[3] It is of historical interest that the concept of MSY as an enforceable criterion for management was first embodied in the International North Pacific Fisheries Convention (INPFC) immediately after World War II. In this the USA, with the acquiescence of Canada, constrained the recently defeated Japanese nation to accept "the Abstention Principle" by which a country would restrain its fishermen from exploiting on the High Seas species/stocks (in this case Pacific salmons, and also halibut) that were already being fully utilized by the coastal state(s). "Full utilization" was in this case defined as taking the MSYs from stocks maintained at MSYLs. Unfortunately the term has more recently been used in less rigorous and sometimes ambiguous ways. The US Government tried, unsuccessfully, to sneak "abstention" into the 1958 Law of the Sea Conventions, but in another form it came to reside in UNCLOS as the notion that if a coastal state was not fully using – sustainably, of course – stocks in its EEZ if should licence others to take the residual.

[4] There are many unofficial definitions implied in the official references mentioned, but all are essentially to the peak of a dome-shaped graph of a curve in which sustainable yield is plotted against either stock size or fishing effort.

[5] "Implementing sustainability in EU fisheries through maximum sustainable yield" Communication. Document Com (2006) 360 final, Brussels 4.7.2006, sub-titled SEC (2006) 868) and the accompanying Commission *Staff Working Document* -"Technical Background". I offered two "Commentaries" on these (10.9.06 on the "Communication" and 11.9.06 on the "Technical background") that were noted by ACFA and are available from the Commission Secretariat and the author.

[6] In recent years there has been some interest among scientists, and hence management authorities, in defining reference points other than MSY-MSYL, some of them described as "optima", and commonly defined as values of the fishing mortality coefficient (***F***) lower than the sustained fishing mortality that would provide maximum sustainable yield (F_{max})) . These are, however, mostly coordinates on a curve of sustainable yield and thus suffer from all the problems of assessing MSYL, MSY and F_{max} . The most comprehensive reference publication for this approach is, I think, "Reference points for fisheries management" by J. F. Caddy and R. Mahon, *FAO Fish. Tech. Pap.* **347**, 1995. See also J. F. Caddy's more recent "Limit reference points, traffic lights, and holistic

approaches to fisheries management with minimal stock assessment input" *Fish. Res*. **1294**; 1-5, 2001.

[7] Holt, S. J. "The Notion of Sustainability", p43-82 *in* Lavigne, D. M. (*Ed*.) "Gaining Ground: In Pursuit of Ecological Sustainability", 425pp. International Fund for Animal Welfare, Mass., USA, and the University of Limerick, Ireland. See also my "Sustainable Use of Wild Marine Living Resources: Notion or Myth?" **in** "Foundations of Environmental Sustainability: The Co-Evolution of Science and Policy" Edited by L. L. Rockwood, R. Stewart and T- Dietz. Oxford University Press Inc. (USA) 2007 (in press).

[8] "Notice sur la loi que la population suit dans son accroissement". *Correspondance Mathématique et Physique* **10**: 113-21, 1838, Anyone interested to follow-up the non-scientific origins of what I call 'logisticism' would be advised to read S. Kingsland "The Refractory Model: The Logistic Curve and the History of Population Ecology", *Quart. Rev. Biol*. **57**: 29-52, 1982, followed by my commentary on that in Endnote 5, above.

[9] If the short period of time is reduced to the infinitesimally small the rate is referred to as an *instantaneous rate* and we begin to talk about the exponential ***e***. That shift is important to scientific practitioners but the distinction is not necessary for the purposes of this paper.

[10] We shall, in Fig. 5,l also come across this symbol being used quite differently for one of the two parameters in a much-used equation for the growth of individual fishes.

[11] The one most commonly used in fishery assessment practices is that suggested by J. J. Pella and P. K. Tomlinson: "A generalized stock production model" *Bull. Inter-Amer. Trop Tuna Commn* **14**: 421-96, 1969.

[12] The models used to construct the graphs in Figure 2 are examples of a class of what are generally called *production models*, in which age- and size-structure of the population is ignored. The most accessible account of these and other models commonly applied in fishery assessments, requiring only school-level mathematics, is E. L. Cadima's "Fish stock assessment manual". *FAO Fish. Tech. Pap*. **393**, 2003, 161pp. Cadima does not, however, discuss depensation or self-regenerating models. (see later)

[13] It was long a standing joke in fisheries science circles that all fish species had a standard natural mortality rate of 0.2. (That is expressed as an exponential coefficient, about 18% per year.

[14] Number per unit area or volume.

[15] An example of this is the still commonly used $F_{0.1}$, which is the fishing mortality rate at the point on such a graph, at which the slope of the graph is one tenth that of the slope at the origin, i.e. when $F \rightarrow$ zero.

[16] " Le mieux est l'ennemi du bien" – Voltaire, 1764

[17] J. D. Reynolds and R. P. Freckleton, in their "Population Dynamics: Growing to Extremes" (*Science* **200**: 567-8, 2005) offered a critique of a paper by R. M. Sibly et *al* in the same issue of that periodical: "On the regulation of Populations of Mammals, Birds, Fish and Insects", p607-9. Sibly and his co-authors reported analyses of time-series of data for 1780 species, finding a high frequency of data sets manifesting concave curves of population growth rate against density (which would, in exploited species, imply MSYL below 50% of carrying capacity). However, these authors unfortunately excluded, by the statistical method they used, the possibility of detecting depensation. The few graphs they provide to illustrate their results do not allow us to discriminate between presence or absence of depensation, and it looks as if most of the data sets used did not include

observations from severely depleted exploited populations. *Science* subsequently published a number of letters criticizing the methods used.

[18] J. A. Hutchings has reviewed the fisheries literature and demonstrated that slower recovery of depleted stocks than expected is common: "Collapse and recovery of marine fishes" *Nature* **406**: 882-5, 2000.

[19] These features were clearly and simply described by a Canadian mathematician/ economist, Colin W. Clark, in his classic "Mathematical Bioeconomics: The Optimal Management of Renewable Resources" John Wiley & Sons, New York, London, Sydney, Toronto. 1976, as well as in several later publications.

[20] *See* D. G. Chen, J. R. Irvine and A. J. Cass "Incorporating Allee effects in fish stock-recruitment models and applications for determining reference points" *Canad. J. Fish. Aquat. Sci*, **59**(1): 242-9, 2002.

[21] "Summary of worldwide stock and recruitment data" (*Can. Tech. Rep. Fish. Aquat. Sci.* **2024**) and "Minimum reproductive rate of fish at low population sizes" (*Can. J. Fish Aquat. Sc.i* **56**: 2404-19): "Depensation in fish stocks: a hierarchic Baysian meta-analysis" (*Can. J. Fish. Aquat. Sci*. **54**: 1976-85.

[22] One of these was devised by the Soviet scientist S. P. Kapitza to describe human population growth throughout history. He presented a paper entitled "World Population Growth" to the 43rd Pugwash Conference on Science and World Affairs: "A World at the Crossroads: New Conflicts, New Solutions", held in Sweden in 1993, and subsequently published in the Annals of Pugwash, pp 539-58. Other versions of this paper have appeared as "World population growth as a scaling phenomenon and the population explosion" in L. Rosen and R. Glasser (*eds*) "Climate Change and Energy Policy" Los Alamos National Laboratory, AIP, NY 1992; and as "A mathematical model for global population growth" *Mathematical Modelling* **4**(6): 65-79, 1992.Kapitza's model is, in his terminology, 'self similar', meaning with characteristics independent of scale, (a property not manifest by the much-used logistic family) and therefore intellectually appealing to the mathematical mind..

[23] Franck Courchamp *et al* have recently pointed out that a more than proportional increase in price (unit value) of a product from wild living resources, as a result of increasing scarcity as they are depleted, can generate the economic equivalent of depensation: "Rarity Value and Species Extinction: The Anthropogenic Allee Effect". (2006). PloS Computational Biology, published in Association with the International Association for Computational Biology. On-line at: http//biology.plosjournals.org. An interesting discussion of this matter for a particular marine species – the minke whale in the northeast Atlantic – is given by E. H. Bulte and G. C. Van Kooten "Marginal Valuation of Charismatic Species: Implications for Conservation. *Environ. Resource Economics* **14**:119-30, 1999.

[24] "On the Dynamics of Exploited Fish Populations". First published in 1957 by the UK Government, its fourth printing, with a historical Foreword by Holt, was published in 2005 by Blackburn Press, New Jersey, USA.

[25] This is explained in detail in R. J. H. Beverton and S. J. Holt "Tables of yield for fishery assessment. *FAO Fish. Tech. Pap*. **38,** 49pp, 1964. [Revision published by FAO in 1966 as Manual of methods for fish stock assessment, Part II: Tables of yield functions.]

[26] For a recent discussion of variability, outside the general fisheries literature, *see* O. N. Bjørnstad and B. T. Grenfell, "Noisy Clockwork: Time Series Analysis of Population Fluctuations in Animals". *Science* **293**: 638-43, 2001.

[27] A simple explanation of the structure, properties and uses of such models is in preparation by the author..

[28] This was/is not, strictly speaking, a *procedure* but rather a set of apparently precise *principles* to be followed in setting TACs. For discussion of a true procedure see, later, the IWC's Revised Management Procedure (RMP).

[29] In the later years an extended population model called BALEEN was used, in which provision was made for dealing with the age at sexual maturity and the sex ratio in the population. The details of this need not concern us here.

[30] This reference to "optimum" must be obscure to everyone who did not participate in the formulation of the NMP during the 1974 meeting of the IWC, enhanced by the fact that the Secretariat forgot at the time to include in the Report of the Commission the text of the Resolution that explained it. It refers to the decision that while regulations would at first continue to be specified in terms of numbers of whales they would later be adjusted in order to meet targets defined in terms of total weight of catches. That decision was never implemented although it was seriously discussed in connection with the regulation of sperm whale catching, where it would have made a significant difference to TACs. Theoretically, MSY by weight would be obtained from a somewhat larger population than one defined by number, but, for depleted stocks, a return to the corresponding MSYL would have been more "painful", economically, for the industry in the transition period.

[31] "Simulation studies on management procedures" *Rep. int whal. Commn* **36**: 429-58. 1986

[32] In the whaling case these include arrangements to ensure compliance with TACs set by the RMP and other regulations, creation of an internationally maintained data-base of DNA samples from each whale legally killed, a credible international observer scheme, strict control over any international trade in commodities from whales, and effective restraint on, and monitoring of, the killing of whales under Special Permits for the purpose of scientific research. We do not concern ourselves with these here as such controls will be specific to each fishery situation.

[33] Simply defined as "an effective procedure; a way of getting something done in a finite number of discrete steps". A more formal, humorous but nevertheless serious, definition is " a finite procedure, written in a fixed symbolic vocabulary, governed by precise instructions, moving in discrete steps 1, 2, 3…, whose execution requires no insight, cleverness, intuition, intelligence or perspicuity, and that sooner or later comes to an end. (David Berlinski "The Advent of the Algorithm: the Idea that Rules the World", Harcourt, New York, San Diego, London 345pp, 2000).

[34] J G. Cooke "The International Whaling Commission's Revised Management Procedure as an example of a new approach to fishery management". **In** *Developments in Marine Biology* **4**, Whales, Seals, Fish and Man. Proceedings of the International Symposium on the Biology of Marine Mammals in the North East Atlantic, Tromsø, Norway, November/December, 1994. [Ed. By A. S. Blix, L. Walløe and Ø. Ulltang] pp.647-57, 1995. Elsevier, Amsterdam, 720pp. Also, by the same author "Improvement of fishery management advice through simulation testing of harvest algorithms" *ICES J. Mar. Sci.* **56**:797-810, 1989. See also, for a non-technical explanation the recent: "The

Notion of Sustainability" by S. J. Holt, 2006, p43-81 *in* "Gaining Ground", *Ed*. David M. Lavigne, *op cit*. The "official" (IWC) description of the CLA by its author is at the time of writing still in press: "The 'C' Procedure for Whale Stock Management" *J. Cet. Res. Manag*. *Special Issue* on CLA7RMP/RMS

[35] This last objective should be applicable also to fisheries regulation if that is enacted in terms of fishing power/effort limitation, but is not readily applicable to fisheries in which recruitment or "availability" are highly variable and that are managed through limitation of allowable catch.

[36] These terms have precise meanings in the world of modeling, that are similar to but not exactly their meanings in normal language. One more might be said to perform better than another if, in aiming at a high cumulative catch it actually led to higher catches but at the same risk of depletion. Robustness is the degree to which the algorithm perform if the underlying assumptions are in some way or to some degree incorrect. Efficiency might relate to overall performance with respect to a suite of objectives.

[37] V. Papastavrou and J. Cooke "The Sustainable Use of Oceanic Wildlife: What Lessons can be Learned from Commercial Whaling?" p 113-28 in Lavigne (*Ed*), 2006, op *cit.*

[38] Unfortunately that is precisely what the Norwegian authorities have done (but without the necessary testing – at least not in public) in order to justify a huge increase in the numbers of minke whales now being killed in the Northeast Atlantic under Norway's "objection" to the IWC's designation of that stock as depleted, hence classified PS under the NMP rules. Norway also has an "objection" to the general moratorium declared in 1982.

[39] Although I have used the term *advice* for the output from application of a CLA (or ACEA, see later) the term *instruction* might be more appropriate. This is because, in this type of management procedure, once management objectives have been agreed in detail and an appropriate algorithm established, adoption of its output is mandatory, it should not be open to haggling over compromises

[40] In the IWC context, and, I think, equally with respect to international fisheries generally the issue is the matter of mutual trust, since each nation (or fishing sector) has particular interests and the scientists tend to be influenced, whether they are aware of it or not, by those interests

[41] See e.g. C. W. Clark "Mathematical Bioeconomics: The Optimal Management of Renewable Resources" (John Wiley, 1976) and many later papers by this and other authors.

[42] "An evaluation of management procedures for implementing a precautionary approach in the ICES context for North Sea Plaice". *ICES J. Mar. Sci*. **56**: 834-45, 1999. An on-going international project entitled Framework for Management Studies (FEMS) is being led led by Kell and funded by the EU Research Directorate and others. One element of it is creation of an open source software framework (code name FLR). A paper by Kell *et al* describing this process and giving references to applications of this approach elsewhere, including to the Atlantic bluefin tuna, is in press: "FLR: an open-source framework for the evaluation and development of management strategies", ICES, 2007.

[43] From here we adopt a new term for the algorithm which generates regulatory actions by a new term more appropriate to fisheries generally than the CLA in IWC

terminology. This is **Allowable Catch and(or Effort Algorithm (ACEA)** since such an algorithm need not be limited in its application simply to generating TACs

[44] This finding has deep implications for the theory of population dynamics and for practice based on that body of theory. The basic reference is Witting's "A General Theory of Evolution: by Means of Selection by Density Dependent Competitive Interactions". (Peregrine Publisher, Arhus, Denmark, pp332, 1997). This book also contains a lucid exposition of the "classical" theory of population dynamics as a preliminary to Wittings critique and revision of that. See also L. Witting's "Optimization of management procedures with control on uncertainty risk" *ICES J. Mar. Sci*. **56**: 876-83, 1999.

[45] Other causes of population oscillations are fairly well understood. They include interactions between predators and prey, and relatively long delays in the animal's life cycle before reaching sexual maturity. This last cause does not enter into baleen whale population dynamics but might occur in the long-lived, late-maturing sperm whale. O. R. Bjøstad *et al* have demonstrated how in an important fish species short- and long-term variability and cycles can arise from the same set of age-structured interactions involving asymmetric competition and cannibalism. "Cycles and Trends in Cod Populations" *Proc. Nat. Acad. Sci. USA* **96**: 5066-71, 1999.

[46] Witting, L. "Reconstructing the population dynamics of eastern Pacific grey whales over the past 150-400 years" J. *Cetacean Res. Manage*. **5**(1): 45-54, 2003. [Published revised version of a 2001 IWC document] *See also* "On inertial dynamics of exploited and unexploited populations selected by density dependent competitive interactions", *IWC Doc SC/D2K/AWMP6* (Rev.), 2001.

[47] Here is Voltaire again, in 1767, to remind us that "En effet, l'histoire n'est que le tableau des crimes et des malheurs" (Indeed, history is nothing more than a tableau of crimes and misfortunes)

[48] For a non-technical discussion of the krill problem see "Ecosystem Management and the Antarctic krill" by S. Nicol and W. de la Mare, *Scientific American* **81**: 36-47, 1993 and for more detailed discussion W. K. de la Mare "Factors to Consider in Developing Management measures for Krill" *CCAMLR Working Paper* WG-Krill-90/14, 1990

[49] The first of which the writer is aware was made by a scientific group associated with ICNAF (now NAFO, the Northwest Atlantic Fisheries Organization) in assessing the consequences of proposed cod-end mesh changes in the trawl fishery for haddock on George's Bank, now a practically extinct industry.

[50] It is perhaps worth noting here that the IWC found it impossible to agree on catch reductions in the Antarctic (under the pre-NMS management regime) until agreement had been reached among participating nations and whaling companies – after six years of negotiation - on national and company allocations of percentages of the TAC.

[51] See, for example, "Policy Proposals and Operational Guidance for Ecosystem-Based Management of Marine Capture Fisheries", compiled by Trevor Ward, Diane Tarte and Eddie Hegeri and Katherine Short, and edited by Veronica Thorp for the Endangered Seas Program of the World Wide Fund for Nature (WWF) International and the Resource Conservation Programme of WWF Australia, and published in 2002 by WWF Australia, 83pp. A two-page summary is also available separately, in English, French and Spanish, written by Simon Cripps and Alison Wilson with the authors of the full report. A recent discussion of EBM by a strong group of scientists is E. K. Pikitch *et al*: "Ecosystem-Based Fishery Management", *Science* (Policy Forum) **305**: 346-7, 2004.

[52] R. Arnason expresses, guardedly, a slightly more optimistic view in his "Economic instruments for achieving ecosystem objectives in fisheries management" (*ICES J. Mar. Sci*. **57**: 742-51, 2000). After noting the extreme diversity within real ecosystems, the huge numbers of inter-specific interactions in them, and the array of possible dynamic behaviours, Arnason writes: "Under these circumstances the question is whether it is possible to manage ecosystem fisheries in a useful manner. The answer to this question is probably 'yes'. The reason is that the outcome of unmanaged fisheries is so poor that in spite of the complexity of ecosystem fisheries, it is not too difficult to improve upon the situation. Optimum management rules are, however, very complicated. This means that it is very difficult to calculate optimum management paths, let alone to implement them. Therefore, anything close to an optimum utilization of an ecosystem fishery may not be achievable in the near future." In a paper contributed to a major ICES conference on "Ecosystem Effects of Fishing" held in Montpelier, France, in 1999, K. J. Sainsbury, A. E. Punt and A. D. M. Smith rightly state – very diplomatically - that "Ecosystem objectives in fisheries management usually flow from high-level national policies or strategies and international agreements. Consequently they are often broadly stated and hence are difficult to incorporate directly in management plans." These authors note that recent advances in what they refer to as "management-strategy-evaluation methods (MSE) rely on simulation testing of the whole management process using performance measures derived from operational objectives. The MSE approach involves selecting operational management objectives, specifying performance measures, specifying alternative management strategies, and evaluating these using simulations. The MSE framework emphasizes the identification and modelling of uncertainties, and propagates these through to their effects on the performance measures." ("Design of operational management strategies for achieving fishery ecosystem objectives" *ICES J. Mar. Sci.* **57**: 731-41, 2000). This is a succinct account of the way that the IWC developed its RMP; in fact one of the authors - Punt - was a member of the IWC development group.

[53] In present circumstances of less than rational fishing practices this relationship is used to justify arguments for *unsustainable* "harvesting" ("culling") of marine mammals, but this is not the place to enter into the ramifications of that debate.

[54] See discussion of this by the late Peter Yodzis "Predator-Prey Theory and Management of Multispecies Fisheries" *Ecological Applications* **4**(1): 51-8, 1994.

[55] There have been numerous attempts to deal with this matter by the construction of multi-species population models. However, as J. F. Caddy and R. Mahon remark ("Reference points for fisheries management" *FAO Fish. Tech. Pap*. **347,** 83pp., 1995) "such models are extremely data-intensive, (and) are still beyond the practical reach even of assessments in well-studied regions such as the NW Atlantic". However, it must be remembered that according to the UN Fish Stocks Agreement of 1995 (which, while specifically directed to the management of fishing on 'straddling stocks' and Highly Migratory Species, is of general application) "the absence of adequate scientific information shall not be used as a reason for postponing or failing to take conservation and management measures." Appropriate measures are, at this time, those based on the proper use of a variety of single-species models.

[56] "The State of Fisheries Science" p25-54 *in* "The State of the World's Fisheries Resources" *Ed*. C. Voitlander, 1994. Lebanon, New Hampshire International Science Publisher

[57] We should not, however, presume, before the general properties of this particular model have been thoroughly explored, that these findings would hold for all species and populations. The yield per recruit curves for shorter lived species with higher mortality rates relative to body growth rates are more flat-topped than the haddock curves, and the corresponding curves from the self-regulating model would also be flatter, although this difference of shape depends also on the age at which fish begin to be exploited (*i.e.* in trawl fisheries depending largely on the cod-end mesh size.) Nevertheless, the arguments for preference for fishing effort control in terms of stability are probably generally correct.

[58] Perhaps most famously by Peter Larkin in "An epitaph for the concept of maximum sustainable yield" *Trans. Amer. Fish. Soc.* **106**: 1-11, 1977 and later in "Concepts and issues in marine ecosystem management" *Rev. Fish. Biol. Fish.* **6**: 139-64, 1996. And most recently and profoundly by Alan Longhurst "The Sustainability Myth" *Fish. Res.* **81**: 107-12, 2006.

[59] For last words on this matter see W. K. de la Mare's "What is Wrong with our Approach to Fisheries and Wildlife management? – An Engineering Perspective" p309-20 in Gaining Ground, *Ed* D. Lavigne, 2006, *op. cit.* And also his "Marine ecosystem-based management as a hierarchical control system" 43pp, MS (in press) School of Resources and Environmental Management, Simon Fraser University, Burnaby B.C. Canada.