Chapter 4

The Notion of Sustainability

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It is sometimes said that we should never believe a scientific theory until it is verified by experience. But…also…we should never believe an observation until it is confirmed by a theory.

João Magueijo 2003[1]

la tenacière des quattre saisons
l'avare ficelée dans ses longitudes
[Proprietress of the four seasons
the miser tied up in her longitudes]

Jules Supervielle, inveighing, it is said, against the meanness of Earth, a limited and unexpandable Heritage[2]

In this chapter, I look mainly at the last one hundred and fifty or so years during which the idea of sustainable use of living resources has emerged, crystallised and been intellectualised and provided with a theoretical cloak and a political mission. Its roots reach down to an earlier period in which hunters, fishers and elites expressed their concerns that adequate breeding stock should be left for future benefit, and fishes, birds, mammals and other animals be given the chance to survive to sexual maturity and/or grow bigger and hence more valuable. I begin with Thomas Malthus, the much misunderstood parson/mathematician who, writing in mid-nineteenth century, is said to have presumed – although in fact he didn't – that biological populations (he focused mainly on humans) tend to increase geometrically until they outrun the resources on which they depend – principally food but also space – and then may crash. Thus, it was thought, the Malthusian hypothesis would lead systems – particularly human societies – towards catastrophe and revolution.

An almost immediate counter to this was the observation that populations seemed to increase along an S-shaped curve and, to "explain" that, the idea of "density dependence" was put forward. Several decades later this led to the presumption that wild animal populations could be "harvested sustainably" at rates commensurate with the slope of the S-curve at any point along it and, furthermore, that a "maximum sustainable yield" could be obtained by cropping at such a rate as to maintain the population at some intermediate level between its natural, unexploited abundance, and its extinction, at the size corresponding with the inflection of the curve. This density-dependence paradigm was, and still is, the core of efforts to manage exploitation for sustainable yields, modulated by considerations of periodic natural fluctuations and cycles, and other transient processes. It has been behind almost all efforts to manage sea fisheries (one of the first applications was to the blue whales, *Balaenoptera musculus,* of the southern hemisphere).

In recent decades the idea of sustainability has been incorporated in national and international policies for economic and social "development", but in several respects such policies – or, rather, the activities they promote – are the antithesis of *biological* sustainability. To justify them a new mythology of control of natural and human processes is being written.

Here I explore some of the mysterious corners of the biological core of the sustainable use notion – with little more than glances at the economic, social and political superstructures that have been erected on it – and conclude that a critical reappraisal of the notion and its implications is now due. The efforts by scientists, politicians and administrators to invent a way of bringing about a sustainable whaling industry (even though few people now want that to happen!) are taken to be the flagship bearing such a reappraisal.

Some implications of transformations from one population or ecosystem state to another, or changes in patterns of variability, are explored, in addition to the concept of precaution, and recent challenges to the root assumptions by the originators of the notion of sustainable use of living resources.

ORIGINS

In choosing a title my first thought was to treat sustainability and sustainable use as a myth. Indeed, among the earliest creation myths of the Eastern Mediterranean, the Levant and the Fertile Crescent Paradise is an apple orchard yielding fruit year after year.[3] However, as will be seen, it seemed more appropriate for this essay to begin, not at the beginning, but with the European Enlightenment and its children. So, is sustainability a modern myth? Not quite, I think, if we abide by the definition of myth in the Oxford English Dictionary (OED):

> A traditional narrative *involving supernatural or fancied persons*, and embodying popular ideas on natural or social phenomena (my italics).

But the next section of the OED gives us, *notion, n*:

> View, opinion, theory, vaguely held or insecurely based.[4]

That's more like it! Glancing over our shoulder, the links between the largely Protestant Enlightenment to the decidedly Roman Renaissance and from there back to the Moslem civilizations and the transfer of Greek ideas both through that religion and through Christianity, and the various versions of the Creation myths, is perhaps worthy of historical treatment, but not here.

We shall see that the idea of paradise gained and lost, possibly repeatedly, persists; history repeating itself – but as tragedy or farce? After the Enlightenment the early horrors of the burgeoning Industrial Revolution, seemingly bringing another loss of rural Paradise, was to lead – the early Socialists thought – to its restoration through the victory of the proletariat and poor peasants in a class war that would bring about a classless society which might change over time but would in principle persist for ever.

Things did not turn out quite like that, especially as the twentieth century spawned and endured global wars that were more wars between empires than among classes. But after the second big one the vague new-old idea of the regaining of paradise began to emerge from its chrysalis of environmentalism, and was ultimately baptized as *Sustainable Development*, its Law being given to us not in tablets of stone but as "Agenda 21". Arguments, continuing, about the interpretation of The Law belong more in the realm of religion than of science. Here we look only at the scientific – or is it pseudo-scientific? – kernel: sustainable use of the Earth's physical and biological resources.

BIRTH, GROWTH AND DEATH

Sustainability is the hybrid (bastard?) child of Steady-State Systems and of Change – "generally used to mean the fact of becoming different". But "natural environmental properties" vary on many time-space scales, so that further definition is necessary. With regard to climate-ocean-biology change we mean a shift from one pattern of variability to another, or a transformation from one state to another. In order to detect the direction, magnitude and frequency of such deviations, we must have a norm or a baseline from which to compare the departures. Since very large spatial changes happen only rarely and slowly very long baseline sets of rather frequent measurements are necessary. There are few such time-series in marine biology, chemistry or physics. An objective for the future is to establish such monitoring systems, because serial measurements of these properties are essential to our understanding of the word "change".[5]

In this essay I shall be writing, on the face of it, almost exclusively about aquatic – especially marine – populations; that is the bulk of my personal experience. But the idea of sustainability, as formally, and largely mathematically, expressed, began with problems of the sea fisheries, and it is in that arena that I think much of its conceptual development has been performed. I am writing, too, as a scientist. I offer no excuse for that since sustainability is a concept invented by, and mostly advocated by, scientists. But it has, of course, a moral and even a religious content, in seeking to take proper account of the desires and likely needs of future human generations, and I – like, I think, most scientists – am sensitive to that. Recently the word has begun to acquire, in some parts of the world, in some societies and in certain contexts, the implication not only of a "light ecological human footprint" but additionally of a light touch with respect to animals that may be "used"

– for which I think the phrases "animal welfare" and "animal rights", though increasingly pronounced, are not fully adequate. I am sensitive to that, too, and it has scientific aspects – relating to the nature and evolutionary "purpose" (sorry, Darwinians!), of pain and discomfort, animal consciousness and culture,[6] the exploration of which has scarcely begun, but I shall leave that out of this essay.

The original of my title – as given me by the organizers of this Forum – was the rather heavy-duty *The History of Managing Population Exploitation: Theory vs Practice; Myth vs Facts.* And that remains my main theme. Notice reference to managing *exploitation*, **not** to managing *populations*, resources, whales, fishes etc. I've spent much of my life opposing the hubris of "managing" the ocean and its contents; a losing battle I'm afraid.

Anyway, that observation opens my way to more pedantic self-indulgence. "Sustainability" is a word given many – somewhat contradictory – meanings, even in its ecological/biological context; in its "development" context it has virtually no meaning as far as I can see; but I'm still open to correction.[7] Here I cannot hold back from quoting a very recent article by Alex Gillespie – a New Zealander and specialist in international law – who describes "sustainable development" as having "a mantra-like quality": "Although this claim [*he is here referring to the notion that human-induced climate change hinders sustainable development – sjh*] has an intuitive appeal, it too is doomed to failure. In an ideal world, the phrase 'sustainable development' could be aired and all would agree and know what was meant by it. However, we do not live in an ideal world and the term has become increasingly lost in a labyrinth of political and philosophical considerations".[8] But at least there have been, and continue to be, serious attempts at *objective* definition. That is not true of many other weasel words and phrases so commonly used in the context of conservation, such as: a "healthy" ecosystem/environment or whatever; "fragile" and "stressed" ditto; "abundant" or "rare"; "balance of nature";[9] "robust";[10] "protection"; "precautionary"; "diversity"; "depleted"; "endangered"; "threatened"; and many more,[11] including, of course, "conservation" itself.[12] I found all these terms in a few pieces of paper produced by various arms of the World Conservation Union (IUCN) – such as its Commission on Ecosystem Management, by the UN Commission on Sustainable Development and under the Convention on Biological Diversity, and even in technical papers by well-intentioned and competent scientists.[13] I think I use the qualifier "objective" advisedly; some of the terms I have listed serve principally a propaganda purpose of those who wish to exploit living resources – "healthy" (about an exploited population of wild animals; what a Cockney merchant might casually describe as "in good nick", just before he sells you a flawed used item!), used a lot by whalers, is a case in point – but others also have a political background, coming from the sections of society that wish to bring exploitation under a modicum of control: witness the IUCN *Red Lists* and the CITES criteria.

"Sustainability " is a term that has now, loosely and mostly ambiguously, been stretched to apply to time-frames of "development" in the politico-socio-economic domain. It is not the only important term stolen – and, I think, misused – from its genesis in relation to the use and states of renewable natural resources. Another, more recently appropriated, is "the precautionary principle", used to justify pre-emptive war. This deviant has recently been admirably deconstructed by David Runciman.[14]

This Forum is really about all the above-mentioned notions, and more besides, but I want to start with a closer look at sustainability itself, with a focus on its biological meaning(s). Our troubles begin with Thomas Malthus – child of the Enlightenment – or, rather, with succeeding interpretations and misinterpretations of what he published in the period 1798 to 1830.[15]

Those works are long, complex and thoughtful. The essence of what concerns us here is captured in words early in *The Second Essay*:

> Population, when unchecked, increases in a geometrical ratio. Subsistence increases only in an arithmetical ratio.

Let us not stop there, however:

> A slight acquaintance with numbers will show the immensity of the first power in comparison with the second. By that law of our nature which makes food necessary for the life of man, the effects of these two unequal powers must be kept equal. This implies a strong and constantly operating check on population from the difficulty of subsistence. The difficulty must fall somewhere and must necessarily be severely felt by a large proportion of mankind.

That is, of course, all about humans. But then:

> Through the animal[16] and vegetable kingdoms, nature has scattered the seeds of life abroad with the most profuse and liberal hand. *She has been comparatively sparing in the room and the nourishment necessary to rear them* (my emphasis).

First, let me dispose of the main misinterpretations.[17] One is that Malthus said it was "wrong to bring in measures of social amelioration, for preventing the death of infants and for keeping the people healthy, for if that were done the problem would become worse". So said Lord (then Sir

John) Boyd Orr in 1948 at a conference on Population and World Resources in Relation to the Family. This "tendentious distortion", as Anthony Flew called it, was made by a physiologist and nutritionist, a Nobel Prize winner, and the first Director-General of the Food and Agriculture Organisation (FAO) of the United Nations. Malthus said no such thing.

A second misinterpretation was that Malthus considered that the destructive interaction between birth rate and nutrition arose from there being an upper limit to the latter, that is the existence of *finite* nutritional resources. Malthus' studies were almost entirely related to political economy, and he saw the conflict as being between two forms of *rate* of increase – geometric (what we often now call *exponential*) and arithmetic (that we would more usually now call *linear*). Even in an infrequent reference to animals and plants Malthus only hinted at the existence of upper limits, and then – as in the above quotation – only to the extent of believing that nature was sparing in the provision of living space and nutritional resources.[18]

Malthus was firmly embedded in the newly emerging tribe of British and French philosophers, historians and political economists, thus influenced by the writings of Adam Smith (1723-1790), Edward Gibbon (1737-1794; Jean-Jacques Rousseau (1712-1778,) and David Hume (1711-1776), these last two being close friends of his father. He had taken Holy Orders but he also graduated as a *Wrangler* at his Cambridge college, Jesus, which was about as good as one could get in mathematics at that time, and he had been elected a Fellow of the Royal Society of London.

The First Essay was essentially a polemic against a then famous French author, Marquis de Condorcet, and an English one, William Godwin, father-in-law of Percy Shelley. Both were enthusiasts for the French Revolution, 1789+, and their writings had been pressed upon Thomas Malthus by his enthusiastic father.[19] Godwin and Condorcet both foresaw and hoped for societies of social and economic equality. While Thomas rejected what might be considered to be programmes for a perfect and egalitarian society, he did so not on ideological grounds but, as he would see it, mathematical and scientific ones. Boyd Orr said Malthus warned against the imminent reaching of a historical stage "where there was not sufficient food to feed the people of the world". But, as Flew noted: "Malthus himself saw his principle of population differently", and observed that "Malthus did never at any stage, see his discoveries as providing a warrant for abandoning piecemeal and realistic efforts for improvement"; thus: "this constantly subsisting cause of periodical misery has existed ever since we have had any histories of mankind, does exist at present, and will for ever continue to exist, unless some decided change takes place in the physical constitution of our nature".[20] Note "our nature", not "Nature". But note also the very significant appearance of "periodical".

Malthus next considers the ways in which "the constant operation of the strong law of necessity (the need for food) acts as a check upon the greater power (reproduction). He wrote, regarding the nature of the check among animals and plants, "Wherever there is liberty, the power of increase is exerted, and the super-abundant effects are repressed afterwards *by want of room and nourishment*, which is common to animals and plants, *and among animals by becoming the prey of others*"(my emphasis). And then: "The effects of this check on man are more complicated". After some discourse on morality, monogamy, social constraints on early marriage and the like, Malthus describes a *cyclical* process in human societies of contentment and misery. And this, he clearly sees, results from the class-structure of societies with which he is familiar: the coexistence of a numerous poor and the far less numerous rich, combined with inter- and intra-generational time-delays in the system.[21]

"This sort of oscillation (*the repetition of the same retrograde and progressive movements with respect to happiness*) will not be remarked by superficial observers, and it may be difficult even for the most penetrating mind to calculate its periods".[22] Malthus then asserts that "…in all old states some such vibration does exist, though from various transverse causes, in a much less marked, and in a much more irregular manner than I have described it…". He then offers reasons why such oscillations have not been remarked upon, one of them being that "the histories of mankind that we possess are histories only of the higher classes". In his "class" theory of population Malthus, the mathematical priest, is a couple of decades ahead of Karl Marx and Freidrich Engels,[23] and, as we shall see, pretty much in line with modern ideas about the "vibrations" of populations.[24]

Although he was writing from an English/European perspective Malthus' data came mainly from censuses of the population of the British colonies in North America. This was of course increasing by immigration as well as by the operation of "the passion between the sexes" of the colonists. Some numbers are given in *A Summary View*: the white US population increased by 36.3% from 1790 to 1800 (average population 3,738,500); by 35.9% from 1800 to 1810 (average 5,087,500) , and by 34.1% from 1810 to 1820 (average 6,861,900). Malthus took this as evidence of geometric increase, with no "vibration" in that period. I would happily regard it as evidence of a slowing of the population increase rate as the population increases, although of course the census data could not have been very accurate (as modern censuses also are not).[25] Such a regression is commonly regarded as evidence of *density dependence of the rate of population increase*.[26]

Before I leave Thomas Malthus in peace I should draw attention to his efforts to promote a rational approach to deep political and philosophical questions. He rails equally against "advocates of the present order of things" and "advocates of the perfectability of man, and of society". Both, he considers, "offend against the cause of truth".[27] And he makes a step towards the dialectic expressed in the sub-titular quotation I attribute to João Maguiero: "It is an acknowledged truth in philosophy that a just theory will always be confirmed by experiment. Yet so much friction, and so many minute circumstances occur in practice, which it is next to impossible for the most enlarged and penetrating mind to foresee, that on few subjects can any theory be pronounced just, till all the arguments against it have been maturely weighed and clearly and consistently refuted".

MATHEMATICAL POPULATION MODELING

Although Malthus was a mathematician he did not express his theories mathematically, at least not in his published works. But less than a decade after publication of "*A Summary View*" a Belgian mathematician, P.-F. Verhulst, had published what he called his *logistique* equation (He later changed the term to "logistic" because of possible confusion with the French meaning: "the art of calculation") describing the growth of a biological population in which the *rate* of increase (strictly, the *proportional* increase rate, that is the numerical increase in a period of time expressed as a fraction – percentage – of the population number during that time) is continuously and progressively reduced as the population grows.[28] This equation predicts a smooth population growth up an S-shaped ("sigmoid") curve to a stable upper limit, usually designated as $\boldsymbol{K}$ and called, variously, the *environmental carrying capacity* or *saturation level*.[29]

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. Such are called pure compensation models, and we shall encounter some of them later in connection with the regulation of whaling and some kinds of fishing.[30,31]

Verhulst's formulation must have come sweetly to the ears of the European establishments and businessmen of the mid-nineteenth century – if they ever heard of it – since it described *stability*, not Malthus's and Godwin's nasty "vibrations" and "oscillations". This was Good News at a time – mid-century – of serious labour disturbances in nearly every country, while politicians and the new capitalists revered the new-fangled idea of "progress" and needed social continuity for profit and capital accumulation.

Eighty years after Verhulst's seminal paper an American demographer, Raymond Pearl, was busily applying a logistic equation to data for the population of the United States of America as well as more generally.[32] Pearl was a re-inventor of the logistic curve; he was at the time unaware of Verhulst's work. While writing the first draft of this essay my attention was drawn to a masterly historical review by Sharon Kingsland.[33] Kingsland unravelled the 1930s and 1940s, but focused on the role of Pearl in the development of ideas about population growth and the strong scientific controversies engendered by his ideas. Pearl actually drew his inspiration from the work of T. B. Robertson,[34] who applied a sigmoidal curve which he called an *autocatalytic* or *self-accelerating* curve but which was identical with the logistic, to data for the growth of individual plants and animals, including humans. His name for it came from an analogy with the dynamics of certain chemical reactions.[31]

At about this time an Italian mathematician, V. Volterra,[35] and an American, A. J. Lotka,[36] were generalizing the logistic model to apply to the interaction between two animal species, such as a predator and its prey, and demonstrating that such a system would generate oscillations.[37] In the same period, however, three Norwegian scientists – Johan Hjort, Per Ottestad and G. Jarn – were applying the logistic theory to the problem of overfishing in the Northeast Atlantic and also particularly to Antarctic whaling, with reference to the rapid diminution of blue whales on which that vast industry had been founded.[38] The idea was pursued by Michael Graham at the English Fisheries Laboratory in Lowestoft with respect to the cod, *Gadus morhua*, and other groundfish species in the North Sea,[39] and later especially by M. B. ("Benny") Schaefer and Oscar Sette, in California, with respect to tunas in the eastern tropical Pacific, and the pilchard (sardine), along the US West Coast.[40] Then, throughout the 1970s the Scientific Committee of the International Whaling Commission (IWC) tried, with limited success, to use a modified form of the logistic to provide advice on the regulation of all commercial whaling.[41] It is remarkable that Kingsland seems to have been completely unaware of this sort of application of the logistic equation; her review concentrates, in the later years, on its use in the analysis of laboratory experiments.[42]

The idea behind these applications is simple in principle. It rests on the assumption that the trajectory of population growth is, in effect, *reversible.* What does that mean? The 18th and 19th century students of human population were close to catastrophic events such as plague, famine and war that brought about sharp declines in population number. After them populations increased again. Technically, these were *perturbations*, the study of which is perhaps the most important way in which we learn about the *dynamics* of processes, whether in physics, population biology or economics. We watch small perturbations to see if the system returns to "normal", and large ones to see whether the system is disrupted. The ease with which a population returns to its earlier state when the force causing a perturbation is removed is called its *resilience*, and the trajectory of that return is a *transient.*[43] In biology a very large perturbation may lead to the extinction of the population, and simple logistic theory is not able to deal with that. But a large one that does not lead to extinction is treated as if nothing very important has happened – a sharply reduced population will, given time and peace, simply bounce back.

Malthus and some of his successors realized that a population that has been reduced by an external event or special internal process does not have the same characteristics as a growing population of the same size, because it is *structurally* different: the sex ratios may be different, the frequencies of children, adolescents, adults will be different, and – in human populations – the class composition will be different, and these differences must be taken into account in predicting the future trajectory.

The biologists studying fish stocks in the 1920s-1970s faced a situation in which populations were being reduced steadily by application of a force – fishing effort – which was prolonged and sometimes sustained, to the point of industrial disaster. Monitoring the population decline itself, together with the collection of statistics on catches and some kind of point estimate of the numbers of fish or whales (or their total biomass) could be used to assess the states of the stocks and provide a basis for formulation of management advice.[44] That can only succeed, however, if some way is found to take structural differences between the growing and the declining population into account. This is partially achieved in the IWC application by devising a population model BALEEN II which was developed from the simple modified logistic originally used.[45] This modification has important implications for management but does not alter the basic properties of the logistic model.[46]

Fisheries scientists are usually much more interested in the weight of catches than the numbers of fish in them, and so more in the biomass of the exploited population than in the numbers of fish in the sea. Expression of this interest calls for knowledge of the age structure of the population and composition of the catches, and about the growth rate of the animals as well as their reproduction and mortality. Throughout the early history of the International Council for the Exploration of the Sea (ICES) the attention to be given to estimating ages of fishes (and of whales, too) was a matter of some controversy. Johan Hjort was a strong advocate of routine and comprehensive age-determination; others, including especially the great Scottish scientist, W. D'Arcy Thompson, were – to say the least, unenthusiastic.[47] It is, I think, worth quoting D'Arcy Thompson's 1899 definition of the task of ICES, just about to be established.[48] Scientists studying fisheries for the smaller pelagic species, such as herring, *Clupea harengus,* were preoccupied by the large annual fluctuations in catches, attributed to variations in mortality of eggs and larvae and reflected in variations in recruitment of young, but catchable and marketable, animals to the exploited population. Great effort was for decades put to efforts to predict these fluctuations and to finding relations between recruit numbers and the numbers of female parents – spawners. Those studying bottom fishes, such as cod, flatfishes, and haddock, saw less year-to-year variability and were thus more focused on the survival of still-growing fish in the exploited part of the population.[49] The development of mathematical models with this in mind began with a Russian scientist, F. I. Baranov.[50] His fundamental work was virtually lost until "rediscovered", in English translation, in the "western" world in the late 1930s, by Michael Graham and others.[51]

The differences that nature presented to different groups of scientists led to the parallel development of two general types of mathematical models, commonly labeled as *production models* (derived from the logistic equation approach) and *age-structured models* (derived from Baranov's approach, taken up by, among others, W. E. Ricker, in Canada, and by R. J. H. Beverton and me, both in the 1950s).[52] The two have rarely come together; I think for the first time in a 1957 book by Beverton and me, and called therein "a self-regenerating model". Limited computing facilities at that time precluded more than a cursory exploration of its properties[53] over a small range of parameter space. We do know, however, that this model reveals that a fish population can be driven to extinction if the fishing effort/mortality rate exceeds a critical level.[54]

For the purpose of considering sustainability in the framework of single-species population models it is convenient to confine discussion to production models (including those with limited structural content such as IWC's BALEEN II.) We must keep in mind, however, that some age-structured models of the self-regenerating type turn out to have some rather different properties.

Through most of the twentieth century biologists studying the conservation of terrestrial (and freshwater) systems were concerned about the possibility of population – or even species – extinctions resulting from intensive "use", while marine biologists had no such concerns. Their aim in "conservation" was primarily prevention of the *economic* extinction of fish stocks, and the maintenance – and, where necessary, *restoration* of depleted populations to ensure future economic value. There have been two rather different approaches to this self-imposed task. One, associated especially with the European side of the North Atlantic, sought to find ways, through regulation, to ensure *continuity* and *stability* in the face of growing fishery pressures generated by changing markets.[55] The other, associated mainly with the North American side, sought *optimization* of fishing, especially through setting the target of Maximum Sustained (or Sustainable) Yield (MSY); this is now embodied in international law of the sea, particularly at a global level. Let us see what that meant in practice. But, first, another look at the logistic function.

If the formula for population growth is in fact reversible then we can say that for any population size a catch could be taken in perpetuity, periodically (usually we think in terms of years) of a size equal to the *slope* of the population growth curve. That is one definition of a *sustainable yield*. According to the logistic, modified Pella-Tomlinson style, *a sustainable yield can be taken when the surviving population is at* ***any*** *level of abundance* other than its pristine state (at carrying capacity). This is easily seen if one plots the slope of the growth curve against the population size, to give one of the two graphs commonly used for illustrative purpose in fisheries research and management. (The other is a plot of sustainable yield against the intensity of fishing – fishing effort or something closely related to that, such as the mortality rate of fish generated by fishing). This yield-population curve is characteristically dome-shaped, with the sustainable yield going to zero at zero population (of course!) and also at maximum population. With the simple logistic the peak of this curve, which is the MSY, is located at a population level (MSYL) equal to half the carrying capacity. In modified versions the peak may be at higher or lower levels; in the whaling assessments of the 1970s it was assumed (rather arbitrarily, as a political compromise, with little scientific basis) to be at 60% of the carrying capacity. In many fishery assessments the implied MSYL is well below 50%, often nearer 30%.

The MSYL is the population size at which the sigmoid curve of population growth begins to turn, its *inflexion* that is, where its slope, which has been increasing, starts to decrease, and where the actual growth, in number – not the relative rate of growth – is highest. Theoretically, if a catch taken at a certain population size is less than the sustainable catch at that size, the population will increase. If that size of catch is continued the population will increase until it reaches a level for which the sustainable yield is the same as the catch being taken; that level must be above the MSY level. When MSY is being identified as the target for management then it is sometimes said that a stock in this state is being *underutilized*. If, however, a catch is taken that is higher than the sustainable yield at that population level then the population will diminish. What happens next, if catches continue at the same size, depends on the starting point. If the population was initially above the MSYL, and if the catch was no higher than MSY the population will stabilize at MSYL or above it. If, however, the population was initially below the MSYL then continued catches of the same size will result in further reduction of the population and eventually its extinction.

So much for simple theory. In practice, however, there are great uncertainties about the yield-population curve, its shape, vertical scale and the values of other parameters defining it. In practice, too, these uncertainties cannot be fully resolved, no matter how much research is carried out. And, further, external factors – such as environmental changes that might affect the carrying capacity, and the impact of other species on the target species (competitors, prey, predators, parasites) are usually unknown or cannot be predicted. The logistic model is essentially *deterministic*, too, while in the real world even well-estimated parameters exhibit statistical variability, to take account of which corresponding *stochastic* models are required.

These considerations have led fisheries scientists to pay close attention to the notion of *precaution*. How this is done can be illustrated by the approach taken by IWC scientists in the 1970s when told to implement what the IWC called the New Management Procedure (NMP) in the wake of the UN Conference of 1972, in Stockholm, on the Human Environment, which had been very critical of the IWC's conservation record. Until then – but only since 1960 – the IWC had a policy of trying to set annual catches at no more than sustainable levels, a policy that had failed dismally for a number of reasons, one being a refusal, despite 20 years of pleas from the scientists, to set catch limits for each species and population separately instead of as a multi-species bloc – the Blue Whale Unit (BWU). In 1974, policy shifted to targeting MSY, but with a precautionary flavour in consideration of the dramatic consequences of over-estimating sustainable yields in the previous era.[56]

Precautions took three forms: (1) classify populations with respect to their level of depletion below the carrying capacity, and allow whaling only on those above or close to the MSY level, approximately (with MSYL assumed to be at 60% no whaling was to be permitted on any population judged to be below 54% of carrying capacity); (2) allow maximum catches to be only a certain fraction of the estimated MSY; this was in practice taken to be 90% (in retrospect not very precautionary!); and (3) as a later amendment, permit no exploitation of hitherto unexploited populations and species until there had at least been satisfactory estimates of the sizes of such populations.[57]

These precautions were very far from adequate. The final blow to the NMP was given by William de la Mare who showed by computer simulation (the first time such a method was used in fisheries studies) that the Procedure would not be conservative of whale populations even if the model was structurally correct and its parameters perfectly estimated.[58] This revelation was instrumental in encouraging the IWC scientists to look at completely different possible ways of managing future whaling for sustainability and with due precaution and safeguards. The declaration by the IWC of an indefinite moratorium on all commercial whaling in 1982, becoming effective in 1986, gave the scientists the opportunity to devise and test (by computer simulation) a Revised Management Procedure (RMP) which has been accepted by the IWC at the political level but not yet implemented, pending agreement on other elements of a Revised Management Scheme (RMS), including such features as an International Observer Scheme and a database of DNA profiles of caught whales.[59, 60]

We need not worry here with the details of the RMP, but the objectives it is designed to meet, as set by the IWC itself, based on the specification of feasible options by the Scientific Committee, are worth noting:

1. There must be only a very low probability of any population being reduced, by accident, over a period of one hundred years, to below a certain minimum size, that size to be much greater than a theoretical or observed level at which biological extinction of that population might happen.
2. The population must, at the end of the hundred-year period, be fairly close – as specified by "tuning" – to the carrying capacity at that time.
3. Providing conditions (1) and (2) are met the *cumulative* catch over a period of 100 years should be permitted to be as high as possible.
4. The catch limits should not vary greatly from year-to-year except to meet unexpected emergencies, this to satisfy industrial operational needs.

The period of one hundred years was originally set by the limitations of computer capacity in the simulation trials. It is, however, also related to the life-spans of the baleen whales, which are of the same order as the human life-span.

Conditions (1) and (2) essentially provide a new definition of *sustainability*; and condition (3) defines *sustainable use*. Condition (4) simply eases some of the organizational and economic difficulties that could be faced by the industry in being subject to such a rigorous management scheme. In addition the Scheme would provide for all annual catch limits to be zero unless otherwise decided, and where non-zero limits are set they would be a small fraction of what would have been permitted under the NMP. The "small probabilities" define the degree of *precaution* adopted. Finally, while it has been tested exhaustively by computer simulation using "data" generated from various population models (the "base model" being the BALEEN II model previously developed for implementation of the NMP), the catch limit algorithm (CLA) does not itself incorporate or depend upon any particular population model.[61]

Successful application of the RMP approach in the future would depend critically on rigorous management and a long-term commitment. All non-zero catch limits must be those specified by the CLA; there would be little if any room for negotiations. Population surveys must be conducted periodically by specified means; failure to do so, or to provide other required data, would lead to an automatic reduction in catch limits and eventual shut-down of the whaling operation. It remains to be seen whether the international community can abide by such constraints, plus some effective enforcement and control measures, for at least several decades.

ALLEE AND HIS EFFECT

Per Ottestad, in commenting on his application of the logistic for assessment of the sustainable yield as a function of population size or fishing intensity, remarked that Raymond Pearl's analysis of the human population series did not prove the validity of the hypothesis that generated it. Many other mathematical functions would fit the data just as well; goodness of fit does not prove that the data have been generated by the processes assumed in the derivation of the equation. Feller elaborated this view.[62] Subsequent modifications of the simple logistic that have been employed in fisheries studies have usually affected the middle and upper bounds of population abundance or density. Apart from the modifications of the Pella-Tomlinson type, which affect the location of the MSYL, the main difficulty found at high population levels is that if for some reason the population over-shoots the notional carrying capacity the logistic model predicts a negative growth rate. As the growth rate is the *difference* between natural mortality and reproduction this is not impossible, since the (natural) mortality rate could perhaps increase in an unexploited population at high density, so as to exceed reduced reproduction. But that can become "uncomfortable" because a rather small over-shoot leads to rapidly accelerating and unrealistic increase in mortality. It is for that reason that Witting (see below) replaced, in his new model, the unruly Pella-Tomlinson function by two others – a function proposed by William Ricker[63] and a power function, neither of which force negative growth at high densities.

In the context of this Forum, and the concept of sustainability, what happens when a population is reduced to a very small size by exploitation (i.e. is *depleted*) is more important. Both the original and modified logistic models force a population to extinction only if the intensity of exploitation is continually increased; this seems unrealistic. In using the Pella-Tomlinson modification in their BALEEN II model the IWC scientists simply selected an arbitrary level below which the model might not apply, and devised management procedures aimed at avoiding the reduction of the population to such a level, whether deliberately (as for the NMP) or by accident (as for the RMP).

Age-structured models such as the Beverton-Holt self-regenerating model can imply thresholds for "safe" population levels; Tony Pitcher has devoted a short paper to this[64] and the definition of a quantity F_{ext} , the exploitation rate that will lead to extinction. But it is not easy to see how this could be estimated from the usual data, and its experimental determination is unlikely to be proposed!

The usual logistic-style production models can easily be modified to generate what has been called the Allee effect,[65] most easily by adding another parameter to the stock-recruitment function; John Shepherd has shown the way,[66] but, again, it is not obvious how that parameter can be estimated. However, theoretical approaches may help us understand the potential dangers of ignoring the effect.[67]

In fisheries studies the Allee effect may be applied either to the relation of recruitment to parent population size or more generally to the curve of yield against population size. In the latter case the simple dome-shaped curve given by the logistic is called a *pure compensation* model; the proportional (or relative) growth rate continuously increases with declining population. But if the proportional growth rate then begins to decrease as the population declines further the model is said to exhibit *depensation.*[68] This introduces an inflexion into the yield-population curve near its lower end. If the depensation process is strong enough, a *critical depensation* curve is generated. The important feature of this is that there then exists a *minimum viable population level.* The Beverton-Holt self-regenerating model exhibits critical depensation.

There have been numerous efforts to suggest what might be the possible biological mechanisms of depensation; they include cannibalism, for example.[69] Ricker put forward hypotheses in connection with the dynamics of Pacific salmon. But how can sustainable use be assured if we do not know whether to expect depensation to occur or, if we do know that, know at what population level it may manifest itself – that is at the level of an inflexion in the yield curve or in stock-recruitment curves? One approach is that taken by the IWC scientists, and also in effect by the scientific advisers to IUCN in the preparation of criteria for designating species as threatened, endangered, etc. – merely to assume it cannot be higher than some *guessed* level. One criterion which may set an upper limit to this threshold is provided by consideration of the natural variability of the unexploited population, if that is known – which is rarely. Clearly, if the threshold were very high the population would be unstable and at some time go spontaneously extinct. Another approach would be simply to observe, by close monitoring, if and when an exploited population shows signs of behaving differently from what is predicted by simpler models, and take rapid corrective action; but a difficulty there is that wild populations can rarely be monitored with sufficient precision in a timely manner.

These considerations lead, I think, to the practical conclusion that the only practicable way to avoid risk of inadvertent extinction or even of undesirable depletion, is to adopt extremely precautionary management measures (and enforce them, of course). That is what has been done in the development of the IWC's RMP; the CLA provides that this lower threshold is as high as the MSYL of the simple logistic – a depletion of 50% from the carrying capacity. Some experience would justify such a choice: whale populations have many times been depleted to substantially less than that level, and have not shown signs of imminent extinction. And even those that have in the past been reduced to, say, less than 10 or even 5% of their unexploited level are still with us, thus not exhibiting *critical depensation*.[70] However, in some cases they do seem to recover very slowly, for several decades, before beginning to show real signs of recovery; possibly they had been in a phase where depensation is manifest, but not critically so. It must be said, however, that this threshold for the RMP was not set only – or even mainly – to avoid possible extinction, but rather to meet the criterion of high cumulative yield provided that was "safe", and that can only come from an abundant stock.

I end this section with the observation that even the simplest assessment models have on occasions been seriously misused by scientific advisers to management authorities. Such misuse has arisen from attempts to simplify assessment procedures, to avoid recognition of the broad lack of relevant information and, sometimes, from carelessness. Collapses of sea fisheries have often been due to refusal of management authorities to heed otherwise good scientific advice. The most common scenario is a sort of compromise: the scientists say sustainability could be attained by setting catch or fishing effort limits at such and such a level; fishers say they need limits substantially higher than that in order to profit from their activity; authorities agree on something in between. But one cannot compromise with Nature; one cannot take more than Nature is ready to yield, at least, not in the long term.

However, the scientific advice has sometimes not been good, quite apart from the consequences of uncertainty and ignorance. The most common such failure has been to ignore the density-dependent reproductive processes and how they behave when a population is being depleted. A commonly used procedure called Virtual Population Assessment or Analysis (VPA) does just that; it is akin to the error, discussed later, of managing by setting catch limits at the level of replacement yield; its temporary effects when used as an interim measure are not usually damaging, but repeated over time, unthinkingly, they can be catastrophic. Another error has been to regulate catching in such a way as to ignore the fact that a population which has appeared robust when it is abundant – because recruitment shows little relationship with parent density – becomes vulnerable when it is depleted and the inevitable stock-recruitment relationship emerges[71] A third pitfall is the use of simplified assessment models that, in certain conditions, can drive a population to depletion if not extinction.[72]

THE MAGIC OF SIGMAS, BELLS AND DOMES

Jugglers with the logistic in the 1930s and the first decades after World War II – at least in the fisheries arena – were struck by the similarity of the first derivative of the simple, original version of that function to the "Gaussian" or "Normal" curve of statistical theory (when they are scaled appropriately) and, conversely, with the near identity of the logistic itself with the integral of the normal curve – accumulated probability – despite their being algebraically quite different. Both are symmetrical and long-tailed, and the logistic derivative is only slightly more "peaked" (more "compact") than the normal curve. Both were applied, for example, to the data from trials to determine the selectivity of fishing nets with respect to size (length) of fish caught.

Although scientists studying whales and dolphins, and also those looking at terrestrial wildlife, usually concern themselves with the numbers of animals, fisheries scientists, and most ecologists are, as noted earlier, interested primarily in the weights of catches and the biomasses of populations. It is perhaps worth recalling here that the applications of the logistic – which was derived from consideration of numbers – was commonly applied, in the fisheries context, as if it equally defined changes in biomass/catch by weight. While that is perhaps harmless in the context of general popular exposition, it has occasionally been confusing when unthinkingly applied in management/conservation calculations. The first application, to whales and whaling, was exceptional in that practical interest was in the *numbers* of particular species of whale caught, the slide into applying the logistic, without modification, to – for example – the catches of North Atlantic cod or to yellowfin tuna, expressed in thousands of tonnes, is questionable. So we should look at the relation between the two.

Many, perhaps most, fishes seem to be able to grow continuously through life, albeit more slowly as they increase in size. The curve of weight of an individual against age is typically S-shaped, with an inflexion commonly at between about 30 and 40% of the asymptotic weight. Naturally, there are wiggles in the curve caused by seasonal changes in growth rate within years, but I shall ignore those here. Various functions have been used over the years to fit annual growth data, the most commonly applied being a function due to von Bertalanffy or some modification of that.[73, 74]

Now consider the total weight (biomass) of a cohort of animals, what fishery biologists usually call a year-class. If it is not exploited the number of animals in the year-class will diminish by natural causes, and if those causes act uniformly through life the decline will be geometric/exponential. The number surviving to a certain age multiplied by the average weight of the individual at that age gives the biomass of the cohort; this is typically an asymmetrical bell-curve with a longish right-hand tail. We could envisage that if we could arrange to capture an entire cohort when it had reached the age shown at the peak of that curve we could maximize our catches. But of course we could not do that in practice. If we were fishing more or less continuously then we would catch some fishes at all ages. It is not too difficult to calculate how intensely we should fish to maximize the catch from the cohort throughout its natural life, though that would be somewhat less than we could get theoretically by catching all at the same "optimal" age.

A little conjuring trick allows us to say, in certain specified conditions, that what could be taken from one cohort throughout its life-span is the same as what could be taken in a single year from all existing cohorts combined. This gives us the Sustainable Annual Yield per Recruit curves (***Y/R***) familiar to fisheries scientists, where the number of "recruits" is the average number of fish attaining "fishable" size each year and so becoming liable to capture. ***Y/R*** values are usually plotted against a measure of *fishing effort* or *intensity*, or the mortality rate due to fishing (***F***). Typically such curves are bell-shaped but skewed to the left; the location of the peak of the curve gives an indication of what has been referred to as an "optimum" fishing intensity – though it is optimal only in a special restricted sense.

Y/R calculations have been widely used to provide scientific advice for managing fisheries for both sustainability and high production. Their usefulness depends on the validity of an assumption that the number of recruits is on average essentially unrelated to the number of sexually mature animals that produced them. For many fishes this is not an unreasonable assumption provided that the population is rather lightly exploited, or if it is increasing; in this latter situation the benefits of management for sustainability might be greater than as calculated. But, of course, it would be a dangerous procedure to apply to a declining population and/or an intensely exploited and hence probably depleted one.

Although ***Y/R*** curves are typically peaked, that is not always so; the existence or otherwise of a peak depends on the relation between the natural mortality rate and one of the parameters of the growth function, and also on the size or age at which fish become liable to capture, relative to their final (asymptotic) size. If the natural mortality rate is relatively high the ***Y/R*** curve against fishing intensity becomes asymptotic. This is dangerous! It leads one to expect that the sustainable catch can be continuously increased – though perhaps only slightly by an unlimited increase in fishing intensity. But, of course, such increase leads more and more rapidly to a decline in the population, and especially of mature adults, so that eventually the numbers of recruits will diminish and the population will crash.[75]

This difficulty can in theory be resolved by combining yield-per-recruit calculations with an appropriate function relating recruit number to the size (number, biomass or other appropriate measure taking into account variations of fecundity with age or size of fish) of the preceding parent "stock". (There is a voluminous literature on so-called "stock-recruitment relationships" in connection with fisheries management.) As I have already mentioned this combination provides what have been called *self-regenerating yield curves*, the general properties of which are not unlike those provided by generalized logistic models.[76] However, they do differ in two specific ways: they take explicit account of the age-structure of the population, and they are used to calculate weight of fish in catches and populations rather than numbers. They can also have an additional property of predicting population extinction under certain circumstances of excessive fishing intensity, without the stock-recruitment relationship itself having *depensation* specifically written into it.[77]

MORE MODELING

We have seen that the logistic models would "allow" some catches to be taken repeatedly and sustainably at any level of population, although approaches such the IWC's NMP and RMP would in principle set limits to that by prescribing minimum population sizes and/or levels to below which there must be minimal or no risk of the population being driven towards extinction by exploitation. There are two quite different reasons for trying to prevent use – driven by search for profit – from depleting populations of whales, fishes or other wildlife to "dangerously" low levels. One is, of course, the fear of accidental extinction. The other is to provide for exploited populations to remain abundant or to recover to abundant levels. There can be several reasons for this latter wish. One, obviously, is that abundant populations can in principle provide higher absolute yields and also better returns for effort than depleted ones. For certain types of so-called non- or low-consumptive use, such as whale watching and other forms of ecotourism, high abundance may have an intrinsic value – though this is not necessarily so: much effort is put into spotting rare species. But increasingly it is being appreciated that controlling exploitation so that abundances of primary target populations are high may be a safeguard against unwanted "damage" (however that might be defined) to the ecosystems of which those populations are integral elements. To evaluate this we need very different kinds of models, and those we have now are, I think, far from adequate for that purpose.

Nowadays, these considerations of possible biological "damage" fall under the rubric of "preserving biological diversity" around which an enormous volume of documentation has been produced in recent years, and an astronomical number of words spoken. Several dimensions of diversity have been identified: genetic diversity within the species, or population; diversity of species populations; diversity of species; diversity of ecosystems and, I suppose, global diversity.[78] To these I would add potential for continued evolution, for which genetic diversity is a necessary but not sufficient condition, and also "cultural diversity" with respect to the animal kingdom. Sustainability should therefore encompass protection of all these forms, and sustainable use must in future provide for the possibility of *substantial* use while maintaining diversity in all its forms as far as practicable.[79] This calls for balancing a variety of objectives, with priorities set among them, just as the IWC's RMP aims to do in a much more restricted field. A brief look at some of the emerging ways of dealing with this situation seems to be in order. It is also timely in view of growing pressures to "cull" some species in order to "save" others.[80] In particular, considerable efforts are being made to convince us that the present global crisis in sea fisheries is, at least in part, due to consumption of fishes and squids by whales, dolphins, seals and perhaps by other wild predators. All such efforts are directed at sub-optimal use of the species to be culled (in single-species terms, and if it has a market value) and, generally, *unsustainable* use. These pressures are therefore a potential threat to the notions of sustainability and precaution as they are commonly now understood, even if not always in precise terms.[81]

The orthodox approach to this issue is the construction of multi-species models comprised of two or more – sometimes very many more – single-species elements.[82]

The elements, or primary modules, are usually quite simple ones, sometimes without the internal density-dependences that would provide for their individual stability or resilience. Such models involving interactions between only two or three species may be constructed from logistic elements, and the differential-integral equations defining them may be formally soluble.[83] When there are more elements to be taken into consideration solutions must be found for specific situations by computation, usually involving iteration – that is, a process of repeated calculation and successive approximation until the answer converges, hopefully, to a correct value, number or pattern. Modern computers permit this, but a price paid can be that one may be "unable to see the wood for the trees", and to know whether the particular solution obtained has any more general validity, and especially whether it is a unique one.

In most current many-species models the variables are not population numbers and corresponding reproductive and mortality rates, but rather biomasses, sometimes of species populations but also of groups of species assumed to occupy the same or similar *niches* in the ecosystem in question, or even certain *trophic levels*, such as "primary producers" (usually by photosynthesis), "herbivores", "primary predators", "top predators", "scavengers", "reducers" (anaerobic bacteria for example) and the like.[84] Such models deal with the transfers of organic matter (biomass, essential and critical elements such as molecules containing nitrogen, carbon, silicon, phosphorus, iron) and of metabolic energy among the elements.[85]

The complex structure of such models is well illustrated in an ecosystem diagram provided by Peter Yodzis.[86] Even if numbers and formal relationships among elements and modules (groups of elements) were to be specified in such a diagram, and iterative solutions were to be found by very long computation, the results would always be extremely sensitive to any errors in estimates of parameter values or in definitions of structural relationships. This matter of sensitivity has often been over-looked, even though testing is in principle simple, if laborious – merely by running the model over and over again with a suite of different values. In reviewing this problem Anne Hollowed and her co-authors had this to say after their examination of four types of models, which they classed as descriptive multi-species, dynamic multi-species, aggregate system, and dynamic system:

> Populations are regulated by competition for food (food limitation), predation and environmental variability. Each factor may influence different life-history stages, locally or regionally.[87] However, most multi-species models address only a sub-set of these factors, often aggregated over functionally different species or age groups. Models that incorporate the important interactions at specific stages and scales will be necessary if they are to continue to supplement the information provided by single-species models.[88]

I think these authors are over-optimistic. Even the dynamic stability of such models is practically impossible to determine, although examination of their structure might indicate whether they will certainly or possibly exhibit *chaotic*, that is unpredictable, behaviors in response to perturbations.[89]

In recognizing such problems the IWC scientists took a different route to taking into consideration multi-species issues for the practical purpose of providing scientific advice for a possible sustainable and precautionary exploitation of baleen whales. This involved, during the development of the RMP, testing the robustness of various proposed single-species population CLAs in situations of hypothesized drastic environmental change. The scenarios tested included sudden changes not only in the general biophysical environment but also changes – reductions or increases – in "carrying capacity" and/or population growth rate, and gradual changes of similar magnitude over many years. In this case "the environment" includes significantly interacting competitors, predators and the like, be they other types of whale or other kinds of animals. The validity of this approach depends upon a more or less correct determination of the time-scales of change – which includes especially the life spans of the animals involved – and periodic monitoring of events, also on a commensurate time-scale. This approach is described in numerous Annexes to several reports of the IWC Scientific Committee, and some of its implications are described by W. K. de la Mare.[90]

GEOGRAPHY

So far we have concentrated on one dimension only of the problem of sustainability – potentially unlimited and continuous time. Another dimension – space – has been given much less attention, particularly in theoretical studies. Recently, however, the idea of declaring *marine protected areas* (MPAs), particularly as places where exploitation will not be permitted (*closed areas* in other terminologies) as a conservation measure has been explored by a number of authors. Ray Beverton and I were, I think, the first to look at the idea mathematically (and quite crudely!) by hypothesizing that bottom fishes such as plaice, diffused randomly as well as moving periodically between spawning and feeding grounds in adjacent areas), and we applied the well-known techniques of physical diffusion to do this. The idea was eventually picked up again by Sylvie Guenette *et al.*[91] and reviewed by Sumaila *et al.*[92]

Although potentially important for fisheries management this literature scarcely mentions sustainability as such. In general the idea of the reserve is to set limits on fishing effort and to redistribute it, and the issues of sustainability are, I think, essentially the same as consideration in the time dimension. Examples of this limited modeling approach are provided by Carl Walters and others.[93]

More directly relevant to our task here is, I think, the work of Alec McCall[94], based on a large body of theoretical literature about population dynamic models in heterogeneous environments, reviewed by S. A. Levin.[95] In this context the central concept of Density Dependent Habitat Selection (DDHS) refers to a special category of habitat selection by animals (much of the basic work is on birds) in which population size and local density are important factors influencing choice of habitat and hence the relative distribution of the population among habitats. Most models portray arrays of discrete habitats, but in application to aquatic systems a subset of the theory models, spatially, continuously varying habitat; the difference is fundamentally no more than envisaging on the one hand geometric changes with time and on the other exponential changes with time. The basic approach is to imagine a matrix of small "cells" within which changes in local population density/number are described by the logistic or a variant of it. In each place the values of one or the other or both of the two parameters that specify the logistic – the carrying capacity, $\boldsymbol{K}$, and the intrinsic rate of population growth, $\boldsymbol{r}$ – define the habitat suitability there.[96] Another parameter or function describes the dynamics of movement between one cell and another.

A "commonly observed phenomenon associated with DDHS", writes McCall, "is *expansion and contraction of population range* or differential utilization of marginal habitat with changes in population abundance".[97] This process can be envisaged as follows (again I quote McCall):

> If habitat suitability (or per capita growth rate) is depicted geographically as increasing downward, habitats can be described as a continuous geographic suitability topography having the appearance of an irregular basin, whose shape may also vary over time. According to the ideal free distribution, the population will fill this basin as if it were a (viscous) liquid under the influence of gravity.[98]

This "basin model" can be used to examine the relationship between range and population abundance and so has important consequences for the consideration of sustainability.[99]

If sustainable use in the time dimension is considered, for example, to be a level of use that does not drive populations close to an inflexion of the density-dependence curve where depensation may begin (see below), then the equivalent in the spatial dimensions would be a threshold beyond which the target's range should not be forced to reduce further for fear of subsequent spontaneous contraction. Similarly, if sustained use involves taking no more than will cause the population to decline no further than it may already have done, then the geographical equivalent would be the maintenance of the current range. *Restoration* of a depleted population similarly has both temporal and spatial dimensions. What emerges clearly from DDHS theory is that population abundance and distribution are inseparable features of dynamics.

This is an appropriate place for a warning about the notions of the population size, or *abundance*, and *density*. These terms frequently appear in the literature of population dynamics and related management theory as virtual synonyms. This may not be a problem if range and distribution do not change over time. But, if they do, then the two quantities must be carefully distinguished. Ultimately, that is probably nearly always, since concurrent changes in both total abundance and range are surely the norm, not the exception.

Here we have been considering the expansion and/or contraction of ranges of populations. As with the transition of the concept of natural population growth to that of reduction by exploitation – regarded, by default, as reversible – so it is tempting to see the reduction of the range of a population as simply the reverse of the natural expansion of a population over a new area. This might be a reasonable starting hypothesis in looking at sustainability, but has pitfalls. Where, in the time dimension, a population that has been reduced and then "protected" may encounter a situation where the resources available to it are very different from those pertaining before – for example another, competing, species has expanded into the "niche" previously occupied – then, in the spatial dimension, other species may have moved in to occupy part of the original range.

Theoretical and field studies of the biology of the two dimensions – time and space – have developed largely independently, and in different contexts. (They might be coming together with increasing interest in "protected areas" and the like as conservation and management tools.) Indeed McCall[100] observed that, even within the studies of the spatial dimension,

> Cross references among the various treatments of DDHS are exceedingly rare, even in review articles. This lack is especially

> surprising, given that the Fretwell-Lucas and Verner-Orians theories first appeared and are well known in ornithological contexts. These reviewers, and hence many ecologists, may not have recognized fully the unifying principles of DDHS underlying the various models.

Nor, I would add, have the unifying principles underlying the separate studies of the time and the spatial dimension of population dynamics yet been sufficiently appreciated. In this connection, and with reference to the historical starting point of this essay – with Malthus in the eighteenth century – it is interesting to note (again I rely on McCall's words):

> the independent development of concepts akin to DDHS in the field of economics, extending back to the work of David Ricardo, who pioneered the concepts of diminishing returns and economic rents in the early nineteenth century.[101]

McCall further notes that F. H. Knight explored these ideas as early as 1924, in relation to social welfare, and discussed the "marginal value theorem", that was independently discovered in the biological context of optimal foraging some forty years later by E. L. Charnov.[102]

A distinguishing feature of the spatially focused population theories, in contrast with the main thrusts of the temporally focused studies, is the importance they give to understanding the "mechanics" of biological evolution. So it may be that it is by the confluence of the two intellectual streams that we shall find the way to use populations and ecosystems sustainably while preserving the evolutionary capacities of those systems.

GOOD VIBRATIONS

Oscillations, sometimes sliding into unpredictable chaos, are an almost universal feature of even moderately complex systems, as Robert May demonstrated more than thirty years ago.[103] Their existence and ubiquity deny any universal interpretation of sustainability in terms of the generalized logistic model, where a sustainable catch can be taken from a population whatever its size (other than at carrying capacity), and a maximum sustainable catch taken at some intermediate size. The possible existence of processes generating depensation – particularly critical depensation – and overcompensation, also preclude such a simplistic definition.

We have seen that fisheries scientists, especially those studying the smaller pelagic species, were long preoccupied with annual fluctuations in catches, caused mainly by fluctuations in the numbers of young recruits entering the fishery. Ray Beverton and I, with others of the time, showed – in the 1950s – that if such fluctuations were more or less random then this would not, in itself, necessarily invalidate a management process based on consideration of steady states of populations.[104] The existence of oscillations, especially perhaps those with harmonics, whether caused by processes intrinsic to the population itself, or by interactions with other populations, or by periodic environmental changes more generally, force us – if we want to retain the notion – to consider more subtle definitions of what was once called "wise use" – conservation based on maintenance of viable exploited populations at relatively high, essentially unchanging, levels.[105] To begin to do that we must appraise the scales and frequencies, and causes, of a wide variety of types of oscillation in marine systems. We begin with the ocean itself, and as whole, and for examples of this I am especially indebted to the remarkably comprehensive and accessible summary of modern findings in oceanology by Bruno Voituriez.[106]

The vast world ocean circulation, generated by the interactions of changing salinity and temperature, and hence density (the thermohaline circulation, known more popularly as "the conveyor belt"), involves the movement of most of the water in the ocean through a cycle, in part near the surface, in part at the ocean bottom, from and between the North Atlantic, North Pacific and tropical Indian Ocean, and the great Southern Ocean.[107] This circulation has a period of about 1500 years. It is generated by the interactions of the ocean with the atmosphere in terms of water and heat transfers, and is particularly driven by the Antarctic Circumpolar Current which is generated by prevailing westerly winds at high southern latitudes, themselves the result of the great torrent, at up to 200km/hr, of cold, heavy air falling from the high Antarctic ice-cap. The details of this circulation have changed many times during and between a succession of ice-ages; the last was about 18,000 years ago, but these ages have been traced back through the preceding interglacial period of 120,000 years and eventually back to over 500,000 years ago.

Within this general circulation there are local and regional oscillations, the first of which to be identified was the so-called El Niño – La Niña, which appeared to affect alternately the two sides of the North and Equatorial Pacific and was linked with large changes in fish catches, especially of anchovy, off Peru and northern Chile. Subsequently it was found that this was a partial regional manifestation of a large regional process called the El Niño-Southern Oscillation (ENSO); El Niño is the warm phase of ENSO; La Niña its cool phase.[108] While it is repeated every few years ENSO has no clear periodicity. But it can be identified and characterized by the Southern Oscillation Index (SOI), which is based on the difference of atmospheric pressure at sea level between Tahiti and Darwin, and from its oceanic component using sea-surface temperature anomalies in the eastern equatorial Pacific, or the sea-level anomalies along the equator.[109] Similarly a North Atlantic Oscillation (NAO) is defined as the difference in atmospheric pressure between the Azores anti-cyclone and the low sub-polar pressure near Iceland. Like the SOI the NAO also varies – when the pressure off Iceland falls that at the Azores rises, and *vice versa*. Reconstruction of the NAO back to about 1700 AD, using data from the growth rings of trees, reveals oscillations of periods of 2, 8, 24 and 70 years. The climates of Europe, northwestern Asia and the northwestern coast of North America are, especially in winter, closely linked with the NAO index. Thus, in this sub-system we are looking at periodic changes on decadal scale.

From these analyses, backed by theory and observation, it emerges that the regional oscillations are in reality vibrations in the great conveyor, with, necessarily, differences in timing of the various consequences. This recognition gives us now a basis for interpretation of vast periodic changes in fisheries over scales of decades and centuries. Before that we should note that the details of biological production processes, providing the basis for the fluctuations of fisheries, are largely determined by the existence of *divergences* between water masses (zones within a current or, more often, at the interface between two currents), towards which subsurface water flows, causing the thermocline – the layer of sharp temperature change[110] – to be near the surface, and convergences (corresponding zones towards which surface water flows, causing a deepening of the thermocline). The divergences and other upwellings (mainly caused by westerly winds impacting the west coasts of the continents) are usually, but not always, associated with high primary biological production.[111] *Eddies*, or *gyres*, on the other hand, are usually, especially in their centers, markers of oceanic "deserts"; they are whirlpool-structures characteristic of mid-scale turbulence, major loops of the oceanic circulation associated with the main subtropical anticyclonic circulations in the Atlantic and Pacific.[112]

With all that in mind let us look first at the dramatic collapse of the cod stocks in the North Atlantic in recent years.[113] There is no doubt that this is primarily the result of excessive fishing. After the Basque whalers discovered the great Newfoundland bank stock, after they had pursued the North Atlantic right whale, *Eubalaena glacialis*, to near extinction (in about the middle of the second millennium AD), that fishery was sustained for several centuries. Even in the 1970s it seemed that the recruitment to this stock or stocks was essentially independent of the parent stock size, as was commonly believed in relation to groundfishes (demersal species, traditionally caught by bottom trawls). However, as fishing pressure increased further (in this case mainly as a result of the opening up of larger markets for frozen fish that had previously been served by fresh and then iced fish) the parents were reduced to levels at which an effect on recruitment was induced (but not noticed, and not immediate because it takes cod a few years to reach sexual maturity) and this was followed by the beginning of serious decline. But, even though the normal annual variation in cod recruitment is not so great as in, for example, the herrings, sardines and anchovies, one or more "unlucky" years of low recruitment were sufficient to trigger a catastrophic decline. But there was no evidence of large-scale natural oscillations in this species.

In 1970 the fishery off Peru for anchovy, the world's largest fishery by far – by weight though not by value – collapsed, at the peak of its production. This was attributed at the time to the onset of an El Niño that year. But the previous El Niño events in 1965 and 1969 had not affected catches. Nevertheless the fishermen and authorities were content to blame the El Niño scapegoat rather than look to a consequence of overfishing. This theory led to a great deal of scientific research on a topic of obvious high economic importance. But, still, the catches increased again from about 1973 and were not much if at all diminished by an El Niño event in 1997-98. Why not?

The anchovy does not live alone in these waters; it shares them with the sardine. When the anchovy is scarce the sardines are fished more intensively. But the sardine appeared to be immune to the El Niño phenomenon. The expansion of the Peruvian anchovy fishery was triggered by the collapse of the Californian sardine fishery between 1945 and 1950. Until then the anchovy had been "protected" in the interest of the guano producers, but guano gradually lost its value with the advent of synthetic phosphate fertilizers. So the anchovy fishery could expand dramatically. BUT, it was later noticed that large swings in sardine production in Japan preceded by a certain time lag the vicissitudes of the Californian industry, and subsequently the swings of sardine catches in Peru followed the same pattern. The fishery data alone do not permit a conclusion as to whether there is a 50-60 year cycle in alternating anchovy and sardine production in the Pacific, but analysis of scales of both species in the ocean sediments off California, provide a history from 270 to 1970 AD showing a fairly regular cycle with a 60-year period. Analysis of catches in the long history of Japanese sardine fishing has revealed a corresponding, but apparently less regular cycle since the early 17th century, with peaks in 1650, 1710, 1820, 1935, and 1985.

So, sustainable use of the anchovy and sardine resources of the Pacific would apparently involve understanding such natural oscillations and predicting them. However, the fishery for salmon species in Alaska also shows somewhat dramatic changes, coincident with changes in sardines and anchovies. It turns out that the warm phase of the Pacific Decadal Oscillation (PDO)[114] favours the salmon of Alaska and the sardines of California, Peru and Japan, while the cool phase favours only the anchovies.

Let us now return to the North Atlantic. The once great herring fishery collapsed in the 1960s and 1970s. Thereafter there was much controversy over whether that was due to fishing or to natural causes. There is now no doubt that it was triggered by the onset of fishing for young herrings from which to make fishmeal and oil. But the European herring fishery is very ancient, and it was undoubtedly "sustainable", in the common sense, for many centuries. Still, as Voituriez writes:

> The long history was not without incident and, in certain cases, notably that of the Norwegian Sea stock, boom periods for the fishery alternated with others in which the herring almost completely disappeared.

Overall records are not of long enough duration to allow unquestioned appraisal of these variations but there exist one thousand years of good records for the gatherings of herring in the Swedish coastal region of Bohuslän, in the Skagerrak between the Baltic and the North Sea. There have been nine periods of great abundance; in more recent years these were: 1556-90 1660-80, 1747-1809, 1877-1906. These so-called Bohuslän episodes are indicators of perturbations which, beyond the Skagerrak, concern the whole of the North Atlantic and have an impact on the fishery, not only of the herring *but also of the North Atlantic sardine*. Sardines inhabit different waters from the herring; they do not thrive in cold water. Catches of the two species taken near the moving boundary of warmer and cooler water, in the Southern North Sea and The Channel, will tend to alternate, and these alternations have now been shown to be related to the NAO. The NAO fluctuates on various time-scales, and the positive and negative anomalies may extend over several years or even decades. We do not have direct measurements of the NAO prior to the mid-nineteenth century, but the history has been reconstituted indirectly from the length of the season in which the coasts of Iceland are ice-bound; this is possible from the analysis of tree-growth rings and from the cores of the Greenland icecap. Voituriez comments, significantly:

> The last recorded Bohusiän episode dates back to 1877-1906. The NAO did not cease to oscillate then and another should have occurred in the 1960s when the negative anomaly of the NAO was at its maximum. But it did not. Why? Probably because the considerable increase in the fishing effort which led to the collapse of all the stocks in the 1960s-1970s made the climatic signal quite secondary and insignificant.

The last fisheries example given by Voituriez is for the bluefin tuna fished in the Mediterranean, for which we have reliable catch data since the sixteenth century.[115] These show oscillations of very wide amplitude (but no long-term trend), and period of about 100-120 years that cannot be attributed to changing social or economic conditions, nor to repeated overfishing since the fishing effort has been nearly constant. The causes remain unclear; hypotheses range from climatic variations modifying the migratory path, periodic changes in conditions governing larval survival, and the intrinsic dynamics of the species amplifying by resonance the random variability of recruitment. In a sense this fishery has been sustained, even though it is highly and regularly variable. But a change in the effort – for example by introduction of another kind of fishing gear and an expansion of markets – could change that situation rapidly. What is very clear however is that too short-term a view could lead to completely wrong conclusions about management, depending on circumstances; in this case long, almost continuous, declines in catches for half a century (repeatedly) can look like serious overfishing demanding restrictive regulation. On the other hand, focus on a long period of steady increase can, in different circumstances, encourage more intensive fishing. Such considerations may also remind us of a common attitude of fishers in the cases of fisheries with highly variable annual recruitments, which is that when there is a good year-class it should be exploited very intensively, before the fish all die from natural causes; this has sometimes been expressed in religious terms: God gave us such good luck, it is sinful not to take advantage of that.

In all the examples given there appears to have been something of a climatic break around 1975, a period when we passed from the "classical scenario" of the El Niño to a more peculiar regime, with a predominance of negative anomalies in the SOI. It was also a period when the PDO switched from a cold to a warm phase (with serious consequences for salmon, sardines and anchovies), and when the NAO inverted, passing from a negative anomaly (cold) to a positive one (warm). The climate dynamics are of planetary scale, so it is not surprising that these oscillations are not independent of each other. Indeed, air-temperature data analysed by the UN Intergovernmental Panel on Climate Change reveal an oscillation for the entire northern hemisphere with a period of 65-70 years. A Russian meteorologist, L. B. Klashytorin, has looked at these data through definition of an Atmospheric Circulation Index (ACI), calculated from the atmospheric pressure field over the Atlantic and Eurasia. With that tool Klashytorin analysed global fish catches over the past 100 years and showed that the 60-year variations in the ACI closely reflected the yields of salmon, herring, sardines and anchovies. This global synchrony, linking the oscillations of fisheries to atmospheric conditions, is not surprising, considering that they are mediated through oceanic processes.[116]

So, in our efforts to attain sustainability we have to cope with natural "vibrations" of various periods and types and amplitudes, generated by external events, that are to be expected but are not entirely regular and therefore predictable. And also oscillations derived from the internal structure of the exploited populations as well as their interactions with other populations. Furthermore we always encounter extreme difficulty in disentangling these two general types and causes of change. But before we leave these problems arising from various kinds of variability we need to confront yet another challenge to our ability to use living resources sustainably.

CHALLENGING THE ROOTS

In recent years Lars Witting, a Danish scientist working in Greenland, has cogently argued that the assumption that the rate of population growth when the population is small is geometric/exponential is not valid. His argument is derived from considerations of population genetics. If there is some genetically inherited element of variation in the reproductive powers or mortality probability among individuals, then this will have survival value and the natural population as a whole will evolve in the expected direction. It turns out that the intrinsic rate of population increase would not be exponential but, rather hyper-geometric in form.[117] When this function is used to replace the exponential assumption in otherwise traditional population models, it is found that they exhibit oscillations.[118] This might look like a purely academic finding, but it has great practical implications.

Under long protection, the gray whale population of the Northeast Pacific and the Arctic Ocean recovered from near extinction by the American commercial whaling of the late nineteenth century. That recovery has been monitored by sightings from shore stations on its migration route to and from the breeding areas of Southern California and Mexico; such monitoring is facilitated by the fact that this route passes close to the western coasts of North America for several thousand miles. The trouble is that, despite continued substantial catches by indigenous people in Siberia (authorized by the IWC), and despite the severe reductions over the past century in its available breeding grounds, the gray whale has recovered too far. It is now two or three times as numerous as would be expected by the usual kind of back-extrapolation of population size taking account of the recorded catches over a long period. Furthermore, the difference cannot be explained by hypothetical large unrecorded catches, historically, by the indigenous people of North America or the Arctic. The "standard" population models simply do not work. However, Wittings modified model *does* account for the present high numbers, and it predicts that the population is now close to a peak and will soon begin to decline, regardless of any exploitation pressure.[119] Based on the standard BALEEN II model the IWC Scientific Committee has advised that "a take of up to 482 (gray) whales per year is sustainable." Witting's model, on the other hand, predicts, according to its author, that constant future annual catches of 50 or 170 whales (the present authorized annual "aboriginal subsistence" catch is about 180 whales) may cause the extinction of the population during the current management regime, regardless of any possible adverse environmental change. The calculated population trajectories fit the data well for the thirty-year period of sightings surveys. *The period of oscillation is of the order of two centuries.*

So it seems that the gray whale history lends considerable support to Witting's hypothesis. If indeed it is valid it has profound implications for our concepts of sustainability, particularly in terms of precautionary assessments of acceptable future catches. As it happens, the IWC Scientific Committee's view has no immediate practical consequence, mainly because three of the four main range States – Mexico, USA and Canada – within whose Exclusive Economic Zones this species mostly lives do not wish to engage in commercial whaling. Nevertheless, continuation of the large "aboriginal subsistence" catches by Russian nationals in the Arctic could eventually have a devastating effect.

The gray whale is the only species for which we have a long time-series of population estimates made by what would now be regarded as a consistent and reliable method. This species does have a life-style distinctly different from that of other baleen whales (it is, for instance, not a pelagic but a benthic feeder), but that does not justify an assumption that the population dynamics just described are unique to it. At this point it would be reasonable to assume that, until we have contradictory evidence, such dynamic behaviour would probably be demonstrated by other species.

Evidently, the existence of cycles, in general, whether derived from Witting inertial dynamics, internal population structure (Malthus-Clark vibrations), interactions with other species (Volterra-Lotka-May type), regional or global swings in ocean climate (as summarized by Voituriez) or sustained ocean changes (such as the retreat of the Antarctic sea-ice edge which also might have a long-term cyclic component) suggest that it is time to discard simple ideas about steady states, equilibrium, and stable sustainable yields that might be altered only by casual environmental changes.

ECONOMIC SUSTAINABILITY

This book is focused on ecological sustainability, not its economic – possibly illegitimate – cousin. Nevertheless the two are related and some words may be appropriate here.

Economists, when creating mathematical models intended for application in managing the use of renewable natural resources, especially living resources, naturally include in their constructions modules pertaining to the dynamics of the resources themselves. Unfortunately, the crudest and simplest models available have almost always been used for this purpose. Sometimes they do not even have density dependence or other regulatory feedback processes incorporated. More usually the simple logistic is the chosen formulation. In certain circumstances this may not matter, but sometimes the choice is crucial. We have seen some of the failings of the simple logistic, and also of some of its modified forms – for example that it does not confront the possibility of the resource being driven to extinction, except under infinite exploitation pressure, which is hardly realistic in any circumstances.

A use that is biologically sustainable (regardless of the precise meaning given to the phrase, in context) will not necessarily be economically sustainable. The history of industrial whaling is a case in point. If such whaling had been limited to biologically sustainable levels in the days when the great whales were enormously abundant – say the 1920s – then, given the available hunting and processing technologies and the types of markets, an industry would probably have been economically sustainable because it was profitable and because it permitted both operating costs to be covered and capital to be accumulated for replacement of ships and equipment and for research, both on the natural resources and on the improvement of the technologies. If, however, a precautionary regime aimed at biologically sustainable use, such as the RMP/RMS, is put into effect with respect to whale stocks that are still very far below their carrying capacities there is no guarantee that such use will be economically sustainable. Even hunting for the still rather abundant minke whales in the Southern Ocean, that is now carried out by a single "pelagic expedition" (the operating time of which is now split between the Antarctic and the North Pacific, for economic reasons), has to be heavily subsidized by the Government of Japan and is surely not economically sustainable.

Continuation of an industry after the resource has been depleted, through seeking biological sustainability by severe restraints on exploitation (catch limits and the like), will usually be extremely painful, socially and economically. The vast profits that may have been acquired during the biologically unsustainable preceding phase have usually been spirited away into other enterprises; this is what happened with respect to Norwegian and British Antarctic whaling up to their end, in the 1960s-early 1970s. Those profits helped fuel, respectively, the growth of the Norwegian shipbuilding industry and the road haulage industry of the United Kingdom. So a sort of "sustainable development" was ensured. Before the end "exit strategies" were prepared (secretly, of course) by companies in both countries and, while lip service was paid to the IWC's efforts to stabilize the industry through sharply reduced catch limits, the reality was that it was economically more desirable to continue for a limited period at a biologically unsustainable level.

With a global crisis in the fishing industry now, mainly caused by overfishing, it must be very tempting for corporations (usually with sympathetic governments behind them), to opt for continued unsustainable levels of catch while exit strategies are prepared. It is not so easy, politically, to do this since the broad adoption of the sustainability philosophy by the international community in recent decades, mainly through the series of UN special conferences since 1972. Unfortunately, the new focus on multi-species and ecosystem management policies offers a loophole for those desiring to pursue the unsustainable-exit course, as they would appear to legitimize the over-exploitation of some resources in order to maximize the use of others and "optimize" the total use.

Naturally, those resources that are economically most valuable would be the ones chosen for selective over-exploitation; that, in the ocean, is usually the bigger predators. A provision in the *UN Convention on the Law of the Sea* to impede this has received scant attention since it was adopted in the 1980s; it provided, clearly though rather cryptically, for the limitation of the exploitation of prey species so that the biologically dependent predators would not suffer the loss of their food to the degree that it might reduce their reproduction and growth. At the same time a shift has stealthily been brought about with respect to the politics of sustainability. The World Conservation Strategy promulgated by the United Nations Environment Programme (UNEP) and the World Conservation Union (IUCN), with the support of such bodies as the World Wildlife Fund (now the World Wide Fund for Nature, WWF) originally proposed that if a wild living resource is used, such use should be (biologically) sustainable. But this requirement is now commonly interpreted – even by its proponents – as meaning that such resources *must* be used, albeit sustainably.

Rather late in the day economists began to correct the errors they had made in the first decades after World War II by failing to consider the effect of the *discount rate* in their models. They were brought up sharply by the work of a Canadian mathematician, Colin W. Clark. Clark's publications are voluminous, and many are applications to whaling and fishing; the most accessible one on this particular topic is perhaps his chapter in May (ed.).[120] Clark writes:

> It is a standard hypothesis of dynamic economic theory that firms behave in such a manner as to maximize the present value of their profits, discounting future revenues at a rate equal to the 'opportunity cost' of capital – that is, the rate of interest that the firm's owners or stockholders would expect to earn on alternative investments. From the social point of view, discounting implies a preferential treatment of present over future (human) generations.

Thus it is a powerful force counter to the pursuit of sustainability. In their recent analysis of the fisheries of the North Atlantic, Daniel Pauly and Jay Maclean have expressed the effect of discounting in a slightly different, but equally valid, way.[121]

VULNERABILITY

This is a commonly mentioned notion in discussion of conservation and sustainable use of wild living resources, and may relate to their responses to natural environmental changes or to human depredation or other intrusive behaviour. It may be applied to individuals but, in the present context, usually to a *type* of animal, species and population. It seems obvious that types of animals that are easily visible to, or otherwise detected by, humans are more vulnerable than those that are not. Whales and dolphins are more vulnerable than deep-sea squids, for example. The vulnerability of species is most usually now expressed by biologists in terms of whether they have evolved to follow a ***K***-life history strategy or an ***r*** one (***K*** is the so-called carrying capacity [asymptote] in the logistic and related models; ***r*** is the intrinsic rate of natural increase, commonly presumed to be a constant exponent, possibly genetically determined). The energy available to an organism capable of reproduction may be directed towards the survival and growth of that organism, or towards the production of offspring, or towards some partitioning between the two. Any change in the allocation of energy will influence the species' bionomic strategy, and hence the parameters of the population model applied to it.[122] T.R.E. Southwood (1977)[123] considered that "Each organism will have a bionomic strategy, expressed through its size, longevity, range and migration habit – which are not, of course, all independent variables – that is summarized by the parameters of appropriate population models. This strategy", he wrote, "will evolve to maximize the *fitness* of the organism to its environment. Hence the organism's *habitat* may be viewed as a template against which evolutionary forces fashion its bionomic or ecological strategy". He then defined three qualities of habitat: *duration stability* (the length of time a particular habitat remains in a particular geographical location, and favorable to the organism); *temporal variability* (the extent to which the carrying capacity, ***K***, of the habitat varies during the time that a site is tenable by the organism); and *spatial heterogeneity* (continuity versus patchiness).

First, consider the matter of size. The size of a species is positively correlated with generation time; generally the bigger the animal the longer between generations.[124] As a species evolves a change in size – commonly to be larger – will move it one way or another along the ***r*** - ***K*** spectrum, and ***r*** is more sensitive to changes in generation time than is ***K***. Then, larger species tend to have an advantage over smaller ones in inter-specific competition, and the allometric (out of proportion) growth of offensive or defensive appendages (legs and arms, tentacles, claws) will enhance this ability and that, combined with longevity, allows the possibility of a high level of parental care and protection. And the size of an individual will influence the size of its habitat, including the possibility of moving within it.

K-strategists have a stable habitat (the ratio ***r/H*** being relatively small – ***H*** is the length of time a habitat remains favorable) and so evolve towards maintaining their populations at equilibrium levels. So, they will be selected for large size, long generation times and lower ***r***. So high levels of fecundity are not needed for survival; if low birth rates can be matched by higher survival; the young will be few but relatively large. However, populations of ***K***-strategists suffering perturbations need to return quickly to equilibrium levels in the face of inter- and intra-specific competition for habitat/resources. Because their mortality rates are low this is accomplished by changes in the birth rate. Thus the birth rate is sensitive to population density and will rise rapidly if density falls. ***K***-strategists are unlikely to be well adapted to recover from population densities driven far below their carrying capacity, and are thus vulnerable even to extinction.[125]

In contrast, ***r***-strategists are continually colonizing habitats of a temporary nature (***r/H*** is not small) and they are exposed to selection at all population densities. They are opportunists. High ***r*** is achieved by high fecundity and short generation time. They are typically small. Competitive ability is not important; other than high fecundity their defence against predators comes from synchrony (shoaling, flocking) and 'hide and seek' facilitated by short range mobility. ***r***-strategists tend to be resilient rather than vulnerable in the sense we are using here.

K-strategists tend to have stable populations at high densities or abundances, but to exhibit depensation at low densities. *r*-strategists would not be expected to exhibit depensation, but would fluctuate about high population numbers and exhibit over-compensation. Other things being equal (which, of course, they rarely are in practice!) ***K***-strategists will be more vulnerable to human depredation than ***r***-strategists.

There is, however, another dimension to the matter of vulnerability. That is the particular nature of species' interactions with humans. Curiosity may place them in a difficult position in confrontation with a predator who is cleverer or much more powerful – but unobtrusively – than they are. If the individuals, or parts of them, have a high market value and are readily transportable to distant markets they become especially vulnerable. Changes in those conditions can be disastrous for them or, sometimes, their successors.[126]

Consider the herring of the Northeast Atlantic. A fishery for that ***r***-selected species was continuous for many centuries; to all intents and purposes it was biologically sustainable, even though it fluctuated – sometimes quite dramatically – and probably oscillated. At one time in the late nineteenth century, and even well into the twentieth century, there were several thousand sailing vessels hunting for the herring, as food for humans, and marketed fresh or salted. Many scientists thought the species was virtually inexhaustible. Even the introduction of steam- and diesel-powered vessels did not result in population collapse. However, in the second half of the twentieth century the processing technology changed drastically and over just a few years. Herring were turned into fish-meal and oil, especially to supply protein and fats, mainly for livestock feed supplements. The market price was low, compared with that for human food; this called for greatly increased catching to maintain profits, the introduction of new types of fishing gear and, most importantly, the catching of smaller, younger animals. In a few years (relative to the previous long period of sustainability) the herring population crashed, and it has only partially recovered – probably, in part, because the economic and social pressure has been so great that fishing has been permitted to resume before recovery had proceeded far enough.

The lesson? Evolving towards an ***r***-strategy does not confer invulnerability to modern human predation. Regaining economic sustainability, long-term, even if rigorous catch limits had been promulgated and fully enforced, would be difficult, painful and perhaps even impossible. At very low population levels even small catches, misjudged with respect to uncertainties of many kinds, would be likely to lead to further depletion, at some time. Recovery to high population levels, and a severely precautionary limit to catches, would not supply the fish-meal and oil market competitively due to low prices per tonne and the existence of competitive products of another kind. I think only a return to restrained catching of adult fish for human consumption from a virtually fully recovered stock could possibly ensure renewed sustainability.

THE TIMEFRAME AND QUALITY OF SUSTAINABILITY

Our subject is the sharing of use of a resource amongst users. The users might be different nation states or a variety of social groups differing in the manner in which they use the resource and/or the purposes to which the fruits of use are put. The users might be the present human generation or population on the one hand, and generations to come on the other. The fact that "generations" are overlapping in time is a significant consideration in this matter. In recent times a matter of concern to some is our sharing of this planet, specifically the biosphere, with other species.

Time I

The problems of sharing across generations and between current users are often closely linked. The FAO Department of Fisheries recently published a series of case studies of fisheries in which the allocation of fishing rights was the focus.[127] I provided an analysis of the process of "sharing" the Antarctic baleen whale resources, especially in the 1960-1970s during which success in obtaining an agreement to reduce catches to a currently sustainable level was completely dependent on a simultaneous agreement on the sharing of such reduced catches among five states and several groups of companies engaged in industrial-scale pelagic whaling in the Antarctic.[128] Gerald Elliot, who worked for most of his life in the world's largest whaling company – Christian Salvesen, of Leith, Scotland – and was eventually its Chairman, has published a fascinating first-hand account of how this worked, with reference to decisions made by the then Chairman, Harold Salvesen, which included preparing an exit strategy from whaling on the assumption that it would never be made sustainable[129] through international agreement and enforcement. This is worth quoting here:

> Harold had no illusions about the decline of the whale stocks. As early as 1945 he had warned Salvesen shareholders that the whaling industry had a limited life. Without taking the initiative in proposing a reduction of catch, he accepted the general policy of the British Government of getting catch quotas down to sustainable levels. But Harold, true to himself, did not swallow intellectually the generally accepted thesis that a self-renewing natural resource should only be harvested at a level that allowed it to be sustained for the future. He would point out to me that in economic terms it might be right to use the exist-

> ing capital equipment to take as many whales as possible up to the point where there were so few left that they were not worth catching. That would give immediate benefit to the whaling companies and the world's supply of wealth. Whale stocks would be brought to a new level, but not so far as to be in danger of disappearing, and they would eventually recover. Against this had to be set, in world terms, the loss of the far greater wealth that the whales could bring in future if harvested as a sustainable resource. But, he argued, even if we rate the interests of future generations as high as our own, it is by no means certain that whales will have any economic value in the future. Their products may well be replaced by others that can be produced at less cost. Harold never pursued this line of thought in public. He was as conscious as anyone of long-term world interest, but he felt that sustainable harvesting, like any other policy, should be argued out and not accepted as self-evident.[130]

Salvesen ceased whaling after making sure that the company would be able to sell its vessels and equipment to others who decided to carry on for longer, *and that those sales would carry with them the agreed shares of quota* (these had, in fact, a much higher market value than the hardware). The proceeds were used to start a large, and until now fairly successful, road-haulage company.[131] Similarly, proceeds from Norwegian Antarctic whaling created a "sustainable" city – Sandefjord – and a renowned shipbuilding industry. Whales and whaling provide a spectacular example, but they are not unique; uses of other marine resources have followed similar lines. Indeed, it was argued by some scientists and authorities until as late as the 1950s that restraints on fishing were unnecessary because the activity would cease as soon as stocks had been sufficiently reduced.

There were two errors in this line of thinking. One was failure to recognize that in industries based on a mixture of species, caught more or less simultaneously, exploitation of the more vulnerable (and usually more valuable) species would continue as virtually a "by-catch" of an industry now targeting mainly other, less valuable but still abundant, species, thus really threatening the continued existence of the former. In Antarctic whaling this was the mix of blue, fin, sei and humpback whales included in the notorious Blue Whale Unit (BWU) by which catch limits were set. In the North Sea trawl fisheries it was the skate (a species of ray that, like other elasmobranches, has a low reproductive rate but, unlike them, fetched high prices in major markets) that drew the booby prize for being the first exterminated marine commercial fish, as an unregulated by-catch of the industry focused on flatfishes and gadoids. The other error was failure to see that greater profit could be derived from a still abundant resource, or from a depleted one allowed to recover, provided the discount rate was not too high. ("Too high" is measured by the ratio of the discount rate to the net reproductive rate of the resource; whales, like hardwood trees, have slow net rate growth/reproductive rates and are hence especially vulnerable to high discount rates.)

Time II

Time is virtually the lost dimension of both the theory and the practice of sustainable use of renewable resources. The logistic equation and its derivatives predict that a population will attain its final abundance only after an infinite time has passed. They also generally predict that the population will stabilize, following a perturbation, only after an infinite time. It is obviously not possible to base management practice formally on such a paradigm.[132] One practical way around this dilemma may be to define a finite time by which a "recovering" population would be expected to reach some fraction of an "equilibrium" or "steady state" size (the so-called carrying capacity) – say 99 or 95%.

More generally one might arbitrarily terminate the period of transition from one steady state to another at the point where say 99 or 95% of the difference between the two states has been achieved. Another way of evading the issue is, occasionally, to deploy the terms "indefinite" or "indeterminate". These have been used in relation to administrative decisions (such as those defining moratoria on "use" or the creation of protected areas or designation of protected species and the like) meaning "until the authority concerned may decide otherwise". I think it is obvious, however, that whatever theorists do with integro-differential equations solved with respect to an infinite time of expression, a finite time limit must be specified and set in any attempted implementation of the notion of sustainability.

In terms of the human users of renewable resources the reality is that present users may have a primary interest in continued use *by themselves* later in life, and maybe by their families. Next priority may be use by the next generation in their society, but particularly by their own descendents. Concern and advance care might apply to the generation after that (grandchildren) in societies where family structures persist and where the descendents are likely to continue to base their survival on continuation of the family occupation. Sometimes, in discussion of this matter, it is assumed that the next generation can be left to make its own decisions about leaving resources in good order for the following one. And, of course, we cannot know what might be the preferences and choices of future generations – such as whether they will want to eat whale meat or a butter substitute from whale oil or to use them as a resource for tourism or basic scientific research, or even not to "use" whales at all.

The interests of the actual users – fisher-folk, whalers – are usually not the same as those of the society whose markets they supply, although both are linked by the behaviour of those markets. This was clearly understood by Michael Graham, one of the first students of the logistic, who argued that the interests of the fishermen and their families came first, and that if their continuity could be assured by restraints on fishing effort then the nation(s) would benefit from a good steady supply of fish.[133] But he could not have anticipated in the 1930s that in the not so distant future a main use of fish would be for conversion to fish-meal to provide food supplements for livestock raising and aquaculture (which, being largely based on the catching of smaller, younger fish, could threaten the existence of the resource in a way that old-style fishing never did – well, hardly ever), and which in turn would be largely replaceable by similar products from soy beans and sunflower seeds. Nor did many people, in and before the 1930s, expect that few sons of fishermen would become fishermen themselves, at least in Western Europe.

So, our view ahead is quite limited and perhaps can only practically be thought of in terms of a few overlapping human generations, at most. Also, realistically, it must be expected that no management regime can last for ever; in fact modern societies are sufficiently unstable and their practices rather arbitrarily variable that any such regime will probably endure, at most and in rather exceptional circumstances, for just a few decades. But in considering the sustainable use of a living resource, account equally has to be taken of the generation duration of the resource organisms themselves. In some cases, such as whales and perhaps some fishes, and terrestrial mammals and birds, and trees, this may be of the same order as that of humans. In other cases, such as herrings and anchovies, the generation time is much shorter, relatively, and modeling and simulation testing for a regime of sustainable use (and possibly restoration of an already depleted resource) will take a somewhat different form. The regime will also depend critically on the degree of natural variability – usually annual – of the resource, and this as we have seen, is correlated (negatively) with the life-spans and sizes of the animals in question.

A complicating factor is the possible natural oscillatory behaviour of the exploited population. In cases where the cycles may be of short duration it could be reasonable to fix a duration lasting a few cycles, and focus on the mean population levels through those cycles. If, however, the expected oscillations are of long duration, as, for example, in the case of whales assessed by Witting's models then the practical management horizon might be no more than one cycle, or even less. In this case the decision about what is "sustainable" and what is not is distinctly more complicated.

This linking between the generation times of humans and of exploited wild animals is understood by most developers of (hopefully) sustainable management regimes. However, what is still not usually taken into consideration is the possibility of long natural cycles of growth and abundance – long, that is, in relation to the generation interval. Witting's study of the gray whale provides a good example. Would we regard a whaling management regime that provided a high probability that the wave-length (perhaps a couple of centuries) and amplitude (3-or-more-fold swings), and the very-long-term mean of abundance were not substantially altered, as ensuring sustainable use? Similarly if the vast long cycles of ocean features, apparently reflected in oscillations of fish abundances and hence catches, are substantiated and general, fisheries managers and scientists really do have to go back to their drawing boards.

There are also limits to our calculating ability, as well as to our imagination and foresight. In developing the RMP the IWC scientists decided they could only reasonably conduct simulations through one hundred years. Now, a decade later, they could certainly work on a longer time-scale, but would it be worth it? Could anyone seriously think that some agreed management regime would endure for more than a century? A consequence of this is that management objectives would not be defined in terms of permanent sustainability or of more or less steady year-to-year catches, but rather in terms of the cumulative catch over the full period of simulation, and how high it could be without risking inadvertent resource depletion. There can be no reference to such theoretical but hazy notions as that of MSY and similar "sustainable" targets, even if the simulation models have that concealed within them.

In summary I would suggest that, among the many temporal features demanding that we not consider sustainability in terms of infinite time, and considering the new approaches to management illustrated by the IWC's RMS/RMP, the most important is the likely duration of the instruments of human societies that would operate any management scheme for sustainable use of wild living resources.[134]

Quality

In, I think, 1948, at a Plenary Session of the Permanent Commission for Northeast Atlantic Fisheries, in London, the Commissioner for France – a biologist, M. Furnestin – waved two frying pans, a larger one and a smaller one. "This" he said (if my memory serves me correctly), shaking the smaller pan, "is a French pan; French housewives like to sauté small soles. And this – waving the bigger one – is an English (he didn't even say British) pan in which your housewives like to fry plaice, and bigger soles if they can get them".

Plaice and soles were caught in the same trawling operations in the North Sea (although astute fishermen knew where to go to take advantage of some species segregation on the fishing grounds). The UK wanted larger-meshed nets to be legislated (to benefit the plaice fishery but which would have allowed most of the slimmer soles to escape), and the fishing effort at least stabilized. Any idea that there could be agreed an optimal catch that would satisfy both parties flew out of the window that day. Following it, Michael Graham asked Ray Beverton and me to try to work out "equivalent" regulations to resolve this dilemma, by looking at what change in fishing intensity would be equivalent in its results to a certain change in mesh size. Some rough judgments could be made, but an adjustment to give equal expectation of total yield would not provide the same catch composition, and vice-versa. We developed the notion of "eumetric (well-measured) fishing", but its application to multi-species fisheries was difficult.

It is usual in considering marine resources to discuss some optimization of a sustainable catch by weight. In a few cases – whaling is one – discussion turns on numbers rather than biomass. (In the whaling case, this is not unreasonable – at least as far as baleen whales are concerned – because last year's calves have generally grown to an economically useful size by the time they have gone to the Antarctic to feed and, being concentrated, become vulnerable to whalers, and because individuals grow rather quickly to near maximum size.) But whalers have always been interested in quality. Southern hemisphere whaling locations and seasons were determined and legalized for many decades in such a way as to try to optimize individual weight and hence oil production. This is one reason why whaling – and fishing – regulations can become complicated: catch limits, protected areas, closed seasons, size limits for the market, preference for certain gears and operational methods, and so on. One-dimensional regulation by catch limits will not lead to the desired end. And the market alone will not lead to some sub-optimisation when different users have differing quality requirements. Such considerations apply also when the various uses are qualitatively different. For example, if whaling and touristic whale watching are carried on together, the tourists' aim to see whales that do not flee from ships may be frustrated.[135]

In an exploitation system such as trawling it might be assumed that the catches are close to being a random sample of the available fish, or at least of those big enough to be retained by the net. Even such unselective extraction nevertheless changes, over time, the size- and age-distribution of the population, and hence its "quality", and hence the quality of future catches if, for example, the market prefers bigger fish to smaller fish. Such changes can be calculated in advance, at least to a first approximation and taken into consideration in the search for both biological sustainability and continued profit. However, all fishing and hunting operations are selective, and many extremely so, but rarely in known ways. (Even bottom-trawling is not really unselective; fishermen go to where they know some segregation of smaller and larger fish will occur on the grounds; some individuals will be more able than others to escape the net, and so on.) The maintenance of a resource population that not only will not diminish under exploitation but will retain and persist with desired qualities, such as age-composition or "condition" (fatness; ratio of weight to an appropriate power of a linear dimension) presents serious obstacles.

Hunters of terrestrial animals – especially the larger mammals – may place quality over abundance. For instance, like whalers, they do not want emaciated individuals that have lost their body fat nutritional reserves for one reason or another. However, their definitions of quality go further; for example they do not wish to see numbers of sick, lame, emaciated, or just plain elderly individuals in the population they are exploiting. This desire commonly leads to highly selective "culling" by resource managers; a sort of "tidying-up" of the population in question, as well as selectivity rules to be followed by the licensed hunters. It is interesting to note that such operations have been necessitated in many situations because of the elimination, by humans, of the species such as scavengers and predators that would perform that function in more natural conditions, especially by selectively taking the more vulnerable individuals, such as the young and the old and infirm. I think, from slight experience working in the Scottish Highlands in the 1950s, of red deer and the extermination of the wolf, and grouse and the extermination of the wild cat, as well as the near-eliminations of predatory and scavenging birds; and also the attempts to "manage" vicuña populations in Peru, for wool or meat, in a situation of diminishing populations of feline predators. It is little wonder that the theoretical studies I have outlined here have been more applied to marine than to terrestrial situations, although in the latter there have been some rather naïve applications of logistic theory.

Selective elimination or depletion of preferred, larger species, can lead to apparent large changes in the trophic structure of marine ecosystems. A well-known example is the sequential depletion of the southern great whales in their order of size: first the blue whale, then the fin and humpback, then the sei and Bryde's, and the process halted, perhaps only temporarily, at the smallest, the minke. This obvious fact has led some scientists to hypothesize that the smaller species have increased at the expense of the depleted larger ones, but it is difficult – even misleading – to deduce this from the sequence of catch statistics. A more important example, and one that is more difficult to interpret, is the fishing down, and almost out, of larger fish species in a region, with corresponding and sequential rises in the catches of smaller species. This can look as if the smaller ones are "taking over" the ecosystem, and that might be so, but is extremely difficult to either demonstrate or dismiss. Such hypotheses have been explored by Daniel Pauly and his collaborators, and will not be pursued further here; they merely, in our context, emphasise that selective removals in a search for sustainability, will occur at the ecosystem level as well as the population level, with considerable practical consequences.[136]

RECAPITULATION AND CONCLUSIONS

The word "sustainable" has been used with several meanings, not all of them well defined, and not all mutually compatible. Let us first consider the taking of a "small" yield repeatedly from a large previously unexploited population. Standard logistic type theory would tell us that this will reduce the average population size, even if only slightly; we probably wouldn't notice it. If the population was fluctuating before, or oscillating, it will continue to do that, and after a long period we might begin to notice the latter behaviour. The North Sea herring fishery went on like that for centuries, and by most standards the catches were very large, on average. Many other such examples could be cited. The idea that some people have, from repeatedly bad experiences, that sustainable use is never feasible, does not withstand the scrutiny of history.

Standard theory also tells us that even if we intensify our exploitation, to the degree that we begin to notice the population is getting smaller, we can still have a sustainable yield if we are careful. This conclusion depends on the assumed reversibility of the population growth curve implied by our theory. My own skepticism about reversibility has been well expressed by a physicist, Arnold Sommerfeld:

> Reversible processes are not, in fact, processes at all; they are sequences of states of equilibrium. The processes which we encounter in real life are always irreversible processes.[137]

However, as soon as we look at a population with an age-structure (or, for that matter, any other sort of meaningful structure) things are not quite like that. A growing population, when it has reached a given number, will have a particular age-composition, and that will not be a stable composition. Stability of age composition, if it comes at all, arrives at the same time (actually, rather later) as the population closely approaches carrying capacity. A population driven down by exploitation to the same given number will also not have a stable age-composition, and neither will it have the same age-composition as that of the growing population of the same numerical size. To achieve either of those states the process of extraction would have to be very selective, and carefully so. Random selection, even if attainable, will not do the trick, and nor will the kind of selection normally encountered in, say, a fishery, which depends on the nature of the fishing gear, and the location and timing of its deployment, among other things. For these reasons such an exploitation pattern will not be formally sustainable.

But, to continue, we might think that if we simply observe the rate at which the population tends to increase after we have reduced it, and then relaxed our exploitation "pressure", and then continue to take just that much each year or whatever exploitation period we chose, the population will not change and we shall have achieved sustainability. That has been called a strategy of estimating and taking the *replacement yield*, which has been on occasion adopted by the IWC (always said to be a temporary measure, pending better assessments, but commonly continued by default) and in some fisheries. But, taking no account of the characteristics of the out-of-equilibrium age-structure this can be a disastrous policy if pursued blindly; in commonly met circumstances the population is likely to continue to decline. A naïve replacement yield management strategy is to be avoided; it does not in itself lead to sustainability.[138]

If our daring and greed pushes the population down further, we begin to enter the realm of instability, whether or not depensation is then the name of the game. Then not only is sustainability elusive, but the eventual climb back will be painful – for us. And if Nature is playing tricks with "vibrations", as it appears is her wont, her habit, then our calculations become more difficult, more uncertain in their outcomes. The *logistique* – the art of calculation – has its own limits.

In our era, sustainability is more easily advocated than achieved, easier said than done. Existing mathematical models, as well as apparently rational arguments, that do not truly express "laws of nature", are not even framing testable hypotheses, are not even plausible when examined closely, and do not match our admittedly limited historical experience, are not what we need in a quest for sustainability. If that *is* the Holy Grail it will be found by humility, not secured by brute force, stealth or confidence tricks.[139]

A quotation from Witting's aforementioned reconstruction of the population dynamics of the gray whale is, I think, appropriate here; it follows his discussion of evidence that the vibrating population of this "over-recovered" species has already begun to decline:

> With the abundance estimates and catch histories being consistent with cyclic population dynamics it would seem to be a wise strategy if candidate Strike Limit Algorithms *[SLAs, the aboriginal subsistence equivalents of the commercial CLAs – sjh]* were tested against the hypothesis of cyclic dynamics, particularly as the abundance data indicate a decline that is faster than the decline of the fastest declining inertia model (so far examined). …the accepted SLA must be able to cope even with a crashing population.
>
> Both the management objectives of the IWC and the framework used to evaluate candidate SLAs *[and CLAs – sjh]* have been developed only for traditional density-regulated dynamics. Traditional management objectives are often defined relative to the MSY and the MSY level, which are concepts that apply only to cases where the intrinsic growth rate is constant. For inertial dynamics, the intrinsic growth rate is an initial condition so that most population abundances are associated with a suite of both positive and negative realized… growth rates. Among other things this implies that there is no single curve of sustainable yields and, thus no well-defined harvest optimum as assumed by the IWC.

And, of course, not only by the IWC, but as now – unfortunately – embedded in the United Nations Convention on the Law of the Sea. As a management objective MSY had neither sound theoretical foundations nor empirical justification. It reflects an urge for the institutionalization of greed as a governing principle, and was rightly mocked by Peter Larkin in a well-known polemic.[140]

The vigour with which MSY has been "marketed" internationally, especially by successive Governments of the United States, has long puzzled me. Recent declassification of hitherto restricted documents from the first decade after the end of World War II throws some light on this, and perhaps warrants an extended endnote. But, first, let me quote from a letter, dated 29 May 1956, from Michael Graham (then Director of Fisheries Research, England and Wales) to Milner Schaefer (then with the I-ATTC) who had sent Graham the manuscript of a paper on the application of logistic curve theory to Pacific tuna fisheries. Graham, in his usual charming way, first remarks that asking for a frank and critical appraisal of a manuscript "is a sure opening gambit to killing quite a promising friendship"! While appreciating Schaefer's clarity, Graham observes that "I am not sympathetic to it because the problem of fish conservation is not so clear that we can write about it in an authoritarian way without running the risk of emphasizing what may in the future turn out to be less important points. For example, I think that yield curves may sometimes be very flat-topped … and I wonder whether we have hold of sufficient theory to take account of the interaction of fish species, which might be of superlative importance.[141] I am still teaching this", writes Graham; "Find which direction to go in and take a small step that way".[142]

I see only two possible ways forward, out of this dilemma. Perhaps they can both be taken, in differing circumstances. One is the traditional one, really: just take what we truly *need*, and define "need" frugally, or even parsimoniously. The other is the route offered by the IWC scientists and – if they can only get around to agreement – by the collective governments of IWC Member states. That is a truly precautionary regime for managing resource use, adequately monitored and universally enforced[143] and complied with, based – in our everlasting ignorance – on extensive computer simulation of as many scenarios as we can imagine.[144]

And forget the "balance of nature". *Gaia* does not "balance"; she vibrates and swells, sometimes explodes, but always with ripples, and her sometimes smiling calm can be deceptive. We do not, and cannot "manage" her; we use her and in doing so stress her, though we cannot destroy her because we are part of her and we shall not endure so long. If we want to use her sustainably, to ensure a little more of our own future, then we have to tread very, very carefully or she will rumble and grumble, and might even spit at us.[145]

In this essay I have sought to trace one strand of descent, as it were, from Malthus and some of his 19th century contemporaries, followers and critics, through some of the highways and byways of population dynamics. There is another strong strand, perhaps two: the evolution of Evolution – through Charles Darwin, Robert Chambers, Alfred Russel Wallace, Herbert Spencer *et al.*, and the discovery of scientific genetics, through Gregor Mendel, Francis Galton, Karl Pearson *et al*. The redoubtable T. H. Huxley was caught up in both, and Karl Marx and Freidrich Engels mixed in for good measure. Those along both the strands were much concerned, from time to time, about applications of theory to both humans and to other animals, as were the participants in the development of ideas about population growth and sustainability. Is it going too far, perhaps, to think that the three strands might at last become plaited together, creating a new synthesis through the approach I have identified with the work of Lars Witting? [146]

Damasio wrote, a few years ago, in *Descartes' Error: Emotion, Reason and the Human Brain*:

> Although Biology and culture often determine our reasoning, directly or indirectly… we must recognize that humans do have room for freedom, for willing and performing actions that may go against the apparent grain of biology and culture.[147]

Now, as we have seen, Malthus was a child of the Enlightenment, a core paradigm of which was the "abyssal separation between body and mind", characterized by the notion of "rationality". In his thoughtful study, "Waking the Sleepwalkers: Globalisation and Sustainability," William Rees has made a plea for reuniting these human faculties under the rubric *enlightened rationality* which, he says,

> recognizes, among other things, that modern humans remain myth-making creatures and that *to achieve sustainability we must create a new cultural myth* (my emphasis)… Our present, increasingly global, myth actually reinforces our biological propensity to expand and fill (to overflowing) all available ecological space. Our once successful evolutionary strategies are now propelling (us) along a destructive course on a finite planet.[148]

What might be the constituents of such a myth, which could redefine the "Notion" which is the subject of my essay? In "Waking the Sleepwalkers" Rees expresses succinctly an idea I have expressed during many discussions about the relationship between the objectives of "conservation" and those of "animal welfare", and elaborated in an unpublished paper to the Fourth International Congress on Bioethics, held in London a few years ago. "The bottom line", he writes, is that we must come to value and defend the Earth for more than the economic gains of exploitation." Fair enough! But, Rees reminds his readers, "Scientists in particular, their feelings numbed by Cartesian objectification, often feel queasy when talking about love and respect, empathy and compassion, particularly when applied to their objects of study…but, following Damasio, the equally human capacities for reason and emotion…cannot be ripped asunder". Rees then asserts that:

> Most rational people will agree that we still need nature to survive and… that **we generally do not protect or save that which we do not love** (again, my emphasis).[149]

In this light it may be both rational and necessary for modern society to acquire a sense of genuine love for the natural world, a world, I will reiterate, of which we are an intrinsic part.

Such love obviously has to embrace both the human and the non-human. Our love for the non-human might range from care for individual sentient animals to care for, for example, biodiversity.[150] But here my focus is on the extent of love for humanity. This has many dimensions, not least in space and time. In recent decades we have heard much public debate about mankind (I prefer *humankind*) and its "common heritage", especially in the context of the deep ocean, the Antarctic continent and the moon, regions of relative inaccessibility and mystery. Much of that debate is about the *sharing* of the heritage, among presently existing humans. But humankind is a concept that embraces both the past – our past – and all conceivable futures.

Why is this latter so important when we talk about sustainability? It is, I suggest, because it determines the real timeframe of our definition of sustainability once we have discarded the idea of it stretching to the World's End or even – perish the thought – to infinity. In discussing this I have referred to the practical limitations of computer simulation, the generation times of that which we wish to use sustainably, and to the expected duration of any administrative/regulatory/political system – or even ethical system – that is supposed to ensure such use. Perhaps it would be fruitful to talk about how far into the future can we really extend our love for humanity, as judged by the degree to which we are prepared to modify our present behaviour so that it may be fulfilled – beyond ourselves, now; our own old age; our friends and younger contemporaries; our children and their children? Grandchildren? How far indeed?

Now, I end by returning to some impassioned words from Bruno Voituriez (whom I have already quoted in several places in this essay), with a little of my editing in consideration of its context:

> The growing 'humanisation' of our planet is not, contrary to what is often said, a mortal menace for Earth and the life on it, which has seen worse and is certainly capable of resisting humanity's efforts tending to change it, even to destroy it. This 'humanisation' is, above all, a menace to mankind itself, thus exposed to grave difficulties that are generators of deadly conflicts. We can no longer say – as the scientists of the nineteenth century might have said: …if it does not master its own evolution. The fact is we do not master anything, and we know that in our stochastic world, our capacity for prediction will always have limits whatever may be our efforts to reduce the uncertainties, as has been attempted for fisheries, for exam-

> ple, by the adoption of the 'precautionary principle'. Far from providing a methodology for decision-making this approach is only a principle of action based on admission of ignorance, albeit a recognized and no longer camouflaged ignorance. The objective of scientific research is to reduce that ignorance… The problem is now planetary and scientists are being called upon to simulate the functioning of the planet Earth, by going back through their archives so as to know Earth's history better, by multiplying observation networks, and by modeling Earth so as to propose future scenarios. Given the results of research, the scenarios the research proposes, and the uncertainties they hide, two extreme extrapolations are possible. First of all, to deny a phenomenon on the pretext that it has not been formally proved… A second plausible attitude is the precautionary approach, in the strongest use of the term, or more precisely the negation of this approach as a principle of action, thus turning it into a principle of reaction opposing any management and development plans in the name of an obscure ecology that makes humanity the enemy of the planet and a kind of outlaw on the earth. Even if 'all is for the best in the best of all possible worlds' let us guard against thinking that all goes wrong in the worst of all possible worlds. We are the future of the human race and we have only the resources offered by the planet on which we live and our intelligence to make the best of it. If there is anything that can be labeled 'Common World heritage' it is precisely the Earth, which we must bequeath to future generations and which we are (and they will be) obliged to manage together.

LAST WORDS

Just as I thought I had finished the final revision of this review I happened across John Bellamy Foster's scholarly "Marx's Ecology: Materialism and Nature" (Monthly Review Press, New York, 2000), containing a chapter ("Parson Naturalists") on 19th century discussions about population among the likes of Malthus, David Ricardo, Percy Shelley, Pierre Proudhon, Karl Marx, Freidrich Engels and Charles Darwin. Foster points out that although Malthus, in his first *Essay* on population was attacking the ideas of Godwin and Condorcet, the controversy had its roots in an earlier publication: a work by Scottish Minister, Robert Wallace, in 1761, affirming exponential growth and worrying about the eventual exhaustion of the finite resources on which humans depend. What we see here is the beginning of doubts about the notion of eternal "progress" coming from Enlightenment optimism.

What Marx didn't like about the Malthusian package was that as far as humans are concerned he believed – I think rightly – that the increase in *available* resources was not linear but rather itself exponential, as a consequence of the rise of science and of industrialisation. In the first half of the nineteenth century no one seems to have realised that the rate of population increase might itself one day slow down, smoothly. One difficulty in this debate was that Parson Malthus substantially changed his mind on several matters between the first and second *Essays*, and again in the third, *Summary View*.

In these series of corrections and amendments, Malthus made it clear that he was not talking about absolute limits to the resources themselves but about limits of access to them: as he put it "easy means of subsistence". Both Marx and Malthus understood that this was a social phenomenon, deriving from the class structure of society.

In his chapter on "The Metabolism of Nature and Society" (Marx's theme), Foster reviews Marx's analysis of "sustainability", defined in much the same way as in the Report of the Brundtland Commission. Marx's formulation was "An entire society, a nation, or all existing societies taken together, are not owners of the earth. They are simply its beneficiaries, and have to bequeath it in an improved state to succeeding generations as *beni patres familias* [good heads of the household]". The passing on of resources in good order Marx repeatedly referred to as "the chain of human generations", while being reminded by Engels, the chemist, that non-renewable resources were being squandered irretrievably at an increasing rate. Marx thought that what we would now call *sustainable development* was attractive but "of very little practical relevance to capitalist society" which depended, for stability and eventually its survival, on continuous economic growth. In this he reminded me of Mahatma Ghandi's purported response to the question:

"What do you think of Western civilisation?"

"That would be a good idea!"

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I have benefited greatly, during the years in which this essay gestated, from conversations – and sometimes arguments – with several friendly colleagues, and occasionally

with less friendly opponents. Among the former I mention especially the late Ray Beverton, from the 1940s, the late Geoffrey Kesteven from the 1950s, the late Douglas Chapman from the 1960s, Bill de la Mare, Kees Lankester and Justin Cooke from the 1970s, and assorted members of the IWC Scientific Committee and participants in some other international scientific assemblies. Late night rapping with the late David McTaggart, neighbour and founder of Greenpeace International, fuelled by the good wines of Tuscany and Umbria, also played its part, as did hours spent with my assistant over three years, Olga Nève, walking in the Umbrian and Welsh countrysides.

I am grateful, too, to the International Fund for Animal Welfare (IFAW), and especially its luminaries through the period I have been associated with it: Brian Davies, its Founder; Fred O'Regan, now its President; Chris Tuite and Vassili Papastavrou, for their prolonged support. David Lavigne, now IFAW's Science Advisor and Executive Director of the International Marine Mammal Association (IMMA) has been the most persistent of the arguifiers for a couple of decades. Leslie Busby, now CEO of the Third Millennium Foundation created by McTaggart, frequently listened, apparently attentively, when I have tried to put into words the slight and elementary mathematics of which I am still capable. Mary Carmel Finley, a sharp-eyed and enthusiastic historian of fisheries matters, has introduced me to some aspects of the MSY-debates/scams of which I had only been half aware. Then I am in debt to the people of Blackburn Press, New Jersey, who, by inviting me to write a Foreword to a new edition of a book I wrote half a century ago with Raymond Beverton,[151] unwittingly caused me to think again about the idea of sustainability in the fisheries context. Likewise, conversations with Mario Ruivo, especially in the context of our work together in the Soares Commission (Independent World Commission on the Ocean – IWCO) stimulated reflections on the role of the theories of political economy in this business. Sheryl Fink, also of IMMA and IFAW, has been oh, so patient, in finding and sending me copies of scientific papers that my self-imposed isolation in the hills of Italy and Wales made difficult of access. And lastly, I take this opportunity to express my appreciation to the late Sir Peter Scott, as well as to my friend, the late Professor Peter Jewell, for introducing me to the arguments within the IUCN/SSC about whether elephants and other bulky animals such as whales should be "culled for their own sakes" as well as for the being of the ecosphere.

NOTES AND SOURCES

[1] Quoting an unnamed "famous astronomer", in *Faster than the Speed of Light: the Story of a Scientific Speculation.* Heinemann, London, 2003. Thanks to David Lavigne, the astronomer can be identified as Sir Arthur Eddington. David also has drawn my attention to another version of this important idea: "Scientists are perennially aware that it is best not to trust theory until it is confirmed by experience. It is equally true, as Eddington pointed out, that it is best not to put too much faith in facts until they have been confirmed by theory". *[Unfortunately many scientists seem not to be "perennially aware" of this. – sjh]* The writer – Robert A. McArthur ["Coexistence of Species". pp. 253-259 in *Challenging Biological Problems*. Edited by J.A. Behnke. AIBS, Univ. Oxford Press, NY, 1972] – continues "Ecology is now in the position where the facts are confirmed by theory and the theories at least roughly conformable by facts. But both the facts and the theories have serious inadequacies providing stumbling blocks to present progress." I think the first of these two propositions is debatable.

[2] Quoted by Bruno Voituriez, 2003; see below.

[3] Perhaps the most accessible reference is to the highly individualistic *The Greek Myths*, by Robert Graves, in two volumes, Penguin, 1955.

[4] This is actually the second of four meanings; the others are not applicable.

[5] John McGowan and John Field, in their contribution to a recent book: *Oceans 2020: Science, Trends, and the Challenge of Sustainability*. Eds J. G. Field, G. Hempel and C. P. Summerhayes, Island Press, 2002, 365 pp. The quotation is from p. 41 in the Field and McGowan chapter pp. 9-48, "Ocean Studies").

[6] See for example H. Whitehead *Sperm Whales: Social Evolution in the Ocean.* Univ. Chicago Press, 431pp, 2003. See also Michael Bond, "A way with whales". *New Scientist*, 15 May 2004:43-5. [Interview with H. Whitehead.]

[7] But possibly only by someone who has read and absorbed all of *Sustainable Development: Mandate or Mantra?* edited by W. Chesworth, M. R. Moss and V. G. Thomas, Faculty of Environmental Sciences, Univ. of Guelph, 2002, 140 pp.

[8] "Small island states in the face of climatic change: the end of the line in international environmental responsibility". *UCLA Journal of Environmental Law and Policy* 6/22/2004.

[9] The ugly head of this phantom is still being raised by those connected with hunting, shooting and fishing – especially shooting whales – who say something like "We have spoiled the balance of nature by unsustainable killing; now let us try to restore it by killing more of something else". Charles Elton poured justified scorn on this 'balance' notion nearly eighty years ago in his *Animal Ecology*, 1927 (Sidgwick and Jackson, London).

[10] Here I mean the term as used to identify the character or state of a resource that someone wants to be allowed to exploit, for gain, not its technical use in relation to the testing of mathematical models and algorithms.

[11] Some of these terms have been assigned reasonable definitions in the context of classifying the status of species and populations for CITES and the Red Data Books, now Red Lists, produced by IUCN (*threatened*, *endangered* are among these). Depletion is commonly used in an economic context also with respect to stocks of non-renewable resources, and in relation to management of use of marine living resources,

it has taken specific meanings in particular cases. Such emotive words as "healthy" and phrases such as "in good shape" as applied to populations or ecosystems are purely propagandistic and essentially meaningless, the sort of language recently castigated by Francis Wheen in his *How Mumbo-Jumbo Conquered the World: A Short History of Modern Delusions*, Fourth Estate, 2004, 342 pp.

[12] See David Lavigne "The return of Big Brother". *BBC Wildlife Magazine*, May 2004: 70-72. A relevant quotation from Alexis de Tocqueville (1846) was given a couple of years ago by the Editors of a group of lectures on Environment, Energy and Resources: "An abstract term is like a box with a false bottom: you may put in it what ideas you please, and take them out again without being observed" ["Introduction: Clearing Away the Undergrowth", by W. Chesworth, M. R. Moss and V. G. Thomas, to *Sustainable Development: Mandate or Mantra*, University of Guelph, 2002, 140 pp.] D.M. Lavigne has a valuable paper in that book (pp. 63-91), with a useful bibliography: "Ecological Footprints, Doublespeak, and the Evolution of the Machiavellian Mind".

[13] The nearest to hand is the otherwise excellent "Design of operational management strategies for achieving fishery ecosystem objectives". by K. J. Sainsbury, A. E. Punt and A. D. M. Smith*, ICES Journal of Marine Science* 57:731-41, 2000. This is one of many in a special ICES volume on "Ecosystem effects of fishing".

[14] "The Precautionary Principle: Tony Blair and the language of risk". *London Review of Books.* 1 April 2004: 12-5. This idea was originally expressed as a desirable prohibition of release of chemicals into the planetary environment before sufficient testing had been carried out to ensure that no irreversible harm would be done to it. It has recently, frequently been confused with *mere caution in the face of uncertainties and the unknown*. One of the very few uses of the Principle in the realm of marine conservation and protection was made by the International Whaling Commission (IWC) in the late 1970s – i.e. before the term came into popular and political use – when it amended its so-called New Management Procedure (NMP) for setting annual "sustainable" catch limits for whales to provide that there should be no commercial exploitation of a previously unexploited whale population until certain prior conditions had been met, namely, in this case, provision of an acceptable estimate of the number of whales in the putative "stock".

[15] "An Essay on the Principle of Population as it affects the future Improvement of Society, with Remarks on the Speculations of Mr Godwin, M. Condorcet, and Other Writers" (published anonymously in 1798, called here *The First Essay*); "An Essay on the Principle of Population; or a View of its Past and Present Effects on Human Happiness; with an Inquiry into our Prospects respecting the Future Removal or Mitigation of the Evils which it occasions" (published under Malthus' own name in 1803, called here *The Second Essay*); "A Summary View of the Principle of Population" (1830, called here *A Summary View*). In between were several substantively different versions of *The Second Essay* as well as numerous articles on political economy, the general features of which were mostly incorporated in *A Summary View*.

[16] In *A Summary View,* Malthus states his position that "Elevated as man is above all other animals by his intellectual facilities, it is not to be supposed that the physical laws to which he is subjected should be essentially different from those which are observed to prevail in other parts of animate nature" but "The main peculiarity which distinguishes man from other animals, in the means of his support, is the power which he possesses of very greatly increasing these means." In the collection of essays Malthus acknowledges his debts particularly to David Hume, Adam Smith and Henry Wallace: "The most important argument I shall adduce (concerning 'the perfectability of man') is certainly not new, and it may probably have been stated by many writers that I never met with. I should certainly not think of advancing it again, though I mean to place it in a point of view in some degree different from any that I have hitherto seen…"

[17] In this task I must acknowledge debt to the illuminating *Introduction* by Anthony Flew to the edited versions of *The Second Essay* and *A Summary View* published in 1970 and 1982 by Penguin, under his sub-title "A household word, but misunderstood". Flew quotes an unnamed cynic: "The classics are like the aristocracy; we learn their titles and thereafter claim acquaintance with them".

[18] Malthus was explicit about this: "No limits whatever are placed to the production of the earth; they may increase for ever and be greater than any assignable quantity; yet still the power of population being a power of a superior order, the increase of the human species can only be kept commensurate to the increase of the means of subsistence by the constant operation of the strong law of necessity acting as a check upon the greater power" (Chapter II of *The First Essay*).

[19] Condorcet was active and influential in the Revolution's first phases but fell out with the revolutionaries and told the Convention that Robespierre had "…neither ideas in his head nor feelings in his heart". Godwin, as Flew writes, was "similarly inspired, albeit from a safer distance".

[20] Actually Malthus was more forceful and eloquent in his commentary on ideological matters: "The advocate for the present order of things is apt to treat the sect of speculative philosophers either as a set of artful and designing knaves who preach up ardent benevolence and draw captivating pictures of a happier state of society only the better to enable them to destroy the present establishment and to forward their own deep-laid schemes of ambition, or as wild and mad-headed enthusiasts whose silly speculations and absurd paradoxes are not worthy of the attentions of any reasonable man". Malthus was particularly ironic concerning Godwin's "solution" to the population-nutrition problem, which was, apparently, to conjecture that "the passion between the sexes may in time be extinguished"!

In this passage Malthus argues that "a satisfactory history, of one people, and of one period, would require the constant and minute attention of an observing mind during a long life" and he continues to list the particular population features that should be monitored.

[21] Here I am using modern terminology of population dynam-

ics in preference to quoting long passages from the *Essays*.

[22] The originator of the notion of oscillation was in fact Condorcet. "When the increase of the number of men surpassing their means of subsistence the necessary result must be either a continual diminution of happiness and population, a movement truly retrograde, or, at least, a kind of oscillation between good and evil? In societies arrived at this term will not this oscillation be a constantly subsisting cause of periodical misery? Will it not mark the limit when all further amelioration will become impossible …?" [In modern terminology a *(stable) limit cycle*. See for example *Theoretical Ecology: Principles and Applications*. Edited by R. May, Blackwell, Oxford. Second edition 1981. And, in a broader context *Mathematical Bioeconomics* by C. W. Clark. John Wiley & Sons, 1976].

[23] Their classic joint effort, *The Communist Manifesto*, was published in 1848. It is not widely known that Karl, also, was a considerable mathematician: *Mathematical Manuscripts of Karl Marx*, New Park Publications, London, 1983. 280 pp. This English translation contains a revealing technical Preface by S. A. Yanovskaya, written for the 1968 Russian edition: especially with regard to Marx's efforts to explain obscure features of calculus to his slightly less numerate friend, Engels.

[24] Oscillations, in single- and few-species population theory, arise from interactions between two or more components of the system (competitors, predators and prey, different age-classes of the population). They can also arise – and this is new – from intrinsic rates of natural increase not being, as Malthus – and many others after him – thought, geometric/exponential. We shall come to that revolutionary idea later. Here, we note that in Malthus' design, the upper, land-owning and smaller class (the predator) and the larger, newly mostly landless and more numerous class (the prey), must be distinct from each other, i.e. there must be no or negligible "diffusion" between the classes, to produce the predator-prey system oscillations that later became familiar to population biologists.

[25] Remarkably, a linear plot of rate of increase against average population size in each decade, implying logistic growth, "predicts" an upper limit to the US population being reached at about 480 million, about double the present population Still plenty of room, then!

[26] *Density dependence* may be regarded as a *constitutive metaphor* – a term familiar to historians of science – of the discipline of population dynamics. This is "a metaphor that constitutes, at least for a time, an irreplaceable part of the linguistic machinery of scientific theory. Where no literal paraphrase is known, usually at the inception of a new theory, scientists depend upon this metaphor to develop their thoughts. It is, in turn, articulated, probed and extended by other scientists, to the extent that it ceases to be simply a metaphor and enters the process of thought itself, performing the vital cognitive function of framing the discursive patterns of the theory. Eventually, as the new science becomes established, and it is increasingly possible to assign more literal names to processes, so the importance of the metaphor declines. A similar pattern can be seen in social thought. For example nineteenth century physics provided the constitutive metaphor for neo-classical economics" (David Stack, 2003. For full reference, see endnote 146). Similarly, classical economics, from Adam Smith on, provided the powerful metaphor of "competition" to ecology.

[27] "The speculative philosopher", he writes, "… with eyes fixed on a happier state of society, the blessings of which he paints in the most captivating colours, he allows himself to indulge in the most bitter invectives against every present establishment, without applying his talents to consider the best and safest means of removing abuses and without seeming to be aware of the tremendous obstacles that threaten, even in theory, to oppose the progress of man towards perfection." A true Social Democrat, it seems, our Thomas!

[28] "*Notice sur la loi que la population suit dans son accroissement*". *Correspondance Mathématique et Physique* 10:113-21, 1838, followed by "*Recherches mathématiques sur la loi d'accroissement de la population*". *Mem Acad Roy. Belg.* 18:1-38, 1845, and "*Deuxieme mémoire sur la loi d'accroissement de la population*". *Mem. Acad. Roy. Belg.* 20:1-32, 1847. The young Verhulst began his work on population growth at the instigation of his mentor, Adolphe Quetelet, who proposed, in 1835, that the resistance to growth was proportional to the square of the speed at which the population increased; this notion appealed to him because he saw in it a direct analogy to the resistance that a medium opposes to a body traveling through it. Verhulst reasoned that in the early stages of growth a population would increase exponentially until such time as crucial resources became limited. He called that "break" level the *normal* population, and numbers exceeding that a *superabundant* population. His mathematical formulation did not, however, follow his verbal reasoning, since the logistic does not follow from the idea that growth shifts abruptly from an exponential rate to a slower "logistic". Verhulst did realize that his logistic was only one of several possibilities; in his 1847 memoire he suggested that the obstacles to growth might be proportional to the ratio of the superabundant to the total population.

[29] In published papers of the 1930-50s the S-curve is commonly referred to either as an *ogive*, though this usage seems to have ceased. An ogive is a term used in Gothic architecture, referring either to the intersection of vault ribs where the direction of curvature changes, or a window that comes to a point at the top. In English this also became an *ogee*, apparently from the difficulty that medaeval English masons had in pronouncing French words. In the New World (Webster's dictionary) the derived second meaning became more explicit: "A graph each of whose coordinates represents the sum of all the frequencies up to and including a corresponding frequency in a frequency distribution", i.e. the integral of such a distribution, though only if the distribution is essentially bell-shaped. In fisheries science the term was mainly used to describe the curve of probability of a fish being retained in a trawl cod-end as a function of its length, approximated to in population equations by so-called "knife-edge selection" concentrated at the inflection (turning point) of the ogive.

[30] Many functions that have been used to describe either (or both) growth of individuals (increase in size – length or weight) and populations (increase in number or biomass) have an asymmetrical sigmoid form; examples are the growth

functions due to B. Gompertz (*Phil. Trans. Roy. Soc. London* 115: 513-85, 1825) and L. von Bertalanffy ("Untersuchungen ueber die Gestzlichkeiten des Wachstums I." *Roux' Arch. Entwicklungsmech*., 131: 613-52, 1934). The integral of the familiar "bell curve" (*Gaussian* or *normal* distribution) is a symmetrical sigmoid that looks like the logistic in some applications and over a fairly wide range of time and population size, but has distinctly different properties. The properties of many of these functions are usefully tabulated by R. Christensen *Data Distributions. A Statistical handbook*. Entropy, Lincoln MA, 300 pp, 1984. Pearl and Reed were not entirely satisfied with only a symmetrical growth pattern, and in the process of freeing the logistic from its restrictive symmetry generalized their original equation by adding arbitrary terms to it; this allowed better fits to more data series but, of course, destroyed any pretence that the simple logistic expressed a universal law.

[31] An important but I think little-known discussion of the properties of various sigmoid curves is given by W.E. Ricker "Growth rates and models", pp. 677-743 in *Fish Physiology, Volume VIII, Bioenergetics and Growth*, Edited by W.S.Hoar, D.J.Randall and J.R.Brett, Academic Press, 1979. Ricker is concerned primarily with equations for describing the growth in size of individual animals, but notes and comments upon the parallel use of similar – even identical – equations to graduate population data.

[32] "On the rate of growth of the population of the United States since 1750 and its mathematical representation". *Proceedings of the National Academy of Science USA*, 6: 275-88, 1920; and *The Biology of Population Growth*, Knopf, New York, 260 pp, 1925; see also Pearl, R. and Reed, L. J. "On the mathematical theory of population growth" *Metron* 3(1): 6-19, 1923. It is significant that the US census data that Pearl fitted with a simple logistic did not extend beyond the inflexion – about 1915 – of the fitted curve. And even as a purely empirical process it did not have serious predictive power, even though it happened to predict that the US population would reach about 200 million by the twenty-second century. (The present population is about 250 million.)

[33] "The Refractory Model: the logistic curve and the history of population ecology". *Quarterly rev. Biol.* 57: 29-52, 1982. Pearl had some reservations about this because he noticed that Robertson's data did not in fact follow the *symmetrical* curves given by his equation, and because the similarity between chemical and growth curves implied nothing about the underlying mechanisms of growth. Both Robertson, and Pearl and Reed, realized that populations and individuals occasionally or periodically underwent bursts of growth that were not *fitted* or "explained" by the logistic or its variants. To deal with this they postulated epochs or episodes (they called them, erroneously, "cycles") of successive logistic increase when a major change, such as an industrial revolution (in the case of population growth) or in available resources (in the case of chemical reactions) created the opportunity for growth beyond the limiting value dictated under the existing system.

[34] "On the normal rate of growth of an individual and its biological significance". *Arch. Entwicklungsmech. Org*. 25: 581-613, 1908; and, in the same year, "Further remarks on the normal rate of growth of an individual and its biological significance". *Arch Entwicklungsmech. Org*. 26: 108-18.

[35] "*Variazioni e fluttuazioni del numero d'individui in specie animali conviventi*" [Variations and fluctuations in the number of individuals in animal species living together]. *Memorie Academia Lincei* **2**:31-113, 1926; and *Leçons sur la Théorie Mathématique de la Lutte pour laVie.* Gauthier –Villars, Paris, 1931. See also "Population growth , equilibria and extinction under specified breeding conditions. A development and extension of the logistic curve". *Human Biology* 10(1): 1-11, 1938.

[36] *Elements of Physical Biology*. Williams and Wilkins, Baltimore, 1925.

[37] I have given a short summary of these and subsequent developments in "The experience of Antarctic whaling: – Appendix: Reflections on sustainability and precaution" in *Management of Shared Fish Stocks*, pp. 131-50. Edited by A. I. L. Payne, C. M. O'Brien and S. I. Rogers. Blackwell, Oxford, 2004. This book constitutes the Proceedings of a symposium organized by CEFAS in July 2002 to celebrate the centenary of fisheries research at its Lowestoft laboratory, in Suffolk, England.

[38] "The Optimum Catch: Essays on Population". *Hvålradets Skrifter* 7: 92-127. Hjort was the Grand Old Man of fisheries science in Norway, and a major luminary in North and Western Europe; his name on a paper gave it great weight at the time, but this application was probably devised by Ottestad: "A mathematical model for the study of growth". Essays on Population, *Hvålradets Skrifter* 7: 30-54, 1933. Hjort and his colleagues referred to the difference between reproductive and natural mortality rates as *regeneration*, a difference that IWC scientists have commonly referred to as *net reproductive rate*.

[39] "Modern theory of exploiting a fishery, and application to North Sea trawling". *Journal du Conseil International pour l'Exploration de la Mer* 10: 264-74, 1935; "The sigmoid curve and the overfishing problem". *Rapports et Procès-Verbaux des Réunions du Conseil International pour l'Exploration de la Mer*, 110: 15-20, 1939. This and several other papers mentioned in this essay, published between 1935 and 1983 are conveniently reproduced in *Key Papers on Fish Populations*, Edited by D.H.Cushing. IRI Press, 1983, 403 pp. This volume has useful linking commentaries by the editor., whose own important 1983 contribution on "Stock and Recruitment" closes the anthology.

[40] "Some aspects of the dynamics of populations important to the management of the commercial marine fisheries*". Inter-American Tropical Tuna Commission Bulletin*, 1(2): 26-56, 1954 [by Schaefer]; "Growth of the Pacific coast pilchard fishery to 1942". *US Fish and Wildlife Service Research Report*, 29, 31 pp, 1951 [by Schaefer, Oscar Sette and John Marr].

[41] S. J. Holt "Whales and Whaling". Chapter 112 in *Seas at the Millennium: an Environmental Evaluation*, Vol 3: 73-88. [Edited by C. R. C. Sheppard].

[42] An interesting feature of Kingsland's treatment of the earlier history is her account of the controversy about whether the logistic was a scientific *law*, as Pearl maintained, or was sim-

ply an equation that could be used to graduate data? Could it validly be used to make predictions, or not? Kingsland quotes F. E. Smith who, in 1952, expressed ambivalence towards these existing models (Verhulst-Pearl, Lotka-Volterra) – "Experimental methods in population dynamics: A critique". *Ecology*, 33: 441-450. Smith recognized the value of armchair thinking along deterministic lines as a way of generating concepts, but was strongly critical of the lack of correspondence between the logistic theory and the experiments which purported to verify it. In writing that "The degree of acceptance of such concepts…is astonishing". Smith was responding justifiably to a prolific scientific literature on the logistic curve in which the notions of what constituted a law, theory, model, hypothesis or proof were frequently confused. And Kingsland writes that the logistic "was put forward not as a convenient description, but as a law of growth, and was vigorously criticized by statisticians, economists and biologists" over the next fifteen years, before being for the most part discarded. Yet it survived and finally emerged in a different context as one of the central models of experimental population biology in the late 1930s and 1940s. I would add that a similar 'emergence' occurred in the context of fisheries and wildlife conservation and management, and has remained a powerful but hidden force to this day.

43 These terms are sometimes given slightly different formal meanings.

44 The most sophisticated way of doing this was devised by an Australian scientist with engineering training, William K. de la Mare, in the context of the management of whaling: "Fitting population models to time series of abundance data". *Rep. Int. Whal. Commn* 36: 399-418,1986. The computer program is given in: "The model used in the HITTER and FITTER programs". *Rep. Int. Whal. Commn* 39: 150-151, 1989 [Report of the Scientific Committee, Annex I]. de la Mare applies his engineering background to the field of fish and wildlife management in Chapter 21.

45 The main modification adopted was to introduce a non-linear dependence of the population growth rate on density, using an equation put forward in a fisheries context by J. J. Pella and P. K. Tomlinson: "A generalized stock production model". *Bull. Inter-Am. Trop Tuna Commn* 14: 421-496, 1969. This particular modification of the simple logistic was originally devised by F. J. Richards in a different, botanical context: "A flexible growth function for empirical use". *J. Exp. Bot*. 10: 290-300, 1959. Regarding the BALEEN II model, see Punt, A. E. "A full description of the standard BALEEN II model and some variants thereof". *J. Cetacean Research and Managemen*t (Suppl), 1: 267-76, 1999.

46 For several biologists in the first half of the twentieth century the logistic and related sigmoid curves, with their upper and lower asymptotes and inflections, had an almost mystical significance, beyond their role in fitting equations to empirical data series. Hints of this are to be seen in Michael Graham's classic of fisheries science and management, *The Fish Gate* (Faber & Faber, 1943). Graham sought to explain these ideas in simple language, and to blend or reconcile them with the then current alternative treatment of the growth and deaths of animals in a cohort, in lectures given to third year undergraduate students at the new University of Salford (ex-Royal College of Advanced Technology). Edited versions of those lectures were post-humously published by Manchester University Press, in 1971 as *A Natural Ecology,* an inspiring but sadly neglected work. A different approach was taken by Graham's associate, J.Z.Young, in his magisterial *The Life of Vertebrate*s, published by Oxford U.P. in 1950, reprinted 1952. In his exposition of Graham's *Great Law of Fishing* – that unlimited fisheries become unprofitable – Young comments "The aim of regulation is nowadays not so much to save the stock from undue reduction or extinction, but rather to crop it in such a way as shall make fishing profitable". However, he bases his argument essentially on presumed density dependences of growth and perhaps also of natural mortality in the animals of exploitable size, both sexually mature and immature, rather than simply on differences in the age composition of lightly fished and more intensively fish stocks, as did Graham and, before him, E.S.Russell, in *The Overfishing Problem* (Cambridge U.P., 1942).

47 *ICES Science Symposia* Vol. 215, August 2002 "100 Years of Science under ICES" contains a wealth of documentation relating to this controversy as well as to the evolution of stock assessment procedures more generally. Of particular note are "Overfishing, science and politics: the background in the 1890s to the foundation of the International Council for the Exploration of the Sea" (J. Smed and J. Ramster, pp 13-21); "Realising the basis for overfishing and quantifying fish population dynamics" (Ø. Ulltang, pp 443-452); "ICES involvement in whaling and whale conservation, and implications of IWC actions" (S. J. Holt, pp 464-73); "From fisheries research to fisheries science, 1900-1940. The Bergen and the ICES scenes: tracing the footsteps of Johan Hjort" (G. Saetersdal, pp. 515-22).

48 Arthur Went, in his insider's history of ICES, quotes D'Arcy Thompson's text that became the definition of what we might now refer to as 'the ICES mission statement': "That…it be recognized as a primary object to estimate the quantity of fish available for the use of man, to record the variations in its amount from place to place and from time to time, to ascribe natural variations to their natural causes, and to determine whether or how far variations in the available stock are caused by the operations of man, and, if so, whether, when and how measures of restriction and protection should be applied". (A. E. J. Went "Seventy Years Agrowing. A History of the International Council for the Exploration of the Sea 1902-1972". *Rapp. Proc.-Verb. Cons. Int. Explor. Mer*, 165, 252 pp., 1972).

49 Unlike mammals and birds most fishes continue to increase steadily in weight throughout their lives, and also to remain fecund throughout adulthood.

50 "*Kvoprsy o biologicheskikh osnovanlyahk rybnogo khozyaistva*" *(On the question of the biological basis of fisheries). Nauchnyi Issledovatelskii Ikhtiologicheskii InstitutIsvestya (Report of the Division of Fish Management and Scientific Study of the Fishing Industry)*1: 81-128, 1918.

51 See R. J. H. Beverton (posthumous) and E. D. Anderson "Reflections on 100 years of fisheries research". *ICES Marine Science Symposia* 215: 453-63, 2002; and Ulltang, Ø.

"Realizing the basis for overfishing and quantifying fish population dynamics" *ICES Marine Science Symposia* 215: 443-452, 2002.

[52] D. W. Skagen and K. H. Hauge "Recent development of methods for analytical fish stock assessment within ICES". *ICES Marine Science Symposia* 215: 523-31, 2002.

[53] This is explained in my paper "Fifty years on" in a special volume of *Reviews in Fish Biology and Fisheries*, 8:357-66, 1998 and in my Introduction to the third printing (Blackburn, New Jersey, 2004) of the 1957 monograph *On the Dynamics of Exploited Fish Populations* written jointly with Beverton.

[54] See T. J. Pitcher "A cover story: fisheries may drive stocks to extinction". *Rev. Fish Biol. and Fisheries* 8: 367-370, 1998.

[55] A contributory factor to this difference between North American and European fisheries management strategies was undoubtedly the greater diversity of the fishing operations, preferences and markets in western Europe.

[56] Apart from the fact that the governments procrastinated over the imposition of much lowered catch limits, and then compromised between what the scientists advised and the industry wanted, the scientific assessments of the 1960s were later found to be in error (over-optimistic) because of a twofold mistake in the interpretation of data for ages of baleen whales in catches, as well as in the unreliability of estimates of the numbers of whales.

[57] For more on the topic of commercial whaling, see Papastavrou and Cooke, Chapter 7.

[58] "Simulation studies on management procedures". *Rep. Int. Whal. Commn* 36: 5-60, 1986.

[59] For an account of the RMP Catch Limit Algorithm (CLA) see papers by its author, J. G. Cooke, especially "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. [Edited by A. S. Blix, L. Walløe and Ø. Ulltang] pp. 647-57, 1995. Elsevier, Amsterdam, 720 pp. Also: "Improvement of fishery management advice through simulation testing of harvest algorithms". *ICES J. Mar. Sci.* 56: 797-810, 1989.

[60] An crucial feature of the RMS/RMP as currently being negotiated is the provision that all catch limits are set by default to zero, and can only be made non-zero under a suite of quite stringent conditions. One way of looking at this is the application of the Precautionary Principle to all stocks, rather than only to hitherto unexploited stocks as in the amended NMP. However, additional data are required other than an estimate of population number, principally a series of data for historical catches.

[61] It is in the development of the Revised Management Procedure (RMP) that the term *algorithm* came into common use in the context of the management of whaling and the quest for sustainability. In "The Advent of the Algorithm" (Harcourt, New York, San Diego, London, 2000). David Berlinski provides a logician's definition: "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." Berlinski also gives us a looser definition "for the wider world from which mathematics arises and to which the mathematician must like the rest of us return", thus: A set of rules; a recipe; a prescription for action; a guide; a linked and controlled injunction; an adjuration; a code; *an effort made to throw a complex verbal shawl over life's cluttering chaos*.

Justin Cooke argues (pers. lett., 2004) that the so-called New Management Procedure (NMP) – adopted by the IWC in 1975, and used to set catch limits and classify whale stocks until the commercial moratorium came into effect in 1996 – is properly speaking not a "procedure" since it tells the manager and the scientist what is intended to be done but not how to do it. In this it shares properties with virtually all the current "rule systems" of fisheries management.

[62] Feller, W. "On the logistic law of growth and its empirical verification in biology". *Acta Biotheoretica* 5: 51-66, 1940. The practical consequences of not understanding this can be very great. For example, the United Nations regularly publishes predictions of future global and regional human population growth. These are based on a model not unlike the BALEEN II used by whaling biologists, a logistic derivative. The UN corrects the parameter values occasionally, having noted, for example that the birth rate in China has unexpectedly fallen. However, Serge Kapitza (son of the internationally famous Soviet physicist, and himself a physicist), produced a population model having as a major feature *self-similarity,* which, in other contexts may be called a fractal dimension ("World Population Growth". Doc. C4.1.Kap to Pugwash Meeting No. 197, 43rd Pugwash Conference on Science and World Affairs, A World at the Crossroads: New Conflicts; New Solutions. Sweden 1993.) This produces a classic-looking sigmoid growth curve but one which, when fitted to the same data produces very different predictions for the coming decades. These kinds of projections are produced to give flesh to the idea that "we must do something about all this", so a little more attention to the ways they are made would be in order.

A nice example of the ways that two people presented with the same information can reach very different conclusion comes from a quip I first heard from Sir Peter Scott, famous conservationist, painter, sailor and flier, a Renaissance-Man if ever there was one. "An optimist is someone who thinks this is the best of all possible worlds; a pessimist fears that may be so."

[63] Ricker, W. E. "Handbook of computations for biological statistics of fish populations". *Bull Fish. Res. Bd Canada*, 119, 1958.

[64] Pitcher, T. "A cover story: fisheries may drive stocks to extinction". *Rev. Fish Biol. Fisheries* 8: 367-70, 1998.

[65] From Allee, W. C. *Animal Aggregations*. Univ. Chicago Press, 1931.

[66] Shepherd, J. G. "A versatile new stock recruitment relationship for fisheries and the construction of the sustainable

yield curve". *J. Cons. Int. Explor. Mer* 40: 67-75, 1982.

[67] Stephens, P. A. and Sutherland, W. J. "Consequences of the Allee effect for behaviour, ecology and conservation". *Trends in Ecology and Evolution* 14: 401-405, 1999; Courchamp, F., Clutton-Brock, L. and Grenfell, B. "Inverse density dependence and the Allee effect". *Trends in Ecology and Evolution* 14: 405-410, 2001.

[68] I adopt here the terminology used by Clark, C. W. *Mathematical Bioeconomics: The Optimal Management of Natural Resources*. John Wiley and Sons, 1976, 352 pp. The feature *depensation* is called *inverse density dependence* by Courchamp *et al.,* 1999.

[69] Cannibalism in fishes usually involves consumption of eggs, larvae and juveniles by adults. Examples are cod in the North Atlantic, Pacific salmons, and anchovies (Hunter, J. R. and Kimbrell, C. A. "Egg cannibalism in the northern anchovy, *Engraulis mordax*". *US Fishery Bull.* 78: 810-816, 1980).

[70] Perhaps the Northern right whale is an exception, as it appears thus far not to be recovering from extreme depletion, although this might be the result of increases in other threats from human activities, such as entanglement in fishing gear and lethal collisions with ships.

[71] See my Foreword to the fourth printing of Beverton, R. J. B. and Holt, S. J. *On the Dynamics of Exploited Fish Populations*, Blackburn, 2004.

[72] An example is that used to estimate world fishery potential, using a derivation of the simple logistic, by J. A. Gulland in "The Fish Resources of the Ocean", *FAO Fish Tech. Pap*. 97: 1-4, 1970.

[73] See discussion in Beverton, R. J. H. and Holt, S. J. (1957 and 2004) *On the Dynamics of Exploited Fish Populations*, HMSO, UK and Blackburn Press, New Jersey.

[74] For a deeper critical analysis of this matter see "The Biology of Fish Growth", by A.H.Weatherley and H.S.Gill, Academic Press, 1987, and Ricker, 1979, referenced in endnote 31.

[75] Misjudgment of this has led to the demise of valuable fisheries, such as for herring in the Northeast Atlantic, hastened by a switch away from catching mature adults as food for humans to very young fish for conversion to fishmeal and oil as feed-supplements for livestock.

[76] I have reviewed these in my Foreword to the fourth edition (2004) of my monograph written with R. J. H. Beverton (1957).

[77] See Pitcher, T. J. (1998). "A cover story: fisheries may drive stocks to extinction". *Rev Fish Biol.Fisheries* 8: 367-70.

[78] For more on biological diversity, see Willison, Chapter 2.

[79] Unfortunately – as so often – science is not always in accord with "common sense". The latter tells us that diversity – or rather, perhaps, *complexity*, the difference being that complexity involves significant relationship among the parts – will enhance "stability". There is considerable scientific literature, as well as experimental studies and some field experience, suggesting just the opposite. This is thoroughly examined in Robert May's chapter "Patterns in Multi-species Communities", pp. 197-227, in May *et al.*, 1981. The scientific jury is, I think, still out on that question.

[80] See Boyd, I. "Culling predators to protect fisheries: a case of accumulating uncertainties". *Trends in Ecology and Evolution* 16: 281-282, 2001.

[81] I have elaborated this concern in an article in the new newsletter of the ACCOBAMS agreement under the Convention on Migratory Species (CMS): "Sharing our seas with whales and dolphins" *FINS* 1(1): 2-4, 2004 [Monaco, and at http://www.accobams.org/download/newsletter/fins_01.pdf].

[82] An overall review of this matter is given in May, R. M. *Exploitation of Marine Communities*. Report of the Dahlem Workshop on the Exploitation of Marine Communities, 1984, Springer, Berlin.

[83] The classic among such models is, I think, Anderson, E. P. and Ursin, E. "A multi-species extension to the Beverton and Holt theory of fishing, with accounts of phosphorus circulation and primary production". *Meddelelser fra Danmarks Fiskeri- og Havundersgelser* 7:319-415, 1977. This already hints at a transition towards biomass-, critical nutrient- and energy exchange modeling. An important contribution was made a few years later by Ola Flaaten, "The Economics of Multispecies Harvesting: Theory and Application to the Barents Sea Fisheries", *Studies in Contemporary Economics*, 162 pp, Springer-Verlag, Berlin, 1988. Flaaten reminds us that "the recognition of the necessity of harvesting the predator to increase the yield of the prey is not entirely new", and cites the belief of the Italian biologist, Umberto d'Ancona – associate of Volterra – that "the predators of this [Adriatic] sea, the sharks, ought to be decreased by increasing harvest intensity. That would make it possible to increase the yields of the more valuable prey stocks" (*Dell' influenza della stasi peschericchia del periodo 1914-1918 sul patrimonio ittico dell' Alto Adriatico. Memoria CXXVI*, Comitato Talassografico Italiano, 1926.) Flaaten also noticed that Charles Darwin made a similar assertion in *The Origin of Species*, 1859, regarding "game" birds and mammals and the "vermin" that preyed on them.

[84] *Trophodynamics* is the study of ecosystems from that point of view. This is associated originally with R. L. Lindeman, "The tropho-dynamic aspect of ecology". *Ecology* 23(4):399-418, 1942.

[85] Mass and energy transfer models include ECOPATH, ECOSIM and ECOSPACE, associated especially with the names of Daniel Pauly and Carl Walters. A review of the applications of these is given in "Ecopath, Ecosim and Ecospace as tools for evaluating ecosystem impact of fisheries." Pauly, D., Christensen, V. and Walters, K. *ICES J. Mar. Sci* 57:697-706, 2000. Other basic papers are: Pauly, D. and Christensen, V., "Stratified models of large marine ecosystems, a general approach, and an application to the South China Sea", in *Stress, Mitigation and Sustainability of Large Marine Ecosystems*, pp. 148-74, 1993. (Edited by K. Sherman, L.M. Alexander, and B.D. Gold, AAAS, Washington DC); Pauly, D. "Use of Ecopath with Ecosim to evaluate strategies for sustainable exploitation of multi-species resources". *Fisheries Centre Reports* 6 (2) 1998, 49 pp. Vancouver, BC, Canada; Pauly, D., Soriano-Bartz, M.L. and Palomares, M.L.D.. "Improved construction, parameterisation and interpretation of steady-state ecosystems". pp. 1-13, in "Trophic Models of Aquatic Ecosystems", *ICLARM Conference Proceedings* 26, 1993.; Christensen, V. and Pauly, D. "Changes in models of aquatic ecosystems approaching

carrying capacity". *Ecological Applications* 8(1), (Suppl):104-9, 1998.

[86] Yodzis, P. "Must top predators be culled for the sake of fisheries?" *Trends in Ecology and Evolution* 16(2):78-84, 2001. See also Yodzis's "The indeterminacy of ecological interactions as perceived through perturbation experiments". *Ecology*, 69:508-15,1988.

[87] I think it is of interest that Michael Graham's "A Natural Ecology" (referenced above) includes a diagram, somewhat similar to more recent and complicated ones by Yodzis, centred on the herring of the North Sea, and featuring the differences of diet between various age classes of that species. His Diagram 3, illustrating synecology, deals with the herring and the trophic levels "below" it, down to the diatoms and flagellates. Beyond that, however, what Graham writes in the accompanying text is relevant to our present arguments about "culling" predators for human benefit: "As I sketch this diagram (due to Sir Alistair Hardy) on the board in the lecture room I add the cod, which feeds on herring, and feeding on the cod there would be seals, and feeding on the seals there would be polar bears and Eskimo. There would also be the numerous fishermen who in historic times have fished the cod…Competing with the cod for herring we should have to add gannets and toothed whales, and competing with the seals for cod we should add Greenland sharks. Competing with the herring for krill are the whalebone whales and many (species of) pelagic birds. It is evident that the more one knows about any ecosystem, the more difficult it is to show a tidy diagram of its synecology, and that is true of the web of life as it exists in nature". Graham might have added, to complicate things further but not unnecessarily, that cod eat themselves – bigger cod commonly feed on smaller ones.

[88] A. B. Hollowed *et al.* "Are multispecies models an improvement on single-species models for measuring fishing impacts on marine ecosystems?" *ICES J. Mar. Sci* 57:707-19, 2000.

[89] These authors are clearly aware of the intractable difficulties, despite their guarded optimism, and their conclusions are worth recalling in full "What is the implication of these ideas? First, it is clear that multi-species interactions need to be placed within the context of the myriad other factors and processes influencing these systems. Second, multi-species interactions occur within a spatial and ontogenetic structure – models that lack this structure are unlikely to have any predictive capacity because of the complexity of the interactions. Third, this complexity means that models with quite different properties may be developed for any one system. Therefore, predictions need to be addressed within a rigorous and testable modeling framework. Finally, the multi-species interactions of most interest in determining the impacts of fishing on marine ecosystems are those that cause marked departures from the current conditions – models constrained by equilibrium processes are unlikely to capture these departures".

[90] "Marine ecosystem-based management as a hierarchical control system*". Mar. Policy* 2(1):5-68, 2005.

[91] Guenette, S., Lauck, T. and Clark C. "Marine reserves: from Beverton and Holt to the present". *Revs. Fish Biol. And Fisheries* 8: 251-272, 1998.

[92] Sumaila, U. R., Guénette, S., Alder, J. and Chuenpagdee, R. "Addressing ecosystem effects of fishing using marine protected areas". *ICES J. Mar. Sci*. 57: 752-60, 2000.

[93] Walters, C. J., Christensen, V. and Pauly, D. "Structuring dynamic models of exploited ecosystems from trophicmass-balance assessments*". Revs Fish. Biol.* 7:127-42, 1997; Walters, C.J., Pauly, D. and Christensen, V. "Ecospace: a software tool for predicting mesoscale spatial patterns in trophic relationships of exploited ecosystems, with special reference to impacts of marine protected areas". *ICES CM* 1998/:S:4 20 pp., 1998 [a spatially explicit model that includes movement rates to compute exchanges between grid cells and habitat preferences]; Watson, R. and Walters, C. "Ecosim and MPAs: a quasi-spatial use of Ecosim". pp. 15-18 in *Use of Ecopath with Ecosim to Evaluate Strategies for Sustainable Exploitation of Multi-species Resources*. Edited by Pauly, D., Fisheries Centre, UBC, Vancouver. 6(2), 1998. [This is a simple model based on ECOPATH with quasi-spatial relations between biomass and fishing mortality.]

[94] McCall, A. D. *Dynamic Geography of Marine Fish Populations*, 1990, Books on Recruitment Fisheries Oceanography, Univ. Washington, Seattle, 153 pp.

[95] "Population models and community structure in heterogeneous environments", pp. 295-320 in *Mathematical Ecology*, edited by T. G. Hallam and S. A. Levin, Springer-Verlag, Berlin, 1986. See also Rosenzweig, M. I. "A theory of habitat selection". *Ecology* 62: 327-35, 1981.

[96] S. Fretwell proposed this term, in *Populations in a Seasonal Environment*, Princeton Univ. Press, 1972, 217 pp. The general theory was spelled out by Fretwell and H. Lucas in "On the territorial behavior and other factors influencing habitat distribution in birds". *Acta Biotheoretica* 19: 16-36, 1970. Other terms for the notion of *suitability*, such as "environmental density", "fitness", "reproductive value, even "goodness" have been used by various other authors.

[97] A phenomenon examined in depth by Brown, J. H. "On the relationship between abundance and distribution of species". *American Naturalist* 124: 255-279, 1984.

[98] This leads to four statements: 1. The free surface of the liquid will be approximately level, corresponding to the uniform realized suitability resulting from the ideal free distribution; 2. The "shoreline" corresponding to habitats whose basic situation is exactly equal to the uniform realized suitability, establishing the range of the population; 3. The depth of the liquid at any location is proportional to the density-dependent reduction in its realized suitability at that location, and is proportional to local density; 4. The total volume of liquid in the basin is thereby functionally related to total population size.

[99] It was used in the IWC scientists' examination of the *robustness* of proposed CLAs. H. S. Gordon analysed fishermen's choices among alternative fishing grounds and produced habitat utilization diagrams remarkably like those of Freewell, "An economic approach to the optimum utilization of fishery resources". *J. Fish. Res. Bd Canada* 10: 442-57, 1953. Beverton and Holt, 1957, supposed that fishing effort/intensity would distribute itself in such a manner as to lead to fish densities on all grounds affected by the fishing being reduced to about the same value, with allowance being

made for factors arising from the fact that the human effort starts from and returns to certain places on the margins of the fish distribution.

[100] McCall's book has nearly 150 bibliographic references on the subject.

[101] David Ricardo (1772-1823), author of *The Principles of Political Economy* (1817), was a contemporary of Thomas Malthus, and had an interesting interaction with him. He wrote in 1815 that "In all that I have said concerning the origin and progress of rent I have briefly repeated, and endeavored to elucidate , the principles which Malthus has so ably laid down on the same subject…".

[102] "Optimal foraging, the marginal value theorem". *Theoretical Population Biology* 9: 129-36, 1976.

[103] See R. M. May "Stability and complexity in model ecosystems", *Monographs in Population Biology* VI, Princeton, 1973; "Biological populations with non-overlapping generations: stable points, stable cycles, and chaos". *Science* 186: 645-647, 1974.

[104] In fact this is only strictly true for deterministic models; stochastic models can behave very differently.

[105] For more on the evolution of the conservation movement, see Lavigne, Chapter 1.

[106] "The Changing Ocean. Its effects on climate and living resources". *IOC Ocean Forum Series* IV, UNESCO, Paris, 169 pp., 2003.

[107] First described by Broeker *et al.* in *Nature* 315: 21-26, 1985. The Indian and Pacific Oceans' mechanism is described thus: "Warm and salty surface water moving northward though the Atlantic is driven into the North Atlantic and the Norwegian Sea where it is cooled. Its density increases causing it to sink to great depths and return to the South Atlantic, then to the Indian and Pacific Oceans. [This sinking is enhanced by influx of melted sea ice water from the North Polar ocean and freshwater from the Greenland Icecap which, though cold, is less dense]. This deep water diffuses slowly towards the surface where it is taken up by surface currents and carried back to the North Atlantic". The eastward-flowing Antarctic Circumpolar current is deflected to its left (i.e. northward) by the Cariolis force arising from the earth's spin, until it comes into contact with warmer and less dense water of sub-tropical origin.

[108] Further information about the ENSO phenomenon is given in Voituriez, B. and Jacques, G. "El Niño: Fact and Fiction", *IOC Ocean Forum Series*, I, 2000, UNESCO, 128 pp.

[109] An *anomaly* is defined as the difference between the value of a parameter at a given moment and its long-term mean value. It is thus a deviation in time rather than in space, but the concept can be extended to the spacial dimension.

[110] More formally, a layer of water in the ocean in which the temperature decreases rapidly, and commonly limits vertical mixing between the surface mixed layer and the deeper water, and thus impedes the movement of essential nutrients. The *pycnocline*, the layer of water in which the density increases rapidly with depth, may be coincident with the thermocline. The *nutricline*, in turn associated with the pycnocline, is the layer in which there is a rapid change in the concentration of nutrients with increasing depth.The periodic but irregular changes in the location of boundary phenomena – depth of thermocline etc.– and geographic location of divergences and convergences in the open ocean are usually referred to as *undulations*.

[111] The Antarctic Divergence, at about 65ºS., is anomalous, because it brings up water from a very great depth. The high biological productivity is not manifest until the newly-surfaced water reaches about 40ºS., 2000 km to the North, about 200 days later. In that time production has been limited by complex interaction of deficits of a series of nutrient elements, including especially silicon (necessary for the growth of diatoms) and iron. The supreme importance of iron in this region was proven in 1999 by the Southern Ocean Iron Release Experiment (SOIREE) carried out in the Circumpolar Current south of Tasmania. The other purpose of that experiment was to verify or otherwise the role of the Southern Ocean as "Manager of the Atmosphere's Carbon-dioxide".

[112] In general, oceanic *fronts* where different water masses meet are biologically productive (other things being equal), and recent studies have shown that many predatory animals – including whales – are able to detect them and congregate along those lines. Another important boundary system, especially in the Antarctic, is the limit of sea-ice, which, of course, shifts latitudinally through the seasonal cycle. It is also known to have changed the latitude of its average summer location through the past century – the Antarctic sea-ice boundary at a given season is retreating towards the pole and thus is shortening. (Satellite observations over a few decades confirm what has been revealed from historical studies of the geographical distribution of whaling vessels "hugging" the ice edge, carried out by W. de la Mare.) The significance of this is that diatoms are held frozen in the ice-edge during the winter and released as the ice melts in spring, providing nutrition for grazing zooplankters such as krill and so driving their multiplication, which in turn attracts the larger predators.

[113] For more on the collapse of cod stocks, see Hutchings, Chapter 6.

[114] Out-of-phase oscillations in the sea-surface temperature of the Central North Pacific, on the one hand, and of he eastern boundary and the eastern part of the inter-tropical Pacific on the other.

[115] The fish are caught in traps, mostly in Sicily, and the catches have been monitored closely by fiscal authorities, collectors of the ecclesiastical tithe, customs officers and investment bankers!

[116] Klyashtorin went further. He reasoned that the shifts of fluids on the planet modify the speed of the Earth's rotation; indeed the El Niños of 1982-83 and 1997-98 are associated with a tiny reduction in the rate of rotation and hence a lengthening of the day. The ACI is well correlated with the rotation rate, so, Voiteruez asks "Could the speed of rotation become an index of the evolution of marine ecosystems?"

[117] See Witting, L. *A General Theory of Evolution, by Means of Selection by Density Dependent Competitive Interactions*. Peregrine, Århus, Denmark, 1997, 332 pp.

[118] Witting, L. "Population cycles caused by selection by density dependent competitive interactions". *Bull. Math. Biol.*, 62:

1109-1136, 2000.

[119] Witting, L. "Reconstructing the population dynamics of eastern Pacific 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.

[120] Clark, C. 1981."Bioeconomics". pp 387-408 in Theoretical *Ecology: Principles and Applications*. R.M. May, ed. (Blackwell).

[121] *In a Perfect Ocean: The State of Fisheries and Ecosystems in the North Atlantic Ocean*. 175 pp. Island Press, 2003: "A larger reason why we find ourselves with an impoverished ocean is because past generations did not care about us and discounted what appeared to them as future benefits to be gained from exploiting the North Atlantic. Our generation is no better… A factor in policy-making known as the discount rate essentially calculates that the value of an unexploited resource declines over time (by the same percentage for each year), and eventually approaches zero, at least as far as our generation is concerned." Some economists seek to justify the failure to consider future generations by claiming that our descendents will have found substitutes for depleted resources, and there is some validity in this for some kinds of resources. However, the result of policy analysts discounting future fishery benefits, in making cost-benefit analyses, is that they are skewed toward exploitation of the resources by the present generation. "This", say Pauly and Maclean, "puts the burden of proof in policy debates on those who would argue for resource restoration." And, I would add, severely impedes efforts towards sustainable use now.

[122] These are the words of T. R. E. Southwood "Bionomic Strategies and Population Parameters". pp. 30-52 in *Theoretical Ecology: Principles and Applications*, Edited by R. M. May, second edition, 1981.

[123] "Habitat, the temple for ecological strategies". *J. Anim. Ecol.* 46: 337-366, 1977.

[124] Southwood suggested this might be because longevity is inversely related to total metabolic activity per unit body weight.

[125] The fossil record reveals many instances where an evolutionary line has evolved to increased size, until extinction occurs ("Cope's rule"; Cope, E. D. *The Origin of the Fittest*, Appleton and Co., New York, 1887). These lines have become more and more closely adapted to specialized and hitherto stable habitat through progressive ***K***-selection. A profound analysis of these issues has been provided recently, in evolutionary-genetic-mathematical terms, by L. Witting: "Major life-history transitions by deterministic directional natural selection", *J. Theoretical Biol.* 225: 389-406, 2003.

[126] For a general account of this matter see especially Ludwig, D., Hilborn, R. and Walters, C. "Uncertainty, Resource Exploitation, and Conservation: Lessons from History". *Ecological Applications* 3(4): 547-549, 1993.

[127] "Case studies on the allocation of transferable quota rights in fisheries". Edited by Shotton, R. *FAO Fish. Tech. Pap*. 411, 2001, 373 pp.

[128] Holt, S. J. "Sharing the catches of whales in the Southern Hemisphere". *FAO Fish. Tech. Pap*. 411: 322-373, 2001.

[129] Elliot, G. *A Whaling Enterprise: Salvesen in the Antarctic*. Michael Russell, Norwich, UK, 1998, 190 pp. [See especially p. 129.]

[130] It is worth recalling here that several fisheries scientists have advocated consideration of such a strategy, the most well-known and articulate being, I think, Martin Burkenroad. It is, however, associated with Burkenroad's and other's claims that the effects of fishing on fish stocks had not been convincingly demonstrated, except perhaps with respect to the effects of two world wars on demersal species in the North Sea. Some decades later the swarming of large factory trawlers, with European registries, off the coasts of developing countries, especially off western Africa, led to the concept of "pulse fishing" and hence revived questions regarding the link between sustainability and continuity of exploitation.

[131] For more on Salvesen, see Papastavrou and Cooke, Chapter 7.

[132] Readers wishing to explore further the nature of infinity and its multiple forms, and especially of infinite time, might find pleasure in reading *Infinity (A Brief History of): The Quest to Think the Unthinkable*, by Brian Clegg, Robinson, London, 2003, 255 pp.

[133] Graham, M. *The Fish Gate* Faber, London, 1943.

[134] In his review of "The State of Fisheries Science" (pp 25-54 in *The State of the World's Fisheries Resources*, 1994, edited by C. Voigtlander, Lebanon, New Hampshire, International Science Publications), R.J.H. Beverton noted that long-range planning by the fishing industry [*and hence, presumably, a practical time-horizon for both management and management related research - sjh*] "extends over the 20-year or so life-span of its major capital facilities".

[135] For more on whale watching, see Corkeron, Chapter 11.

[136] See Pauly, D. *et al*. "Fishing down marine food webs". *Science* 279: 860-863, 1998; Jackson, J. B. C. *et al*. "Historical overfishing and the recent collapse of coastal ecosystems". *Science* 283: 629-38, 2001; Hempel, G. and Pauly, D. "Fisheries and Fisheries Science in Their Search for Sustainability", pp. 109-35, 2002 in *Oceans 2020*.

[137] *Thermodynamics and Statistical Mechanics. Lectures in Theoretical Physics*, Vol V, trans by J. Kestin. New York Academic Press, 1956, p. 19. Quoted in the biological context by G. Tyler Miller Jr: *Energetics, Kinetics, and Life: an Ecological Approach*. Wadsworth Publishing, 1971, p. 143. In turn quoted and expounded by Wes Jackson "Agriculture: The Primary Environmental Challenge of the 21st Century". pp. 85-99 in *The Human Ecological Footprint*, Kenneth Hammond Lectures on Environment, Energy and Resources, 2002 Series, Faculty of Environmental Sciences, University of Guelph, Ontario, Canada, 2004. Edited by W. Chesworth, M. R. Moss and V. G. Thomas.

[138] This is not the place to discuss the details of why an estimate of so-called replacement yield is not the same as the theoretical sustainable yield. It has been applied especially in situations where there is more than the usual uncertainty as to the dynamics of the population, and especially about its

age-composition and the relation between parent numbers and subsequent recruitment. Most commonly a presumed current rate of increase in number – were exploitation to pause – is calculated from minimal data; which, multiplied by an estimate of the current population size, is taken as the replacement yield. But the rate of increase depends, in part, on the incoming recruitment, which is some function of an earlier population size. While little harm will be done in many cases if this is used to establish an *interim* management measure, say a Total Allowable Catch (TAC) for one or two years, this is usually – whatever might be said at the time – repeated for several years; that is because the original uncertainties are rarely if ever over-come in the iterim. So, *repeated* application of this measure can endanger the population over time. The danger is especially acute for species in which there is a strong correlation between the number in the sexually active part of the parent population and the subsequent number of recruits into the exploited phase of the population, as in marine mammals and, possibly, the relatively slowly reproducing fishes such as elasmobranches (sharks and rays). As this is being written it seems that the Government of Canada has made exactly this mistake in announcing the "rationale" for its recent large increase in its permitted "cull" of harp seals in the Northwest Atlantic.

[139] After reading an early draft of this essay David Lavigne challenged me to redefine our *Holy Grail*, if it is not sustainability. That is perhaps something for the Forum as a whole to tackle. But I would begin with something that has a broad, long-term (but not infinite) idea of sustainability embedded in it but bearing also the notions of precaution, frugality and parsimony. In his unusual little book entitled *Muddling Toward Frugality* (Shambhala, Boulder, 1979), Warren Johnson, one time professor of geography at San Diego State University, California, noted that the word frugality came originally from the Latin *frugalior*, meaning useful or worthy, and *frux*, meaning fruitful or productive, giving, he said "a nice feeling". "However" he observes, "the word has changed over the years, and has come to mean thriftiness, the abstention from luxury and lavishness". In his book he stays with the original meaning, "to suggest economic conditions in which society is obliged by force of circumstances to make full and fruitful use of all its resources". Professor Johnson was a super-optimist; in his Preface he wrote: "If the Earth is to be a true home for us, a place of refuge and nurture, we may as well start to think about how we can make it such a place. The task will not be as difficult as it may sound, and requires no wishful thinking about technological breakthroughs, effective government, or heightened human consciousness. We can move towards a sustainable way of life easily if we accept the logic of frugality."

[140] Larkin, P. A. "An epitaph for the concept of maximum sustained yield". *Trans. Am Fish. Soc*. 106: 1-11, 1977. Peter Larkin was, however, as much concerned with the failure of managers to act on scientific advice as with the conceptual failings of the MSY paradigm and management strategy.

[141] Here Graham confirms that the work by Ray Beverton and myself, under his direction, was not pedagogic in intent, but exploratory.

[142] An alternative to finding an advantageous direction and moving in it is commonly thought to be to define an end target, a "reference point" in current jargon. MSY was pressed as more suitable than, say, some economically or socially determined optimum especially in any international context; something that perhaps every country could agree on regardless of its economic system or state. A very different light is, however, thrown on this by state documents of the immediate post-war period concerning fisheries of the USA and Japan, especially as they concern whales, Pacific salmon and tuna. These have been analysed most thoroughly by a historian at the University of California at Berkeley, Prof. Harry Scheiber. (*Inter-Allied Conflicts and Ocean Law, 1945-53: The Occupation Command's Revival of Japanese Whaling and Fisheries*. Institute of European and American Studies, Academia Sibica, Taipei, Taiwan, 2003, 233 pp.)

Just as it had long been UK and Norwegian policy, while competing with each other, to work together to prevent any other countries engaging in pelagic whaling in the Antarctic, the USA (and Canada) sought ways of keeping Japan out of the then very lucrative salmon fisheries off their west coasts. The occasion was the negotiation of an International North Pacific Fisheries Convention (INPFC), focused on salmon. In that context an abstention principle was invented. The idea was that if existing fishing states – primarily coastal states – were already exploiting a resource at the level of MSY then other states should agree to abstain from entering that industry. Evidently, Japan was unlikely to accept a scarcely concealed discriminatory rule without a *quid pro quo*. That which was granted was an assurance that the Government of the Occupying Power would not impede Japanese fisheries expansion elsewhere – including as it happened Antarctic whaling, but not only that.

The situation changed somewhat when the value of the US Pacific tuna fishery vastly exceeded that of the salmon fisheries, in which – it turned out later – the US would come into vigorous conflict with Latin American competitors and, eventually, Japan, Taiwan and other Asian states. However, for the time being the abstention principle could be turned upside down. The tunas being initially under-exploited, it could be argued that the MSY target justified – even demanded – that the populations be **reduced** to the supposed MSY levels. Much later this same argument was used by Japanese delegations to the IWC to claim that since the minke whales of the southern hemisphere had not been exploited before 1970, good management would ensure that they were reduced by whaling as fast as possible to a putative MSY level; anything other than that – even a more cautious depletion – would be "wasteful".

The last stage in this extraordinary political process concerning exclusion/abstention/non-exclusion/sharing is found in its converse form in Article 62 of UNCLOS, regarding Exclusive Economic Zones: "The coastal State shall determine its capacity to harvest the living resources of the EEZ. **Where the coastal State does not have the capacity to harvest the entire allowable catch it *shall*,** through agreements or other arrangements etc., **give other States access to the surplus of the allowable catch**…" Note that in this case it is the coastal State (and eyes were really on *developing* coastal

States) that has no option but to use "fully" or to share.

[143] As to compliance, in the fisheries context, see for example W. Edeson, D. Freestone and E. Gudmundsdottir "Legislating for sustainable Fisheries. A guide to Implementing the 1993 FAO Compliance Agreement and the 1995 UN Fish Stocks Agreement". *Law, Justice and Development Series*,.The World Bank, 2003, 151 pp.

[144] Although not affecting the principle of the management scheme developed by the IWC some practical problems have arisen, not thought about when this initiative was launched. It seems likely that, even if the specified conditions for setting non-zero catch limits were to be met, the (precautionary) limits would be too small to justify commercial interest. In the time that has elapsed since the RMP/CLA was agreed whaling administrations have surely worked this out for themselves, even though the IWC and its Scientific Committee have not officially performed the calculations. In such circumstances it seems to me unlikely that any of the countries still seriously interested in resuming legitimized commercial whaling would, in the end, accept the proposed RMS. There could therefore be a reversion to the Salvesen's exit strategy: continue depleting the remaining fairly numerous whales (essentially only the minke) and then pull out. This is indeed what the authorities of Norway appear to have decided, as they steadily increase catches of minke whales from the depleted population in the Northeast Atlantic, under their objections to the IWC's closure decisions of the 1980s, and now using the absurd excuse that these whales are threatening the North Atlantic cod and herring stocks. Current Norwegian catches are already severalfold higher than would be granted under the RMP as approved by the IWC. At the present time it seems the only impediment to this policy might be the limitations of the market for minke meat and blubber, rather than restrictions on catch imposed by any international authority

[145] I feel at one with Lynn Margulis, who wrote: "We people are just like our planet-mates. We cannot put an end to nature, **we can only pose a threat to ourselves**". The notion [*here comes that word again! sjh*] that we can destroy all life, including bacteria thriving in the water tanks of nuclear power plants or boiling in hot vents, is ludicrous. I hear our non-human brethren snickering: "Got along without you before I met you, gonna get along without you now." They sing about us in harmony. Most of them, the microbes, the whales, the insects, the seed birds, are still singing. The tropical forest trees are humming to themselves, waiting for us to finish our arrogant logging so they can get back to their business of growth as usual. And they will continue their cacophonies and harmonies long after we are gone." (Closing paragraph of "The Symbiotic Planet: A new look at evolution", Phoenix, 1998.) And, I would say, evolution will continue to plod its relentless way.

[146] For much more on the evolutionary and genetic threads in the history of political economy see *The First Darwinian Left: Socialism and Darwinism 1859-1914*, by David Stack New Clarion Press, Cheltenham, England, 2003, 149 pp.

[147] New York, Avon Books, 1994. Damasio is a neurologist who has spent much of his life studying the function of the human brain and the relationships between reason and emotion, thought and feelings.

[148] Pp. 1-34 in Chesworth, Moss and Thomas (eds.), 2004. See endnote 137, above.

[149] For more on the subject of love, see Lavigne *et al.*, Chapter 26.

[150] Perhaps "biodiversity", a current, all-pervasive buzz-word, examined recently by Ronald Brooks who asked the question "The Paradox of Biodiversity – Is Conservation Ethical, Aesthetic, Utilitarian or an Adaptive Strategy?" ("Earthworms and the Formation of Environmental Ethics and Other Mythologies: a Darwinian Perspective". pp. 59-91 in *Malthus and the Third Millennium*, Kenneth Hammond Lectures on Environment, Energy and Resources, 2000 Series, University of Guelph, Ontario, Canada, 2001. Edited by W. Chesworth, M.R. Moss and V.G. Thomas.) Brooks labels biodiversity as "a virtually holy grail not just for biologists, but for naturalists, environmentalists, politicians and policy makers. But why? Certainly not for any scientific reasons. As I have argued for earthworms, there is little scientific evidence that biodiversity is necessary, beneficial or even natural". Further on, Brooks' comments link clearly again to the issue of sustainability and sustainable use. "One could argue that protection of biodiversity is about as unnatural as true altruism, in other words as unnatural as it gets. Perhaps this conclusion can guide us to a true and fulfilling conservation ethic, one that requires sacrifice rather than self-serving and hypocritical platitudes. But, do we want to give nature the respect we sometimes give people, or is nature a commodity to be managed and placed firmly in the free market?"

Biodiversity and/or other fashionable and related buzz-phrases such as "ecosystem management" and "precautionary principle" could perhaps be themes for a second IFAW Forum?

One participant was Sidney
He says sustainable reaches infidney
He drew lots of curves
That unsettled our nerves
But he looked ever so clever, didn't he?

William de la Mare 2004