Advances in Fisheries Science

50 years on from Beverton and Holt

Edited by

Andy Payne, John Cotter and Ted Potter
Centre for Environment, Fisheries and Aquaculture Science (Cefas)
Pakefield Road, Lowestoft, Suffolk

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Cefas

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Editorial

Andrew I. L. Payne, A. John R. Cotter and E. C. E. (Ted) Potter

On the Dynamics of Exploited Fish Populations, written by Ray Beverton and Sidney Holt and published 50 years ago (Beverton and Holt, 1957), is arguably the most respected and influential scientific work issued by Lowestoft's Fisheries Research laboratory during its 105 years of existence. The authors' achievement was to provide a solid foundation for quantitative fisheries science which, even today, is advisable preliminary reading for any researcher aspiring to develop the subject further. As evidence of its continuing importance, the book was reprinted (as Beverton and Holt, 2004) by Blackburn Press in 2004 (with a new Foreword by Sidney Holt), citations of it continue at a rate of >100 per year, some of its early ideas made it into the similarly well cited Graham (1956), and the 50th anniversary of the start of the research (Hulme *et al*., 1947) has already been commemorated by Pitcher and Pauly (1998) with a jubilee issue of *Reviews in Fish Biology and Fisheries*. Sadly, Ray Beverton passed away on 23 July 1995, aged 72. An obituary outlining his distinguished career was published in the *Canadian Journal of Fisheries and Aquatic Sciences* (**53**: 1200–1201).

The Lowestoft Fisheries Laboratory is still situated overlooking the North Sea, but it is now known as the Centre for Environment, Fisheries and Aquaculture Science (Cefas), an executive agency of the UK's Department of Environment, Food and Rural Affairs (Defra). The question of how we should commemorate the jubilee of the publication of Beverton and Holt's work following these earlier efforts was initially a difficult one. Would it be best achieved through the proceedings of another technical symposium, particularly as Cefas had produced one in 2002 to commemorate its own centenary (Payne *et al*., 2004)? We felt not. Perhaps there was interest in commemorating the history and development of the Lowestoft Laboratory, but we knew that that too had been done, by Lee (1992). Beverton's own writing published posthumously in the Pitcher and Pauly (1998) volume as Beverton (1998) provided us with an idea:

> "*Having devoted my career to providing a scientific basis for sound and sustainable harvesting of our natural fish resources, it troubles me greatly that the present state of the world's fisheries is deeply depressing. This is not what Sidney Holt and I were hoping for when we embarked on our immediate post-war endeavours in those heady days of the late 1940s.*"

These problems are unlikely to go away soon. Ray Beverton's words – which are in an otherwise optimistic article – suggest that there is actually a pressing need to take our minds off problems every now and then, and to cheer everyone up by reminding ourselves of some of the good things that have been achieved by scientists in fish- or fishery-related fields. What better opportunity to do this than the 50th anniversary of a historic achievement? Accordingly, Cefas intends this volume as both a tribute and a celebration. Fish and fishery system scientists in Cefas were invited to collaborate with colleagues within and outside the organization to prepare essays (rather than the research reports or reviews they generally produce) on the achievements made over the past 50 years in their specialism. We also asked them to gaze into their crystal ball a little to see where we might need to venture in future.

We saw Sidney Holt's own participation, in terms of writing a *Foreword*, as crucial to the project, and despite being an octogenarian not only writing prolifically but also currently harvesting olives and making wine in central Italy, he immediately and enthusiastically joined the project, showing that his scientific interest had not diminished. It has not been possible to address the full range of Cefas work in this volume, and it focuses mainly upon our work relating to marine fisheries. However, we are particularly pleased to include essays by a number of younger fisheries scientists in Cefas, as well as two papers from our Weymouth and Burnham-on-Crouch laboratory colleagues on work, perhaps peripheral to fisheries *per se*, but nevertheless an important part of the overall current Cefas scientific and advisory output.

In the 50 years since the original Beverton and Holt volume was published, the emphasis for fisheries management has broadened to the point where it is, especially if one is working in the European Union, a Ministerial requirement that one takes the processes that make up the ecosystem in which one's fishery operates into account. Those processes include the anthropogenic and the socio-economic. The context has also widened in the face of the enhanced understanding of the current and apparently accelerating global changes affecting climate that affect fish, mankind and our environment.

Here, we do not attempt to summarize current scientific thinking on global climate change save to refer the reader to the latest International Panel on Climate Change (http://www.ipcc.ch) Summary Assessment Report and to acknowledge that this will change, probably significantly, depending upon the year this book is being read. Also, by way of an introduction to the impacts of climate change on the marine environment we refer the reader to the UK Marine Climate Change Impacts Partnership (MCCIP; http://www.mccip.org.uk), which produced an Annual Report Card for 2006. For a more general treatment of climate change impacts, and in the absence of a chapter on the subject here, we refer the reader to the work of Turrell (2006), who wrote a collaborative report for the Partnership between Fisheries Research Services and the Scottish Fishermen's Federation called *Climate Change and Scottish Fisheries*.

Our own closing authors quote extensively from the Foreword of the original Beverton and Holt book, so it seems appropriate here to do the same from the Introduction to the new edition: "This review …. is written for fishermen…"; an indication of the wider scope, engagement and involvement in the management of fisheries that, as indicated above, applies today, some 50 years on from the publication of the original volume. We would like to think that what we have produced here is of value and interest not just for the present generation of fisheries scientists, but also the educated public and especially the next generation or two of scientific minds. We also draw the attention of readers to the Introduction (Holt, 2004) to the new edition in its entirety; it makes interesting reading as an adjunct to what is written here.

The authors of the final chapter also provide insight into the changing "climate" of the North Sea from the time when it was what we now call Doggerland. They take us through an imagined sequence of likely change and what we would have thought about that change over some 10 000 years. Their title refers to inevitable uncertainties identified by the authors of the original volume, a theme that permeates pronouncements on climate change, ecosystems and modern fisheries management. If the final product seems like propaganda for our profession or the Lowestoft laboratory, so be it. We are sure, too, that some will find the chapters perhaps overly Eurocentric, although wherever appropriate authors were asked to look wider than European waters.

We express particular appreciation to Denis Glasscock, David Riches and Irene Gooch from the Cefas Publications and Graphics Team for their help in preparing some of the figures and compiling the camera-ready copies of the chapters, to Mandy Roberts and Sarah Turner from the Cefas Library for checking the references from source, and to Mary Brown and David J. Brown for the indexing. We enjoyed fulfilling the project, and we warmly thank all the authors (particularly for responding positively to our constant pressure!), reviewers, for so willingly giving of their time, and colleagues and the Publisher. All of them helped keep us focused in turning out what we hope and believe is an interesting, educational and motivating suite of essays.

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Foreword

Sidney J. Holt

When lead editor Andy Payne, on behalf of Cefas, invited me to write a Foreword to this book, I was minded to read again Michael Graham's *The Fish Gate*, written and published during the Second World War. It is a marvellous little book. I first read it in December 1946, between bouts of nausea on board the MV "Platessa" as a young biologist who had dissected a fish but knew nothing about fishing. I noticed my new mentor's conclusion that "The trail of fishery science is strewn with opinions of those who, while partly right, were wholly wrong". Two hundred crisp pages introduced me to the great names of Frank Buckland, C. G. J. Petersen, J. Arthur Thomson, Johann Hjort, E. W. L. Holt (no relation!), C. M. Yonge, Henry Thoreau, T. H. Huxley, John Murray, D'Arcy W. Thompson, P. F. Verhulst, E. S. Russell and the rest, all bright stars in numerous constellations. On nearly every page was a sentence of which could be said "And here is the text of my sermon today….", or could that be the theme for a public debate, and to me Graham said, "Here is the problem….". "But that needs mathematics, and I know little", I protested. "Then go and learn some more"[a]. The next flash of enlightenment came just one month later, as I read E. S. Russell (1942) – *The Overfishing Problem* – by the fire of rationed coal provided by the Ministry of Agriculture, Fisheries and Food for its shivering civil servants. Graham sent me off to London twice a week for a few months to learn statistics, too, at Kings College, in a special course arranged for servants of His Majesty's Government, and the train journeys gave me time to read, digest and absorb V. A. Kostitzin (1939), with its preface by Vito Volterra, and A. J. Lotka (1925) (subsequently re-published in 1956, with corrections, as *Elements of Mathematical Biology*. Dover, New York, 465 pp.). A year later, through correspondence with Bill Ricker in Canada, we were confronted with an English translation, entitled *On the Question of the Biological Basis of Fisheries* of the seminal work of T. I. Baranov (1918).

The authors of a recent review entitled *Current Problems in the Management of Marine Fisheries* (Beddington *et al*., 2007) wrote that "The science that is used to assess commercially exploited species is still dominated by the population models developed by Beverton and Holt for single-species assessments some 50 years ago". That is both flattering and worrying. Is it really possible that the methodology has progressed so little in half a century? They cite the original, 1957, version of the book Ray Beverton and I wrote so long ago, but I would like to have seen references to the Foreword to the third, 1993, printing, by Daniel Pauly, and to my own historical Foreword (Holt, 2004) to the fourth printing, published in 2004. This is because I have become somewhat wary of management by seeking to home in on "reference points", whether the notional maximum sustainable yield (MSY) or somewhere else on a curve of steady-state yield (I don't think the word "sustainable" is to be found in our text!) against stock biomass, fishing mortality rate, fishing effort or other significant variables. It is nearly 30 years since two of those authors – John Beddington and Colin Clark – along with Bob May, Dick Laws and I, tried to model the Antarctic marine ecosystem (May *et al*., 1979), and 20 years since Bill de la Mare demonstrated by simulation how such a search can lead to

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[a] *I have written more about this and the post-war culture at Lowestoft in Holt (2006a).*

catastrophe (de la Mare, 1986a). I think, if he were here, Ray too would have had some concerns, judging by his *Reflections on 100 years of Fisheries Research*, edited by Emory Anderson and published posthumously[b], and Beverton (1998). He was greatly worried about the misuse of our models by their application in inappropriate circumstances. In particular, focus on yield-per-recruit statistics and the unbridled application of Virtual Population Analysis (VPA) could both lead one astray. These events are not surprising considering that we were not engaged in writing a textbook, but simply trying to provide advice on the post-war management of some North Sea trawl fisheries, and inevitably exploring byways of population dynamics in the process.

When Ray and I were together at the Fisheries Laboratory in Lowestoft immediately after the war, it was a vibrant place populated mostly by young scientists that Michael Graham and E. S. Russell had just recruited, several from war-time operational research units. Graham insisted that we all be called "Naturalists" and that we should regard ourselves as being engaged in peace-time operational research[c]. A feature of the culture there was close collaboration with scientists in other European countries, especially but not exclusively through the ICES and Permanent Commission connections, and later, especially through ICNAF, with the fisheries laboratories on the North American east coast. Readers of this book will see, and I hope enjoy, the continued vigour and wide range of those connections, and their extension beyond western Europe and the North Atlantic.

One thing I miss in the chapters assembled here, with their polite scientific language, is the deep sense of what it is to be a sea-going naturalist – hold the *mal-de-mer*. Again I rely on Michael Graham to rescue me, a bumbling writer who saves his skin by quoting Shakespeare or Robbie Burns or Horace or Homer when he runs out of good words: "Initial zeal may take a man to sea [My apologies; women were not permitted aboard British research ships in those days, their presence would make the crew tongue-tied] but that has worn off by the time the sailor has watched a wire for kinks three thousand times, so that the valuable instrument that has just been lowered once more to the sea-bed shall make the return journey safely; it is not enthusiasm that makes the captain keep so good a reckoning that the observation 'stations' are evenly spaced across the sea, despite the tide, current and leeway; every kind of zeal fled hard on the heels of

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[b] *This is an edited transcript of a lecture given by Ray Beverton in Woods Hole, MA, in May 1994. The account given there of work in the period 1946–1951 differs in some respects from my recollections of the period.*

[c] *Michael Graham wrote several books, but the philosophy that guided the post-war "renaissance" of the Lowestoft Laboratory was most clearly expressed in The Fish Gate, published by Faber and Faber in 1943, and dedicated to Commander W. H. Stewart, Master of the laboratory's first research ship, the George Bligh. That would be my "most recommended reading" for any young person embarking on studies about fish and fisheries and mentally inclined to some amalgam of science, history and poetry, who would surely gain both knowledge and inspiration. A taste of it can come from p. 172, in the middle of his antepenultimate chapter, on Theory: "There are many curves and patterns in Nature, which may be seen in D'Arcy Thompson's Growth and Form: but the S-shaped curve promises more than most others, perhaps claiming a place in Nature equal to that of the circle in machinery..... We may well go with Hjort [the great Norwegian marine scientist who, in 1933, with his younger colleagues Ottestad, Jahn and Ruud, applied the logistic to the terrible history of the massacre of the blue whales] in thinking that there is something here that has very wide application, in Nature and in human endeavour." And as I read again the previous chapter of that delightful little book, entitled The Great Law of Fishing, I am struck by the fact that Ray Beverton and I might have done little more than laboriously dot the "i"s and cross the "t"s of what Graham had written a decade earlier – and lost much of the poetry in the process.*

appetite, but the seasick naturalist must attend stations by night and by day, and read the instruments with accuracy."

There have recently been important exchanges of very divergent views, also in *Science*, of the extent to which assessments of the status of fish stocks can safely be based largely on historical catch series (including Stokstad, 2006; Worm *et al*., 2006, 2007; Murawski *et al*., 2007). Experience in the International Whaling Commission (IWC) during the 1980s and 1990s led me to accept that such series are of fundamental importance, provided that management procedures also rely on some measures of stock size or trend, not derived from data from the fishing operations themselves. On this basis the Scientific Committee of IWC recommended, and the IWC itself accepted, a "catch limit algorithm" (CLA) devised by Justin Cooke (Cooke, 1995), to be used for the management of any future commercial exploitation of baleen whales (Mysticeti). Exploration of the robustness and efficiency of the CLA and its general validation were carried out by simulation of the whaling system, which involved the generation of "data" from a variety of population models, in order as far as possible to exclude the possibility that the properties of the adopted procedure were dependent on the properties of a particular model or set of population parameter values. It was de la Mare again who showed us how time-series could be handled efficiently, and later insisted that we were – or should be – looking at the fisheries management problem as engineers rather than as biologists (de la Mare, 1986b, 1998, 2005, 2006). He was ideologically close to Graham in that belief.

The data-generation model used by the IWC was a modification (named BALEEN) of the well-known Pella–Tomlinson generalization of the much used – and abused – logistic; this modification allowed some age and sex structure to be simulated, and a wide range of parameter sets were tested. Whalers and their governments were interested only in the numbers of whales that could be killed and could not be persuaded to take account of the fact that older, bigger whales yielded much more meat and oil than younger, smaller ones, so the models considered dealt only in population numbers, not biomass, and hardly at all with reference to age composition. For general fisheries purposes, however, modelling of length and/or weight distributions is obviously essential. This is where what Beverton and I (using engineering terminology) called a self-regenerating yield model (S–RYM) might be useful. It combined the simple yield-per-recruit model with a simple density-dependent relationship between the number of parent fish and the subsequent number of recruits to the fishery from their reproductive efforts, a relationship that has been used extensively in subsequent research. The S–RYM was very tedious to compute using what was available to us – a robust German (Brunsviga) manual rotary calculator; it called for iterative solution. Nevertheless, we did manage to complete some trials using stock–recruitment data for North Sea haddock (*Melanogrammus aeglefinus*). A feature of the results that I did not notice until very recently was that at very high values of fishing mortality (hence low stock levels) the curve of steady-state yield against stock biomass was, for some parameter sets, inflected, indicating the phenomenon of depensation (also known as the Allee effect), even though the stock–recruitment curve itself did not have that property. In classical population models, the net rate of population increase (crudely, the difference between the reproductive rate and the natural mortality rate) increases steadily – though not necessarily linearly – as the population decreases in size or density; the highest net rate of increase is when the population is tiny, nearly extinct. This process is called compensatory density-dependence. However, it is possible that the net rate of population increase, as the population is reduced, at first exhibits compensation, then begins to decline again. This phenomenon is called depensation. It causes the population to have very different dynamic properties at low densities such as may be encountered in intensely exploited (overfished) situations. One consequence is that the population will recover from a depleted state more slowly than might otherwise be expected when fishing is reduced or pauses. It is theoretically possible for depensation to be "critical", such that the depleted population will move towards extinction even if fishing ceases.

For many years, little notice was taken of the S–RYM. Then, Pitcher (1998) drew attention to it and noted that a hitherto unpublished illustration of it had appeared on the cover of the 1993 reprint by Chapman and Hall of our 1957 book; it is repeated on the cover of the fourth, 2004, printing. Ray Beverton was responsible for getting that through the publication maze and I can only think that he arranged it but told no one. This reminder led me to begin thinking about the S–RYM as a possible data-generator for fisheries applications of the IWC approach to management. The theoretical extinctions to which Pitcher referred would only occur if a high rate of fishing mortality was sustained after the stock had been driven down to critical levels. In the IWC application to whaling, "deep" depletion (or continued exploitation of already deeply depleted stocks), would be avoided by a cessation of whaling when the stock was assumed to be at a level far above any assumed critical level; this was natural because the object of the management procedure adopted in 1974 and revised in a new form in 1991 was not merely to avoid the possibility of extinction or deep depletion, but rather to lead stocks to optimal levels close to a presumed maximum sustainable yield level (MSYL). Furthermore, in our original studies of North Sea demersal species, Beverton and I looked at stocks that were depleted in the sense of being at biomass levels that were below those that would provide a maximum yield-per-recruit, but not so depleted that recruitment was obviously reduced. Also, the size/age composition of the stock and of the catch from it were at least as important as biomass. Therefore, the intent of management was to reduce fishing intensity and thus to improve the stock, with possible additional beneficial results in strengthening average recruitment and in reducing biomass and catch variability. Needs changed when, later, many stocks became seriously depleted by the introduction of intense fishing for young fish, mainly to produce fishmeal and oil, and questions arose as to whether fishing should pause or continue even if drastically reduced.

An opportunity, and for me a stimulus, to look further into this matter arose from the decision in 2006 by the European Commission to propose a change in the EU Common Fisheries Policy (CFP) towards designating MSY as the target reference point for managing fisheries fully under EU jurisdiction, i.e. within the common Exclusive Economic Zone (EEZ)[d]. The motivation for this choice was the identification of that goal – with qualifications – in the UN Convention on the Law of the Sea (UNCLOS) and in UN declarations from major environmental and "sustainable development" conferences in Rio de Janeiro and Johannesburg. There has, of course, been much criticism by the fisheries research community of MSY as a management target, not least by me, and famously by Larkin (1977). However, given the political mandates, it seemed to me worth seeking acceptance of the EC's move by, in effect, *redefining* sustainability and MSY and the process by which the latter would be approached. This the IWC Scientific Committee had done by making the target the attainment of the highest possible *cumulative* catch

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[d] *"Implementing sustainability in EU fisheries through maximum sustainable yield. Communication from the Commission to the Council and the European Parliament". Commission of the European Communities, Brussels, 4.7.2006 COM (2006) 360 Final; and the accompanying "Commission Staff Working Document" entitled "Technical Background to the Commission's Communication...," SEC (2006) 868.*

over a pre-defined period, subject to other constraints[e]. The other constraints were that there would at no time during the defined period be more than a very low – also pre-defined – probability that the stock would be depleted unintentionally below some pre-defined low level; that changes in catch limits set each year would be as small as was feasible and consistent with the main objectives (this would be to the advantage of the industry); and that the stock would be left as large as possible at the end of the management period. The operational constraints were that catch limits are not negotiable during the management period except, very rarely, to meet emergencies that might arise from entirely unexpected events[f]. The idea that sustainability would be defined in terms of a finite and specified time period, rather than, as is usual in current discourse, vaguely, stretching to a presumed infinite time, seems to me to be of fundamental importance, not only for fisheries but for all discussion of sustainable development.

In presenting my proposed application of this procedure to the European Parliament, I added a possible further constraint: that the CLA should be such as to minimize (as far as is compatible with the other constraints and objectives) the probability that it would be necessary to set a zero catch limit, i.e. to close down the fishery, even if only temporarily. Further, it seemed to me that rather than talk about a CLA on the lines of the proposed IWC management system (see below), it would be better to establish an allowable catch and/or effort algorithm (ACEA) to provide for an eventual choice between limitation of catch and limitation of fishing effort, or a combination of both. As I write now the Reporter of Parliament's Fisheries Committee is composing her proposals for Parliament and subsequently for the Council of Ministers and the Commission regarding these issues. Of course, the IWC has decided to adopt a Revised Management Scheme (RMS) that incorporates a Revised Management Procedure (RMP); other elements of the RMS include provisions to ensure compliance and enforcement, and some would like it also to include provisions for less inhumane killing of whales. The RMP incorporates the CLA referred to; it also includes a procedure for applying the CLA to a number of stocks of the same species in a designated region, the geographic boundaries of which, and the degree of mixing between, are uncertain. Also, although the CLA is, strictly speaking, a single-species-stock procedure, the IWC Scientific Committee explained

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[e] *The Development Group of the IWC's Scientific Committee paid scant attention to the choice of time-frame. The period chosen was 100 years, and this was primarily because of limitation of available computing power at the time; the requirement increases as a power function of the length of the period. This also is harmonious with the inter-generational periods and life expectancies of both whales and humans, and it also makes sense to take into consideration the expected duration of stable management provisions and structures. Recently, scientific advisors to the Government of Norway have noted that a longer period through which to calculate cumulative catches will shift the risk and permit higher catches in the short term and hence would benefit present whalers/fishers, naturally at the expense of the future. For an account of this, see Papastavrou and Cooke (2006).*

[f] *My proposals along these lines are contained in two submissions to the EC Advisory Committee on Fisheries and Aquaculture (ACFA): "Commentary on Commission Staff Working Document" dated 11.09.06, and "Commentary" dated 10.09.06. Subsequently, I wrote two technical papers prior to consideration of the Commission's proposals by the European Parliament. One of these was for the Worldwide Fund for Nature European Policy Office ("New Policy Objectives and Management Procedures for European Fisheries. A Commentary and Suggestions", 55 pp., 27.01.2007) and the other, less technical, for the Greens|European Free Alliance ("A Commentary and Suggestions to The Greens/European Free Alliance in the European Parliament", 23 pp., 08.02.2007). These were circulated in the Fisheries Committee of Parliament, accompanied by my summary of them presented at a Hearing on the issue by Parliament.*

how it can deal with management of several co-existing and possibly interacting species without calling upon the development and use of multispecies population models, that are extremely data-intensive and which introduce additional uncertainties. The arrangements for developing and testing candidate RMPs were, I think, unique in the world of fisheries science. A Development Group was initially comprised of five competing persons or teams (ultimately only three, de la Mare, Cooke, and Butterworth and Punt, the last two also having contributed to this volume) – the Japanese and Icelandic contestants having dropped out of the contest. The group adopted their own test criteria and rules, the late Geoff Kirkwood led the collective, and a few others, including myself, participated with one aim being to try to think of situations that would test the candidate procedures to destruction.

During my work for the European Parliament, I realized that although in general the self-regulating model could only be computed iteratively (not, of course, now so difficult as it was 50 years ago!) it could be solved directly in a special case, this being when only the mature segment of the stock is exploited. This makes it easier to explore some of the general properties of the model. My advisory to WWF Europe contains both the quite simple algebra and some illustrations. As the European Commission deals with management of some deeply depleted stocks, aimed at their restoration, the possibility of depensation in the stock–recruitment function used could become critically important. It has been the custom to assume that there is no depensation unless the opposite is shown to be likely. In the circumstances, that is clearly not a precautionary null hypothesis, and recent reviews have shown that depensation may be quite common (Myers *et al*., 1995, 1999; Liermann and Hilborn, 1997)[g].

For a modified S–RYM to be considered possibly as a suitable data-generator for simulations to be undertaken to develop a robust and efficient ACEA, it is, I think, necessary to incorporate a stock–recruitment function other than the commonly used Beverton–Holt asymptotic hyperbolic form or the other most commonly favoured function proposed by Bill Ricker, in which recruitment begins to decrease at high parent numbers. In our concern especially for safe management of the continued exploitation of stocks that are already intensely exploited, what happens at the right-hand side of a curve of recruitment against some appropriate measure of stock size is of little importance; what matters is the behaviour of the function near the origin. Many stock–recruitment functions have been proposed over the years, and it is not uncommon for biological rationales to be mounted in favour of them. Again, it seems to me that the important issue is not the rationale, but simply their geometric properties. Few of those proposed provide for depensation at low densities, and those that do are mostly inflexible in other respects. I have proposed (in my advisory to WWF Europe) a very simple function with the properties desirable for testing candidate ACEAs, and have illustrated its basic properties.

Figure 1 illustrates the properties of a simple equation that can mimic many types of previously published relationships and is convenient to use in simulations using “data” generated from self-regenerating models. It is $R = B^m/(1 + B^n)$, where R is the number of

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[g] *For details and further consideration of this matter, see Holt (2007). One problem we face in discussing it is a not uncommon misunderstanding of Occam’s Razor, wherein it is assumed that a preferable function is one with fewer parameters. Therefore, the Beverton–Holt and Ricker stock–recruitment functions can both easily be caused to exhibit the Allee effect – depensation – by adding a parameter. This is illusory because the simple form can equally be regarded as having the extra parameter but with value unity. As we shall see, however, other flexible models/functions can be formulated with no additional parameters.*

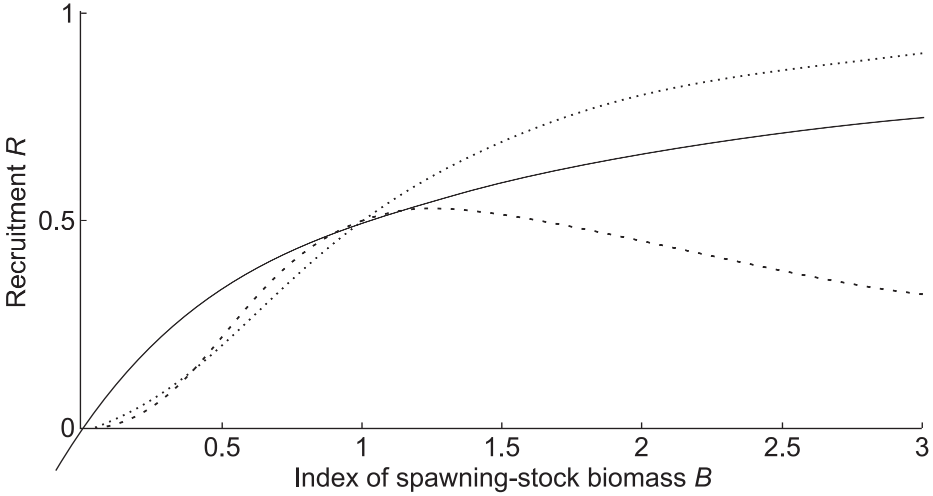

Figure 1. Recruitment as a function of the size of the spawning stock.

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

Now I offer a caution. Lars Witting, a Danish geneticist–evolutionist working in Greenland, has recently put forward cogent arguments that what has usually been called the intrinsic growth rate, **i**, of an animal population cannot, for evolutionary reasons, be an exponential function as assumed by P. F.Verlhurst, the "father" of the logistic population model, and in practically all subsequent theoretical studies in population dynamics. The simple argument is that if we begin with a small population in which individuals have a range of values of reproductive and mortality potentials, in which there is some genetic element, then natural selection will lead to a population in which the resulting average intrinsic growth rate takes what Witting termed a hyper-exponential form (Witting, 1997, 2003). If correct, Witting's finding may have enormous implications for fish stock assessment and the management of fishing (Holt, 2006b).

Witting was persuaded by colleagues in the IWC Scientific Committee to look at the data for the exploitation history of the eastern Pacific grey whale that was almost exterminated by commercial whaling, "modern" style, towards the end of the 19th century, but which subsequently recovered under protection. That recovery has been monitored better than for any other whale species, mainly because the species swims fairly close to shore in its annual two-way migration between the Arctic and breeding lagoons and coastal areas in Mexico (and once upon a time, also in Southern California), so can be counted visually from various locations along the coast. The trouble is that it has recovered to very much higher levels than can be accounted for by consideration of its well-documented catch history, even without taking into account that in the intervening period much of its original breeding area has been lost to human industry and habitation. A feature of population models incorporating Witting's hypothesis is an expectation of long cycles of abundance, quite different from cycles driven by other oscillation-inducing features of orthodox dynamics such as interspecies interactions and long time-delays between birth and maturity. In short, the abundance data are well fitted by Witting's model and not at all by orthodox procedures. The latter result in estimates of current sustainable yield of grey whales at several hundred animals, over and above the couple of hundred a year killed by the Russians on behalf of the aboriginal people of northeastern Siberia. Witting's assessment is that the current sustainable yield is zero (actually negative), because the whale population is now near the peak of a natural cycle and will soon decline regardless of whether it is hunted.

Lars Witting is not the only scholar making waves in the field of population dynamics. Another – but who has not concerned himself with marine animals – is a Russian physicist, Sergei Kapitza, whose interest has been in the long-term history of human populations, so he pursues the path cut in the 19th century by Malthus, Verlhurst, Pearl and others. Kapitza's population model for humans gives a time-trajectory that looks superficially like the familiar logistic, but has very different properties. For a start it exhibits strong depensation, with the relative rate of increase of small initial populations accelerating as they grow, decelerating only when they have attained a substantial fraction of what will be their eventual asymptotic size (Kapitzka, 1992)[h]. His model is derived from theoretical principles and has one property not at all common in this field but beloved of many physical scientists – it is self-similar, i.e. its properties are independent of scale. I am not suggesting that Kapitza's work is as fundamental or as revolutionary as that of Witting, but rather give these examples to illustrate the possible emergence of a new paradigm in this field, challenging some of the simplistic assumptions of more than a century ago on which our population dynamics house – is it a house of cards? – has been built.

So what else is new? Two current fashions now occupy much space in the scientific literature, and references to them will be found in several chapters of this book. The trigger words are "environment" and "ecosystem", words that are rare to the threshold of visibility in Beverton and Holt (1957) but at least deserve comment here, even though a few words cannot do justice to these important topics. The former was, 50 years ago, not an all-embracing term, but implied the surroundings of an object of study, with which the object interacted in some way. Chemical pollution, even habitat destruction, were not yet recognized problems in the 1950s, but the possible effects of fishing – especially bottom-trawling –- on the seabed and its biota was a subject of concern and controversy, though there were few data and no consensus. This situation seems to persist today with respect to deep-water trawling, and I think the concern is justified even if proof of significant damage (except to corals) is lacking. The interaction of our living object, an individual plaice (*Pleuronectes platessa*) with its environment, was obviously very

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[h] *S. P. Kapitza "World Population Growth" A paper with this title was presented to the 43rd Pugwash Conference on Science and World Affairs: "A World at the Crossroads: New Conflicts, New Solutions", held in Sweden in 1993, and subsequently published in the Annals of Pugwash, pp. 539–558. Another version of the paper had appeared as "World population growth as a scaling phenomenon and the population explosion" in L. Rosen and R. Glasser (eds), Climate Change and Energy Policy, Los Alamos National Laboratory, AIP, NY, in 1992, and as the reference given.*

important in one respect: its grazing on benthic food, in this case mainly small bivalve molluscs and worms. There is an immediate problem: we would need at least a three-species model to explore the dynamics of that predation. The classic two-species models of Lotka and Volterra would not do the trick, and even they were "simple models with very complicated dynamics", as Bob May later showed (May, 1976). Further, there were no field data. Yet it was important, we thought, to try to take some account of the possibility of density-dependent growth in size, and the best we could do was to take some account of metabolic rates and food consumption measured in a few – a very few – experimental situations, and to apply static rather than dynamic models to interpret them.

If we now move forward 40 years we find the IWC Scientific Committee facing similar difficulties: developing a single-species management system but concerned about possible environmental changes, including changes in the whales' food supplies, which may or may not be caused by the activities of the whales themselves, possible competition between the several target species with overlapping diets, and physical changes in the ocean. There was no way to model these and other phenomena, and not only because data were sparse. It had become clear that practical application of multispecies models, for instance, suffered from the fact that the outcomes were seriously sensitive to the particular functional forms built into the models to represent interactions among pairs of elements within them. Simplistic assumptions of linearity, analogous to the assumptions in the logistic population model, were all well and good for exploring general properties, but by no means safe as instruments for management. The solution offered by the CLA developers was simply to assume huge changes in "the environment" in both the short and the long term, persistent or ephemeral, and to find efficient algorithms that were robust to such changes of unknown cause and provenance, the effects of which would be corrected by the periodic monitoring process built into the procedure. That seems to me the way to go in fisheries management more generally, rather than through the building of ever more complex multispecies models that also include explicit environmental variables, all of ever-increasing sensitivity and, eventually, uncertainty, regardless of the amassing of vast quantities of biological and other environmental data. There, I have laid myself open to vigorous contradiction!

Very early in my life as a scientist I was advised "Don't spend too much time reading 'the literature'. Go solve the problem, then visit the library to see if someone else already did it." Sometimes I feel that there are few new questions under the sun. Again, Graham in *The Fish Gate* wrote of the magic of the ogive. He had commented on Gompertz and Verhulst putting a cap on Malthus, thinking "what would happen to the numbers of the population if there were some brake or check, as it might be some increase of mortality, or disinclination to breed so young as before, that acted increasingly as the population became more dense." Then, "I need hardly add that there are many unanswered queries. Do we use it [the sigmoid] for a single species or for the weight of all taken together? Does it hold at very low levels, or is there a threshold below which extinction comes? Should herring be counted in with trawl fish? If food fishes are reduced, and inedible kinds increase, has the maximum limit been lowered? If so, is the lowering permanent or reversible? Does the trawl by its action on the bed of the sea raise the maximum limit? Or does it lower it? In the end, though, practice is better than theory. It is comforting to turn away from theory… Whatever argument there may be about the best theory, there can be none about the best action…." Here, Graham was intending international agreement to prevent the fishing fleets growing again to the excessive capacity they had reached pre-war.

As for "the ecosystem approach to management", I am tempted to reply as Mahatma Gandhi reportedly did to the question "What do you think about western civilization?": "That would be a good idea!" In my view the "ecological" concept of the *ecosystem*, like that of the *biosphere, sustainability* and even of *Gaia*, has become trivialized by its entry to the eco-political vocabulary and, even worse, by becoming a meaningless oxymoronic couplet – "ecosystem approach" – like "sustainable development". The founding references to these marvellous ideas and discoveries are read too infrequently and – I suspect – not at all by those who utter them most. To them I would recommend study of Jacques Grinevald's brilliant, synthetic Introduction to Mark McMenamin's English translation of V. I. Vernadsky's book, *The Biosphere*, first published in Moscow in 1926, my year of birth (Vernadsky, 1998)[i].

Now, stepping down from my pulpit, I will say that we humans are not yet ready to manage marine ecosystems (although we are pretty good at wrecking terrestrial ones). In fact we don't "manage" any wild marine populations, and the best we can hope for is to learn how to manage our own behaviour, which certainly affects them, and we are not doing too well at that, either, notwithstanding the cautious optimism of Beddington *et al.* (2007). Nevertheless we do have the option of managing our multiple-use of pieces of ocean space coherently, and in such a way as to ensure maintenance of their biodiversity[j] and biological productivity, and their ability to continue to provide a variety of goods and services for ourselves and for future generations. If that is "ecosystem management", then I'm all for it.

Let me return just once more to *The Fish Gate*, because for proper perspective we must look wider than science and deeper than a mere 50 years and, like the great Tuscan painter Piero della Francesca, bring together mathematics and art. Closing his derivation of the sigmoid and his praise of the ogive, Michael Graham wrote "…we notice that it also commends itself because of its elegance, because of its resemblance to the curve of a classical moulding. That appeal is far from irrelevant, to my way of thinking: it expresses just that pattern among turmoil that it is a schoolman's duty to trace out – it makes sense in a world that is all too tempestuous. I am writing a history and a biology of fishing, and I have tried to portray a little of the life of the fishermen and of the merchants, of

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[i] *My own take on one of the items mentioned is given in Holt (2006b). Other reading in the present context that I recommend in that same book are Lavigne's Introductory chapter (Lavigne, 2006) and the concluding chapter by Lavigne et al. (2006).*

[j] *Here is another important idea rapidly becoming a buzzword. My advised corrective reading is Ronald Brooks' "Earthworms and the Formation of Environmental Ethics and Other Mythologies: a Darwinian Perspective", pp. 59–91 in "Malthus and the Third Millennium", the Kenneth Hammond Lectures on Environment, Energy and Resources, 2000 Series, University of Guelph, Ontario, Canada, 2001 (eds W. Chesworth, M. R. Moss and V. G. Thomas). Brooks poses the question "The Paradox of Biodiversity – Is Conservation Ethical, Aesthetic, Utilitarian or an Adaptive Strategy?" and calls biodiversity "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?" Sweet and sour food for thought.*

the fish and of their food. The sun and the sea-bed, the net factory and the coal-mine, the prison, the villa and the slum: the marks on scales and the terror of drowning; the courage of youth and the patience of age: all those things go to make fishing, and if I did not think them necessary to a proper appreciation of the subject I would not have written this book. But I think that the most multifarious of processes can be put in summary form, if only you can get the real meaning of them, just as a few sentences in the Magna Carta said all that was needed about the polity of England in those days, and they stand us in good stead still. Hopes and fears of honest men and rogues, all can be governed by those few clauses. It is in the same sense, not in any narrow sense at all, that I think the S-shaped curve governs fishing, and also identifies fishing with a very great number of other processes of growth in Nature".

In closing, I commend the readers of this book to the advances and failings of marine science since Ray Beverton and I penned our original work 50 years ago, and leave readers with these few thoughts as they look at and appraise some of the things that have happened in our corner of science, and its practice, in half a century – and more – and ponder "where next?"

Sidney Holt

Paciano
Umbria
Italy
5 July 2007

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One hundred and twenty years of change in fishing power of English North Sea trawlers

Georg H. Engelhard[1]

ABSTRACT: Fishing vessels differ in fishing power—that is, in the quantity of fish they would catch per unit time if they were fishing at the same time and location—and there is a general trend of increasing fishing power over time. Typically, fishing power studies are limited to comparisons over 1–2 decades, but here I attempt to quantify this trend for English North Sea trawlers over the past 120 years. A review of fishing history shows how sailing trawlers, steam trawlers, and currently both motor otter trawlers and twin-beam trawlers have in turn dominated the trawl fisheries. A huge, overall increase in fishing power has occurred but the trend has been all but linear: fishing power has sometimes "leapt" forward within a few years, but at times has also stagnated for decades. Compared with historical sailing trawlers, motor otter trawlers around the Millennium are estimated to have 50 times higher cod fishing power, and twin-beam trawlers to have 100 times higher plaice fishing power. However, this does not mean that fisheries have become more profitable, because increases in catch rates have lagged far behind those in fishing power, and everything points in the direction of great overcapacity of the current international North Sea trawling fleet.

Keywords: fishing power, fleet dynamics, gear changes, (over)capacity, propulsion method, technological creep

INTRODUCTION

About a decade ago, some brave fisheries scientists in Lowestoft went on board an old sailing trawler, the *Excelsior*, and using a replica of a traditional 1880s beam trawl, fished on plaice (*Pleuronectes platessa*) grounds in the southern North Sea for a week. The aim was to gain insight into the fishing power of the type of vessel that, 120 years ago, was responsible for thousands of tonnes of fish being landed in Britain. The experiment was not considered to be successful because virtually no fish were caught despite the scientists' hard labour (Millner *et al*., 1997). Why was that? Did the crew or the scientists simply lack the fishing skills? Or was the sea a hundred years ago so much richer in fish resources that even a sailing trawler could easily catch sufficient to sustain a fisher's family? In other words: was the zero catch a consequence of a lack of fishing power or reduced abundance of fish?

Clearly, fishing power (sometimes referred to as catching power) has improved steadily over the past century, but very little is known about the speed or the magnitude of the change. Fisheries scientists have addressed this issue since the early days of this field of research: see, for example, Garstang (1900) on the dramatic increase in fishing power when the era of steam-powered propulsion followed that of wind-powered. The continuous improvement in fishing power is also a question that will intrigue a fisher,

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[1] *G. H. Engelhard (georg.engelhard@cefas.co.uk): Centre for Environment, Fisheries and Aquaculture Science, Pakefield Road, Lowestoft, Suffolk NR33 0HT, UK*

not the least those senior fishers who have witnessed technological improvements themselves (and who may not always have seen these reflected in better catches, e.g. when stocks began to shrink).

Beverton and Holt (1957a) provide a range of calculations of fishing power. Their book appeared in the period when steam trawling was gradually giving way to motor trawling (with diesel engines), and they made several comparisons of fishing power between the two. Although more refined, their methods used the same principle as Garstang's half a century before, namely to compare the catch per unit effort (cpue) of a base vessel (base fleet) with data available over a number of years, with the cpue of other vessels (fleet or fleets) that are newly developing. They stressed the importance of standardizing the comparison – ideally, vessels need to operate at the same time and in the same location in order to attempt to standardize for local differences in abundance (note that although straightforward theoretically, such data are in practice often difficult to obtain). Beverton and Holt also provide an early attempt to account for vessel characteristics, such as gross tonnage, and their effects upon fishing power. This makes it easier to distinguish between changes in the fishing power of a fleet caused by changes in gear and fishing technology, and those attributable to increases in the size or engine power of vessels. Such an approach requires the availability of data on the characteristics of individual vessels, which is not often available in historical datasets.

Standing on the shoulders of these giants of fisheries science, and using their basic methodology, I here make a rather bold attempt to address the question: to what extent has fishing power changed over 120 years of English trawling in the North Sea? The period is divided for the purpose into five principal eras, for which I describe the main changes in the fishing fleets, and the changes in their fishing power from one era to another using available cpue data. I conclude by making a standardized comparison across the full time-span.

ERA 1 – 14TH TO 19TH CENTURY: FROM SAILING TO EARLY STEAM TRAWLING

References to some form of trawl fishing in England date back to the 14th century: in 1376/77, a royal commission under King Edward III prohibited the use of a controversial new fishing gear called the "wondyrchoun" that had then been in use in the Thames Estuary for about 7 years. This early, 10-feet-wide beam trawl was already accused by traditional line and net fishers of catching large quantities of small fish in the estuary and destroying "the spat of oysters, mussels and other fish upon which the great fish are accustomed to be fed and nourished" (Graham, 1956; Kennelly and Broadhurst, 2002). Opposition against the trawl continued throughout history, but never halted its development.

There is confusion about how trawling was extended to the open sea, as carried out from wooden sailing vessels. There are claims that the step was taken contemporaneously by fishers from Barking (Thames Estuary) and Brixham (Devon) (Holt, 1895). According to Alward (1911), this means of fishing originated along the shallow sandy coast of Holland, seabed ideally suited to trawling, and was brought to England by Dutch seamen who settled in Brixham after the armada of Prince William of Orange landed there in 1688. However accurate this statement may be, it is clear that Brixham fishers used light beam trawls in the western English Channel well before the French Revolution. The fishery began to expand during the Napoleonic wars, apparently benefiting from provisioning problems associated with high fish prices (Robinson, 2000a). When Anglo–French hostilities ended in 1815, Brixham trawlermen gradually began to explore fishing grounds farther east in the Channel, and settled in fishing towns close to these new grounds. Working from Ramsgate, they reached the southern North Sea in 1821. During the following decades, these fishers gradually advanced farther north in the North Sea, and settled in a number of east coast ports, including Lowestoft, Scarborough, Hull and Grimsby, which developed as important trawling stations (Wimpenny, 1953; Robinson, 1996, 2000a).

Driven by the industrial revolution, subsequent population growth and increasing food demands, especially in newly developing industrial centres, the British sailing trawl industry in the North Sea expanded greatly during much of the 19th century (Robinson, 2000a). Of crucial importance was the construction of the railway network, which opened up the industrial centres as inland markets for selling fish products in a fresh state: fish brought ashore during the late afternoon were transported by rail overnight to reach the inland markets as early as the next morning. There was significant innovation in the design of sailing trawlers between about 1850 and 1880, the period of most marked expansion of the sailing trawl fleet (Figure 1): vessels became larger, carried two masts instead of one and used larger beam trawls with greater catching capacity. During the 1870s when trawling by sail in the North Sea reached its peak, auxiliary steam engines were installed to haul the trawls, and there was widespread use of a "boxing fleet" system, allowing sailing trawlers to stay at sea for longer while their catches were taken ashore by steam cutters – fast, steam-powered vessels that on an almost daily basis travelled between the ports and the fishing grounds until the 1890s (Robinson, 2000a, b). However, despite these developments, it was steam power that caused the decline in trawling by sail from about 1880 on.

Figure 1. Sailing trawler LT337 *Fern* being towed out of Lowestoft harbour by a paddle steamer. Painting by Joe Crowfoot. © Crown Copyright.

Steam had first been used in British sea fisheries in the 1850s, in the form of paddle vessels, such as two paddle steamers introduced in 1856 to Grimsby. However, these initial attempts could not cover the working expenses, and died out (Alward, 1911, 1932). The first commercially successful steam trawlers were converted paddle tugs that during the late 1870s worked out of northeastern English ports (Robinson, 2000b). It was, however, during the 1880s that the steam trawling industry really took off, with the arrival of the first purpose-built steam screw trawlers in Scarborough and Grimsby (1881), Hull (1885), and within a few years each of the other major fishing ports. Steam trawlers had a range of advantages over sailing trawlers. They were not subject to the mercies of the wind, could range further, trawl at considerably greater depths and tow fast enough to encourage the switch to the otter trawl, which was a more effective gear for many fish species than the beam trawl. Further, the supremacy of the steam trawler was ensured by the combination of iron hulls, and later steel hulls, and compound, then triple-expansion, steam engines. This was coupled with a change in vessel ownership structure, from skipper ownership to the development of limited liability steam trawling companies (Alward, 1932; Robinson, 2000b).

Garstang (1900) quantified this first, major change in fishing power of North Sea trawlers. Observing that in the sailing trawl fleet virtually no change in vessel design and only limited change in fishing practice had taken place since about 1880, he adopted the sailing trawler or "smack" as a standard unit of fishing power, and expressed the average fishing power of steam trawlers in terms of smack units. Based on the average annual catches of vessels fishing on the same grounds during the period 1883–1885, he estimated that compared with sailing trawlers, the first steam trawlers were about 2.6 and 4.6 times as efficient at catching plaice and haddock (*Melanogrammus aeglefinus*), respectively, and that the combined fishing power for all demersal species was four times higher.

Newly built steam trawlers gradually increased in size, and Garstang (1900), assuming that tonnage was equivalent to fishing power, estimated that by 1889 the steam trawler had become five times as efficient as the smack, and 5.5 times by 1893. The fishing gear on these earliest steam trawlers was the beam trawl, which had been adopted from the sailing trawler. There was a further increase in fishing power from 1895 to 1898 with the introduction and widespread use of the Granton otter trawl on steam trawlers. In an otter trawl, two comparatively small otter boards or doors, functioning as underwater kites, generated and maintained the spread of the net, making the large and cumbersome beam of the old beam trawl obsolete. Not only was the otter trawl more efficient at catching large aggregations of fish than the beam trawl in use then (by a factor of 1.37 according to Garstang, 1900; see also Lee, 1915), but it could also more conveniently be stowed aboard ship. By 1898, otter trawls were adopted on virtually all steam trawlers. Garstang (1900) concluded that the resulting total fishing power of a single steam trawler by 1898 had become equivalent to eight smack units, or twice that of the 1884 steam-propelled beam trawler.

ERA 2 – FIRST HALF OF THE 20TH CENTURY: DOMINATION OF STEAM TRAWLING

Around the turn of the 20th century, steam trawlers were being built rapidly in Great Britain, and by 1900 their combined number in English and Scottish east coast ports was no less than 1 251, according to official statistics. There was also a continued expansion of the fishing grounds worked by British steam trawlers, which by 1900 included the entire southern and central North Sea (ICES Divisions IVb and IVc), and by the 1920s, also almost the entire northern part (Division IVa; Alward, 1911, 1932; Engelhard, 2005). Before that, steam trawlers had already begun fishing in distant waters, such as off Iceland (1891) and in the Barents Sea (1905). From about 1900 to the late 1950s, steam trawlers (Figure 2) were by far the most important component of the British fishing fleet, and in most of those years landed at least 80% of Britain's entire North Sea demersal catch. However, there was a general decline in steam trawl effort over much of this period. Moreover, both World Wars caused significant reductions in steam trawl effort and landings, partly because vessel movements were restricted or the vessels themselves were lost in the hostilities, and partly because many vessels were requisitioned by the Royal Navy to be employed on war service, especially as minesweepers. As a result of these temporary, substantial reductions in fishing pressure, however, catch rates of many fish species in the North Sea in the immediate post-war years recovered to record high levels. This may have encouraged the rapid recovery in steam trawl fishing effort following both World Wars.

Meanwhile, the sailing trawl fleet only survived into the 20th century in the relatively shallow, southern North Sea (Division IVc), where it was almost entirely based at Lowestoft. The last sailing trawlers especially targeted flatfish including sole (*Solea solea*), brill (*Scophthalmus rhombus*), turbot (*Psetta maxima*) and plaice, which have relatively high market value and for which a beam trawl is a particularly appropriate capture gear, when compared with the otter trawl used on steam trawlers. This, combined with low running costs, to some extent allowed sailing trawlers to compete with steam trawlers at a time when coal prices were often high. It could, however, not stop the

Figure 2. Great Yarmouth docks in the 1930s when steam drifters, along with steam trawlers, dominated British fisheries. Note YH89 *Lydia Eva* (right), England's sole surviving steam drifter and currently in the nation's "Core Collection of Historic Vessels". © Crown Copyright.

demise of the sailing trawl fleet, which was accelerated by the two World Wars. The total number of British first-class (>15 ton net) sailing trawlers (including all coasts) declined from 925 in 1900 to 380 in 1920. Then, from 41 vessels still fishing in 1937, only one remained active in 1946 (Engelhard, 2005).

Wimpenny (1953) reviewed the main gear developments during the first half of the 20th century, the so-called golden age of steam trawling. The original Granton otter trawls which had been introduced to steamers in 1894 were in general use until the First World War, but thereafter it became practice to strengthen the groundrope with rollers so that trawlers could work grounds that were previously too rough and which had been estimated to occupy about 17% of the North Sea floor. The gear was further improved by tickler chains spread across the mouth of the trawl in front of the groundrope, which stirred up the fish in front of the trawl that would otherwise have stayed too low to be captured. A further modification was the Vigneron–Dahl gear, first introduced in 1923 and in general use by 1926. This consisted of lengths of cable introduced between each otter board and the net, with the effect of sweeping a wider area than the normal trawl opening, and causing more fish to be herded into the mouth of the net. It also allowed a reduction in the size and hence the resistance of the net (Graham, 1956). The Vigneron–Dahl gear, compared with the standard otter trawl, was estimated to have improved the fishing power of steam trawlers by a factor of 1.5 for haddock (Bowman, 1932) and 1.25 for plaice (Wimpenny, 1953).

Based on the co-occurrence for many decades of both sailing and steam trawlers in the southern North Sea, and following Garstang's (1900) approach, I have attempted to quantify the fishing power of North Sea steam trawlers in terms of contemporary smack units (Figure 3). Note that Lowestoft sailing beam trawlers are here designated as the base fleet (*sensu* Beverton and Holt, 1957a), given that their fishing methods appeared to have remained practically unchanged since the late 19th century, and it is against those that the cpue of steam trawlers is being compared. Calculations were based on the cpue of cod (*Gadus morhua*) and plaice by sailing and steam trawlers, matched by year and by area or rectangle, for two periods where sufficient data were available: 1906–1914 (based on Board of Agriculture and Fisheries, 1908, ff.) and 1924–1932 (based on Ministry of Agriculture and Fisheries, 1921, ff. and Defra Statistical Charts, catalogued in Engelhard, 2005). The effect of vessel tonnage was not taken into account in this comparison, which instead shows how fishing power differed between a typical sailing trawler and a steam trawler at that time.

It appears that, in both periods, the typical steam otter trawler caught about four times more plaice, and about 10–20 times more cod per hour fished than the contemporary sailing beam trawler. The greater difference in fishing power for cod than for plaice relates to the otter trawl being better suited to catching roundfish and the beam trawl to catching flatfish; in addition, the faster towing speed of steam trawlers gave extra advantage when relatively fast-swimming fish such as cod were being caught (cf. Main and Sangster, 1983).

Surprisingly, these values do not suggest that the fishing power of the typical steam trawler operating in the southern North Sea during the inter-war years was better than during immediate pre-WWI years. In fact, it even appears that their relative fishing power for cod (compared with sailing trawlers) decreased from 1924 to 1932, albeit from a likely peak just after WWI. This was despite the several gear developments mentioned above, and notwithstanding a number of new, large steam trawlers being built then. However, almost all new steam trawlers became employed in trawl fisheries beyond the North Sea,

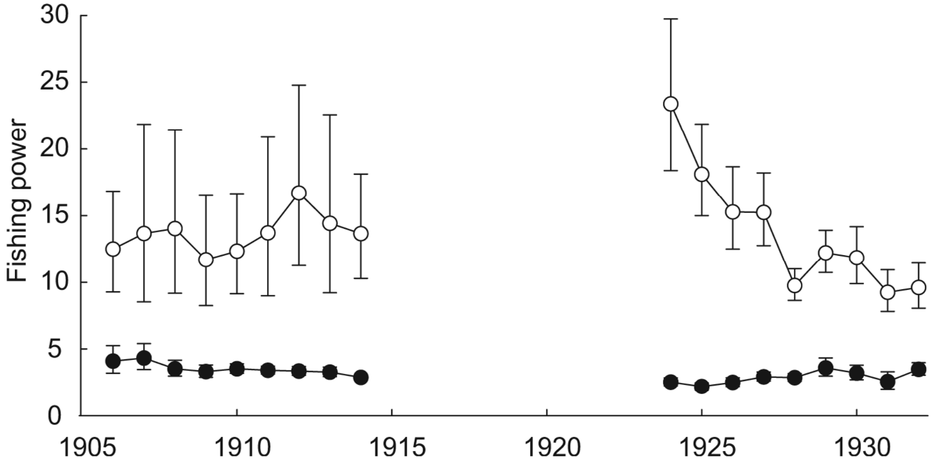

Figure 3. The relative fishing power of the steam otter trawler fleet compared with the sailing beam trawler fleet in the southern North Sea during the periods 1906–1914 and 1924–1932, catching cod (open symbols) and plaice (closed symbols). Fishing power is defined as the ratio between steam and sailing trawler cpue for the same year and within the same area. For each year, symbols indicate the geometric means (with standard error) by area, but note that the data for the two periods may not be strictly comparable. First, in 1906–1914 effort was quantified as days absent from port, and in 1924–1932 as number of hours fished. Second, in 1906–1914 fisheries statistics were aggregated spatially into four so-called regions based on depth contours (regions A1, B2, B3 and C3 in Board of Agriculture and Fisheries, 1908), whereas in 1924–1932 the data are by statistical rectangle. Nevertheless, the figure is considered representative of general trends in fishing power.

such as around Iceland (Robinson, 2000b) and in the northern North Sea, where cod and haddock are more abundant. Although it is probable that there was some size increase in trawlers operating in the southern North Sea, no precise information on this is available (Wimpenny, 1953). Moreover, those steam trawlers that were employed on War Service during WWI had often been the largest and most modern vessels then available; hence, during the inter-war years a relatively large proportion of old vessels was employed in fishing. This was also generally a period of stagnation or decline for many trawling ports (e.g. Boston, having lost half its trawlers during WWI, ceased to exist as a major trawling port in the 1920s), and only the distant-water trawl fisheries (especially Hull) expanded markedly in those years (Robinson, 2000b). Finally, one of the assumptions in these fishing power calculations, the consistency of the fishing power of the base fleet of sailing trawlers, may have been compromised to some extent. First, there might have been some efficiency increase, for example if only the most successful sailing trawlers remained in the declining fleet while less successful ones were decommissioned; second, vessels might have altered their species-targeting strategies; third, owing to the strong decrease in the total number of sailing trawlers over those years, the remaining vessels in this fleet may well have benefited from better catch rates through the concurrent release of competitive interactions with other sailing trawlers (cf. Rijnsdorp *et al.*, 2000).

The overall pattern, however, suggests that at least within the southern North Sea, the fishing power of steam trawlers changed very little between the pre-WWI and inter-war years. Nevertheless, it is likely that the northern North Sea witnessed a more robust increase in the fishing power of steam trawlers (cf. Wimpenny, 1953).

ERA 3 – 1950s AND 1960s:
STEAM GIVING WAY TO DIESEL

I consider it again likely that from 1930 to the early 1950s, there was little change in the average fishing power of British steam trawlers fishing the North Sea. In particular, the fleet of the 1950s was mostly old: as late as 1952 no fewer than 637 vessels of the British near- and middle-water fleet[a] of 817 vessels >70 feet long had been built before 1921 (Robinson, 1996). This resulted partly from under-investment in near-water fisheries during the difficult inter-war years (Robinson, 1996, 2000b), and partly from the fact that as in WWI, those trawlers requisitioned by the Navy to serve in WWII as minesweepers were usually the larger and newer ones of the fishing fleet. During warfare many of those vessels were lost, often with their crews. Then, after the war, surviving Admiralty trawlers were only gradually released from naval service. Finally, large new steam trawlers built immediately after WWII were mainly destined to fish the distant grounds, so older vessels dominated the steam trawl fleet working the North Sea.

Nevertheless, a number of important changes did take place in steam trawlers during the decades post-WWII. Originally, all steam trawlers burned coal, but in 1946 the first oil-fired steam trawlers were introduced. Still driven by steam, those vessels replaced coal with a fuel much easier and cleaner to handle, less bulky and at the time still relatively cheap. Soon thereafter, all new steam trawlers were built as oil burners, and many old coal burners were converted (King and Pulfrey, 1991; Robinson, 2000b). Generally, though, oil-fired steam trawlers had a short life-span because of competition with a segment of the trawling fleet that, although it had already existed before the war, now underwent rapid technological innovations – motor trawlers.

The internal combustion engine had already been used in trawl fisheries before WWI, mainly in Devon and Cornwall; the English fleet in 1912, the first year for which data are available, included six motor trawlers. England's motor-trawl fleet remained small throughout the inter-war years and, within the North Sea, was limited to some 30–40 vessels active in the southernmost and westernmost parts (there was more extensive motor trawling in the English Channel; Engelhard, 2005). Early motor trawlers were often converted sailing craft with a small petrol or paraffin combustion engine, so were about equal in average tonnage. During the period 1924–1932, the fishing power of motor trawlers, in terms of cod or plaice caught per hour fished, appears to have been about 1.2–2.0 times that of contemporary sailing trawlers (Figure 4). In addition to better catch rates attributable to motive power, motor trawlers shared the advantage of steam trawlers of being able to move quickly to and from the fishing grounds, although they could not operate as far from port as steam trawlers. A significant issue in early years, especially with large trawls, was that it proved particularly problematic to adapt the

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[a] *In British fisheries statistics, "Near and Middle Waters" comprise the North Sea, Irish Sea, English Channel and Bristol Channel, and waters adjacent to the Faroes, Rockall, the West of Scotland and Ireland. "Distant Waters" include, historically most importantly, Iceland, the Barents Sea and waters adjacent to Bear Island, Spitzbergen, Norway, Greenland, Labrador, Newfoundland and Portugal.*