



Food for Thought

Contribution to the Themed Section: 'A tribute to the life and accomplishments of Sidney J. Holt'

MSY needs no epitaph—but it was abused

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The maximum sustainable yield (MSY) concept is widely considered to be outdated and misleading. In response, fisheries scientists have developed models that often diverge radically from the first operational version of the concept. We show that the original MSY concept was deeply rooted in ecology and that going back to that version would be beneficial for fisheries, not least because the various substitutes have not served us well.

Keywords: carrying capacity, ecosystem-based fisheries management, multispecies MSY, Sidney Holt

Introduction

Although maximum sustainable yield (MSY) is enshrined in national and international law (e.g. in the UN Convention on the Law of the Sea—UNCLOS 1982), the original concept of Schaefer (1954) derived from the logistic curve of population growth is frequently viewed by fisheries and other scientists as an outdated notion, which has been bypassed by a better understanding of ecological and human systems (Larkin, 1977; Corkett, 2002; Finley and Oreskes, 2013).

Sidney Holt, to whom this issue of the Journal and thus this essay is dedicated, also loathed the concept (Pauly, 2020), as frequently expressed in his private correspondence with the authors. Especially, he often pointed out that there was no single MSY value for a given stock, but rather what he termed “local” MSY values because MSY depends on the size or age at first capture, i.e. the selectivity of the gears used in the fishery (Beverton and Holt, 1957; Froese *et al.*, 2018). He also often found the published results of fitting catch and effort data to an equilibrium parabola as highly questionable. As we shall see, this is understandable, but near the end of his life, he relented and proposed a rational

application of the concept in a letter to the European Commission (Holt and Froese, 2015).

As well, the MSY concept is often criticized by aquatic ecologists who believe that this single-species construct stands in the way of ecosystem-based fisheries management (EBFM) or one of its variants. We have been part of the latter group, judging the original MSY concept as too simplistic with often very unsatisfactory fits, but after using a new Bayesian Monte Carlo Markov Chain approach for fitting the model to available time-series data of catch and cpue for hundreds of stocks globally (Palomares *et al.*, 2020) (rather than using the original parabola fitting, which Sidney Holt rightly ridiculed), we now think we were wrong. We now believe that the MSY concept, although it applies to single-species management (Froese *et al.*, 2008, 2016b), can be, if applied correctly, more useful than many of the overly data-hungry and potentially over-parameterized implementations of EBFM.

To reestablish the compromised credibility of MSY, however, we must first look at its history (Tsikliras and Froese, 2016) roots, which actually go back to very basic Darwinian concepts.

Density-dependent population growth

Evolutionary biology (and there is no other; see [Dobzhansky, 1973](#)) postulates that:

- (1) all organisms produce more offspring than can be accommodated by the environment they inhabit;
- (2) These offspring all differ in heritable fashion; and
- (3) (1) and (2) will lead to differential survival and the enhancement of advantageous traits ([Darwin, 1859](#)).

While (2) and (3) need not further concern us, notably because they involve longer time-periods than considered here, item (1) is crucial because it implicitly identifies the intrinsic growth rate (r) and carrying capacity (k) for each population of organisms ([Figure 1](#)).

[Malthus \(1798\)](#), whose influence on Darwin was crucial ([Herbert, 1971](#); [Pauly, 2004](#)), was the first to explicitly define the growth rate of a population and to compute it for a (human) population. Mathematically, Malthus' model is commonly expressed as:

$$N_{t_2} = N_{t_1} e^{r(t_2 - t_1)}, \quad (1)$$

where N_{t_1} is the population size in numbers at time t_1 , N_{t_2} is at time t_2 , and r is the intrinsic rate of population growth.

[Verhulst \(1838\)](#) was the first to define carrying capacity mathematically. His model can be represented as:

$$\frac{dN}{dt} = r N_t \left(1 - \frac{N_t}{k}\right), \quad (2)$$

where dN/dt is the instantaneous increase in numbers at population size N_t and k is the carrying capacity of the environment for this population.

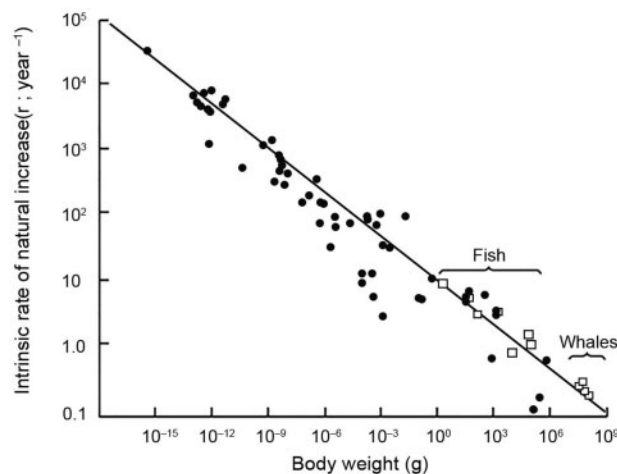


Figure 1. This (virus and) bacteria-to-whale plot is from [Blueweiss et al. \(1978\)](#), with addition by [Pauly \(1982a\)](#), and it shows that the intrinsic growth rate of populations (r) can be roughly predicted from the size of the organisms in question. However, additional parameters must be considered for more precise estimations; see e.g. FishBase (www.fishbase.org) for fish.

Things are more complicated than that in nature where population growth rate and carrying capacity vary, but the concepts embodied in (1) and (2) have served us well. Thus, a huge amount of work in ecology is devoted to establishing the carrying capacity and its changes in various ecosystems (see e.g. [Del Monte-Luna et al., 2004](#)). Similarly, an enormous amount of research is devoted to estimating the intrinsic growth rate of populations, which is primarily a function of the body size of the organisms in question ([Figure 1](#)), but which can vary as a function of longevity and fecundity, as illustrated in FishBase (www.fishbase.org) for fishes.

The first half of the 20th century saw different attempts to identify principles or a “law” that would provide a quantitative criterion by which to assess the status of a fishery, and much good science was performed in the hope to achieve this ([Baranov, 1918](#); [Graham, 1935](#)).

The first abuse

Unfortunately, politics intervened on the way, and the first version of MSY was put together as a rhetorical device by [Chapman \(1949\)](#). His invention ([Figure 2](#)) was a Gaussian curve of sustainable yields as a function of fishing intensity; on its left side was “inadequate” fishing, as reportedly occurred with the Pacific tuna stocks in Central and South America that the US fleet wanted to exploit, and on its right side was “excessive” fishing, as reportedly occurred in Alaska salmon that Japan wanted to fish ([Finley, 2011](#); [Pauly, 2012](#); [Finley and Oreskes, 2013](#)).

Needless to say, this construct, published in an obscure magazine of the US State Department, had no underlying theory describing a Gaussian relation between sustainable yields and effort, but it won the day: Chapman’s “MSY” became the basis of international fisheries negotiation to the great chagrin of Ray Beverton and especially Sidney Holt, who, in the early 1950s, had jointly developed, based on [Graham \(1935\)](#), a scientifically sound approach to rational fisheries management ([Beverton and Holt, 1957](#)).

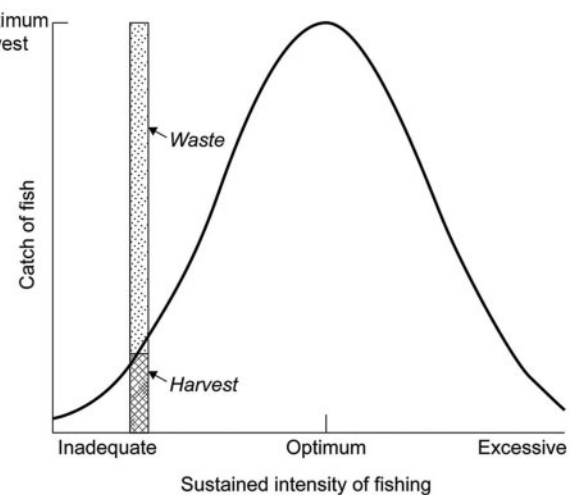


Figure 2. The first and fake representation of a “model” featuring maximum sustainable yield, as published by [Chapman \(1949\)](#). W. M. Chapman never presented a rationale for the Gaussian shape.

Putting things right

In 1954, M. B. Schaefer resolved the embarrassing situation by formulating his surplus yield model (Schaefer, 1954, 1957), which builds on (1) and (2) above, i.e.

$$Y = r B_t \left(1 - \frac{B_t}{B_0}\right), \quad (3)$$

where Y is the equilibrium yield or the surplus production of biomass, B_t is the biomass at time t , and B_0 is the “virgin” or unexploited biomass, the equivalent of carrying capacity k expressed as weight of the population.

Schaefer (1954) set his model in the context of the biology and ecology of his time, as evidenced by his citation of texts such as Lotka (1925), Pearl (1925), Gause (1934), and Nicholson (1947). The Schaefer surplus production model was quickly accepted by the authors of fisheries science textbooks, probably because it summarized in a simple equation a variety of concepts (mortality, growth, and reproduction) that fishery biology students had to know about (Figure 3).

Subsequent implementations of the MSY concept did not try to fit independent pairs of catch and abundance to the equilibrium parabola resulting from (3), but rather to estimate the values of r and k that best explain the observed interannual changes in biomass (B_{t+1}) given the biomass (B_t) and catch (C_t) in the previous year (4) (see Quinn and Deriso, 1999 for similar implementations):

$$B_{t+1} = B_t + r B_t \left(1 - \frac{B_t}{B_0}\right) - C_t. \quad (4)$$

Recent state-of-the-art implementations of (4) are implemented as state-space models using a Bayesian approach combined with Monte Carlo Markov Chain sampling so that prior information on productivity and stock status can be considered and observation and process errors can be separated from the uncertainty in estimates of r and k (Froese et al., 2017; Pedersen and Berg, 2017; Winker et al., 2018).

A further development combines (4) with a simple hockey-stick model of recruitment, such that parameter r , which combines rates of mortality, somatic growth, and recruitment, is reduced linearly if stock size B_t falls below 25% of unexploited stock size B_0 (Froese et al., 2017):

$$B_{t+1} = B_t + 4 \frac{B_t}{B_0} r B_t \left(1 - \frac{B_t}{B_0}\right) - C_t \mid \frac{B_t}{B_0} < 0.25. \quad (5)$$

Model drift

Other fisheries practitioners have modified the original Schaefer model, but without presenting a convincing theory for their changes. Thus, Pella and Tomlinson (1969) proposed replacing the parabola of the Schaefer model by a family of lumped curves derived from:

$$Y = r B_t \left[1 - \left(\frac{B_t}{B_0}\right)^{m-1}\right], \quad (6)$$

where r and B_t are as defined previously, and m was an added parameter determining the shape of the curves, without a firm base in evolutionary ecology or population dynamics, often fixed beforehand based on assumptions, or estimated *ad hoc* from the data at hand (Figure 4a).

The often extremely bad fit of the curve(s) in question to the available data (see e.g. the non-symmetric curve in Figure 4b) should have caused this approach to be dropped. But the Pella and Tomlinson model offered the flexibility that some managers and scientists had asked for. Unfortunately, that flexibility can be abused by arbitrarily choosing a low value of m in (6), resulting in MSY occurring at biomass levels that are much lower than $1/2$ carrying capacity, thus presenting a given stock in better condition than predicted by the original Schaefer model.

Shortly thereafter, Fox (1970) proposed an “exponential” version of the surplus yield model with the new property that “the population can never be eliminated by any finite level of fishing effort” (Fox, 1970, p. 84). This model, which can be seen as a special case of the Pella–Tomlinson model (with $m = 1.0$ and B/B_{MSY} at 37% of carrying capacity), also has no basis in biology. It produces a yield curve with a long tail on the right side, instead of the symmetric parabola of the original Schaefer model. It was, for example, applied to multispecies assemblages in the Gulf of Thailand, which tended to generate concave catch-per-effort over effort curves (Pauly and Chuenpagdee, 2003). The long tail on the right (similar to that in Figure 4b) of such multispecies curves is partly due to the transformation of the exploited ecosystem in question, i.e. the loss of large, slow-growing species (low r) and their replacement by smaller, more resilient species (high r). Stationarity of parameters (here: r and k) over the examined

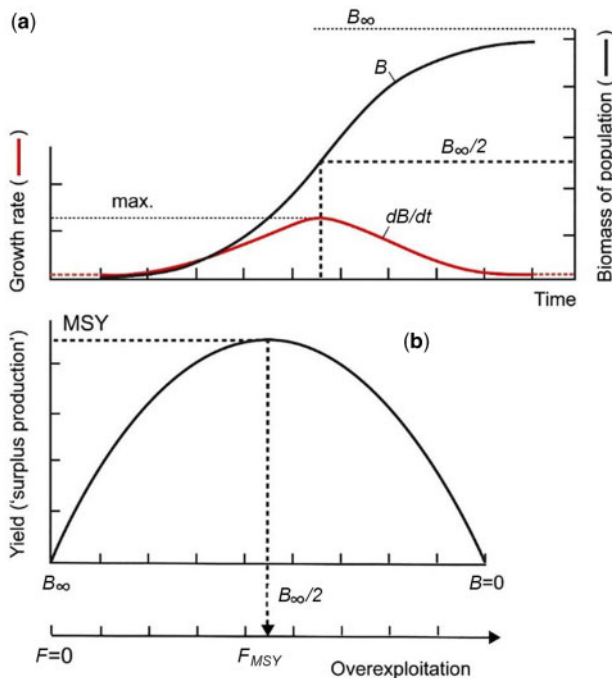


Figure 3. Basic elements of the Schaefer surplus production model. (a) A population invading an open space or recovering from a catastrophic decline will typically grow in sigmoid fashion, i.e. exponentially at first, then with a declining rate as carrying capacity is approached. (b) The first derivative of the population growth curve [red line in (a)] plotted against the biomass from a parabola of surplus production vs. biomass, whose maximum occurs at $B_0/2$ (see text).

period, the basic (if often unstated) assumption of assessment models, was abandoned in such applications.

Moreover, attempts to produce better fits of non-symmetric curves to the available data by ignoring the equilibrium assumption led to misinterpretations of the data and very dangerous conclusions for managers. For example, looking at Figure 4b and assuming low effort marks the beginning of the fishery on a stock with close to unexploited biomass, then the initial catches obtained from low effort will be high because of the high abundance of fish in the water, as predicted by the non-symmetric curve. But these are not equilibrium catches and rather will decrease towards the predictions of the parabola if the respective effort was maintained. Similarly, the two points with the highest effort in Figure 4b, if maintained indefinitely, are unlikely to produce the relatively high yields predicted by the non-symmetric curve, but much more likely the lower equilibrium yields predicted by the parabola. Considering that such high effort would probably push stock size down into the range where recruitment may be impaired (5), true equilibrium yield may be well below half of what is predicted by the supposedly better fit of the non-symmetric curve.

In summary, we have the situation that the fisheries management agencies of several major countries of the world used MSY biomass levels of 30–40% of carrying capacity and very gradual decline in biomass after the peak in yield, while seemingly relying on a model explicitly stating that biomasses lower than 50% of carrying capacity are overfished and stock decline will be rapid.

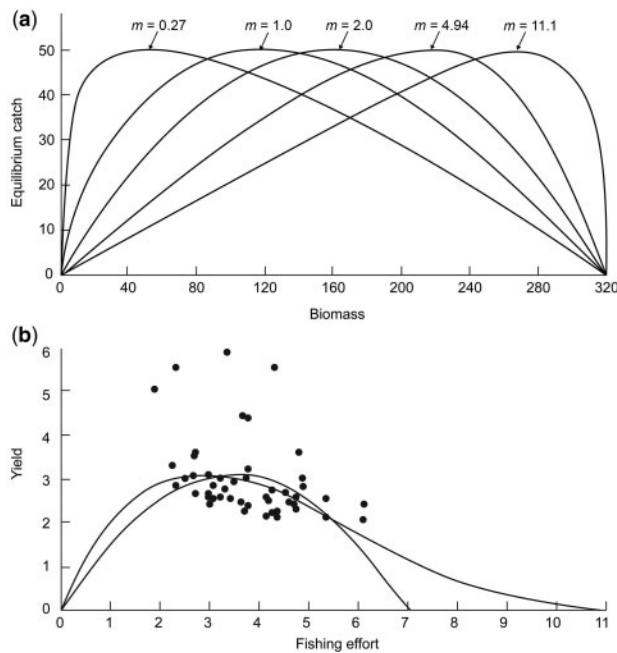


Figure 4. Examples of the equilibrium (= sustainable) yield curves that can be reportedly generated by the Pella–Tomlinson model. (a) By varying the parameter m , a family of curves can be generated. Thus, for example, with $m = 0.27$, the model predicts MSY to occur at about 12% of carrying capacity (adapted from Figure 1 in Pella and Tomlinson, 1969). (b) An application of the Pella–Tomlinson model to catch and effort data on Pacific halibut, compared to the parabolic Schaefer model (Ricker, 1975, example 13.5), supposedly demonstrating the superiority of the former model (adapted from Figure 4 in Rivard and Bledsoe, 1978).

This is further aggravated by the fact that the official stock assessments that produced these estimates are often biased downward because they are based on time-series that are truncated (Prefontaine, 2009), i.e. fail to include available information that suggest much higher earlier biomass (see e.g. Rosenberg *et al.*, 2005).

Note that applications of the yield-per-recruit model of Beverton and Holt (1957) also often suggest maximum productivity between 30 and 40% of unfished biomass. However, this is typically the result of much too high fishing pressure with sub-optimal selectivity causing high fishing mortality of juveniles. We reproduce here as Figure 5 the graph that Sidney Holt (Holt and Froese, 2015) sent to the European Commission in support of his argument that target fishing pressure should be well below the MSY level. If the proposed target level of $F_{\text{lower}} \approx 0.6F_{\text{msy}}$ is combined with the length at first capture that generates the maximum catch for a given F (Beverton and Holt, 1957), then the resulting relative biomass is above 50% of carrying capacity (see Figure 2b in Froese *et al.*, 2016b). This demonstrates the compatibility of the yield-per-recruit model of Beverton and Holt (1957) and the MSY model of Schaefer (1954), if both are applied with optimal selectivity and catch levels.

Another form of abuse of the MSY concept occurs when it is applied to an ensemble of discrete populations. An example of such abuse is the computation of a single MSY based on adding the biomasses of independent seamount-specific populations of orange roughy (*Aplostethus atlanticus*). This obviously does not make sense because the orange roughy populations on different seamounts do not interact such that a declining biomass of one would affect the density, and hence population growth, of the other (Clark *et al.*, 2000). In addition, these orange roughy stocks were managed with a so-called “hard limit” at 10%, a “soft” limit at 20%, and a target value of 30–40% of carrying capacity (MRAG, 2016), a double misuse of the MSY concept which led to the collapse of numerous seamount spawning aggregations (Clark, 2001).

A similar strategy is currently applied to the krill fishery in Antarctica, which justifies its extraction of local populations of

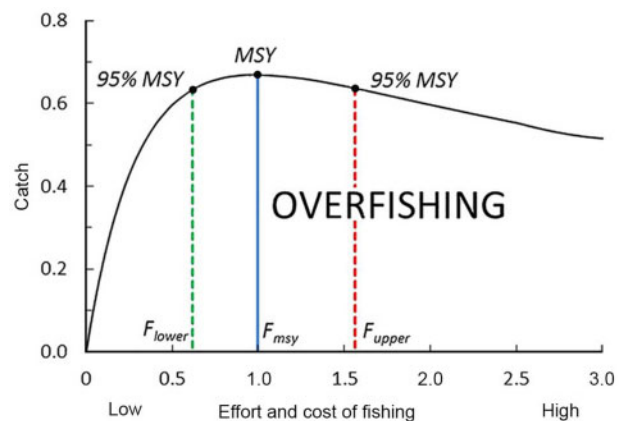


Figure 5. This figure (from Holt and Froese, 2015, with permission) had as its original caption: “Relation between fishing effort or cost of fishing and predicted long-term catches. Note that 95% of the theoretical maximum catch can be obtained with substantially lower effort and cost (F_{lower}) and thus with substantially higher profits for the fishers”.

krill (*Euphausia superba*) with the observation that “[t]he actual annual catch is around 0.3% of the unexploited biomass of krill”, referring to all krill populations in Antarctica rather than to the exploited populations (see www.ccamlr.org/en/fisheries/krill-fisheries-and-sustainability).

The point here is that rates of mortality, growth, and reproduction, which are, we recall, the mechanisms that determine the intrinsic rate of population growth, occur at the scale of local populations, not of species composed of multiple populations.

Why MSY and EBFM are compatible

In principle, most fisheries scientists and relevant legislations and regulations agree that MSY should be a limit, and not a target, for fisheries management (UNFSA, 1995; Froese *et al.*, 2008, 2016b; CFP, 2013; Punt *et al.*, 2014), notably because if it were a target, and successfully implemented, then there would be a 50% probability that the biomass of the managed stock would be below the level that can produce MSY. This generally implies that target biomass should be set above the MSY level, as is done explicitly in recently formulated fisheries regulations (e.g. CFP, 2013).

Moreover, attempts to maximize the rent from fisheries, whether implemented via $F_{0.1}$ (Gulland and Boerema, 1973) or by setting effort at the level which generates maximum economic yield (MEY), as e.g. required in Australia (DAFF, 2007; HSP, 2018), also imply that optimal biomass for stable stock and profitable fishing should be above the MSY level. At biomass levels of e.g. 60% or more of carrying capacity, populations should be much more capable of fulfilling their ecological roles as prey or predator than at the 30–40% levels targeted by supposedly more advanced fisheries models, while at the same time supporting good catches close to the economic optimum.

Thus, with MSY as a limit (see above), fisheries scientists would propose a goal that produces high return for fisheries, high catch for consumers, and far more fish in the water than at present. Moreover, single-species stocks of forage fish should be maintained at biomass levels above 60% of carrying capacity to provide food for fish-eating seabirds, marine mammal populations, and other large predators (Cury *et al.*, 2011; Pikitch *et al.*, 2012).

We are aware that it is not possible to manage multispecies fisheries such that they would get the sum of single stock MSYs. This is obvious from the above mentioned general need to preserve high levels of forage fish to stabilize ecosystems and fisheries, but also from special predator–prey interactions such as documented for central Baltic cod (*Gadus morhua*) and sprat (*Sprattus sprattus*) (Köster and Möllmann, 2000) or from cyclic alternations between systems dominated by anchovy (*Engraulis ringens*) or sardine (*Sardinops sagax*) off Peru (Muck, 1989). Another example is negative correlation between biomass of northern shrimp (*Pandalus borealis*) and Atlantic cod (*G. morhua*) (Worm and Myers, 2003). In two of his last papers (Froese *et al.*, 2016a; Pauly *et al.*, 2016), Sidney Holt joined us in refuting a proposal calling for simultaneous MSY level exploitation of all species in the oceans, from zooplankton to birds and whales (Garcia *et al.*, 2012). In contrast, given the present realities, rebuilding commercially important fish populations towards levels near 60% of unexploited biomass would satisfy what presently appear to be conflicting demands for more fish for consumers, profits for the fisheries sector, and more fish in the water for the conservation community and thus for all.

We are also aware that the assumption of stationarity inherent in most of the above considerations is questionable in an increasing number of cases, given anthropogenic impacts on both the biosphere and the climate. Thus, while the intrinsic rate of population growth (r) may not be much impacted by our activities, the carrying capacity (k) of many exploited populations has changed radically in recent years. Thus, the carrying capacity of multiple species of cephalopods appears to have increased in recent decades, due to the fisheries-induced depletion of large fish, their main predators (Doubleday *et al.*, 2016), as has the carrying capacity of penaeid shrimps in different parts of the world (Pauly, 1982b; Walters *et al.*, 2008) and that of lobster in the Gulf of Maine (Steneck *et al.*, 2011). This is similar to the effect of ocean warming, the reason why fish, since the mid-1970s, tend to shift or expand their distributions poleward, as shown in multiple contributions covering one or a few species (e.g. Perry *et al.*, 2005) or the bulk of the exploited marine fauna (Cheung *et al.*, 2013). In all such cases, the simple models presented here would estimate the average carrying capacity over the period considered. While that may be sufficient for a preliminary assessment of stock status, it may be better to split the time-series data into reasonably stable periods and assess those separately.

Conclusion

In summary, Larkin’s (1977) epitaph for MSY was premature and likely influenced by the misapplications and distortions of the concept occurring in the 1970s. As for Sidney Holt, he had every reason to be outraged by the politics around the MSY concept, such as illustrated in Figure 2, and the lack of biology in its subsequent developments. He especially despised the notion of a single MSY value, when, in fact, that value is a function of length or age at first capture. He, however, conceded, if grudgingly, that surplus production models were better than no assessment in data-limited situations and better than the various schemes to continue overfishing, such as the F_{upper} approach illustrated in Figure 5. We believe that we have much to gain by rehabilitating M. B. Schaefer’s concept of MSY.

Data availability statement

No new data were generated or analysed in support of this research.

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