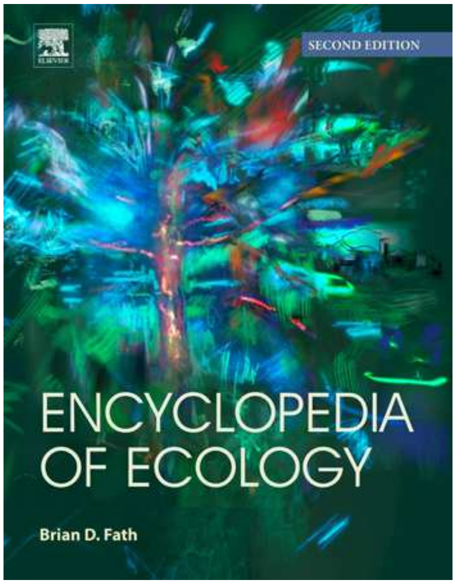

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Maximum Sustainable Yield

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Introduction

Although the term "over-fishing" was coined already in the mid-1850s (Cleghorn, 1854), the overexploitation of marine fisheries resources was only realized in the early 1900s, when the first study (Garstang, 1900) and articles on overfishing (Petersen, 1903; Kyle, 1905) were published. By that time, the need for simple and easy to understand guidance on catch limits emerged. The maximum catch that a population can support seemed to be an excellent reference point for fisheries management.

Maximum Sustainable Yield (MSY) is the most well-known acronym in fisheries science and, as a concept, has a history of around 100 years (Baranov, 1918). It was formulated in the 1930s when mathematical models were introduced in population ecology (Hjort *et al.*, 1933) and bloomed in the 1950s with the development of surplus production models.

Today, MSY has been adopted by the vast majority of regional management bodies (Hilborn and Walters, 1992; Quinn and Deriso, 1999; Mace, 2001; Hart and Reynolds, 2002; EC, 2009; Pauly and Froese, 2014) and it is therefore widely used as a reference point in the assessment of exploited populations (stocks) around the world.

The MSY Concept

Definition of MSY

MSY (also called maximum surplus production, maximum equilibrium catch, maximum constant yield, maximum sustained yield, sustainable catch: Ricker, 1975; Hilborn and Walters, 1992; Quinn and Deriso, 1999; Mace, 2001) is the highest theoretical equilibrium yield that can be continuously taken from a stock under existing (average) environmental conditions (FAO, 2001). It is the highest catch that still allows the population to sustain itself indefinitely through somatic growth, spawning, and recruitment (Graham, 1943; FAO, 2001).

MSY was formally introduced by Milner Schaefer (Schaefer, 1954) who developed the model named after him based on the logistic curve of population growth (**Fig. 1**). Plotting the first derivative (= the slope) of that curve over the corresponding biomass (the collective weight of the individuals at a certain time) shows the increase in biomass (termed surplus production or yield) with time, in the form of a parabolic curve (**Fig. 2**). The interpretation of the parabola is easy: at the left end there is zero biomass and therefore zero yield. At the opposite end, where the population is at carrying capacity of the ecosystem for this stock, there is no surplus production by definition and thus again zero yield. In other words, initially the population grows exponentially, unrestricted by environmental conditions. But as population size approaches carrying capacity, growth slows down and eventually

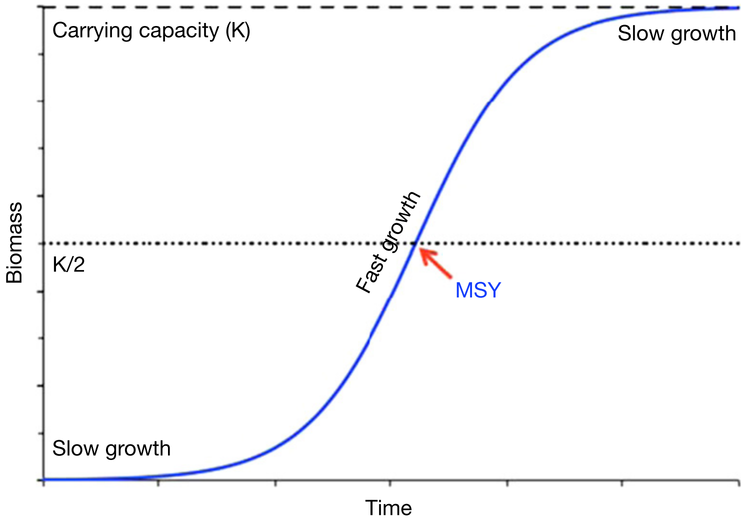

Fig. 1 The logistic (sigmoid) curve of population growth over time. The carrying capacity (K) and MSY (=K/2) are indicated along with phases of slow and fast population growth.

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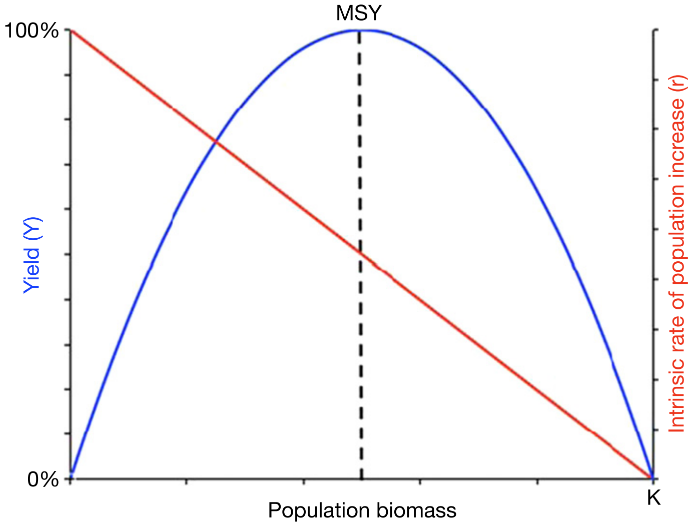

Fig. 2 The parabolic curve of surplus production or equilibrium yield (as % of MSY) as a function of population biomass (as % of carrying capacity, *K*). The second *Y*-axis shows the intrinsic rate of population increase r, which in the Schaefer model is maximum at zero biomass and declines linearly to zero at carrying capacity. Note that MSY is produced at half of r_{max}.

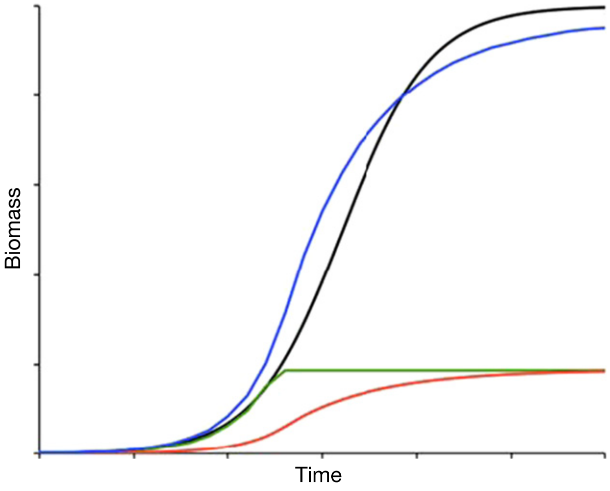

Fig. 3 The theoretical logistic curve of population growth over time (*black line*) compared with a hypothetical curve (*blue line*) resulting solely from the number of deaths (mortality: *red line*) and the number of replacements through recruitment (reproductive success: *green line*), which is more or less constant above about a quarter of carrying capacity.

seizes. Because of the symmetric shape of the logistic curve, maximum surplus production or yield is reached at half of maximum population size in the Schaefer model (**Fig. 2**; see "Methods to Estimate MSY section"). Taking away this maximum surplus production by fishing prevents the population from growing any further, basically keeping it at half of maximum population size, producing maximum surplus forever; hence this is the point of MSY.

In this simple model, the rate of population increase *r* is a linear function of biomass, maximum at zero population size, and zero at carrying capacity (Hart and Reynolds, 2002; Quinn and Deriso, 1999).

Various explanations have been offered for the typical S-shape of population growth, such as improved somatic growth at low population size versus increased intraspecific competition at high densities (Hart and Reynolds, 2002). Carrying capacity (*K*) has been interpreted in Malthus' terms as being caused by limited food availability (Seidl and Tisdell, 1999). However, today most ecologists agree that the main driver of population growth is the interplay between reproductive success and mortality (Charnov, 1993; Sibly et al., 2012): once the number of new individuals equals the number of deaths population growth seizes. At low population sizes, new individuals exceed the number of deaths and population growth is exponential. But while the number of deaths remains proportional to population size, the production of new individuals slows and reaches a more or less constant value once the population has grown beyond about a quarter of carrying capacity. As a result, the exponential growth slows to a linear growth at about half of carrying capacity and declines thereafter, approaching carrying capacity in an asymptotic curve (**Fig. 3**).

Density effects causing death by starvation are thought to apply mostly to early life stages (Houde, 1987; Bailey and Houde, 1989; Hüssy *et al.*, 1997) and cause a limit to reproductive success, as indicated by the green curve shown in **Fig. 3**.

Today, the MSY definition most widely used is the one proposed by Ricker (1975). According to "the green book" of Ricker, MSY is defined as the largest average catch or yield that can continuously be taken from a stock under existing environmental conditions but for species with fluctuating recruitment the maximum catch may be obtained by taking fewer fish in some years than in others (Ricker, 1975).

Related Biological Reference Points

Current fisheries management is based on fishing mortality and biomass reference points that correspond to MSY, although MSY itself is rarely used as a reference point. Two related reference points are applied: one is the fishing mortality or fishing pressure (F_{MSY}) that, if applied over a time span similar to generation time, will eventually result in a catch equal to MSY (**Fig. 4**) where F describes the part of the total mortality rate that is caused by fishing. For example, $F = 0.6$ means that about 60% of the fish that are there on average over the year will be killed by fishing. The other related reference point is the biomass at MSY, B_{MSY}, which is the smallest stock size that can support catches equal to MSY, and which is the biomass corresponding to the peak in **Fig. 2**.

In age-structured assessment models, the fishing mortality that results in the maximum yield per recruit (F_{MAX}) is close to F_{MSY} if the yield per recruit versus F curve has a well-defined peak. However, if that peak is less well defined, as in **Fig. 4**, then F_{MAX} may be substantially larger than F_{MSY} (Longhurst, 2006).

Methods to Estimate MSY

MSY, F_{MSY}, and B_{MSY} can be estimated from surplus production models, which require catch and effort or an index of biomass or relative abundance (e.g., catch per unit of effort) as input. Alternatively, these or similar reference points can be obtained from age-structured models, which are, however, more data demanding.

Surplus Production Models

Surplus production models are used to assess stock status and exploitation in data-limited areas where reliable information on age and length structure and natural mortality are not available (Beverton and Holt, 1957; Punt, 2003). They are applied not only to stocks with available commercial catch data and some index of exploitable biomass, such as catch per unit of effort (CPUE) derived from scientific surveys, but also to migratory stocks and crustaceans that are difficult to age (Polacheck *et al.*, 1993). They assume that sustainable catch is a simple function of population biomass, regardless of the size and age composition of that biomass (Holt, 2014).

The most widely used surplus production model is the one developed by Schaefer (1954):

$$B_{t+1} = B_t + r_{max} B_t \left(1 - \frac{B_t}{K}\right) - C_t$$

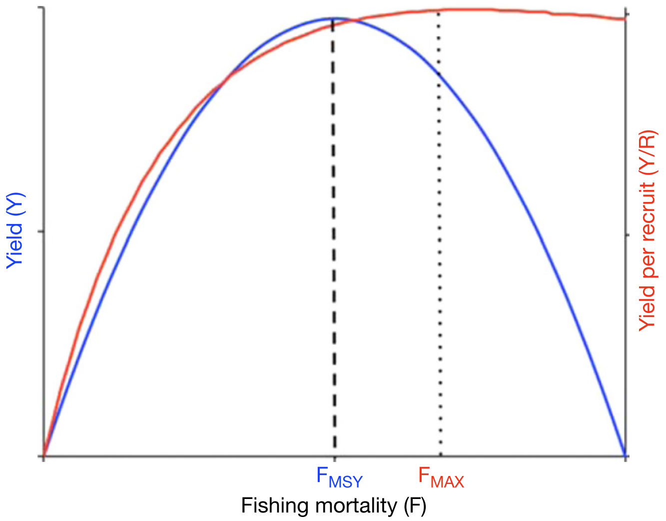

Fig. 4 Difference between the position of F_{MSY}, the fishing mortality expected to yield MSY in a surplus production model (*blue line*) and those of F_{MAX}, the mortality from yield-per-recruit curves (*red line*).

where B_t is the biomass of the stock at time t and $t + 1$, r_{max} is the maximum intrinsic rate of population increase, K is a parameter which corresponds to the unfished equilibrium stock size or carrying capacity, and C is the catch per unit of time (usually a year).

Surplus production or yield (Y) is calculated as:

$$Y = r_{max}B_t\left(1-\frac{B_t}{K}\right)$$

MSY is calculated as:

$$\mathrm{MSY} = \frac{r_{max}}{2}\times\frac{K}{2} = \frac{r_{max}K}{4}$$

where r_{max} is the maximum intrinsic rate of population increase, B_t is the population biomass at time t, and K is the carrying capacity of the ecosystem for this population (Schaefer, 1954).

Another surplus production model was developed (Fox, 1970) that assumes a logarithmic relation between biomass and catch:

$$B_{t+1} = B_t + r_{max}B_t\left(1-\frac{log(B_t)}{log(K)}\right) - C_t$$

where variables and parameters are as defined above.

In the Fox model surplus production or yield is calculated as:

$$Y = r_{max}B_t\left(1-\frac{log(B_t)}{log(K)}\right)$$

MSY is calculated as:

$$\mathrm{MSY} = \frac{r_{max}K}{e}$$

In the Schaefer model, maximum yield (MSY) is obtained at 50% of carrying capacity and in the Fox model at 37% of carrying capacity. Pella and Tomlinson (Pella and Tomlinson, 1969) proposed a model with a third parameter p that determines the shape of the yield curve and allows maximum production to occur at any biomass.

The Pella-Tomlinson model is:

$$B_{t+1} = B_t + \frac{r_{max}}{p}B_t\left(1-\frac{B_t}{K}\right)^p - C_t$$

where variables and parameters are as defined above and p is a shape parameter that results in the Schaefer curve if $p = 1$ and approximates the Fox curve if p approaches 0.

Surplus production or yield is calculated as:

$$Y = \frac{r}{p}B_t\Big(1-\left(\frac{B_t}{K}\right)^p$$

MSY is calculated as:

$$\mathrm{MSY} = r_{max}K\left(\frac{1}{1+p}\right)^{\left(\frac{1}{p}+1\right)}$$

The Schaefer surplus production model is the one most commonly used in fisheries management because of its simplicity and applicability in data-poor stocks.

Age-Structured Models

In cases where age and length data are available, surplus production models have been replaced by age-structured models that also provide estimates of MSY and relevant reference points but these models are data demanding (Hilborn and Walters, 1992; Mace, 2001) and require population age and length, growth parameters, mortality and maturity, as well as selectivity of the main gears. Estimates of MSY, F_{MSY}, and B_{MSY} are typically obtained from stochastic simulations.

Age-structured models are widely used in assessing stocks and require estimates of mortality, maturity, catch, and abundance per age group, but these models are not suitable when only catch and biomass data are available.

Economic Considerations

Only 150 years ago, the advisor on fisheries to the British Government (Huxley, 1884) declared that humans were unable to overexploit marine fish stocks. The subsequent advent of steam trawlers and the collapse of North Sea herring (Dickey-Collas *et al.*, 2010) proved him wrong and for over 75 years it was well understood that fisheries need to be regulated to sustain fish stocks and profitable fisheries (Graham, 1943). This can be easily demonstrated by adding cost of fishing (which increases about linear with effort) and profits (the difference between the value of the catch and the cost of fishing) to the parabola graph of the relation between yield and effort (**Fig. 5**). In most fisheries the cost of fishing at the MSY level is less than the value of the maximum sustainable catch and maximum profit or maximum economic yield (MEY) is actually obtained with even less fishing effort, simply because the linear decline in cost is steeper than the corresponding decline in catch near the peak of the parabolic curve (**Fig. 5**). Unfortunately, effort in most fisheries in the world is far above the MSY level resulting in low catches and economic loss (Costello *et al.*, 2012; Froese *et al.*, 2017). This is possible because governments give handouts (= subsidies) to the fishers, which lower the cost of otherwise economically unsustainable overfishing.

MEY is the antidote to the illusion of most fishers (and some politicians) that higher fishing effort results in higher profits. In reality, profits decline once effort exceeds the MEY level and catches decline once effort exceeds the MSY level (**Fig. 5**).

History and Legal Status of MSY

MSY is based on the classical ecological concept of logistic population growth that was developed in the 1830s (Verhulst, 1838), continuing the earlier work of Robert Malthus on demographics (Malthus, 1798). The first application of the logistic model on marine species was by Johan Hjort and his colleagues in the 1930s, who studied the blue whale fishery, based on mortality and reproduction data (Hjort *et al.*, 1933). They developed the notion of optimal catch, which occurred at intermediate exploitation levels based on their observations on fin whales in Iceland, cod and herring in Norway, and plaice in the southern North Sea (Holt, 2014). Hjort *et al.* (1933) showed that the greatest rate of population growth increase occurs when the population size is about half its ultimate size and that there was a maximum catch that could be sustained, later termed MSY (Hart and Reynolds, 2002).

Shortly after Hjort's work, Michael Graham further developed the logistic population growth equation and applied it to fisheries data (Graham, 1935, 1943). He identified slow and fast population growth phases, with fast growth, low density and younger fish at low population sizes and slow growth, high density and many old fish at large populations near carrying capacity (Graham, 1935). Based on his observations from several species, he argued that "*a lower fishing rate would give as great a yield when the stock became stabilized at that rate*" (Graham, 1935). Later, Graham concluded that "After a certain point the total yield of a fishery does not increase any more, whatever the fishermen do" and clearly linked exploitation to economics when he wrote that "the benefit of efficient exploitation lies more in economy of effort than in increase of the yield" (Graham, 1943).

Schaefer (1954) developed the eponymous Schaefer model using the logistic growth curve on Californian sardine. He replaced population numbers with biomass and defined surplus production as yield. Thus, he formally introduced the concept of MSY, then termed maximum equilibrium catch (Schaefer, 1954). Schaefer preferred the expression maximum equilibrium catch to optimum catch "as being more descriptive of exactly what is meant" (Schaefer, 1954). Schaefer, who was working with tuna, had to ignore age composition because there was not, at the time, a way of determining the age of an individual tuna (Holt, 2014).

In fact, MSY was in use as a theoretical concept a few years before the publication of Schaefer's surplus production model, when it was adopted as the scientific foundation of the US High Seas Policy, in 1949 (Chapman, 1949; Finley, 2011). MSY adoption was

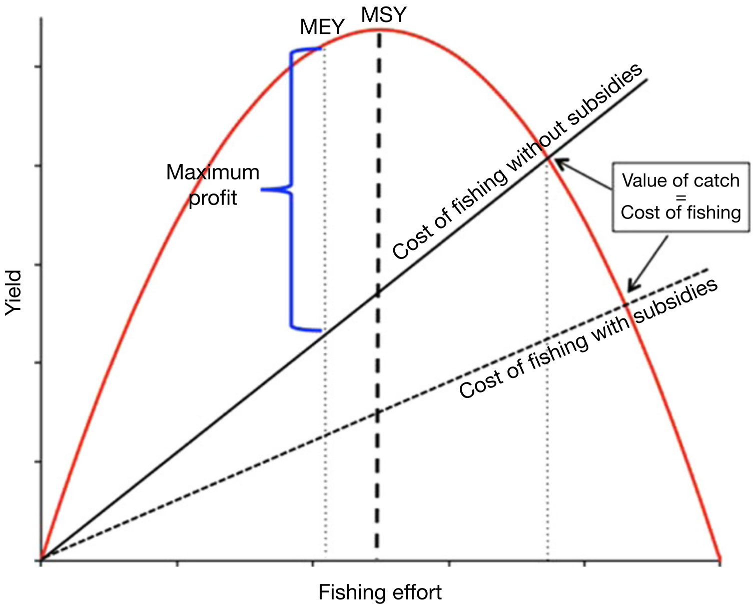

Fig. 5 Yield (*red line*) as a function of fishing effort, with cost of fishing with (*dashed black line*) and without subsidies (*continuous black line*) assumed to increase about linearly with effort. Profit is the difference between the value of the yield and the cost of fishing, with a maximum economic yield (MEY, *dotted vertical line*) obtained from effort and catches below the MSY level (*dashed vertical line*). If costs of fishing are lowered by subsidies, fishing can continue beyond the break-even point, where the value of the catch equals the cost of fishing (second *dotted vertical line*).

largely based on Graham's theoretical analysis (Graham, 1943; see the section "History and Legal Status of MSY") and his conclusion that less fishing can provide in some cases more fish. It was later that MSY was quantified with the Schaefer's surplus production model, and then, in 1955, adopted as the goal of international fisheries policy at the Rome Conference on fisheries problems (Smith, 1994).

After the late 1950s, MSY has been adopted as the primary management goal by several international organizations (IWC, IATTC, ICCAT, ICNAF) and countries (Mace, 2001; Froese *et al.*, 2011). The United Nations Convention on the Law of the Sea (UNCLOS, 1982) made the MSY approach mandatory for fisheries in the exclusive economic zones (EEZs) of its signatories, which were obliged to include the MSY concept into national or regional fisheries legislation (Mace, 2001). All 39 then existing regional fisheries organizations (RFMOs) agreed to manage their mandated stocks such that they were capable of producing MSY (Longhurst, 2006). The follow-up conference on the United Nations Fish Stocks Agreement (UN, 1995) clarified in its Appendix II that during a phase of reducing excessive fishing effort, the one associated with MSY could be used as a target, but that once that target had been reached, MSY had to be treated as a limit, that is, fishing effort should be less than the one resulting in MSY.

For example, in the MSA (2006) the goal of fisheries management is defined as "optimal yield," which is "prescribed on the basis of the MSY from the fishery, as reduced by any relevant economic, social, or ecological factor" (Froese *et al.*, 2011). In addition, fisheries management based on MSY has been formally implemented in New Zealand (MFNZ, 2008), Australia (DAFF, 2007), and Europe (EC, 2013). In most of these areas MSY-based policies have been quite successful in rebuilding stock biomass (Hilborn, 2007a; Mesnil, 2012).

Critique of MSY

The implementation of MSY as a catch that can be taken continuously independent of recruitment, stock size, stock structure, and environmental conditions has been questioned and criticized early on (e.g., Beverton and Holt, 1957; Larkin, 1977; Sissenwine, 1978). Its assumptions, uncertainties, limitations, and misapplications have been repeatedly pointed out (Hilborn and Walters, 1992; Caddy and Mahon, 1998; Punt and Smith, 2001; Hilborn, 2007b; Kesteven, 1997; Holt, 2009). For example, MSY cannot be determined for a stock unless this stock is overexploited, that is, the top of the parabola (=MSY) needs to be well surpassed for it to be determined. Therefore, MSY and optimum fishing effort cannot be predicted in early stages of developing fisheries and stock assessments should focus on detecting it as rapidly as possible (Hilborn and Walters, 1992). Once MSY is detected, fishing effort should be reduced by up to 30% in order to achieve sustainability (Hilborn and Walters, 1992). Also, the assumption of average recruitment and average environmental conditions may lead to wrong advice in highly fluctuating stocks (Hilborn and Walters, 1992). The dependence of MSY on size at first capture and age structure in the stock is ignored (Longhurst, 2006; Holt, 2009; Anderson *et al.*, 2008). MSY is achieved by setting limits on fishing mortality but, as different fishing gears select and target different composition of species and some species are not targeted at all, MSY is rarely attained simultaneously for all species within an area (Maunder, 2002). The social aspects mentioned in UNCLOS (1982) have often been misunderstood as allowing for temporary overfishing to secure employment. The recovery potential of depleted stocks is overestimated by the simple parabola (Quinn and Deriso, 1999; Hutchings and Reynolds, 2004).

It is argued that surplus production models are too simple to fully describe the dynamics of populations subject to variability in recruitment, interactions with other species, catchability, selectivity, environmental conditions, and changing climate (Pella and Tomlinson, 1969) and they require a good contrast between fishing effort and stock abundance (Hilborn and Walters, 1992).

Improving MSY

The epitaph for MSY of Larkin (1977) was rather premature (Barber, 1988) as it was referring to the early, simplistic application of MSY that was considered a viable fishing target with constant catch removal. MSY has been conceptually transformed through time and improved (Kesteven, 1997; Mace, 2001) to become a limit that should be avoided (*target reference point* refers to a desirable state at which management should aim while *limit reference point* refers to an undesirable state which management should avoid: Caddy and Mahon, 1998), which brings the MSY concept in line with contemporary scientific views (Mace, 2001; Mesnil, 2012). Concerning the social issues, there is no conceivable scenario where overfishing is good for society because it results in subsequent lower catches and food supply, and lower future profits and fewer jobs in the sector.

The wide-spread critique that MSY ignores environmental conditions and species interactions is actually overstated (Froese *et al.*, 2017), because the key parameter r_{max}, the maximum intrinsic rate of population growth, summarizes in a single value the interplay of natural mortality (caused mostly by predation), somatic growth (driven by food availability), and recruitment (strongly determined by environmental conditions). In other words, environmental and climatic effects are summarized in their impact on the survival of adults, that is, natural mortality (M), the availability and nutritional value of food, and the effort associated with acquiring it are summarized in somatic growth (k), and the interannual variability in environmental conditions that determine the survival of eggs and larvae are summarized in recruitment (i.e., the number of individuals surviving to join the exploited population) (Pauly and Froese, 2014). In other words, varying food availability, interspecific relationships, environmental/climate changes, and selectivity of the fishing gear are all incorporated in r_{max}. Increasing size at first capture will increase MSY, overfishing of prey species will decrease MSY.

Because of species interactions such as competition for resources and predator–prey relationships it is not possible for all populations to deliver MSY at the same time (Walters *et al.*, 2005). But achieving, for example, 90% of MSY for all commercial fish and shellfish will already result in a substantial overall reduction of anthropogenic mortality for most target and nontarget species and will restore their biomasses to levels that should allow them to fulfill their roles as prey and predators in the ecosystem (Mace, 2001).

Forage fish (anchovies, herrings, sardines, and sand eels) are the crucial link between lower and upper trophic levels in the food web because they transport energy from millimeter-sized phytoplankton and zooplankton to the larger fish eaters of the food web (Baxter, 1997; Pikitch *et al.*, 2012). For that reason they must be fished less and should be used for human consumption rather than for animal feed (Froese *et al.*, 2016a).

Conclusion

It is now well established that fisheries management failed to preserve fish populations and some scientists have blamed it on the MSY concept (e.g., Mesnil, 2012). But is it a matter of science or a matter of administration and policy if stocks are in bad shape? So far, MSY has not been proven wrong as a concept but its estimation was not always correct and the administrative measures taken for its adoption were often inadequate or inappropriate (Kesteven, 1997). After its reform and continuous update, MSY remains a useful concept and a realistic approach to fisheries management and administration (Kesteven, 1997) and according to an anecdotal quote attributed to John Gulland "MSY is the most important concept in fisheries management" (Mangel *et al.*, 2002). On top of that MSY carries a simple message that appears sensible to politicians and stimulates support by the public (Mesnil, 2012) and for that reason it is still widely used in assessing stock status and exploitation. It can be easily improved by considering size structure and setting catch length (L_C) close to optimum length (L_{OPT}) (Froese *et al.*, 2016b). If $F < F_{MSY}$ and L_C is close to L_{OPT}, "pretty good" catches below but close to MSY are possible, with minimized impact on stock and environment. Pretty good yield (PGY) is a term introduced by Alec MacCall (National Marine Fisheries Service, Santa Cruz, CA, United States, retired) in 2000, proposing catches of about 80% of MSY as a meaningful and realistic target.

Acknowledgment

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See also: **Behavioral Ecology:** Age Structure and Population Dynamics. **Ecological Data Analysis and Modelling:** Ecological Models: Individual-Based Models. **Evolutionary Ecology:** Fecundity. **General Ecology:** Carrying Capacity; Growth Models; Age-Class Models

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