The maximum sustainable yield leads to extinction of species in most single and multispecies fisheries

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The Commission of the European Communities passed a resolution in 2006 to implement sustainability in EU fisheries through application of the maximum sustainable yield (MSY) based policy\(^1\). It is shown here that attempts to reach MSY will lead towards extinction of species for every fishery that includes fishing of at least one trophic level which is directly or indirectly used as food for a higher trophic level. Because this condition is met by most single and multispecies fisheries, attempts to reach MSY should be discouraged instead of being legally prescribed as a goal. Based upon above result advice is given on how to manage a fishery which will not drive species to extinction.

Maximum sustainable yield (MSY) has been postulated by Shaefer\(^2\) for a fishery on an isolated population of fish which is growing according to the logistic law. Today, more than fifty years later and a recent support for this approach from the Rio Declaration, and Johannesburg Implementation Plan\(^3\), legal attempts are being made to apply MSY approach in the management of the world fisheries in order to preserve overfished stocks\(^1,4,5\). Typically, the model in mind is an isolated logistic population with a proportional fishing strategy. The MSY is achieved when fishing effort is adjusted to the
optimum, which is half the biotic potential. The biotic potential is the instantaneous per capita growth of a population when it is not limited by food or other environmental constraints. In a constant environment, the resulting equilibrium population of fish under optimum proportional fishing is stable and approaching a value equal to half the carrying capacity\(^6\). In many marine ecosystems this value is observed as an indicator of a fully exploited fishery\(^1\). In other words, when a fished population is found to be below half of the pristine population (i.e. the population prior to fishing), the population is termed overfished. When a population is overfished, the catch per unit effort (CPUE) decreases as the fishing effort increases. A decrease in CPUE is a prime indicator of overfishing\(^7\). However, the implementation is often carried out by regulating a quota and this must be subject to bang-bang control\(^6\). Contrary to the strategy where fishing effort is set constant, this strategy assumes appropriate monitoring.

Initially, the calculation of MSY was done for a constant environment but later it was extended to an environment with random biotic potential\(^8\) and periodic carrying capacity\(^9\). The conclusion is that as we include more environmental factors and details of fish life cycle\(^10\), MSY is likely to decrease dramatically.

**Single species fishery in an ecosystem.** Attempting to reach MSY of a single species fishery in an ecosystem where other fish species are present will have fundamentally different consequences depending on whether or not the target species is at the top of at least one food chain. Let us illustrate the situation with a food chain consisting of only three trophic levels (Fig. 1).
If the target species is at the top of a food chain (Fig. 1a), increasing the fishing effort to reach MSY will cause the stock to decrease to approximately half of its original value (carrying capacity) prior to fishing. Hence, this part of the effect is the same, at least qualitatively, as in the fishery of an isolated population. However, its prey population i.e. the trophic level just below the fished species (Predator1 in Fig.1a) will increase. This increase is often mistaken as an invasion of the prey population and therefore an opportunity to fish the lower trophic level. If this is attempted, the top trophic level will decrease below the optimum value and hence we will record overfishing of the top trophic level.

In summary, fishing only the top trophic level to the MSY value is unlikely to cause extinction of other species in an ecosystem. The possibility exists, however, that the next lower trophic level which has increased wipes out or decreases to the brink of existence some other species that we have not considered. In order to prevent this from happening one should install monitoring of species that are likely to fall into this category, and in case their population decreases below an acceptable value, one should urgently stop fishing the top species until the critical fish species recovers well above the safe level. This would guarantee sustainability of other species at the expense of reaching MSY of the target species.

If we attempt to fish only the trophic level below the top one (Predator1 in Figure 1b), decreasing this level approximately to half will not meet the MSY11. More importantly, reaching MSY implies that its predator (Predator2 in Fig 1b) will have gone to extinction.
Its prey population (Prey in Fig.1b) will increase and hence there will be no danger of it going to extinction.

Analogously, fishing only the prey population to MSY (Fig 1) implies extinction of its predator and hence the rest of the food chain. It is important to have in mind that CPUE will not start to decrease until direct and indirect predators to the trophic level we are exploiting have gone to extinction.12

In this case two important measures must be made prior to commencement of setting the fishing policy: a) calculate the impact on the top predator and predict its density; b) if the density is not a threat to the existence of the top predator, commence fishing its prey and start monitoring prey and predator populations. As monitoring data arrive, recalculate the impact and adjust fishing intensity, not to obtain MSY and not to the point of a decrease in CPUE, but to allow the existence of the top predator above a critical density which will guarantee its sustainability.

Multispecies fishery in an ecosystem. When one attempts to reach MSY of a multispecies fishery in an ecosystem, the situation changes fundamentally again.11 This is most clearly seen in a prey-predator system13,14 (Fig. 2).

The conclusion reached by Volterra15, known as the Volterra principle, is that if the fishing effort decreases, the prey population will decrease and the predator population will increase. The effect is reversed if the fishing effort increases (as shown in Figure 2). However, Volterra was not interested in analyzing MSY. For this kind of fishery MSY is
defined as the maximum sustainable yield of both prey and predator i.e. their sum or total (MSTY).

In contrast to an isolated population, MSTY as well as a decrease in CPUE, imply the extinction of predator. This is easy to verify for the Volterra prey-predator model. The same is the case for the Rozenzweig-McArthur prey-predator model and for the Volterra model in which prey is assumed to grow according to the logistic law. In general, does an attempt to reach MSTY induce extinction of predator in every prey-predator system? Yes, and we can see this from Fig. 2 without resorting to numerous existing mathematical models of the prey-predator system. Because a part of prey biomass is lost as a result of the mortality of the predator population (second lower right arrow in the Fig. 2), clearly the MSTY can be reached only after the predator population is eliminated. An important consequence is that as we increase the fishing effort (to obtain MSTY) the CPUE will not decrease as long as the predator exists. Therefore, the widely spread practice which maintains that we should fish until catch per unit effort (CPUE) starts to decrease is a misleading indicator borrowed from an isolated single species case. In any prey-predator system subject to equal fishing effort on both prey and predator the eventually obtained MSTY will be composed of prey only.

Let us now extend the prey-predator system into a food chain (Fig. 3) and attempt to harvest all trophic levels with equal fishing effort, similar to a trawler fishery.

In this case the maximum sustainable total yield (MSTY) will represent the maximum of the sum of yields on all fished populations. Applying the same type of argument we used in the prey-predator system, we arrive at the conclusion that MSTY will be reached and
CPUE will start do decrease only after all predators have gone to extinction. This is because only then will the loss of prey biomass through mortality of predators be eliminated and hence contribute more to the yield.

If we understand the term sustainable fishing to mean that all the trophic levels in a food chain must persist, then it follows that the MSTY is inconsistent with sustainable fishery. In other words, MSTY will not be reached and CPUE will not start do decrease as long as a single predator population exists.

Another corollary is that if we fish only two trophic levels such that the lower level is directly or indirectly used as a food for the higher trophic level, prior to reaching MSTY, the higher predator (and all trophic levels that directly or indirectly feed on it) will certainly become extinct. If in terms of management we want to respect the declaration on biodiversity, we cannot strive to reach MSTY simply because we are working against survival of multiple species in an ecosystem.

In general, for a food chain of n trophic levels (n≥2) there will be \( \sum_{i=2}^{n} \binom{n}{i} \) combinations of multispecies fisheries and n-1 single species fisheries where attempting to reach MSTY (or MSY in single species fishery) will lead to the extinction of at least one species. These numbers represent a majority of all fisheries in food chains with two or more trophic levels. For example, in a food chain with 3 trophic levels, out of 7 possible different fisheries, 2 single species fisheries and 4 multispecies fisheries will lead, to the extinction of at least one species. Fishing only the top predator to MSY will not lead to extinction of other species.
Another ubiquitous subgraph of a food web in an ecosystem is a cycle of matter. A single cycle with only two trophic levels and decomposers is shown in Fig. 4.

Maximizing the sum of yields of the prey and predator populations in order to obtain MSTY again leads inevitably to the extinction of the predator population. This is because only then is the natural burial of matter into sediments originating from prey and which passed through predators reduced to zero. The statement holds regardless of the form of equations which govern dynamics of populations in a cycle of matter.

Let us now move on to a conclusion valid for a general food web. In almost every ecosystem there will be one or more subgraphs which represent food chains or food cycles. Again, it is clear that for the majority of single species and multispecies fisheries attempting to reach MSTY will be in violation of the agreed declaration that all species must persist. Although the MSTY may be obtained for several target species, the resulting price will be that a number of other species will be lost\textsuperscript{18}, including some of the target species.

Hence, the claim that a management strategy which attempts to reach MSY (which in this case should more appropriately be called MSTY) will conserve at least the target species\textsuperscript{1} does not hold true in general. Furthermore, if applied, it will most likely drive some other not targeted species towards extinction.

Our results have several important management implications.
First, the validity of the supposedly conservation-wise advice "fish until the yield per unit effort starts to decrease" is limited to fishing a single population which is the top predator in an ecosystem. In a multispecies fishery the yield per unit effort will not start to decrease until all fished predators above the lowest trophic level subject to the fishery have gone to extinction, or at least to oblivion. Hence, a very elegant indicator discovered to hold for a single species fishery must be abandoned as entirely misleading and extremely dangerous in case of a multispecies fishery.

Second, the current practice to monitor only what fishermen are catching is also based on the concept of fishing an isolated population and is fundamentally insufficient to assess the effects of multispecies fisheries in ecosystems. Monitoring all species in an ecosystem, especially slow growing and inefficient predators, regardless of whether they are fished or not, is a necessary condition prior to deciding whether to allow fishing and must continue as long as fishing is carried out.

Third, it is necessary to insure that prior to permitting the commencement of fishing, all fish populations which are included in our biodiversity indicators are far from being endangered. Then and only then, our indicator of a fully exploited fishery may be that the top predator is at the half of its pristine value. However, as stated above, one should carefully monitor other slow growing and inefficient predators and competitors, because as the fishery progresses, they will continue to be as they have been so far - the first to be decimated or go extinct\textsuperscript{14,19,20,21}.
References


12. For simplicity consider a general prey (N) - predator (P) system with harvesting prey only. The biomass equations are: \( \frac{dN}{dt} = f_1(N) - f_2(N) P - e N \); \( \frac{dP}{dt} = f_2(N) P - m P \)
where \( f_1(N) \) is a prey population growth function, \( f_2(N) \) is a specific predation function, \( e \) is a harvesting effort of prey and \( m \) is a specific natural mortality rate of the predator. The yield in equilibrium, \( Y = e N^* \), is a linear function of \( e \) and hence it does not have a maximum as long as the predator population exists. This means that CPUE will not start to decrease until the predator population is gone to extinction.


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Figure legends

**Figure 1.** Arrows indicate a biomass flux in a food chain with three trophic levels. Fishing: a) the top trophic level; b) the second trophic level. As a consequence, the fished trophic level will decrease (-) while others will increase (+) or decrease depending on their position in the food chain.

**Figure 2.** Fishing both the prey and predator. An arrow indicates a flux of biomass. Increasing fishing effort on both prey and predator causes the predator population to decrease (-) and prey population to increase (+).

**Figure 3.** Graph of an indiscriminate exploitation of a food chain. An arrow indicates a flux of biomass.

**Figure 4.** Flow of mass during fishing of prey and predator in a cycle of matter.
Figures

Figure 1:

<table>
<thead>
<tr>
<th>a) fishing</th>
<th>b) fishing</th>
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<tbody>
<tr>
<td>(-)</td>
<td>(+)</td>
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<tr>
<td>↑(-)</td>
<td>↑(-)</td>
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<tr>
<td>Prey → Predator₁ → Predator₂</td>
<td>Prey → Predator₁ → Predator₂</td>
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<td>↓</td>
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<tr>
<td>natural mortality</td>
<td>natural mortality</td>
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Figure 2:

Fishing
↑(+)
↑(-)
Prey → Predator
↓ ↓
natural mortality

Figure 3:

fishing
↑ ↑ ↑ ↑
Prey → Predator₁ → Predator₂ → … → Predatorₙ
↓ ↓ ↓ ↓
natural mortality

Figure 4:

fishing
↑ ↑
Prey → Predator
↑ ⊳↓
Decomposers ← natural mortality
↓
burial into sediments