APPROACHING THE POTENTIAL OF WORLD MARINE FISHERIES

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ABSTRACT

During the last 60 years, the world marine fisheries potential has been estimated between $22 \cdot 10^6$ tons and 1 $400 \cdot 10^6$ tons.

However, there are no certain indications of when and with what probability such potential will be reached.

By fitting a logistic curve to the observed world marine catch, corrected for discards and illegal, unreported and unregulated fishing, here we calculated that such potential stands between $132 \cdot 10^6$ tons and $153 \cdot 10^6$ tons and might be achieved as soon as the year 2027, with 95% confidence.

RESUMEN: Potential de la captura marina global.

En los últimos 60 años, el potencial de la pesca marina mundial se ha estimado entre $22 \cdot 10^6$ toneladas y 1 $400 \cdot 10^6$ toneladas.

Sin embargo no aún no existen indicios de cuándo ni con qué probabilidad dicho potencial será alcanzado.

Ajustando un modelo logístico a datos de captura marina mundial, corregidos para descartes, captura ilegal, no reportada y no regulada, en la presente contribución se estimó que la captura máxima potencial de la pesca marina se encuentra entre $132 \cdot 10^6$ toneladas y $153 \cdot 10^6$ toneladas; cifras que podrán alcanzarse, con el 95% de confianza, tan rápidamente como en el año 2027.

REZUMAT: Abordarea potenţialului mondial marin de pescuit.

În ultimii 60 de ani, potențialul pescuitului marin global a fost estimat între 22×10^6 tone şi 1.400×10^6 tone.

În orice caz, nu există indicații sigure când şi cu ce probabilitate acest potențial va fi atins.

Prin ajustarea unei curbe logistice a capturii marine mondiale, corectate pentru capturi ilegale, nedeclarate şi nereglementate de pescuit, am calculat că un astfel de potențial ar fi între 132×10^6 tone şi 153×10^6 tone şi ar putea fi realizat până în anul 2017, cu 95% confidență.

INTRODUCTION

Since 1950 there has been a major concern about how much the global marine catch can increase. While 60 years ago the estimations of the potential of the world oceans were as optimistic as 1 $400 \cdot 10^6$ tons (Pike and Spilhaus, 1962), in 1996 we witnessed a very distant maximum catch of ~ $88 \cdot 10^6$ tons (www.fao.org). Since then, the global marine catch has been between roughly 80 and $85 \cdot 10^6$ tons and the latest available estimates of the fisheries potential range from $100 \cdot 10^6$ tons (Garcia and Grainger, 1996) to $146 \cdot 10^6$ tons (Chassot et al., 2010). Obviously, there must be a limit to the marine capture fisheries in the climate changes and human impact circumstances in which negative signals in this respect were registered all over the world (Ruchimat, 2012; Khoshnod et al., 2015; Bănăduc, 2016); however how much more the total marine catch can increase and when this limit will be achieved are questions that still need a reliable answer. The aim of the present paper is to offer such an answer.

MATERIAL AND METHODS

We fitted a logistic model to the corrected world marine catch using the maximum likelihood method in order to estimate the marine fisheries potential, or the asymptotic theoretical catch. We computed the associated confidence intervals, the calendar year when this level will be achieved and compared our estimation with several others made by different authors.

World marine catch statistics (1950-2007) were obtained from FAO's FIGIS system (http://www.fao.org/figis). Search fields included: (country) all continents excluding China (Watson and Pauly, 2001); (fishing areas) marine areas; (species) aquatic plants, crustaceans, marine fishes, miscellaneous aquatic animals (excluding reptiles and amphibians) and mollusks. Aquatic tetrapods were excluded from the analysis because landings are reported as numbers rather than biomass.

Time series were corrected for discards and for illegal, unreported and unregulated fishing (IUU) that can represent a substantial amount of fisheries catches. The historical maximum percentage of discards (1992-2001) and IUU (1980-2003) have been estimated in 25% and 21% respectively, in relation to the total marine fisheries recorded catches (Alverson et al., 1994; SOFIA, 2008; Agnew et al., 2009). Because we are referring to the maximum possible potential, the summation of both percentages (46%) was considered for correcting the entire world catch time series (Fig. 1).

Logistic curve fitting and confidence intervals estimation

We used the logistic model proposed by Quinn and Deriso (1999):

$$C_{est,t} = \frac{K_C C_i e^{rt}}{K_C - C_i + C_i e^{rt}}$$

Equation 1

where $\underline{C_t}$ is the corrected catch at time t; $\underline{K_C}$ is the carrying capacity of the global marine catch, or the marine fisheries potential, expressed in millions of tons; $\underline{C_i}$ is the initial catch record of the time series; and $\underline{r}$ is the rate of increase. We fitted Equation 1 to the corrected world catch using the maximum likelihood method.

The likelihood approach is useful to: 1) find parameters of a given model that provide the best fit to the data and explicitly incorporates the uncertainty (maximum likelihood estimator); 2) compare alternative hypothesis between different values of the parameters (likelihood profile); and 3) calculate confidence bounds on parameters (likelihood ratio test). Given initial guess-estimate values of $\underline{K_C}$, $\underline{C_i}$ and $\underline{r}$ and the history of global catches, Equation 1 allow us to generate an estimation of the catch for any time ($\underline{C_{est,t}}$) which is then compared to the observed data.

According to Ritz and Streibig (2008), the log-likelihood estimator is:

$$LL_t = -\frac{n}{2}[2\pi + 1 - \ln(n) + \ln(RSS)]$$

Equation 2
where *RSS* is defined as:

$$RSS = \sum_{t=1}^{n} \frac{(C_t - C_{est,t})^2}{n}$$

Equation 3
Equation 2 is maximized across the parameters K_C, C_i and *r*. The resulting values provide the best possible fit to the observed data.

We computed the 95% confidence intervals for the parameter K_C following three consecutive procedures. First we constructed a likelihood profile, consisting in a systematic search over K_C for finding the log-likelihood associated to other values of this parameter (from 100 to 200 in steps of 0.003) while keeping C_i and r as constants in those values that maximized the log-likelihood. Henceforth, this profile will be called P1. Secondly, we applied the likelihood ratio test, or R:

$$R = 2[L(Y|p) - L(Y|p_{MLE})]$$

where $L(Y|p_{MLE})$ is the log-likelihood associated with the maximum log-likelihood estimate (MLE) of K_C and $L(Y|p)$ is the log-likelihood of another value of the parameter. This formula was calculated for all values of the profile. Lastly, considering that R has a chi-square distribution (X^2) with one degree of freedom, we estimated the 95% confidence intervals by noting that the probability or Pr ($X^2 < 3.84$) = 0.95 (Hilborn and Mangel, 1997). Since R is a symmetric function around the p_{MLE}, the extreme parameter values within the range of values that satisfies Pr are the lower and upper confidence bounds. We calculated the percentage of the estimated K_C that each $C_{est,t}$ represents, observing the year when 95% and 99% of this parameter was attained.

Finally, for comparing different available estimates of the maximum potential catch we constructed another profile, which will be called P2. In this case, we made 30 000 fits by fixing the parameter K_C (from 100 to 200 in steps of 0.003) while setting C_i and r to vary freely and recording the maximum log-likelihood of each fit. We also computed confidence bounds following the procedures described above.

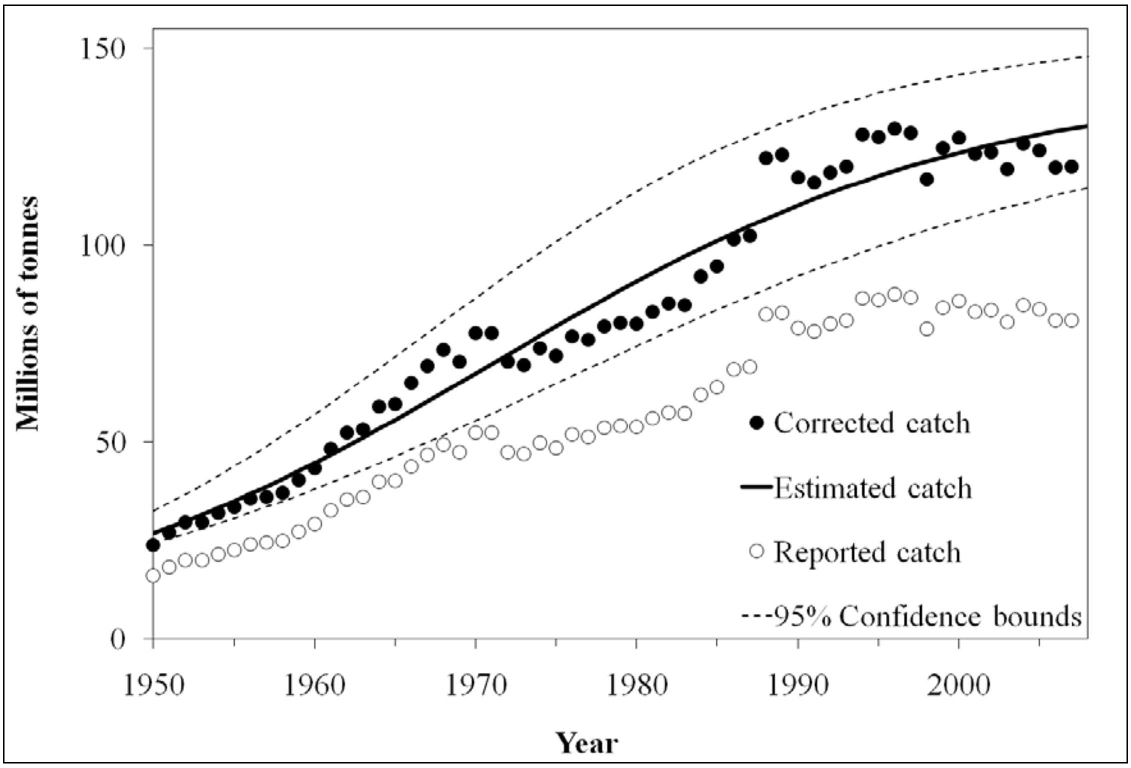

Figure 1: Corrected (filled circles) and reported (empty circles) world marine fisheries production. Correction consisted in the addition of 46% to the reported catches; 25% corresponds to discards (Alverson et al., 1994; SOFIA, 2008) and 21% for illegal, unreported and unregulated fishing (Agnew et al., 2009). Solid line represents the estimated catch using a logistic model; dotted lines are the 95% confidence bounds.

RESULTS

Reported and corrected world marine catch, as well as the logistic curve fitted to the corrected data and related confidence bounds, are shown in figure 1.

Both log-likelihood profiles and the comparison between several estimates of the marine fisheries potential are shown in figure 2. P1 indicates that for a single fit the estimate of $\underline{K_C}$, from 30 000 other different values of this parameter, is the best one given the observed data (for the fit that maximized the log-likelihood, $\underline{K_C}$ was set as a free parameter and $\underline{C_i}$ and $\underline{r}$ were kept as constants). On the other hand, P2 represents the maximum log-likelihood associated to 30 000 different fits for the same dataset (setting $\underline{C_i}$ and $\underline{r}$ as free parameters while keeping $\underline{K_C}$ as a constant in each fit).

A value of $141{\cdot}10^6$ tons for $\underline{K_C}$ maximized the log-likelihood in both profiles. The 95% confidence limits for P1 are $137{\cdot}10^6$ tons and $145{\cdot}10^6$ tons; for P2 are $132{\cdot}10^6$ tons and $154{\cdot}10^6$ tons. By looking the MLE in P2, 95% of $\underline{K_C}$ may be surpassed in 2015 and 99% of the potential will be reached around the year 2039 (Tab. 1).

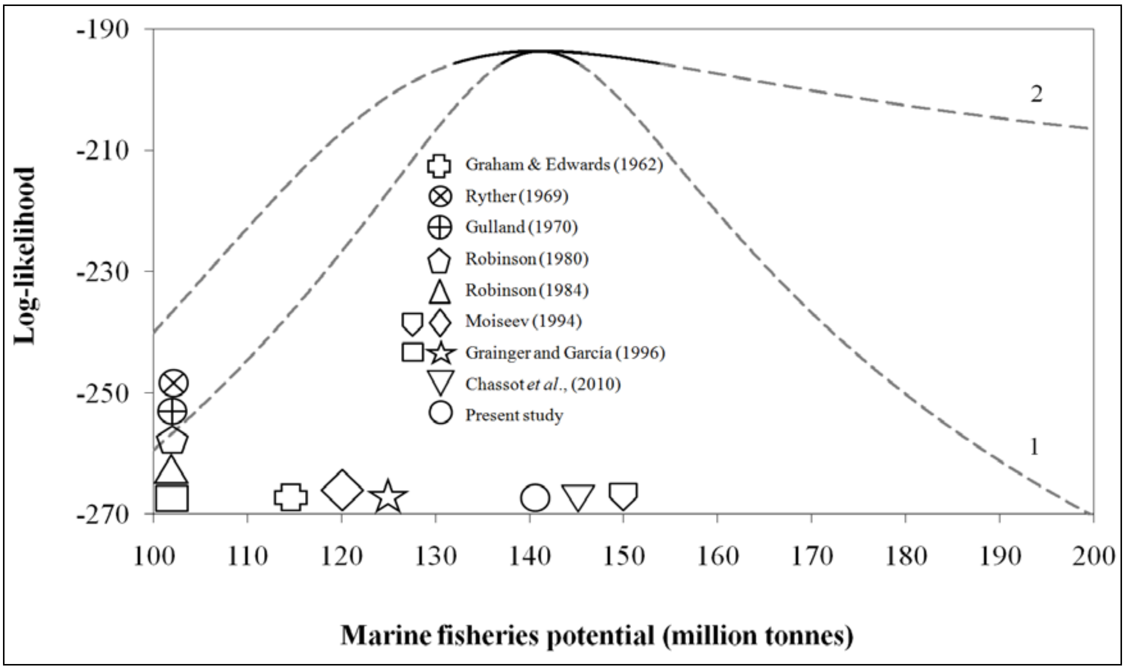

Figure 2: (1) Log-likelihood profile for the parameter $\underline{K_C}$ (marine fisheries potential) of the logistic model, expressed in million tons, applied to the world marine catch (1950-2007; corrected for discards, illegal and unreported fishing); and (2) profile of the maximum log-likelihood associated to different fits applied to the same historical data. Symbols represent the magnitude of different estimates of the marine fisheries potential and the authors of those estimates. In some cases, author(s) presented more than one estimate. Estimates higher than $200{\cdot}10^6$ tons and lower than $100{\cdot}10^6$ tons are not shown. Solid black lines represent 95% confidence bounds. Dotted lines are the log-likelihood values outside the confidence limits.

Table 1: Parameter values of the logistic model estimated by the maximum likelihood method, applied to the corrected world marine catch. Values correspond to the best possible fit, from a total of 30,000 runs. The carrying capacity ($\underline{K_C}$) and the initial estimated catch ($\underline{C_i}$) expressed in million tons; $\underline{r}$ is the intrinsic rate of increase; 95% $\underline{K_C}$ and 99% $\underline{K_C}$ is the calendar year when that percentage of the parameter will be achieved. LL: lower limit; MLE: maximum likelihood estimate; UL: upper limit (95% confidence bounds).

Parameter	Profile 2		
	LL	MLE	UL
$\underline{K_C}$	132	141	153
$\underline{r}$	0.06	0.07	0.08
$\underline{C_i}$	23	26	30
95% $\underline{K_C}$	2028	2015	2006
99% $\underline{K_C}$	2056	2039	2027

DISCUSSION

The results derived from both profiles converged in the value of the parameters that maximized the log-likelihood and also in the magnitude of the maximum log-likelihood, thus making P1 a particular case of P2. This is, from 30 000 fits made in P2, the one in which $\underline{K_C}$ was fixed in $141 \cdot 10^6$ tons resulted in the same values of $\underline{C_i}$ and $\underline{r}$ that maximized the log-likelihood in P1. However, the size of the confidence bounds in P2 is 2.5 times bigger than in P1. This difference is due to the covariance (the product of individual variances; Mendenhall and Schaeffer, 1973) between the parameters $\underline{C_i}$ and $\underline{r}$ (in P1 only $\underline{K_C}$ varies). Moreover, the confidence bounds in P1 are symmetrical but in P2 are 30% slanted to the right hand of the profile in relation to $141 \cdot 10^6$ tons. Our interpretation is that the corrected catch, whose historical maximum is $129 \cdot 10^6$ tons, provides stronger support to those fits in which $\underline{K_C}$ was fixed near this maximum. As $\underline{K_C}$ moves farther from $129 \cdot 10^6$ tons, the uncertainty progressively increases because there is no observed data greater than that figure. This also can be seen in the overall shape of P2 in contrast to P1 (Fig. 2).

Estimate versus estimate

Pauly (1996) and Garcia and Grainger (2005) compiled several estimates, made since 1950, of the maximum marine fisheries potential, ranging from $22 \cdot 10^6$ tons to $1400 \cdot 10^6$ tons. Some of these are based on the observed catch trends (Thompson, 1951; FAO 1953; Finn 1960; Meseck, 1962; Gulland, 1970; Grainger and Garcia, 1996), others are extrapolations from known areas to the global ocean (FAO, 1953; Finn, 1961; Graham and Edwards, 1962; Gulland, 1970), several consist in computations from primary production and food chains (Pike and Spilhaus, 1962; Graham and Edwards, 1962; Chapman, 1965; Schaefer, 1965; Ricker, 1969; Ryther, 1969; Gulland, 1970; Chassot et al., 2010) and two are inferred from biomass estimations (Moiseev, 1994). In P2 we compared our estimate of the marine fisheries potential with those estimates falling between $100 \cdot 10^6$ tons and $200 \cdot 10^6$ tons. With the data available until 2007, any approximations falling outside these limits are unrealistic (Fig. 2).

For instance, there is a discrepancy between the lower limit of $\underline{K_C}$ ($132 \cdot 10^6$ tons) and the upper limit of the maximum potential global catch estimated by Grainger and Garcia (1996) which is $125 \cdot 10^6$ tons. Such difference may rely in the fact that they did not correct historical global catches for discards nor IUU fishing, therefore their figure does not correspond to our MLE ($141 \cdot 10^6$ tons; Tab. 1). This means that if the goal is to maximize the likelihood of our fit in some statistically meaningful value by fixing $\underline{K_C}$, while letting the other two parameters to vary freely, it must be fixed at least in $132 \cdot 10^6$ tons. In fact, those estimates around $100 \cdot 10^6$ tons are also derived from catch records uncorrected for other sources of additional biomass. On the other hand, the estimate of $146 \cdot 10^6$ tons made by Chassot et al., (2010), derived the primary production available for marine fisheries, does incorporates the IUU catch and falls within the 95% confidence bounds, further supporting our conclusions. The estimates of Moiseev (1994), based on the total biomass of large fish and other organisms and their production-biomass ratios are also similar and statistically significant. The log-likelihood associated to all other estimates is negligible (Fig. 2).

There is another prediction of the marine fisheries potential that, although not statistically significant with respect to ours, must be acknowledged. Robinson (1979) calculated that the demand for fish for direct human consumption would reach roughly $97 \cdot 10^6$ tons (including freshwater fish) by the year 2000. If we subtract the observed catch from continental waters to the total marine production in that same year, disregarding discards and IUU fishing, then Robinson’s projection results surprisingly accurate.

Moreover, the difference between some estimates of the maximum potential marine catch and the correspondent observed catch, indicative of how close we are to that level, has been exponentially reducing since the 1970's and may become as small as four million tons in the next 40 years (Fig. 3). Such trend cannot be attributable to a lowering in the carrying capacity of the world oceans, because since 1996 the total corrected catch has fluctuated within a limited range of ~ $10 \cdot 10^6$ tons (Fig. 1) and the rate of catch increase shows a slightly negative value (– 0.003; Grainger and Garcia, 1996). Worryingly then, these evidences point out that we are rapidly approaching the limit of the world marine fishery production.

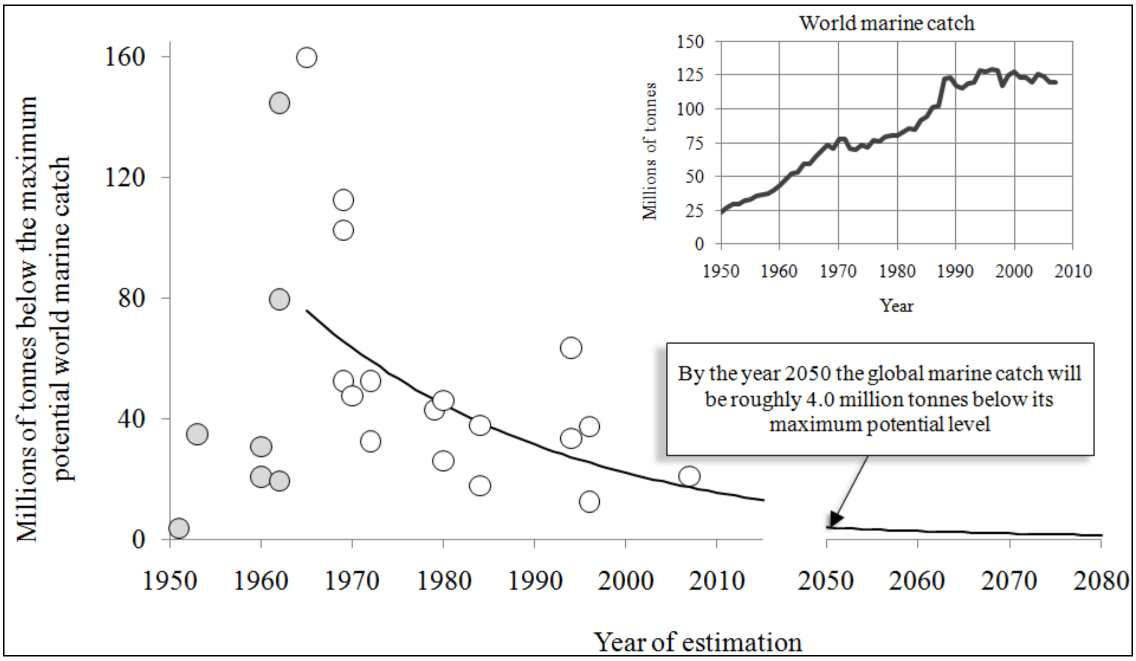

Figure 3: Differences between some estimates of the marine fisheries potential and the corresponding observed catch. Except for the last observation, all data are uncorrected for discards, illegal and unreported fishing. Estimates were taken from Gulland (1983), Pauly (1996) and Garcia and Grainger (2005). A negative exponential line was fitted to the empty circles. The world marine catch is approaching its maximum potential level as the difference between the two is getting smaller. Inner graph (historical marine catch from 1950 to 2007, corrected for illegal and unreported fishing) highlights that such approach is not due to a lowering in the fisheries carrying capacity.

Fisheries potential and climate change

Climate change is currently recognized as a major driver for marine ecosystems changes at different scales; however, considerable uncertainties and research gaps remain on its potential synergies with other factors such as pollution and fishing pressure (Barange and Perry, 2009). We believe that our estimation will not change under the expected climate change scenarios because of two observations: first, that the World Ocean is warming but trends are not geographically homogeneous. For example, there is mounting evidence indicating that eastern boundary currents regions, where a large proportion of industrialized fisheries operate, have been cooling for the last few decades (Bakun, 1990; Demarq, 2009). Secondly, the global fisheries have already experienced climate variations much larger than those expected from climate change, at least for the timeframe of the next few decades.

Marine fisheries potential

We have identified at least three different factors that might lead the current global (corrected) catch levels towards the maximum marine fisheries potential. First, although Watson and Pauly (2001) cast doubt on the veracity of the catch records from China, whatever that amount is must be added to the actual total production. There are estimations from knowledgeable authors pointing out that during the last decade, the catch from marine fisheries in China has fluctuated around 12.3 and 12.7 million tons (Huanh Shuolin, Shanghai Ocean University, personal communication), which represents 35% of the estimated potential (i.e. the difference between the upper and lower limit of our estimate and the maximum observed catch).

Secondly, as food demand increases, new fisheries may be eventually recruited to the current list of world fished stocks (i.e. deep sea resources, lantern fishes, myctophids, pelagic red crab, krill, etc.). For example, according to the Marine Stewardship Council (www.asoc.org), the krill fishery in the Southern Ocean (certified as sustainable in June 2010) yielded 118 000 tons during the 2007/2008 fishing season and the Total Allowable Catch in 2010 was set in 620 000 tons, but it has not yet been achieved. If this species, being a first level consumer, produced a modest increment in the global marine catch, we can expect an even smaller contribution from new fisheries targeting higher trophic levels.

Although more uncertain than the former, the potential available catch from underexploited and overexploited marine stocks may also be an additional source of biomass, assuming that all marine fisheries could be driven to their maximum productivity level. Nonetheless, we are now aware that the interdependence between exploited populations of different species within an ecosystem makes it impossible to simultaneously maintain them all at their maximum sustainable yields (Link, 2002). This implies that the current relative proportion between underexploited, fully exploited and overexploited marine stocks should not change substantially. Hence, the amount of catch that can be obtained from this source will also be rather limited. Garcia and Grainger (2005) suggested an alternative way to produce significantly more catch: increasing fishing pressure on top predators, reducing presently abundant cetaceans to reduce in turn their consumption, further increasing the abundance of prey and thereby allowing an increase in their harvest. In spite that such a strategy represents a sort of "ecosystem management", the authors consider that it may have undesirable ecological consequences (hyper-fluctuating ecosystems, massive oxygen depletion).

According to our calculations, the likelihood that the sum of all these additional sources exceeds $34 \cdot 10^6$ tons, with respect to the corrected catch in 2007 ($119 \cdot 10^6$ tons) and to the upper limit of $\underline{K}_C$ ($153 \cdot 10^6$ tons), is statistically insignificant.

During the last decade, the percentage of fully exploited, overexploited and underexploited marine stocks has been related to the fishery system efficiency. However, as we approach to the maximum potential catch, other indicators may arise. For example, the speed and distance at which the total marine catch would depart below the lower limit of $\underline{K_C}$ might be regarded as a new fishery management compass. If more stocks were to become systematically overexploited and depleted, then the total catch would be expected to decline. Alternatively, if more fisheries are managed at their maximum productivity levels, then the total catch will tend to remain stable. Even the large fluctuations of massive fish resources such as small pelagics (averaging 30% of total marine catch) will produce a limited range of variation around $\underline{K_C}$, likely smaller than the range between the estimated confidence bounds, since the maxima and minima of these species are not in phase (Lluch-Belda et al., 1989; Omori and Kawasaki, 1995), making our estimation still more robust.

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