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Review Article

Stock Effect of Bio-Economic Indicators in an Over-exploited Fishery of the Gulf of Mexico

Ernesto A. Chávez* and Alejandra Chávez-Hidalgo

CICIMAR, IPN, Av IPN s/n Col. Playa Palo de Sta. Rita, El Conchalito La Paz, BCS 23096

***Corresponding author:** Ernesto A. Chávez, CICIMAR, IPN, Av IPN s/n Col. Playa Palo de Sta. Rita, El Conchalito La Paz, BCS 23096

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Abstract

The main bio-economic indicators of a pelagic fishery of the Northern Gulf of México (the Gulf Menhaden *Brevoortia patronus* Goode), was examined to understand their 8 performance as a result of simulated trials of the age of first catch and the fishing mortality. First, the validity of simulation was tested rebuilding numerically the performance of biological data and catch over time. A simple approach was made assigning economic value to the catch per-kg and the cost of fishing, so the output of biological variables could be linked to their corresponding economic performance, under the dynamics of the exploited stock, before adding value to the catch. As a part of results, the historical trend of a declining yield, suggests that the fishery has been over exploiting the juveniles, and even tough this condition has been sustained for more than forty years, this process produces nearly 400 thousand t, while it could yield more than one million t if it exploits only adult fish. On testing the economic indicators of the stock response as effect of the age of first catch, it is evident that the current yield is well below the Maximum Sustainable Yield, which might be higher if only adult fish are the targets of the fishery. The same occurs with the Maximum Economic Yield. The Benefit/Cost displays an inverse relationship with the Cost per t. It was found that the fishery could profit more than three hundred million USD if the age of first catch is re-addressed to get only adults as fisheries target. It is clear that this approach could be adopted as useful tool for decision-making and fisheries management.

Keywords: *Stock assessment, Maximum sustainable yield, Maximum economic yield, Overexploited fishery, Gulf menhaden*

Introduction

One of the problems of fisheries management deals with use of formal procedures of evaluation of exploited stocks in order to derive quantitative regulations able to foresee accurate consequences after the application of certain management actions [1-5]. However, a few years ago, it was stated that fisheries overexploitation and unsustainability are still not widely understood [6], despite cascade effects have been reported [7,8]. Fortunately, after twenty years, with much scientific research work done on this problem, it is much better understood. Therefore, there are multiple examples of mismanagement of fisheries resources, with regrettable consequences leading to the over exploitation of many fish resources and their consequences in their environment [9-12]. In the present paper, populations are evaluated by reconstructing the age structure of each of the years analyzed. The potential catch, benefits, direct jobs, and earnings per fisher can be estimated in several scenarios by changing the fishing mortality *F*, and the age of first catch, *tc*. In this way it is possible to test the response of the biologic and socio-economic variables of each fishery with reference to the maximum sustainable yield *MSY*, and the maximum economic yield *MEY*.

Many Fisheries at a worldwide level, have been declared chronically overexploited [13]. However, stock assessments and management regulations are usually addressed towards limitations of access, reduction of fishing seasons, reduction of fishing effort, establishment of closed areas, etc., but fisheries scientists as advisers and managers do not usually pay attention in the effects of mesh openings as means to control the age of first catch (*tc*), allowing to catch only adults of the fish stock and giving to juveniles usually caught, the opportunity to survive to the adult age and having the chance to breed at least only once in their lifetime. An examination of the population parameter values of several fisheries shows that *tc* value is at least one year lower than the age of first maturity (tm). This is a circumstance that unavoidably leads these fisheries towards a condition of overexploitation, which in the case of the Gulf Menhaden and other cases, becomes a chronical condition that often leads to a biological and economic crisis. It is remarkable to find out that management regulations usually ignore the need to increase mesh openings to allow juvenile fish being released from the nets and capturing only adults [14].

Methods

The assessment of the Menhaden stock was made by using a simulation model [15,16]; is based on the general principles of the assessment of exploited fish stocks and is conducted with usually fifteen years of catch data. Thus, with the purpose of formulating better management options, a meta-analysis of data was conducted to evaluate the performance of the fisheries with reference to the output of this model. In each of these options, catch data and the values of the population parameters are used, from the references or estimated directly [17-20] and are indicated in Table 1. The associated costs and economic benefits of the fishery are taken as a reference for the bio-economic analysis. The model proposed allows

Table 1: Population parameter values, units, equations and source or comments used for the evaluation of the Gulf Menhaden fishery are indicated.

Parameter	Value	Meaning	Source, equation
K	0.4	Bertalanffy	Gedar 03
L	24 cm (fl)	Bertalanffy	Gedar 03
W (g)	*12*	Length – weight, g	*a*Lb*
-to	1.01	Years-Bertalanffy	Gedar 03
l		length at age t (Bertalanffy)	$l=L\ [1- e^{(-k(t-to))}]$
a	0.0005	$a*L^b$, Length - weight	Gedar 03
b	3.18	$a*L^b$, Length - weight	Gedar 03
tc	*1*	*Age of 1st catch*	Gedar 03
tm	2 Years	Maturity age	Gedar 03
M	0.6	Instantaneous rate	Jensen (1996, 1997)
F		*Fishing mortality*	
F_{MSY}	0.6	*F* at *MSY*	
E	*F/(M+F)*	Exploitation rate	
E_{MSY} at F_{MSY}	0.5385	*FMSY/(M+FMSY)*	
R		Recruits (1 yr old)	Beverton-Holt
Y		Yield (Catch equation)	
C		Costs/season)	(Cost/boat/day)*Boats*Days
B		Benefits	Total catch value, USD
B - C		*Profits*	
B/C		Economic efficiency	

testing of as many exploitation possibilities as fishing data allow, in a dynamic programming exercise that can provide answers to logical questions such as: What will happen to the biomass of the stock and the economic yield if the size of first capture is increased? What will be the biological and economic consequences if fishing effort is doubled? What is the maximum effort that the fishery can sustain and fail to deliver benefits of at least 10 percent above costs? And what are the economic expectations for the next season if the cost of fuel increases in a certain proportion? Population parameter values used as input of the simulation and the corresponding equations are in Table 1.

Among the results obtained with the use of this model, the evaluations carried out indicate that for a combination of *tc* and *F* values, the estimated performance describes a dome-shaped response surface; if a single value of *tc* is taken and the response of the stock is observed, the yield is shown as a curve that at certain *F* level attains a maximum value and declines after this point. The output also describes the number of jobs as a function of *F* as a line with the same trend as that of potential capture; the benefit/cost ratio is a curve that declines as *F* increases. In general, the *MSY* level is at a higher value of *F* than in the case of the economic yield (*MEY)*. In high-value fisheries, such as lobster, this value coincides with *MSY* at the same *F*. In addition, it is remarkable to find out that the cost of fishing increases with higher *F* intensity, making the activity unprofitable with higher values.

For the economic analysis of the resource, it is necessary to feed the model with data such as the number of fishing days that each season lasts on average, the number of boats and the number of fishers per boat. The total costs are obtained by multiplying the costs/ship/day by the total number of ships in operation. Ideally, estimates of economic data are made after examining the fishing log from a trading trip [21]. The maximum social value can be determined in two ways, the first is the level of maximum employment (the maximum number of fishers). The second is the maximum profit per fisher. The economic and social values as input data were the value per kilogram landed and the number of fishers during the last fishing season. It is desirable to use a long series of economic data, but these variables though exist, they are not easily available nor collected in a systematic way like those of the catch and effort and for now the estimate that is made by the model roughly reconstructs the economic history of the fishery, with the risk of incurring in certain errors. This problem will cease when a diagnosis of the current situation be made as a basis for the rationale and future management of the resource.

Benefits are determined by subtracting total costs from the total value of the catch. Costs and value are linked to the catch and the other variables in the model. The populations are evaluated by reconstructing the age structure of each one during the series of years of the analyzed data. The potential catch, benefits, direct jobs, and profits per fisher are estimated under the scenarios sought, changing the *F* and the *tc*. In this way, it is possible to test the response of the socio-economic variables of the fishery with reference to *MSY* and *MEY*. In this context, benefits are obtained by subtracting total costs from the total value of the catch; costs and value are linked to the catch and the other variables in the model.

It is amazing to find out that more than six decades ago Beverton & Holt [22] stated the principle that yield tends to increase with higher values of the age of first catch and displayed this in the well-known figure of yield per recruit. In addition, with the advent of computers and profuse modelling, it is not understood why this problem has not been tackled by fisheries scientists in the following years after that paper. Therefore, this essay was written with the purpose of showing evidence that for any exploited stock, there is a *MSY* value which is the maximum catch that can be extracted from an exploited stock in the long term, as one of the many equilibrium values that any fishery can have. It is pertinent to mention that in some cases there are huge differences between the *MSY* and the optimum yield (*OY*), which is the maximum harvest producing the highest benefit indefinitely. *OY* is a particular case of the equilibrium *MSY* values, corresponding to the highest yield that an exploited stock can produce. In addition, when economic values are explicitly considered, it is possible to talk about the *MEY*, which is closely equivalent to the *MSY*, but values of these variables do not coincide at the same *F* value. Fishing effort was not explicitly considered in this paper, based on the amount of noise usually implicit in it; instead, the spread sheet allowed that catch equation was fitted backwards and most of the significant amount of uncertainty disappeared in the stock assessment process.

The Gulf Menhaden

Despite the distribution range of the Gulf menhaden spreads over the Gulf of Mexico, and beyond, the fishery takes place in the brackish-waters of the Mississippi river delta, where the coastal areas contain high *Cla* values, in contrast with the low *Cla* content along the southern Gulf, where there is much lower productivity (an order of magnitude lower than along the northern Gulf) [23], which does not allow the high stock biomass of this fish as along the vicinity of the Mississippi river delta.

It is pertinent to mention that the catch trend shows an even decline since 1987 (data after Gedar 03 2021) [24], with 640 thousand t in 1987 to 414 thousand t in 2020, as shown in Figure 1, which was drawn to display the fitting process of catch and reconstructed data as a part of the model calibration. No fishing effort data were used to avoid the noise implicit in its use. Population structure was rebuilt in the simulation by applying backwards the stock assessment equations.

Once the population structure was rebuilt with the current parameters of the fishery, successive trials were applied to each age of first catch of the simulated stock, and this way the stock response could be measured. With the purpose of having an economic output, explicit consideration of the catch value before landing, the number of boats, the catch per trip, and the cost per trip were taken into consideration. The analysis presented in this paper deals within the scope of the so-called stock effect [25,26], it refers to the idea that unit operating costs are sensitive to the size of the exploited fish stocks; in other words, the analysis is referred to the performance of bio-economic indicators inside the fishery, before landing the catch.

With this information in the model, and by knowing the stock response as consequence of different values of the *F*, it was possible to determine the potential catch, the profits, the benefit/cost ratio, the *MSY*, the *MEY*, the best *tc*, and other bio-economic variables useful for fisheries management, produced as model outputs. As it was stated before, population parameter values were obtained from FishBase, and Gedar 03 2021. Estimation of some population parameter values were obtained with the aid of Froese 2006; Froese & Binohlan 2000 [27].

Results

Profits and Benefit/Cost Ratio

Despite its declining trend, the Gulf menhaden is a very productive economic activity, displaying profits above 160 M USD in 1987 to around 70 M USD in the year 2020 (Figure 2). The same statement is valid for the Benefit/Cost, whose values (times the cost of fishing) range from 86 in 1986 to 47 in 2011. During the last five years of the series, the economic activity displayed a significant increase up to 116 in 2020 (Figure 2).

Optimum Yield

The *MSY* use to be the target of many fisheries; however, it is not usually mentioned that it is not a fixed parameter, it is a variable

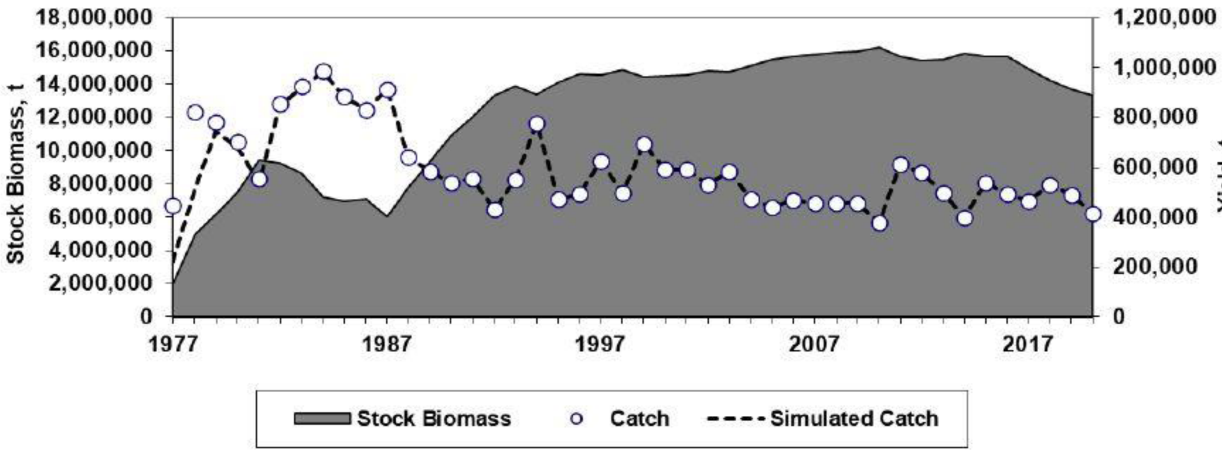

Figure 1: Model fitting of the catch and assessment of the biomass of the Gulf menhaden for the years 1977-2020.

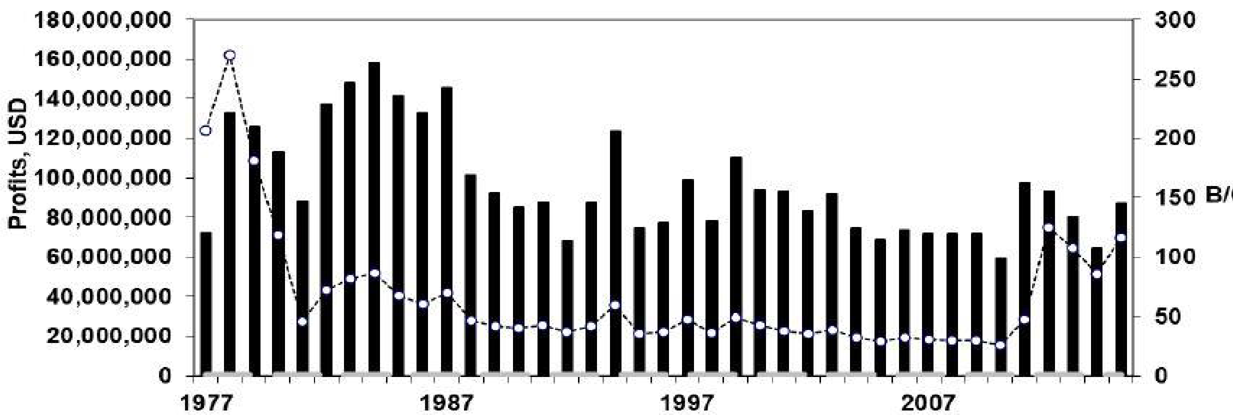

Figure 2: Trend of profits, in USD and *B/C* ratio of the Gulf menhaden fishery since 1977.

which depends on the age of first catch and therefore there are as many *MSY* values as age groups are in a given stock, being the optimum that one which is at or near the oldest age class in the fishery; in this case it would be the catch of 3.3 M t at the age of eight years profiting 527 M USD at the same age. For obvious reasons, it would be no practical the application of *tc* = 8 years and the most convenient option could be choosing seven years instead. Any other values are sustainable and are maximum for each age class before the last one. Under the *MSY* (Figure 3A) and the *MEY* (Figure 3B), the stock responds the same way and both variables display in an analogous way as a function of *tc*.

Economic Variables

As a result of the analysis, it was found that there is an inverse relationship between the costs of exploitation and the *B/C* ratio (Figure 4). This is an evident condition, because it is logical to expect that the exploitation of the fishery is subject to higher costs when the stock is less abundant and vice versa.

Under-Exploited or Over-Exploited?

The main reason why the consideration that the Gulf menhaden is overfished, as stated in the title of the present paper, is because from the viewpoint of the author, based on this and previous analysis, the stock is exploited as overexploited of recruits in a condition such that is shared by many fisheries around the world [28-32] and there are countless examples evidencing this problem. The analysis of this and other fisheries lead to the conclusion that the main reason for the over exploitation of recruits may be economic, because often occurs in pelagic stocks which are very productive and display high turnover rate. They are often linked to high economic value, product of high catch volumes, as it is the case of the Gulf menhaden; this fishery is very productive for its high landings and for its high profits. Then, it has been exploited for long time and the yield shows a declining trend to the point of capturing near 400 thousand t per season in the last few years, as compared to the landings of near one million t per season recorded in the middle eighties. It is amazing to realize that nobody has pointed this situation before, despite that the historical decline of catch is an evident fact and the teams in charge of evaluations refuse to accept this condition of the fishery, stating that "the Gulf of Mexico menhaden stock is not experiencing overfishing and is not overfished" (Gedar 03 2021). The authors of the present paper believe that the main reason why nobody has called the attention on the condition of an overexploited fishery is because the menhaden has been very profitable for many decades, confirming what was stated above. Then if nobody pays attention on this problem, the condition will continue until the turnover rate of recruits becomes critical, the stock biomass to be not enough to replace the stock and the fishery to become unprofitable [33]. This is evidence confirming that the Gulf menhaden is under a condition of overexploitation of recruits [34], a problem common to many other fisheries [35-39].

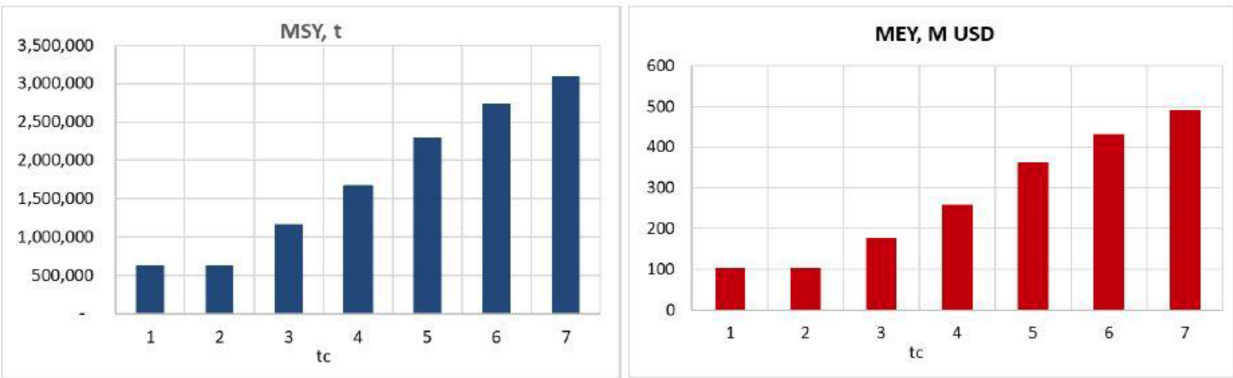

Figure 3: Maximum sustainable yield (*MSY*), 3A, and Maximum economic yield (*MEY*), 3B, of the Gulf menhaden fishery as a function of *tc*. In the first case the units are metric tons (t) and in the second case the units are Million USD

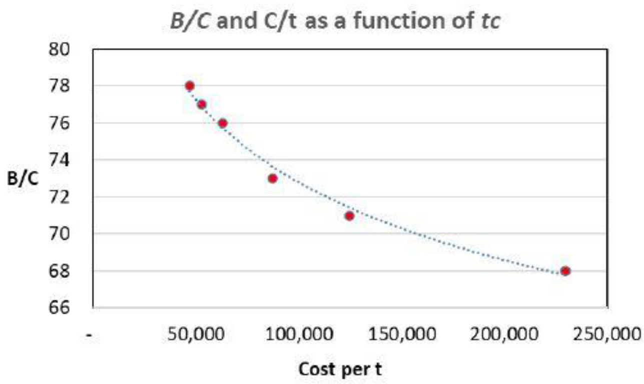

Figure 4: Relationship between the Benefit/Cost ratio (*B/C*) and the Costs of exploitation per t (*C/t*, USD) in the Gulf menhaden fishery. Each dot represents a *tc* value, being the first two overlapped on the right end of line trend, corresponding to *tc* ages of 1 and 2 years. The horizontal axis indicates the cost per t.

As result of the analysis, it was found that a nearly four times higher catch could be obtained by applying $F = 0.4$, as shown in Figure 5, where the exploitation rate (E) and the F estimated for the years 1977-2020 are displayed. It is pertinent to mention that it is not desirable to increase the F in an overexploited stock because the number of recruits would get exhausted in a few more fishing seasons and the whole fishery would fall into a collapse in brief time.

Numerical analysis and simulation of fisheries systems allow estimating potential yields, amongst other options; one of them deals with the possibility of doing a long-term forecast of the expected performance of the stock under different exploitation policies, with a very reasonable accuracy. In this case, after rebuilding the structure of the population, it is possible to estimate the expected potential yield by application as many feasible management options of F and the tc in a modern and flexible approach of the Beverton- Holt (1957) yield per recruit method. In this study case, three age classes, one, three- and five-years old fish were used as an example to demonstrate in first place, that the current fishery is overexploited of recruitment by applying a $tc = 1$, as shown in Figure 6. The trend line of each one of the three age classes selected here for demonstration display the outputs of the expected yield as a function of F. In the last few years of catch records, the F value estimated is $F = 0.11$ and the yield is $Y = 414{,}730$ t; then by looking at the expected potential yield by exploiting only adults ($tc = 3$ and $tc = 5$), would allow a much higher stock biomass to catch, and the F could be three times the current one being able to yield more than 1.1 M t, without the risk of depleting the fishery.

Horizontal lines showing the F_{MSY} and the E_{MSY} values are indicated as reference, showing that the fishery is exploited below the limit reference points since 1988. This is an apparent situation, because by increasing the F above the current values, the yield would decrease instead of increasing (Figure 6).

Discussion

By examining the causes of over exploitation of the most productive world fisheries, it is generally aknowledged that the most common problems of overexploitation of a fishery may occur after the application of excessive fishing effort, by overexploitation of recruits or both, leading to an excess of fishing capacity [40-43], despite clear

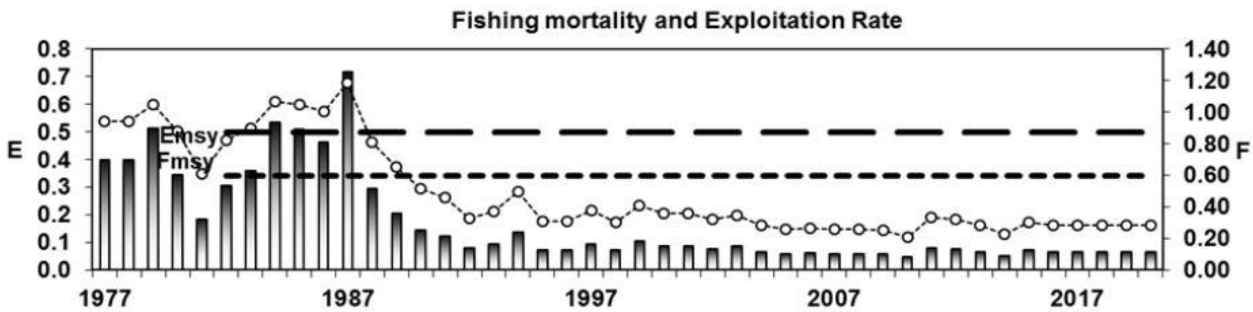

Figure 5: Historic trend of the *F* (bars) and the *E* (dotted line) in the menhaden fishery for the period 1977 – 2020.

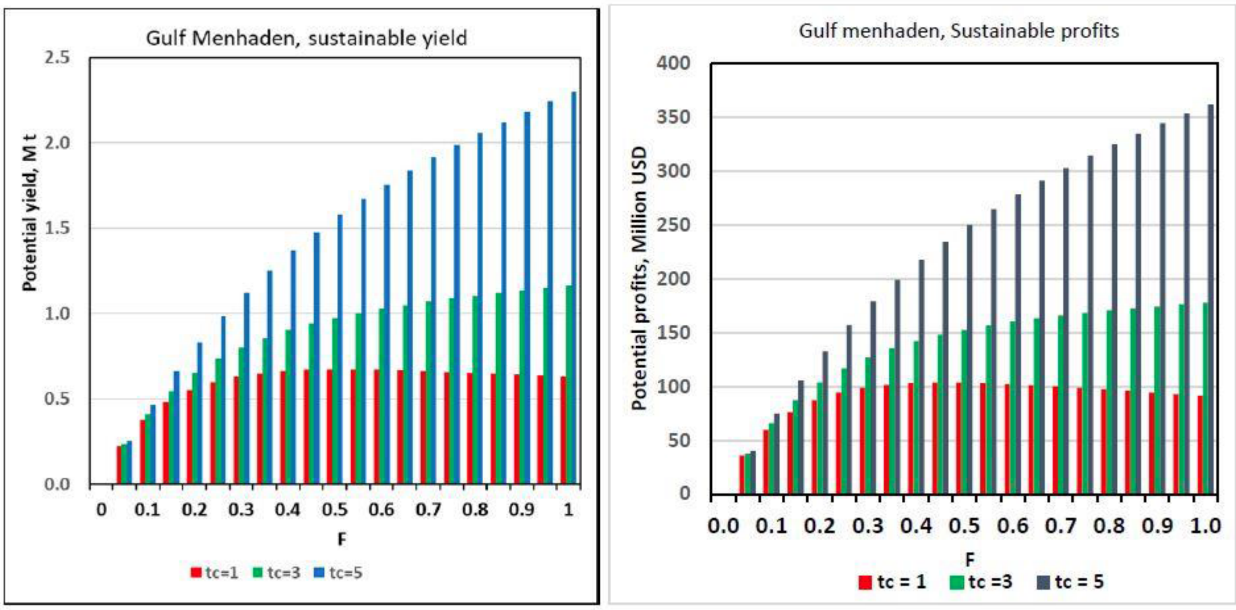

Figure 6: A. Expected yield of the Gulf menhaden fishery under three scenarios, as a function of fishing mortality. The lowermost line corresponds to the current condition with tc=1, whose maximum yield could hardly produce 670 thousand t at the maximum at F=0.4. By contrast, after applying the same F, with tc=3, the fishery would yield 904 thousand t; with tc=5, the fishery would harvest 1.3 M t. In the last two cases, only adult fish would be exploited. B. Economic performance of the fishery by expressing the profits in Million USD as a dependent variable. In the current condition (tc=1) the maximum profit is \$104 M. By applying the same F, with tc=3 the fishery would produce \$142 M; with tc=5, the fishery would profit \$218 M. Other variables are the same as in Figure 6A.

recommendations and reference points are defined [44,45]. This is the case of the Gulf menhaden, exploited in the northern Gulf of Mexico, and whose huge biomass makes it one of the most productive fish stocks at world level (Myers & Worm 2003).

Production of the Gulf menhaden fishery was briefly examined because of the Deep-Sea Horizon oil spill in 2010 awakened the interest on it by the authors, but an impact of the oil spill on its stock biomass immediately after that event was not evident. A ban was temporarily imposed to the fishery during this disaster, but the fishery continued shortly afterwards. However, no evidence of depletion could be observed in the stock biomass if there was any, as it is not shown in Figure 1.

Overexploitation of fish stocks is a major concern in many world fisheries. It is the case for not just the Gulf menhaden, but it occurs in many others and it has been pointed as one of the reasons why the world fisheries production display decreasing trends since more than fifty years ago [40,41], claiming for urgent rebuilding of stocks, Despite reference points and statements on the management have been provided (Caddy 1999; Caddy & Mahon 1995).

It has been stated that close to 90% of the world's marine fish stocks are fully exploited, overexploited or depleted, threatening the chance of renewal of stock biomass, because the gradual reduction of production capacity of the stocks to the point that a stock may be exhausted becoming incapable to restore its biomass as consequence of the lack of enough reproducers, compromising the sustainability of a fishery [42-44]. There are several causes leading fisheries to an overexploited condition, like illegal fishing, subsidies, fishing overcapacity and degradation of environment, as the more common ones. The effects of overexploitation are often expressed as social and economic crises on the harbours and ports where the reduced catches are landed, and where much infrastructure and services stop being in use leaving many people out of jobs. Contrary to what has been expressed in most of stock assessments [45], in this paper the use of fishing effort data was deliberately ignored, but once the model was fitted, it was possible to do an estimation of the number of fishing days, without the noise that is usually implicit in the current stock assessment procedures.

An undesirable perspective of the current condition of the Gulf menhaden, is maybe the worst case of a more general problem, biomass overexploitation not necessarily expresses the more critical consequence of this fishery, which has been gradually overexploiting its juveniles for decades. In this activity, the age groups caught by the fishery include since the age class of one year of age, but the stock reaches the age of sexual maturity at the age of two years; this implies that the fishing gears are catching all age classes. By consequence, the portion of the stock caught by the fishing gears include juveniles that otherwise would have the chance of reaching the adulthood and contributing to replace the stock with the products of their reproduction. In the Gulf menhaden fishery, catch trend over time displays a slight but consistent decline, evidencing the effect of a gradual reduction of the population turnover rate, which as far as it persists without change, eventually would lead the fishing activity into a crisis, becoming unprofitable, because the cost of fishing would make the fishery unviable. A reduction of the stock biomass would lead to an increase of fishing because it will make the fishery more expensive, to the point of reaching the economic equilibrium limit, this is when the fishing stops being profitable.

In order to conclude this paper, it is considered that despite the Gulf menhaden still is a productive fishery, with profits near to one hundred million USD, it could profit more than three hundred million USD if the owners of the fishing fleet decide to open the meshes of fishing gears, and the age of first catch is re-addressed to get only adults as target of the fishery. Evidently, the adoption of this fishing strategy would imply some previous trials of selectivity using several mesh openings, and results could allow choosing the most suitable one [46-52]. However, in order to achieve the expected goals in the desired size-frequency of the new catch, the adoption of the new mesh size should be applied to the whole fishing fleet, so the new selectivity can have impact on the whole exploited stock; otherwise it would not have the expected effect. It is considered that the use of the new mesh sizes, may take a couple of years to achieve the expected results.

Author Credit Statement

EC and ACH developed the paper concept; EC created the draft and structure of the paper; both authors contributed to writing and editing.

Declaration of Competing Interest

The authors declare that they have not known competing financial interests or personal relationships that could have appeared to to influence the work reported in this paper.

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