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Abstract

This paper presents a discrete-time bio-economic model of Northern Atlantic bluefin tuna.

The bluefin tuna is caught by several gears, targeting different age classes in different areas. To properly capture the dynamics of this species, an age-structured and multi-gear model was used. The model captures the dynamic interrelations between gears. In this way, the migrations are implicitly modelled, as gears can be associated with age classes and locations.

Three cases are simulated and analysed: open-access, total allowable catch (TAC) and constant fishing effort. Two alternative links between the economic and biological parts of the model were used and it is shown that the simulation results are very sensitive to the functional form of the production function. For both functional relations there are substantial gains to be had by departing from a situation of open access to a regulated one.

Keywords: Bio-economic applied model, bluefin tuna,

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1. Introduction

The Northern Atlantic bluefin tuna (*Thunnus Thynnus*) is a paradigmatic example of the difficulties faced in managing highly migratory species during the last decades. This issue has become the most important problem in the management of ocean fishery resources(see Munro, G.(1998)).

The management of the Northern Atlantic bluefin tuna falls under the aegis of the **International Commission for the Conservation of Atlantic Tunas (ICCAT)[1], created in 1969. This Commission comprises 23 fishing nations and is responsible for collecting** information and provides scientific based management measures in order to maintain the populations of tunas and tuna-like species at maximum sustainable catch levels.

According to most recent assessment of bluefin tuna stocks (1996), both the Western and the Eastern Atlantic stocks[2] are severely depleted. Whereas in the West Atlantic ICCAT's regulations have been observed, in the East Atlantic the scenario is just the opposite and, maintaining the present levels of catches, a complete depletion of the Eastern stock is most likely within a few years.

This severe stock depletion scenario may be explained by some factors. One is that bluefin tuna is a very highly priced species, even being referred to as "the most valuable wild animal on earth". The high prices are a result of the high demand of the Japanese market. This demand is directed to large and high-quality bluefin tuna, whereas the other specimens are confined to the local markets and receive significantly lower prices. Another factor is that this species has a schooling behaviour and the harvesting technology has improved significantly during the last decades, namely the use of sonar and aircraft to detect the schools.

The purpose of this paper is to show the potential of an age-structured and multi-gear bio-economic model to explain the dynamics of North Atlantic bluefin tuna fisheries under different scenarios, namely open-access, total allowable catch (TAC) and constant effort. Different production functions are considered in order to analyse their impact on the results, and to evaluate the model predictability.

The paper is organised as follows. The following section presents a description of the fishery. In section 3, the model is specified. In section 4, general economic assumptions are provided, regarding prices and costs. In section 5, the model is applied to the East Atlantic fishery. Two functional links between the biological and economic parts of the model are used: effort proportional to fishing mortalities (section 5.1) and Cobb Douglas catch functions (sections 5.2). For each, three cases are analysed: open access, constant TAC and constant fishing effort. In Section 5.3 the results of the two modelling alternatives are compared. In section 6, a similar analysis is undertaken for the West Atlantic fishery. Finally, section 7 presents some concluding remarks.

2. The Fishery

2.1 Biology and Migration

The Northern Atlantic and Mediterranean bluefin tuna is a large oceanic pelagic and is also the largest of the tunas. Its normal length, in adult stage, is between 1.60 and 2.40 metres but it can reach more than 3 metres (of fork length). Individual fish can weigh up to 650 Kg. Statistics reveal that bluefin tunas can live up to 25 years, although the oldest age considered reliable is 20 years. They are opportunistic feeders, commonly feeding on other fishes and squid. Like many other tunas, the bluefin tuna tend to be found in schools of similar-sized individuals. Small bluefin tuna are also found in schools mixed with other species of similar size, such as albacore, yellowfin, bigeye and skipjack tunas.

There exist two major spawning areas both characterised by warm waters that reach temperatures of 24° C. In the West Atlantic, the spawning area is in the Gulf of Mexico and in the Florida Straits. In the East Atlantic, the spawning is located in the Mediterranean around the Balearic Islands and the southern Tyrrhenian Sea.

The bluefin tuna is distributed on the West, from Brazil to Labrador, on the East from the Canary Islands to Norway, in the North Sea, in all of the Mediterranean and in the Southern Black Sea. Occasionally it reaches Iceland and Murmansk.

The two existing stocks tend to migrate within their own area. The Standing Committee on Research and Statistics (SCRS) of the ICCAT has acknowledged occasionally transatlantic migrations, estimating that the mixing between stocks is only about 3-4%.

2.2 North Atlantic bluefin tuna fisheries[3]

Total catch of North Atlantic bluefin tuna has an increasing trend since the early 70s, reaching in 1995 a maximum of 41,616MT. This increasing trend as well as most of the catches is due to the East Atlantic and Mediterranean stock. The West catches have decreased during this period and stabilised at around 2,000MT since the 80s.

The North Atlantic bluefin tuna fisheries are characterised by a variety of vessel types and fishing gears operating out of many countries. Different fishing gears target different quality and size of bluefin tuna, which have different market values. The prices for big size and high quality specimens are significantly higher than the prices for remaining ones. The traditional and most important fishing gears are the purse seine, trap, baitboat, longline, and rod and reel. These gears differ according to the location of the fishery and differences in efficiency may also be found.

Throughout the years, the importance of each gear has changed. Certain fisheries, such as traps, go back to ancient times. Other fisheries, such as the Atlantic longline and the Mediterranean purse seine, reached full development in the mid 1970s. The distribution of the different gears in the Atlantic and the Mediterranean Sea has also changed through time. One of the most important changes has been the reallocation of the longline fishery, mainly Japanese, from the West to the East stock. Figures 1a and 1b present the distribution of the main fisheries up to and after 1970, respectively.

According to estimates available the bluefin tuna stocks, in the North Atlantic and Mediterranean Sea, seems to have experienced a decrease since 1965.

The decrease in the stock was more pronounced in the West Atlantic in the period 1970-1982. In the early 1980's, the state of the stock led the ICCAT to enforce severe measures, in order to prevent it from complete depletion. Although there exists clear economic incentives for the bluefin tuna harvest, due to the japanese high price demand, the regulations have proved effective by decreasing the catches and stabilizing the stock, although at a low level. These measures have taken, so far, the form of upper bounds on catches and fishing efforts, limits on the length and weight of the fishes being harvested, and catch prohibition in certain areas or periods[4]. Some reasons can be advanced for the success of the regulations, such as the few number of countries participating in the fishery and the small levels of present catches (below 2500 MT).

The estimates of the East Atlantic stock show a smooth decreasing trend, at least since 1970. This trend was the result of a substantial increase in the bluefin tuna harvest.

Since 1974, some ICCAT regulations, concerning the bluefin tuna catches, have entered into force. Nevertheless, their impact has not been significant since the measures have not been respected, not only by the ICCAT's members but also by the non-member countries fishing in the Northern Atlantic.

The high bluefin tuna price in the Japanese market, as well as the depletion of the Southern bluefin tuna stock in the Pacific Ocean (see Geen and Nayar(1988)) are some of the factors clearly behind this scenario of stock over-exploitation. Also, the increase in prices creates a strong incentive to spend a significant part of the rent produced within the fishery in technological improvement, in order to increase the catches. In fact, this is confirmed by the reports of the ICCAT, not only for longline but also for all the gears, which state that, recently, there has been a strong investment in technological improvement in the fishing gears. Specifically, there have been investments on instruments for the detection of bluefin tuna, including the use of aircraft, efficient radar, etc., that accurately detect the location of the bluefin tuna schools.

3. The Model

An age-structured and multi-gear time discrete dynamic model was developed to simulate the Northern Atlantic bluefin tuna fishery. As the overall fishery for the Northern Atlantic bluefin tuna comprises a number of sub-fisheries, typically defined geographically and by fleet/gear, and targeting different age classes, the complexity of the biological model, developed by Kirkwood and Barry (1997), was considered to be important. This is so, not only because it captures the inter-relation between the different gears, the associated age classes and locations but, also, a good forecasting power is essential, in the short run, due to the severe state of depletion of the stocks.

The model equations, presented in appendix, are organised in the following way:

A- Age-structured biological model[5].

B- Profit equations for gear s in year t

$$\Pi_{j,s,t} = P_{j,s} C_{j,s,t} - W_{j,s} E_{j,s,t}$$

where j refers to the stock; s the sub-fishery index; t is the year index; P is the average price per gear; C the catch; W the average cost per unit of effort and E is the level of effort.

For the revenue estimation an average price by gear was used. Although it is known that prices by age vary significantly, this assumption is not a very strong one. The reason behind this is the assumption of constant selectivities[6] in the forecasting period. This makes the distribution of catches for each gear, among the age classes, more or less stable.

C- Closing the Model

The link between the biological and economic components of a bio-economic model is a topic of ongoing research. In this paper two alternative links (see Conrad and Clark (1987)) were tested (Equation 16 and 16´ in appendix). The first one is a constant proportional relation between fishing mortalities by gear and the effort level:

$$Fmax_{j,s,t} = q_{j,s,0} E_{j,s,t}$$

where Fmax is the fishing mortality at maximum selectivity[7] and t = 0 corresponds to the year base, 1995. The values of effort in the year base used to estimate $q_{j,s,0}$ are presented in Table 1[8].

This relation is close to the use of the following catch functions:

$$C_{j,s,t} = q_{j,s} E_{j,s,t} B_{j,t}$$

where C stands for catches, E for effort, B for stock and q is a constant catchability coefficient.

This function implicitly assumes that catch per unit of effort is directly proportional to the density of fish in the sea, and also, that the density of fish is directly proportional to the abundance ($B_{j,t}$). Although very commonly used on applied bio-economic models, this relation may not be appropriate in the presence of schooling effects, as the above assumptions do not hold.

As an alternative, a second link was established allowing the catch-stock elasticity to be different from one[9].

$$C_{j,s,t} = q_{j,s} E_{j,s,t} B_{j,t-1}^{\alpha_s}$$

where α_s represents the catch-stock elasticity for each gear.

As gear catches depend differently on the stock, stock elasticities were used accordingly. For the gears that make use of very advanced methods of detection (longline, purse seine, bait boat and Rod and Reel) a low catch-stock elasticity was assumed (0,2). As trap and remainder are much more stock dependent a higher value was used (0,8)[10]. The catch-effort elasticity was considered to be unitary in order to compare with the case of effort proportional to fishing mortality, isolating the impact of lowering the catch-stock elasticity.

D- Model dynamics

Three cases were simulated, the open access case simulates the market dynamics in the absence of regulation, the constant TAC case and the constant effort case simulates the impact of those two kinds of regulatory instruments. Imposing a constant TAC is different from imposing a constant level of effort because as the stock recovers not only the catch per unit of effort grows but also the impact varies among the different gears. The main assumptions for each case are presented bellow:

Case 1: Open access

To model this scenario, it is assumed that effort varies with the previous year's profit, according to the following relation:

$$\frac{E_{j,s,t}}{E_{j,s,t}} = \beta_{j,s} * \text{sign}\left(\Pi_{j,s,t-1}\right)$$

The adjustment parameters $\beta_{j,s}$ were determined, based on the evolution of fishing effort for the most recent years, therefore, different values for different gears were used accordingly and are presented in Table 2.

Case 2: Constant Total Allowable Catch (TAC)

The most common management regulation in fisheries management is the establishment of a TAC. Constant TACs, for the forecasting period, were simulated, assuming that the 1995 share of each gear in the total catches is maintained constant.

Case 3: Constant effort

Another typical regulation in fisheries management is to restrict effort. Several simulations were made in order to analyse the impact of a constant level of effort. For different levels of catches in 1996 (maintaining the 1995 shares), the corresponding levels of effort, for each gear, were calculated and maintained constant thereafter.

For all three cases, a forecasting horizon of 25 years (1996-2020) was considered, and the net present value of profits (NPV) was calculated for that period.

4. General Economic Assumptions

4.1 Prices

Price data from several sources were obtained. The most consistent price database of bluefin tuna is the one included in *The Statistics of Import-Japan Customs House* (1985-96). The average prices by gear estimated were mainly based on this database, taking into account for each gear/country, the proportion that goes to the local market and to the Japanese market and the respective prices. The computations are explained in detail in an auxiliary memorandum (Memorandum 2.1) and the selected average prices are presented in Table 3.

A 4% rate of discount was used to evaluate the NPV of each sub-fishery, during the forecasting period. This value was considered reasonable according to other applied studies, using similar investment horizons, such as the *"Final Environmental Impact Statement for the Western Atlantic Bluefin Tuna"*(1995), and long-run interest rates published in FMI reports.

4.2 Costs

Published cost data for these fisheries is almost non-existent. The few available data was gathered in Memorandum 2.2. Average costs per unit of effort were then estimated, assuming that profits, for the base year (1995), were a percentile margin of the revenues. Given the fact that, at the present, some gears are more profitable than others, the margins are different among gears. The margins as well as costs per unit of effort used in the simulations are presented in Tables 4 and 5. These values for average costs were then assumed to remain constant in the forecasting period.

Being aware of the fact that this was a very crude assumption for calculating average cost, these values were compared with the available cost data, namely for longline (East and West Atlantic) and purse seine (West Atlantic). We concluded that the differences were not highly significant (see Memorandum 2.2).

5. East Atlantic Fishery

In this section the results of the three simulated cases are presented for the East Atlantic fishery. The two alternative links between the biological and economic model are considered: a proportional relation between effort and fishing mortality and a Cobb-Douglas catch function.

5.1 Effort proportional to fishing mortality

The main results of the simulations assuming a proportional relationship between effort and fishing mortality are shown in Figure 2 and Tables 6 and 7.

In the open access case, a competitive scenario was generated where profits in all sub-fisheries tend towards zero as the number of periods increases. Table 4 shows that the aggregate NPV over 25 years is negative (-41,054,000 USD) due mainly to the losses of the LL and Trap sub-fisheries. These gears that target mainly large bluefin tuna experience high losses, in the short run, as the corresponding age classes are severely depleted. On the contrary, bait boat presents surpluses, on the short run, as it targets small bluefin, which is less depleted in the beginning of the fo ecacting period. Note that the values of profits obtain in this scenario depend on the market adjustment coefficients (β) used, higher values of β will speed up the open access equilibrium.

Regarding stock behaviour, Figure 2 shows that total biomass at the end of the forecasting period (112,200 MT) in the open access scenario is not far from that of 1995, although it presents ups and downs as a result of the oscillations in the catches. These results confirm that open access is compatible with non-depletion of the stock for certain functional relations between fishing mortalities and effort or, in other words, for certain catch functions.

In the constant TAC case, several values of TAC were simulated and the total NPV of profits, for all gears, was maximised for a TAC = 25,000 MT. As in the open access case, very different short run profit behaviour occurs for each of the sub-fisheries. In fact, bait boat and purse seine accumulate surpluses whereas all others have losses. The main reason for this is that the different gears target different age classes, and their biomasses do not behave uniformly[11]. In the long run, all subfisheries expirience significant gains, although not evenly distributed.

In this case, the biomass presents an increasing trend during the simulation period as can be seen in Figure 2. As catches are constant, this results in a decreasing trend for the fishing mortalities and the resulting effort, in turn implying cost decreases. As revenues are constant profits thus tend upwards.

Simulations were also conducted, allowing the TAC to change within the forecasting period. If TAC can be higher as the stock biomass recovers, the NPV will also be higher, and the simulation results are closer to the ones resulting from constant effort case.

In the case of constant effort, the maximum total NPV of profits was obtained keeping constant the levels of effort corresponding to a total catch of 10,000 MT in 1996. Also, this regulation instrument maximises gains, this occurs mainly because, assuming a linear catch-function, for the same level of effort catches increase significantly as the stock recovers. In this scenario, maximising NPV of profits would imply a huge decrease in effort, to about 25% of the 95[th] levels, implementing this policy would have significant social costs.

From Table 4 emerges the result that there are substantial gains in regulating this fishery. The scenario that maximises total NPV is the optimal level of constant effort. It is interesting to note that all gears have the highest NPV in this case, with the exception of bait boat for which that occurs in the case of an optimal TAC. The reason behind it is that, for all gears except the bait boat, big bluefin tuna is an important target. Presently, the corresponding age classes are severely depleted so it pays to have a dramatic decrease in effort, in the short run, in order to recover the stock. This effect is not so important for bait boat because this gear targets mainly small bluefin tuna, age 1 and 2, whose stock is less depleted.

Concerning the total catches, the values presented in Table 7 indicate that the different cases imply very different catch behaviour during the simulation period. In the open access case, catches present some oscillations with an average of about 30,000 MT. In the TAC case, it remains constant at 25,000 MT and in the case of constant effort it presents an increasing trend (starting from 10,000 MT, in 1996, and reaching catches near 50,000 MT by the end of the forecasting period).

The effort dynamics is also very distinct in each of the three cases. In the open access the different gears present different trends, e.g. the bait boat increases the effort level relatively to 1995, whereas remainder maintains and purse seine, longline and trap decreases. In the TAC all gears decline gradually as stock recovers, and in the constant effort there is a sharp decrease in 1996 to about 25% of 95th values.

5.2 Cobb- Douglas catch functions

In this section the results of the model simulation using a Cobb-Douglas catch function are analysed. Figure 3 and Tables 8 and 9, presented bellow summarise the main results.

The simulation results obtained with the open access scenario are in accordance with ICCAT's concerns on the bluefin tuna fishery. In the short run, catches increases significantly (rising above 50,000 MT in 1998) and the stock is completely depleted by the year 2000, as can be seen in Figure 3.

For the TAC case, 25,000 MT yield the maximum NPV of profits as when using a proportional relation between effort and fishing mortality.

In case of constant effort, the maximum NPV was obtained for levels of effort corresponding to 20,000 MT in 1996. That implied effort decreases to about 50% of 95th values.

From Table 8, we can conclude that open access yields, for all gears, substantially lower NPV of profits than the two regulated scenarios. It is interesting to note that all gears present higher NPV in the case of optimal constant effort level than in the case of optimal TAC. Table 7 shows that in the case of open access there are very high levels of catches (average above 40,000 MT) but only for a short period of time before the collapse of all the fisheries. In the constant effort case it starts with 20,000 MT in 1996 and reaches 34,072 MT in 2020.

Regarding the effort dynamics in the short run, open access scenario predicts significant increases, whereas the regulated scenarios imply effort decreases.

5.3 Comparing the two alternative catch functions

As expected, the results are very sensitive to the function used to link the biological and economical models. The open access case implies very different dynamics for the two alternative links between the biological and economic models. Using a proportional relation between fishing mortality and effort, catches vary around 30,000 MT (Table 7) and the stock does not tend to depletion within the forecasting period. In contrast, a Cobb Douglas relation leads to a sharp increase in catches and the stock tends to depletion in the short run. The relative performance of the gears is also very different. A clear example of it is the remainder that experiences the highest profits for the former relation, as the stock does not tend to depletion, and highest losses for Cobb Douglas relation as catches are highly sensitive to stock, which decreases substantially in the short run.

As the open access case is close to the present state of this fishery in the East Atlantic, we may conclude that proportional relationship between fishing mortalities and effort levels does not describe properly the dynamics of the bluefin tuna in the East Atlantic. In fact it does not predicts two known facts: first, the 96th catches, already published by ICCAT, were above 40 000 MT and second, the level of effort are still increasing in many of the sub-fisheries. Also, it contradicts the common belief that unless regulations are enforced the depletion of the stock is a likely scenario within a few years time.

By using Cobb-Douglas type catch functions these results were obtained. Reducing the stock elasticity of the catch function is more in tune with the schooling nature of the bluefin tuna.

It is interesting to note that, in the case of a TAC, both alternatives yielded a 25,000 MT, as the TAC providing maximum NPV. This value corresponds to the quotas that ICCAT is trying to enforce[12].

In the case of constant effort, using a proportional relationship between fishing mortality and effort implies, in the short run, a significant decrease in the fishing efforts, in order to maximise NPV. This is not the case when using Cobb Douglas functions with low stock elasticity, as the subsequent stock recovery is not a determinant factor on the catches.

6. West Atlantic Fishery

6.1 Effort proportional to fishing mortality

The main results obtained by using a proportional relation between effort and fishing mortality are presented in Tables 10 and 11.

In the open access case, as in East Atlantic, a competitive scenario was established and again the stock does not experience a sharp decrease. Table 11 shows that the average catch between 1996 and 2020 (2,524MT) is above present quotas. In this scenario the NPV of profits is positive, but at a lower level than any of the regulated scenarios.

In the TAC case 2,000 MT yields the highest total NPV. It is interesting to note that this value is near the recommended TAC for 1996 (2,200 MT).

The constant effort levels that maximises NPV of profits is around 50% of 95th levels, which corresponds to a catch level of 1,250 MT in 1996. Total catches increases as stocks recover, reaching 2,417 MT in 2020 (see Table 11).

The main conclusions that result from the comparison of the three cases are qualitatively similar to ones obtained for the East Atlantic stock. Table 10 shows that the optimal regulated scenarios generate considerable gains when compared to open access.

6.2 Cobb- Douglas catch functions

The main results for the West Atlantic simulations using Cobb-Douglas Catch functions are presented in Tables 12 and 13 bellow.

Table 12 shows that the case of constant effort yields the highest NPV of profits for every sub-fishery. The open access case presents signifficantly lower NPV than the optimal TAC (2000 MT) and optimal constant effort (about 75% of 95th levels and corresponding to 1,750 MT in1996).

As in the East Atlantic, open access leads to very high catches, in the short run, which results in the depletion of the stock in 2006. The case of constant fishing effort presents an increasing trend in catches, starting from 1,750 MT in 1996 and reaching 2126 MT in 2020.

7. Concluding remarks

This paper present an age structured multi-gear bio-economic model that has the potential to capture the inter-relations between the different gears that target different age classes of bluefin tuna in different locations.

The link between the biological and economic parts of the model was established through two alternative functional relations: effort proportional to fishing mortality and a Cobb- Douglas type catch function. In this framework three cases were analysed, namely open access, constant TAC and constant fishing effort.

Assuming a proportional relation between fishing mortality and fishing effort, the open access does not lead the stocks (East and West Atlantic) to depletion, but the rents of the different gears are exhausted. In contrast, using a Cobb-Douglas catch function, **with low stock elasticity, for some of the gears, the depletion of the stocks is the most likely scenario within a few years. This last case is more reliable as this species presents a** clear schooling behaviour, being then able to predict some *apriori* expected results under an open access scenario

Using the Cobb-Douglas catch functions the main results are that, under a scenario of open access, catches would continue to increase and, most likely, the stocks would be severely depleted within a few years. These results contrasts with the ones obtained under the other functional relation, where the returns are expected to decrease in the short run but the expected depletion of the stock would not happen, due to the high costs of harvesting as stock gets exhausted.

The TAC case revealed that, under both alternatives, the suggested TACs by the ICCAT are not only biological sustainable, but also economically superior to the non-regulated scenario.

The comparison between the three cases reveals that the total NPV of the open access scenario is significantly smaller than the NPV obtained through an optimal TAC or an optimal constant level of effort.

The model is also able to capture the complexity of the bluefin tuna fisheries taking into account the relationship between the various sub-fisheries. This opens the possibility to evaluate the impact of different regulatory instruments on each of the main sub-fisheries.

This model opens fields for future research, namely the analysis of possible regional agreements for the management of North Atlantic bluefin tuna and the evaluation of the impact of new members, or of catches by non-contracting parties. This model can also be extended to a stochastic framework by using a stochastic stock recruitment function.

APPENDIX

Bio-economic model

Population numbers

$$N_{j,a,0} = \tilde{N}_{j,a} \quad \text{for } 1 \le a \le 10, \tag{1}$$

$$N_{j,1,t} = SRR_j(SSB_{j,t-2})e^{\Phi} \tag{2}$$

$$N_{j,a,t} = N_{j,a-1,t-1}e^{-M_{j,a-1}-F_{j,a-1,t-1}} \quad \text{for } a = 1,2,\ldots,9;\ t = 1,2,\ldots \tag{3}$$

$$N_{j,10,t} = N_{j,9,t-1}e^{-M_{j,9}-F_{j,9,t-1}} + N_{j,10,t-1}e^{-M_{j,10}-F_{j,10,t-1}} \tag{4}$$

$$SSB_{j,t} = \sum_{a=1}^{10} Mat_{j,a,t} N_{j,a,t} W_{j,a,t} \tag{5}$$

$$B_{j,t} = \sum_{a=1}^{10} N_{j,a,t} W_{j,a,t} \tag{6}$$

Catch at age by sub-fishery

$$F_{j,s,a,t} = FMax_{j,s,t}.Sel_{j,s,a} \tag{7}$$

$$F_{j,a,t} = \sum_{s=1}^{S} FMax_{j,s,t}.Sel_{j,s,a} \tag{8}$$

$$C_{j,s,a,t} = \frac{F_{j,s,a,t}.N_{j,a,t}}{\sum_{s=1}^{S}(F_{j,s,a,t} + M_{j,a})}\left(1 - e^{-\sum_{s=1}^{S}(F_{j,s,a,t}+M_{j,a})}\right) \tag{9}$$

$$CB_{j,s,t} = \sum_{a=1}^{10} C_{j,s,a,t}.W_{j,a} \tag{10}$$

$$FMax_{j,s,t} = FMult_{j,s,t}\tilde{F}Max_{j,s} \tag{11}$$

$$Q = \sum_{s=1}^{S} Q_s \tag{12}$$

$$Q_{Rem} = Q_S = Q - \sum_{s=1}^{S-1} Q_s \tag{13}$$

$$Q_s = \sum_{a=1}^{10} \frac{FMult_{j,s,t} . \tilde{F}Max_{j,s} . Sel_{j,s,a} . N_{j,a,t} . W_{j,a,t}}{\sum_{i=1}^{S} \left(FMult_{j,i,t} . \tilde{F}Max_{j,i} . Sel_{j,i,a} + M_{j,a} \right)} \left(1 - e^{-\sum_{i=1}^{S} \left(FMult_{j,i,t} . \tilde{F}Max_{j,i} . Sel_{j,i,a} + M_{j,a} \right)} \right) \quad (14)$$

for $s = 1,2,\ldots,S$

Economic dynamics

$$\Pi_{j,s,t} = \sum_{a=1}^{10} \left(P_{j,s,a,t} . C_{j,s,a,t} - W_{j,s,t} . E_{j,s,t} \right) \quad (15)$$

$$\Pi_{j,s,t} = \overline{P}_{j,s,t} . C_{j,s,t} - W_{j,s,t} . E_{j,s,t} \quad (15')$$

$$FMax_{j,s,t} = q_{j,s,0} E_{j,s,t} \quad (16)$$

$$C_{j,s,t} = q_{j,s} E_{j,s,t} B_{j,t-1}^{\alpha_s} \quad (16')$$

$$NPV_{j,s} = \sum_{t=0}^{T} \Pi_{j,s,t} . \frac{1}{(1+r)^t}, \text{ for } t = 0 \rightarrow 1995 \text{ and } T \rightarrow 2020 \quad (17)$$

j The stock with j = East Atlantic, West Atlantic;

a The age index, for ages 1 to 9 and a plus group of fish aged 10 or over;

t The year index, with t = 0 corresponding to the beginning of 19^5;

s The sub - fishery index, with s = 1,2,...,S;

$N_{j,a,t}$ The number of individuals of age a at the start of year t in the j stock;

$\tilde{N}_{j,a}$ The estimated number of individuals of age a at the start of 1995 in the j stock;

$SRR_j()$ The stock recruitment relationship for the j stock and Φ is a Normal Random variable with mean 0 and variance σ^2;

$SSB_{j,t}$ The spawning stock biomass for the j stock in year t;

$M_{j,a}$ **The instantaneous natural mortality rate at age a in the j stock;**

$F_{j,a,t}$ **The instantaneous fishing mortality rate at age a during year t** in the j stock;

$Mat_{j,a,t}$ The proportion mature at age a in year t in the j stock;

$W_{j,a,t}$ The average weight of fish aged a in year t in the j stock;

$B_{j,t}$ The total j stock biomass;

$F_{j,s,a,t}$ The fishing mortality rate in year t exerted by sub - fishery s on fish aged a in the j stock;

$FMax_{j,s,t}$ The fishing mortality rate at maximum selectivity exerted in year t by sub - fishery s in the j stock;

$Sel_{j,s,a}$ The selectivity at age a exerted by sub - fishery s in the j stock;

$F_{j,a,t}$ The fishing mortality rate at age a for the overall fishery on the j stock in year t;

$C_{j,s,a,t}$ The catch numbers at age for each sub - fishery s in the j stock and in year t;

$CB_{j,s,t}$ The total catch biomass for each sub - fishery s;

$FMult_{j,s,t}$ The F - multiplier for sub - fishery s in year t for the j stock;

$\tilde{FMax}_{j,s}$ The fishing mortality rates estimates at maximum selectivity appying to each sub - fishery s and the remainder sub - fishery for the last year before simulation;

Q_s The total quota for each specified sub - fishery $s\,(s = 1,2,\ldots,S-1)$,

Q_{Rem} The total quota for the remainder sub - fishery;

Q The total quota;

$\Pi_{j,s,t}$ The profit by sub - fishery in year t for the j stock;

$P_{j,s,a,t}$ The average price for sub - fishery s in year t for the j stock and age a;

$\overline{P}_{j,s,t}$ The average price for sub - fishery s in year t for the j stock;

$W_{j,s,t}$ The average cost of a unit of effort for sub - fishery s in year t for the j stock;

$E_{j,s,t}$ The effort of sub - fishery s in year t for the j stock;

$q_{j,s,0}$ A constant;

$NPV_{j,s}$ The net present value for sub - fishery s for the j stock;

r The discount rate.

References:

Bjorndal, T.,1988. The Optimal management of North Sea Herring, *Journal of Environmental Economics and Management*, 15 :9,29

Bjorndal, T., Conrad ,J., Salvanes,K.1993. Stock Size, Harvesting Costs, and the Potential for Extinction. *Land Economics*, 69(2):156-67.

Conrad, J.M. and Clark, C. W. 1987. *Natural resource economics: notes and problems*. Cambridge University Press.

Costa Duarte,C., Brasão,A., Pintassilgo, P. 1998. North Atlantic and Mediterranean Bluefin Tuna: Biological and Economic Issues. Working Paper nº 322 FEUNL .

Geen,G., Nayar,M., 1988. Individual transferable Quotas in the Southern Bluefin Tuna Fishery: An Economic Appraisal. *Marine Resource Economics* 5:365-387.

Kirkwood, G. P., Barry, C.J. 1997. Specifications of a Biological and Catch Prediction Model for Northern Bluefin Tuna. FAIR project PL 96.1778 - The Management of High Seas Fisheries.

Munro, G.R, 1998. The Management of High seas Fisheries and the United Nations Conference on Straddling Fish stocks and Highly Migratory Fish Stocks: A Review: University of British Columbia, Vancouver, Canada

Final environmental impact statement for a regulatory amendment for the Western Atlantic bluefin tuna fishery, 1995. U.S. Department of Commerce.

Memorandum 2.1. "Northern Atlantic and Mediterranean Bluefin Tuna Fisheries: The Analysis of the Price Data"1998 FAIR project PL 96.1778.

Memorandum 2.2. - "Northern Atlantic and Mediterranean Bluefin Tuna Fisheries: The Analysis of Cost Data" (1998).

The Statistics of Import -Japan Customs House (1985-96).

SCRS/96/26. Detailed Report for Bluefin Tuna (1996).

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[1] For a more detailed information on ICCAT, namely members and objectives see Duarte, C., Brasão, A. and Pintassilgo, P. (1998).

[2] Since 1982, for the purpose of stock assessment ICCAT has assumed the existence of two distinct stocks, West and East Atlantic (the latter including the Mediterranean Sea). A line of separation between them was also established at that time.

[3] For a more detailed information on stock and catch evolution see Duarte, C., Brasão, A. and Pintassilgo,P. (1998)

[4] For more information on this subject see Duarte, C., Brasão, A. and Pintassilgo, P. (1998)

[5] Developed by Kirkwood and Barry. See Eq. (1) to (14) in appendix.

[6] For definition see equation 7 in the appendix.

[7] Fishing mortality and selectivity for a given age are concepts often used on biological models. The first is an index of fishing mortality, as the name suggests, and can be approximated by the ratio of the catch over

the stock. The second corresponds to the ratio of the fishing mortality at a given age to the fishing mortality at the age where it reaches the highest value.

[8] There are no published data on total effort in each fishery. Some estimates were made based on published partial information. A detailed description of the calculations is presented in an auxiliary memorandum (Memorandum 4.2).

[9] A similar production function was proposed for a schooling species in Bjorndal, T. (1988).

[10] The values of α, assumed in the model simulations are not based on any empirical estimation. However, they are considered reasonable values for a schooling species (see Bjorndal, T. (1988) and Bjorndal, T., Conrad, J., Salvanes, K., (1993)) and furthermore, the values of catches predicted for 1996 by the model are in accordance to the values of catches later published by ICCAT for 1996.

[11] Age 10+ (ten years and more), for example, presents an initial decrease followed by an increasing trend, whereas age 1 and 2 increase in the beginning and tend to stabilise thereafter.

[12] ICCAT recommends catch reductions in 25% of the 1994 or 1995 levels by the end of 1998. This corresponds to catches of about 25,000 MT, value that is considered as a sustainable catch and would lead spawning stock biomass (SSB) to increase to about 3 times the level of 1995 within 20 years.

Figure 1: North Atlantic Bluefin Tuna Main Fisheries

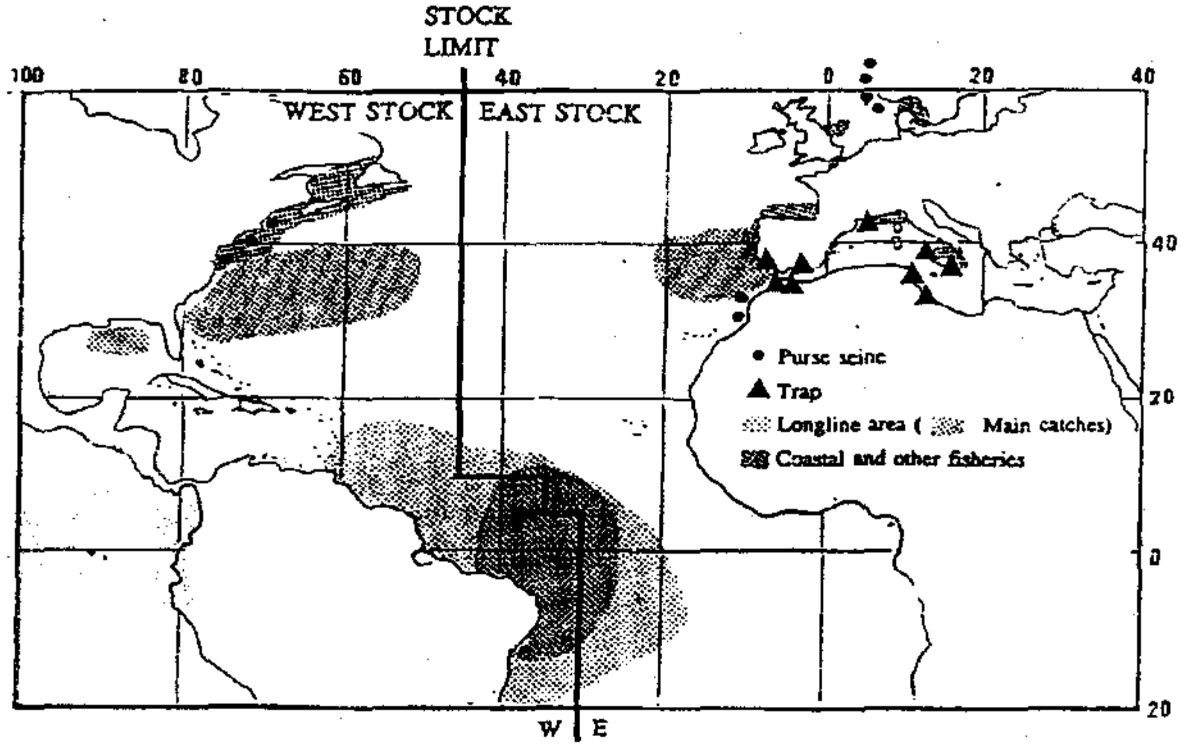

Fig. 1a. Historical main fisheries (up to 1970) in Atlantic Ocean and Mediterranean Sea.

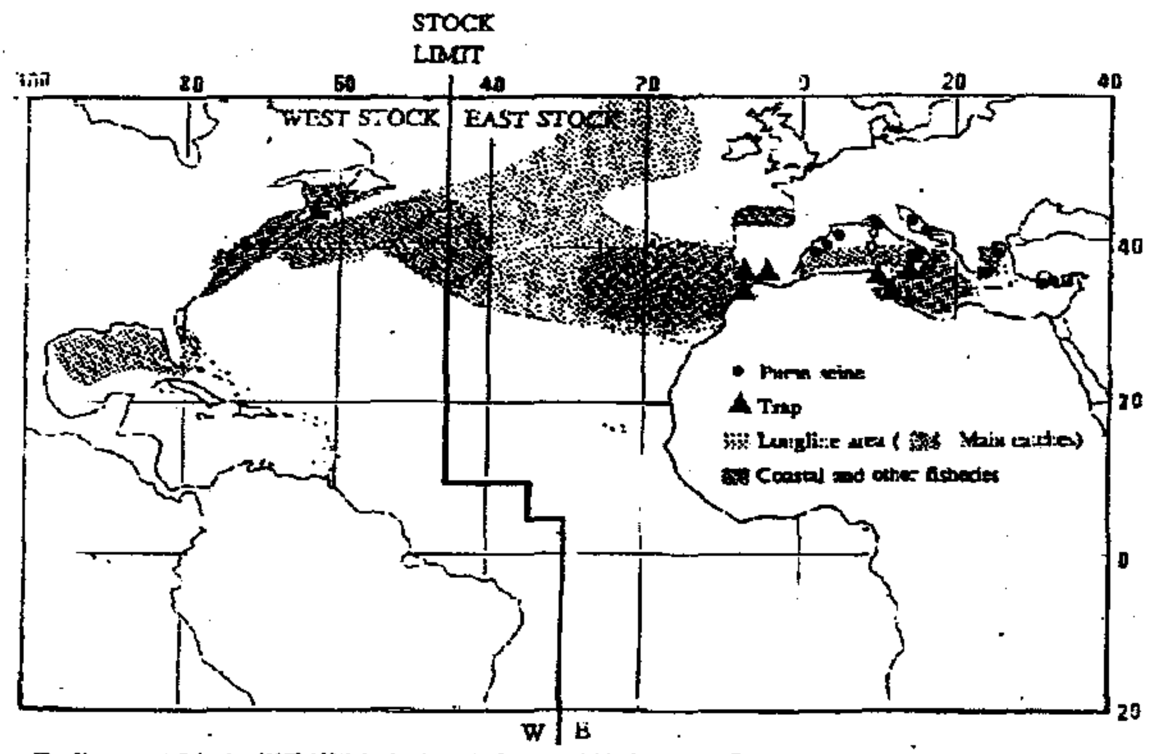

Fig. 1b. Actual fisheries (1970-1994) in the Atlantic Ocean and Mediterranean Sea.

Source: ICCAT

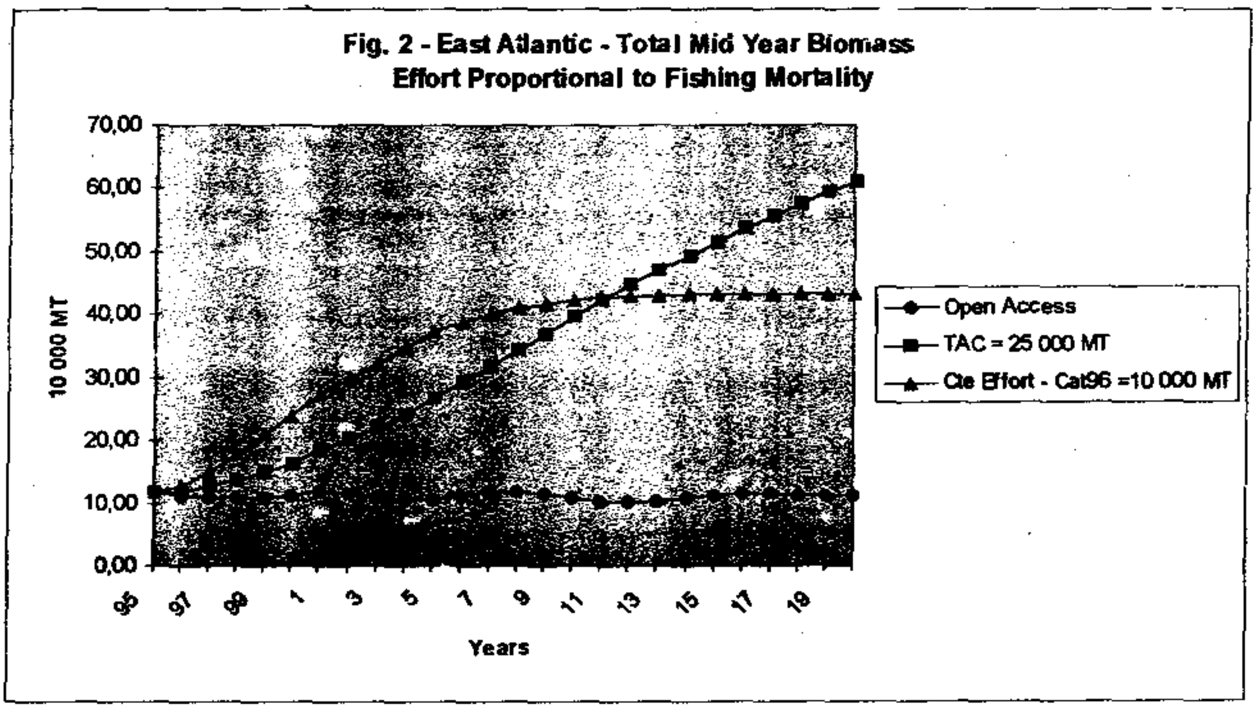
Fig. 2 - East Atlantic - Total Mid Year Biomass
Effort Proportional to Fishing Mortality
70,00
60,00
50,00
40,00
30,00
20,00
10,00
0,00
10 000 MT
95
97
99
1
3
5
7
9
11
13
15
17
19
Years
Open Access
TAC = 25 000 MT
Cte Effort - Cat96 =10 000 MT

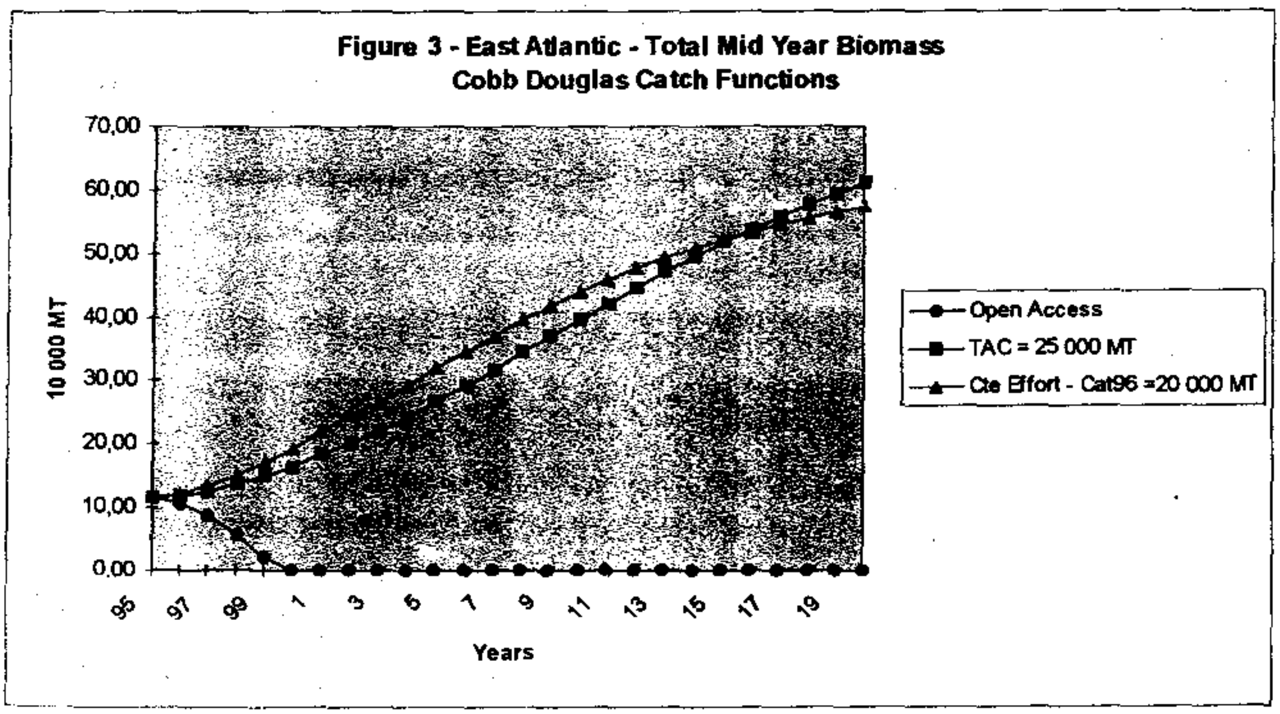
Figure 3 - East Atlantic - Total Mid Year Biomass
Cobb Douglas Catch Functions
70,00
60,00
50,00
40,00
30,00
20,00
10,00
0,00
10 000 MT
95
97
99
1
3
5
7
9
11
13
15
17
19
Years
Open Access
TAC = 25 000 MT
Cte Effort - Cat96 =20 000 MT

Table 1: Estimated levels of effort for 199[illegible]

	East Atlantic		West Atlantic	
Gears	**Effort**	**Units of effort**	**Effort**	**Units of effort**
LL	9294	Fishing days	527	Fishing days
PS	2114	Fishing days	145	Days at sea
Trap	2066	Trap days	-	-
BB	2274	Fishing days	-	-
R&R	-	-	74429	Fishing hours
Remainder	21510	Days at sea	156	Fishing days

Table 2: Adjustment Parameters β

Gear	**East**	**West**
LL	0,25	0,1
PS	0,1	0,1
Trap	0,2	-
BB	0,2	-
R&R	-	0,1
Remainder	0,01	0,1

Table 3: Average Prices by gear

	Price (USD)/kg	
Gear / Stock	East Atlantic	West Atlantic
LL	17	17
PS	9	18
Trap	25	-
BB	5	-
R&R	-	18
Remainder	17	20

Table 4: Costs per unit of effort - East Atlantic

Gear	Margin (%)	Cost (USD)	Unit of effort
LL	10	21,152	Fishing days
PS*	10	67,792	Fishing days
Trap	0	22,483	Trap days
BB	5	6,846	Days at sea
Remainder	0	3,440	Days at sea

*Note that for PS one fishing day correspond to more than three days at sea.

Table 5: Costs per unit of effort - West Atlantic

Gear	Margin (%)	Cost (USD)	Unit of effort
LL	5	22,327	Fishing days
PS	5	29,412	Days at sea
RR	5	239	Fishing hours
Remainder	5	32,680	Fishing days

Table 6: East Atlantic - NPV by gear – (Linear)

Gear / Case	Open access	TAC = 25,000 MT	Constant Effort Catch 96=10,000MT
LL	-57,511	1,205,497	2,968,938
PS	26,254	828,152	1,121,008
Trap	-38,696	230,389	603,759
BB	1,424	62,762	45,572
Remainder	27,474	404,294	953,095
Total	-41,054	2,731,095	5,692,373

Values in 1,000 USD.

Table 7: East Atlantic - Catch by gear – (Linear)

Gear / Case	Open Access Average (1996-2020)	TAC Catch (1996– 2020)	Constant Effort Catch at 2020
LL	6,988	8,026	21,893
PS	13,723	11,049	16,004
Trap	461	1,161	3,149
BB	4,436	2,047	1,377
Remainder	4,524	2,718	7,047
Total	30,134	25,000	49,470

Values in metric tonnes.

Table 8: East Atlantic - NPV by gear – (C-D)

Gear / Case	Open Access	TAC = 25,000T	Constant Effort Catch 96 = 20 000 MT
LL	19,340	467,047	495,396
PS	12,128	340,399	361,061
Trap	-34,289	163,684	393,244
BB	-3,952	27,188	29,844
Remainder	-94,359	260,731	626,393
Total	-101,134	1,259,048	1,905,937

Values in 1,000 USD.

Table 9: West Atlantic - Catch by gear – (C-D)

Gear / Case	Open Access Average (1996-2000)	TAC =25,000MT Catch (1996-2020)	Constant Effort Catch at 2020
LL	16,291	8,026	8,795
PS	17,978	11,049	12,108
Trap	879	1,161	3,269
BB	3,816	2,047	2,243
Remainder	2,687	2,718	7,657
Total	41,651	25,000	34,072

Values in metric tonnes.

Table 10: West Atlantic - NPV by gear – (Linear)

Gear / Case	Open Access	TAC =2,000MT	Constant Effort Catch 1996 = 1,250 MT
LL	-105	51,654	54,757
PS	4,678	29,682	40,231
RR	-1,361	108,328	128,141
Remainder	7,093	37,372	51,121
Total	10,305	227,036	274,250

Values in 1,000 USD

Table 11: West Atlantic - Catch by gear – (Linear)

Gear / Case	Open Access Average(1996-2000)	TAC Catch (1996-2020)	Constant Effort Catch at 2020
LL	671	637	646
PS	398	218	313
RR	1,020	909	1,112
Remainder	435	235	347
Total	2,524	2,000	2,417

Values in metric tonnes.

Table 12: West Atlantic - NPV by gear – (C-D)

Gear / Case	Open Access	TAC=2,000 MT	Constant Effort Catch 96 = 1,750 MT
LL	1,567	23,406	23,662
PS	568	8,477	8,569
RR	2,368	35,370	35,757
Remainder	2,350	25,237	34,215
Total	6,853	92,490	102,204

Values in 1,000 USD

Table 13: West Atlantic - Catch by gear – (C-D)

Gear / Case	Open Access Average (1996-2006)	TAC Catch (96-2020)	Constant Effort Catch at 2020
LL	1,115	637	639
PS	381	218	219
RR	1,591	909	912
Remainder	327	235	356
Total	3,414	2,000	2,126

Values in metric tonnes.