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Optimal Management of the Northern Atlantic Bluefin Tuna

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Abstract *This paper analyzes the optimal management of the Northern Atlantic bluefin tuna, both eastern and western stocks. The analysis is based on a deterministic multi-gear and age-structured bioeconomic model. In order to assess the importance of the gear structure in this fishery, the model is optimized in two scenarios. In the first, the strategies are restricted to the gear mix of the base year, whereas in the second, the optimal gear mix is estimated. For both scenarios, optimal constant strategies are determined. The corresponding optimal use is then compared with an open-access scenario. Also, optimal non-constant strategies are explored. As expected, the gear structure of the fishery proved to be highly relevant in the optimal payoffs. In particular, the unrestricted strategies yield rents substantially higher than the restricted ones. Also, the optimal management of the bluefin tuna fishery, in both the East and West Atlantic, would imply significant reallocation of the gear shares.*

Key words Bioeconomic model, bluefin tuna, open-access, optimal management.

Introduction

The management of highly migratory species has become one of the most challenging issues in the management of ocean fishery resources (Munro 1999). This paper studies one of these species, the Northern Atlantic bluefin tuna. The overall fishery is comprised of a number of sub-fisheries, typically defined geographically and by fleet/gear, and targeting different age classes, with different efficiency and economic value. For that purpose, a multi-gear and age-structured bioeconomic model is developed. Through this approach, the impact of each gear in stock dynamics, as well as their inter-relationships, is accounted for in the analysis of the optimal management of this species.

During the 1990s, bioeconomic models became an important tool in the applied study of the optimal management of fishing resources (Sylvia and Enriquez 1994; Kennedy 1992; Placenti, Rizzo, and Spagnollo 1992). In particular, the use of models disaggregated by age and gear (Thunberg, Helser, and Mayo 1998), as well as

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multi-species and multi-location models (Placenti, Rizzo, and Spagnollo 1992) has become increasingly important. One of the main strengths of these models is that they can be used to study different age and gear allocation patterns. Thunberg, Helser, and Mayo (1998) used a disaggregated model to evaluate the economic implications of tradeoffs between alternative age-specific selection patterns in the U.S. Atlantic silver hake fishery. One of their main conclusions was that shifting fishing pressure to younger classes results in short-run gains that are not sustainable. Regarding tuna fisheries, studies by Campbell and Nicholl (1995) and Campbell (1999) suggest that the optimal management of tuna fisheries in the Western and Central Pacific may require significant reallocations of fishing effort between the different gears. Geen and Nayar (1988) also emphasize the importance of fleet structure in the Southern bluefin tuna fishery.

The purpose of this study is to analyze the optimal management of the Northern Atlantic bluefin tuna through optimization of the bioeconomic model. The optimal management strategies are considered to be those that maximize total net present value of profits (TNPV). They are estimated in two alternative scenarios. The first considers that the gears maintain their relative position, as in the base year (1995), and the other considers that the gear structure is unrestricted. For both scenarios, constant strategies were optimized: constant total allowable catch (TAC) and constant fishing effort. In addition, the optimal use under non-constant strategies is also explored. The optimal management strategies are compared with open-access simulation outcomes.

The paper is organized as follows. First, a brief description of the fishery and the management system is provided. Second, the bioeconomic model is defined — this includes the model structure, the estimation of the model parameters, and a reference to sensitivity and retrospective analysis. Third, the optimization analysis is discussed. Fourth, the optimal constant management strategies are presented for the East Atlantic and for the West Atlantic. Fifth, the analysis of the optimal management is extended to non-constant strategies. Finally, some concluding remarks are presented.

The Fishery[1]

The Northern Atlantic and Mediterranean bluefin tuna is an oceanic pelagic and is the largest and most valued of the Atlantic tunas.

Although this species can be found in all the North Atlantic waters, there are two different stocks. In fact, there are two major spawning areas, and each stock tends to migrate within its own area. In the West Atlantic, the spawning area is located in the Gulf of Mexico and in the Florida Straits. In the East Atlantic, the spawning area is located in the Mediterranean around the Balearic Islands and the Southern Tyrrhenian Sea. According to the migration patterns, bluefin tuna is distributed in the west, from Brazil to Labrador; in 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. Also, like many other tunas, bluefin tend to be found in schools of similar-sized individuals.

The total catch of Northern Atlantic bluefin tuna has shown an increasing trend since the early 1970s, reaching a maximum of 48,514 metric tons (MT) in 1996 (ICCAT 1998). This increasing trend is mainly due to increased catches in the East Atlantic and the Mediterranean. The western catches decreased significantly in 1982 and stabilized at around 2,000 MT thereafter.

The Northern Atlantic bluefin tuna fishery is rather complex, as it is harvested

[1] For a more detailed description of this fishery see Costa Duarte, Brasão, and Pintassilgo (1998).

by a variety of vessel types and fishing gears operating out of many countries. Different fishing gears target different quality and size of bluefin, which have different market values. The prices for large size, high-quality specimens are significantly higher than the prices for all others.

The most important fishing gears in the East Atlantic are the purse seine, trap, baitboat, and longline. In the West Atlantic, the prevailing gears are the purse seine, longline, and rod and reel. These gears, and their efficiency, differ according to the location of the fishery.

The importance of each gear, as well as the distribution of the different gears in the Atlantic and the Mediterranean, has changed over time. One of the most important changes has been the reallocation of the longline fishery, mainly Japanese, from the West to the East Atlantic. The distribution of the main fisheries since 1970 is shown in figure 1.

The management of the Northern Atlantic bluefin tuna falls under the aegis of the International Commission for the Conservation of the Atlantic Tunas (ICCAT). This organization was established in 1969 through the International Convention for the Conservation of Atlantic Tunas. This Convention attributed two primary functions to the ICCAT, "… scientific assessment of Atlantic tuna and tuna-like fishes…" (Art. IV) and giving "…recommendations, applicable to tuna and tuna-like species … that will permit the maximum sustainable catch …" (Art. VIII).

In 1974, ICCAT recommended limiting bluefin tuna fishing mortality to recent levels in the entire Atlantic and Mediterranean. This recommendation entered into force in 1975, and many recommendations and resolutions have been adopted by ICCAT regarding the conservation and management of the bluefin tuna thereafter. Present regulations (ICCAT 1998), for both East and Western stocks, range from catch limits (distributed in

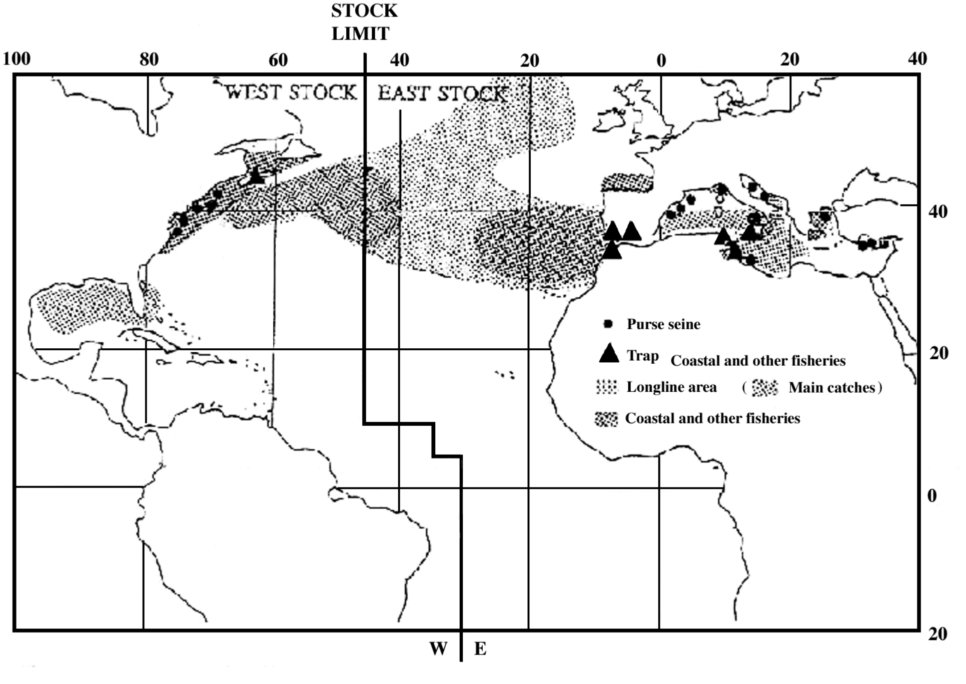

Figure 1. North Atlantic Bluefin Tuna Main Fisheries
Source: ICCAT (1996b)

quotas for member countries) and prohibition of juvenile landings, to closing seasons (no longlining in the Mediterranean in June-July by vessels of more than 24 meters).

Despite the wide range of regulations, enforcement in the East Atlantic has always been ineffective. This is due, in great part, to the high number of participants in the fishery, both members and non-members of the ICCAT. Since 1982, regulation of the West stock has been successful in restricting catches and stabilizing stock, although both at very low levels.

According to the most recent stock assessment (ICCAT 1998), both the eastern and western stocks are severely depleted. One of the core factors behind this is the high price of bluefin on the Japanese market. This market has a strong and selective demand for large, high-quality specimens, for which it is virtually the only consumer. The depletion of the Southern bluefin tuna stock in the Pacific Ocean is another factor behind the pressure on the northern Atlantic bluefin tuna stocks (Geen and Nayar 1988). The increase in prices also creates a strong incentive to spend a significant part of the fishery rent on technological improvements, in order to increase the catches.[2]

The Model

In this section, the bioeconomic model used in the simulation and optimization analysis is explained.

The core aim of a bioeconomic model is to represent the dynamic inter-relationship between the economic and biological variables. The structure of this model emerged from the combined analysis of the theoretical modeling of fisheries and the data available to pursue it, and severe data constraints were clearly a determining point in this study. As Rodgers (1998) suggests, there is only one approach when this problem arises, "… build the model and determine intuitively those coefficients that cannot be estimated for lack of data. It is then possible to test the sensitivity of the objective function to them. Then it is possible to demonstrate the potential of the model…" This approach was adopted when no other was available. Fortunately, the dynamics of the main variables are strongly supported by the sensitivity and retrospective analysis of the model (Brasão, Pintassilgo, and Costa Duarte 1999).

Model Structure

The bioeconomic model is composed of two sub-models, the biological and the economic, linked by the gear catch functions. The glossary of symbols is presented in table A1, and the model equations are presented in the appendix.

Biological Sub-model

The biological part consists of an age-structured, multi-gear and discrete time model [equations (A1) to (A11)], which was developed for the Northern Atlantic bluefin tuna fishery in Kirkwood and Barry (1997). An interesting aspect of this model is that a system of S (number of gears) non-linear and simultaneous equations (A11) is

[2] This is confirmed by the reports of the ICCAT, which state that recently there has been a strong investment in technological improvement in fishing gear. Specifically, there have been investments in instruments for the detection of the schools, such as the use of aircraft, efficient radar, etc.

solved for each time period. The solution of this system is the vector of fishing mortalities at maximum selectivity, which is used to compute the instantaneous fishing mortalities [equations (A7) and (A8)].

Harvest Function

The link between the biological and economic components of a bioeconomic model is established through equalizing equation (A11) to equation (A12), a Cobb Douglas catch function, by gear.[3] This type of production function is frequently used for schooling species (Kennedy 1992; Bjørndal 1988), because in this case the usual assumption, where catch per unit of effort (CPUE) is proportional to stock, is not realistic (Conrad and Clark 1987). Also, equation (A12) relates total catch by gear to a measure of effort that can be evaluated in economic terms.

Economic Sub-model

Regarding the revenue equation (A13), an average price by gear was used. Although it is known that prices vary significantly with age, this assumption is not a very strong one — as the selectivity coefficients by gear [equation (A7)] are considered to be constant during the forecasting period. This assumption introduces some stability on the age distribution of the various gears' catches. The option for average prices by gear, instead of prices by gear and age classes, was due to the lack of sufficient age-disaggregated price data. In addition, prices are also assumed to be time invariant. Although some authors have recognized the importance of incorporating price-quantity relationships (Thunberg, Helser, and Mayo 1998; Kennedy 1999), many others assume constant prices when the fishery is only a small fraction of the market (Yew and Heaps 1996; Amundsen, Bjørndal, and Conrad 1995). In the case of the bluefin tuna fishery, although price clearly depends on supply, it also depends on the Southern bluefin tuna supply, and to a smaller extent, on the supply of other tunas. As there are other important determinants in the price, the assumption of constant price was adopted. By incorporating a negative price-quantity relationship, the short-run profitability would decrease in the open-access and increase in the regulated scenarios. In the former, the price would decrease due to the increase in catches. In the latter, the opposite would occur. So, in the short-run, constant prices can be viewed as an extreme case, where the difference of economic gains between regulation and open-access is at a minimum.

The cost function represented by equation (A14) is a general aggregate function, where total cost by gear is a linear combination of revenue and effort level. The inclusion of revenue is due to the common practice in fisheries, in which the crew receives a share of the results. As we did not model at the vessel level, and as most fleets also pursue significant activities targeting other species, fixed costs were not considered (Thunberg, Helser, and Mayo 1998; Amundsen, Bjørndal, and Conrad 1995).

The gear profit function, given by equation (A15), is calculated for each time period as the difference between revenue and cost. For each gear, the sum of the discounted profits, within a time horizon, yields its net present value (NPV). Equation (A16) represents the TNPV of overall fishery profits.

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[3] The lack of data at boat level led us to model the dynamics at gear level (as in Thunberg, Helser, and Mayo 1998).

Open-Access Dynamics and Exit Condition

The entry-exit behavior of vessels is not specifically modeled, but is implicit in the dynamics of the aggregate effort by gear.

In this paper, the open-access dynamics were modeled assuming that effort varies with profits according to the relationship presented in equation (A17). The key determinant of the dynamics, in the short-run, is the existence or absence of profits and not its magnitude, as it is assumed that there are natural constraints to effort changes. A profit interval where there are no effort adjustments was also considered in order to avoid effort movements for profits, or losses, not significantly different from zero. As fleets, like other economic agents, tend to leave an activity whenever short-run losses are too high, an exiting condition [equation (A18)] was introduced.

Model Parameters

The values of the parameters used in the simulation and optimization of the model are presented in tables 1 and 2.

Biological Sub-model

All the biological parameters were estimated by Kirkwood and Barry (1997),[4] using mainly ICCAT's data (ICCAT 1996b). In particular, several functional forms were tested for the recruitment relationship [equation (A2)], and these authors recommended a bilinear recruitment function.

Production Function

In most applied studies of schooling species using constant elasticity production functions, the estimates of catch-effort elasticity are very close to 1, and the catch-stock elasticity is very low. For the Northern anchovy fishery, Opsomer and Conrad (1994) present a catch-stock elasticity equal to 0.4, while for the minke whale (Amundsen, Bjørndal, and Conrad 1995) and herring (Bjørndal 1988), the estimate is not significantly different from zero.

Due to data limitations, econometric estimation was not possible in this study. Therefore, we used values within the range of the parameters published in the literature on schooling species. A sensitivity and retrospective analysis was performed in order to evaluate the impact on the dynamics of the model.

In the bluefin tuna fishery, some gears use very advanced methods of detection (longline, purse seine, bait boat, and rod and reel). For these gears, in which catches do not depend greatly upon the stock, a low catch-stock elasticity (0.2) was used. For traditional gears (trap and the remainder category), which are considered to be more stock dependent, a higher value (0.8) was used.

The effort levels considered for the base year were computed by extrapolation from ICCAT samples (ICCAT 1996a) and are presented in table 1.

The parameters $q_{j,s}$ define scales on the production functions. As econometric estimation was not possible, we adopted the implicit scale for the base year (1995).

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[4] In the manuscript, "Specifications of a Biological and Catch Prediction Model for the Northern Bluefin Tuna" (1997), Kirkwood and Berry present all the biological data and estimations needed to run the model.

Table 1
Production Function Parameters and Levels of Effort for 1995

	East Atlantic			West Atlantic		
Gears	*q*	Effort	Units	*q*	Effort	Units
Longline	32.0369	9,294	Fishing days	48.5422	527	Fishing days
Purse seine	193.9020	2,114	Fishing days	60.3435	145	Days at sea
Trap	0.0003	2,066	Trap days	–	–	–
Bait boat	33.3941	2,274	Fishing days	–	–	–
Rod & reel	–	–	–	0.4905	74,429	Fishing hours
Remainder	0.0001	21,510	Days at sea	0.0026	156	Fishing days

Table 2
Economic Parameters of the Model

	East Atlantic				West Atlantic			
Gears	Prices (USD/kg)	Margin (%)	wg	Unit of Effort	Prices (USD/kg)	Margin (%)	wg	Unit of Effort
Longline	17	10	14,102	Fishing days	17	5	15,265	Fishing days
Purse seine	9	10	45,185*	Fishing days	18	5	20,092	Days at sea
Trap	25	0	15,738	Trap days	—	—	—	—
Bait boat	5	5	4,638	Days at sea	—	—	—	—
Rod and reel	—	—	—		18	5	163	Fishing hours
Remainder	17	0	2,408	Days at sea	20	5	22,417	Fishing days

Note: * For the PS, in the East Atlantic, one fishing day corresponds to more than three days at sea.

The values were computed by solving the production function and applying the base year values for catches (ICCAT 1996b), the biomass (Kirkwood and Barry 1997), and total effort.

Despite the simplicity of the assumptions, the constant elasticity production function is able to provide the model with reasonable forecasting and retrospective power.

Economic Parameters

Economic data for the bluefin tuna fishery is sparse and scattered throughout many sources. Data from different sources were collected, and the most consistent were selected for estimating the model parameters.

Prices

The most consistent price database of bluefin tuna is the one used by the Japan Customs House (1997). Average prices by gear were computed based mainly on this database. The values used take into account information on the gear/country structure and the proportions that go to the local market and the Japanese market. The selected average prices are presented in table 2.

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* (U.S. Department of Commerce 1995), in which a 3.6% discount rate is used.

Costs

Published cost data for the bluefin tuna fishery is almost nonexistent. The revenue coefficient in the cost function was assumed to be 0.3 for all gears in both the East and West Atlantic, as it approximates the empirical crew shares. The parameter associated with effort was computed assuming that profits for the base year (1995) were a percentile margin of the revenues. These coefficients were computed assuming that, at present, some gears are more profitable than others and so have higher margins. The margins, as well as the effort coefficients on the cost function, are presented in table 2.

The few available cost data, namely for longline (East and West Atlantic) and purse seine (West Atlantic), support the values used.

Open-Access Dynamics and Exit Condition

It was assumed that a level of profit (or loss) equal to or smaller than 10 times the cost per unit of effort will not induce changes in effort.

The effort adjustment parameters, $\beta_{j,s}$, were determined based on the evolution of estimated fishing effort for the most recent years. Therefore, different values for different gears were used accordingly. For the East Atlantic {0.25, 0.1, 0.2, 0.2, 0.01} were used for longline, purse seine, trap, bait boat, and remainder, respectively, whereas for the West Atlantic {0.1} was assumed for all gears.

Regarding the exit condition, equation (A18), a reasonably high value was used for the parameter $h_{j,s}$ (0.5 for all gears). Thus, any fishing gear in which the cost is higher than revenues by more than 50% exits the fishery.

Simulations use a time horizon of 25 years, which was considered a reasonable period. This horizon ensures, for most simulation scenarios, a good tradeoff between computation time and stock stabilization.

Sensitivity and Retrospective Analysis

In Brasão, Pintassilgo, and Costa Duarte (1999), the results of the sensitivity analysis of the parameters is presented in more detail, for both the optimization and open-access scenarios. In particular, the following parameters were tested: prices, catch-stock elasticity used in the production function, profit margins considered for the base year, and effort adjustment.

In the optimization of the fixed gear structure case, for both East and West Atlantic, the same study concludes that, in general, the optimal constant strategies are not sensitive to the parameter values. However, for some parameters, the impact on the TNPV is significant. This also occurs in the open-access simulations. Based on these results, it can be concluded that the optimal values of the decision variables are not very sensitive to the values of the parameters, but the same does not apply to the overall value of the fishery.

In the aforementioned study, a retrospective analysis was also performed to evaluate the robustness of a forecasting model. It consists of going back in the sample period and forecasting using the parameters of the original model. Only the information available at the starting period[5] is used, and the dynamics of the model correspond to the open-access scenario, in which fishing effort changes according to profitability. The differences between the forecasts within the sample and the real data are a good indicator of the model's power to capture the dynamics of the system.

The results of this analysis show that for the East stock, the model is able to capture the dynamics of the catches in the 1990s and, in particular, their increasing trend (figure 2). Total catches shifted from a stable trend in the second half of the 1980s, to a sharp increase in the 1990s. One key factor behind this change was the access to the Japanese market and the resulting increase in prices. In the study, it is shown that by allowing for lower prices in the 1980s, the model is also able to predict the trend of catches since the early 1980s.

For the West Atlantic, the open-access scenario does not represent the dynamics of the catches in recent years, as after 1982 the regulations were successful in restricting catches and stabilizing stock, although at a very low level.

Optimization Analysis

The optimal management strategies are estimated by determining the decision variables that maximize total payoff (TNPV) within the time horizon of the model, subject to the model constraints.

The optimal use of the fishery is computed for two different scenarios. In the first, the strategies are restricted to a fixed-gear structure (*i.e.*, the decision variables maintain their relative position as in 1995). In the second, the gear structure is unrestricted. Some determining aspects motivated the choice of these two particular scenarios. As far as negotiations are concerned, scenario 1 is clearly relevant. In fact, this fishery involves a high number of countries using different combinations of gears and, therefore, as recent ICCAT recommendations indicate, proportional allo-

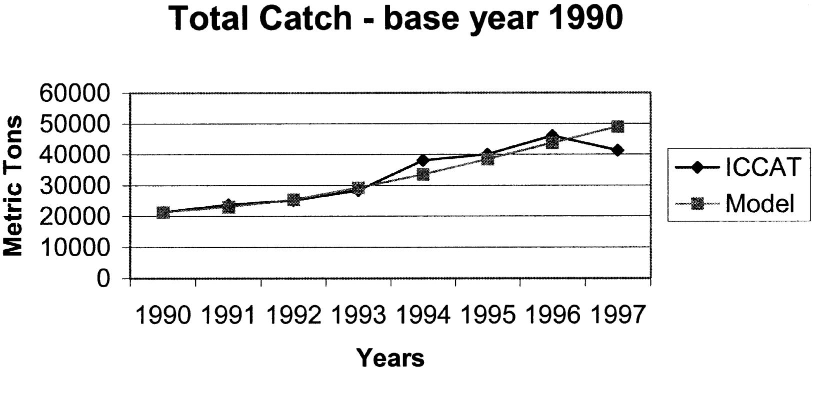

Figure 2. Retrospective Analysis of the Model

[5] The analysis uses the values for the number of fish at the starting period, catches, and fishing mortalities for that year. There is no updating of information.

cation is a relevant practice (ICCAT 1997). However, as other applied studies show, there can be substantial improvements in the optimal payoffs by changing the gear allocation (Campbell 1999). Due to the complex nature of the bluefin tuna fishery, this is an important aspect. Therefore, a scenario with unrestricted gear structure is also considered.

For both scenarios, constant and non-constant optimal strategies were estimated. In the case of constant strategies, constant TAC and constant effort were considered[6] — implemented through quota regulation and effort control, respectively.

For this, a non-linear constrained optimization problem is defined and solved using Matlab programming. The optimization routine uses sequential quadratic programming (SQP).[7] In general terms, the non-linear optimization problem solved in all cases can be defined as follows:

$$\max_{x} F(x) \tag{1}$$
$$G(x) \leq 0$$
$$vlb \leq x \leq vub,$$

where the objective function, $F(x)$, represents the TNPV of profits, and the vector of decision variables (x) represents either the catch or fishing effort by gear. $G(x) \leq 0$ represent the equality and inequality constraints. In order to obtain results with some empirical relevance, limits needed to be established for the expansion of some of the gears, namely trap and remainder. Those limits were based on historical data.[8] In the model, *vlb* and *vub* are two vectors of the lower and upper bounds of the variables.

Optimal Constant Management Strategies

East Atlantic

The optimal constant management strategies for each of the scenarios were estimated, and the overall optimal strategies, in this case the constant effort, as well as the corresponding payoffs, are presented in table 3. For the East stock, the following gears are considered: longline (LL), purse seine (PS), trap, bait boat (BB), and remainder (Rem).

As expected, in both scenarios a substantial increase in TNPV can be gained by departing from the open-access to the optimal regulated strategies. Also, the results show that gear structure is relevant for the overall value of this fishery.

In figures 3 and 4, catch and biomass simulation outcomes are shown for both the optimal strategies and open access. The optimal strategies shown correspond to the constant effort policy case. The graphs show that in the optimal regulated sce-

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[6] The optimal constant escapement (total biomass net of the harvest) was also estimated. As both the initial levels of the Eastern and Western Atlantic stocks are very low, the optimal constant escapement is severely constrained — making it a low payoff strategy. Thus, this strategy was not considered.

[7] Constr – Optimization Toolbox (The Math Works, Inc.).

[8] *e.g.*, for the East Atlantic historical data reveals that, since the early 1970s, trap catches are below 5,000 MT and were at maximum historical value of 9,044 MT in 1965 (ICCAT 1995). Most of the traps are concentrated around the Strait of Gibraltar and Southern Italy and may not be efficiently implemented in other areas. Thus, a maximum of 10,000 MT was considered. The remainder category represents artisan gears, and, according to the historical data, 5,000 MT is a reasonable catch limit.

Table 3
Optimal Strategy and Net Present Values – East Atlantic

	Scenario 1		Scenario 2		Open Access
	E/E_{95}	NPV	E/E_{95}	NPV	NPV
LL	0.5	385.7	1.63	1,371.2	44.8
PS	0.5	281.1	0	0	27.5
Trap	0.5	266.7	1.50	997.9	–18.0
BB	0.5	22.5	0	0	–1.1
Rem	0.5	335.6	0.34	347.5	–45.7
Total	0.5	1,291.7	—	2,716.5	–7.6

Note: Values in 10^6 USD.

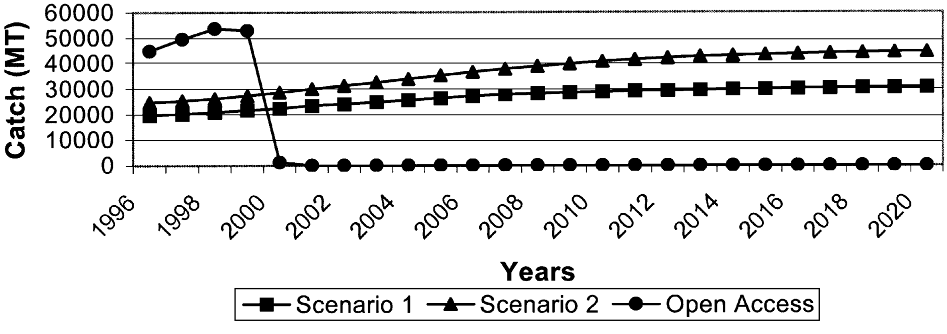

Figure 3. Total Catch – Constant Strategies – East Atlantic

narios, catches increase progressively as a result of the stock recovery. In open-access, the sharp catch increase in the short-run leads to stock depletion. By comparing scenarios 1 and 2, it is interesting to note that scenario 2 shows both higher catches and better performance in terms of stock recovery throughout the forecasting horizon. This clearly shows the importance of gear structure in the biological dynamics of the model.[9]

As expected in a deterministic context, the constant effort strategy provides higher NPV of profits than the constant TAC, as catches increase with stock recovery.

In scenario 1, the optimal TAC corresponds to 65% of the total catch in 1995 (25,706 MT), whereas the optimal constant effort policy results in a 50% effort reduction. The latter is more catch restrictive in the short-run (19,652 MT in 1996) but less in the long-run (30,753 MT in 2020), due to the stock recovery. It is interesting to note that in this scenario the optimal TAC is very close to ICCAT recommendations.[10]

[9] This can also be noted from the following two scenarios: if only longline is allowed to catch, the optimal TAC is 33,157 MT and the biomass in 2020 is 829,040 MT. Allowing only bait boat, the optimal TAC is 11,818 MT, and the total biomass in 2020 is only 465,580 MT. So, longline with a much higher catch, is able to better preserve the stock. Note that longline targets large bluefin, whereas bait boat targets small.

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

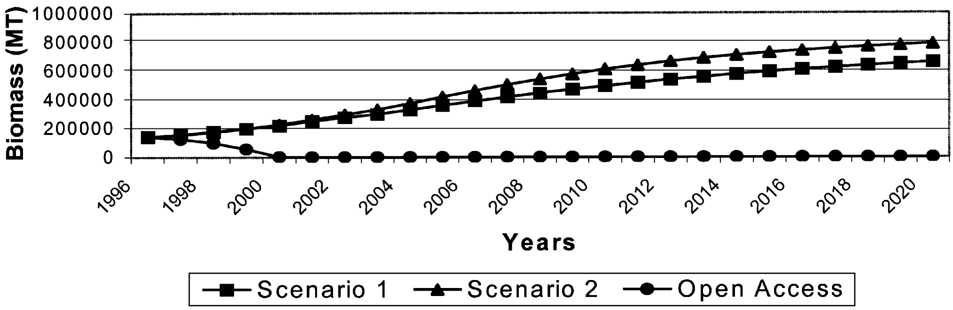

Figure 4. Total Biomass – Constant Strategies – East Atlantic

In scenario 2, the optimal TAC allocation is to increase longline catches by about 8%, relative to 1995 (12,849 MT), allow trap and remainder catches at their upper bounds, and eliminate purse seine and bait boat. The optimal constant effort presents a similar gear structure. At the optimal allocation, trap effort level is at the upper bound (50% above the 95th level) and longline increases 63%, while remainder effort reduces to 34% of the 1995 level. The significant decrease for the remainder is a consequence of the restrictions imposed. Again, constant effort is more catch restrictive in the short-run (24,738 MT in 1996) but less in the long-run (44,618 MT in 2020).

Behind the optimal allocations results in scenario 2 are the differences in economic efficiency and the different impact on the biological dynamics of the different gears — as they target different age classes.

Trap is the gear that earns the highest price, as the fish suffer minimum damage. According to Japanese data of imports, the artisan gears also receive a high price. In this model, the traditional gears (trap and remainder) also present the highest stock elasticity, as they are the gears that benefit the most from stock recovery. If there were no bounds to the expansion of both these fleets, they would dominate any optimal strategy. However, this result is not empirically reasonable, as both these fleets are geographically restricted to a small area. It is then considered that they both will be at the limit imposed.

Longline is economically more efficient than purse seine and bait boat, mainly because it receives a much higher price — as it targets older age classes. Therefore, significant economic gains can be obtained by this gear as the stock recovers.

Although purse seine is presently the dominant gear (a share close to 50% in recent years), it is very damaging to the fish, which leads to prices substantially lower than those received by the longliners, even for the same age classes. Bait boat, used mainly in the Bay of Biscay, catches small bluefin tuna, which is not demanded by the Japanese market, and so does not represent a significant economic value.

This result is in accordance with previous studies on tuna fisheries, where similar reallocation strategies are suggested (Campbell and Nicholl 1995; Campbell 1999). In particular, they suggest contraction of purse seine, which is the prevailing gear, and the expansion of longline.

In this study, the criterion used to select the optimal policy is only TNPV. Nonetheless, by considering issues such as unemployment costs, stochasticity, or decreasing demand function, the relative position between constant TAC and constant effort could change. In fact, the optimal constant effort is more restrictive than the optimal TAC in the short-run, leading to a greater negative impact in short-run unemployment. Another limiting factor frequently mentioned for the constant effort policy is that real enforcement is more difficult to implement. In fact, in the presence of economic incentives in the fishery, the units of effort might be used more intensively, therefore undermining regulations. However, this problem could be avoided if the constant effort is implemented not by effort control but by quota regulation, where the quotas correspond to the constant effort (as in Steinshamn 1998).

The results might also be affected by considering a recruitment function with regular cycles, or allowing for a stochastic recruitment function. This has implications in terms of whether constant catch or constant effort yields the highest expected profit (Hannesson and Steinshamn 1991) and on the mean and variation in size of the fish stocks and net revenues (Steinshamn 1998).

In determining optimal policy, Kennedy (1999) considers both consumer and producer surplus in the objective function. This criterion could also have impact on the ranking of the policies. Note that in the short run, a decrease in catches implies a decrease in consumer surplus. Therefore, in terms of consumer surplus, the constant TAC policy is preferable to the constant effort in the short run.

West Atlantic

In this section, an optimization analysis similar to that of the East Atlantic is presented for the West Atlantic. It is worth mentioning that the two stocks present significant differences in the dimension, gears used, and targeted age classes. In the West, the stock has been severely depleted for over a decade, and the economic value of the overall fishery is smaller.

For the Western stock, four gears are considered: longline (LL), purse seine (PS), rod and reel (RR), and remainder (Rem). As the remainder represents mainly the artisan gears, which present natural growing constraints, upper bounds were also defined.[11]

The optimal strategies obtained, as well as the corresponding TNPV, are shown in table 4. As in the East Atlantic, the constant effort case yields higher TNPV than TAC, for both scenarios, and there are substantial gains in departing from open-access to an optimal regulated policy. The catch and biomass evolution for the optimal strategies (constant effort) in both scenarios and the open-access is very similar to the East Atlantic case, qualitatively.

For this stock, the optimal TAC for scenario 1 is about 87% of 1995 catch (1,980 MT), and the optimal effort levels are reduced by 34%. As in the East Atlantic, restricting effort is the optimal constant policy, although it is more catch restrictive in the short run (1,739 MT in 1996) and less in the long run (2,087 MT in 2020).

In scenario 2, the optimal strategy is to expand purse seine substantially and allow the remainder to fish at the upper bound. Note that in the West fishery, the purse seine is both economically and biologically more efficient than the longline, which explains this result. In this strategy, the increase in the purse seine catches[12] would bring the gear catches up to the levels that existed before the regulations of 1982 (*e.g.*, 2,320 MT in 1975), when it was one of the dominant gears. This expansion in purse seine contrasts with results obtained for the East Atlantic, in which purse seine is eliminated. This is due to the different features of this gear on both sides of the Atlantic, namely in terms of age class target. In the West Atlantic, purse seine tar-

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[11] The remainder category was restricted: 500 MT in the TAC case and 0% effort increase in the constant effort case.
[12] From 249 MT in 1995 to 1,897 in 1996 and 2,144 MT in 2020, in the constant effort case.

Table 4
Optimal Strategy and Net Present Values — West Atlantic

	Scenario 1		Scenario 2		Open Access
	E/E_{95}	NPV	E/E_{95}	NPV	NPV
LL	0.76	16.1	0	0	–1.3
PS	0.76	5.8	7.4	61.6	0.2
RR	0.76	24.3	0	0	–1.6
Rem	0.76	21.1	1.0	32.4	–1.0
Total	0.76	67.3	—	94.0	–3.7

Note: Values in 10^6 USD.

gets giant bluefin tuna, whereas in the East Atlantic, it also targets small specimens.

It is also interesting to note that in 1997 the shares of total catch (ICCAT 1998) were {18%, 12%, 53%, 17%} for longline, purse seine, rod and reel (+ sport), and remainder, respectively. One reason behind such a large gap between the present gear structure of catches and the optimal one, is that the former does not represent the relative economic efficiency of the different gears, as catches are highly regulated. In fact, criteria such as fairness and equity, as well as the ease of monitoring catches, are behind the present allocation.[13] The high value of the other gears, regarding recreational benefits and employment relative to purse seine, is also argued.

In the West Atlantic, as in the East, ICCAT's catch recommendations (2,200 MT for 1995–96 and 2,354 MT for 1997–98) are close to the optimal TAC obtained, especially in the second scenario (2,397 MT).

Optimal Management under Non-constant Strategies

Herein, the extension of optimal management of bluefin tuna to non-constant strategies is explored.

The optimization for non-constant strategies usually raises a set of troublesome issues. As stated in Kennedy (1992), the optimal annual harvest profiles for multi-cohort fisheries tend to be highly irregular, particularly for the initial years. This phenomenon is referred to as periodic fishing, or pulse fishing in the extreme case where zero fishing alternates with high levels of fishing.

For the bioeconomic model presented in this paper, the optimization routines used do not converge to a single annual sequence of TACs or levels of fishing effort. The length of the time horizon, together with the complexity of the bioeconomic dynamics, is clearly behind this result.

In order to overcome this problem, the range of the decision variables was restricted by imposing reasonable upper limits. This can be seen as an appropriate procedure, as the management of Northern Atlantic bluefin tuna, like most straddling and highly migratory species, aims not only to achieve optimal management of the stock, but also its conservation. Furthermore, the UN Agreement relating to the conservation and management of straddling and highly migratory fish stocks emphasizes the importance of precautionary limits on catches (Tahindro 1999). In a con-

[13] For more details on the allocation of catches see, "Final Environmental Impact Statement for a Regulatory Amendment for The Western Atlantic Bluefin Tuna Fishery" (U.S. Department of Commerce 1995).

text of worldwide over-fishing, the UN Agreement provides "Guidelines for the application of precautionary reference points in the conservation and management of straddling fish stocks and highly migratory fish stocks." In particular, it refers to conservation or limit reference points, which set boundaries intended to constrain harvesting to safe biological limits, so that the stocks can produce maximum sustainable yield (MSY).

A significant difference, as compared with the case of constant strategies, is that for equivalent upper limits, the optimal sequence of annual TACs is equivalent to the optimal sequence of annual levels of fishing effort. As the TAC is presently the most common policy instrument used in fishery management worldwide, the optimal annual sequence of TACs for bluefin tuna was analyzed for both the East and West Atlantic.

Assume a constant gear structure, as in the base year (scenario 1). In this section, the TAC is considered to be variable during the first 25 years, thus the simulation period was extended to 50 periods in order to avoid bias for the values of the latest TACs towards the upper limits. The TAC is considered to be variable during the first 25 years and constant thereafter.[14]

East Atlantic

In the optimization procedure, a precautionary limit on annual catches of 40,000 MT is considered.[15] In this framework, the optimal policy is now to declare an initial harvest moratorium of five periods and harvest 40,000 MT thereafter. The optimal TAC and the stock evolution for the first 25 periods are presented in figure 5.

As this figure shows, the optimal policy results in a significant stock recovery, although lower than in the constant strategy case. The progressive trend of the stock towards stabilization after initial recovery suggests that 40,000 MT is, for the particular level and composition of the stock after the moratorium, close to a maximum sustainable catch.

Regarding TNPV, this non-constant policy yields 1,580.1 million USD in the first 25 years, which is about 22% higher than the TNPV in the optimal constant policy.

In order to evaluate the role of the discount rate in the results, 10% and 20% discount rates are also considered. With these rates, the optimal policy is similar, but with a shorter harvest moratorium: four and three periods, respectively. It is, nonetheless, worth noting that this occurs under conservation restrictions. In their absence, high discount rates imply optimal policies, which lead the stock to depletion.

West Atlantic

As for the East Atlantic, the optimal policy is determined, and a precautionary limit on catches of 2,500 MT is considered.[16] The optimal policy is to declare a four-period moratorium, catch 1,300 MT in the fifth period, and 2,500 MT thereafter —

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[14] Thus, 26 variables are optimized: the TAC for the first 25 years and the constant TAC for the last 25 years. Among other formulation options, this particular one was selected as it not only solves the bias of the last periods, but also accounts for the impact on the stock dynamics of the harvest during the first 25 periods. Another option would be to consider the value of the variables in the 25th period to remain constant thereafter. This formulation, although extending the analysis to an infinite time horizon, does not capture the dynamics of the model after the 25th period.

[15] Historical data show that catches above this limit tend to lead biomass to depletion.

[16] The model simulations show that, with the present gear mix, 2,500 MT is close to a maximum sustainable catch, following a stock recovery through an initial harvest moratorium.

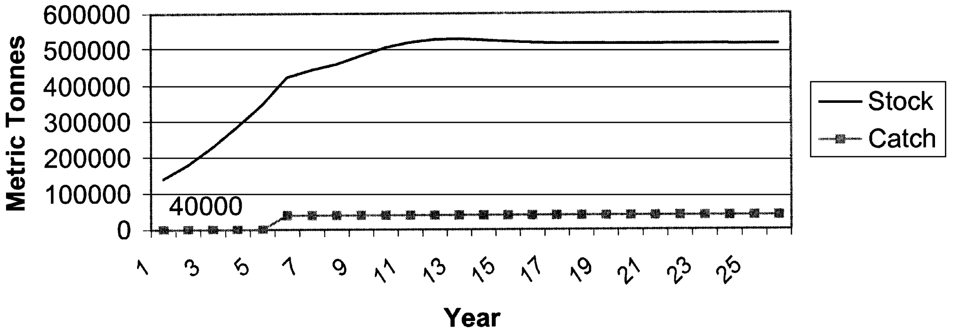

Figure 5. Optimal TAC and Stock Evolution – Non constant Strategies – East Atlantic

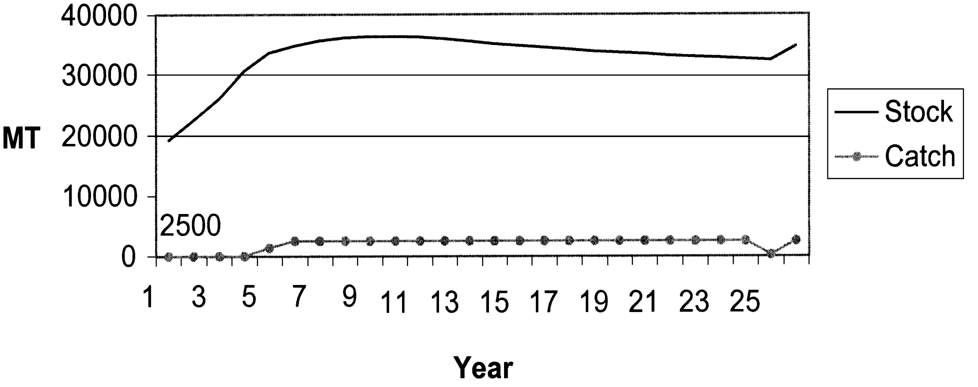

Figure 6. Optimal TAC and Stock Evolution – Non constant Strategies – West Atlantic

with the exception of 25th period (200 MT).[17] The TAC and the stock evolution are represented in figure 6. The TNPV for the first 25 years is 75.4 million USD, which is 12% higher than in the optimal constant policy.

By considering different discount rates, it can be concluded that the optimal policy is not sensitive to this parameter. In fact, for 10% and 20% discount rates, the optimal policy is to declare a harvest moratorium of three and two years, respectively, and catch 2,500 MT thereafter.

What would be the impact of extending the optimization from constant strategies to non-constant strategies in scenario 2? In order to address this question, additional restrictions would have to be imposed; otherwise, the model would not converge. A scenario was considered in which the decision variables are not only the annual TACs, but also the share of each gear used. It is assumed that there are precautionary limits on harvest and that the gear shares remain constant through time, which is equivalent to an instantaneous adjustment to a permanent optimal gear structure.

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[17] As it is assumed that the TAC is constant from t = 26 to t = 50, the optimal path calls for a TAC decrease at t = 25 in order to allow for a higher initial stock for the remaining periods.

In this setting, the optimization results for both the East and the West Atlantic, indicate that the optimal permanent gear structure is exactly the same as in the constant case. Namely for the East Atlantic, trap and remainder reach their natural limits; whereas, the remaining share corresponds to the longline gear. Furthermore, as in the case of constant strategies, there are substantial gains by reallocating gear shares to an optimal structure. Therefore, it can be concluded that, as far as the importance of the gear structure is concerned, the simpler scenario of constant strategies is able to capture the main features of the problem.

Concluding Remarks

This paper shows that through the use of a multi-gear, age-structured bioeconomic model, important aspects of the optimal strategies for a complex fishery, such as bluefin tuna, can be captured.

In order to assess the importance of the gear structure in this fishery, two optimization scenarios were considered: one in which the strategies are restricted to the gear mix of the base year, and the other where strategies are unrestricted.

The optimization for constant strategies in the two scenarios, shows that the policy of regulating effort yields higher payoff than the optimal TAC. It is also concluded that there are substantial gains by departing from open-access to an optimal regulated scenario. In the restricted gear structure scenario, the optimal strategy is a significant effort reduction for both the East (50%) and West Atlantic (34%).

As expected, the gear structure of the fishery proved to be highly relevant regarding optimal payoffs. In particular, the unrestricted strategies yield rents substantially higher than restricted ones. Behind this result are important bioeconomic interactions among the different gears, as they present very different economic efficiencies and target different age classes.

The optimal results imply dramatic changes in the gear structure of the fishery. In particular, for the East Atlantic the optimal effort strategy is to increase longline by 63%, allow traps to expand up to their natural limit, decrease remainder by 66%, and virtually eliminate purse seine and bait boat.

The results suggest that the present gear structure of catches, in both the East and West Atlantic, is far from optimal. This remains valid by extending the optimization to non-constant strategies. In this case, the optimal management of both stocks calls for an initial harvest moratorium and catches at precautionary limits thereafter.

Possible extensions of the model include: introducing stochastic fluctuations (*e.g.*, in the recruitment function), setting gear prices by age class, and estimating demand functions.

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Appendix
The Model Equations

Biological Submodel

Population Numbers

$$N_{j,0,a} = \tilde{N}_{j,a} \quad \text{for } 1 \le a \le A \tag{A1}$$

$$SRR = N_{j,t,0} = \begin{cases} R_{\max} \text{ if } SSB_{t-2} \ge SSB_{\min} \\ R_{\max} \dfrac{SSB_{t-2}}{SSB_{\min}} \text{ if } SSB_{t-2} < SSB_{\min} \end{cases} \tag{A2}$$

$$N_{j,t,a} = N_{j,t-1,a-1} e^{-M_{j,a-1} - F_{j,t-1,a-1}} \quad \text{for } a = 1, 2, ..., 9; \; t = 1, 2, ... \tag{A3}$$

$$N_{j,t,A} = N_{j,t-1,9} e^{-M_{j,9} - F_{j,t-1,9}} + N_{j,t-1,A} e^{-M_{j,A} - F_{j,t-1,A}} \tag{A4}$$

$$SSB_{j,t} = \sum_{a=1}^{A} Mat_{j,t,a} N_{j,t,a} W_{j,t,a} \tag{A5}$$

$$B_{j,t} = \sum_{a=1}^{A} N_{j,t,a} W_{j,t,a} \tag{A6}$$

Catch at Age by Gear

$$F_{j,t,a,s} = FMax_{j,t,s}.Sel_{j,a,s} \tag{A7}$$

$$F_{j,t,a} = \sum_{s=1}^{S} FMax_{j,t,s}.Sel_{j,a,s} \tag{A8}$$

$$CN_{j,t,a,s} = \frac{F_{j,t,a,s}.N_{j,t,a}}{\sum_{s=1}^{S}(F_{j,t,a,s} + M_{j,a})}\left[1 - e^{-\sum_{s=1}^{S}(F_{j,t,a,s}+M_{j,a})}\right] \tag{A9}$$

$$CB_{j,t,s} = \sum_{a=1}^{A} CN_{j,t,a,s}.W_{j,a} \tag{A10}$$

$$C_{j,t,s} = \sum_{a=1}^{A} \frac{FMax_{j,t,s}.Sel_{j,a,s}.N_{j,t,a}.W_{j,t,a}}{\sum_{s=1}^{S}(FMax_{j,t,s}.Sel_{j,a,s} + M_{j,a})}\left(1 - e^{-\sum_{s=1}^{S}(FMax_{j,t,s}.Sel_{j,a,s,i}+M_{j,a})}\right) \tag{A11}$$

for $s = 1, \ldots, S$

Harvest Function

$$C_{j,t,s} = q_{j,s}\, E_{j,t,s}\, B_{j,t}^{\alpha_s} \tag{A12}$$

Economic Submodel

$$Rev_{j,t,s} = \overline{P}_{j,s} * C_{j,t,s} \tag{A13}$$

$$Cost_{j,t,s} = wg_{j,s} * E_{j,t,s} + \gamma_{j,s} * Rev_{j,t,s} \quad s = 1,\ldots,S \tag{A14}$$

$$\Pi_{j,t,s} = Rev_{j,t,s} - Cost_{j,t,s} \tag{A15}$$

$$TNPV_j = \sum_{s=1}^{S}\sum_{t=1}^{25} \Pi_{j,t,s} * \left(\frac{1}{1+r}\right)^t \tag{A16}$$

Open-access Dynamics

$$E_{j,t,s} = \begin{cases} (1-\beta_{j,s})E_{j,t-1,s} & \text{if} \quad \Pi_{j,t\text{-}1,s} \leq -\Pi_{b\,j,s} \\ E_{j,s,t-1} & \text{if} \quad -\Pi_{b\,j,s} \leq \Pi_{j,t-1,s} \leq \Pi_{b\,j,s} \\ (1+\beta_{j,s})E_{j,s,t-1} & \text{if} \quad \Pi_{j,t\text{-}1,s} \geq \Pi_{b\,j,s} \end{cases} \tag{A17}$$

Exit Condition

$$Cost_{j,t-1,s} > (1+h_{j,s}) * Rev_{j,t-1,s} \tag{A18}$$

Table A1
Glossary of Symbols

Variables		Coefficients	
N	No. of Fish (Beginning of Year)	*M*	Instantaneous Natural Mortality
$\tilde{N}$	Estimated No. Fish (Beginning of 1995)	*Mat*	Maturity Rate
SRR	Stock Recruitment Relation	*W*	Average Weight
SSB	Spawning Stock Biomass	*q*	Production Function Parameter
F	Instantaneous Fishing Mortality	α	Catch-Stock Elasticity
Fmax	Fishing Mort. at Maximum Selectivity	*wg*	Costs Parameter
B	Total Biomass	γ	Crew Share
Sel	Selectivity	*r*	Interest Rate
CN	Catch Numbers	β	Effort Adjustment Parameter
CB	Catch Biomass	Π_b	Profit Bound
E	Effort	*h*	Exit Condition Parameter
C	Catch		
Rev	Revenue	Indices	
Cost	Cost	*j*	Stock (*j* = East Atl., West Atl.)
$\overline{P}$	Average Price	*t*	Time ($t = 1,\ldots,T$), $T = 25$ (2020)
Π	Profit	*a*	Age ($a = 1,\ldots,9,A$), $A = 10+$
TNPV	Total Net Present Value	*s*	Gear ($s = 1,2,\ldots,S$)