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The East Atlantic Bluefin Tuna Fisheries: Stock Collapse or Recovery?

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Abstract *A discrete time, multi-gear, and age structured bio-economic model is developed for the East Atlantic bluefin tuna fisheries, a paradigmatic example of the difficulties faced in managing highly migratory fish stocks. The model is used to analyse alternative management strategies for the Regional Fisheries Management Organisation (RFMO) managing this fishery, and to investigate some of the policy implications. For the various scenarios, the optimal stock level varies between 500–800,000 tonnes, which compares with a stock level of 150,000 tonnes in 1995. In other words, there is a very strong case for rebuilding the stock. Moreover, the sustainability of the stock is threatened unless a recovery programme is implemented; indeed, the alternative may be stock collapse. Second, to rebuild the stock, Draconian measures are called for: either outright moratoria over fairly lengthy periods, or possibly a more gradual approach to steady state given by a Total Allowable Catch (TAC) at a low level for an extended period of time. Third, the cost of inefficient gear structure is very high indeed.*

Key words Bioeconomic model, bluefin tuna, optimal management.

JEL Classification Code Q22.

Introduction

Straddling and highly migratory fish stocks pose formidable management problems. Cases of severely depleted stocks are well known, due mostly to perverse economic incentives and inefficient regulations. One example is given by the East Atlantic bluefin tuna, a highly migratory species. Until now, this fishery has essentially been open access and, as a consequence, the stock has been severely overexploited with the distinct possibility of stock collapse (Brasão, Costa-Duarte, and Cunha-e-Sá 2000). Yet, several countries, both coastal and distant water fishing nations, consider entering this fishery because of the high market value of the tuna. The decline in bluefin tuna stock to the extent where it is almost an endangered species, and where there have been calls for its trade to be regulated by the Convention on International Trade in Endangered Species (Martinez-Garmendia and Anderson 2005), has raised

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considerable concern about its management. The highly migratory nature of the resource, combined with a large number of actual and potential players as well as ineffective management, makes it a difficult management problem. Yet, improved management bears the promise of very beneficial consequences in terms of substantial economic rents.

According to the Law of the Sea, the high seas beyond 200-mile Exclusive Economic Zones (EEZs) were considered to be international common property open to all nations. The many conflicts between fishing nations and the severe depletion of many straddling and highly migratory stocks proved the inadequacy of this legal setting to deal with the sustainable management of these stocks (Munro 1999). According to the UN Fish Stocks Agreement, coastal countries and distant water fishing nations should cooperate in the management of straddling and highly migratory fish stocks, to be carried out through RFMOs, with the objective of long-term sustainability of the stocks (UN 1995). The success of RFMOs in terms of managing highly migratory fish stocks remains to be seen.

A discrete time, multi-gear, and age structured bio-economic model is developed for the East Atlantic bluefin tuna. The objective is to analyse alternative management strategies and their policy implications that could be taken as guidelines by an RFMO managing this fishery**.** In this context, the optimal stock level is determined as well as an investment (recovery) path for the resource. Given that bluefin tuna is harvested by several different gears that target different age classes, as well as by a number of different countries, the impact of the harvest on the stock will depend on the combination of technologies (gear types) used and the countries participating in the fishery. For this reason, a number of different scenarios will be analysed. However, non-constant harvesting strategies will be formulated. To our knowledge, such a flexible approach has not previously been employed in the analysis of the management of Northern Atlantic bluefin tuna.

The paper is organised as follows. In the next section, a brief description of the East Atlantic bluefin tuna fishery is presented. In the third section, the bioeconomic model, consisting of a model of population dynamics and an economic model, is developed. Optimal management is examined in the fourth section, while the concluding section discusses policy implications.

The East Atlantic Bluefin Tuna Fishery

The Northern Atlantic and Mediterranean bluefin tuna (*Thunnus thynnus*) is a large oceanic pelagic fish and is the largest of the tunas. It can grow to a length of over two metres and weigh more than 500 kg; the largest bluefin tuna recorded was 679 kg (Ono 2004). Bluefin tunas can live up to 25 years. They are opportunistic feeders, commonly feeding on other fish and squid. Like other tunas, the bluefin tends to be found in schools of similar-sized individuals.

In 1982, the International Commission for the Conservation of Atlantic Tunas (ICCAT) established a dividing line between the East and West Atlantic, separating the stocks in order to facilitate stock assessment. The two existing stocks tend to migrate within their own area. Although there is a certain amount of mixing between stocks, they are managed separately, allowing us to focus exclusively on the eastern stock. The two stocks are also managed separately by ICCAT.

The eastern stock is distributed from the east of the Canary Islands to Norway, in the North Sea, in Ireland, in the entire Mediterranean Sea, and in the southern Black Sea. Occasionally, it goes to Iceland and Murmansk. Bluefin tuna move according to food abundance and water temperature. Spawning is located in the warm waters (around 24ºC) of the Mediterranean around the Balearic Islands and in the south of the Tyrrhenian Sea, starting in June and continuing until July. In the beginning of this season, a great flow of bluefin tunas can be observed. Afterwards, some specimens remain in the Mediterranean throughout the year, and others, either young or adult, leave these waters and go to Morocco, the Viscaya Gulf, the Canary Islands, and the Madeira Islands. The larger bluefin tuna can be found in the North Sea and along the Norwegian coast, since they are more resistant to colder waters. In winter they return to the tempered waters of the African coast.

Catch and Stock Development

Bluefin tuna is the most valuable fish in the ocean. High-quality tuna fetches a price premium in the Japanese sashimi market, where a single fish can command a price of up to US$100,000 (Dalton 2005, see also Martinez-Garmendia and Anderson 2005). Moreover, price has been increasing in recent years due to a worldwide decline in catches of high-quality tuna. Prices vary substantially with different gear types and over the season, due to variations in fish quality, size, and fat content (Martinez-Garmendia and Anderson 2005).

Bluefin tuna fisheries are characterised by a variety of vessel types and fishing gears operating from many countries. Different circumstances—economic, biological, geographical, and political—dictate the choice of gear type. The traditional and most important gear types in the East Atlantic are the purse seine, longline, trap, and bait boat. The *purse seine* is a huge net that is cast into the sea, gathering fish in its sweep. Generally, the fish caught are of medium size and weigh about 150 kg. When the net is hauled up, the fishermen jump into the water and beat the tunas to death with a stick rendering a very stressed and damaged catch. As a consequence, their price is about US$9 per kg (see table 1 for average prices for the different gears). The *longline* consists of a cable to which smaller independent cables are attached at intervals of several metres. These smaller cables carry numerous hooks. With this gear the fish die slowly, reducing the stress involved and, therefore, yielding a higher price of US$17 per kg. The *trap* is a kind of labyrinth created in the sea that leads the fish to an area where they remain until they are taken at convenience. The bluefin tuna attracted to these areas are generally large spawners, and at the time of harvest they do not suffer stress and are not damaged. Therefore, the quality is very high and a premium price is fetched—an average of US$25 per kg. The *bait boat* catches the fish using live bait and fishing rods. The fish caught are smaller since the strength of the fishermen is required to land the catch. As a consequence, the

Table 1
Economic Parameters of the Model—1995 Values

Gear	Price (P) (US$/kg)	Cost (c) per Unit of Effort (US$)	Unit of Effort
Longline	17	14,102	Fishing days
Purse Seine[1]	9	45,185	Fishing days
Trap	25	15,738	Trap days
Bait Boat	5	4,638	Days at sea
Remainder	17	2,408	Days at sea

Note: [1] For the purse seine, one fishing day corresponds to more than three days at sea.
Source: Pintassilgo and Costa Duarte (2002).

price is low—US$5 per kg. In addition, a number of other minor gears participate in the fishery; as a catchall we call them "remainder."

Throughout the years, the importance of each gear type has changed. Certain fisheries, such as trap, go back to ancient times. Other gear types, such as the longline and the Mediterranean purse seine, reached full development in the mid-1970s. The spatial distribution of the different gears has changed through the years. The most important change in this respect has been the relocation of the longline fishery to latitudes above 40º and longitudes between 20º and 50º west; *i.e.*, to fishing grounds on the high seas outside coastal state 200-mile EEZs.

Historically, more than 50 countries have participated in the fishery for bluefin tuna; currently, 25–30 participate. European countries such as Italy, France, and Spain use bait boat, longline, purse seine, and trap. Distant water fishing nations (DWFNs), such as Japan, come to the high seas of the North Atlantic to catch bluefin tuna using longline. In the 1970s, annual catches varied between 10,500 tonnes in 1970 and 22,300 tonnes in 1976 (figure 1). Subsequently, catches increased and reached a maximum of 52,737 tonnes in 1997. Thereafter, there was a decrease to 30,000 tonnes in 2000, mainly due to lower stock levels.

Stock size decreased from 210,000 tonnes in 1971 to 133,000 tonnes in 1981 (figure 1). Thereafter, stock remained fairly stable, experiencing a slight increase in 1993–94; in 2000 it was at roughly the same level of 150,000 tonnes.

The situation is very grave. If the current trend is maintained, a complete stock collapse is expected (Brasão, Costa-Duarte, and Cunha-e-Sá 2000). Already the trap fishery off Sicily, a mainstay of the island's economy since the Middle Ages, is facing extinction (Owen 2003). It may seem paradoxical that the most profitable fishery, trap, will become extinct first. This is because tuna may simply disappear from the waters where the trap fishery takes place, rather than due to the fishery becoming unprofitable in the more traditional understanding of the term.

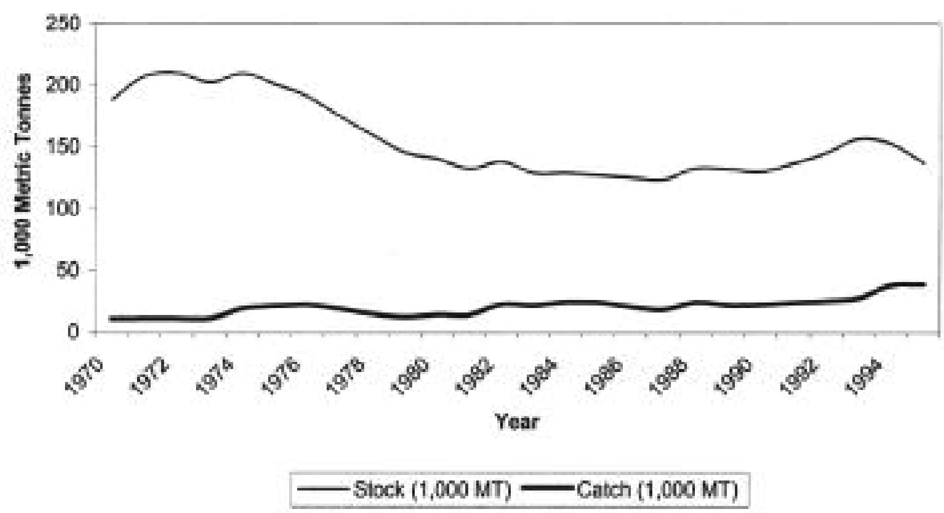

Figure 1. Bluefin Tuna Catches and Stock Evolution in the East Atlantic (including the Mediterranean Sea)
Source: ICCAT.

Tuna farming has also become fairly widespread in the Mediterranean. However, unlike aquaculture, where fish are bred and reared in captivity, tuna farming is based on juvenile fish captured in the wild that are reared to market size and then exported, mainly to Japan for "sushi" consumption. This tuna farming, which has been subsidised by the EU, has put the stock under even greater pressure.[1]

The lower number of participants in the fishery is primarily due to reduced stock levels as compared to historical figures. This has been compounded by the fact that as the stock declines, the distribution area of the stock is reduced, which explains why countries like Norway, Iceland, and Russia are not currently active in the fishery. Nevertheless, the situation points to a potential threat to the stock; if and when the stock recovers, there are many potential entrants. This is compounded by the high value of the fish. Therefore, as the stock increases, so will fishing pressure. Thus, the success of a recovery programme critically depends on compliance with regulations; in particular, control of harvests and of (new) entrants to the fishery.

Management

Bluefin tuna is classified as a highly migratory fish stock. According to the 1995 UN Fish Stocks Agreement,[2] both coastal states and high-seas fishing states are required to cooperate directly or through the establishment of sub-RFMOs or RFMOs to this end (UN 1995). Such cooperation is intended to ensure the long-term sustainable exploitation of straddling and highly migratory fish stocks. Participation in an RFMO is open to all countries having a "real" interest in the relevant fishery.[3]

The management of the Northern Atlantic bluefin tuna is the responsibility of ICCAT. ICCAT was established in 1969 with two main functions: to provide scientific assessments of Atlantic tunas and tuna-like fish and to give management recommendations that will permit a sustainable fishery. At present, there are 23 contracting parties to ICCAT. These include coastal states in Europe and Africa as well as DWFNs such as Korea and Japan.

As early as 1974, ICCAT recommended limiting the bluefin tuna catch in both the Atlantic and Mediterranean. In spite of the recommendations being officially implemented in 1975, they had no or little impact, as they were not respected. Present regulations include catch limits (quotas for each member country), prohibition of juvenile landings, and closed seasons (no longlining in the Mediterranean in June-July by vessels of more than 24 metres) (ICCAT 1998). So far, the regulations have proved to be rather ineffective. This is due to the inability of ICCAT to monitor and enforce its regulations, which is compounded by the large number of participants in the fishery, members as well as non-members of ICCAT.

The Bio-economic Model

A bio-economic model consisting of a model of population dynamics and an economic model is developed to analyse the Northern Atlantic bluefin tuna fishery. The model is programmed in Matlab as a non-linear equation system to be solved for each time period. The simulation chooses TAC quotas and the best combination of

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[1] www.wwf.org.uk/news/scotland/n_0000000518.asp
[2] The UN Fish Stocks Agreement has recently acquired the status of international treaty law.
[3] See Bjørndal and Munro (2003) on the management of straddling fish stocks and highly migratory fish stocks.

gear types in order to maximise the net present value from the fisheries. The optimisation process is time consuming and several attempts may be necessary in order to achieve convergence (Kennedy 1992).[4]

The Model of Population Dynamics

The model of population dynamics for the Northern Atlantic bluefin tuna consists of an age-structured, multi-gear, discrete time model, which was developed by Kirkwood and Barry (1997). The model, which is presented in the appendix, is solved for each of 60 time periods (years). An interesting feature of the model is that a non-linear system of $S = 5$ (number of gear types) equations is solved for each time period. The stock is composed of 10 different age classes. A model as complex as this one is necessary to account for the number of sub-fisheries involved, representing different technologies and the year-class structure of the stock.

In this model, recruitment is assumed to occur at discrete time intervals. Moreover, recruits will normally join the parent population one year after spawning. This approach has been used in several applied studies; *e.g.*, for North Sea herring, as in Bjørndal (1988).

We will first examine stock evolution under natural conditions; *i.e.*, in the absence of harvesting. This will be done by simulating the model for base case parameters (see appendix). The period up to 2100 is considered. As we can see from figure 2, the total biomass increases until approximately 2040 and stabilises thereafter at a steady-state level—the carrying capacity of the environment—of about 1,200,000 tonnes.

Based on simulations of the model, we can develop a growth function, which is plotted in figure 3. As expected, the higher the biomass level, the lower the biomass growth. Growth falls to zero when the stock reaches the carrying capacity of the environment.

Growth rate is not monotonically decreasing in stock size. For some levels of stock size, the growth rate is constant or even increasing. This can be explained by the recruitment function considered and the initial age class composition of the stock. For the given recruitment function, which is a bilinear relationship,[5] and the initial composition of the stock, we observe that from year to year the number of fish increases in most instances, while in some cases it decreases. This explains the curvature of the growth rate. If, on the other hand, the steady state represented the initial age composition, then relative growth would be monotonously declining in stock size, as expected.

The Economic Model

In the model, five different gear types, $s = 1, \ldots, 5$, are considered: the longline (LL), the purse seine (PS), the trap, the bait boat (BB), and the remainder. The economic model is set out in equations 1–5:

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[4] Some simulations took a week to perform due to the fact that the bioeconomic model incorporates different age groups, several gears, and is solved for many years. For each simulation, several initial values were tested in order to guarantee that the results did not depend on the starting point. The range of the initial values tested was extensive, so the optimisation results can be considered as being applicable globally rather than locally.

[5] The recruitment function is taken from Kirkwood and Barry (1997), who estimated various functional forms with the bilinear giving the best fit.

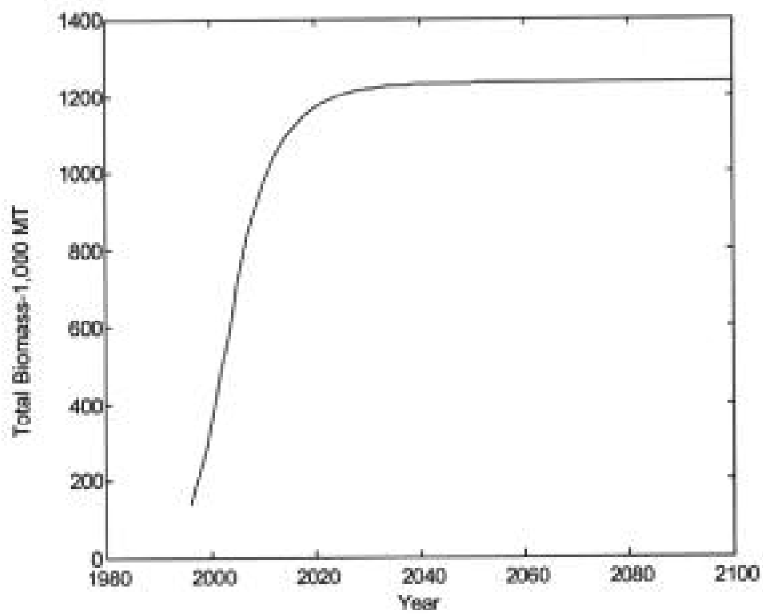

Figure 2. Biomass Evolution with no Catches

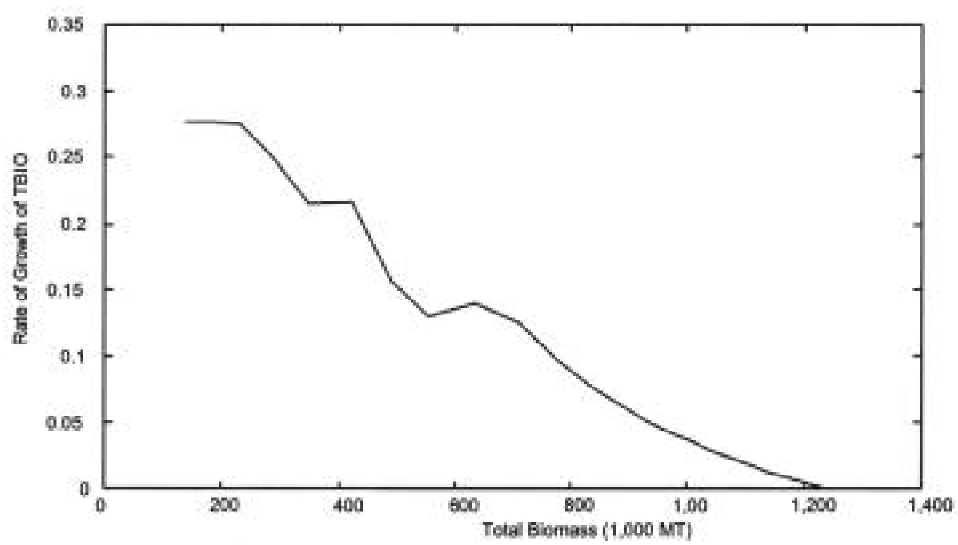

Figure 3. Growth Function for Bluefin Tuna
Note: The growth rate is defined as $[B(t) - B(t-1)]/B(t-1)$, where $B(t)$ represents the total biomass, and t is the time period.

$$\mathrm{Re}\,v_{t,s} = (1 - \gamma)P_s C_{t,s} \tag{1}$$

$$C_{t,s} = q_s E_{t,s} B_t^{\alpha_s} \tag{2}$$

$$Cost_{t,s} = c_s E_{t,s} \tag{3}$$

$$\Pi_{t,s} = \mathrm{Re}\,v_{t,s} - Cost_{t,s} \tag{4}$$

$$TNPV = \sum_{s=1}^{S} \sum_{t=1}^{T} \left(\frac{1}{1+r}\right)^t \Pi_{t,s}. \tag{5}$$

$\mathrm{Re}\,v_{t,s}$ is the revenue per gear type s in time t, P_s is the price per gear type, γ is the crew share per gear type, $C_{t,s}$ is the catch per gear type in time t, q_s is the catchability coefficient per gear type, $E_{t,s}$ is the effort by gear type s in year t, Bt is stock size in year t, $Cost_{t,s}$ is the cost per gear, c_s is the unit cost parameter for gear type s, $\Pi_{t,s}$ is profits per gear type s in year t, *TNPV* is the TNPV of the fishery, and r is the discount rate.

For the revenue function (equation [1]), an average price per gear type is used. It is common practise in many fisheries that the crew receive a share (γ) of revenues, while $(1 - \gamma)$ is the share of revenue received by the boat owner. This is also the case with the bluefin tuna fishery, where the share of the crew in revenues is 0.3; *i.e.*, $\gamma = 0.3$.[6]

The link between the model of population dynamics and the economic model is established through equation (2), which gives the harvest function. Harvest (C) is a function of the catchability coefficient, q_s, which varies with gear type,[7] effort (E) and stock size (B). When modelling the harvest of bluefin tuna, a harvest function where the stock-output elasticity (α) is less than one is considered. This type of production function is frequently used for schooling species (*e.g.*, Bjørndal 1988; Kennedy 1992). In the bluefin tuna fishery there are gear types that use very advanced methods of detection. For these gear types—longline, bait boat, and purse seine—whose catches do not depend much on the existing stock, a low stock-output elasticity of 0.2 is assumed. For the more traditional gear types, trap and remainder, which are more stock dependent, the value is assumed to be 0.8. This means that harvesting by some of the most important gears is quite unresponsive to changes in stock size. A consequence of this is that the stock is very vulnerable to depletion under an open-access regime (Bjørndal 1988; Brasão, Costa-Duarte, and Cunha-e-Sá 2000).

For the cost function (equation [3]), we adopted a function where total cost by gear type is a linear function of the level of fishing effort. Fishing effort for the various gear types is defined in table 1, which also gives cost per unit effort. Fixed costs were not considered since most fleets also target other species. Thus, in this model formulation, marginal cost of effort is constant for each gear type. Nevertheless, the cost per unit harvested will vary for different stock levels due to the stock-output

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[6] Ideally, the opportunity cost of labour should have been used, but due to the complexity of the model and data availability, this was not feasible.

[7] The value of this variable was obtained by solving the production function in order to find q_s, applying the base year values for catches, biomass, and total effort (those for 1995). Econometric estimation was not possible due to lack of data.

elasticity. Moreover, these costs will vary among gear types, due to different marginal costs and different stock-output elasticities.

Profits are given by equation (4). The sum of the net present values for all gear types gives the total net present value (TNPV) (equation [5]).

Optimal Management

We now examine the optimal pattern of catches that maximises the TNPV of the fishery; *i.e.*, equation (5), subject to the model of population dynamics and other constraints, as specified below. The optimisation process was conducted in the following way: a grid was established for different combinations of starting values for the TAC for each gear type. The different paths were then simulated, the net present values were estimated and ranked, and the highest one chosen. The net present value was the same for numerous starting values for the TAC so that a global optimum was obtained.

Pintassilgo and Costa Duarte (2002) analysed how constant effort and constant TAC policies could improve the economic performance of bluefin tuna fisheries over an open-access fishery for a 25-year period. These assumptions impose severe constraints on the solution. Therefore, the current analysis goes beyond that by investigating *non-constant* optimising strategies over a 60-year period, a period that is sufficient for the stock to attain a steady state. Moreover, a number of alternative scenarios for future management will be analysed based on important characteristics of the fishery.

Presently, this fishery has five different main gear types. In the first scenario, we assume this will be the case also for the future and impose it as a restriction on optimisation; in particular, we assume that the share of catch for the different gear types is the same as in 1995. As an alternative, we consider a flexible gear structure in order to see whether these five gear types are in fact the most efficient combination. In this optimisation, we still impose constraints on some of the gears' catches. According to historical data, the trap has never harvested more than 10,000 tonnes, and the remainder has always stayed below 5,000 tonnes per year. Trap is the most profitable gear (table 1). With a flexible gear structure, one would expect it to outperform the other gears. However, as there are biological and technological constraints on its expansion and the gear can be used only in certain geographical locations (above), the upper limit imposed is reasonable. As mentioned, remainder consists of a diversity of different gears; an expansion beyond what has been observed historically is most unlikely.

Initially, we thus consider two scenarios:

A1. The status quo fleet—a constant relative gear type structure as of 1995, where all current gear types remain in the fishery.[8]

B1. A flexible gear structure, consisting of the most efficient gear types, with upper limits on the harvests by trap and remainder.

The discount rate is set at 4% in all scenarios.[9]

Initial stock size is at a low level (figure 1). An optimal programme may, there-

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[8] In 1995, the shares of the different gear types in catches were: longline 0.321, purse seine 0.4419, trap 0.0464, bait boat 0.0819, and remainder 0.1087.

[9] This is in accordance with other applied studies, using similar investment horizons, such as the US Department of Commerce, National Marine Fisheries Service (1995) and long-run interest rates published in reports from the International Monetary Fund.

fore, involve an initial and possibly lengthy moratorium of the fishery (Clark 1985). This policy may appear to be rather Draconian. Therefore, as an alternative to scenarios A1 and B1, we impose a constraint on each scenario that catches in any given year may not be less than 10,000 tonnes. We denote these alternatives as scenarios A2 and B2, respectively. Optimisation results for the four scenarios specified are given in table 2.

The TNPV results show that in fact the initial gear structure (scenario A1) is not optimal. Indeed, optimality implies that two gears should be shut down; namely, bait boat and purse seine (scenario B1); this would increase TNPV from US$937 million to US$3,040 million.

The stock and catch evolution for scenario A1 is shown in figure 4. Interestingly, it gives rise to pulse fishing (Clark 1985). There is a moratorium for the first 10 years, followed by fishing for 13 years, then a further moratorium of five years, *etc.* In other words, the cycle is 13 years of fishing followed by a five-year moratorium.

During the moratorium, the stock increases to a level of about 800,000 tonnes. As fishing commences, stock size is gradually reduced to a level of 499,500 tonnes at the point when the new moratorium is imposed. During fishing periods, harvest is 55,000 tonnes. This outcome can be explained by the fact that purse seine and bait boat target young bluefin tuna, with consequent effects on the stock age structure.

In scenario B1, the pattern of catches is characterised by a 13-year moratorium for longline, a three-year moratorium for trap, and a four-year moratorium for remainder. Thereafter, longline attains 35,000 tonnes, trap 10,000 tonnes, and remainder 5,000 tonnes; *i.e.*, a total annual harvest of 50,000 tonnes. The brief moratorium period declared for the trap is explained by the high profitability of this gear type followed by remainder, which has the second highest profitability.

Table 2
Comparison of Alternative Management Scenarios—4% Discount Rate

	Scenario A1: All Gears	Scenario A2: A1 with Min. 10,000 MT Catch	Scenario B1: Longline, Trap, and Remainder	Scenario B2: B1 with Min. 10,000 MT Catch
Total net present value (mill. US$)	937	741	3,040	2,790
Moratorium period (years)	10[a]	n.a.	[13, 3, 4]	n.a.
Optimal steady-state stock (tonnes)	499,510–800,000[b]	499,040–800,000[b]	811,130	807,360
Optimal steady-state harvest[c] (tonnes)	55,000	55,000	[35,000; 10,000; 5,000]	[35,000; 10,000; 5,000]

Notes: n.a. = not applicable.
[a] Moratorium from years 1 to 10, 23 to 28, and 41 to 46.
[b] Stock levels during the last (lower stock level) and the first year of the fishing period, respectively.
[c] Harvest levels are rounded off to the nearest 1,000 tonnes.

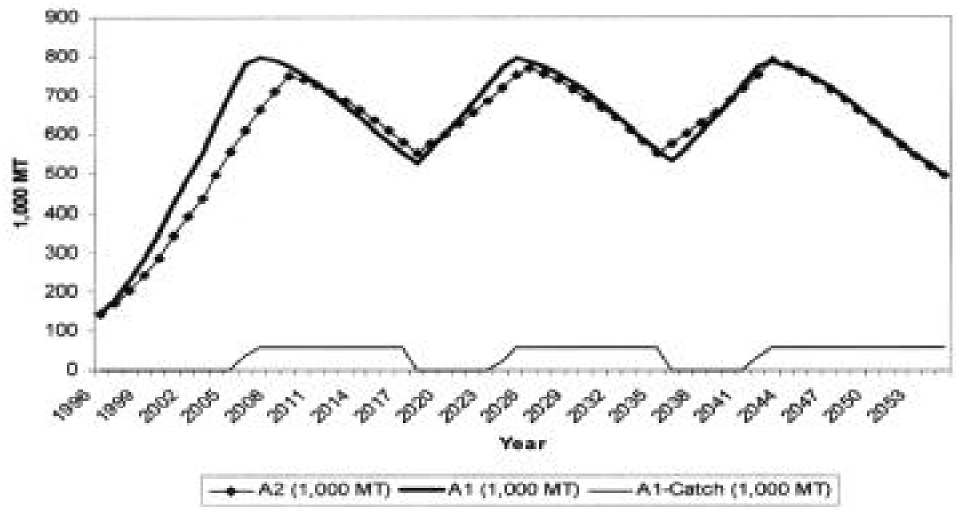

Figure 4. Stock Evolution in Scenarios A1 and A2 and Catch Evolution in Scenario A1

The stock and catch follow the pattern shown in figure 5. When longline enters the fishery after the moratorium, the stock has reached a level of 860,000 tonnes. The subsequent development of the fishery is very interesting. After 25 years, catches of longline are reduced to 30,000 tonnes and then to an annual catch of 16,000 tonnes for three years, before increasing again to 35,000 tonnes. Catches are again reduced during years 35–37. The catches of trap and remainder, on the other hand, always remain at their steady-state levels. Gradually, the stock approaches 811,000 tonnes, which can be considered the steady-state stock level that maximises the TNPV of the fishery.

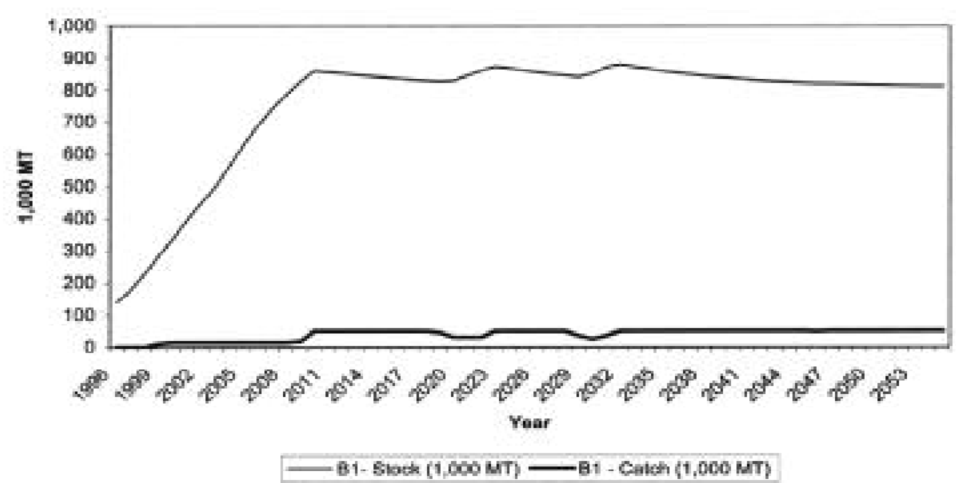

Figure 5. Stock and Catch Evolution in Scenario B1

As an alternative to scenarios A1 and B1, we imposed a constraint on each scenario that catches in any given year may not be less than 10,000 tonnes. Results for these alternatives—scenarios A2 and B2—are also given in table 2.

The same steady-state stock and harvest levels are achieved as for the main alternatives, although the optimal stock level is approached more slowly (see figure 4 for scenario A2). Qualitatively speaking, the policies are similar to those of scenarios A1 and B1: pulse fishing for scenario A2, and non-constant annual catches for scenario B2.

It is interesting to note that the gradual approach (A2 and B2) implies a reduction in TNPV of about 20% as compared to the optimal approach (A1 and B1). However, the steady state is approached with a delay; *i.e.*, steady-state net revenues are delayed as compared with the optimal approach. The tradeoff is, of course, influenced by the discount rate.

All four scenarios have also been investigated under the assumption of a 10% discount rate (table 3). The higher discount rate is seen to cause very substantial reductions in the TNPVss of the various scenarios as compared with the initial case. Scenarios A1 and B1 involve marginally shorter moratorium periods than in the case of a 4% discount rate. Nevertheless, the moratorium periods are still substantial, and with a higher discount rate, this has a profound effect on TNPV. On the other hand, steady-state stock and harvest levels are not affected much, and policies are qualitatively similar to those for the lower discount rate.

Policy Implications

As a highly migratory fish stock, the East Atlantic bluefin tuna is to be managed by an RFMO (UN 1995; Munro 1999; Bjørndal and Munro 2003). The RFMO entrusted with this responsibility will be faced with daunting tasks in terms of formulating and imposing policies on the participants of the fishery, as well as enforcing them. The

Table 3
Comparison of Alternative Management Scenarios —10% Discount Rate

	Scenario A1: All Gears	Scenario A2: A1 with Min. 10,000 MT Catch	Scenario B1: Long line, Trap, and Remainder	Scenario B2: B1 with Min. 10,000 MT Catch
Total net present value (mill. US$)	284	151	960	774
Moratorium period (years)	9	n.a.	[11,3,3]	n.a.
Optimal steady-state stock (tonnes)	519,090	475,720	805,360	805,400
Optimal steady-state harvest (tonnes)	55,000	55,000	[35,000; 10,000; 5,000]	[35,000; 10,000; 5,000]

n.a. = not applicable.

fact that a large number of countries participate in the fishery makes it difficult to arrive at a cooperative solution. This is the case even if some "natural" coalitions can be developed; *e.g.*, between European countries that are EU-members or DWFNs (Costa Duarte, Brasão, and Pintassilgo 2000). Moreover, the stability of the solution can be questioned (Brasão, Costa-Duarte, and Cunha-e-Sá 2000). Finally, as we are dealing with an extremely valuable stock migrating over vast areas of ocean, the new member problem takes on special significance (Kaitala and Munro 1997; Pintassilgo and Costa Duarte 2001).

Despite these problems, the empirical analysis has resulted in a number of novel, interesting results with important consequences for an RFMO. First, for the various scenarios, the optimal stock level varies between roughly 500–800,000 tonnes.[10] This compares with a stock level of 150,000 tonnes in 2000. In other words, there is a very strong case for rebuilding the stock. The costs of not instituting a recovery programme are very substantial in terms of foregone economic rents. Moreover, the sustainability of the stock is threatened unless a recovery programme is implemented.

It should be noted that purse seine is one of the gears that is eliminated as part of an optimal gear structure. Purse seine is currently the most important gear type. However, it has lower selectivity than any of the other gear types (table A3). Thus, from an ecological point of view, there are also arguments for eliminating this technology.

Second, to rebuild the stock, Draconian measures are called for: either outright moratoria over fairly lengthy periods, or possibly a more gradual approach to steady state given by a TAC at a low level for an extended period of time.

Third, the cost of inefficient gear structure is very high indeed.[11] The cost of maintaining the current gear structure (scenario A1) involves a very substantial loss in net present value compared with the optimal structure (scenario B1), regardless of the rate of discount. Also, the optimal policy (B1) calls for the elimination of certain gear types. Comparable results were found by Bertignac *et al.* (2000), who analyse the management of skipjack, yellowfin, bigeye, and Southern albacore tuna in the Pacific Ocean. These stocks are harvested by a number of different gear types. The authors found that the current fleet structure is suboptimal. To maximise rents, certain gear types should be virtually eliminated, while the effort of remaining gear types should be reduced substantially. Martinez-Garmendia and Anderson (2005) found similar results for the West Atlantic bluefin tuna fisheries, calling for the elimination of inefficient gear types in order to maximise rents.

Fourth, generally speaking, non-constant policies are called for. Scenario A1 calls for pulse fishing with a 13-year fishing period followed by a five-year moratorium. Scenario B1 results in a "milder" form of pulse fishing, where there are periods with reduced harvests for longline, while the harvests of trap and remainder are maintained at their sustainable levels. The qualitative difference between these two scenarios is due to the fact that the current gear structure is imposed on scenario A1.

Kennedy (1992), using a multi-cohort bioeconomic model to analyse the western mackerel fishery, also found pulse fishing to be optimal. However, Kennedy also explicitly modelled adjustment costs for fishing effort and found that they diminished the advantage of pulse fishing as compared to strategies that allowed for

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[10] The lower level is the stock level in the last year of the fishing period, cf. tables 2 and 3, scenarios A1 and A2. The average stock level is substantially higher.

[11] Here, only efficiency in the bluefin tuna fishery is considered. If what is herein an inefficient gear type also participates in other fisheries, it may be efficient over its entire application of effort.

positive harvesting in all periods. In our context, adjustment costs would mean that the difference in TNPV between strategies A1 and A2/B1 and B2 would be less than those in tables 2 and 3.

In a fishery where price is dependent on quantity, an optimal policy will often involve some harvest even if the stock is low in order to take advantage of the high price. On the other hand, as stock increases, increasing catches will be constrained by the declining price (Grafton, Sandal, and Steinshamn 2000). In our analysis, price is assumed constant. Qualitatively, however, the high profitability of trap plays a role somewhat similar to that of a quantity-dependent price: in scenario B1, the initial moratorium for trap is very brief, only three years, despite the fact that the initial stock is very depleted. Furthermore, while catches of longline are reduced in later years, those of trap are always maintained at their maximum level due to the high profitability of this gear. This point has not previously been made in the literature.

On the one hand, we have seen that the optimal policy for the bluefin tuna fishery is to shut down some of the existing gear types, namely bait boat and purse seine, and, on the other hand, to declare a temporary harvest moratorium. Shutting down gear types that have been active for a long time may lead to social costs, as it will impose a loss on the fishermen involved. A moratorium may also lead to the exit of a number of fishermen. Moreover, as the moratorium periods are different for each gear type, those excluded from the fishery or with a long moratorium may have incentives to harvest using gear types with shorter moratorium periods.

Policy recommendations on the bluefin tuna fishery require that all these issues be taken into account. Sooner rather than later, if nothing is done the stock will be reduced to such low levels that the sustainability of the fishery is threatened. Only Draconian measures will guarantee the long-term sustainability of the stock and the fishery.

The East Atlantic bluefin tuna is an example of a highly migratory fish stock facing severe overexploitation. Yet, several countries continue to harvest this species, while others consider entering the fishery because of its high market value. Thus, the maintenance of these recommendations requires cooperation among all the countries involved in the fishery through the RFMO, as well as strict monitoring and enforcement.

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Appendix: Model of Population Dynamics

All symbols are defined in table A1. The model of population dynamics, from Kirkwood and Barry (1997), is described in equations (A1) through (A11).

Population Numbers

Equation (A1) gives the initial numbers of fish per age. Equation (A2) is the recruitment function. A bilateral recruitment function is specified. Equations (A3) and

(A4) are the number of fish per year as a function of fishing mortality and natural mortality. Equation (A3) concerns ages 1 until 9, and equation (A4) represents the number of fish at ages 10 and over. Equation (A5) is the spawning stock biomass as a function of the maturity rate, the number of fish, and the average weight by age. Finally, equation (A6) is the total biomass level by year.

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

$$N_{t,0} = f(SSB_{t-}) = \begin{cases} R_{\max} e^{\delta} \text{ if } S_{t-1} \ge SSB_{\min} \\ R_{\max} \dfrac{S_{t-1}}{SSB_{\min}} e^{\delta} \text{ if } S_{t-1} < SSB_{\min} \end{cases} \tag{A2}$$

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

$$N_{t,A} = N_{t-1,9} e^{-M_9 - F_{t-1,9}} + N_{t-1\,A} e^{-M_A - F_{t-1,A}} \tag{A4}$$

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

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

Catch at Age and Gear

Equations (A7) through (A11) relate to catch by gear. Equation (A7) is the instantaneous fishing mortality by year, age, and gear as a function of the fishing mortality at maximum selectivity, and selectivity. Equation (A8) is the fishing mortality by year and age. Equation (A9) is the catch numbers as a function of fishing mortality, the number of fish, and natural mortality. Equation (10) is catch in weight in period *t* for gear *s*.

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

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

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

$$C_{t,s} = \sum_{a=1}^{A} CN_{t,a,s}.W_a \qquad \text{(A10)}$$

$$= \sum_{a=1}^{A} \frac{FMax_{t,s}.Sel_{a,s}.N_{t,a}.W_{t,a}}{\sum_{s=1}^{S}(FMax_{t,s}.Sel_{a,s} + M_a)} \left(1 - e^{-\sum_{s=1}^{S}(FMax_{t,s}.Sel_{a,s} + M_a)}\right), \quad \text{for } s = 1, \ldots,$$

Running the Model

Stock numbers in 1995 represent the starting point for the various analyses performed.

Table A1
Definition of Symbols

Variables		Coefficients	
N	Nº of fish (beginning of year)	*M*	Instantaneous natural mortality
Ñ	Estimated nº fish (beginning of 1995)	*Mat*	Maturity rate
SSB	Spawning stock biomass	*W*	Average weight
F	Instantaneous fishing mortality	*q*	Production function parameter
FMax	Fishing mort. at maximum selectivity	α	Catch-stock elasticity
B	Total biomass	c_s	Cost per unit effort
Sel	Selectivity	γ	Crew share
CN	Catch numbers	*R*	Interest rate
E	Effort	δ	Instantaneous growth rate
C	Catch		
Rev	Revenue	Indices	
Cost	Cost		
P	Average price	*T*	Time (t = 1,…,T), T=60 (2056)
Π	Profit	*a*	Age (a = 1,…,A), A=10+
TNPV	Total net present value	*s*	Gear (s = 1,2,…,S)
R_{max}	Scaling parameter		
S_{t-1}	Stock at period t – 1		

Table A2
Model Parameters

Variables	Values
Recruitment Function	
Rmax (number of fish)	1,572,724
SSB_{Min}	8.01 E7
δ	0.113
Production Function	
Biomass in the base year	149,651.15 tonnes
Initial Conditions	
Average weight by age	[5.3; 11.8; 19.3; 33.3; 51.8; 74.5; 95.3; 121.6; 145.5; 245.1]
Number of fish by age	[1,572,724; 1,016,007.65; 385,195.51; 403,719.36; 533,995; 190,799; 166,737; 116,904; 26,341; 100,694]
Fishing mortality at maximum selectivity (LL, PS, BB, Trap, Rem)	[0.3353; 0.3645; 0.0487; 0.1207; 0.1141]
Effort in 1995 (LL, PS, BB, Trap, Rem)	[9,294; 2,114; 2,066; 2,274; 21,510]
Catches in 1995, MT (LL, PS, BB, Trap, Rem)	[12,849; 17,689; 1,858; 3,277; 4,352]

Source: Kirkwood and Barry (1997).

Table A3
Selectivity by Gear (Rows) and Age (Columns)

	1	2	3	4	5	6	7	8	9	10+
Longline	0.01	0.01	0.02	0.04	0.07	0.14	0.23	0.31	0.51	1
Purse Seine	0.36	1	0.92	0.33	0.22	0.13	0.23	0.23	0.24	0.53
Baitboat	0.04	0.01	0.01	0.02	0.06	0.15	0.25	0.32	0.47	1
Trap	0.92	1	0.46	0.26	0.18	0.1	0.04	0.02	0.02	0.03
Remainder	0.28	0	0.08	0	0	0.06	0	0.96	0.51	1