Stochastic Bio-economic Model of Northern Atlantic and Mediterranean Bluefin Tuna[*]

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Abstract

The purpose of this paper is to study the implications of introducing a stochastic stock in a multi-gear and age structured bio-economic model for the Northern Atlantic Bluefin tuna. In order to account for variations on the recruitment, uncertainty is introduced on a bilinear recruitment function, and it is represented by an exponential random error term leading the stock to be, on average, higher than in the deterministic case.

Both the bionomic equilibrium and the optimal management of this species are examined. In the latter, two alternative instruments are studied: the constant total allowable catch and the constant effort and the purpose is to maximize the expected total net present value. The conclusions enhance that the results do not differ significantly from those in the deterministic model, that is, the fishing effort should be the policy instrument to adopt, both in the East and the West Atlantic.

Despite the previous reasoning, the shock on recruitment should be taken into account, as certain realizations of the random variable may lead to different results. In particular, for low Bluefin tuna stock levels, it is optimal to regulate the caches instead of the fishing effort, to ensure the stock recovery.

Keywords: Stochastic Bio-economic model, Bluefin tuna, Optimal management.

Contents

1. Introduction

An important problem in fisheries economics concerns the optimal management of transboundary and highly migratory fishing stocks. Situations of severe depleted stocks are well known, due mostly to economic incentives and the absence of efficient regulations. The Northern Atlantic Bluefin tuna falls in this group of concerns. Being characterized by two separate stocks, the Eastern and Western Atlantic, it has been harvested at a high rate by several different gears that target different age classes, especially in the East Atlantic[1]. Still, several countries, both coastal and distant water fleets are tempted to enter this fishery because of the high market value placed upon this species, especially by the Japanese market. Owing to this pressure, the Bluefin tuna stock has decreased giving rise to some concern. It, therefore, calls for both national and international regulations, monitoring and enforcement, although the highly migratory nature of the resource has resulted in a difficult management problem.

A bio-economic model was developed in Pintassilgo (1999) in order to study the optimal use of Bluefin tuna in a deterministic context. Two different management policies were considered: the constant total allowable catches and the constant fishing effort. The results enhance that it is optimal to restrict effort, both in the East and the West Atlantic[2].

Nevertheless, it seems obvious, from the observation of the real world that uncertainty should be introduced in the aforementioned model. In fact, for the Bluefin tuna, the recruitment is stochastic and it can result in occasionally huge recruitment that can improve the Bluefin tuna stock, reducing the present concern with this species. In fact, the case of the spring spawning herring that recovered from a severe depletion owing to an occasionally huge recruitment (Bjorndal 1998). Therefore, the present study differs from earlier work in the sense that it introduces uncertainty on the Bluefin tuna recruitment, thus representing an extension to the deterministic model.

In this paper, a stochastic discrete time multi-gear and age structured bio-economic model is developed. In order to account for variations on the recruitment, which result from empirical observation, uncertainty is introduced on the recruitment function, and

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[1] In 1982, the International Commission for the Conservation of tunas (commonly known as ICCAT), established a dividing line bewteen the East and West Atlantic separating the stocks based on morphometric differences, in order to facilitate the stock assessement

[2] For more detailed information see Pintassilgo (1999).

according to Kirkwood and Barry (1997), it is represented by an exponential random error term leading the stock to be, on average, higher than in the deterministic case.

The purpose of this paper is to study the implications of uncertainty on the bionomic equilibrium and the optimal management policies. In the latter, the constant total allowable catches (TAC) and the constant fishing effort are examined as economic policies that remain effective over time and across a broad range of objectives and are adaptable in the face of stochastic changes to the resource or its environment.

The open access quickly becomes unprofitable and is seen to involve substantial depletion of the stock. Concerning the optimal management of this species, the regulation should be undertaken through the effort both in the East and the West Atlantic. This result is somehow expected as regulation through effort allows for more flexibility in the adjustment. The results enhance the similarity between the optimal policy choices obtained in both the deterministic and stochastic models. Nevertheless, the shock on the recruitment should be taken into account as for certain realizations of the random variable the results may reveal the constant TAC as the optimal economic instrument to regulate this fishery, due to the low level of the Bluefin tuna stock. Thus, the manager must be aware that the regulation through the fishing effort may turn out to be an inefficient measure.

The paper is organized as follows. In the next section, the stochastic bio-economic model is explained, emphasizing the introduction of the stochastic elements. Section 3 presents the results both for the open access and the optimal management. Section 4 gives some insights on the optimal results obtained after uncertainty is resolved and finally, section 5 concludes the paper.

2. Stochastic Bio-economic Model

An age-structured and multi-gear time discrete stochastic bio-economic model is developed to examine the Northern Atlantic Bluefin tuna fishery. Kirkwood and Barry (1997) developed a biological model in order to capture the inter-relations between the different gears, the associated age classes and locations. Both the biological equations and the economic model, including the links between these two models, have been described in detail in Pintassilgo (1999). As the model used in this paper is

an extension to a stochastic context, we will not go into detail once again of all the equations. An effort will be made in the explanation of the new elements introduced under uncertainty. Nevertheless, a general description of the model is presented in the Appendix.

2.1 Model Description.

In the biological model developed by Kirkwood and Barry (1997), the recruitment is assumed to occur at discrete time intervals. Moreover, recruits will normally join the parent population one-year after spawning. In fact, this kind of approach has been used in several applied studies, namely for the Norwegian Spring Spawning Herring studied in Bjorndal (1988).

Three different recruitment functions were examined: the Shepherd, the Beverton and Holts and the bilinear recruitment functions. The latter recruitment function with a lognormal error provided the best fit to the stock-recruitment data. Figure 1 presents these functions.
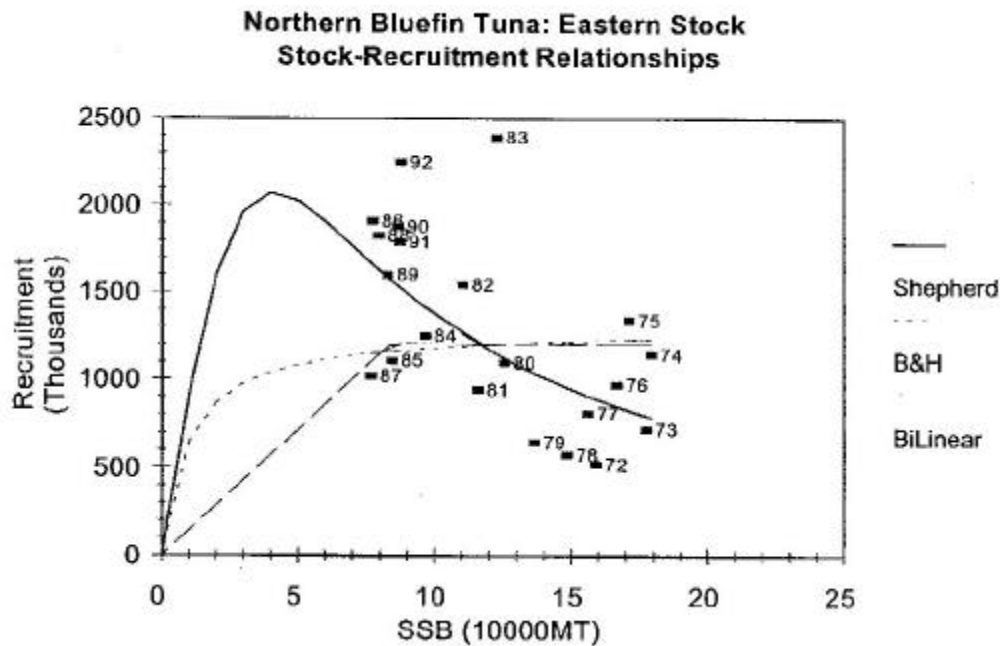

Figure 1

Source: Specification of a Biological and Prediction Model for Northern Bluefin Tuna.

In the bilinear relationship, the recruitment is assumed to be on average constant at R_{max}, for spawning stock biomasses (SSB) above a minimum level, but on average it declines nearly to zero for SSBs below that minimum.

As uncertainty is introduced, the functional form is given by:

$$R_t = \begin{cases} R_{max} e^d & \text{if } S_{t-1} \geq SSB_{min} \\ R_{max} \dfrac{S_{t-1}}{SSB_{min}} e^d & \text{if } S_{t-1} < SSB_{min} \end{cases}$$

where $d \sim N(0, s^2)$, and R_t is number of recruits to the juvenile population as a function of the previous year's spawning stock.

Note that an exponential multiplicative error is considered. As the expected value of this random variable is greater than one, the average stochastic biomass will clearly be higher than the deterministic biomass. There is an upward bias that is in accordance with the historical data.

Additionally, a second element of stochastic variation was incorporated: uncertainty around the estimated stock levels at age at the beginning of 1996, reflecting uncertain current stock levels. Therefore, the initial stock levels are described by $N_{j,i,0} = \tilde{N}_{j,i} e^q$ for $1 \leq i \leq 10$, where θ follows a normal distribution with mean zero and coefficient of variation equal to 0.1. As nothing is said on this matter, a multiplicative lognormal error is assumed to be reasonable. The stock recruitment relationship parameters for the East and the West Atlantic stocks used in this study are presented in table 2 below.

Table 2: Bilinear Stock Recruitment relationship parameters

	Eastern Stock	Western Stock
R_{max}	1572724	70581
SSB_{min} (10000 MT)	8.01	0.828
s^2	0.113	0.098

2.2 Model Implementation

Two stochastic bioeconomic models were developed in Matlab, for the East and West Atlantic respectively, in order to examined the bionomic equilibrium as well as the optimal management of Bluefin tuna. Several Matlab procedures have been

created so as to perform simulations and optimizations of the models. The forecasting period is 25 years, as it seems a reasonable horizon for economic analysis and regulation enforcement. Nevertheless, this forecasting horizon was extended to 100 years and the optimal management results were not significantly affected.

An error term for each forecasting period is needed. In order to account for this random variable, two samples of errors were created in Matlab, respecting the distribution, the mean and the variance suggested both for the East and the West Atlantic (these samples are shown in the appendix). These samples were then introduced in the simulation of the open access and in the optimization procedures. Note that the sample is quite small. Nevertheless, a larger sample of errors does not imply changes in the optimal results. Therefore, due to huge complexities introduced in computational terms, we opted for a smaller one.

Open Access

The Bluefin tuna stock has been traditionally harvested by several countries, both coastal and distant water fleets. The lack of cooperation between these nations led to a situation of overexploitation of the species. In contrast to the West Atlantic where some regulation was enforced for this fishery in the eighties, the East Atlantic fishery is characterized by an open access scenario, which is leading to the decrease in the Bluefin tuna stock.

In the open access case, the fishing nations are myopic in the sense that they are only concerned with the best decision in each period separately, given the previous year's profit results. Concerning the Matlab procedures, the expected value of each relevant variable is simulated, given on one hand the sample of errors created and on the other hand that each event may happen with equal probability.

As in the deterministic model, the market dynamics in this case is established through the effort in the following way:

$$
E_{j,t,s} = \begin{cases} (1 - b_{j,s})E_{j,t-1,s} & \text{if} \quad P_{j,t-1,s} \leq -Pb_{j,s} \\ E_{j,s,t-1} & \text{if} \quad -Pb_{j,s} \leq P_{j,t-1,s} \leq Pb_{j,s} \\ (1 + b_{j,s})E_{j,s,t-1} & \text{if} \quad P_{j,t-1,s} \geq Pb_{j,s} \end{cases}
$$

Whenever there is a considerable change in profits effort changes accordingly by a certain proportion, otherwise the effort remains unchanged.

Optimal Management

In the management of fishery resources several policies may be recommended. Of particular interest are policies that remain effective over time and across a broad range of objectives and are adaptable in the face of stochastic changes to the resource or its environment. In the present work, two alternative policy instruments were examined: the constant total allowable catch and the constant fishing effort.

For the purpose of this analysis, it is assumed that the resource in question is managed by a risk neutral sole owner whose objective is to maximize the discounted expected total net present value over 25 years, in order to choose the best policy instrument to preserve the Bluefin tuna stock, that is:

$$MAX \; E\left\{ \sum_{S=1}^{G} \sum_{t=1}^{T} \left[P_{j,s} C_{j,S,t} - TCost_{j,s} \right] \frac{1}{(1+r)^t} \right\}$$

where T=25 is the last forecasting year and G is the number of gears. In the East Atlantic G=5 and in the West Atlantic G=4.

For both the East and the West Atlantic, two models of optimal management are presented. The first uses total catches as a control variable while the second assumes that fishing effort can be regulated.

3 Results

The results of the two models will be examined, both for the open access and the optimal management.

3.1 Open Access

In this model, several simulations were undertaken. It is interesting to begin by examining the average stochastic recruitment evolution. Note that, the recruitment for

the 25 years of analysis and for each vector of errors from the sample defined above was calculated and afterwards an average recruitment by year was obtained.
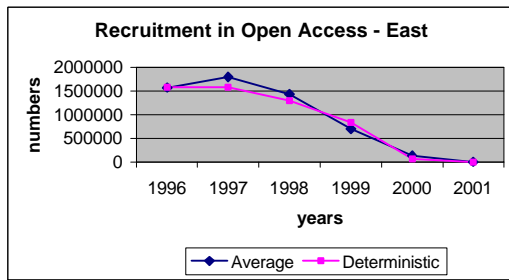
Figure A
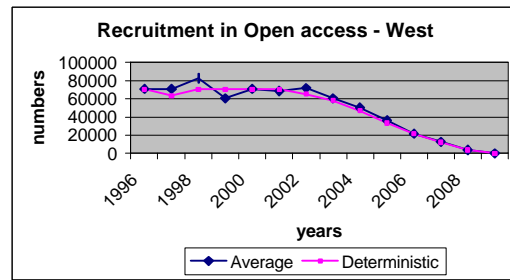
Figure B

The average stochastic recruitment is initially at its maximum but as the spawning stock biomass decreases, it also decreases. It is clear that the trend followed in this case is close to the deterministic model. Note that there are no huge recruitment implied by this sample of errors.

The results for this scenario are displayed in Figures 1 and 2 below. Note that only the evolution of some variables is shown in these figures, both for the East and the West Atlantic. Two arguments are advanced: (i) the evolution of these variables is similar, (ii) these are representative of the overall results, revealing the most important changes that resulted from the uncertainty in recruitment. Nonetheless, all the results are presented in the Appendix.
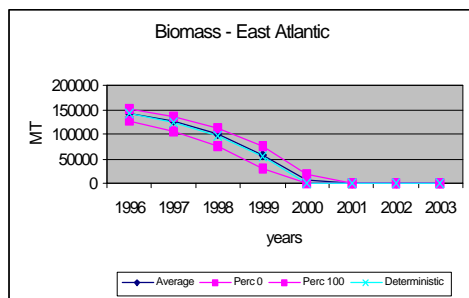
Figure 1a: Biomass evolution
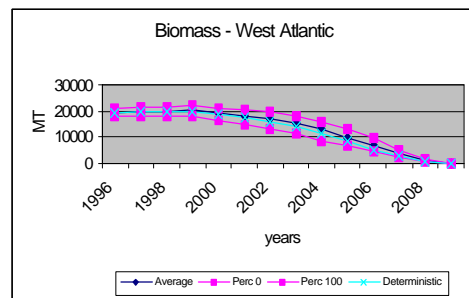
Figure 2a: Biomass evolution
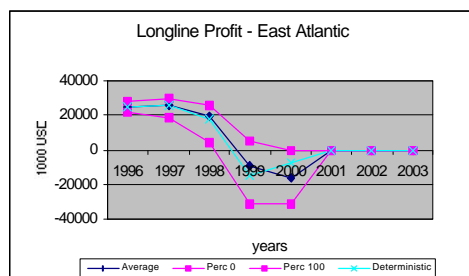
Figure 1b: Longline Profit evolution
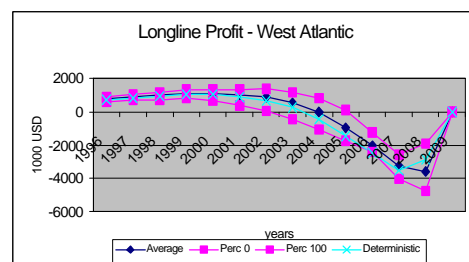
Figure 2b: Longline Profit evolution
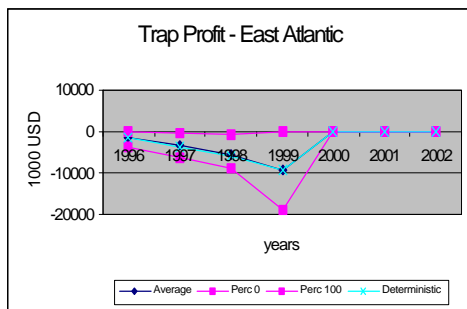
Figure 1c: Trap Profit evolution

Figure 1: Results for the East Atlantic
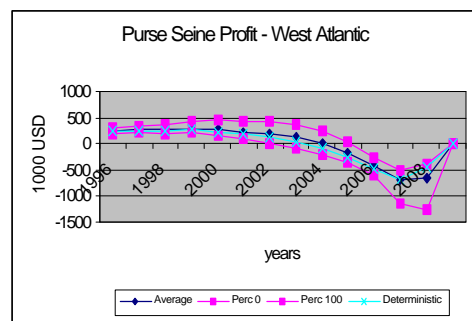
Figure 2c: Purse Seine Profit evolution

Figure 2: Results for the West Atlantic

The situations depicted are not surprising and do not differ significantly from the results obtained in the deterministic model. As expected, the average stochastic stock is above the deterministic stock, given the way the error term was introduced and whose mean is greater than one. Nevertheless, the impact of this uncertainty is not significant on average. As can be seen from the figures above, the deterministic and stochastic trends are very close. This may be explained by the fact that the stock decreases very fast and the error has a smaller effect on small numbers.

Additionally to the average variables, two percentiles were calculated: the percentiles zero and 100, which represent the values below which are zero and one hundred percent of the sample values, respectively. These percentiles give some insight about the variability introduced on each relevant variable. It is important to examine and take into account the limit scenarios that may occur, in order to manage efficiently the resource.

Examining the results, it is clear that some variability exists. Despite the low variability in the biomass, note for instance, the case of the longline and trap profits in the East Atlantic that, in certain situations, may attain very negative levels whereas in others it can remain positive throughout the period before the extinction of the species. In the former situation, the fishing gears experience such huge losses that the expected total net present value is negative, resulting from a smaller Bluefin tuna biomass and consequently lower catches. In the latter scenario, certain fishing gears, the ones shown in the figures above, may not experience any loss while harvesting this species. This is the result of a higher biomass and higher catches. Note however that there is no effect on the moment of total depletion of the stock. This is explained

in the following way: in the scenario of greater losses, the biomass is smaller due to low levels of recruitment. Therefore the catches are smaller and the losses are higher. In this case, in the following year, the effort decreases and catches are even lower, and so on. This leads the stock to be less harvested being depleted at the same moment as in the deterministic context. The opposite reasoning can be applied for the scenario of no losses. Both the above results implied by the uncertainty were not possible to attain in the deterministic context.

3.2 Optimal Use

As in the deterministic model, the two alternative policies to be enforced are the constant total allowable catches and the constant effort. In the former, a constant catch is determined and in the latter, the effort in 1996 is a percentage of that in 1995.

It is clear that the constant effort is more flexible for the fishing gears, allowing for higher net present values than the former. Nevertheless, when the stocks are very low due to severe depletion, a stricter policy such as the constant total allowable catch may be advisable in order to allow for a better recovery of the stock, as we will see later.

The study focused on two different cases. In the first, it is assumed that all fishing gears will either be subjected to a total allowable catch whose distribution among gears is based on the shares observed in 1995, or will change equally the fishing effort. This scenario will be denoted restricted optimization hereon. In the second, in both the constant allowable catch and the effort change, the gear structure is unrestricted. This will be denoted by unrestricted optimization. The former scenario is examined because, given the existing fishing gears, it seems reasonable to adopt a specific policy that maintains the existing structure of fishing gears and regulates them as a whole. It may be difficult and unpopular to implement a policy that shuts down a specific gear, as it will happen in the second scenario.

Again, it is interesting to start by examining the average stochastic recruitment.
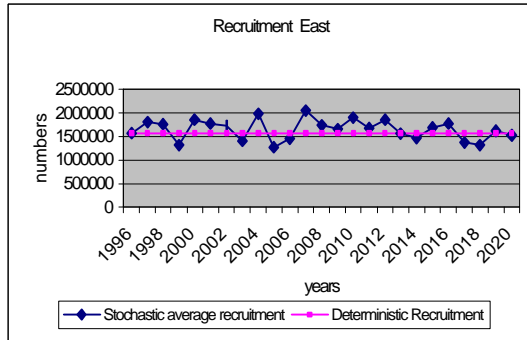
Figure 1
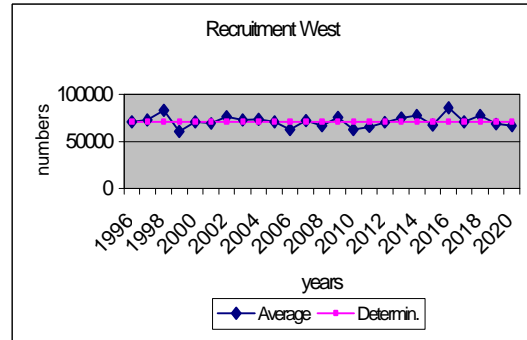
Figure 2

Note that in both the constant TAC and constant effort scenarios, the spawning stock biomass is always above the spawning stock minimum, thus, the recruitment is always at its maximum. The stock evolution is not different from the deterministic one.

The optimal management results are displayed in Tables 3 and 4, beginning with the restricted optimization.

Table 3: Results from the restricted optimization

	East Atlantic		West Atlantic	
	Best policy	ETNPV(10^6)	Best policy	ETNPV(10^6)
Stochastic TAC (MT)	*26 178*	*1 021.0*	*1 987*	*62.071*
Deterministic TAC (MT)	25 706	985.5	1 980	61.389
Stochastic Constant Effort	*0.53*	*1 476.4*	*0.76*	*68.432*
Deterministic Constant effort	0.50	1 291.7	0.76	67.271

It is interesting to analyze some of the previous results. Focusing on the expected total net present value (ETNPV), it is interesting to observe the difference in value resulting from the implementation of both a TAC and a constant effort. The explanation may be associated with the more flexibility of the effort instrument, as said earlier. As the Bluefin tuna biomass is larger on average, the economic agents may optimally adjust the recommended effort to the harvest. Therefore, the effort is to be regulated, both in the East and the West Atlantic.

The second situation examined is the unrestricted optimization whose results are given in table 4 below.

Table 4: Results from the unrestricted optimization

	East Atlantic		West Atlantic	
	[LL,PS,TRAP,BB,Rem]	ETNPV(10^6)	[LL,PS,TRAP,BB,Rem]	ETNPV(10^6)
Stochastic TAC (MT)	*[13 784,0,10 000,0,5 000]*	*2 424*	*[0, 1 844, 0, 500]*	*93.980*
Deterministic TAC (MT)	[13 834,0,10 000,0,5 000]	2 372	[0, 1 897, 0, 500]	93.3
Stochastic Constant Effort	*[1.78, 0,1.5,0,0.34]*	*2 800*	*[0, 7.8, 0, 1]*	*94.672*
Deterministic Constant effort	[1.63, 0, 1.5, 0, 0.34]	2 762	[0, 7.4, 0, 1]	94.4

The results of the stochastic unrestricted optimization do not differ substantially from the results of the deterministic model, for this sample of errors. Therefore, the fishing effort should be regulated, both in the East and the West Atlantic.

Thus, the optimal management of Northern Atlantic Bluefin tuna can be settled upon a deterministic bio-economic model without any prejudice of obtaining inaccurate economic results, given the parameters considered in the biological model. In fact, owing to this similarity of the results of the two models, the deterministic model should be used as the stochastic one adds a great complexity to the Matlab program.

4 Results after uncertainty is resolved

In the previous section, the expected total net present value was optimized given the overall sample of errors. Nevertheless, only one realization of the random error will occur and it is interesting to examine whether the optimal policy decided both in the deterministic context and on the earlier section remains effective for the realizations of all the vectors of errors, given the sample studied. Note that we leave the stochastic context and start working on a sort of deterministic context, given that uncertainty is resolved and a specific error vector is observed. Additionally, this will allow for a better knowledge of the eventual impacts of the different error vectors.

From the results obtained, it can be said that, in the East Atlantic, the constant effort is the optimal policy to be applied either in the stochastic optimization or after the uncertainty is resolved, independently of the realization of the random variable.

Nevertheless, in the West Atlantic the results are not that straight forward. The previous section discussed that a constant fishing effort policy should be implemented instead of a constant TAC. Nonetheless, if the optimization is undertaken for the realization of each vector of error, it can be concluded that, for certain realizations, the optimal policy becomes the constant TAC and not the constant fishing effort. This result occurs whenever the uncertainty leads to lower biomass levels. Comparing the results obtained maximizing the total net present value with respect to both instruments in these specific cases, if the TAC is implemented, the results reveal an initial fishing effort which is higher than that obtained from the implementation of a constant fishing effort but becomes lower in the year 2020. The same reasoning is applied to the catches. Concerning the profits, these follow the same trend as the previous variables. Given this, the total net present value is higher when a TAC is applied. This result is clear. For low levels of the Bluefin tuna stock, it is necessary to implement a more strict policy that control the harvesting rates allowing the stock to recover. In this cases, regulate the fishing effort would not allow for a strict control over the catches and could lead to an excessive catch, endangering the species.

Thus, if the manager chooses to regulate the fishing effort, this decision may turn out to be sub-optimal, depending on the realization of the random variable. The manager should be aware of this possibility.

This analysis is important in that it gives some insight of the possible scenarios that may occur and about what is the best policy and instrument to use for each realization of the error term.

5. Conclusions

The Northern Atlantic Bluefin tuna is a species that urges to be regulated in order to prevent its stock from being totally depleted. Owing to its highly migratory nature, both national and international cooperation is necessary to enforce optimal regulations. Furthermore, it is characterized by a stochastic recruitment that is taken into account in the analysis.

Focusing on the bionomic equilibrium, the results show that the open access quickly becomes unprofitable and is seen to involve substantial depletion of the stock, both in the East and the West Atlantic. Additionally, the introduction of uncertainty in

the recruitment function does not affect the average results, which are similar to those found in the deterministic model.

Concerning the optimal management results, the conclusions are identical. The similarity between the stochastic and the deterministic results may be explained by the low variance suggested for Bluefin tuna.

Nonetheless, for the purpose of this species and this study, it can be concluded that the optimal policy to be implemented should be decided based on the deterministic model in order to avoid extra and unnecessary complexities to the Matlab model.

In spite of this result similarity, the shocks on the recruitment should be taken into account, to give the manager some insight about the possible scenarios that may occur after uncertainty is resolved. In particular, it is interesting to note that for low levels of recruitment leading to low levels of the biomass, it is optimal to restrict the Bluefin tuna catches so as to allow for the stock recovery. Therefore, in these cases, restrict the fishing effort turns out to be a sub-optimal economic policy.

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Appendix A

The Model Equations

Biological sub-model

Population numbers

(1) $N_{j,0,a} = \tilde{N}_{j,a}$ for $1 \le a \le A$

(2) $N_{j,t,0} = SRR_j \left(SSB_{j,t-2} \right)$

(3) $N_{j,t,a} = N_{j,t-1,a-1} e^{-M_{j,a-1} - F_{j,t-1,a-1}}$ for $a = 1,2,...,9;\ t=1,2,...$

(4) $N_{j,t,A} = N_{j,t-1,9} e^{-M_{j,9} - F_{j,t-1,9}} + N_{j,t-1,A} e^{-M_{j,A} - F_{j,t-1,A}}$

(5) $SSB_{j,t} = \sum\limits_{a=1}^{A} Mat_{j,t,a} N_{j,t,a} W_{j,t,a}$

(6) $B_{j,t} = \sum\limits_{a=1}^{A} N_{j,t,a} W_{j,t,a}$

Catch at age by gear

(7) $F_{j,t,a,s} = FMax_{j,t,s} . Sel_{j,a,s}$

(8) $F_{j,t,a} = \sum\limits_{s=1}^{S} FMax_{j,t,s} . Sel_{j,a,s}$

(9) $CN_{j,t,a,s} = \dfrac{F_{j,t,a,s} . N_{j,t,a}}{\sum\limits_{s=1}^{S} \left(F_{j,t,a,s} + M_{j,a} \right)} \left(1 - e^{-\sum\limits_{s=1}^{S} \left(F_{j,t,a,s} + M_{j,a} \right)} \right)$

(10) $CB_{j,t,s} = \sum\limits_{a=1}^{A} CN_{j,t,a,s} . W_{j,a}$

(11) $C_{j,t,s} = \sum\limits_{a=1}^{A} \dfrac{FMax_{j,t,s} . Sel_{j,a,s} . N_{j,t,a} . W_{j,t,a}}{\sum\limits_{s=1}^{S} \left(FMax_{j,t,s} . Sel_{j,a,s} + M_{j,a} \right)} \left(1 - e^{-\sum\limits_{i=1}^{S} \left(FMax_{j,t,s} . Sel_{j,a,si} + M_{j,a} \right)} \right)$

for $s = 1,...,S$

Harvest function

(12) $C_{j,t,s} = q_{j,s}\,E_{j,t,s}\,B_{j,t}^{a_s}$

(13) $C_{j,0,s} = sh_{j,0,s} * C_{j,0,s}$

(14) $E_{j,0,s} = sh_{j,0,s} * E_{j,0,s}$

Economic sub‑model

(15) $Re\,v_{j,t,s} = \overline{P}_{j,s} * C_{j,t,s}$

(16) $Cost_{j,t,s} = wg_{j,s} * E_{j,t,s} + \boldsymbol{g}_{j,s}\left(\overline{P}_{j,s} * C_{j,t,s}\right)$

(17) $\boldsymbol{P}_{j,t,s} = Re\,v_{j,t,s} - Cost_{j,t,s}$

(18) $TNPV_j = \displaystyle\sum_{s=1}^{S}\sum_{t=1}^{25} \boldsymbol{P}_{j,t,s} * \left(\dfrac{1}{1+r}\right)^{t}$

Open Access Dynamics

$(19)\; E_{j,t,s} = \begin{cases} (1 - \boldsymbol{b}_{j,s})E_{j,t-1,s} & if \quad \boldsymbol{P}_{,j,t\text{-}1,s} \leq \text{-}Pb_{j,s} \\ E_{j,s,t-1} & if \;\; \text{-}Pb_{j,s} \leq \boldsymbol{P}_{,j,t\text{-}1,s} \leq Pb_{j,s} \\ (1 + \boldsymbol{b}_{j,s})E_{j,s,t-1} & if \quad \boldsymbol{P}_{p,j,t\text{-}1,s} \geq Pb_{j,s} \end{cases}$

Exit condition

(20) $Cost_{j,t-1,s} > \left(1 + h_{j,s}\right) * Re\,v_{j,t-1,s}$

Table A1: Glossary 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
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	∏b	Profit bound
E	Effort	h	Exit condition parameter
C	Catch		
Rev	Revenue		
Cost	Cost		
$\overline{P}$	Average Price	**Indices**	
Π	Profit	j	Stock (j=East Atl., West Atl.)
TNPV	Total Net Present Value	t	Time (t=1,…,T), T=25 (2020)
		a	Age (a=1,…,A), A=10+
		s	Gear (s=1,2,…,S)

Table A2: Economic Parameters of the Model

Gears	East Atlantic				West Atlantic			
	Prices (USD/Kg)	β	wg	Unit of effort	Prices (USD/Kg)	β	wg	Unit of effort
Longline	17	0.25	14,102	Fishing days	17	0.1	15,265	Fishing days
Purse Seine	9	0.1	45,185*	Fishing days	18	0.1	20,092	Days at sea
Trap	25	0.2	15,738	Trap days	_	_	_	_
Bait Boat	5	0.2	4,638	Days at sea	_	_	_	_
Rod & Reel	_	_	_		18	0.1	163	Fishing hours
Remainder	17	0.01	2,408	Days at sea	20	0.1	22,417	Fishing days

*Note that for the PS, in the East Atlantic, one fishing day correspond to more than three days at sea.

Table A3- Shares of Catches by Gear - in the Base Year (1995)

	East Atlantic			*West Atlantic*		
Gears	EU	OCS	DWFN	USA	CAN	DWFN
Longline	0.22	0.19	0.59	0.16	0.01	0.83
Purse Seine	0.78	0.22	0	1.00	0	0
Trap	0.57	0.43	0	-	-	-
Bait Boat	1	0	0	-	-	-
Rod & Reel	-	-	-	0.81	0.19	0
Remainder	0.74	0.26	0	0.28	0.72	0

Appendix B

B1. East Atlantic

Table B1.1: Biomass evolution (in MT)

	1996	1997	1998	1999	2000	2001	2002
Average	141815	125974	100154	59027	6900	0	0
Deterministic	141180	124430	97040	54950	1310	0	0
Percentile 0	128570	106730	75600	29570	0	0	0
Percentile 100	151310	135210	112580	74820	19560	0	0

Table B1.2: Catch evolution by gear (in MT)

	1996	1997	1998	1999	2000	2001	2002
LONGLINE							
Average	15888	19393	23144	24549	3047	0	0
Deterministic	15875	19349	23013	25673	541	0	0
Percentile 0	15581	18764	21892	14189	0	0	0
Percentile 100	16097	19673	23707	27309	8525	0	0
PURSE SEINE							
Average	19248	20674	21712	20795	2923	0	0
Deterministic	19232	20628	21590	21196	593	0	0
Percentile 0	18876	20004	20538	12435	0	0	0
Percentile 100	19501	20974	22241	22546	8413	0	0

TRAP							
Average	1780	1349	899	524	0	0	0
Deterministic	1773	1282	841	427	0	0	0
Percentile 0	1646	1134	689	0	0	0	0
Percentile 100	1875	2056	1420	820	0	0	0
BAITBOAT							
Average	3890	4558	5222	4824	930	0	0
Deterministic	3887	4548	5193	3708	176	0	0
Percentile 0	3815	4410	4940	2945	0	0	0
Percentile 100	3941	4624	5349	6438	2619	0	0
REMAINDER							
Average	4169	3757	3094	2273	0	0	0
Deterministic	4154	3717	3016	1895	0	0	0
Percentile 0	3855	3288	2470	0	0	0	0
Percentile 100	4391	4053	3466	3592	0	0	0

Table B1.3: Effort evolution by gear

	1996	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**
LONGLINE							
Average	11618	14522	18152	21363	3729	0	0
Deterministic	11618	14522	18152	22690	1009	0	0
Percentile 0	11618	14522	18152	14195	0	0	0
Percentile 100	11618	14522	18152	22690	9263	0	0
PURSE SEINE							
Average	2325	2558	2814	2994	592	0	0
Deterministic	2325	2558	2814	3095	183	0	0
Percentile 0	2325	2558	2814	2055	0	0	0
Percentile 100	2325	2558	2814	3095	1511	0	0
TRAP							
Average	2066	1719	1375	1232	0	0	0
Deterministic	2066	1653	1322	1058	0	0	0
Percentile 0	2066	1653	1322	0	0	0	0
Percentile 100	2066	2479	1983	2086	0	0	0
BAITBOAT							
Average	2729	3275	3930	4031	1092	0	0
Deterministic	2729	3275	3930	3144	315	0	0
Percentile 0	2729	3275	3930	2826	0	0	0
Percentile 100	2729	3275	3930	5597	2730	0	0
REMAINDER							
Average	21510	21312	21099	24009	0	0	0
Deterministic	21510	21295	21082	20871	0	0	0
Percentile 0	21510	21295	21082	0	0	0	0
Percentile 100	21510	21725	21508	43097	0	0	0

Table B1.4: Profit evolution by gear

	1996	1997	1998	1999	2000	2001	2002
LONGLINE							
Average	25242	25990	19432	-9114	-16330	0	0
Deterministic	25089	25471	17877	-14459	-7795	0	0
Percentile 0	21589	18512	4539	-31322	-31158	0	0
Percentile 100	27726	29330	26135	5002	0	0	0
PURSE SEINE							
Average	16189	14669	9651	-4265	-8344	0	0
Deterministic	16091	14376	8879	-6320	-4523	0	0
Percentile 0	13846	10448	2255	-14532	-16738	0	0
Percentile 100	17783	16554	12981	2186	0	0	0
TRAP							
Average	-1324	-3184	-5433	-9162	0	0	0
Deterministic	-1481	-3571	-6095	-9179	0	0	0
Percentile 0	-3718	-6164	-8759	-18857	0	0	0
Percentile 100	29	-304	-636	0	0	0	0
BAITBOAT							
Average	835	617	-126	-1997	-18596	0	0
Deterministic	824	581	-229	-1747	-858	0	0
Percentile 0	572	100	-1114	-3680	-36208	0	0
Percentile 100	1014	848	319	-1327	0	0	0
REMAINDER							
Average	-2186	-6613	-13981	-30766	0	0	0
Deterministic	-2360	-7039	-14868	-27709	0	0	0
Percentile 0	-5923	-12149	-21366	-63960	0	0	0
Percentile 100	459	-4079	-10547	0	0	0	0

B2 . West Atlantic

Table B2.1: Biomass evolution (in MT)

	1996	1997	1998	1999	2000	2001	2002	2003
Average	19383	19810	19924	20382	19458	18147	16978	15126
Deterministic	19210	19593	19600	19905	18873	17364	15952	13943
Perc 0	17893	18145	17902	18044	16585	14806	13144	11085
Perc 100	20900	21291	21433	22108	21196	20163	19547	17924

2004	2005	2006	2007	2008	2009
12746	9813	6642	3751	1219	0
11351	8222	5367	2914	697	0
8753	6675	4369	2480	382	0
15918	13148	9419	5194	1920	0

Table B2.2: Catch evolution by gear (in MT)

	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
LONGLINE														
Average	807	891	982	1085	1182	1282	1391	1490	1545	1468	1235	991	509	0
Deterministic	805	890	979	1080	1175	1271	1375	1472	1554	1311	1084	863	301	0
Perc 0	794	876	961	1059	1145	1231	1323	1278	1097	937	786	646	159	0
Perc 100	819	904	996	1103	1203	1310	1432	1548	1663	1761	1647	1316	868	0
PURSE SEINE														
Average	251	253	256	262	268	272	276	279	273	259	238	193	87	0
Deterministic	250	251	251	252	250	245	241	235	225	211	194	155	44	0
Perc 0	247	248	247	247	243	238	232	224	214	203	168	135	30	0
Perc 100	255	281	310	342	374	406	443	479	511	486	449	356	177	0
ROD & REEL														
Average	1151	1272	1401	1548	1687	1830	1985	2133	2236	2138	1798	1443	622	0
Deterministic	1150	1270	1397	1541	1677	1814	1962	2101	2218	1872	1547	1232	352	0
Perc 0	1133	1250	1371	1511	1634	1757	1888	2007	1723	1469	1214	976	193	0
Perc 100	1169	1291	1422	1574	1716	1869	2043	2209	2373	2513	2586	2066	916	0
REMAINDER														
Average	277	302	330	367	387	398	397	365	305	223	118	6	0	0
Deterministic	275	308	338	377	397	409	382	343	262	182	0	0	0	0
Perc 0	260	263	260	262	245	224	183	144	107	78	0	0	0	0
Perc 100	294	329	364	410	436	461	495	508	462	357	246	137	0	0

Table B2.3: Effort evolution by gear

	1996	1997	1998	1999	2000	2001	2002	2003
LONGLINE								
Average	580	638	701	772	849	934	1027	1126
Deterministic	580	638	701	772	849	934	1027	1130
Perc 0	580	638	701	772	849	934	1027	1027
Perc 100	580	638	701	772	849	934	1027	1130
PURSE SEINE								
Average	145	146	147	150	155	159	164	169
Deterministic	145	145	145	145	145	145	145	145
Perc 0	145	145	145	145	145	145	145	145
Perc 100	145	160	176	193	212	234	257	283
ROD & REEL								
Average	81870	90060	99060	108970	119870	131860	145040	159550
Deterministic	81870	90060	99060	108970	119870	131860	145040	159550
Perc 0	81870	90060	99060	108970	119870	131860	145040	159550
Perc 100	81870	90060	99060	108970	119870	131860	145040	159550
REMAINDER								
Average	156	166	181	197	216	234	245	246
Deterministic	156	172	189	208	228	251	251	251
Perc 0	156	156	156	156	156	156	140	126
Perc 100	156	172	189	208	228	251	276	304

2004	2005	2006	2007	2008	2009
1207	1206	1096	987	631	0
1243	1118	1007	906	421	0
924	832	749	674	251	0
1243	1367	1367	1230	991	0
171	171	170	155	87	0
145	145	145	131	50	0
145	145	131	118	38	0
311	311	311	280	173	0
172947	173904	158054	142253	76295	0
175500	157950	142150	127940	48660	0
143590	129230	116310	104680	30080	0
175500	193050	212350	191120	103450	10
233	210	141	9	0	0
226	204	0	0	0	0
114	102	0	0	0	0
304	274	246	222	0	0

Table B2.4: Profit evolution by gear (in 1000 USD)

	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
LONGLINE														
Average	752	873	974	1129	1110	1004	878	545	-42	-940	-2041	-3271	-3571	0
Deterministic	736	851	937	1070	1028	876	684	274	-475	-1467	-2469	-3556	-2840	0
Perc 0	601	690	728	821	671	402	63	-465	-1050	-1722	-2445	-4045	-4788	-1
Perc 100	899	1029	1147	1343	1356	1335	1363	1177	819	85	-1267	-2596	-1933	0
PURSE SEINE														
Average	248	263	270	290	269	230	192	119	3	-173	-414	-675	-652	0
Deterministic	242	255	255	265	231	179	127	46	-73	-250	-468	-674	-440	0
Perc 0	198	206	198	203	151	82	12	-86	-217	-359	-593	-1131	-1250	0
Perc 100	296	339	378	435	447	427	425	353	245	23	-275	-520	-386	0
ROD & REEL														
Average	1136	1320	1471	1706	1677	1517	1326	821	-80	-1463	-3158	-5054	-4623	0
Deterministic	1112	1286	1416	1617	1553	1324	1034	415	-717	-2217	-3731	-5374	-3512	0
Perc 0	908	1042	1100	1240	1014	607	94	-773	-1745	-2602	-3868	-6113	-5624	-1
Perc 100	1358	1554	1734	2029	2049	2018	2059	1778	1238	128	-2107	-4316	-2482	0
REMAINDER														
Average	384	487	555	701	566	305	37	-424	-996	-1610	-1584	-122	0	0
Deterministic	357	460	507	623	443	93	-283	-829	-1402	-2012	0	0	0	0
Perc 0	144	185	145	169	-71	-368	-633	-1110	-1615	-1967	-2908	-3045	0	0
Perc 100	626	756	859	1085	985	820	728	290	-353	-1082	0	0	0	0

B3. Sample of errors

Table B3.1: Error Sample - East Atlantic

1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
0,11	0,0787	0,0072	-0,3375	-0,3184	-0,1259	-0,3986	-0,3549	0,495	0,0187
-0,0267	0,516	-0,2039	-0,4529	0,1578	-0,3037	0,0121	-0,2109	0,18	0,1859
0,0278	0,2576	0,7519	0,1099	0,2902	0,2284	0,1865	0,3367	0,4233	0,0148
-0,1101	-0,3894	0,195	0,0806	-0,118	0,2999	0,5306	-0,3725	-0,0087	-0,3733
0,0393	-0,1987	-0,2201	-0,3633	-0,016	0,1275	-0,1111	-0,168	-0,0121	-0,0587
0,442	0,2237	-0,0925	-0,0077	-0,3052	-0,3508	0,1256	0,3031	0,4298	-0,0432
-0,5523	-0,3553	-0,0846	-0,4365	0,4146	0,5024	0,0793	-0,4721	0,2215	-0,8594
-0,1766	0,2413	0,3659	0,1683	0,9318	-0,0539	0,1444	-0,6612	-0,1835	-0,6348
-0,1079	0,4157	-0,2122	-0,7816	-0,414	0,3549	-0,0381	0,1275	0,3174	-0,7128

2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
-0,4092	-0,0139	-0,3793	-0,4536	-0,0878	0,3205	0,0432	0,2207	-0,3926	-0,1548
-0,0685	-0,6906	0,0446	0,5355	0,3423	-0,5313	-0,0264	-0,2291	-0,3444	-0,4149
-0,1056	0,0762	0,335	0,4087	-0,1824	0,3066	-0,0579	-0,1129	0,182	0,3133
0,2524	0,1681	-0,1739	-0,188	-0,2532	0,3112	-0,0835	-0,0504	-0,423	0,1051
-0,3218	0,4345	0,1482	0,4306	-0,1673	-0,3761	0,2715	0,0138	-0,2542	-0,03
0,206	0,6577	0,7618	-0,1257	0,7523	-0,0536	-0,2364	0,1894	-0,0169	0,3911
-0,1798	1	0,1476	-0,3865	0,2981	-0,0953	0,348	-0,1227	0,4511	0,3391
-0,0363	0	-0,2261	-0,3033	-0,052	0,3184	0,5212	0,1442	-0,1885	0,0603
-0,2167	-0,2368	-0,3423	-0,0612	0,5113	-0,0129	0,4126	-0,234	0,0025	-0,2632

2016	2017	2018	2019	2020
-0,0882	-0,4078	-0,4435	0,313	0,0038
0,0971	-0,1443	0,0188	-0,1237	-0,1563
-0,1917	-0,5038	-0,0169	0,1859	0,0281
0,9043	0,0974	-0,4783	0,083	-0,4826
-0,6753	0,3644	-0,3298	-0,2314	0,4503
0,2215	-0,5211	-1	0,1817	-0,3392
0,0719	-0,1006	0	-0,0641	-0,0266
-0,2593	-0,3171	0	-0,6408	-0,0219
0,1973	-0,0844	0,1614	0,2246	-0,0263

Table B3.2: Error Sample - West Atlantic

1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
-0,1694	-0,4175	0,3358	-0,2229	-0,0035	-0,0003	-0,0781	0,1241	-0,0826	-0,5209
0,1565	0,4001	-0,1715	0,0816	-0,0041	-0,1817	0,6688	-0,0806	-0,4413	0,5541
-0,0861	0,6926	0,4722	-0,6089	-0,5261	-0,1795	-0,0582	0,0028	0,262	-0,2261
0,0366	-0,185	-0,205	-0,3383	-0,0149	0,1188	-0,1034	-0,1565	-0,0113	-0,0547
-0,1292	-0,1585	0,5071	0,0253	-0,3384	-0,352	0,5434	0,6065	0,5119	-0,3932
0,4198	0,1215	0,123	-0,5345	0,0713	0,2146	-0,1993	-0,3139	-0,0581	-0,33
-0,6002	0,1471	0,3989	0,1999	0,4323	0,4132	-0,2847	-0,7218	0,56	0,1223
0,204	-0,1181	-0,2071	0,0779	-0,1201	-0,1654	0,0173	0,3925	-0,7889	0,1831
-0,1035	0,2489	-0,2457	-0,3954	0,2087	-0,436	-0,4071	-0,1894	-0,466	0,1749

2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
-0,3221	0,0761	-0,3934	-0,1087	-0,2947	-0,3677	-0,3197	-0,1257	0,0544	-0,0364
0,1019	-0,3503	0,1942	0,3975	-0,2805	0,0423	-0,0435	-0,3642	0,3706	-0,0048
-0,2259	-0,063	-0,0064	0,0873	0,3313	0,1946	-0,548	0,2183	0,254	0,1992
-0,2997	0,4046	0,138	0,401	-0,1558	-0,3502	0,2528	0,0129	-0,2367	-0,0279
-0,0668	-0,0623	0,0963	-0,1792	-0,3061	-0,1399	0,3387	0,7428	0,0718	-0,0835
-0,0224	0,0874	0,4299	0,0563	-0,1697	0,5116	0,2583	0,0722	0,2103	-0,1591
0,0064	-0,1271	-0,4805	0,0693	-0,4303	-0,2627	-0,0653	0,2366	0,1176	-0,4212
-0,3156	0,2956	-0,7588	-0,0701	0,0182	-0,1329	-0,0635	-0,4737	-0,3526	-0,2551
-0,0868	-0,405	-0,2781	-0,3088	-0,0224	-0,7559	-0,2174	-0,4356	0,1032	0,1874

2016	2017	2018	2019	2020	2021
0,3331	-0,0768	-0,4751	0,003	0,0223	0,0991
0,1679	-0,2243	-0,2052	0,0984	0,0334	0,5786
0,4101	0,1024	-0,2107	-0,0467	-0,7667	0,1482
-0,6289	0,3393	-0,3072	-0,2155	0,4193	-0,2846
0,2197	-0,1526	0,583	0,3465	-0,3843	-0,2097
0,2681	0,0841	0,1956	-0,3279	0,4807	0,136
0,4639	0,0102	0,5855	-0,3785	-0,245	-0,2402
0,1148	-0,1835	0,4813	0,0438	-0,5831	-0,1422
0,0461	-0,0318	-0,8249	0,0088	-0,2743	0,0831