The Evaluation of Fisheries Management: A Dynamic Stochastic Approach†

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Abstract

Most existing studies evaluating the management of fisheries fail to reproduce the observed dynamics of the resource. We present an alternative approach: assuming that the stock growth path is affected by productivity shocks that follow a Markov process, we calibrate the growth path of the resource such that the observed dynamics of resource are matched. In this context, an efficient policy consists of applying a different exploitation rule depending on the state of the resource and the constant-escapement rule is not the efficient policy.

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1 Introduction

Efficiency in managing the exploitation of fishery resources has been widely analyzed in resource literature.[1] In general terms, these studies only focus on show how far is the optimal steady state values of biomass and catches from the observed path, and the goodness of the bioeconomic model used to reproduce the observed dynamics of the resource and catches is never checked. However, we think that good reproduction of the observed data is a minimum condition that any fishery assessment study must satisfy. In particular, we believe that the better the model reproduces the observed evolution of the biomass the more reliable the assessment of the exploitation is.

In this paper we present an alternative approach that allows us reproduce better the stylized facts of the fishing ground. This is a stochastic approach in which we assume that the stock growth path is affected by stochastic productivity shocks that follow a Markov process.[2] We calibrate the growth path of the resource to match the observed dynamics of the resource and captures. This approach is very well known and developed in other economic areas, but it is harddly used in natural resources economics.[3] As far as we know only Singh, Weninger and Doyle (2006) uses a similar stochastic technique to analyze numerically the importance of costly capital adjustment in fishery models with random stock growth.

With this kind of approach, we do not limit our work to comparing the observed paths of captures and biomass with the stationary values from a deterministic model. Our analysis goes further into the calculations of the optimal exploitation rules associated with both the size and the productivity of the biomass. Summarizing, with productivity shocks affecting the growth of the biomass, an efficient policy consists of applying a different exploitation rule depending on the state of the resource, and we could say that the stock is always in transition, jumping from one steady state to another.

This stochastic approach is applied to the European Southern Stock of Hake (ESSH). We study this fishing grounds for three reasons. First, it is considered as individual admin-

[1]Among others, Garza-Gil *et al.* (2003), Del Valle *et al.* (2001), Grafton *et al.* (2000), Garza-Gil (1998), Flaaten and Stollery (1996), Amundsen *et al.* (1995)).

[2]Productivity shocks can reflect that the biomass may be affected by biological cycles (Larrañeta and Vazquez (1982)) or any other ecological uncertainty element.

[3]Kydland and Prescott (1982) can be considered as the pioneer article in aplying the calibration technique to evaluate macroeconomic models in quantitative manner.

istrative units by the International Council for the Exploitation of the Sea (ICES), which advises the European Commission on their management. Second, it has been analyzed previously by Garza-Gil (1998) with the traditional approach. This previous research allow us to focus on the calibration of the growth resource because it shows information about capturability functions, prices of captures and costs of effort. Third, biomass evolution shows a monotonic (dramatically) descending trend and the ICES recommends a recovery plan to ensure safe and rapid rebuilding.

Our results show that in aggregate terms, catches have been even lower than would correspond to efficient exploitation. However, the timing of captures has not been appropriate and the exploitation has not been able to protect the resource. This inefficiency has meant a reduction of potential profits by 35% in the fishery. Moreover the ESSH is in a dangerous situation; in particular, our results show that an efficient exploitation policy would bring the stock up to ICES recommended levels. We also illustrate how captures should be shared between the two existing fleets once the fishing ground is recovered. Our results indicate that efficient exploitation will require a larger proportion of the total captures to go to the artisanal fleet than is currently the case.

Other authors have introduced uncertainty into the dynamics of the resource. Androkovich and Stollery (1989) simulate a stochastic dynamic program to quantify the relative merits of different policies for regulating the Pacific halibut fishery. More recently, Danielsson (2002) and Weitzman (2002) analyze the relative performance of different methods of fisheries management when there are some risks involved. Both include “ecological” or “environmental” uncertainty in the biological dynamics of the fish stock. Sethi, Costello, Fisher, Hanemann and Karp (2005) develop a theoretical model that incorporates uncertainty about, among others, variability in fish dynamics assuming Markovian transitions. Our work is on the same line as these studies; in particular we assume that the current state of productivity may depend on past productivity.

The paper proceeds as follows. In the next section the traditional approach to the evaluation of fisheries management is presented. In particular, we show with an example how poorly this approach may reproduce the observed dynamics of the biomass. In Section 3 an alternative stochastic approach is proposed. First a multifleet fishery model with stochastic biomass dynamics is developed, and secondly, a method for calibrating the growth path of the resource is proposed. The model is adapted to characterize the ESSH fishery in Section 4. Subsection 4.1 presents the calibration of the fishing ground and in Subsection 4.2 assess fishery management and reports what would have happened if side-payments between fleets had been allowed. Section 6 concludes the paper with a policy recommendation discussion.

2 The Traditional Approach

The literature of fishery efficiency assessment has traditionally followed a deterministic steady state approach that considers that an efficient policy consists of maintaining the exploitation levels of the fishing ground at steady state values. In this section we show the effects that this approach may have on the expected evolution of the resource.

Let us consider that the stock of the fishing ground we want to evaluate, X_t, is characterized by the following dynamics

$$X_{t+1} = F(X_t) - Y_t, \tag{1}$$

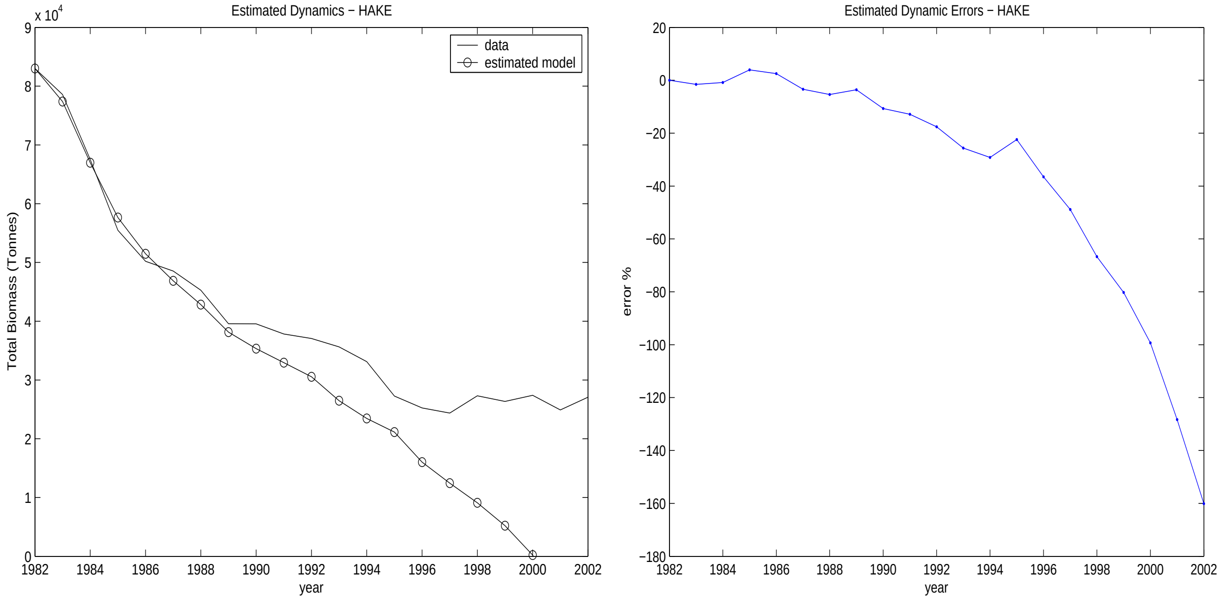
where Y_t is total catches and F is the gross growth of the biomass, which depends upon the stock of resource, X_t.

The traditional approach consists of the following steps: *i)* The dynamics of the resource are estimated using data on stock and captures, *ii)* An appropriate parametric form for the gross growth of the stock, F, is selected based on this estimation, *iii)* The complete theoretical problem is solved[4], and *iv)* Parameters estimated in steps *i)* and *ii)* are used to evaluate the fishery according to the solution of the theoretical model. The problem of this procedure is that the estimated dynamics of the resource (step *i)*) are never checked against the data used to estimate them. That means that we may be using an estimation for evaluation which may be inappropriate. We show an example of this effect.

Let us consider the ESSH for the period 1982-2002[5]. Our estimation results point to the Ricker as being the functional form that best fits the data of this fishery.[6] The traditional approach would use the estimation of the parameters of this functional form to evaluate the

[4]Other functional forms such as capturability and profit functions are usually involved in the theoretical problem.
[5]Data used are shown in Table 4 in Appendix A.
[6]We show how this selection is made in section 4.1.

Figure 1: Estimated Dynamics. ESSH



efficiency of the fishing ground without checking the goodness of the estimated parameters in reproducing the observed dynamics of the resource. However, this is very simple to do. Thus given X_0, the dynamics of the resource imply a synthetic path of stocks, $\{\hat{X}_1, \hat{X}_2, \hat{X}_3, ...\}$, which can be calculated as follow. $\hat{X}_1 = \hat{F}(X_0) - Y_0$ where $\hat{F}$ is the estimated gross growth function. Then $\hat{X}_2 = \hat{F}(\hat{X}_1) - Y_1$ and so on.[7]

Figure 1 reproduces the resource evolution of the ESSH implied by the traditional approach using the above mentioned estimated gross growth function and taking the initial stock as given. We can observe that the traditional estimation reproduces the observed evolution of the stock very poorly. In particular from 1989 on the estimated stock is lower than the observed one and the distance between obseved data and data implied by the estimated dynamics increase with time (in absolute terms). Notice that the traditional estimation would imply the disappearance of the hake stock in 2000.

We claim that using an approach that reproduces better the evolution of the dynamic

[7]Observe that these are not the prediction of $X's$ implied by the estimation. These would be $\widetilde{X}_1 = \hat{F}(X_0) - Y_0$, $\widetilde{X}_2 = \hat{F}(X_1) - Y_1$,... Therefore the $\hat{X}_i - X_i$ are not the prediction errors of the estimation but the distance between the observed data and the synthetic data implied by the estimated dynamics.

resource leads to more reliable results in evaluating the efficiency of resource management.

3 A Stochastic Approach

In this section a new stochastic approach is presented to evaluate the efficiency of fishing resource management. Firstly, we present a multifleet bioeconomic model in which the resource is affected by stochastic productivity shocks. Secondly, since the model has to be simulated, we describe how to calibrate it, i.e. how to choose values for the parameters that reproduce the main stylized facts of the fishing ground.

3.1 The Model

Let us consider a fishing ground in which the dynamic of the stock, X_t, is given by

$$X_{t+1} = F(X_t, z_t) - Y_t, \tag{2}$$

where Y_t represents total catches and F is the gross growth of the biomass, which depends upon the stock of resource, X_t, and a productivity random shock, z_t. In particular we assume

$$F(X_t, z_t) = e^{z_t} f(X_t), \tag{3}$$

where z_t is a random variable with mean zero which follows a Markov process with a transition matrix, $\pi(z_t, z_{t+1})$. We assume that the realization of z_t is known at the beginning of the period t.

We consider that n heterogeneous fleets operate in the fishing ground. Catches of fleet i, $y_{i,t}(\xi_{i,t}, X_t)$, depend on its own effort, ξ_i and on the stock of fish. Therefore, total catches are a function of all individual efforts and of stock,

$$Y_t = \sum_{i=1}^{n} y_{i,t}(\xi_{i,t}, X_t). \tag{4}$$

Let us assume that the common fishery is managed by a benevolent regulator who maximizes the expected present discount value of the future profits of the fleets,

$$E_0 \sum_{t=0}^{\infty} \beta^t (\Pi_{1,t} + \Pi_{2,t} + ... + \Pi_{n,t}),$$

where E_t represents the expectation taken at time t and β is the discount factor. $\Pi_{i,t}$ represents the profit of fleet i in period t, defined as the difference between its revenues, $p_{i,t}y_{i,t}$, and the effort cost, $\omega_{i,t}\xi_{i,t}$. Moreover, the regulator may place constraints on total captures by fleets, i.e. $Y \in \{Y_{min}, Y_{max}\}$. Y_{max} can be understood as the maximum amount of fish that can physically be captured by the fleets at their current size. Y_{min} can be interpreted as the minimum amount of captures that the fleet must take in order to maintain minimum revenues for current fleets given their fishing capacity. Formally the benevolent regulator problem is given by the following Bellman's equation

$$V(X, z, Y_{min}, Y_{max}) = \max_{(X', \{\xi_i\}_{i=1}^n)} \sum_{i=1}^{n} \Pi_i(z, X, X', \xi_i) + \beta E_{z'} \left[V(X', z', Y_{min}, Y_{max})/z \right], \quad (5)$$

$$s.t. \begin{cases} \Pi_i = p_i y_i(\xi_i, X_t) - \omega_i \xi_i, \\ Y = \sum_{i=1}^n y_i(\xi_i, X), \\ X' = e^z f(X) - Y, \\ z \in [z_1, ..., z_m], \pi, \\ Y \in \{Y_{min}, Y_{max}\}, \end{cases}$$

where a prime on a variable indicates its value for the next period and the notation $E_{z'}$ means that the expectations is over the distribution of z'.

A solution of this problem is a value function $V(z, X, Y_{min}, Y_{max})$, policy functions $\{\xi_i(X, z, Y_{min}, Y_{max})\}_{i=1}^n$ and $g(X, z, Y_{min}, Y_{max})$ such that:

1. Given X, z, Y_{min} and Y_{max}, $V(z, X, Y_{min}, Y_{max})$ is the value function that solves the benevolent regulator problem, and $\{\xi_i(X, z, Y_{min}, Y_{max})\}_{i=1}^n$ are the maximizing effort choices.

2. Total catches $\sum_{i=1}^n y_i(\xi_i(X, z, Y_{min}, Y_{max}), X)$ are within the interval (Y_{min}, Y_{max})

3. Individual effort and stock target are compatible, i.e. $X' = g(X, z, Y_{min}, Y_{max}) = e^z f(X) - \sum_{i=1}^n y_i(\xi_i(X, z, Y_{min}, Y_{max}), X)$

In other words, given the current stock, X, the benevolent regulator chooses an optimal effort rule and a stock target for which the total catches in each period, $Y = \sum_{i=1}^n y_i(\xi_i, X)$, are within the allowed range of catches, $Y \in \{Y_{min}, Y_{max}\}$, and the stock target is sustainable, that is $X' = e^z f(X) - Y$.

3.2 Calibration Procedure

In order to simulate the model we need to calibrate it, i.e. to choose values for the parameters that reproduce the main stylized facts of the fishing ground analyzed. Since we have introduced stochastic productivity shocks into the gross growth function, we focus on illustrating how to choose the parameters in the dynamic resource equation, (2).[8]

The first step in calibration consists of selecting an appropriate parametric form for the gross growth function, $f(X_t)$. Suppose that a potential functional form depends on a parameter set $(k_1, ...k_r)$.[9] Then, if data on stock and captures are available, we can estimate those parameters from the dynamic resource equation, (2), which in logarithm terms can be expressed as

$$\ln(X_{t+1} + Y_t) = \ln f(X_t | k_1, ..., k_r) + z_t. \quad (6)$$

After examining the results of the estimations for different functional forms, we choose the most appropriate according to the usual econometric criteria.

Second, once the parameters have been estimated, the stochastic process, z_t, is calibrated in such a way that the sequence of productivity shocks reproduces the stock given total catches for the observed period. In order to do this, we have to choose m equidistant values for the state of the productivity shock, that is $(z_1, z_2, ...z_m)$. Given these values for the states of z, the transition matrix, π, for the Markov chain that discretes a continuum process in m states is calculated following the method proposed by Tauchen (1986).[10] The number of states of nature and the values that they take are chosen such that deviations of the observed path for the stock from the synthetic one implied by the model are minimal.

Once the model has been calibrated, the Bellman equation that represents the regulator problem, equation (5), is solved numerically. In Appendix B, we outline how this is done.

In the following sections we apply this procedure to calibrate the dynamic resource equation in the ESSH fishery where two different fleets operate (the trawler and the artisanal fleets).

[8] The parameters that appear in the capturability functions can be calibrated with traditional procedures.

[9] In practice, we can use the traditional functional forms for the growth function, i.e. logistic, Cushing, Ricker, Gompertz and others.

[10] Implementing Tauchen's method requieres the estimation of the first order autocorrelation coefficient from the estimated errors, $\hat{z}_t$.

4 The European Southern Stock of Hake (ESSH)

The ESSH is a fishing ground allocated around the Atlantic coast of the Iberian Peninsula (Divisions VIIIc and IXa).[11] Hake (*Merluccius merluccius*) is a late maturing fish. Males mature at 3-4 years old (27-35cm) and females at 5-7 years old (50-70 cm).

Two fleets fish on hake in the ESSH: the Spanish and Portuguese trawl and artisanal fleets. The trawler fleet is quite homogeneous and uses two kinds of gears: bottom trawl and pair trawl. This fleet has shown a general downward trend in effort over the last decade. The artisanal fleet is very heterogeneous and uses a wide variety of gears: traps, nets, longlines, etc. Hake is caught throughout the year, though sea conditions may produce some fluctuations. Most of the captures are used for human consumption.

Hake is managed by annual TAC with associated technical measures in the ESSH. The agreed TAC was 8,000 toness in 2002, 7,000 tonnes in 2003 and 5,950 tonnes in 2004. However catches in most years did not reach the TACs. In order to protect juveniles, fishing is prohibited in some areas during part of the year and the minimum landing size is 27cm.[12]

Biomass dropped from about 84,000 tonnes in the early 1980s to 27,000 tonnes in 2002 (see Table 4 in Appendix A). This reduction is reflected in captures, which dropped from 22,000 tonnes to 6,000 tonnes in the same period. The ICES Advisory Committee for Fisheries Management considers that the stock is outside safe biological limits and recommends a recovery plan to ensure safe and rapid rebuilding. Such a recovery plan must include a provision for zero catch for 2004 until strong evidence of rebuilding is observed (ICES Annual Report 2003). However, the Scientific Technical and Economic Committee on Fisheries (STECF) considers that more investigations are needed to define appropriate biological points, although it agrees with the ICES advice that a recovery plan should be applied (STECF Review of Scientific Advice for 2004, section 2.33).

[11]Hake is one of the most important species in European Atlantic waters. The ICES considers that for biological and management purposes the hake population must be divided into two different stocks: the Northern Stock (Ireland and Bay of Biscay) and the Southern Stock (Atlantic coast of the Iberian Peninsula).

[12]The minimum landing size was introduced into regulations in 1989. This has produced a structural break in the length distribution series: before 1989 half of the individuals were below 27 cm, but since 1989 the proportion of these individuals in the landing has decreased sharply.

For more details about biological and technical characteristics of this fishery see the report by the ICES Working Group on the Assessment of Southern Stock of Hake, Monk and Megrim (WGHMM). Garza-Gil (1998) uses this fishery to illustrate how individual transferable *quotas* may help to achieve efficient exploitation in a multifleet setting. Also this fishery is used to show how a tax on effort can yield socially optimum operating result (Garza-Gil *et al.* (2003)).[13]

4.1 Calibration

To evaluate the optimal exploitation policy for the ESSH, we calibrate the model assuming stochastic productivity shocks. First the parameters from the dynamics resource equation are calibrated following the procedure developed in Subsection 3.2.

An appropriate functional form for the gross growth of the biomass, $F = e^{z_t} f(X_t)$, is chosen from among different candidates analyzed. Table 1 shows the estimation results of the dynamic resource equation considering five alternative gross functions: Cushing, logistic, logistic with minimum viable population size (MVPS), Ricker and Gompertz. We use data on stock and total captures from 1982-2002 in the ESSH. These data were drawn up by the ICES WGHMM and are shown in Table 4 in Appendix A. Given the non linear character of these gross growth functions, the dynamic resource equation expressed in logarithms, equation (6), is estimated using non linear least squares.

Following Meade and Islam (1995) a functional form is deemed to be suitable for use if all the parameter estimates are significantly different from zero. Among the suitable functional forms we choose the one with the lowest sum of square errors, i.e. in accordance with the Akaike criterion[14], provided the estimated biological aggregates are sensible. The estimation results in Table 1 point to the Ricker as being the functional form that best fits the data.[15] The Ricker function defines the gross growth function as $f(X_t) = X_t e^{r(1-X_t/K)}$,

[13]Our paper addresses the problem of efficient exploitation in a different manner than Garza-Gil (1998) and Garza-Gil *et al.* (2003). While they consider exploitation in the steady state, we analyze the transition from the initial situation to the steady state in the presence of productivity shocks.

[14]The suitable functional forms in the case analysed have the same number of parameters.

[15]Logistic function with MVPS and the extended logistic function are not considered suitable because the parameter estimates are not significantly diffent from zero. Cushing, Logis-

Table 1: Growth Function Estimations for the ESSH

	Estimation	t-statistics	Sum Square Error
Cushing Function $f(X_t) = AX_t^{\alpha}$			
MSY=13,326	$\mathbf{X}_{MSY}$= 111,293	**MCC**=320,468	
A	3.8793	28.134676*	0.052878
α	0.8931	2.9820643*	
Logistic Function $f(X_t) = rX_t\left(1 - \frac{X_t}{K}\right) + X_t$			
MSY=12,219	$\mathbf{X}_{MSY}$= 65,374	**MCC**=130,748	
r	0.3738	9.8149288*	0.052428
K	130,749	5.0834094*	
Logistic with MVP $f(X_t) = rX_t\left(\frac{X_t}{k_0} - 1\right)\left(1 - \frac{X_t}{K}\right) + X_t$			
MSY=-110,335	$\mathbf{X}_{MSY}$= 453,612	**MCC**=638,286	
r	-0.3836	-3.1926058*	0.052408
K	638,286	0.079101568	
K_0	142,126	0.768117981	
Extended Logistic $f(X_t) = rX_t^{\alpha}\left(1 - \frac{X_t}{K}\right) + X_t$			
MSY=12,168	$\mathbf{X}_{MSY}$= 69,334	**MCC**=146,516	
r	1.0347	0.21310542	0.052303
α	0.8983	1.91120203	
K	146,516	1.5106097	
Ricker Function $f(X_t) = X_t e^{r(1-X_t/K)}$			
MSY=12,172	$\mathbf{X}_{MSY}$= 66,352	**MCC**=138,448	
r	0.3234	10.529445*	0.052407
K	138,448	4.7900225*	
Gompertz Function $f(X_t) = rX_t \ln\left(\frac{K}{X_t}\right) + X_t$			
MSY=12,851	$\mathbf{X}_{MSY}$= 96,665	**MCC**=262,762	
r	0.1329	3.4292341*	0.052754
K	262,762	1.7779578*	

* Statistics significant at the 5% level

where $r > 0$ is the intrinsic growth rate and K represents environmental carrying capacity. The results of this estimation imply $\hat{r} = 0.3234$ and $\hat{K} = 138,448$. Both estimates are significantly different from zero at the 5% level with t statistics of 10.5294 and 4.7900 for r and K, respectively. With these estimations of the parameters r and K, the Maximum Sustainable Yield (MSY) is $12,172$ tonnes, the biomass required for the MSY is $66,352$ tonnes and the Maximum Carrying Capacity (MCC) is $138,448$ tonnes.[16] We can observe that current stock, at about 27,074 tonnes in 2002, is far below that required to maintain MSY. This supports the ICES prediction of current stock being outside safe biological limits and the recommendation for zero captures in order to rebuild the stock.

Once these parameters are estimated, the stochastic process is calibrated in such a way that the sequence of productivity shocks reproduces the stock and total catches observed from 1982 to 2002. In order to do this, we take seven equidistant values for the state of the productivity shock, that is

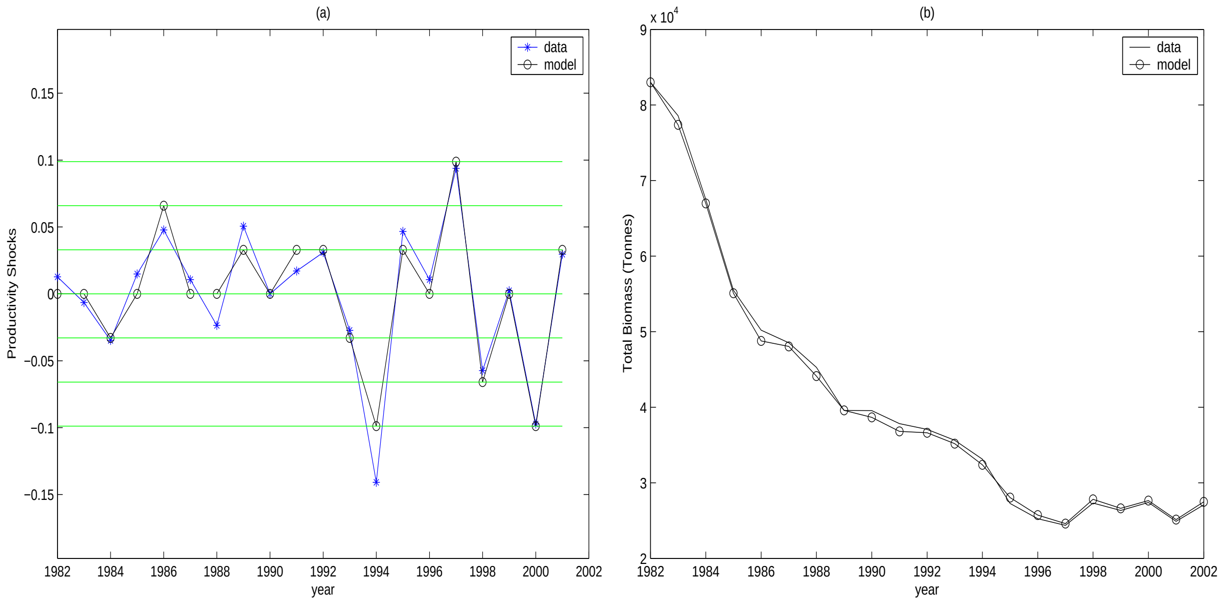
$$z \in \{-0.0988, -0.0659, -0.0329, 0.0000, 0.0329, 0.0659, 0.0988\}.$$

Given the information from the estimated errors, $\hat{z}$ and the values for the states of z, we calculate the transition matrix, π, for the Markov chain that discretes a continuum process in seven states following Tauchen (1986). The calibrated values are

tic and Gompertz functions fit the data well, but according to the Akaike criterium the Ricker function was chosen because it presents the lowest sum of squared errors in the parameters and the estimated biological aggregates are sensible. The P-test of Davidson and MacKinnon (1981) was also calculated to select among the suitable functional forms. However the test was inconclusive, probably due to the small sample size (21 observations).

[16]The MSY is the maximum net growth of the biomass. In other words, the value of the net growth for a stock level such that $\partial \left(F\left(X_t \right) - X_t \right) / \partial X_t = 0$. Recently, the National Marine Fisheries Service of the USA has started to call this yield "long-term potential yield". The MCC is the maximum stock compatible with a null net growth of the resource, i.e. X_t such that $F(X_t) = 0$.

Figure 2: ESSH Dynamics (a) productivity shocks (z_t); (b) biomass dynamics (X_t).



$$\pi(z, z') = \begin{pmatrix} 0.0001 & 0.0205 & 0.1356 & 0.3460 & 0.3433 & 0.1325 & 0.0220 \\ 0.0010 & 0.0299 & 0.1687 & 0.3686 & 0.3134 & 0.1035 & 0.0149 \\ 0.0024 & 0.0424 & 0.2046 & 0.3829 & 0.2789 & 0.0789 & 0.0100 \\ 0.0045 & 0.0585 & 0.2419 & 0.3877 & 0.2419 & 0.0585 & 0.0067 \\ 0.0079 & 0.0789 & 0.2789 & 0.3829 & 0.2046 & 0.0424 & 0.0045 \\ 0.0128 & 0.1035 & 0.3134 & 0.3686 & 0.1687 & 0.0299 & 0.0032 \\ 0.0198 & 0.1325 & 0.3433 & 0.3460 & 0.1356 & 0.0205 & 0.0023 \end{pmatrix},$$

where $\pi_{i,j} = Pr[z = z_i | z' = z_j]$.

Figure 2 illustrates the observed and calibrated productivity shocks and stock, in panels (a) and (b) respectively, from 1982 on. Notice that the productivity shocks estimates reproduce the path of the observed stock (panel b) quite well.

In calibrating the capturability function we follow Garza-Gil (1998), who considers there to be two different fleets operating in this fishery. Each fleet, $i = 1, 2$, fishes with the following production function,

$$y_{i,t} = \xi_{i,t}^{\theta_i} X_t^{\lambda_i},$$

where ξ_i is the effort applied by fleet i and θ_i and λ_i are the elasticity of fleet i's captures with respect to effort and stock, respectively. The two fleets are heterogeneous in the sense that the inputs behind the effort are different for the two fleets. In particular, effort is given by

$$\xi_{1,t} = d_{1,t}^{\gamma_1} T_t^{\gamma_2}, \tag{7}$$

$$\xi_{2,t} = d_{2,t}, \tag{8}$$

where d and T represent days operating in the fishery and capacity of vessels, respectively. Fleets 1 and 2 represent the trawler and the artisanal fleet, respectively. Parameters γ_1 and γ_2 represent the elasticity of the trawler fleet's effort with respect to the number of days fishing and the capacity of its vessels, respectively. Observe that with these production functions and the sharing rule we can express effort in fishery 2 as a function of effort in fishery 1,

$$p_1 - \frac{w_1 \xi_{1,t}}{\theta_1 y_{1,t}(\xi_{1,t}, X_t)} = p_2 - \frac{w_2 \xi_{2,t}}{\theta_2 y_{2,t}(\xi_{2,t}, X_t)}, \qquad \Longrightarrow \qquad \xi_2 = \xi_2(\xi_{1,t}, X_t).$$

Table 2 indicates the capturability and market parameters used for our analysis. The parameters comes from Garza-Gil (1998), where the reader will find how they are obtained and their statistical properties. Note that the estimated parameters show that the larger the stock is, the lower the share of the trawl fleet in total catches will be.[17]

4.2 Evaluation of the Management of the ESSH

Now we can investigate whether the observed exploitation paths for 1982-2002 in the ESSH can be considered efficient given the initial conditions of the stock, $X_0 = X_{1982}$. To generate the dynamic transition from the initial situation to the stochastic steady state we solve the following dynamic programming,

$$V(z, X, Y_{min}, Y_{max}) = \max_{X', \xi_1, \xi_2} \sum_{i=1}^{2} \Pi_i(z, X, X', \xi_i) + \beta E_{z'} \left[V(z', X', Y_{min}, Y_{max})/z \right],$$

[17] It is easy to prove that the relative share of fleet i in total captures is given by $(\lambda_i - \lambda_j)\xi_1^{\theta_1}\xi_2^{\theta_2}X^{\lambda_1+\lambda_2-1}$, $\forall i \neq j$, which is negative provided $\lambda_i < \lambda_j$.

Table 2: ESSH Fleets

Trawler (Fleet 1)	
Value	Parameters
$\theta_1 = 0.64313$	Elasticity of trawl effort (days per GRT)
$\lambda_1 = 0.18324$	Elasticity of Stock (Tn)
$p_1 = 4,346.2$	Euros per Tn.
$w_1 = 205.507$	Euros per day and GRT
$\gamma_1 = 0.16729$	Trawl Effort function
$\gamma_2 = 0.83271$	Trawl Effort function
Artisanal (longline and fixed gillnet) (Fleet 2)	
Value	Parameters
$\theta_2 = 0.18874$	Elasticity of trawl effort (days per GRT)
$\lambda_2 = 0.68537$	Elasticity of Stock (Tn)
$p_2 = 6,568.3$	Euros per Tn.
$w_2 = 370.342$	Euros per day
Source: Garza-Gil (1998)	

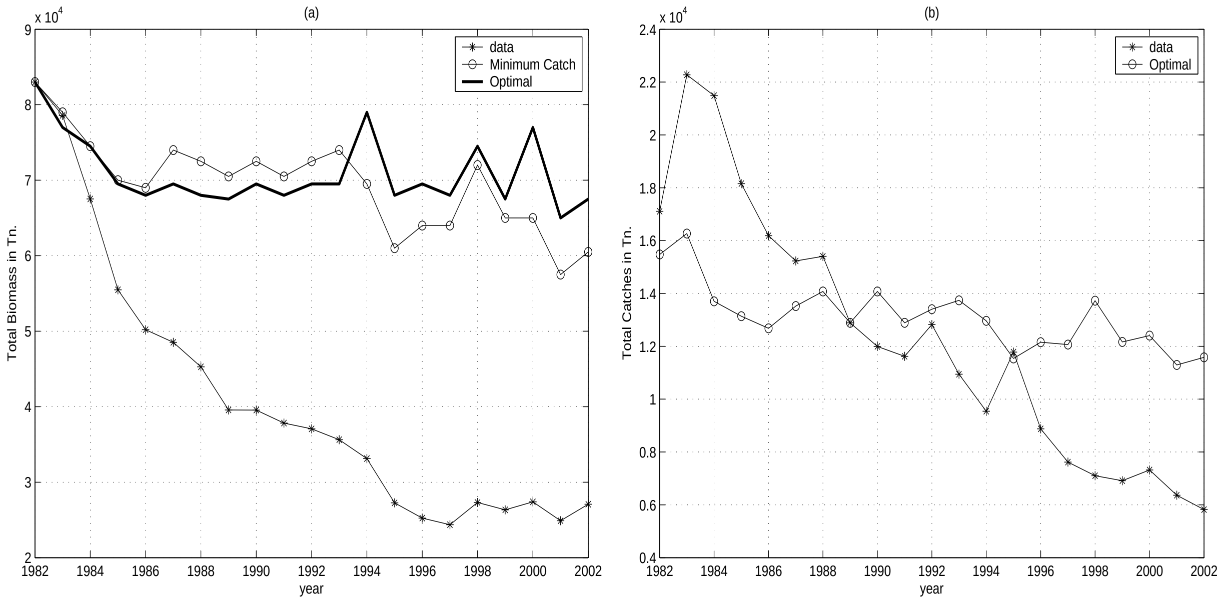
$$s.t. \begin{cases} \sum_{i=1}^{2} \xi_i^{\theta_i} X^{\lambda_i} = e^z e^{r(1-X/K)} X - X' \geq 0, \\ Y = \sum_{i=1}^{2} \xi_i^{\theta_i} X^{\lambda_i}, \\ z \in [z_1, z_2, z_3, z_4, z_5, z_6, z_7], \pi(z, z'), \\ Y \in \{Y_{min}, Y_{max}\}, \end{cases}$$

where the profits are given by

$$\Pi_i(z, X, X', \xi_i) = p_i \xi_i^{\theta_i} X^{\lambda_i} - w_i \xi_i.$$

We solve the dynamic program without restriction ($Y_{min} = 0$) and with a lower bound on catches ($Y_{min} = 5,000$ Tn.). Optimal paths for the stock in both cases and real data are shown in Figure 3, panel (a). We can see that optimal exploitation would have maintained the stock fairly constant with oscillations between 80,000 tonnes and 60,000 tonnes. These oscillations are smaller if the minimum captures bound is not considered. Comparing the optimal stock paths with the data we can conclude that the ESSH has been managed in a very inefficient way. This is consistent with the ICES position that the stock is outside

Figure 3: (a) Optimal Stock vs data; (b) Optimal Catches vs data with minimum catches of 5,000 Tn.

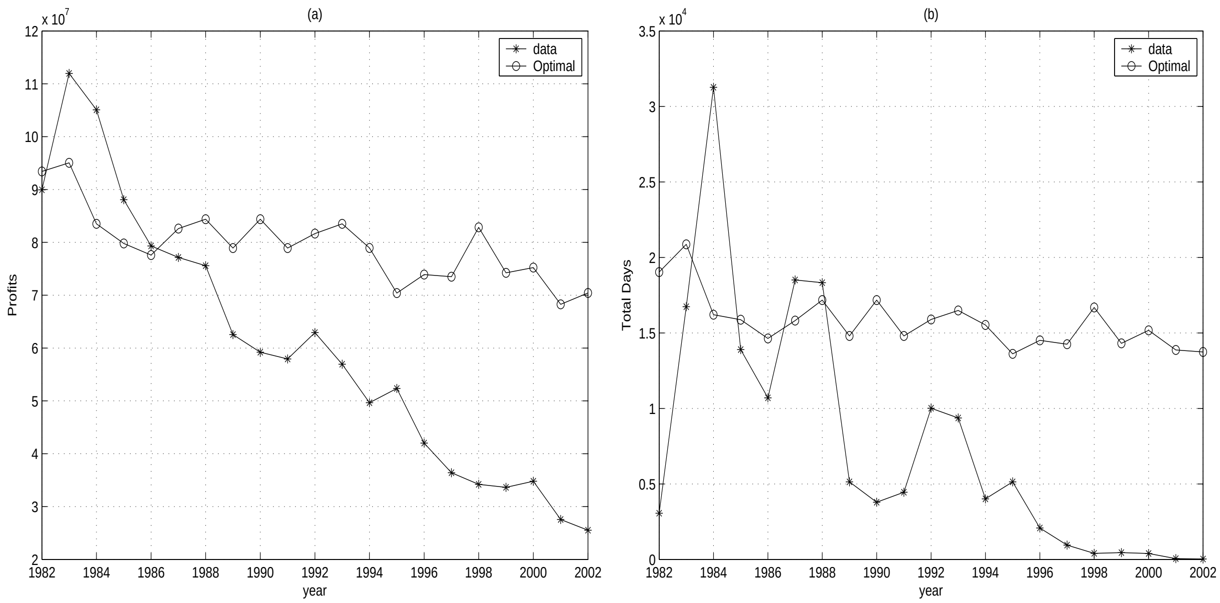


safe biological limits and that it should be rebuilt. Since the optimal path associated with a minimum catch of 5,000 Tn. is consistent with the current ICES objective, we decided to use it as our benchmark for the rest of our simulations.

Figure 3, panel (b), illustrates the optimal evolution of captures in the benchmark case and actual captures. Results show that until 1989 captures were greater than they should have been for optimal exploitation. In particular, in 1983 captures were about 23,000 tonnes when optimal exploitation called for 16,000 tonnes. This excess of captures during the 1980's resulted in depletion of the stock. In 2002 biomass was about 27,000 Tn. while optimal exploitation would have led to a resource stock of 60,000 Tn.

Figure 4 in panel (a) illustrates the path of aggregate profits associated with optimal exploitation, with catch restrictions and with the observed data. Results show that optimal exploitation would have implied low variability in aggregate profits over the period analyzed. By contrast, observed profits dropped drastically in the fishery due to the overexploitation of the stock in the early 1980s. In particular, we see that if the fleets had fished efficiently profit in 2002 would have been almost 2.8 times the observed level. A similar pattern appears in panel (b), where the effort of the artisanal fleet is shown. We see that the artisanal fleet

Figure 4: (a) Profits with minimum catches of 5,000 Tn , (b) Total Effort of Artisanal fleet (days) vs data with minimum catches of 5,000 Tn.



has reduced its effort enormously; however, optimal management of the fishery would have enabled the initial level of effort to be maintained with no great variation.

Figure 5 illustrates the efficient sharing of total catches between the two fleets. This illustration is presented for two different levels of the resource stock: a low stock (20,000 Tn) which represents a level close to current stock, and a high stock (60,000 Tn) which is close to the optimal level. We observe several points. First, the larger the total captures are the larger the share for the trawler fleet is (i.e. the capturability function is increasing). The intuition for this result is clear. When captures are low the more efficient (artisanal) fleet fishes most of them; however, as captures increase, the trawler fleet increases its catches by a greater proportion because the artisanal fleet reaches its maximum capacity. Second, the higher the resource stock is, the lower the participation of the trawler fleet in total captures is. This is because an increase in stock implies more captures and, therefore, a more than proportional increase in the captures of the less productive fleet (trawlers). And third, for levels of stock and captures close to the optimal levels (i.e. stock close to 60,000 Tn and captures about 12,000 Tn), the optimal sharing of catches implies that only the artisanal fleet would operate in the fishery.

Figure 5: Capturability functions

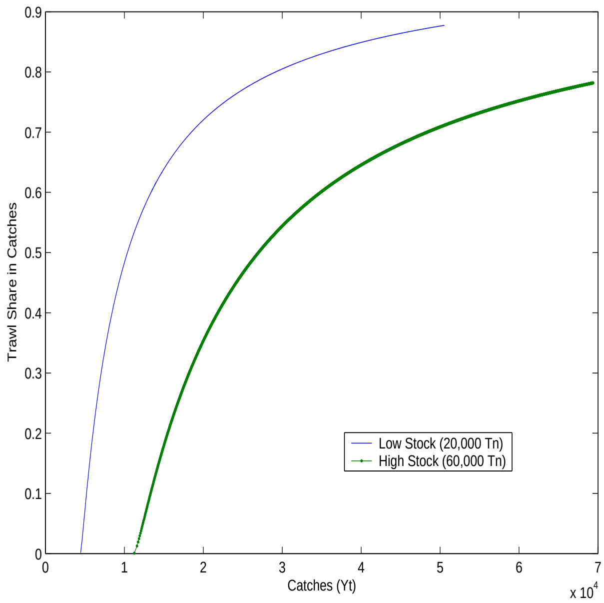


Table 3 quantifies the deviations of the observed catches and stock from the efficient ones in aggregate discounted terms. Aggregate captures are 18,000 tonnes less than optimal when restrictions in captures are considered. This means that aggregate captures have deviated no more than 6% from optimal ones. However, Figure 3 shows the timing of the fishing was not appropriate. Overexploitation of the resource in the early 1980s reduced the stock enormously and this led to the reduction of captures in the 1990s. This process has led to stock being less than half the optimal level. In terms of aggregate profits, the fishery has lost more than 317 million euros, which represents 35% of the current profits. However, this loss has not been shared out evenly among fleets. While the trawler fleet has increased its profits by more than 214 million euros (93%), the artisanal fleet has lost more than 531 million euros (80%). Summarizing, we can say that the ESSH has been overexploited. This has dissipated profits but has also reduced artisanal participation.

5 Discussion

Any dynamic model used to evaluate the management of a fishery must be able to reproduce a biomass path that is compatible with observed capture and stock paths. We propose an alternative stochastic approach where the stock growth path is affected by productivity shocks that follow a Markov process. The advantage of this approach is that it allows us to

Table 3: Optimal Stock, Catches and Profits for the ESSH

	Data	**Optimal**	**Min. Catch**
Catches and Stock(1)			
$\sum_{t=1982}^{2002} Y_t$	257,438	258,639	275,759
$\sum_{t=1982}^{2002} y_t^{trw.}$	107,828	11,960	4,852
$\sum_{t=1982}^{2002} y_t^{art.}$	246,610	246,679	270,907
X_{2001}	27,074	67,500	60,500
Profits(2)			
$\sum_{t=1982}^{2002} \beta^{t-1982}\Pi_t$	889.61	1176.30	1206.14
$\sum_{t=1982}^{2002} \beta^{t-1982}\pi_t^{trw.}$	229.17	33.38	14.19
$\sum_{t=1982}^{2002} \beta^{t-1982}\pi_t^{art.}$	660.44	1142.92	1191.95

(1) Tons of Hake; (2) Million Euros

reproduce the stylized facts of the fishery better than the traditional deterministic approach.

The existence of stochastic productivity shocks has policy recommendation implications, in both form and substance. For instance, if resource productivity depends on past productivity, both efficient TACs and sharing out depend on the size of the biomass and productivity shocks. Maintaining rules constant over time is not generally the right way to manage a fishery. TACs must adjust to productivity shocks. Moreover, if several fleets operate in the fishery the relative capture (*quotas*) of each fleet also has to vary over time with productivity changes. This is the case of the ESSH, where two heterogeneous fleets operate. Our results show that the larger the stock is the larger the share of the artisanal fleet must be. This is because the artisanal fleet obtains a higher quality product with a cost that drops substantially when the stock of the resource increases. Therefore, given that relative captures of each fleet change over time, implementing an ITQ system that allows captures to be shared out in a permit market each year seems a reasonable instrument for managing fisheries with heterogeneous fleets.

On the other hand, if our aim is to evaluate the benefits associated with the implementation of an ITQ system, we cannot limit the analysis to comparing steady states calculated from parameter estimations that do not adequately reproduce the resource dynamics. A correct assessment of the potential benefits from the implementation of ITQ systems must consider *quotas* as variables that depend on the size and productivity of the biomass because the participation of each fleet depends on relative productivity. In the case of the ESSH the artisanal fleet, whose productivity increases with the stock, would buy all the permits in the auction as long as the stock reaches the efficient value. At the same time, the participation of the trawler fleet would drop from the current level to zero.

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A Data

Table 4: Stock and Catch Data for the ESSH. 1982-2002

Year	1982	1983	1984	1985	1986	1987	1988
Stock	83008	78,582	67,521	55,478	50,200	48,524	45,277
Catches	17,108	22,376	21,485	18,152	16,185	15,232	15,405
Year	1989	1990	1991	1992	1993	1994	1995
Stock	39,569	39,549	37,832	37,065	35,622	33,1227	27,257
Catches	12,887	11,994	11,618	12,824	10,944	9,542	11,782
Year	1996	1997	1998	1999	2000	2001	2002
Stock	25,247	24,365	27,316	26,339	27,394	24,899	27,074
Catches	8,875	7,619	7,100	6,911	7,318	6,365	5,817

Source: Report ICES CM 2004/ACFM:02. From Table 6.1.13

B Appendix: Numerical Solution of Bellman's Equation

Suppose we want to solve numerically the following non-stochastic Bellman equation,

$$V(X) = \max_{X'} \left[u(X, X') + \beta V(X') \right],$$

where a prime on a variable indicates its value for the next period.

We start by selecting the widest possible grid of values of variable X, i.e. $\mathbb{X} = (X^0, X^1, ..., X^m)$. Let be $\mathbb{V}_0(\mathbb{X}) = (V_0(X^0), V_0(X^1), ..., V_0(X^m))$ a vector of initial values of the function V for each of the elements in $\mathbb{X}$. Given $\mathbb{X}$ and $\mathbb{V}$, the following Bellman equation is solved for all $i = 1, ...m$

$$V_1(X) = \max_{X'} \left[u(X, X') + \beta V_0(X') \right],$$

where $X = X^i$ and $V_0(X') = V_0(X^i)$.

Once this step is solved, $\mathbb{V}_0$ and $\mathbb{V}_1$ are compared using some kind of measure. For instance, we can say that $\mathbb{V}_0$ and $\mathbb{V}_1$ are sufficiently equal whenever $\parallel \mathbb{V}_1 - \mathbb{V}_0 \parallel < \epsilon$ holds for any ϵ as close to zero as we want.

If $\mathbb{V}_0$ and $\mathbb{V}_1$ are not sufficiently equal, the process is repeated for any $i = 1, ...m$, taking as the initial value of $V_0(X')$ the result obtained in the first iteration, i.e. $V_1(X^i)$. Then $\mathbb{V}_2$ is calculated and so on. In general, given a $\mathbb{V}_n$, the following equation is solved

$$V_{n+1}(X) = \max_{X'} \left[u(X, X') + \beta V_n(X') \right],$$

until vectors $\mathbb{V}_n$ and $\mathbb{V}_{n+1}$ are sufficiently equal according to our measure criterion.

Suppose now that the Bellman equation we want to solve is stochastic,

$$V(X, z) = \max_{X'} \left\{ u(X, X', z) + \beta E_{z'} \left[V(X', z') \mid z \right] \right\},$$

where a prime on a variable indicates its value for the next period and $E_{z'}$ means that the expectation is over the distribution of z'. The procedure for solving this stochastic Bellman equation numerically is the same as before. The stochastic variable is treated as the state variable X and the calibrated distribution of z is used in calculating $E_{z'} \left[V(X', z') \mid z \right]$.