The Evaluation of Fisheries Management: A Dynamic Stochastic Approach[†]

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March 2003

Abstract

In this article, we analyze how to evaluate fishery resource management under "ecological uncertainty". In this context, 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. First, we propose a method for calibrating the growth path of the resource such that observed dynamics of resource and captures are matched. Second, we apply the calibration procedure proposed in two different fishing grounds: the European Anchovy (Division VIII) and the Southern Stock of Hake. Our results show that the role played by uncertainty is essential for the conclusions. For European Anchovy fishery (Division VIII) we find, in contrast with Del Valle *et al.* (2001), that this is not an overexploited fishing ground. However, we show that the Southern Stock of Hake is in a dangerous situation. In both cases our results are in accordance with ICES advice.

Keywords: Fisheries Management

JEL Classification: Q22, Q28.

[†] We acknowledge financial support from the ERDF, Fundación BBVA, Ministerio de Ciencia y Tecnología and Universidad del País Vasco.

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1 Introduction

Efficiency in managing the exploitation of fishery resources has been widely analyzed in resource literature. Most of the existing works focus on the behavior of fisheries in the steady state (among others, Del Valle *et al.* (2001), Garza-Gil (1998), Flaaten and Stollery (1996), Amundsen *et al.* (1995)). In general terms, these works use a steady state approach that considers that an efficient policy consists of maintaining the exploitation levels of the fishing ground at steady state values. When the resource stock is outside the steady state, the exploitation must adjust to reach that state.

However, in analyzing the management of fishery resources we should not focus only on the steady state. For instance, if the productivity of the resource exhibits biological cycles and the reproductive cycle changes from year to year, efficient exploitation does not imply keeping captures constant.[1] On the contrary, total allowable captures each year must be determined by current productivity.

The main focus of our work is the evaluation of fishery resource management under "ecological uncertainty". 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, under ecological uncertainty the 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.

In this context of uncertainty, adequately reproducing the dynamics of the resource is crucial in evaluating the exploitation of the fishery ground.[2] In order to reproduce the observed dynamics, we assume that the stock growth path is affected by stochastic productivity shocks that follow a Markov process. We calibrate the growth path of the resource to

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[1] To see why biological cycles can exists, see for example Larrañeta and Vazquez (1982).

[2] Models used to develop the steady state approach assume deterministic parameters. This allows us to charactere the steady state of the fishing ground which, in most cases, is unique and stable. However, parameters used to calculate this steady state are poor at reproduce the biomass dynamic. This means that the biomass path generated from the estimated parameters and observed captures is far from the biomass path used to estimate the parameters. In short, since most articles only focus on steady states, the goodness of the parameters in reproducing the observed dynamics of the resource is never checked.

match the observed dynamics of the resource and captures.

The calibration procedure proposed is applied in two different fishing grounds. First we analyze the European Anchovy fihery (Division VIII) in which the fleet can be considered homogeneous in the sense that all ships fish with the same technology. Second, we analyze the Southern Stock of Hake. In this fishing ground, two different fleets operate (the trawler and the artisanal fleet).[3]

Our results show that the role played by uncertainty in resource growth is essential to the conclusions. For European Anchovy (Division VIII) we find, in contrast with Del Valle *et al.* (2001), that this is not an overexploited fishing ground. This result is in accordance with the ICES advice of keeping the precautionary stock level because it is inside safe biological limits. However, we show that the Southern Stock of Hake is in a dangerous situation; in particular, our results show that an efficient exploitation policy would bring the stock up to ICES recommended levels. Moreover, we 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 that 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 to regulate 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. In all these works uncertainty is modeled assuming that there are time independent shocks that affect the fishing ground. In contrast, we consider that productivity shocks are not time independent; in particular, we assume that the current state of productivity may depend on past productivity.

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[3] We use European Anchovy (Division VIII) and the Southern Stock of Hake for two reasons. First, both are considered individual administrative units by the International Council for the Exploitation of the Sea (ICES), which advises the European Commission about their management. Second, both are fishing grounds that have been analyzed previously by other authors (Del Valle at al. (2001) and Garza-Gil (1998), respectively). The existence of their papers allow us to focus on the calibration of the growth resource because they show information about capturability functions, the price of captures and the cost of effort.

The paper proceeds as follows. In the next section we build the model and propose a method forcalibrating the growth path of the resource. The model is adapted to characterize the European Anchovy fishery in Section 3. Subsection 3.1 presents the calibration of the fishing ground and in Subsection 3.2 the evaluation of the fishery is analyzed. Section 4 applies the analysis to the Southern Stock of Hake and reports what would have happened if side-payments between fleets had been allowed. Section 5 concludes the paper with a policy recommendation discussion.

2 The Model

Let us consider a fishing ground in which the dynamics of the stock, X_t, are given by

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

where Y_t are 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

$$F(X_t, z_t) = e^{z_t} f(X_t), \tag{2}$$

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

$$Y_t = \sum_{i=1}^{n} y_{i,t}(E_{i,t}, X_t). \tag{3}$$

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, $\omega_{i,t}E_{i,t}$. 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 the current fleets given their fishing capacity. Formally the benevolent regulator problem is given by

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

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

A solution of this problem is a value function $V(z, X, Y_{min}, Y_{max})$, policy functions $\{E_i(X, z, Y_{min}, Y_{max})\}_{i=1}^n$ 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 $\{E_i(X, z, Y_{min}, Y_{max})\}_{i=1}^n$ are the maximizing effort choices.

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

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

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, $Y = \sum_{i=1}^n y_i(E_i, X)$, are within the allowed range of catches, $Y \in \{Y_{min}, Y_{max}\}$, and the stock target is sustainable, that is $X' = e^z f(X) - Y$.

2.1 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 productivity shocks into gross growth function, we focus on illustrating how to choose the parameters in the dynamic resource equation, (1).[4]

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

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 $(k_1, ...k_r)$.[5] Then, if data on stock and captures are available, we can estimate those parameters from the dynamic resource equation, (1), which in logarithm terms can be expressed as

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

After examining the results of the estimations for different functional forms, we choose the most appropriate according to the usual econometric criteria. Let us call it $\hat{f}(X_t|k_1, ..., k_r)$. Second, from the estimated errors of the chosen functional form,

$$\hat{z}_t = \ln(X_{t+1} + Y_t) - \ln \hat{f}(X_t|k_1, ..., k_r),$$

we estimate an AR(1) process $\hat{z}_{t+1} = \rho\hat{z}_t + \varepsilon_{\hat{z}}$, obtaining an estimated autoregressive coefficient $\hat{\rho}$ which is used latter on in the procedure.

Finally, 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 and 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 $\hat{\rho}$ and the 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). The number of states of nature and the values that they take are chosen such that deviations of the observed paths for the stock and catches from those implied by the model are minimal.

In the following sections we apply this procedure to calibrate the dynamic resource equation in two different fishing grounds. First we analyze the European Anchovy fishery (Division VIII) in which the fleet can be considered homogeneous in the sense that all ships fish with the same technology. Second, we analyze the Southern Stock of Hake. In this fishing ground, two different fleets operate (the trawler and the artisanal fleet).

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

3 The case of the European Anchovy fhishery

European Anchovy Division VIII is a fishing ground along the Bay of Biscay.[6] Anchovy (*engraulis encrasicholus*) is a short-lived species that is fully mature at one year old, in the Spring following its hatching.

Two fleets fish on anchovy in the Bay of Biscay and the pattern of each fishery has not changed in recent years. Spanish purse seines operate mainly in Spring in Divisions VIIIb-c.[7] French pelagic trawlers fish in summer, autumn and winter in Divisions VIIIa-b. Most fish have spawned at least once before being caught. The French fish outside the spawning season and the Spanish fish outside the spawning area. The number of Spanish purse seines for anchovy has remained stable since 1990 and a slight increase in the number of French pelagic trawlers has been observed in the last five years. A sharp increase in fishing effort for anchovy in the Bay of Biscay has occurred since 1987 mainly due to increased efforts by the French pelagic trawler fleet.

Like the main stocks of the EU, the Bay of Biscay anchovy stock is managed by annual TAC.[8] Since the stock is inside safe biological limits in 2002, the ICES Advisory Committee for Fisheries Management has not established explicit management objectives for this stock apart from precautionary criteria (ICES Annual Report 2002).

For more details about biological and technical characteristics of this fishery see Lucio *et al.* (1989) and the reports issued by the ICES Working Group on the Assessment of Mackerel, Horse Mackerel, Sardine, and Anchovy (WGMHSA). Moreover, Del Valle *et al.* (2001) analyze the role that resource users (through fishermen's guilds) play inside the institutional

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[6] The anchovy is one of the most important species that lives in European Atlantic waters from the central part of the Bay of Biscay to the West of Galicia. However, ICES considers that for biological and management purposes the anchovy population has to be divided into two different stocks: the South-east corner of the Bay of Biscay (Division VIII) and the Atlantic Iberian Coast (Division IXa). See ICES CM 2003/ACFM:07, page 390.

[7] The most of the fleet goes for tuna fishing in summer time and small anchovies are used as live bait for this fishing.

[8] DG XIV Fisheries requested ICES to consider the need to develop specific harvest strategies for short-lived species such as anchovy. The ICES's advice is to fix a preliminary TAC at the beginning of the year based on analytic assessment in the autumn, and to review it in the half of the year when the results from egg and acoustic surveys became available. This advice is in accordance with Scientific Technical and Economic Committee on Fisheries (STECF) recommendations.

regime management of this fishery.

3.1 Calibration

In order to evaluate the optimal exploitation policy in the Bay of Biscay anchovy, we calibrate the model assuming stochastic productivity shocks. First, following the procedure developed in Subsection 2.1, the parameters from the dynamics resource equation, (1), are calibrated.

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 have used data on the stock and total captures from the period 1987-2001 in European Anchovy Division VIII). These data were compiled by the ICES WGMHSA and are shown in Table 8 in Appendix A.

As Table 1 illustrates, the Ricker is the functional form that best fits the data.[9] The Ricker defines the gross growth function as $f(X_t) = e^{r(1-X_t/K)}X_t$, where $r > 0$ is the intrinsic growth rate and K represents environmental carrying capacity. For this case, the dynamic resource equation(1) is estimated expressed in logarithms,

$$\ln(\frac{X_{t+1}+Y_t}{X_t}) = \beta_1 + \beta_2 X_t + z_t.$$

The results of this estimation by OLS imply $\hat{r} = \widehat{\beta}_1 = 0.8658$ and $\hat{K} = -\widehat{\beta}_1/\widehat{\beta}_2 = 379010.82$. Both estimates are significantly different from zero at the 5% level (t statistics[10] are 2.8771 and 2.6714 for r and K, respectively), $R^2 = 0.371$ and statistic $F = 7.069$. With these estimations of the parameters r and K, the Maximum Sustainable Yield (MSY) is $167,646$

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[9] The Cushing and the logistic with MVPS do not fit the data at all. Gompertz and the logistic function fit the data well, but we have chosen the Ricker function because the parameters are both significantly different from zero with right signs and provide more realistic values for the MSY, X_{MSY} and MCC (see real data for the stock and captures in Appendix A).

[10] Since the structural parameter $K = -\beta_1/\beta_2$, its t-statistic is calculated using as variance for K an approximation based on Taylor's expansion (see Cox-Hinkley 180, pp 105),

$$\widehat{\sigma}^2_K \simeq \left[\frac{\partial k}{d\beta_1}\right]^2_{(\widehat{\beta}_1,\widehat{\beta}_2)} \widehat{\sigma}^2_{\beta_1} + \left[\frac{\partial k}{d\beta_2}\right]^2_{(\widehat{\beta}_1,\widehat{\beta}_2)} \widehat{\sigma}^2_{\beta_2} + \left[\frac{\partial k}{d\beta_1}\right]_{(\widehat{\beta}_1,\widehat{\beta}_2)} \left[\frac{\partial k}{d\beta_2}\right]_{(\widehat{\beta}_1,\widehat{\beta}_2)} \widehat{cov}^2_{\beta_1,\beta_1}.$$

Table 1: Estimations for European Anchovy (Division VIII)

	Estimation	t-**statistics**	$\mathbf{R}^2$	F-**statistics**
Cushing Funtion $f(X_t) = AX_t^{\alpha}$				
MSY=147,483	$\mathbf{X}_{MSY}$= 64,907	**MCC**=357,863		
A	7185.9544	1.239648	0.114	1.537
α	0.30560293	2.852119*		
Logistic Function $f(X_t) = rX_t\left(1 - \frac{X_t}{K}\right) + X_t$				
MSY=137,278	$\mathbf{X}_{MSY}$= 203,159	**MCC**=406,317		
r	1.3514348	3.165800*	0.384	7.480*
K	406317.44	2.8248*		
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=1.51E12	$\mathbf{X}_{MSY}$= 663,034	**MCC**=994,552		
r	-2.3875288	2.427384*	0.452	4.531
K	994552.26	1.3025046		
K_0	-0.23088632	-0.92573929		
Ricker Function $f(X_t) = X_t e^{r(1-X_t/K)}$				
MSY=104,057	$\mathbf{X}_{MSY}$= 167,646	**MCC**=379,011		
r	0.86583367	2.870697*	0.371	7.069*
K	379010.82	2.6713804*		
Gompertz Function $f(X_t) = rX_t \ln\left(\frac{K}{X_t}\right) + X_t$				
MSY=151,382	$\mathbf{X}_{MSY}$= 142,181	**MCC**=386,488		
r	1.0647196	3.238887*	0.457	10.110*
K	386487.90	0.24933569		
* Statistics significant at the 5% level				

tones, the biomass required for the MSY is $104,057$ tonnes and the Maximum Carrying Capacity (MCC) is $379,011$ tonnes.[11] This means that actual captures are far below the MSY level, which supports the ICES advise of no explicit management plan for this fishing ground.

From the estimated errors,

$$\hat{z}_t = \ln\left(\frac{X_{t+1}+Y_t}{X_t}\right) - \hat{r} + \frac{\hat{r}}{\hat{K}}X_t,$$

we estimate an AR(1) process $\hat{z}_{t+1} = \rho\hat{z}_t + \varepsilon_{\hat{z}}$, obtaining an estimated autoregressive coefficient $\hat{\rho}$=-0.3981, which is significant at the 10% level.

Once these parameters have been estimated, the stochastic process is calibrated in such a way that the sequence of productivity shocks reproduces the stock and total catches observed from 1987 to 2001. In order to do this, we have taken seven equidistant values for the state of the productivity shock, that is

$$z \in \{-0.6721, -0.4480, -0.2240, 0.0000, 0.2240, 0.4480, 0.6721\}.$$

Figure 1 shows the observed and calibrated productivity shocks and stocks in panels (a) and (b), respectively, from 1987 on. Given $\hat{\rho}$ 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 (see Tauchen (1986)). The calibrated values are

$$\pi(z,z') = \begin{pmatrix} 0.0000 & 0.0016 & 0.0307 & 0.1921 & 0.4060 & 0.2922 & 0.0773 \\ 0.0002 & 0.0060 & 0.0727 & 0.2945 & 0.4052 & 0.1899 & 0.0316 \\ 0.0008 & 0.0185 & 0.1445 & 0.3804 & 0.3410 & 0.1039 & 0.0110 \\ 0.0032 & 0.0478 & 0.2419 & 0.4143 & 0.2419 & 0.0478 & 0.0032 \\ 0.0110 & 0.1039 & 0.3410 & 0.3804 & 0.1445 & 0.0185 & 0.0008 \\ 0.0316 & 0.1899 & 0.4052 & 0.2945 & 0.0727 & 0.0060 & 0.0002 \\ 0.0773 & 0.2922 & 0.4060 & 0.1921 & 0.0307 & 0.0016 & 0.0000 \end{pmatrix},$$

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

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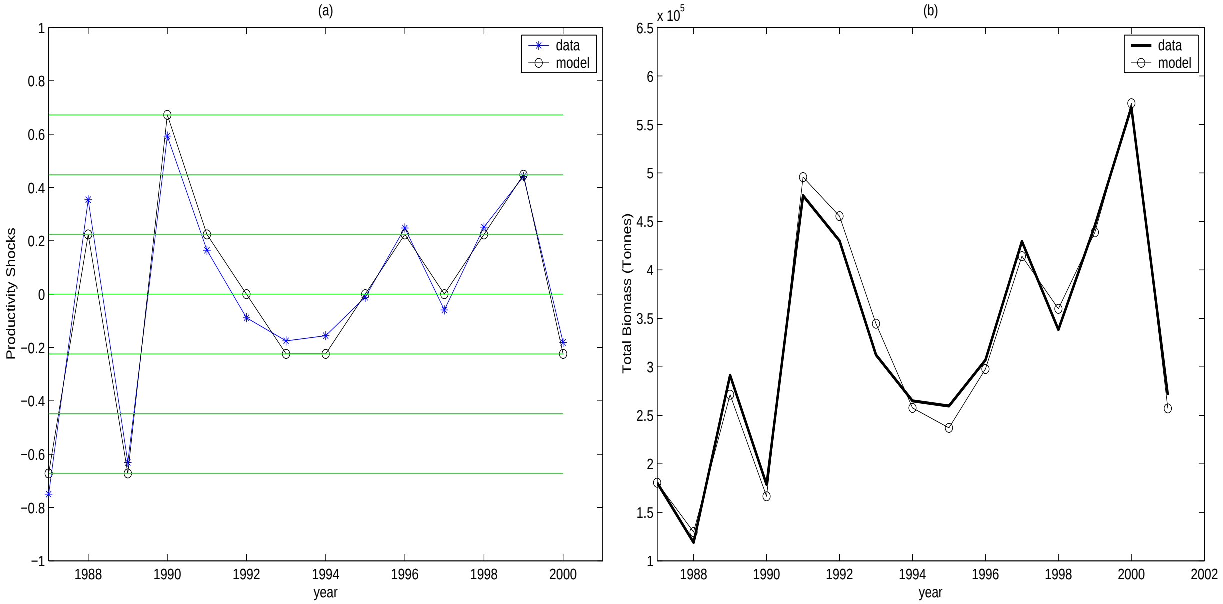
[11] The MSY is the maximum net growth of the biomass. In other words, the value of the net growth for a stock level such that $\partial\left(F\left(X_t\right) - X_t\right)/\partial X_t = 0$. Recently, the National Marine Fisheries Service of the USA has started to call this yield "long-term potential 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 1: Anchovy Dynamics (a) productivity shocks (z_t); (b) biomass dynamics (X_t)



Following Del Valle et al. (2001) we use a Cobb Douglas production function in which total captures are a function of total number of vessels, E, and the stock of the resource, X_t,

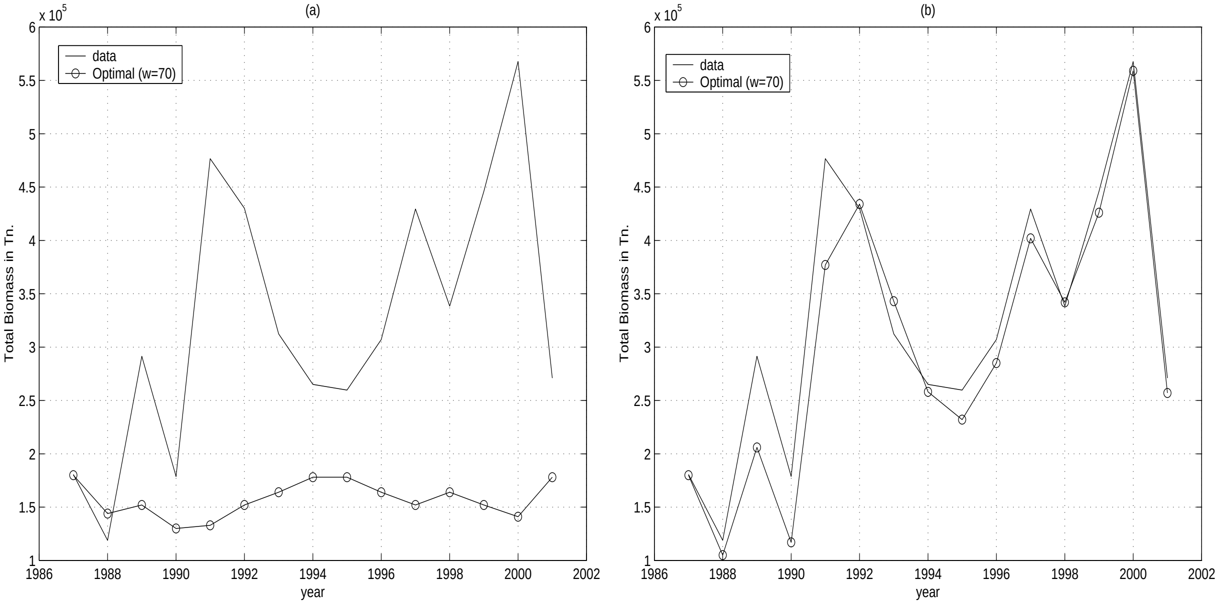
$$Y_t(E_t, X_t) = BE_t^{\theta} X_t^{\lambda},$$

where θ and λ are the elasticity of the captures with respect to the effort and stock, respectively. Table 2 shows the parameters used for our analysis.

Table 2: European Anchovy Fleet

Value	Parameters
$\theta = 0.66562$	Elasticity of effort (number boats)
$\lambda = 0.68226$	Elasticity of the Stock
$B = 0.31991$	Total factor productivity
$w/p \in [40, 100]$	Tn.
Source: Del Valle *et al.* (2001)	

Figure 2: Optimal Stock vs data (a) without maximum; (b) with maximum catches of to 40,000 Tn.



3.2 Evaluation of European Anchovy Stock Management

To generate the dynamic transition from the initial situation to the stochastic steady state we solve the following dynamic program,

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

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

where the profits, in real terms, are given by

$$\Pi_i(z, X, X') = e^z e^{r(1-X/K)} X - X' - \omega \left(\frac{e^z e^{r(1-X/K)} X - X'}{B X^{\lambda}} \right)^{1/\theta},$$

and the real cost of effort is $\omega = w/p$.

We solve the dynamic program without restriction ($Y_{min} = 0$) and with an upper bound on catches ($Y_{max} = 40,000$ Tn.). Optimal paths for the stock in both cases are illustrated in Figure 2, panel (a) and panel (b), respectively. Our results are consistent with ICES recommendations. The stock is inside safe biological limits. Observe that the efficient stock in the absence of an upper bound on captures is fairly constant and varies between 100,000 tonnes and 200,000 tonnes.[12] However, the efficient path when an upper bound on captures is imposed is much higher and more volatile. That is, when unconstrained captures are not allowed stock becomes more volatile. Since the number of vessels is (almost) fixed, we consider it more appropriate to use the efficient path, imposing the upper level of captures as our benchmark.

Table 3 shows the deviations of the observed exploitation paths from the optimal ones with maximum catches of 40,000 tonnes. Aggregate captures are 164,000 tonnes less than optimal for the period analyzed. This means that effective exploitation has deviated by more than 27% from the efficient policy. This underexploitation has protected the stock. In 2001 biomass was about 270,000 tonnes while optimal exploitation would have required a lower resource stock of 257,000 tonnes.

Table 3: Optimal Stock and Catches

	Data	**Optimal**
Catches and Stock(1)		
$\sum_{t=1987}^{2001} Y_t$	431,477	595,010
X_{2001}	270,000	257,000

(1) Tonnes of Anchovy

Table 4 quantifies aggregate discounted profits for the whole period analyzed under both scenarios, effective exploitation and efficient exploitation ($\sum_{t=1987}^{2001} \beta^{t-1987}\Pi_t$ and $\sum_{t=1987}^{2001} \beta^{t-1987}\Pi_t^*$, respectively). These profits are shown for different values of the real effort cost. As we expected, the higher the real cost of effort is, the lower the profit of the fishery is regardless of the degree of management efficiency. We can see that for a medium real cost of effort ($w/p = 70$), optimal exploitation would have entailed an increase in profits of 30%. In the same line Figure 3, panel (a), illustrates how much, in percentage terms, profits would have increased if exploitation had been efficient with a constant TAC of 40,000 tonnes. Results show that profits would have increased by at least 25%.

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[12] We have checked that this path is associated with a high and very volatile level of catches.

Figure 3: Maximum catches of 40,000 Tn (a) Increase in Profits; (b) Optimal number of boats

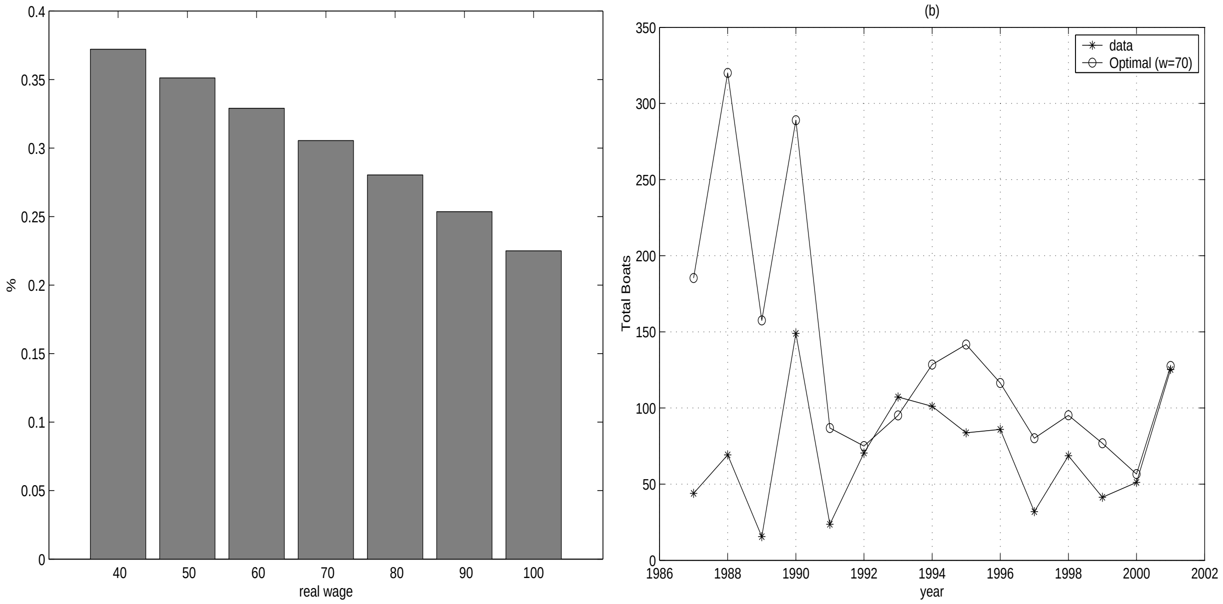

Table 4: Optimal and Observed Profits

	real cost						
Profits (1)	**40**	**50**	**60**	**70**	**80**	**90**	**100**
$\sum_{t=1987}^{2001} \beta^{t-1987}\Pi_t$	251,370	244,220	237,080	229,930	222,790	215,640	208,500
$\sum_{t=1987}^{2001} \beta^{t-1987}\Pi_t^*$	344,920	330,000	315,080	300,170	285,250	270,033	255,410

(1) Tonnes of Anchovy

Figure 3, panel (b), illustrates the evolution of the optimal and observed number of boats operating in the fishery under the maximum catch restrictions. We can see that the effective number of boats has varied between 20 and 150 while efficient exploitation would have required more than 200 boats in some periods. This is consistent with the fact that the stock is inside the safe biological limits. Moreover, since deviations of effective stock from efficient stock are larger at the beginning of the period, optimal management would have implied larger captures (and more boats) during the first periods analyzed.

4 The Southern Stock of Hake

The Southern Stock of Hake is a fishing ground allocated around the Atlantic coast of the Iberian Peninsula (Divisions VIIIc and IXa).[13] 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 operate on hake in the Southern Stock: the Spanish and Portuguese trawl and artisanal fleets. The trawl 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 Southern Stock. The agreed TAC was 8,900 tonnes in 2001 and 8,000 tonnes in 2002. However the 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.[14]

Biomass dropped from about 84,000 Tn. in the early 1980s to 29,000 Tn. in 2001 (see Table 9 in Appendix A). This reduction is reflected in captures, which dropped from 23,000 Tn to 7,000 Tn in the same period. The ICES Advisory Committee for Fisheries Management considers that the stock is outside safe biological limits and recommends that fishing mortality be as close to zero as practicable in order to rebuild the stock (ICES Annual Report 2002).

For more details about biological and technical characteristics of this fishery see the report elaborated by the ICES Working Group on the Assessment of Southern Stock of Hake, Monk and Megrim (WGHMM) from the ICES. Garza-Gil (1998) uses this fishery to illustrate how individual transferable *quotas* may help to achieve efficient exploitation in a

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[13] 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).

[14] 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.

multifleet setting.[15]

4.1 Calibration

As in the European Anchovy stock, we have chosen the functional form for the gross growth function by estimating the dynamic resource equation, (1), for five alternative gross functions: Cushing, logistic, logistic with minimum viable population size (MVPS), Ricker and Gompertz. Data for the stock and total captures from the period 1982-2001 in the Southern Stock of Hake have been used. These data were elaborated by the ICES WGHMM and are shown in Table 9 in the Appendix A. Table 5 shows the estimation results.

The estimation results in Table 5 point to the Cushing as being the functional form that best fits the data.[16] The Cushing function defines the gross growth function as $f(X_t) = AX_t^{\alpha}$, where $\alpha > 0$ represents the elasticity of the gross stock growth and A is the mean productivity of the resource. For this case, the dynamic resource equation (1) is estimated expressed in logarithms,

$$\ln(X_{t+1} + Y_t) = \beta_1 + \beta_2 \ln X_t + z_t.$$

The results of this estimation by OLS imply $\widehat{\alpha} = \widehat{\beta}_2 = 0.8975$ and $\widehat{A} = e^{\widehat{\beta}_1} = 3.7364$. Both estimates are significantly different from zero at 5% (t statistics are 24.5784 and 3.3863 for α and A, respectively), $R^2 = 0.973$ and statistic $F = 604.101$. With these estimations of the parameters α and A, the MSY is $15,270$ tonnes, the required biomass for the MSY is $133,682$ tonnes and the MCC is $383,950$ tonnes. We can observe that current stock, at about 29,000 tonnes in 2001, 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 captures to be as close to zero as possible in order to rebuild the stock.

From the estimated errors,

$$\hat{z}_t = \ln\left(\frac{X_{t+1} + Y_t}{\hat{A}X_t^{\hat{\alpha}}}\right),$$

---

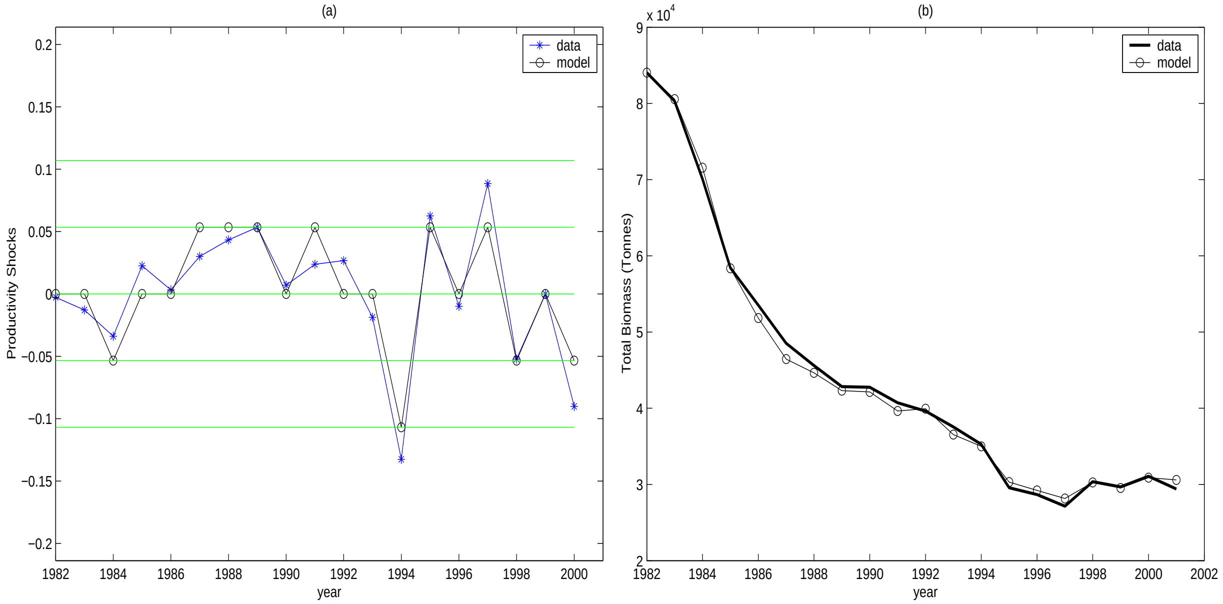
[15] Our paper addresses the problem of efficient exploitation in a different manner than Garza-Gil (1998). While she considers exploitation in the steady state, we analyze the transition from the initial situation to the steady state in the presence of productivity shocks.

[16] The logistic with MVPS does not fit the data at all. Logistic, Gompertz and Ricker functions fit the data well, but the Cushing function has been chosen because the parameters are significantly different from zero with right signs and the R^2 is 0.97.

Table 5: Estimations for the Southern Stock of Hake

	Estimation	t**-statistics**	$\mathbf{R}^2$	F**-statistics**
Cushing Funtion $f(X_t) = AX_t^{\alpha}$				
MSY=15,269	$\mathbf{X}_{MSY}$= 133,682	**MCC**=383,951		
A	3.7364431	3.386450*	0.973	604.101*
α	0.89748744	24.578475*		
Logistic Function $f(X_t) = rX_t\left(1 - \frac{X_t}{K}\right) + X_t$				
MSY=13,308	$\mathbf{X}_{MSY}$= 71,057	**MCC**=142,114		
r	0.37457302	8.412734*	0.323	8.094*
K	142114.15	3.1859139*		
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=3.64E13	$\mathbf{X}_{MSY}$= 2,999,769	**MCC**=4,499,654		
r	-0.37611305	-2.389428*	0.323	3.809*
K	4,499,654	0.010350328		
K_0	-0.030950287	-0.010449096		
Ricker Function $f(X_t) = X_t e^{r(1-X_t/K)}$				
MSY=13,304	$\mathbf{X}_{MSY}$= 73,371	**MCC**=153,020		
r	0.32014410	9.066541*	0.323	8.109*
K	153019.97	3.1751596*		
Gompertz Function $f(X_t) = rX_t \ln\left(\frac{K}{X_t}\right) + X_t$				
MSY=14,514	$\mathbf{X}_{MSY}$= 111,700	**MCC**=303,631		
r	0.12994047	2.830244*	0.320	8.010*
K	303,632	0.24049954		
* Statistics significant at the 5% level				

Figure 4: Southern Hake Dynamics (a) productivity shocks (z_t); (b) biomass dynamics (X_t).



we estimate an AR(1) process $\hat{z}_{t+1} = \rho \hat{z}_t + \varepsilon_{\hat{z}}$, obtaining an estimated autoregressive coefficient $\hat{\rho}$=-0.188809. Given $\hat{\rho}$ and the values for the states of z, we calculate the transition matrix, π, for the Markov chain that discretes a continuum process in five states. The calibrated values are

$$z \in \{-0.1069, -0.0535, 0.0000, 0.0535, 0.1069\},$$

$$\pi(z, z') = \begin{pmatrix} 0.0002 & 0.0880 & 0.4841 & 0.3826 & 0.0451 \\ 0.0031 & 0.1414 & 0.5364 & 0.2947 & 0.0244 \\ 0.0091 & 0.2115 & 0.5550 & 0.2115 & 0.0128 \\ 0.0208 & 0.2947 & 0.5364 & 0.1414 & 0.0068 \\ 0.0414 & 0.3826 & 0.4841 & 0.0880 & 0.0039 \end{pmatrix},$$

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

Figure 4 illustrates the observed and calibrated productivity shocks and stocks, in panels (a) and (b) respectively, from 1982 on. For the data from this fishery, deviations of the observed paths for stock and catches by those implied for the model are minimal.

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

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

where E_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

$$E_{1,t} = d_{1,t}^{\gamma_1} T_t^{\gamma_2}, \tag{4}$$

$$E_{2,t} = d_{2,t}, \tag{5}$$

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,

$$p_1 - \frac{w_1 E_{1,t}}{\theta_1 y_{1,t}(E_{1,t}, X_t)} = p_2 - \frac{w_2 E_{2,t}}{\theta_2 y_{2,t}(E_{2,t}, X_t)}, \qquad \Longrightarrow \qquad E_2 = E_2(E_{1,t}, X_t).$$

Table 6 indicates the capturability and market parameters used for our analysis. 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 Southern Stock of Hake

Now we can investigate whether the observed exploitation paths for 1982-2001 in the Southern Stock of Hake 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,

$$V(z, X, Y_{min}, Y_{max}) = \max_{X', E_1, E_2} \sum_{i=1}^{n} \pi_i(z, X, X', E_i) + \beta E_{z'} \left[V(z', X', Y_{min}, Y_{max})/z \right],$$

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

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[17] It is easy to prove that the relative share of fleet i in total captures is given by $(\lambda_i - \lambda_j) E_1^{\theta_1} E_2^{\theta_2} X^{\lambda_1 + \lambda_2 - 1}$, $\forall i \neq j$, which is negative provided $\lambda_i < \lambda_j$.

Table 6: Southern Hake 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)	

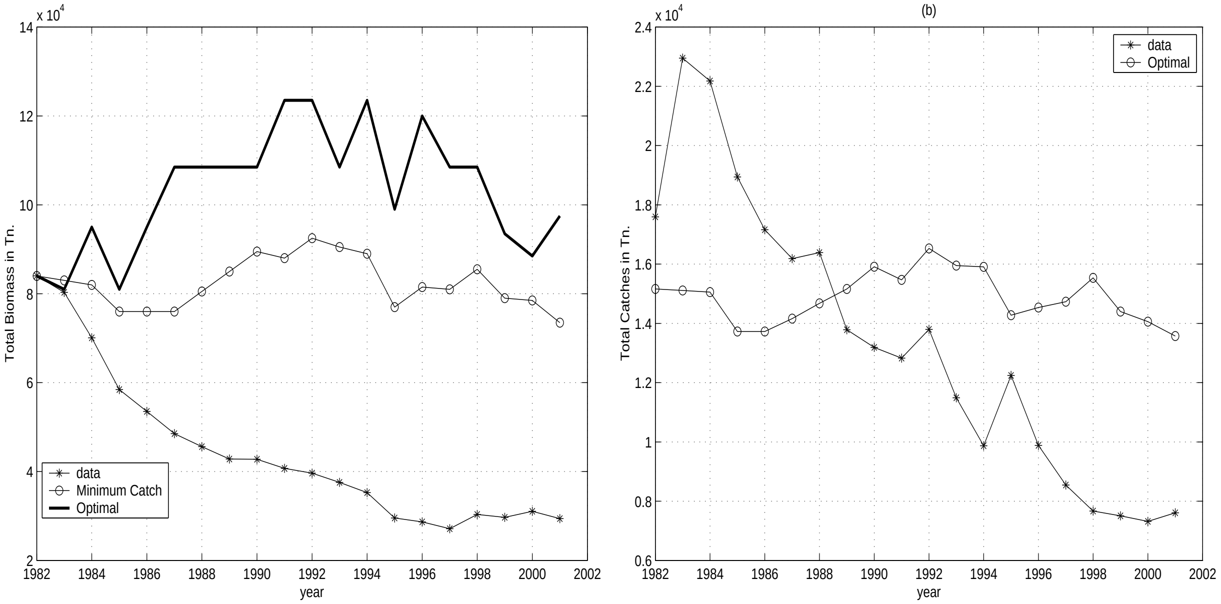
where the profits are given by

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

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 5, panel (a). We can see that optimal exploitation would have maintainted the stock fairly constant with oscillations between 80,000 tonnes and 120,000 tonnes. These oscillations are smaller if the minimum captures bound is considered. Comparing the optimal stock paths with the data we can conclude that Southern Stock of Hake has been managed in a very inefficient way. This is consistent with the ICES position that considers that the stock is outside safe biological limits and recommends that it be rebuilt. Since the optimal path associated with a minimum catch of 5,000 Tn. is consistent with the actual ICES objective, we decide to use it as our benchmark for the rest of our simulations.

Figure 5, panel (b), illustrates the optimal evolution of captures in the benchmark case

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

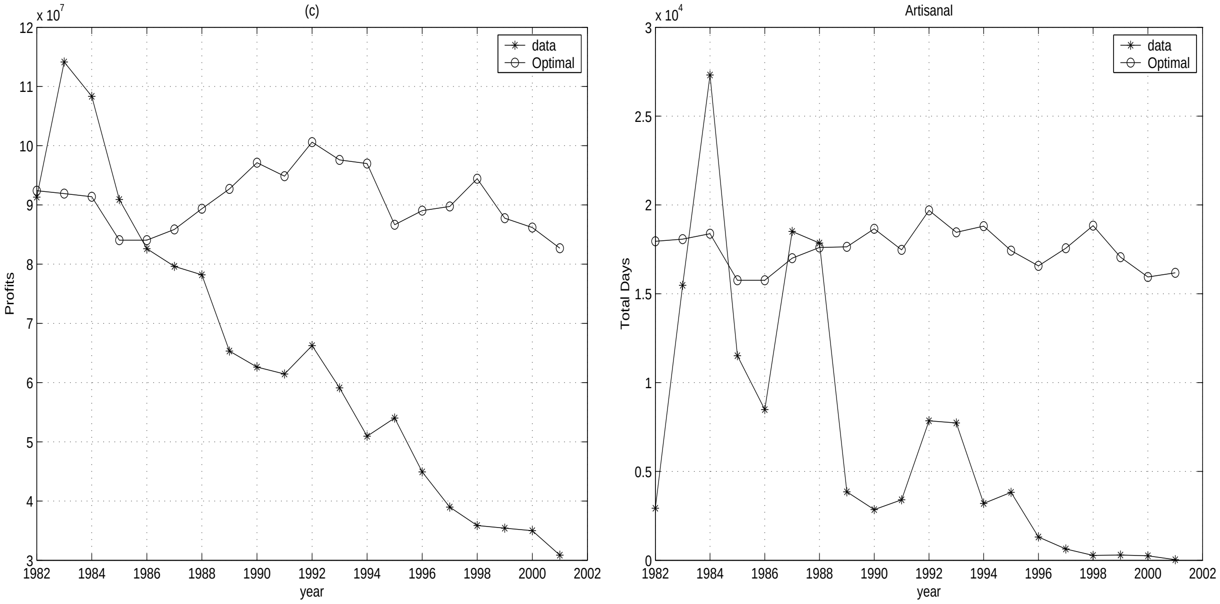


and real captures. Results show that until 1988 captures were greater than they should have been for optimal exploitation. In particular, in 1983 captures were about 23,000 tonnes when optimal exploitation called for less than 16,000 tonnes. This excess of captures during the 1980's resulted in depletion of the stock. In 2001 biomass was about 30,000 Tn. while optimal exploitation would have led to a resource stock of more than 70,000 Tn.

Figure 6 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 2001 would have been at least 28 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 has reduced its effort enormously; however, optimal management of the fishery would have enebled the initial level of effort to be maintened wit no great variation.

Figure 7 illustrates the efficient sharing of total catches between the both fleets, the artisanal and the trawler. This illustration is presented for two different levels of the resource

Figure 6: (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.



stock: a low stock (20,000 Tn) which represents a value close to current stock, and a high stock (60,000 Tn) which is close to the optimal value. 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 fleet (the artisanal) 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 a increase in the stock implies more captures and, therefore, a more than proportional increase in the captures of the less productive fleet (trawlers). And third, for values of stock and captures close to the optimal levels (i.e. stock close to 80,000 Tn and captures about 14,000 Tn), the optimal sharing of the catches implies that only the artisanal fleet operates in the fishery.

Figure 7: Capturability functions

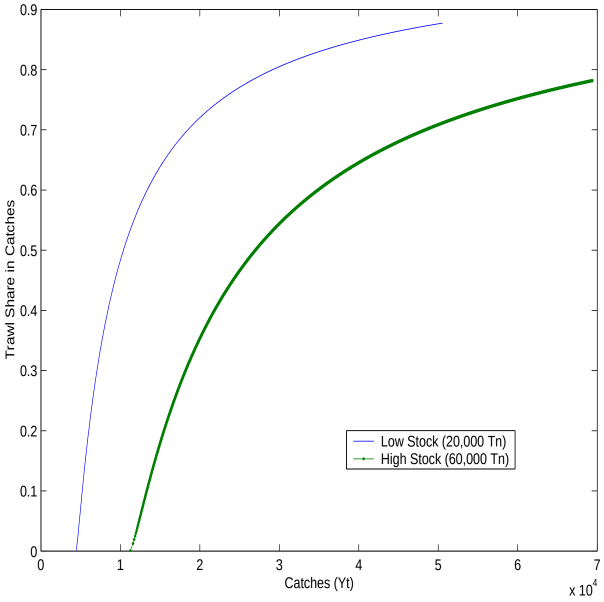


Table 7: Optimal Stock, Catches and Profits for the Southern Stock of Hake

	Data	**Optimal**	**Min. Catch**
Catches and Stock(1)			
$\sum_{t=1982}^{2001} Y_t$	267,132	167,520	181,510
$\sum_{t=1982}^{2001} y_t^{trw.}$	119,532	22,620	1,110
$\sum_{t=1982}^{2001} y_t^{art.}$	147,599	144,900	180,400
X_{2001}	29,403	97,500	73,500
Profits(2)			
$\sum_{t=1982}^{2001} \beta^{t-1982}\Pi_t$	866.77	950.20	1106.90
$\sum_{t=1982}^{2001} \beta^{t-1982}\pi_t^{trw.}$	238.45	81.68	4.70
$\sum_{t=1982}^{2001} \beta^{t-1982}\pi_t^{art.}$	628.32	868.52	1102.20

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

Table 7 quantifies the deviations of the observed catches and stock from the efficient ones in aggregate discounted terms. We can see that aggregate captures have deviated by more than 47% from the optimal when restrictions in captures are considered. This has led to stock being less than one third of the optimal level. In terms of aggregate profits, the fishery has lost more than 240 million euros. However, this loss has not been shared out evenly by fleets. While the trawler fleet has increased its profits by more than 233 million euros, the artisanal fleet has lost more than 473 million euros. Summarizing, we can say that the Southern Stock of Hake has been overexploited. This has dissipated profits but also has reduced artisanal participation.

5 Discussion

Any adequate model of the dynamics of fishery resources must consider the possibility of "ecological uncertainty". In this work we show how to calibrate the parameters of the stochastic process that represents this uncertainty. We propose selecting the dynamic resource parameters such that a biomass path is generated that is compatible with observed captures, and that reproduces the observed biomass path.

The existence of "ecological uncertainty" 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 upon the size of the biomass and productivity shocks. Therefore, wide fluctuations in the biomass level do not neccesarily imply that the fishing ground is being overexploited. This is the case of the European Anchovy fishery, whose species suffers strong oscillations in productivity due to its biological cycle. Our analysis indicates that this is not an overexploited fishery and efficient management consists of allowing high TACs in those years with high productivity shocks. However, since the available capacity of the fleet is restricted, the captures are upper limited. This means that keeping the TAC constant, as the ICES recommends, and letting the stock fluctuate is the efficient policy.

However, 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 Southern Stock of Hake, 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 share out the captures 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 evaluation 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 Southern Stock of Hake, 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 8: Stock and Catches Data for European Anchovy (Division VIII). 1987-2001

Year	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Stock	180,615	118,929	291,383	178,740	476,610	430,063	312,340	265,034	259,664	307,034	429,372	338,385	445,875	567,587	270,899
Catches	15,308	15,581	10,614	34,272	19,634	37,885	40,293	34,631	30,115	34,373	22,337	31,617	27,259	36,994	40,564

Source: Report ICES CM 2003/ACFM:07. From Table 11.7.2.2, page 426.

Table 9: Stock and Catches Data for the Southern Stock of Hake. 1982-2001

Year	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Stock	84,041	80,304	70,082	58,433	53,521	48,524	45,606	42,832	42,764	40,718	39,633	37,557	35,2687	29,566	28,677	27,150	30,356	29,686	31,068	29,403
Catches	17,593	22,950	22,179	18,9412	17,161	16,184	16,391	13,786	13,190	12,828	13,799	11,490	9,872	12,243	9,882	8,545	7,668	7,505	7,318	7,607

Source: Report ICES CM 2003/ACFM:01. From Table 6.1.13, page 281.