# Endogenous Fishing Mortalities: a State-Space Bioeconomic Model

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———— ABSTRACT ————

A methodology that endogenously determines catchability functions that link fishing mortality with contemporaneous stock abundance is presented. We consider a stochastic age-structured model for a fishery composed by a number of fishing units (fleets, vessels or métiers) that optimally select the level of fishing effort to be applied considering total mortalities as given. The introduction of a balance constrain which guarantees that total mortality is equal to the sum of individual fishing mortalities optimally selected, enables total fishing mortality to be determined as a combination of contemporaneous abundance and stochastic processes affecting the fishery. In this way, future abundance can be projected as a dynamic system that depends on contemporaneous abundance. The model is generic and can be applied to several issues of fisheries management. In particular, we illustrate how to apply the methodology to assess the floating band target management regime for controlling fishing mortalities which is inspired in the new multi-annual plans. Our results support this management regime for the Mediterranean demersal fishery in Northern Spain.

Keywords: endogenous catchability functions, stochastic age-structured models, multi-fleet models, fishing mortality fluctuations, floating band target management regime.
Classification: JEL Q22, Q38, C61; AMS 91B76, 92D25.

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# 1    Introduction

Classical dynamic bioeconomic models (Clark, 1985, 1990) have been developed in many dimensions. Recently a wider use of these bioeconomic models has emerged in a multi-fleet framework where vessels, fleets or métiers take individual decisions on effort that affect the trend of the fishery. For instance, Lleonart et al. (2003) develop the MEFISTO bioeconomic model which reproduces the fishing conditions of Mediterranean fisheries. In this model catches by age and gear are determined as a function of the total fishery mortality using the Baranov equation. Fishermen's strategy consist of improving catchability through capital investment to obtain increased fishing mortality. The model is applied to test several alternative management measures. Merino et al. (2007) apply game theory principles to predict effort dynamics at vessel level in the Blanes red shrimp fishery (northwestern Mediterranean). This study assumes that total fishing mortality is proportional to the sum of vessel's nominal effort, with the proportionality factor being the average catchability of all vessels. Under this assumption, they are able to estimate the catchability coefficients for each vessel from historical data and to use them to predict vessel efforts. Ulrich et al. (2011) use a multi-fleet model based on the Fcube advice framework to analyze the effects of using single-species management targets in mixed demersal fisheries in the North Sea. In the case of Guillen et al. (2013), the multi-fleet (and multi-species) framework is used to compare estimations of reference points with single-fleet and species assessments in the Bay of Biscay demersal fishery. The analysis assumes that the effort of each fleet is selected to maximize its landings (or profits) which depend on the fishery mortality level of the fleet.

In all the models mentioned the fleets take individual decisions on effort which are related to total fishing mortality by catchability parameters (per age, specie, defined at vessel, fleet or métiers level). Those models take into account that the individual efforts applied to all vessels (or fleets) ultimately determine the total fishing mortality of the stock and, therefore, they consider that there is an unbreakable link between the decisions taken by the individual

agents and the total fishing mortality that results from those decisions: The latter is the result of the former and the former is calculated based on the latter. In this sense, the total fishing mortality of a stock is an endogenous variable rather than an exogenous one.

Unlike previous multi-fleet bioeconomic studies, we focus on the relationship between individual actions taking by vessels or fleets and the total fishing mortality that results from those actions. To that end, a *balance constraint* between individual decisions (based on total fishing mortality, $F$, and abundance, $N$) and total fishing mortality is introduced in the analysis. The model consistently considers that total fishing mortality must be equal to the aggregate of individual fishing mortalities, i.e. $\sum_g f_g^*(F, N) = F$, where $f_g^*$ stands for the fishing mortality applied by fleet $g$ which is selected under a management maximization criterion. The inclusion of this balance constraint enables future abundances to be projected as a dynamic system that depends on contemporaneous abundance; moreover, throughout these projections the fishing mortality is not constant because it is endogenously determined by the state of the fishery.

This methodology suggests many possibilities in the assessment of the multi-annual plans (MAPs) set by the European Common Fisheries Policy (CFP) (EU, 2013). A major task when designing MAPs is the definition of their objectives. In line with the CFP, those objectives are defined by Biological Reference Points (Hilborn and Walters, 1992; Caddy and Mahon, 1995), which set the exploitation level(s) required to produce the Maximum Sustainable Yield (MSY). In the case of fisheries that target several species simultaneously with different gears, aligning exploitation levels is highly problematic across all species in order to achieve the MSY target for each stock (Da Rocha et al., 2012b; Guillen et al., 2013). The way chosen to overcome this shortcoming was to introduce flexibility in the objectives by allowing a range of values for the single species exploitation level, following the idea put forward by Hilborn (2010) and recently expanded to multispecies by Rindorf et al. (2016). The Scientific Technical and Economic Committee for Fisheries of the European

Commission (STECF) developed and applied statistical approaches to evaluate the impacts of these ranges on policy options (STECF, 2015a,b,c).

In this paper we build a stochastic multi-species multi-fleet *state variable model*, where optimal decisions taken individually by fleets (fleets, métiers or vessels) generate an *endogenous catchability function*, $\theta$, which relates fishing mortality to stock abundance, i.e. $F = \theta(N)$. In our model the catchability function is a summary of the biological and technological iterations in the fishery, and future level of effort by a fleet corresponds to their fishing opportunities (TACs) determined to achieve a specific fishing mortality. As such fishing mortality projections are "endogenous" responses to the "state" variables, the combination of abundance and stochastic processes affecting the fishery, which in the context of policy options evaluation represent different scenarios, allowing the assessment of fishing mortality fluctuations, in the robustness of management options.

As an illustration, the model is applied to the Mediterranean demersal fishery in Northern Spain, focused on black-bellied anglerfish (*Lophius budegassa*), hake (*Merluccius merluccius*) and red mullet (*Mullus barbatus*), which are important targets of the fishery. This fishery has been extensively analyzed at vessel level (Lleonart et al., 2003; Maynou et al., 2006; Merino et al., 2007; Lleonart and Merino, 2010; Maynou, 2014) and it has been found that the past and expected future economic performance of the fleet determines its fishing strategy in the form of modulations of fishing effort (days at sea) within the limits imposed by the regulators.

## 2   Methods

We introduce this section by explaining the logic of our model using a *toy model*. The total fishing mortality, $F$, is simply defined as the instantaneous rate of fishing mortality

(assuming that natural mortality is zero), i.e.

$$\frac{dN/dt}{N} = -F \Rightarrow \log N(t+1) = \log N(t) - F, \tag{1}$$

where $N$ stands for abundance.

Catches are determined by fishing mortality and abundance through the Baranov equation, $C = \frac{F}{(F+m)}(1 - e^{-(F+m)})N$ being $m$ natural mortality. In a multi-fleet framework, individual effort for fleet $g$, $f_g^*$, is the optimal response that maximizes an objective function –e.g. its profits, $\pi_g$–, i.e.

$$f_g^* = \arg\max \pi_g \equiv c_g - \text{Cost}(f_g), \tag{2}$$

with $c_g$ being the catches of fleet $g$ and "Cost" representing the cost as a function of its effort.

If the share of individual catches is proportional to the share of individual efforts, $\frac{c_g}{C} \propto \frac{f_g}{F}$, then $c_g = g(F)Nf_g$. This means that the optimal individual effort that solves equation (2) is a function of the total fishing mortality, $F$ and abundance, $N$, i.e. $f_g^*(F, N)$. Therefore, using a *balance constraint* such as

$$\sum_g f_g^*(F, N) = F, \tag{3}$$

it must hold that the total fishing mortality and the state of the fishery, the log of N, are related by $F = \theta(N)$. Taking into account the stock dynamic equation (1), abundance can be projected by using the data obtained from the current stock assessment,

$$\log N(t+1) = \log N(t) - \theta(N(t)). \tag{4}$$

Equations (1)-(4) are the basis of a multi-fleet model in which individual fleets (fleets or vessels) take their effort decisions considering the total fishing mortality of the fishery as given by a regulator. The inclusion of a balance constraint in the analysis enables the total fishing mortality to be determined endogenously as the result of the individual decisions and the current abundance of the fishery. This contemporaneous relationship between fishing mortality and abundance means that future abundance can be projected exclusively using data on current abundance. The next section extends these basic relationships to a stochastic age-structured multi-fleet, multi-species model.

## 2.1  Model

Consider a stochastic age-structured, multi-species fishery where abundance is denoted by $N_{s,a,t}$ with subscripts $s = 1, .., S$, $a = 1, ..., A(s)$ and $t = 1, ...T$ referring to species, age and time, respectively. In each period $t$ a stochastic number of recruits of each species are recruited, $N_{s,1,t}$.

We assume that recruitment (in logarithm terms) for all the species follows a *1-lag* vector autoregressive (VAR) process that can be expressed as

$$\mathbf{x}_{1,t+1} = \mathbf{c}_{\mathbf{x_1}} + \rho_{\mathbf{x}}\mathbf{x}_{1,t} + \epsilon_{\mathbf{x_1},t}, \tag{5}$$

where $\mathbf{x}_{1,t} = \ln(\mathbf{N}_{1,t}) = \ln[N_{1,1,t}, ..N_{S,1,t}]'$, $\mathbf{c}_{\mathbf{x_1}}$ is a $(S \times 1)$ constant vector, $\rho_{\mathbf{x}}$ is a $(S \times S)$ coefficient matrix and $\epsilon_{\mathbf{x_1},t}$ is an $(S \times 1)$ unobservable zero mean white noise vector process with time invariant covariance matrix $\mathbf{\Omega}_{\mathbf{x_1}}$. Note that the coefficient matrix $\rho_{\mathbf{x}}$ contents the autocorrelation parameter of each species along the main diagonal and cross autocorrelation parameters out the diagonal; i.e. the element $(i, j)$ in matrix $\rho_{\mathbf{x}}$ represents how the recruitment of species $i$ depends on previous year recruitment of species $j$.

The age-structured dynamics of the population for the $S$ species can be represented in a

compact way as the following Leslie model (Leslie, 1945):

$$\mathbf{x}_{t+1} = \mathbf{A}\mathbf{x}_t - \mathbf{Z}_t + \mathbf{c_x} + \epsilon_{\mathbf{x},t}, \tag{6}$$

where $\mathbf{c_x}$ and $\epsilon_{\mathbf{x},t}$ are $(\sum_s A(s) \times 1)$ vectors and $\mathbf{A}$ is a block matrix with dimension $\sum_s A(s) \times \sum_s A(s)$ which incorporate the recruitment dynamics, (5) and $\mathbf{x}_t$ and $\mathbf{Z}_t$ are vectors of dimension $\sum_s A(s) \times 1$ representing recruitment (in logarithm terms) and mortalities of all species. That is

$$\mathbf{x}_t = [(x_{1,1,t}, x_{1,2,t}, .., x_{1,A(1),t}), (x_{2,1,t}, x_{2,2,t}.., x_{2,A(2),t}), ..., (x_{S,1,t}, x_{S,2,t}...x_{S,A(S),t})]',$$

$$\mathbf{Z}_t = [(Z_{1,1,t}, Z_{1,2,t}, .., Z_{1,A(1),t}), (Z_{2,1,t}, Z_{2,2,t}.., Z_{2,A(2),t}), ..., (Z_{S,1,t}, Z_{S,2,t}...Z_{S,A(S),t})]'.$$

A detailed description of the elements in matrix $\mathbf{A}$ can be found in the Supplementary Materials. Note that equation(6) is equivalent to equation (1) in the *toy model*.

At fishery level, the mortality of each species $s$ can be decomposed into fishing mortality, $F_{s,a,t}$, and natural mortality, $m_{s,a}$, as $Z_{s,a,t} = F_{s,a,t} + m_{s,a}$. Moreover, fishing mortality for each age is given by $F_{s,a,t} = p_{s,a}\overline{F}_{s,t}$, where $\overline{F}_{s,t}$, is an indirect measure of the specific fishing effort of species $s$ at time $t$ and $p_{s,a}$, is the age selectivity pattern for that species. The selectivity, $p_{s,a}$, will define which part of the population is being target by fishing. For example a trawl fleet will be more focused on small/younger individuals, while long liners will be directing their mortality to larger/older individuals. In the first case the $p$ will be larger for low values of $a$, and vice-versa.

The fishery is formed by $G$ fishing units, which we refer to fleets for the sake of simplicity. Each fleet $g$ has a different stationary selection pattern for each species and age, which is denoted by $p_{g,s,a}$. As mentioned above $p$ will depend on the part of the population being caught by the fleet. This selection pattern does not vary over time (at least in the short term). Moreover, each fleet is composed of a large number of identical vessels. Each day, a

(representative) vessel from each fleet chooses a level of fishing effort for each species, $f_{g,s,t}$, measured in units of $\overline{f}_{g,s,t}$. Note that we distinguish between the fishery and fleet levels by denoting the respective mortalities by $F$ and $f$.

If the fleets are composed of a large number of vessels, the impact of each vessel on total mortalities and prices can be considered negligible. It can be therefore be assumed that each vessel decides its own fishing effort taking expectations on total mortalities as given. Formally, each vessel selects the fishing effort path that maximizes its expected net present profit taking mortalities as exogenous variables and forming expectations about future shocks on recruitment and prices. Therefore, the representative vessel from fleet $g$ decides what fishing effort will be applied to each species by solving the following maximization problem:

$$\max_{\mathbf{f}_{g,t}} \quad \sum_{t=0}^{\infty} \beta^t E_{\mathbf{x}_{1,t},\mathbf{pr}_t} \left\{ R_{g,t}(\mathbf{Z}_t, \mathbf{x}_t, \mathbf{pr}_t, \mathbf{f}_{g,t}) - \text{Cost}_{g,t}(pr_{\text{fuel},t}, \mathbf{f}_{g,t}) \right\}, \tag{7}$$
$$s.t. \quad Z_{g,t} \quad \text{is taken as given,}$$

where $\mathbf{f}_{g,t} = (f_{g,1,t}, f_{g,2,t}, ...f_{g,S,t})$ represents the vector of fishing efforts applied by the fleet $g$ to all the species, $E_{\mathbf{x}_{1,t},\mathbf{pr}_t}$ is the expectation on future recruitments and prices, and $\beta$ is the discount factor. Note that the revenues of the fleet, $R_{g,t}$, depend on total mortalities ($\mathbf{Z}_t$), abundances ($\mathbf{x}_t$), prices ($\mathbf{pr}_t$) and its own fishing effort ($\mathbf{f}_{g,t}$) and that the costs of the fleet, $\text{Cost}_{g,t}$, depend on the price of the fuel ($pr_{\text{fuel},t}$) and its own fishing effort ($\mathbf{f}_{g,t}$). Note also that the maximization problem (7) is equivalent to equation (2) in the *toy model*. An example of the revenue and cost functions for the case of constant elasticity demands functions for all species and a quadratic cost function for all fleets is illustrated in the Supplementary Materials.

The solution of this maximization problem is a level of fishing effort for each fleet and species that depends on the **state variables** of the fishery, i.e. $\mathbf{x}_t$, $\mathbf{pr}_t$ and $\mathbf{Z}_t$, denoted as $f^*_{g,s,t}(\mathbf{Z}_t, \mathbf{x}_t, \mathbf{pr}_t)$[1]. Taking a first order expansion around reference points for mortalities and

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[1]See the Supplementary Materials for how this expression looks for the case of constant elasticity demand

abundance, $(\overline{\mathbf{Z}}, \overline{\mathbf{x}})$ and stationary values for prices, $\overline{\mathbf{pr}}$, this optimal level of the fishing effort for each fleet and species can be expressed in difference terms as

$$\Delta f^*_{g,s,t} = \mathbf{Jx}_{g,s}\Delta\mathbf{x}_t + \mathbf{JZ}_{g,s}\Delta\mathbf{Z}_t + \mathbf{Jpr}_{g,s}\Delta\mathbf{pr}_t, \tag{8}$$

where $\Delta f^*_{g,s,t} = f^*_{g,s,t} - \overline{f}_{g,s}$, $\Delta\mathbf{x}_t = \mathbf{x}_t - \overline{\mathbf{x}}$, $\Delta\mathbf{pr}_t = \mathbf{pr}_t - \overline{\mathbf{pr}}$, $\Delta\mathbf{Z}_t = \mathbf{Z}_t - \overline{\mathbf{Z}}$ and $\mathbf{Jx}_{g,s}$, $\mathbf{JZ}_{g,s}$ and $\mathbf{Jpr}_{g,s}$ represent the respective Jacobians evaluated at the reference points $(\overline{\mathbf{Z}}, \overline{\mathbf{x}})$ and the stationary value $\overline{\mathbf{pr}}$.

## 2.2   Endogenous fishing mortalities

Although each representative vessel considers total mortalities as given when solving the maximization problem (7), the aggregate mortality of the fishery must be consistent with the result of the vessels' behavior. That is, expectations on total mortality must satisfy the *"rational expectations hypothesis"* (Muth, 1961). Formally, total mortality of species $s$ for a given age $a$ is endogenously determined by

$$Z_{s,a,t} = m_{s,a} + T_s \sum_{g=1}^{G} p_{g,s,a} f^*_{g,s,t}(\mathbf{Z}_t, \mathbf{x}_t, \mathbf{pr}_t), \tag{9}$$

where $T_s$ represents the maximum fishing days for each species. Note that equation (9) is the balance constraint equivalent to equation (3) in the *toy model*.

It is worth highlighting that in a world with *"rational expectations"* the mortality vector $\mathbf{Z}_t$ is an endogenous variable, so fishery managers should not use it as a policy variable. We assume that instead managers decide on a fishing effort variable such as $T_s$. We abstract from other management policy variables such as technical limitations to gears or engines.

Total mortalities can be derived in a two steps process. First, taking as given the state of

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functions for all species and quadratic cost functions for all the fleets

the fishery and $Z_{s,a,t}$, the optimal fishing effort $f^*_{g,s,t}$ for each fleet and species is calculated using expression (8) which is the solution of the vessel maximization problem (7). Second, $f^*_{g,s,t}$ is substituted into equation (9) and we solve for $Z_{s,a,t}$ and the total mortality vector $\mathbf{Z}_t$ is shaped.

From the first step of the proposed procedure, total mortality by age and species can be written in difference terms as

$$\Delta Z_{s,a,t} = \Delta F_{s,a,t} = T_s \sum_{g=1}^{G} p_{g,s,a}[\mathbf{Jx}_{g,s}\Delta \mathbf{x}_t + \mathbf{JZ}_{g,s}\Delta \mathbf{Z}_t + \mathbf{Jpr}_{g,s}\Delta \mathbf{pr}_t]. \tag{10}$$

Solving this equation for $Z_{s,a,t}$, the total mortality vector $\mathbf{Z}_t$ can be shaped as a function of the biological, $\mathbf{x}_t$, and economic, $\mathbf{pr}_t$, states of the fishery, i.e.

$$\Delta \mathbf{Z}_t = \Delta \mathbf{F}_t = \Theta_{\mathbf{x}}(\vec{T})\Delta \mathbf{x}_t + \Theta_{\mathbf{pr}}(\vec{T})\Delta \mathbf{pr}_t, \tag{11}$$

where $\Theta_{\mathbf{x}}(\vec{T})$ and $\Theta_{\mathbf{pr}}(\vec{T})$ represent the *endogenous catchability* matrices that relates fishing mortality to all the states of the fishery summarizing all biological and technical interactions. Formally,

$$\Theta_{\mathbf{x}}(\vec{T}) = \left(\frac{1}{\vec{T}}\mathbf{I}_{\sum A(s)} - \overline{\mathbf{JZ}}\right)^{-1} \overline{\mathbf{JX}},$$

$$\Theta_{\mathbf{pr}}(\vec{T}) = \left(\frac{1}{\vec{T}}\mathbf{I}_{\sum A(s)} - \overline{\mathbf{JZ}}\right)^{-1} \overline{\mathbf{Jpr}},$$

where $\Theta_{\mathbf{x}}(\vec{T})$ and $\Theta_{\mathbf{pr}}(\vec{T})$ have dimensions $(\sum A(s) \times \sum A(s))$ and $(\sum A(s) \times (S+1))$, respectively. The elements of the matrix $\overline{\mathbf{JZ}}$ are weighted average of the Jacobians of the fleets. For example, in the row associated with $Z_{s,a}$, the elements of $\overline{\mathbf{JZ}}$ are equal to $\sum_{s,a} p_{g,s,a}\mathbf{Jx}_{g,s}$.

Equation (11) summarizes the conclusion of our methodology: the total mortality vector can be estimated as a combination of the contemporaneous abundance and stochastic processes affecting the fishery. Expressing fishing mortalities in this manner is very convenient for
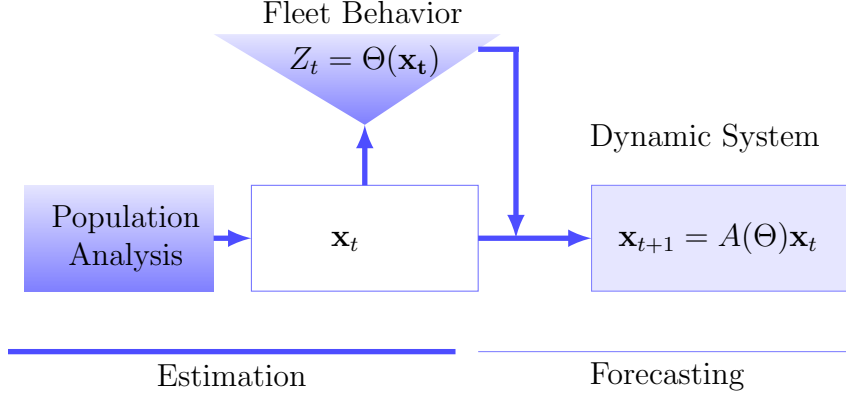
Figure 1: The logic behind endogenous fishing mortality. Population analysis provides data on current stock $(x_t)$. Assuming that fleets take optimal decisions, fishing mortality can be estimated as a function of the current stock, $Z_t = \Theta(\mathbf{x_t})$. This enable future stock $(x_{t+1})$ to be projected

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forecasting purposes because it enables future abundances to be projected as a dynamic system that depends on current abundance. This can be seen by substituting equation (11) into the stock dynamics equation (6) in difference terms,

$$\Delta \mathbf{x}_{t+1} = \left[\mathbf{A} - \Theta_{\mathbf{x}}(\vec{T})\right] \Delta \mathbf{x}_t - \Theta_{\mathbf{pr}}(\vec{T})\Delta \mathbf{pr}_t + \epsilon_{\mathbf{x},t}. \tag{12}$$

Note that throughout these abundance projections the fishing effort is not constant because it is endogenously determined by the state of the fishery that summarizes the biological and economics interactions. Figure 1 illustrates the logic behind this idea for the deterministic case.

# 3    A numerical illustration

In order to assess the relevance of the mortality rates endogeneity in a multi-fleet framework, we apply the methods described above to the Mediterranean demersal fishery in Northern

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Spain (GSA 06, defined in EU, 2011). Figure 2 illustrates the area. The biological population data and technological fleet data used for the calibration of the model are extracted from STECF (2014). The data refer to three species: Black-bellied anglerfish (coded as ANK), Hake, (coded as HKE) and Red mullet (coded as MUT), and to two fleets. Due to the lack of age structured data by fleet, the fleets' information were generated by applying a logistic model to catch-at-age data, roughly approximating one fleet that catches the older fish and another which is more focused on younger individuals.
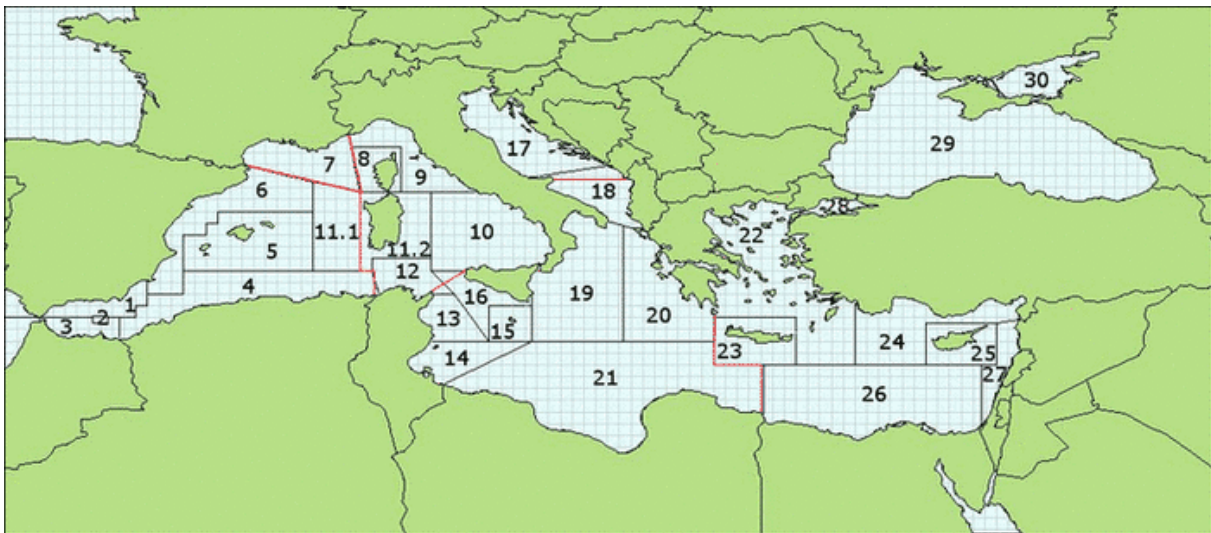


Figure 2: Geographical Subareas of the Mediterranean and Black Seas. GS 06 is located in Northern Spain

## 3.1   Calibration

Parameters of natural mortality, weight and selection patterns by age for the three species are shown in the Supplementary Materials. The selection patterns for each species and age is defined as the sum of selectivity of the two fleets, i.e. $f_{s,a} = f_{o,s,a} + f_{y,s,a}$, where subscripts $o$ and $y$ stand for the fleet targeting old and young fish, respectively. The time series used for abundance, $N_{s,a,t}$, and total mortality, $Z_{s,a,t}$, correspond to 2004-2013. For the same period,

we take the selling prices of the three species from the fish market in Blanes (Spain)[2] which is a Catalan market where the three species are exhaustively sold. Fuel price was taken from the Spanish National Statistics Institute (INE).

The cost function of each fleet is calibrated as a quadratic convex function and the demand function of each species is calibrated as a constant elasticity demand which can be parameterized through the elasticity parameter (see Supplementary Materials for more details). The parameters of these functions are selected in such way that the time series data of the fishing effort generated by the model, $\overline{F}_{s,t}$, match the data for the three species. Summing up mortalities rates over age, the fishing effort for species $s$ can be obtained as

$$\overline{F}_{s,t} = \frac{\sum_a (Z_{s,a,t} - m_{s,a})}{\sum_a p_{s,a}}.$$

Using this expression a time series for specific fishing mortality can be calculated for each species for 2004-2013 based on the data, $\{\overline{F}_{s,t}\}^{data}$. This time series can be compared with the one obtained by solving the multi-fleet bioeconomic model proposed for a particular set of cost and elasticity parameters, $\{\overline{F}_{s,t}\}^{model}$. The parameters are selected in such a manner that the distance between $\{\overline{F}_{s,t}\}^{data}$ and $\{\overline{F}_{s,t}\}^{model}$ is close enough to zero. A more detailed description of the algorithm used is shown in the Supplementary Materials.

The results of the calibration appear in Table 1. Since the cost function of each fishery is calibrated as the sum of a quadratic function for each species, the effects on the costs can be distinguished among fleets and species (see Supplementary Materials for more details). The two first rows in Table 1 show the marginal cost per unit of effort. Observe that this variable is qualitatively different across fleets. While, the highest marginal cost per unit of effort in the fleet targeting older fish corresponds to the fishing of anglerfish and hake, the highest marginal cost per unit of effort for the fleet targeting young fish correspond to the

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[2]Annual average prices for the three species have been calculated based on 71,348 registers from the wholesale market with weights and amounts.

Table 1: Mediterranean Demersal Fishery (Northern Spain)
Calibration

|  | Species | | |
| --- | --- | --- | --- |
|  | ANK | HKE | MUT |
| Marginal Cost per unit of effort (Euros) | | | |
| Older Fish Fleet | 3376 | 2622 | 21947 |
| Young Fish Fleet | 2948 | 6327 | 9178 |
| Fuel impact on marginal cost (Euros) | | | |
| Older Fish Fleet | 60.97 | 63.65 | 25.75 |
| Young Fish Fleet | -67.12 | 51.63 | -337.86 |
| Price Elasticities (absolute terms) | 0.4668 | 0.1069 | 0.1767 |

Source: Own calculations. Equilibrium values for fishery performance and demand functions for 2004-2013 are computed by using the equilibrium $\overline{F}_s$ values calibrated to match time series data.

fishing of red mullet and hake.

Numbers in the third and fourth rows in Table 1 show the impact on the marginal cost of increasing the fuel price in one Euro. Results for fuel impact on the marginal cost are also qualitatively different across fleets. An increase in fuel price would increase the marginal costs of the fleet targeting older fish associated mainly with the fishing of anglerfish and hake and in lesser extent with the fishing of hake. By the contrary, for the fleet targeting younger fish, an increase in fuel price would increase the marginal cost of fishing hake and reduce the marginal costs of fishing anglerfish and red mullet. These differences across species may lead to a substitution of capturing one specie by another when there are changes on fuel prices.

Price elasticities that appear in the last row in Table 1 represent the percentage change in the fish demanded in response to a one percent change in its own price. Observe also that the demand for anglerfish is more sensitive to changes in prices than the demand for hake and red mullet; a 10% increase in the price would represent a reduction of 4.7% in anglerfish's demand, 1.1% in hake's demand and 1.8% in mullet's demand.

Once the multi-fleet model has been adequately calibrated, it can be used to assess the fishery under different scenarios and policies.

## 3.2  Endogenous Status Quo

The main advantage of the multi-fleet model proposed is that it can be used to forecast future total mortalities given the current behavior of fleets. The model endogenously determines total fishing mortalities as a combination of the contemporaneous abundance and stochastic processes affecting the fishery (see equation 11). These estimates are used to project future abundances as a dynamic system that depends on current abundance. It is worth highlighting that throughout the projections, total fishing mortalities are not constant over time but are endogenously determined given the current behavior of fleets. In this sense, these projections can be said to represent what we call the *Endogenous Status Quo*.

In practice, assessing of any policy scenario means comparing biological projections derived from that scenario with the projections associated with maintaining the current fishing effort constant in the future. Our multi-fleet framework indicates that the projections associated with the endogenous status quo are the contra-factual scenario with which any policy scenario should be compared.

The endogenous status quo is forecast for the Mediterranean Hake fishery. Technically we start by estimating total mortalities for 2013, which is the last year for which data are available, and finding matrices $\Theta's$ in equation (11) using the algorithm detailed in the Supplementary Materials. Once $\mathbf{Z}_{2013}$ is known the abundance for the next period, $\mathbf{x}_{2014}$, is projected using the dynamic population equation (6). A realization of the stochastic process for prices is drawn up for 2014, $\mathbf{pr}_{2014}$, using the calibrated VAR process (see Supplementary Materials). Once the new state of fishery ($\mathbf{x}_{2014}$ and $\mathbf{pr}_{2014}$) is known, total mortality for 2014 is forecast again applying the algorithm to find matrices $\Theta's$ in equation (11) and so

on.

Figures 3(a), 3(b) and 3(c) illustrate the forecasting results for specific fishing paths, $\overline{F}_{s,t}$, for all three species, under the endogenous status quo. Figure 3(a) shows the observed data for the period 2004-20013 and a number of forecast paths for the period 2014-2020. All projections are based on the initial condition estimated for 2013 and each represents a different realization of the shocks affecting the fishery. The Supplementary Materials show the estimates of the 1-lag vector autorregresive processes used for recruitment and prices. It can be seen that for all three species, the differences between the forecast paths increase as time goes on.

Figure 3(b) illustrates a box plot with the median and 25th and 75th percentiles of the fishing effort projections for 2014-2020 based on 1000 realizations, normalizing the initial situation around 1 for all three species. It can be seen that the fishing effort in the long term is not equal across species. Hake shows an increase in fishing effort by 2020, while anglerfish and mullet shows a decrease. Moreover red mute shows larger deviations with respect to the 2013 value than anglerfish and hake. Finally, figure 3(c) shows the evolution of the abundance deviations per age for all three species.

## 3.3  Floating Band Target Regime for fishing mortality

The new European Union MAPs set floating band target regimes for controlling reference points for fishing mortalities, borrowing from the ideas of Hilborn (2010). This regime consist of setting lower and upper bounds on fishing mortalities around MSY target points; fishing mortalities floats freely within the band and managers intervene occasionally when it crosses over the band.

In the Mediterranean demersal fishery current fishing efforts are above the targets and most of the species are overexploited (Colloca et al., 2013). The proposed multi-fleet model is

used to project future fishing mortality paths that guarantee that the target is reached in the short term. To that end we assess a policy consisting of reducing the number of the fishing days accordingly (all else being equal). In the benchmark calibration the number of fishing days, $T$, is normalized to one, so the new policy consists of reducing the number of days by a percentage that enables the fishing target to be reached at the beginning of the forecasting period. Table 2 shows the status quo and target fishing mortalities for each species as well as the percentage reduction on fishing days needed to achieve the target. The numbers in the third row should be interpreted such as showing that, for instance, a reduction of 89.22% in the number of fishing days would enable the fishing mortality for hake to be reduced from the current value, $F = 0.7627$, to its target $F = 0.0822$.

Table 2: Floating Target Regime for $\overline{F}$.
Mediterranean Demersal Fishery (Northern Spain)

|  | Species | | |
|---|---|---|---|
|  | ANK | HKE | MUT |
| F target[1] | 0.0995 | 0.0822 | 0.3396 |
| F status quo[1] | 0.6628 | 0.7627 | 0.9511 |
| Reduction in fishing days[2] (%) | 84.99 | 89.22 | 64.30 |

[1] Source: STECF (2014).
[2] To reach $F$ target in 2014. Calculated as (Ftarget - Fsq)/Fsq.

It should be noted that we do not use the bioeconomic model for managing the fishery. Our recommendation is not that the fishing days for hake should be reduced by 89.22%. We state only that if the fishing days for hake are reduced by 89.22% then the fishing mortality target imposed by managers would be achieved in one year. This result is used as a tool to analyze how fleets would respond to such reductions. Formally these responses of the fleets to the policy of reducing accordingly the number of fishing days –the transitional dynamics– are computed around the reference points. The average of the Jacobians are computed to obtain the new $\Theta_{\mathbf{x}}(\vec{T})$ and $\Theta_{\mathbf{pr}}(\vec{T})$ in equation (11) around the target for $F$ shown in Table 2. As initial conditions, we set $\Delta\mathbf{x} = \log N_{2013} - \log N_{\mathbf{target}}$ and $\Delta\mathbf{pr} = [0\ 0\ 0\ 0]$.

Figures 4(a), 4(b) and 4(c) show the projected fishing mortality for the three species under the policy of reducing the number of fishing days accordingly. Figure 4(a) shows the observed data of the fishing mortalities for 2004-2013 and a number of forecast paths for 2014-2020 assuming in all of them that the number of fishing days has been reduced accordingly to guarantee that target $F$ target is reached (see Table 2). All projections are based in the initial condition estimated for 2013 and each one represents a different realization of the shocks affecting the fishery. As expected this policy drastically reduces fishing mortality for all three species and, consequently the target $F$ is reached in 2014. Figure 4(b) illustrates a box plot with the median and 25th and 75th percentiles of the fishing mortality projections for 2014-2020 based on 1000 realizations, normalizing the initial situation around 1 for all three specie. Figure 4(c) shows the evolution of the abundance deviations per age. We see that the projected paths show slightly differences between species. The reduction in fishing days leads to smother forecast paths for hake and anglerfish than for red mullet (see the size of the box plots in Figure 4(b) and the size of the stock deviations in Figure 4(c)). Nevertheless, for the all three species the median of the paths floats around the target $F$ in quiet a narrow band. So in that sense, the model seems to support the floating band target regime inspired by the new MAPs.

The analysis is supplemented by the forecast of the paths assuming that the reduction in the fishing days is accompanied by a permanent shock in fuel prices. In particular, we study the impact of an 5% annual increase in fuel prices. Figure 5 shows the forecasting results under this scenario. Again the results of this policy are quite different from one to another of the three species. The increase in the fuel price leads to an increase in the fishing mortality above its target for anglerfish during the whole period analyzed. In the case of hake, the increase in the fuel price leads to a reduction of the fishing mortality below its target in the short term but to an increase above the target in the long term. The opposite happens with the red mulet; the increase in the fuel price lead to an increase of the mortality above the target in the short term and a reduction below the target in the long term. Again, the

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Table 3: Fishing Mortality $(\overline{F})$
Mediterranean Demersal Fishery (Northern Spain)

| Targets and Policies | Species | | |
| --- | --- | --- | --- |
| | ANK | HKE | MUT |
| F target[1] | 0.0995 | 0.0822 | 0.3396 |
| Reduction in fishing days (all else being equal, %)[2] | 84.70 | 89.40 | 63.14 |
| Reduction in fishing days (5% annual increase in fuel price, %)[2] | 83.72 | 90.14 | 58.38 |

[1] Source: STECF (2014).

[2] Results from the model. Based on 1000 simulations over 7 years.

red mullet shows wider oscillations over the simulated paths than the hake and anglerfish. Fishing mortality oscillations move in a $\pm 2\%$ range for anglerfish and hake while for the red mullet the range is $\pm 3\%$.

Table 3 reports the average reduction on the fishing mortality under the two scenarios analyzed considering the $F$ target for each species. The average levels are based on 1000 simulations over 7 years, 20014-2020. Note that the average reduction of the fishing mortalities implied for the model are very close to the ones considering as needed to reach the $F$ target (compare the second row in Table 3 with the third row in Table 2). When the reduction in the fishing days is accompanied by a 5% increase in fuel price, the policy is pretty effective for anglerfish and hake but less effective for red mullet. Nevertheless, we can state that when the reduction in the fishing days is accompanied by a 5% increase in fuel price, the policy is less effective in reaching the $F$ target than without a permanent increase in fuel price especially for the red mullet case.

# 4   Discussion

This article presents a methodology for endogenously determining catchability functions that relate fishing mortality to stock abundance. We extend the bioeconomic stochastic

models by (Da Rocha et al., 2012a,b, 2013, 2016) to a multi-fleet framework, where the individual behavior of each fishing unit endogenously determines the aggregate performance of the fishery. Fishing units optimally select the level of fishing effort to apply considering aggregate mortality as given. The introduction of a balance constraint enables the total fishing mortality to be determined consistently with the individual decisions.

The key point in the analysis is that decisions taken by individual fishing units about fishing effort are based on expectations as regards total fishing mortalities. But those mortalities are merely the aggregation of individual decisions. So we argue that any bioeconomic model that includes individual fishing decisions must consistently consider a balance constraint that guarantees that the total fishing mortality generated by the model is equal to the aggregate of individual fishing mortalities. This aspect has not been taken into account in previous bioeconomic models disaggregated at fleets, vessels or métiers level (Lleonart et al., 2003; Maynou et al., 2006; Merino et al., 2007; Ulrich et al., 2011; Guillen et al., 2013; Maynou, 2014).

With this approach future abundance can be forecast as a combination of contemporaneous abundance and stochastic processes affecting the fishery. This may seem a subtle distinction but it has important implications from a practical point of view. The main one is that fleet behavior can be estimated from observed abundance and this enables total fishing mortality, $F$, to be forecast. This estimated $F$ can be understood as alternative simulated scenarios, and it can therefore be used as the contrafactual in assessing policy scenarios for any fishing management option.

It is worth highlighting that the number of fishing units is not relevant to our analysis. There could be a single fleet and the total mortality could still be calculated endogenously. The relevant aspect is not the disaggregation aspect of the bioeconomic model but the fact that the decisions on fishing effort are based on expectations as regards total fishing mortality. That is, when decisions about fishing effort are taken, total fishing mortality is considered

as a given variable. In equilibrium these individual decisions must be consistent with the overall mortality generated from them. In summary the size of the fleets does not affect the methodology to calculate endogenous fishing mortalities, although it may affect the variables selected for the management of the fishery when there is uncertainty about the stock (Da Rocha and Gutiérrez, 2012).

It should be also considered that recruitment has been modeled in a very simple manner in this methodology. Uncertainty is included by assuming that current recruitment depends on the previous year recruitment of all species through an autoregressive process. This assumption can be behind the increase in the size of the fluctuations of the simulated fishing mortalities over time (see Figures 3(a) and 3(b)). It would be possible to consider additionally a standard stock-recruitment relationship, such as Beverton-Holt or Ricker, by adding a term in the recruitment equation, (5); in such case, recruitment can be expressed as $\mathbf{x}_{1,t+1} = \mathbf{c_x} + \rho_\mathbf{x}\mathbf{x}_{1,t} + \mathbf{SR}(\mathbf{x_t}) + \epsilon_{\mathbf{x},t}$, where $\mathbf{SR}$ represents the stock-recruitment relationship.

This methodology for endogenizing fishing mortality can be applied to several issues related to fishing management. As an example, in this article we use it to assess the robustness of the F ranges regime based in the new MAPs for the Mediterranean demersal fishery in Northern Spain. This floating band target regime consist of setting lower and upper bounds around $F$ target; fishing mortality floats freely within this band and managers intervene occasionally when $F$ crosses over the band. We use the proposed multi-fleet model to assess a policy that guarantees that the MSY target is reached in the short term. From that point future (endogenous) fishing mortality paths are projected and the size of fluctuations of $F$ over time is examined. This analysis enables us to extract conclusions about the effectiveness of the policy option. In particular, we found that the projections of the endogenous mortalities float around the target $F$ in a quiet narrow band and we can state that this type of management regimen is supported by the analysis.

The population dynamics of the Mediterranean fishery case study is described with a stan-

dard age-structure model and the cost structure and decision making are simpler than previous studies. This simplicity enables the analysis focusing on the novelty of endogenizing the fishing mortality, as a result of the interaction decisions among individual fleets participating in the fishery. For instance, we consider that the cost function of each fleet is the sum of a quadratic function representing each species. This means that we are able to distinguish the contribution of the fishing of each species to the cost of the fleet even though they are often caught simultaneously. The methodology could be applied considering more complex cost functions that better represent the economic interaction of mixed fisheries whenever data are available. Another shortcoming of our analysis is that Mediterranean fisheries are highly multi-specific and we only have considered some of the species caught. We consider our numerical simulation as an example of how to apply the proposed methodology. The study of the fishery could be more realistic in many dimensions; for instance, a secondary species function could be added so that positive profits could be guaranteed as in Lleonart et al. (2003). On the other hand, our analysis is based on year period decisions; but the proposed methodology is generic in this aspect allowing daily, weekly or seasonal analysis. In this sense future research could verify if the narrowness of the floating band around the targer $F$ could be affected by temporal factors as those found in Guillen and Maynou (2014).

Many other issues of fisheries management are susceptible to be analyzed under this perspective. For example, in multi-agent contexts it is very convenient to analyze the strategic interactions between the different fishing units deciding on fishing efforts because they all seek to maximize the benefit from exploiting the same resource (Bailey et al., 2010). These aspects have been studied extensively using game theory principles, at country level (Munro, 1979; Kennedy, 1987), fleet level (Sumaila, 1997) or vessel level (Merino et al., 2007). Applying the methodology proposed here is feasible under those principles: The expectations would be harder to characterize but in the end a balance constraint that relates individual decisions to aggregate variables can be written.

Another advantage of the proposed methodology is that future abundances can be forecast as a combination of contemporaneous abundances and stochastic processes affecting the fishery. This enables future abundance to be estimated in a form abstracted from the model, which may simplify the analysis in some contexts.

Finally, we would like to highlight the fact that this unbreakable link between individual decisions and aggregate variables is not new in other fields such as economics. For instance, in neoclassical (Walrasian) economic models consumers take decisions on the distribution of their income between different goods taking the prices of those goods as given. In this context the aggregation of all consumers decisions determines prices in such a way that the demand and supply of goods balance (Walras, 1900; Arrow and Debreu, 1954). So the methodology that we propose brings to fishery management one of the cornerstones of economic analysis.

# 5   Supplementary Materials

Supplementary material is available at the *ICESJMS* online version of the article. This material is divided in three sections. Section SM1 shows in detail the multi-species age-structured model used to represent the fishery. Section SM2 shows how fleets take optimal decisions for the case of constant elasticity demand functions for all species and quadratic cost functions for all the fleets. Section SM3 shows the biological parameters used for representing the Mediterranean demersal fishery as well as the description of the algorithms used to calibrate the model and the endogenous status quo.

# 6   Acknowledgments

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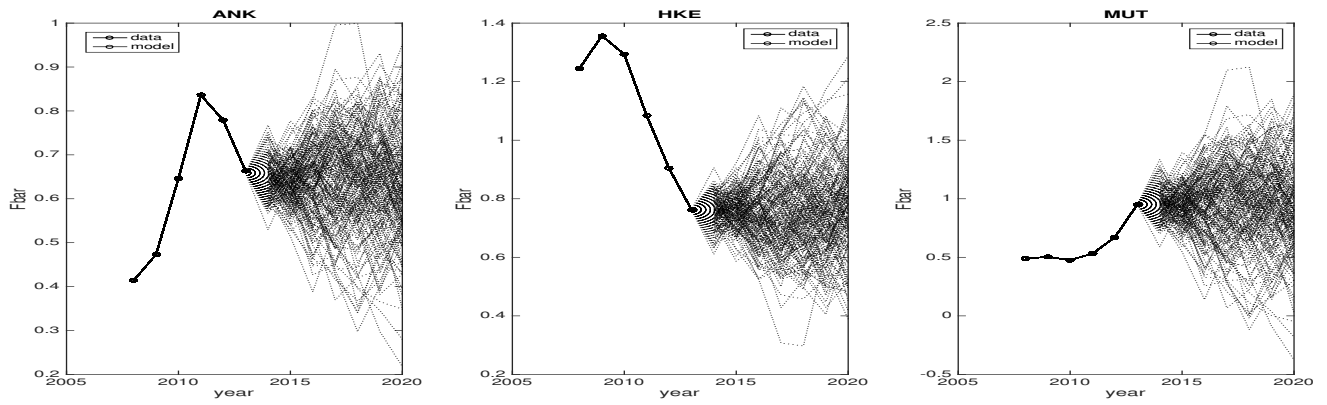
(a) Observed data for 2004-13 and projections of $\overline{F}$ for different realizations of the shocks for 2014-2020
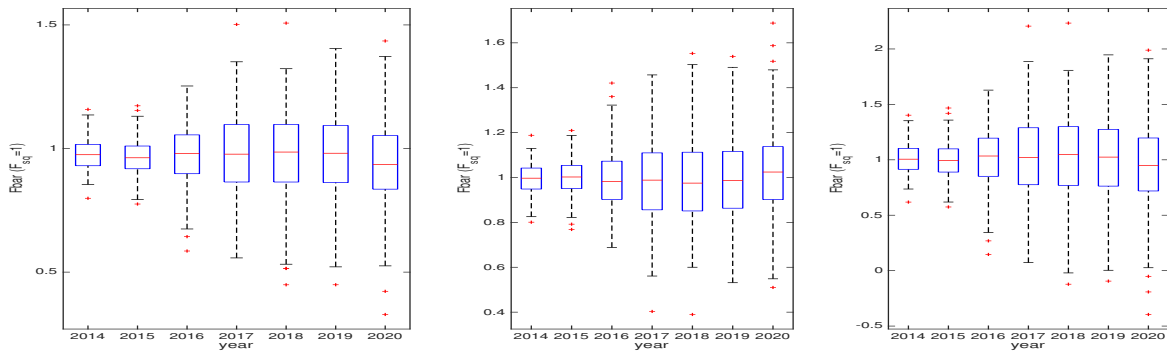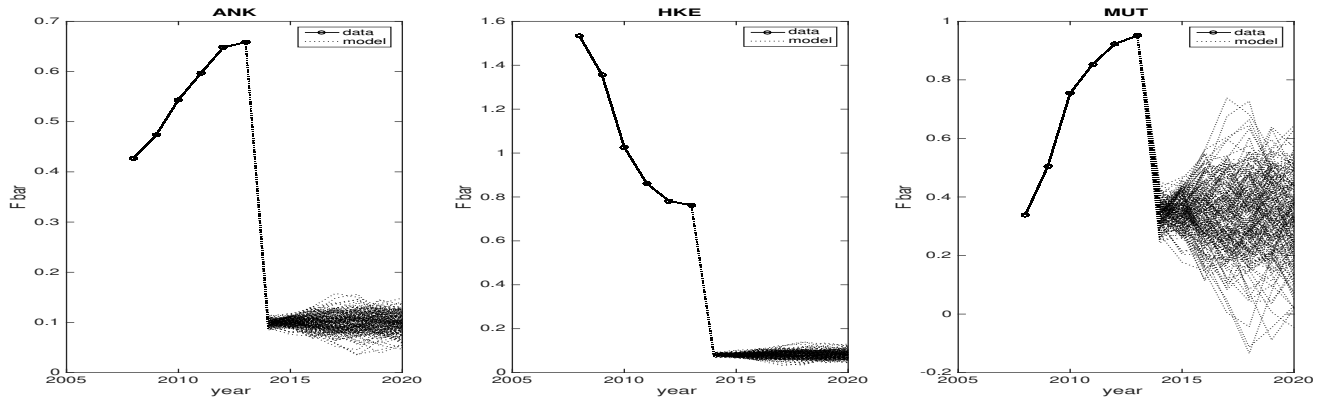


(b) Box plot with the median and 25th and 75th percentiles of $\overline{F}$ projections based on 1000 simulations
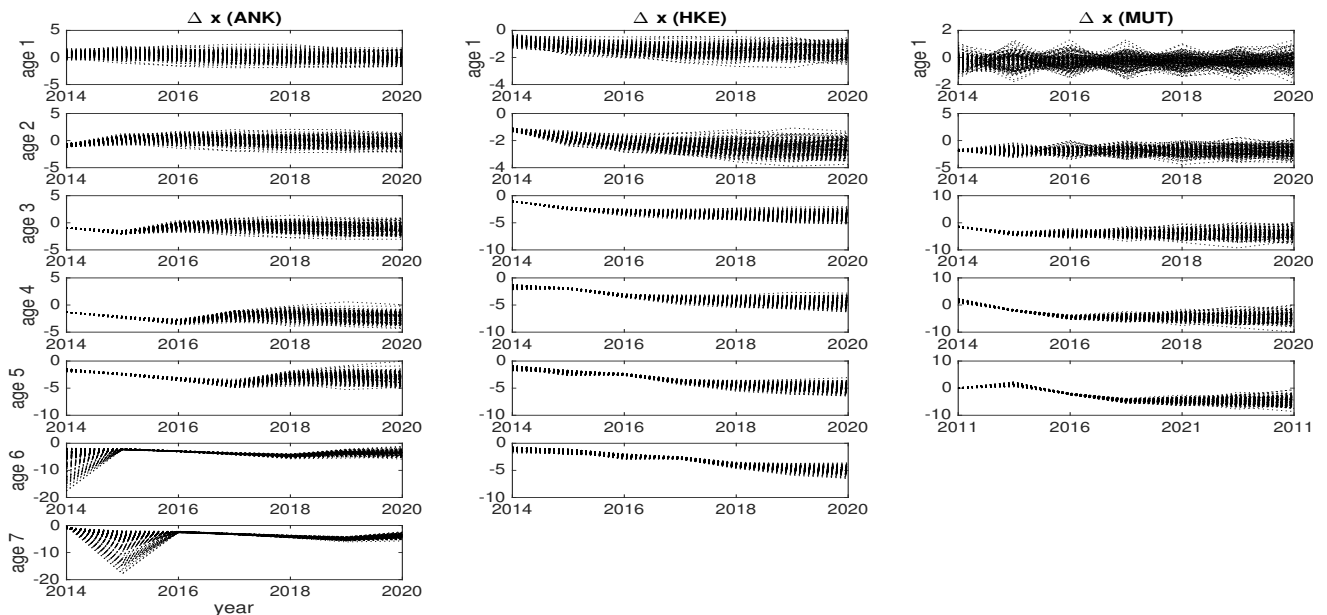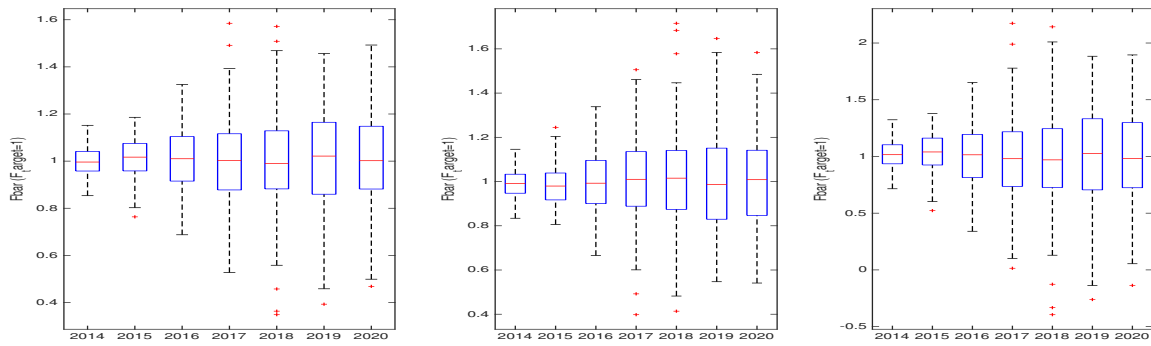


(c) Abundance deviations projections ($\Delta x$) per age for different realizations of the shocks for 2014-2020
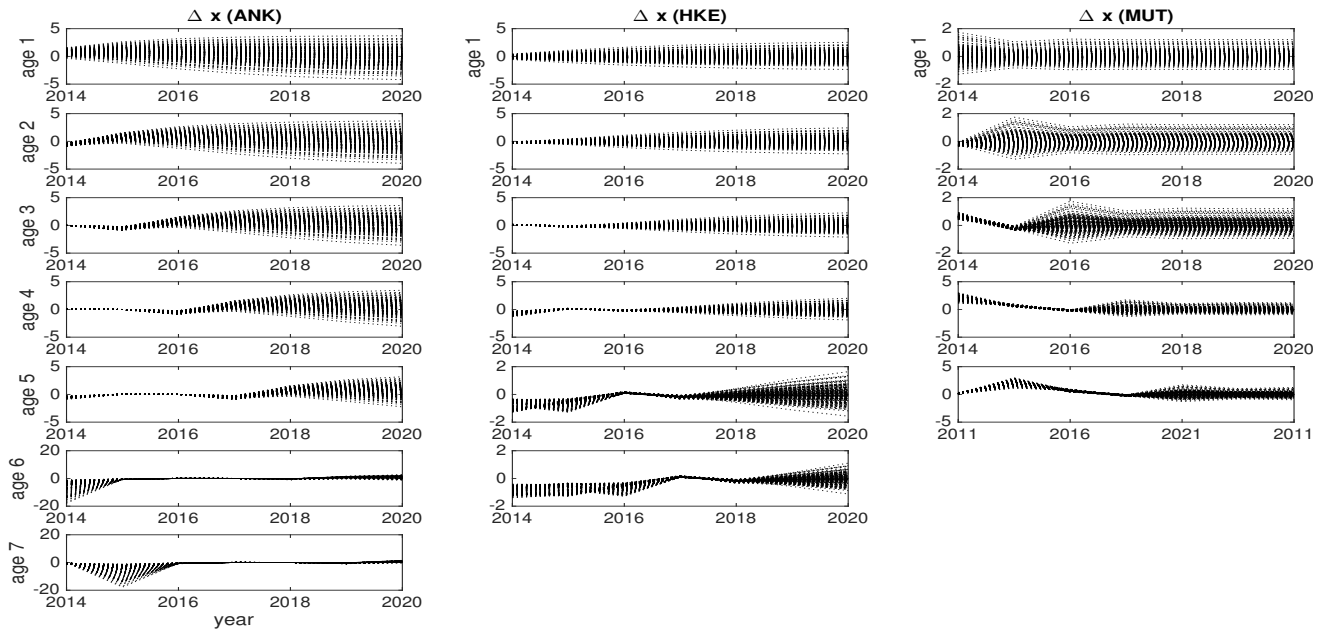
Figure 3: Fishing Mortalities in the Endogenous Status Quo Scenario. Mediterranean Demersal Fishery (Northern Spain). ANK (Blackbellied anglerfish, *Lophius budegassa*), HKE (*Merluccius merluccius*), MUT (Red mullet *Mullus barbatus*)

(a) Observed data for 2004-13 and projections of $\Delta F$ for different realizations of the shocks for 2014-2020



(b) Box plot with the median and 25th and 75th percentiles of $\overline{F}$ projections based on 1000 simulations



(c) Abundance deviation projections ($\Delta x$) per age for different realizations of the shocks for 2014-2020

Figure 4: Floating Band Target Regime for Fishing Mortalities. Projections under the policy of reducing the number of fishing days accordingly. Mediterranean Demersal Fishery (Northern Spain). ANK (Blackbellied anglerfish,*Lophius budegassa*), HKE (*Merluccius merluccius)*, MUT (Red mullet *Mullus barbatus)*
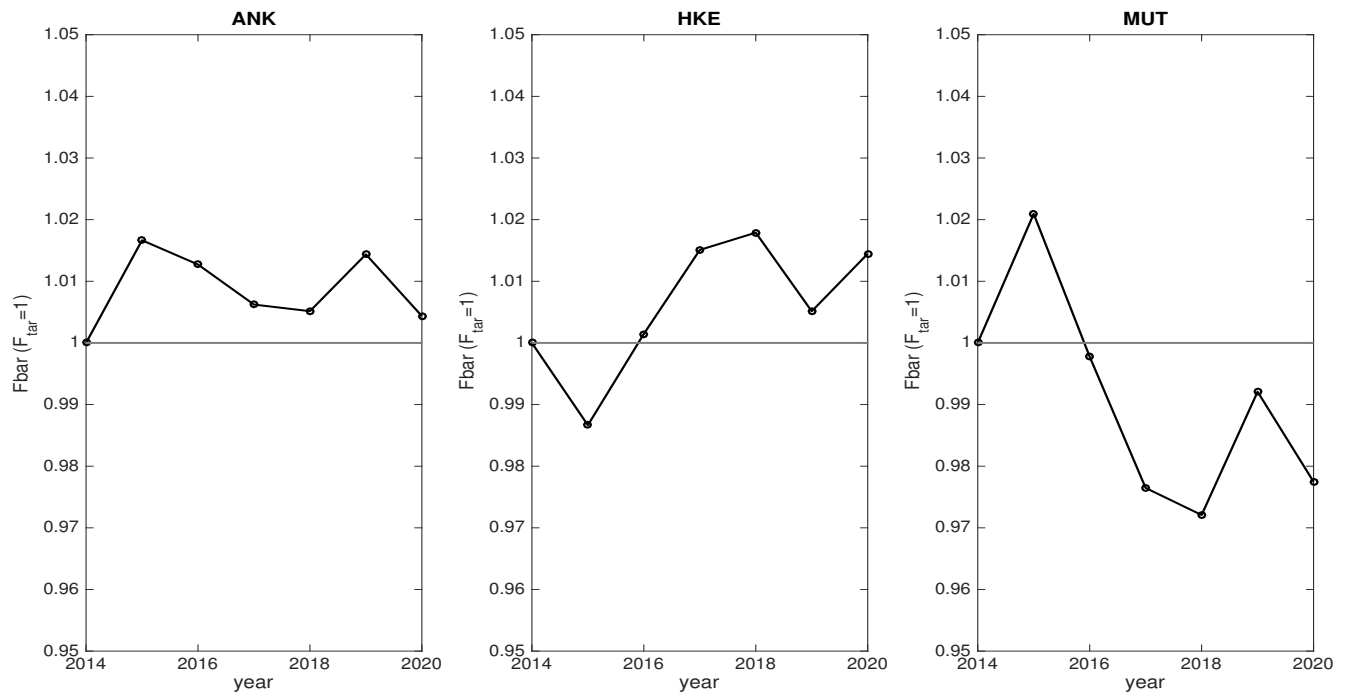
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Figure 5: Floating Band Target Regime for Fishing Mortalities. Projections under the policy of reducing the number of fishing days accordingly accompanied by a 5% permanent increase in fuel price. Mean of fishing mortality projections based on 1000 simulations. Mediterranean Demersal Fishery (Northern Spain). ANK (Blackbellied anglerfish, *Lophius budegassa*), HKE (Hake, *Merluccius merluccius*) and MUT (Red mullet, *Mullus barbatus*)