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Enero 2017

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A dynamic economic equilibrium model for the economic assessment of the fishery stock-rebuilding policies

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January 2017

Abstract

The paper develops and analyses a dynamic general equilibrium model with heterogeneous agents that can be used for assessment of the economic consequences of fish stock-rebuilding policies within the EU. In the model, entry and exit processes for individual firms are endogenous, as well as output, employment and wages. This model is applied to a fishery of the Mediterranean Sea. The results provide both individual and aggregate data that can help managers in understanding the economic consequences of rebuilding strategies. In particular, this study shows that, for the application presented, all aggregate results improve if the stock rebuilding strategy is followed, while individual results depend on the indicator selected.

Keywords: Macroeconomics; General equilibrium model; Multiannual management plans.
JEL codes: Q22

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1 Introduction

Polices regarding rebuilding of fisheries involve important resources at the European Union (EU) level. The consistent evaluation of these policies is a necessary instrument to provide the foundations for their improvement. Indeed, the evaluation of policies requires a general equilibrium model capturing the endogenous character of the agents' decisions, and their effects on the variables of interest, as function of the policies. In this paper a dynamic general equilibrium model with heterogeneous agents is proposed in which stock rebuilding policies change endogenously the behavior of firms. The model presented allows the computation of the changes in most of the socioeconomic variables of interest for policy makers as a function of the implemented policies.

The general equilibrium models explicitly state the existence of an economy with agents, markets and equilibrium conditions. A model with heterogeneous agents in fisheries has been used in the context of individual transferable quotas (ITQ) by Terrebonne [1] and Da-Rocha and Sempere [2]. General equilibrium analysis of the fisheries can also be found in the studies of multiple uses of the ecosystem [3]. It can also explain how the inputs are over-allocated to an open access resource and create a general equilibrium tragedy of the commons in the artisanal fisheries, as in Manning et al. [4]. All these aspects have been analysed in discrete time. The model presented here was not based on the general fishery equilibrium models described above but inspired by the recent developments in macroeconomic theory, as explained by Achdou et al. [5]. It can be used to assess how the economy adapts to a policy shock, for heterogeneous firms, in continuous time. The shock tested is a fish stock-rebuilding policy.

The present paper starts with a description of the current economic scientific advice within the EU. It explains the main shortcomings of it and how can they be reduced using a dynamic general equilibrium model. Section 3 develops the theoretical model and the equilibrium conditions required for its solution. An application of this model is presented in Section 4, using a Mediterranean Sea fishery as an example. The Results section interprets the obtained values, using the economic theory on which this approach is based. A discussion of the usefulness of this modelling approach in the economic assessment of the EU fisheries policies and the future prospects is provided in Section 5. The paper ends with a summary of the main conclusions obtained.

2 The fisheries economic scientific policy advice within the EU

Stock assessment within the EU waters is conducted on a single stock basis by the International Council for the Exploration of the Sea (ICES) in the Atlantic waters and the General Fisheries Commission for the Mediterranean (GFCM), in the Mediterranean and the Black Sea. Using different types of stock assessments (e.g., analytical, using trends of catch per unit of effort, etc.), these organisations provide a Total Allowable Catch (TAC) and/or effort advice on the basis of achieved Maximum Sustainable Yield (MSY), when known. A precautionary approach is employed when the reference points cannot be calculated with sufficient precision. In the same region, the Scientific and Technical Committee for Fisheries (STECF) is in charge of assessing the economic and social consequences of that advice.

The Data Collection Framework (DCF) [6] collects the economic data in fisheries at a fleet segment level. The segments are based on categories of fishing gear and vessel length. Biological data are also collected by the DCF but at a higher disaggregated level.

The current economic advice for EU fisheries is contained in the Annual Economic Report on the EU Fishing Fleet (AER) [7], where economic indicators are provided on a fleet segment basis, and in the economic impact assessment of the multiannual plans (MAPs) [8–11].

The AER presents fishing fleet results based on general accounting rules. However, these rules are only giving a partial overview of the economic impact (i.e., financial and employment indicators of the fishing fleets). This procedure is probably followed to avoid the double accounting involving other economic sectors. Projections of economic variables are also provided by the AER. However, as the STECF notes [12], the projection models used to forecast are based on the correlations between variables. It implies that are not grounded in any economic equilibrium theory.

MAPs contain the goals for fish stock management and a "road map" for achieving these objectives. As pointed out by Punt [13] objectives for fisheries management can be categorized as either "conceptual" (strategic) or "operational" (tactical). Conceptual objectives are generic, high-level policy goals , while operational objectives are expressed in terms of the values for performance measures. Article 1 of the Common Fisheries Policy (CFP) [14] has the conceptual strategy of rebuilding stocks in a way that is consistent with the objectives of achieving economic, social and employment benefits, and of contributing to the availability of food supplies. Article 2 of the CFP has the operational objective that the stock status rebuilt has to be done up to, on single stock basis, levels compatible with the MSY. That is, the final (operational) objective is purely stock-driven and the economic assessment of it is based on a conceptual one.

The economic assessment provided in these MAPs is founded, generally speaking, on the projection of the financial performance of fishing firms based on fishing management implementation models. In other words, the aim is to project the changes in the relationship between nominal fishing effort and fishing mortality and to use identities to convert them into financial variables (i.e, gross revenues, profits) at fishing fleet level. The methods used to provide an economic assessment of the MAPs model a feedback between the biology and the financial results or the financially induced behaviour of the fleets. Some of the models used in the economic assessment of MAPs are based on pure simulation, others on Management

Strategy Evaluation (MSE) and others, on ecosystem balancing and simulation. They are all very useful in providing an empirical framework for scenario comparisons and/or checking the robustness of different management scenarios (MSE-based models). However, they have several shortcomings:

i) The complexity of the feedback mechanisms is another hindrance (see Prellezo et al. [16]). The models tend to interrelate (feedback) the biological and economic features using complex assumptions. The feedback processes used by these models rely on the levels of catches not coinciding with the advised level. This might happen as a result of the overall selectivity changes, the different evolution of the individual fleets, the tactical behaviour of these fleets (including different objectives or different spatial behaviour), and/or the changes in the capacity of the fleets. This complexity creates the "black box" syndrome; in many cases, the economic results cannot be explained using the economic theory. It makes the model validation a complex task and, therefore, the forecasting results can be put in doubt.

ii) The estimation of the economic performance leading from the current stock status (often far from the intended target) to an MSY status implies substantial changes for many of the stocks. This is well beyond the scope and, in many cases, out of range of most projection models. This is an extremely important issue; even for the most up-to-date models, the economic variables are always (for DCF economic data) based on data that are two years old by the time the projections are performed. For example, the AER projects the economic variables of the preceding two years when the report is released [7]. Furthermore, the models are based on strong assumptions in terms of factors availability (except fishing possibilities) and ignore the likely impact of these factors on stock-rebuilding strategies (or the other way around).

The black box syndrome (i) makes the economic results difficult to interpret because of the feedback mechanisms embodied in the models. The general economic theory does not help, simply because the models have been built without considering it. The projections of economic variables (shortcoming (ii)) are not based on the economic theory [12], and especially, when made for several years, cannot be relied on to reflect any kind of economic equilibrium.

The dynamic general equilibrium model presented here demonstrates a solution to stock rebuilding policies (bringing fish stocks to abundance levels compatible with the MSY), using AER data, providing indicators similar to those presented in different impact assessments of the MAPs. It also obtains other indicators (aggregate indicators such as consumer utility), useful in the interpretation of the economic results, that could potentially help policy makers on designing fisheries policies.

3 Dynamic economic equilibrium model for assessing the economic impact of stock-rebuilding policies

Economic equilibrium models help to reduce the shortcomings (i) and (ii) described in Section 2. These types of models take into account the price system, which plays the crucial coordinating and equilibrating role in the economy. The fact that everyone in a given economy faces the same prices generates the common information needed to coordinate individual decisions. This approach has several properties that could allow managers to understand the economic implications of the management policies within the EU [1]. Firstly, it is based on the economic equilibrium, not on the accounting rules; this allows the interpretation of the results using the economic theory. However, it also provides the same indicators as those obtained by using accounting rules. That is, at equilibrium, these identities hold; the results can be read in the same way but might be interpreted using the economic theory. It also provides a new set of aggregate indicators that cannot be calculated using accounting rules.

[1]Note that the model is general enough to be used in contexts outside the EU

Overall, equilibrium models can provide disaggregated and aggregated economic and social indicators (wages and household utility), capital indicators (number of vessels) and macroeconomic aggregate indicators (gross value added -GVA- and wealth). Finally, it considers the heterogeneity of fishing firms; this allows to endogenously consider the capital dynamics.

The model presented here fulfills the requirement for balancing markets and agents via a price mechanism system. Prices balance demand and supply so that all the buyers who want to buy at the current price, and similarly, all the sellers who want to sell at the current price, can and do it, with no excess or shortages on either side. This induces the behaviour that generates aggregate quantities consistent with the prices. The heterogeneity of the companies operating in the economy is considered, as described in the study of Achdou et al. [5]. The model also considers the individual productivity shocks with which the companies are faced. The idea is that the dynamics of the firm size can be explained by stochastic models of evolution with purely idiosyncratic (firm-specific) shocks. This idea has been established for a long time in the relevant literature (see Hopenhayn [17] for a general overview and Weninger and Just [18] or Da-Rocha and Sempere [2] for fishery models).

To build the model (the economy), it is necessary to define the following individual problems: The household problem (sub-section 3.1), the problem of incumbent firms (sub-section 3.2), the fleet dynamics (sub-section 3.3) and the fish-stocks dynamics (sub-section 3.4). It is also necessary to explain the economy itself (i.e. the equilibrium condition of the economy) and the results, considering the steady state and the transitional period.

3.1 The household problem

It is assumed that there is a representative household who owns the firms, supplies labor and consumes the final good, taking prices as given. Households will perform labour (L) and have consumption (C). Note that in this case, the output price is considered a numeraire and wages are denoted as w. Therefore, the households solve a static consumption-leisure maximization problem:

$$\max_{C,L} \quad logC - eL, \tag{1}$$

$$s.t. \quad C = w(t)L + \pi(t) \tag{2}$$

This representative household will maximize its utility, which increases (at a descending rate) with the consumption and decreases with the labour at a constant rate e (des-utility of the labour). In other words, the utility function is quasilinear in labour. The amount of labour supplied is not affected by the wealth effect (Eq.(1)). In this utility maximization, households face a total budget constraint: consumption is equal to the payment received for their labour (w) and the profits (Π) obtained by their production in each time period (t) (Eq.(2)).

3.2 The incumbent firms problem

The problem of incumbent firms can be defined as follows:

$$\max_{l(t),y(t)} \quad y(t) - w(t)l(t) - c_f, \tag{3}$$

$$s.t. \quad y(t) = \sqrt{z \;\; l(t)} \tag{4}$$

That is, it is assumed that firms maximize profits ($\Pi(z,t)$) (Eq.(3)) subject to the available technology (Eq.(4)). Profits are defined as revenues $y(t)$ minus labour costs $w(t)l(t)$, minus fixed operating costs (c_f). The productivity shock (z) follows a stochastic process with a negative expected growth rate, $-\mu$, i.e.,

$$dz = -\mu z dt + \sigma_z dw_z \tag{5}$$

where σ_z is the per-unit time volatility, and dw_z is a random increment to a Weiner process.

Fishing firms produce output by using labour (effort). This effort is supplied by the continuum of identical households presented in sub-section 3.1. To summarise, there are two markets in the economy, one for the final goods (fish) and the other for the labour.

3.3 Fleet dynamics

For prices (i.e., wages) to be calculated, the fleet dynamics must be computed. As described in the study of Weninger and Just [18], it is assumed that the abilities of individual firms change over time. Another assumption is that if a firm wants to remain active, then it must pay a fixed cost (c_f). These two assumptions are associated with changes in the individual firm: some of the firms expand production, hiring staff; others contract, firing staff; and others exit the economy.

The decision to exit depends on the employment $l(z,t)$ and output $y(z,t)$ during the given period. Depending on the choices during this period, the firm must assess the expected value of staying in the fishery and compare it to the present discounted value of profits associated with exiting ($S(t)$, scrap value).

The decision problem of incumbent firms produces two types of decision rules. First, there are continuous decision rules for the optimal choice of output and labour. Second, there is a discrete decision rule $I_{exit}(z,t)$ for the optimal exit/stay decision. Therefore, the distribution of firms is determined endogenously by the exit decisions made by the companies themselves. Given instantaneous profits, the dynamic of the incumbent firm problem is defined by the following stopping time problem:

$$v(z,t) = \max_{\tau} E_0 \int_0^{\tau} \pi(z,t) e^{\rho t} dt + S(t) e^{\rho t}, \tag{6}$$

Equation (6) illustrates the value function representing the time (τ) required by the firm to take a given action (exit the fishery). Note that ρ is the discount rate. The value function is subject to the stochastic process of the productivity shock described in Equation (5).

The solution of this problem (see Equation (B.1) in Appendix B) gives the productivity threshold $\underline{z}$. It is named the break-even productivity. If the individual productivity (z) is lower than the break-even productivity ($\underline{z}$), $v(z,t) = S(t)$, the firms will decide to exit from the economy (fishery); if it is higher, they will remain active. Solving the problem defined by Equations (6-5), it is also possible to compute the measure of firms, $g(z,t)$, that is, the number of vessels of productivity z at the period t. The distribution of firms is determined endogenously by exit decisions made by the firms themselves (see Equation (B.2) in Appendix B).

3.4 Fish stock dynamics

A stock dynamics model is also required to project the evolution of stocks given a management decision. The particular model used is an age-structured model in continuous time. In the age-structured models, the conservation law is described by the following McKendrick-von Foerster partial differential equation [19][20]) (see Appendix A).

Let $n(a,t)$ be the number of fish of age a at time t. For a given fishing mortality trajectory ($F(t)$), catches at age a are equal to $p(a)F(t)n(a,t)$ (where $n(a,t)$ are the numbers at age, $m(a)$ the natural mortality at age and $p(a)$ the selectivity parameter at age). Defining $\omega(a)$ as the weight at age, fishing possibilities for each fish stock ($Y(t)$) should follow the next rule (see Da-Rocha et al. [21] for an application of this dynamic):

$$Y(t) = \left(\int_0^A \omega(a)p(a)n(a,t)da \right) F(t) \tag{7}$$

Ex-vessel prices of each stock and fleet ($P(s, f)$) and catch composition by fleet ($share(f, s)$) are used to generate the value of the catches for each fleet:

$$Q(t) = \sum_{s_f} P(f, s) share(f, s) Y(s, t), \tag{8}$$

where s and f in Equation (8) stand for fish-stock and fleet, respectively.

3.5 Equilibrium conditions

The objective of the problem is to establish the prices (i.e. wages) and quantities (i.e. employment) that generate the income exogenously determined by the stock management decisions and their dynamics (Eq.(8)). However, first it is necessary to close the model. To do so, the feasibility condition in the labour market is required:

$$\int_{\underline{z}(t)}^{\infty} l(z, t) g(z, t) dz \quad = \quad L(t) \tag{9}$$

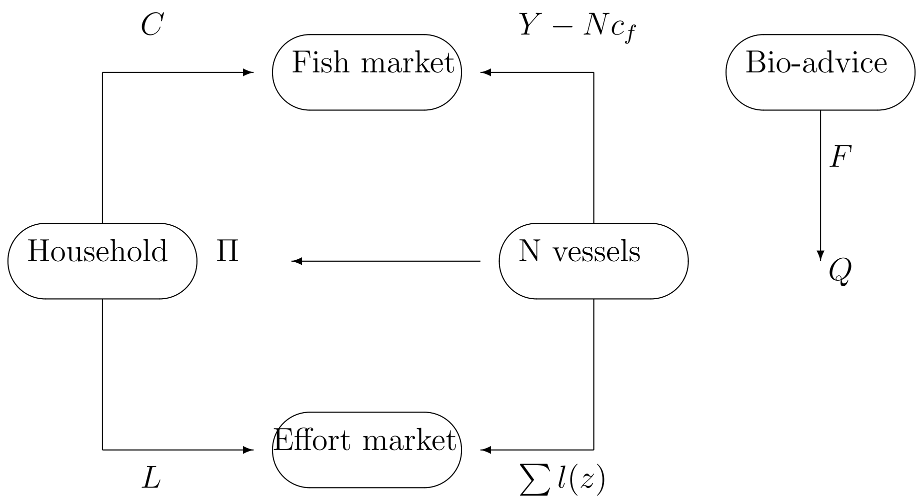
The budget constraint (Eq.(2)) implies that the final output market is in equilibrium. Additionally, there is a maximum quantity $Y(t)$ to be extracted. It implies that the feasibility condition in the output market is:

$$\int_{\underline{z}(t)}^{\infty} y(z, t) g(z, t) dz \quad = \quad Y(t) \tag{10}$$

Given the total value of the fishing possibilities $Q(t)$, obtained from Equation (8) (exogenously), an equilibrium is a measure of firms ($g(z, t)$), wages ($w(t)$), incumbent firms value functions ($v(z, t)$), individual decision rules ($l(z, t)$, $y(z, t)$) and the break-even productivity ($\underline{z}$), such that:

i) Firm optimization problem and firm measure are satisfied (Eq.(6)).

Figure 1: A representation of the economy constructed to provide an economic assessment of the MAPs. Household consumes fish that has to be produced by the fishing vessels and exchanged in the fish market. These vessels demand labour supplied by the household an exchanged in the effort market. The equilibrium of this economy has to explain the biological advice in the form of exogenous fishing possibilities.



ii) Output and labour market clearing feasibility conditions (Eqs.(9-10)) are satisfied.

Finally it is also required to determine the labour supply. From the first-order conditions of the household problem (Eqs.(1-2)) and after some manipulation it can be obtained that:

$$w(t) = e\left[Q(t) - c_f N(t)\right] \tag{11}$$

Equation (11) shows wage as function of the des-utility of the labour (e), the fishing possibilities (Q) and the number of vessels ($N(t)$).

The economy is defined by Equations (6, 10-11).[2] Figure 1 represents this equilibrium graphically and Appendix B mathematically.

[2] Equation (9) is satisfied by the Walras law. Walras proved that the state of the economic system at any point is the solution of simultaneous equation representing the demand for goods (consumers) the supply of goods the producers and the equilibrium condition that supply equals demand on every market.

4 Study system

The application of this methodology is based on a case study of the demersal fisheries of the Western Mediterranean Sea area (FAO area 37.1), which includes the territorial waters of Spain, France and Italy. Bio-economic analysis in the Western Mediterranean have been applied by Lleonart et al. [22] in where the MEFISTO model is applied to the hake of Catalonia and Maynou et al. [23] in where several management strategies are assessed. Marine protect areas economic assessment has been also performed by Merino et al. [24] and an analysis of effort dynamics can also be found in Merino et al. [25].

The main fishing gears in this fishery are bottom trawl nets, longlines and bottom-set nets, and the main demersal species caught in this area are hake, red shrimp, anglerfish and red mullet. This particular example only considers geographical sub-areas (GSA) 1 to 7, exploited by the trawlers from Spain and France. All the segments of these fleets have been merged into two groups, the Spanish and French fleets. The latter only fish for hake (approximately 21% of the stock); the former catch a mix of hake (approximately 29% of the stock), red mullet (26% of the stock), blue and red shrimp, deep water red shrimp and monkfish (the Spanish fleet is the only fleet targeting these three last stocks) [11].

This sea area is managed by input-based regulations (mainly effort control and technical measures) that, according to the Article 2 of the CFP [14], seek to drive the stocks to levels compatible with achieving the MSY (operational objective).

4.1 Scenarios

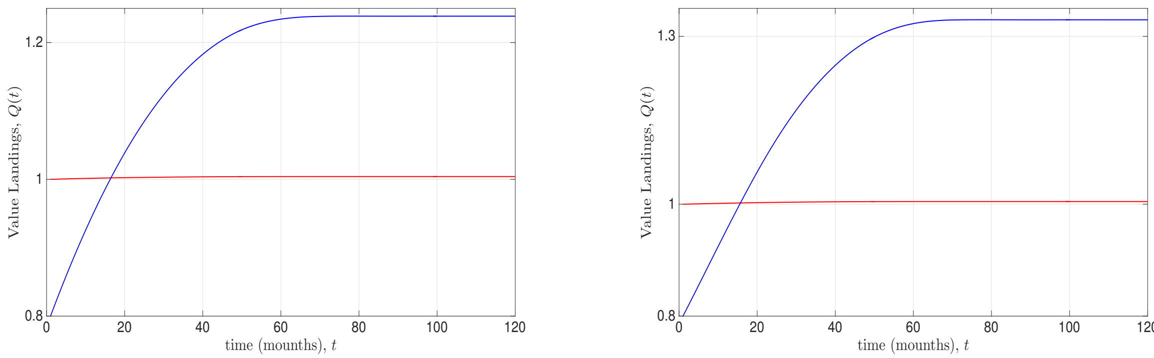
According to Colloca et al. [26] in Mediterranean European countries, 85% of the assessed stocks are currently overfished compared to a MSY reference value. As shown in Table 1 this overfishing also occurs in the GSA studied. This implies that a rebuilding is required for the

Table 1: Stocks reference points and ex-vessel prices considered in the study system. GSA stands for Geographical Sub-Areas.

Species (Stock)	Reference year	F_{ry}/ F_{msy}	Ex-vessel prices (Euro/kg)
Hake (HKE (GSA 1-7))	2014	3.59	6.68 (S)-4.5 (F)
Red mullet (MUT (GSA 1))	2013	4.85	5.92 (S)
Red mullet (MUT (GSA 5))	2012	6.64	5.92 (S)
Red mullet (MUT (GSA 6))	2013	3.27	5.92 (S)
Red mullet (MUT (GSA 7))	2013	3.21	5.92 (S)
Blue and red shrimp (ARA (GSA 1))	2014	3.41	16.15 (S)
Blue and red shrimp (ARA (GSA 5))	2013	1.75	16.15 (S)
Monkfish (ANK (GSA 1))	2013	1.56	12 (S)
Monkfish (ANK (GSA 5))	2013	10.50	12 (S)
Deep water red shrimp (DPS (GSA 1))	2012	1.65	16.15 (S)
Deep water red shrimp (DPS (GSA 5))	2012	1.24	16.15 (S)
Deep water red shrimp (DPS (GSA 6))	2012	5.19	16.15 (S)

(1) Source: STECF [11]. S stands for Spain and F, for France.

fish stocks of this area. The model presented in Section 3 was used to provide an economic assessment of a rebuilding strategy. To do so two different scenarios were compared. In the first scenario, the fishing mortality (F) of the different stocks is kept at the last observed level (far from the F_{msy} -the F compatible with achieving MSY in the long term-, as it can be seen in Table 1). The alternative scenario is to reduce the last observed F by 20%, for all the stocks involved (this percentage is based on an agreement between the EU Commission and the Member States involved in this fishery). The two scenarios were named F_{sq} and F_{80}, respectively.



(a) Spain (b) France

Figure 2: Impact of scenarios on fleets: level of recovery in terms of value of landings by member state. Panel (a): Spain has to recover from 0.8 to 1.333; panel (b) France has to recover from 0.8 to 1.239. *Statu quo* is set at 1.

4.2 Calibration

4.2.1 Management

During the first year, there is a linear relationship between fishing effort and F. It implies that a reduction in F needs a proportional reduction in fishing effort. Equation (8) is used to project the evolution of the stock for the remaining years and provides the total catch possibilities (in value) by stock for the two scenarios described above. Ex-vessel prices and the catch composition by fleet and stock of Equation (8) are obtained from STECF [11] (Table 1). When calibrating the F_{sq}, it should be noted that the projection of the stocks is based on an age-structured model in continuous time different the models used by the STECF to compute the F_{msy}. To make these two computations compatible, F_{max} (the fishing mortality rate that maximizes equilibrium yield per recruit as a proxy of F_{msy}) is calculated using the stock dynamics presented in sub-section 3.4. Then, the F_{sq} is calculated applying the ratio F_{ry}/F_{msy} (F_{ry} stands for the fishing mortality of the reference year -Table 1- obtained from the STECF [11]), to the F_{max}.

Figure 2 demonstrates the difference between the values to be reached by the two Member

States, caused by the differences in the stock composition of their catches. Spain has to recover from 0.8 to 1.239 and France, from 0.8 to 1.333 (1 is the *statu quo*). The model has to explain the income obtained from Equation (8) along the path to the steady state.

4.2.2 The economy

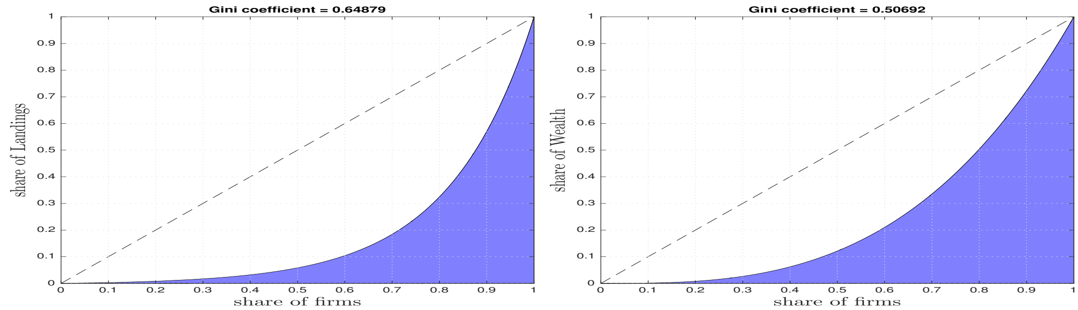
To calibrate the remaining parameters of the economy, the drift of the productivity decline ($\mu = -0.04$), was obtained as described by Weninger and Just [18] and its per-unit time volatility ($\sigma_z = 0.01$) from Da-Rocha et al. [27]. The discount rate (ρ) was set to 0.04 (standard in the macroeconomic theory -see, for instance, Restuccia and Rogerson [28]-).

The other two parameters (c_f and e) are obtained by solving the equilibrium of the model and ensuring that this equilibrium matches the statistics of the fishery. In particular, the fixed cost c_f matches the average value reported by the STECF [11]. The exact values calibrated were 0.022 ($c_f N$) for French and 0.034, for Spanish fleets. Finally, $S(t)$, the scrap value, is assumed to be zero (according to the European Maritime and Fisheries Fund this value will be equal to zero in the year 2018), and total landings (Q) are normalized to 1.

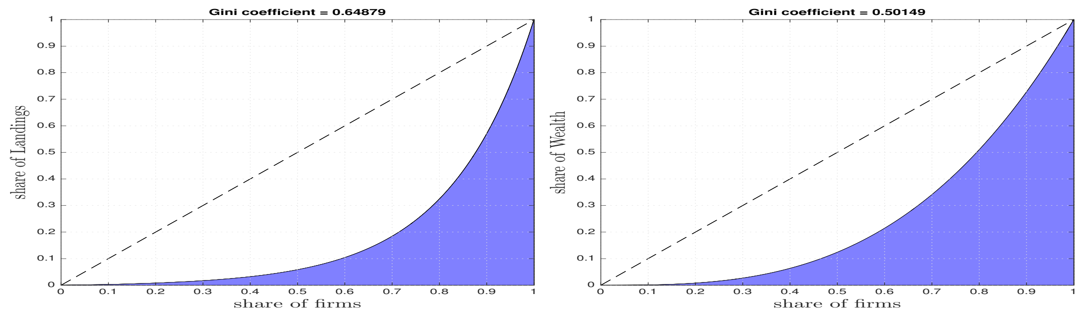
All this calibration procedure produces and initial distribution of the different firms in terms of income and wealth, as shown in the Lorentz curves (the graphical representation of the income and wealth distribution) displayed in Figure 3.

4.2.3 Stocks

Stock data (i.e. numbers at a given age, maturity, etc.) to parametrize Equation (A.1) (Appendix A) and Equation (7) for the different stocks considered in the Table 1 have been obtained from the STECF [11]. See Appendix C for the results of the fittings for each of the stock considered.



(a) Income



(b) Wealth

Figure 3: French (left) and Spanish (right) Lorentz curves at steady state with $Q = 1$: for income (panel a) and wealth (panel b).The straight diagonal lines in the graphs represent perfect equality of income (panel a) or wealth (panel b) distribution; the Lorentz curve lies beneath them (blue lines), showing the reality of income (or wealth) distribution. The difference between the straight lines and the curved lines is the amount of inequality of income or wealth distribution (Gini coefficient).

4.3 Results

4.3.1 The steady state

To evaluate the macroeconomic and welfare implications of changes in fishing mortality, the model generates the optimal response in three (management) variables:

i) Average catch per unit of effort (CPUE) per day at sea and per vessel;

ii) Average days at sea per vessel, $E[l(z)]$;

iii) The number of vessels, $N(t)$.

A measure of nominal fishing effort is obtained by multiplying the corresponding values of the three variables. That is, the nominal effort is the equal to $\text{TFP}(t)E[l(z,t)]N(t)$, where TFP stands for the total factor productivity.

The number of vessels ($N(t)$) represents the number of “standardised” firms. The firms have the operating capital (the vessel) and stay active if they find optimal to pay the idling cost, c_f. Note that for the marginal firm (the less efficient vessel), there is no difference between paying the idling cost of fishing or exiting the economy. This marginal vessel makes negative instantaneous profits, but has a positive opportunity cost of exiting the fishery (see Weninger and Just [18]). Its total expected value of operating the vessel is zero.

Figure 4 shows an example of achieving the break-even productivity ($\underline{z}$) and value functions, $v(z)$, for the fleets in the *statu quo* situation ($Q = 1$) but with different costs (Spanish and French fleets). The results demonstrate that the fleets with higher fixed costs have a higher break-even productivity. In other words, if the vessels remain active while facing increased fixed costs, it is simply because they are more productive.

The break-even productivity can also be used to compute the number of vessels corresponding to each productivity level (Fig. 4).

To understand the differences between the F_{sq} and F_{80} scenarios shown in Table 2 (indicator values for the steady state obtained for the two member states), it has to be noted that fishing mortality is instantaneously reduced in the F_{80} scenario, but will produce higher catches in the future. This would imply higher wages. The reason for this is obtained from the household problem (sub-section 3.1), where increased fishing possibilities imply an elevated consumption level. This increased consumption reduces the marginal utility of labour (time spent at sea). Therefore, at equilibrium, the wages have to increase so that the marginal utility of consumption and the marginal utility of the leisure become equal.

Increased wages induce changes in the effort composition. On the one hand, the demand of

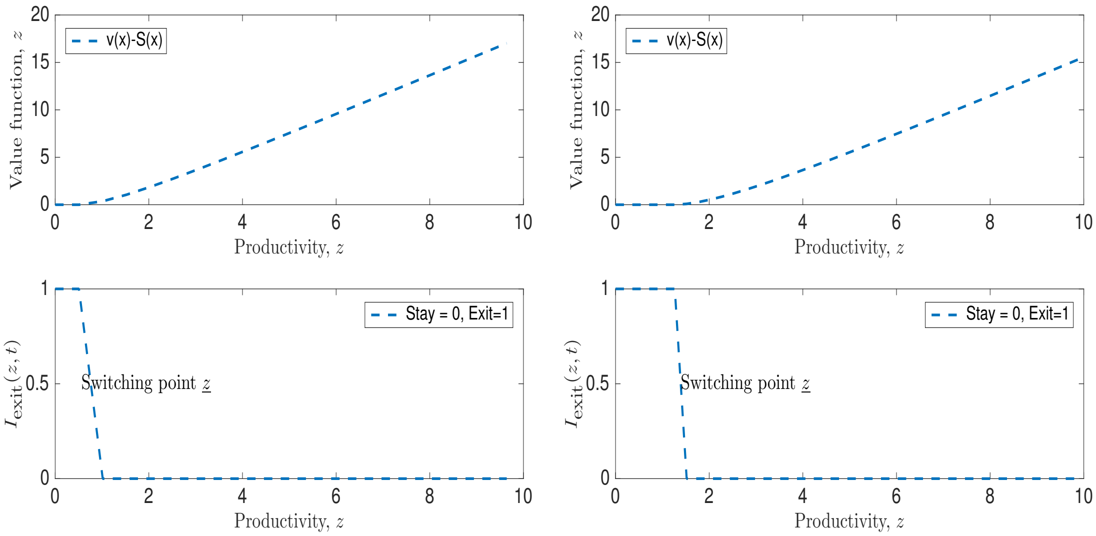
Table 2: Steady-state indicators for French and Spanish fleets under the two scenarios (F_{sq} and F_{80})

France

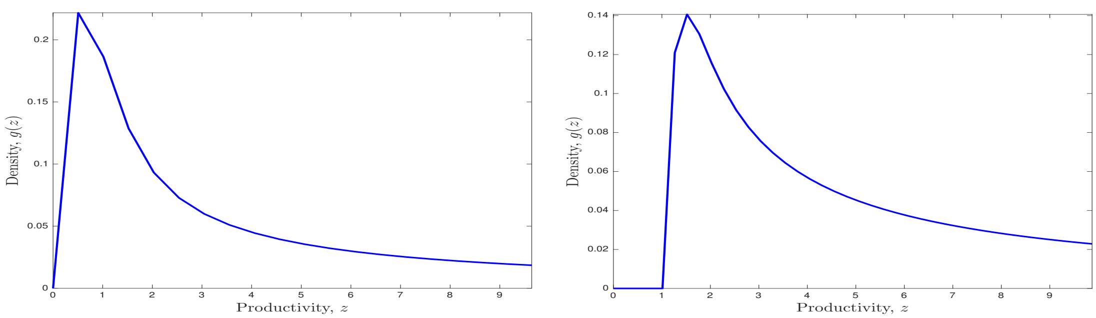
Scenario		F_{sq}	F_{80}
Fleet Size	N	1	1.759
wage	w	1.500	1.980
		Per vessel	
TFP (CPUE per vessel)	$E[y(z)/l(z)]$	3.000	3.960
Days per vessel	$E[l(z)]$	2.004	1.150
Yield per vessel	$E[y(z)]$	6.014	4.556
Profits per vessel	$E[\pi(z)]$	2.874	2.145
Value of vessel	$E[v(z)]$	34.969	25.938
		Inequality	
Revenues	Gini	0.649	0.649
Wealth	Gini	0.686	0.696
		Aggregate Accounts	
GVA	$Q - c_f N$	0.978	1.291
Compensation of employees	wL	0.500	0.665
Gross operating surplus	Π	0.478	0.626
		Welfare	
Utility (social welfare)	$w(C) - eL$	-0.534	-0.260
Total employees	L	0.333	0.336

Spain

Fleet Size	N	1	1.462
wage	w	1.485	1.829
		Per vessel	
TFP (CPUE per vessel)	$E[y(z)/l(z)]$	2.971	3.657
Days per vessel	$E[l(z)]$	2.553	1.753
Yield per vessel	$E[y(z)]$	7.583	6.413
Profits per vessel	$E[\pi(z)]$	3.551	2.966
Value of vessel	$E[v(z)]$	42.263	34.986
		Inequality	
Revenues	Gini	0.573	0.558
Wealth	Gini	0.631	0.625
		Overall	
GVA	C	0.968	1.192
Compensation of employees	wL	0.500	0.619
Gross operating surplus	Π	0.468	0.573
		Welfare	
Utility (social welfare)	$w(C) - eL$	-0.549	-0.344
Total employees	L	0.337	0.339



(a) Exit decision, $c_f = 0.022$ (b) Exit decision, $c_f = 0.034$



(c) fleet heterogeity , $c_f = 0.022$ (d) fleet heterogeity , $c_f = 0.034$

Figure 4: French (left-hand side) and Spanish (right-hand side) vessels: value function (upper panels), z, break-even productivity (center panels) and fleet density $g(z)$ (lower panels)

labour for each vessel is reduced. On the other hand, the elevated wages induce some vessels to exit as the average productivity of the fleet increases. Then, the fleet size has to increase to make the increased number of days at sea compatible with the reduced effort per vessel generated by higher wages. The process is illustrated in Figure 5.

The increased number of vessels intensifies the competition among the vessels and raises the wages. Vessels increase the productivity; TFP per vessel increases. However, on average, the individual vessels spend fewer days at sea, and the total catches per vessel are reduced. As a result, the profits per vessel and vessel value decrease.

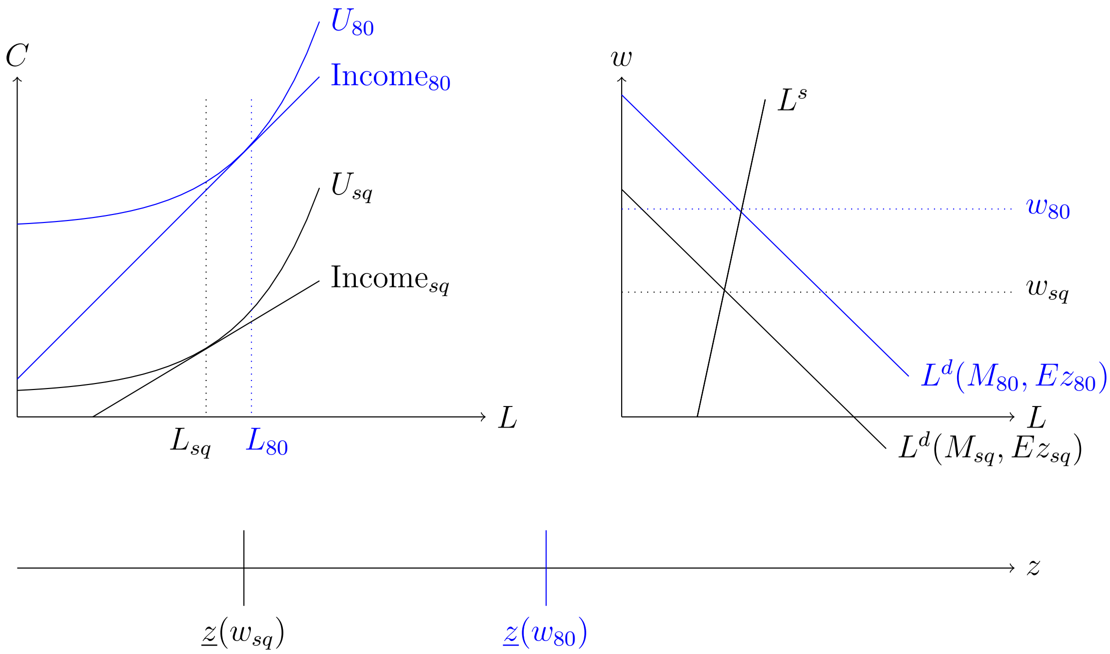


Figure 5: General equilibrium of a stock-rebuilding strategy (F_{sq} to F_{80}). In the steady state the stock-rebuilding strategy (F_{80}) produces higher catches and higher income that increases also the utility (U). Increased wages induce changes in the effort composition making the break even productivity ($\underline{z}(w_{80})$) increase.

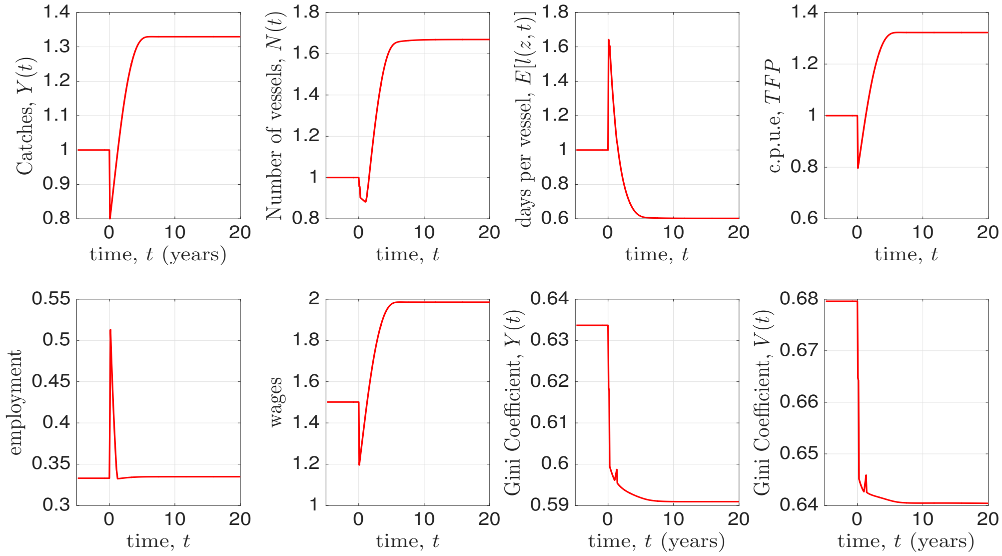
Essentially, the increased future catch possibilities will be translated into an increased number of vessels with reduced profitability. This is a result coming, partially, due to the mild stock effect. If the stock effect would have been considered at individual vessel level, the individual vessels would have been benefited from the improved fishing possibilities. This implies that the number of vessels shown in Table 2 has to be interpreted as the maximum number that will remain active in the fishery. This result will be discussed in Section 5. From the societal point of view (considering aggregate indicators), GVA is increased even if the total costs also rise (augmented number of vessels). Gross operating surplus is also increased by the recovery program. As far as the social utility is concerned, this surplus is also higher under the F_{80} than under F_{sq} scenario; in the case of the French fleet, the value of this indicator almost doubles.

In terms of inequality measure (Gini coefficient), the changes in the revenues are negligible, and the changes in wealth are moderate (less than 2.5%) for both Member States.

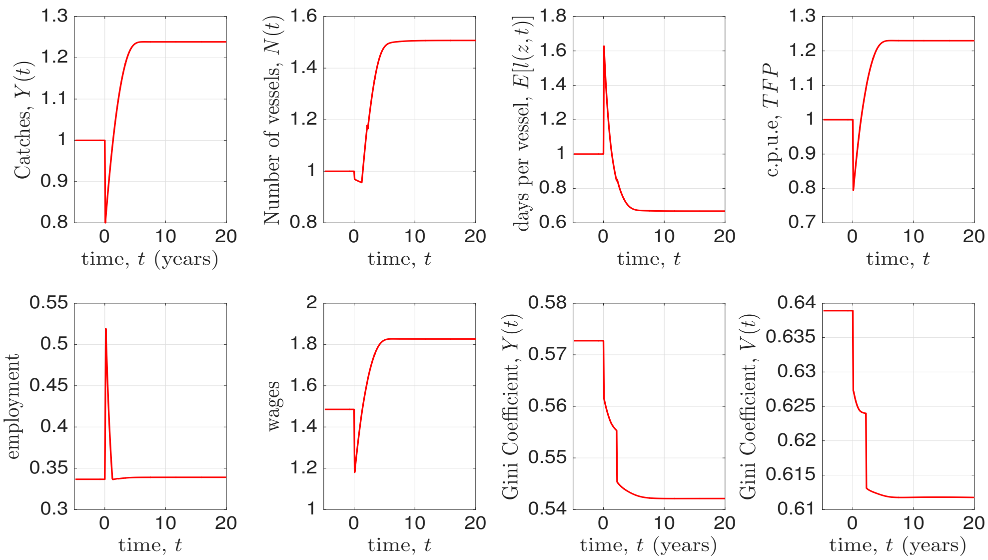
4.3.2 The transition to the steady state

Figure 6 shows the F_{80} scenario for both Member States. Individual (exit/stay) decisions depend on the opportunity cost of exiting; the capital (number of vessels) is highly malleable. Note that at $t = 0$, the capital, $N(0)$, and the measure of firms, $g(z, 0)$ are set. Therefore, deteriorated fishing possibilities at $t = 0$ imply a reduced wage. In a stationary solution, this will mean no exit.

Exit decisions with forward-looking agents depend on the expected forward profits. The higher the number of vessels, the lower will be the fraction of total fishing possibilities available for each vessel. That is, the vessel profitability depends on the individual fishing possibilities rather than on the total ones. Then, the expectations of future individual fishing possibilities are formed. These fishing possibilities have to satisfy Equation (8), in each period.



(a) France, $c_f = 0.022$



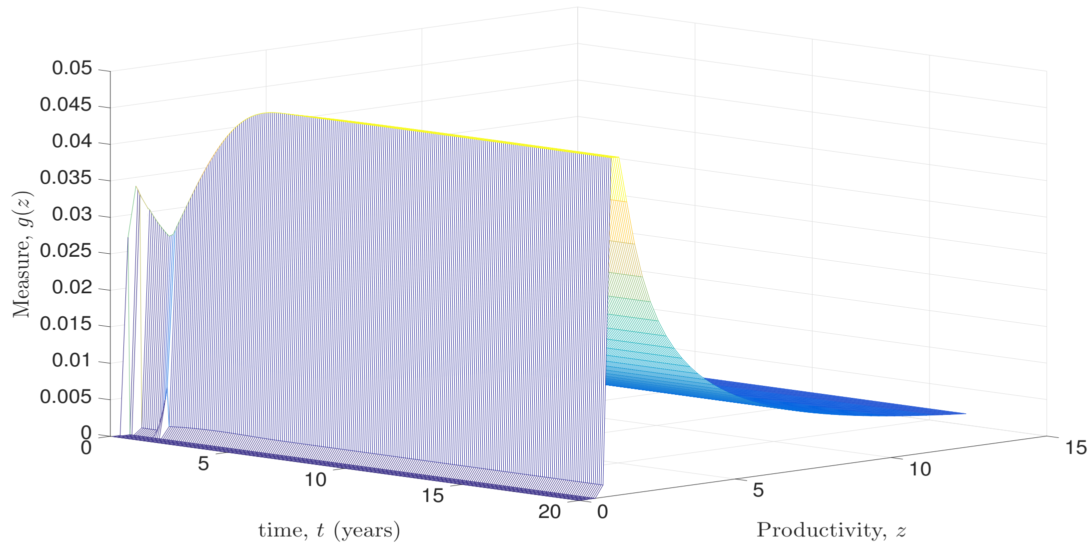
(b) Spain, $c_f = 0.034$

Figure 6: Transition of different indicators to the steady state under the F_{80} scenario for France (panel (a)) and Spain (panel (b)).

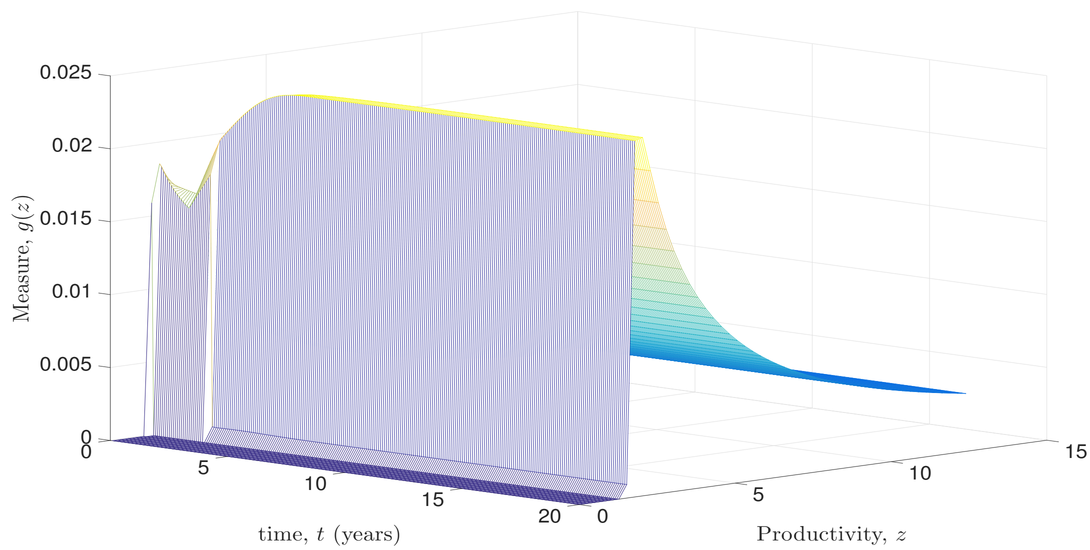
Therefore, the individual fishing possibilities are the prices, which depend on the scarcity of the fishing possibilities. As in the steady state, the equilibrium is the result of adjustments in three margins: CPUE (per day at sea and per vessel), average days at sea per vessel and the number of vessels. A low exit rate generates trajectories where total catches (planned) by the fleet are higher than the fishing possibilities. That is, the price for the individual fishing possibilities will rise. As a result, the sequence of value functions will be shorter, and more exits will be generated during the initial periods (see Figure 7).

5 Discussion

The relationship between capacity and activity in fisheries is a complex issue in the economic scientific advisory process. Modelling the entry-exit behaviour (capacity) of the fishing firms is not straightforward; various approaches have been tested in different studies. Some of the studies present probabilistic models dependent on variables such as history, rights and profitability [29]. Some other approaches simply do not use models but are scenario-based [30]. Such scenarios can be extreme. If a fishing mortality reduction is required, it will affect the average landings/catches of the vessels (if the number of vessels are kept constant) and the other way around a constant average landing/catch with a reduction in the number of vessels that accommodate (depending on production function) this fishing mortality reduction. These two extreme scenarios are created with the expectation that the final result will be somewhere in-between. If aggregated agents are considered, this conclusion holds; however, this is not necessarily true if fishing firms are considered heterogeneous agents. The vessels require a minimum productivity level; below this level, they will exit the fishery, and above it, they will stay. One can consider a productivity required to stay, so-called break-even productivity. This break-even productivity can also be compared with the financial accounting results of the AER. In this report, the break-even revenue is calculated as a threshold of productivity. The higher the vessel costs, the higher their break-even revenue. The results obtained here do not contradict this notion; however, a different way of reading the problem might be proposed. If the vessels are active, it is because they are productive enough in relation to their costs. If they attempt to remain in the fishery, it



(a) France, $c_f = 0.022$



(b) Spain, $c_f = 0.034$

Figure 7: Transition of fleet density F_{80} scenario for France (panel (a)) and Spain (panel (b)).

is because the opportunity cost of exiting is high, even if they face instantaneous negative profits.

Another characteristic of the approach presented here is that the implementation failures are not considered. In fact, there is no feedback mechanism, given that the fishing possibilities are considered exogenous (Fig. 1). As mentioned in Section 2, models used to provide an economic impact assessment for the MAPs do normally focus on this issue. They provide the implementation of a management option for the fishing fleets. This feedback (anticipating the failure of the management by, e.g., not catching the total TAC of a stock due to fishery interactions, or the low price issues of the market) is considered in the next period of the management advice. Following this feedback, the economic (and in some cases, social) projections of the fishing fleet segments are provided, based on the same accounting rules and indicators as the AER. However, it should be noted that the main feature of these types of models is the lack of a clear relationship between the nominal effort and catchability, which makes the aggregation of the nominal effort difficult. The approach most commonly followed to overcome this limitation is to split the fishing effort into smaller homogeneous units of effort (homogeneous in terms of the fishing mortality), such as the fleet and, in some cases, métiers. The more realistic the forecast tries to be, the more matching time and assumptions are required, and the more biased are the results. However, management advice implementation failures are likely to exist and further work should be done in order to fully explain the economic consequences of fish stocks rebuilding policies.

As pointed out by Clark et al. [31], in cases of overexploited fisheries (as in the presented system studied), the questions to be tackled are the extent of the rehabilitation and its rate. These authors also gave us the answer to this question: it will depend on the initial level of capital. Here, the capital is defined by the number of vessels. Further work can be done to resolve this issue; however, to do it, the fishery management has to be instrumented. That is, policy instruments are required to force the vessels to exit or to stay in the fishery [32].

The stock effect (the mild effect that can be seen in the results) is another important limitation. Essentially, the stock effect allows the fishing vessels to increase their participation in the future stock-rebuilding strategies. The modelling approach used here has effectively assessed this effect, in aggregate terms, when the available fishing possibilities are considered (exogenously). However, at the individual vessel level, the stock effect is not considered (Eq.(4)). The existing reports on the size of the stock effect are ambiguous. According to Hannesson [33], the stock effect based on a Schaefer-type model (stock elasticity equal to 1) is the maximum effect. It implies that in real life situations, weaker stock effects are to be found. The effect will depend on the target stock and/or the gear used. For example, the stock effect is weak for the herring in the North Sea [34], while for the trawl fisheries in Norway, it is significant [30]. As Diekert [35] concludes, this effect has to be calculated at the individual vessel level. Up to the knowledge of the authors, the only bioeconomic application at individual vessel level in the fishery studied here is the one done by Merino et al. [25] in where a Schaefer-type model is used. This implies that there are no data for this stock effect at the individual vessel level in the fishery studied here. This limitation implies that the calculated number of vessels (Table 2) has to be considered a maximum and that if this stock effect existed, the obtained number of vessels would be lower. However, as reported by Ward and Sutinen [36], the size of fishing fleet has a strong negative impact on the probability of entry but is independent of changes in the abundance of the stocks. For the fishery analysed by them, the entry probability was independent of the ex-vessel prices and harvest cost. Thus, the assumptions made in this model are supported by some evidence from the fisheries anayzed by these authors. Furthermore, the results of Ward and Sutinen reinforce the necessity of simulating the entry-exit behaviour employing a general equilibrium model that explains these effects using prices.

Another important issue is the leisure-labour substitution effects. First of all it should be noted that technology is in accordance with the fifty-fifty rule, (i.e. 50% of net revenues are accounted for by payments to crew members) as the ones normally applied in the Mediterranean [11], however it is also true that the labour substitution effects is probably different from region to region. It implies that some empirical work is required on this issue in order to ensure that the equilibrium obtained matches the likely values computed from this analysis.

6 Conclusions

A dynamic general equilibrium economic model was created to understand the consequences of fish stock-rebuilding strategies and applied to a Mediterranean fishery as an example. It is concluded that the presented approach for the assessment of the economic consequences of the MAPs in the EU complements the existing strategy (Section 2). It helps to provide a macroeconomic overview of stock-rebuilding policies and explains them on the basis of the current economic theories. The model illustrates the relationship between the economic processes and the biological advice, helping the fishery managers and stakeholders to understand the economic consequences of implementing such advice.

It should be acknowledged that the fisheries, management options and management objectives are too diverse to capture all the characteristics in a single model. Furthermore, the results obtained from the model extract the current limitations in terms of how to deal with the management implementation failures and the general equilibrium, simultaneously, the stock effects at individual vessel level and the leisure-labour substitution effects.

The specific model presented here might be used to start the debate on the EU MAPs economic impact assessment when the biological advice is considered exogenous, that is, the economic consequences of implementing the current (and future) CFP.

7 Acknowledgments

Jose Maria Da-Rocha gratefully acknowledges financial support from the European Commission (MINOUW, H2020-SFS-2014-2, number 634495), the Spanish Ministry of Economy and Competitiveness (ECO2016-78819-R) and Xunta de Galicia (ref. GRC 2015/014 and ECOBAS. Raúl Prellezo gratefully acknowledges financial support from the Basque Government project MULTIPLAN of the Department of Economic Development and Infrastructures of the Basque Government. Luis Taboada Antelo gratefully acknowledges the financial support of the Ramón y Cajal Programme of the Spanish Government.

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A Fish stock dynamics

The particular model used is an age-structured model in continuous time where the conservation law is described by the McKendrick-von Foerster partial differential equation ([19], [20]):

$$\frac{\partial n(a,t)}{\partial t} = -\frac{\partial n(a,t)}{\partial a} - [m(a) + p(a)F(t)]n(a,t). \tag{A.1}$$

Where $F(t)$ is the fishing mortality, $m(a)$ the natural mortality by age and $p(a)$ the selectivity parameter at age.

Equation (A.1) shows that the rate of change of the number of fish in a given age interval (the left-hand side of Equation (A.1)), is equal to the net rate of departure less the rate of deaths. Given all fish ages, the net rate of departure is equal to the first term of the right-hand side of Equation (A.1). This equation also shows how the rate of deaths at age a is proportional to the number of fish at age.

The stock–recruitment relationship and maximum age are the boundary conditions (it was assumed that fish die at age A and recruitment is constant, i.e. $n(0,t) = 1$ and $n(A,t) = 0$. Given that, fishing possibilities for each stock should follow the rule presented in Equation (7) in the main text.

B Definition of equilibrium

The incumbent problem (Equation (6) in the main text) can also be written as a Hamilton-Jacobi-Bellman variational inequality:

$$\min_{I_{\text{exit}}(z,t)} \left\{ \rho v(z,t) - \pi(t,z) + c_f - \mu z \partial_z v(z,t) - \frac{\sigma^2}{2} \partial_{zz} v(z,t) - \partial_t v(z,t), v(z,t) - S(t) \right\} \tag{B.1}$$

The solution of this problem gives the threshold $\underline{z}$ (break-even productivity). For z lower than the exit threshold, $z \leq \underline{z}$, we have $v(z,t) = S(t)$ and firms decide to exit.

The distribution of firms is determined endogenously by exit decisions made by firms themselves. To find the measure of firms over time, $g(z,t)$, the Kolmogorov-Fokker-Planck (KFP) equation is applied:

$$\partial_t g(z,t) \; = -\partial_z[\mu z g(z,t)] + \tfrac{\sigma^2}{2} \partial_{zz} g(z,t) - I_{\text{exit}}(z,t) g(z,t) \tag{B.2}$$

Given the fishing possibilities, $(Y(t))$, an equilibrium is a measure of firms $(g(z,t))$, wages $(w(t))$, incumbents' value functions $(v(z,t))$, individual decision rules $(l(z,t),\, y(z,t))$ and a productivity threshold $(\underline{z}(t))$, such that:

i) (Firm optimization) Given prices $w(t)$, the exit rule, $I_{\text{exit}}(z,t)$ and value function $(v(z,t))$ solve the incumbent problem (Eq.(B.1)), and $l(z,t)$, $y(z,t)$, are optimal policy functions.

ii) (Measure of firms) $g(z,t)$, satisfies the Kolmogorov-Fokker-Planck (Eq.(B.2)).

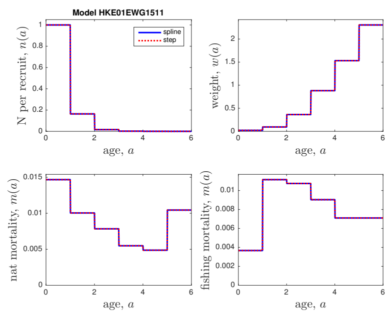
iii) (Market clearing-feasibility) Given individual decision rules and the measure of firms, $w(t)$ and $\underline{z}(t)$, solve Equations (9-10).

The solution of the system is an unknown value function $(v(z,t))$, a measure of firms $(g(z,t))$ and the unknown wage $(w(t))$ that satisfy the following system of partial differential equations:

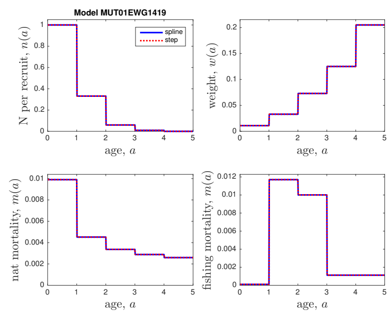
$$
\begin{aligned}
v(z,t) = \max_{\tau} E_0 \int_0^{\tau} \pi(z,t) e^{\rho t} dt + S(t) e^{\rho t}, \\
-\partial_z[\mu z g(z,t)] + \frac{\sigma^2}{2}\partial_{zz} g(z,t) - I_{\text{exit}}(z,t) g(z,t) = \partial_t g(z,t), \\
\int_{\underline{z}(t)}^{\infty} g(z) dz = N(t), \\
\int_{\underline{z}(t)}^{\infty} y(z,t) g(z,t) dz = Q(t), \\
e\left[Q(t) - c_f N(t)\right] = w(t).
\end{aligned}
$$

C Age structured stock dynamics

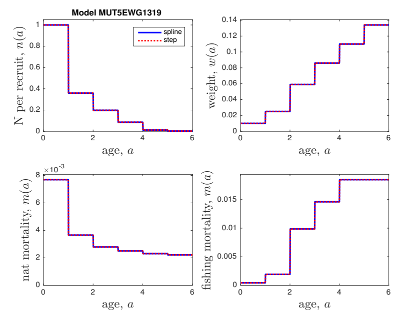
Figure C.1: Age Structured Models. GSA stands for Geographical Sub-Areas.



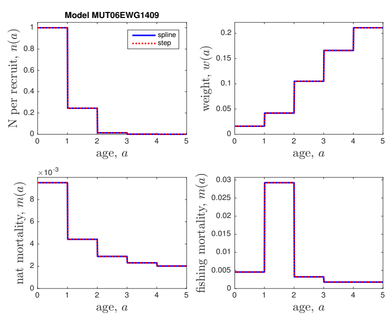
(a) Hake GSA 1



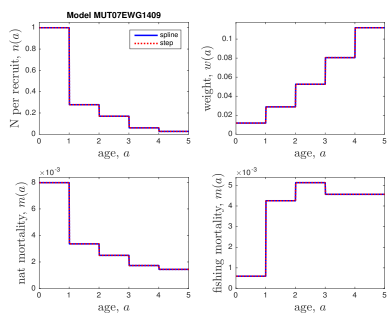
(b) Red mullet GSA 1



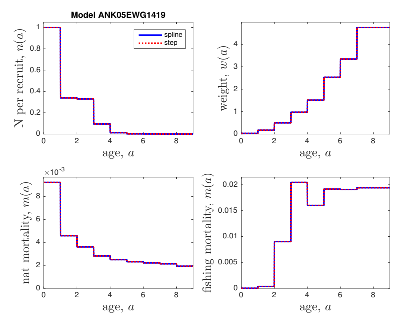
(c) Red mullet GSA 5



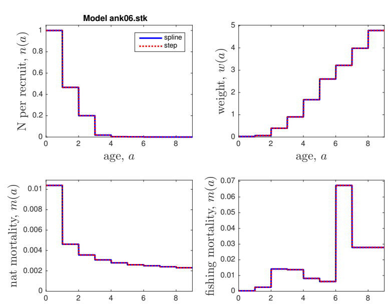
(d) Red mullet GSA 6



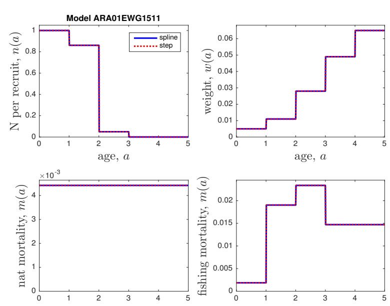
(e) Red mullet GSA 7



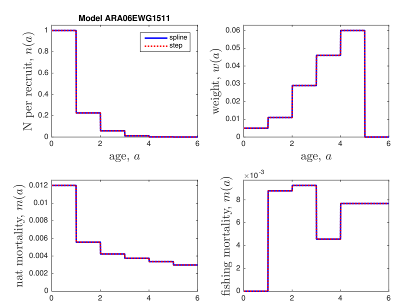
(f) Monkfish GSA 1



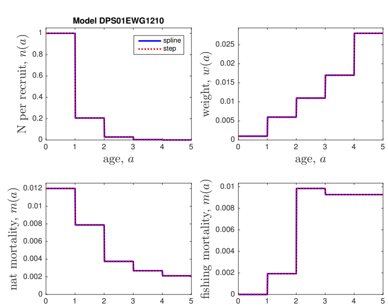
(g) Monkfish GSA 5



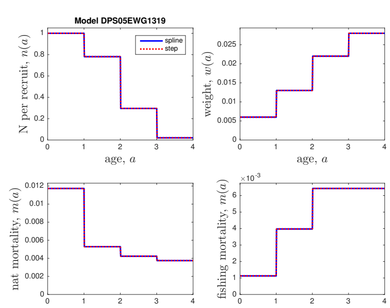
(h) Blue and red shrimp GSA 1



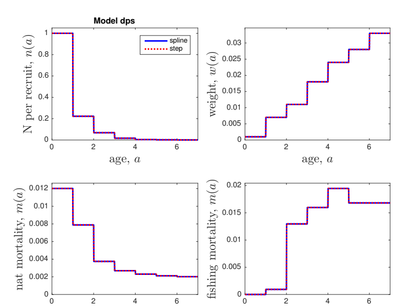
(i) Blue and red shrimp GSA 5



(j) Deep water red shrimp GSA 1

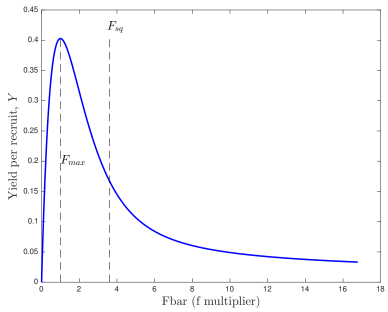


(k) Deep water red shrimp GSA 5

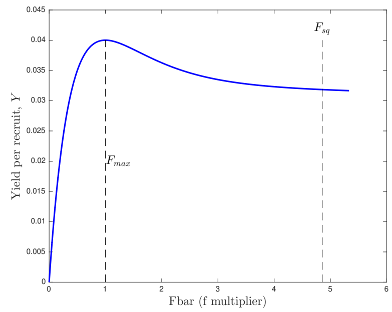


(l) Deep water red shrimp GSA 6

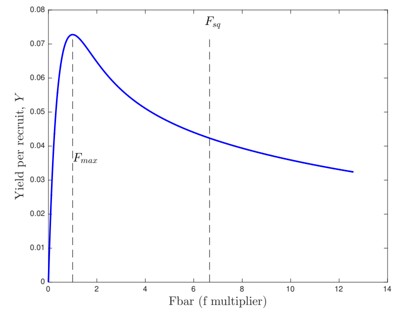
Figure C.2: Target by stock. GSA stands for Geographical Sub-Areas.



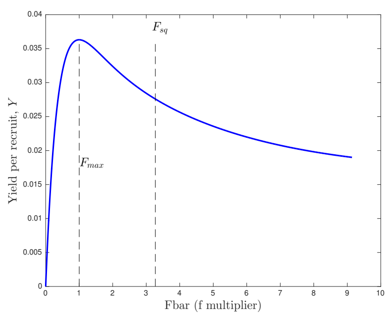
(a) Hake GSA 1



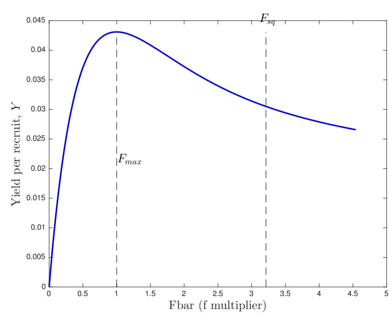
(b) Red mullet GSA 1



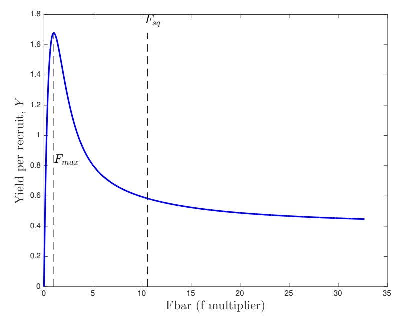
(c) Red mullet GSA 5



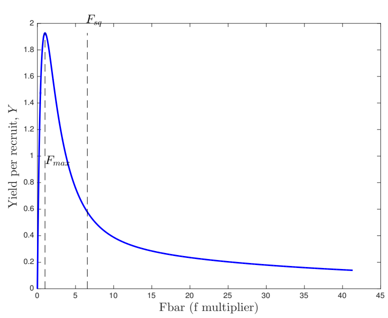
(d) Red mullet GSA 6



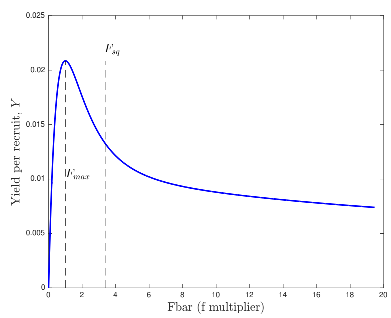
(e) Red mullet GSA 7



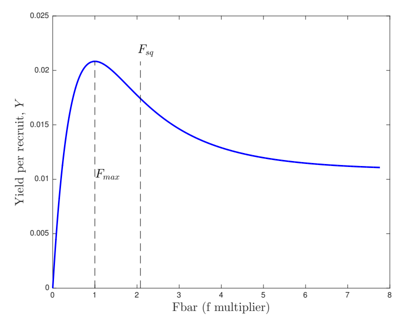
(f) Monkfish GSA 1



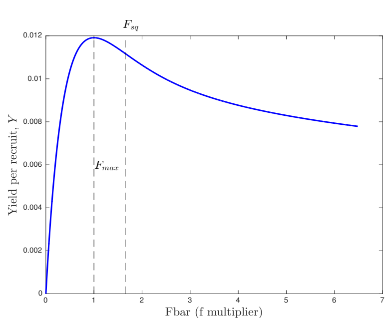
(g) Monkfish GSA 5



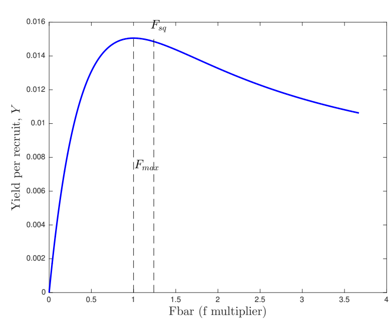
(h) Blue and red shrimp GSA 1



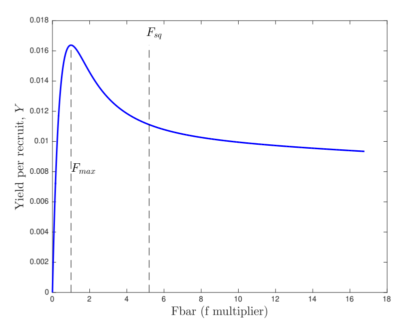
(i) Blue and red shrimp GSA 5



(j) Deep water red shrimp GSA 1



(k) Deep water red shrimp GSA 5



(l) Deep water red shrimp GSA 6