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

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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 plants (vessels) 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

Policies 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 plants. 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 is not based on the general fishery equilibrium models described above but inspired by the recent developments in macro-economic theory, as explained by Achdou et al. [5]. It can be used to assess how the economy adapts to a policy shock, for heterogeneous plants, 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, the General Fisheries Commission for the Mediterranean (GFCM), in the Mediterranean and the Black Sea and the International Commission for the Conservation of Atlantic Tunas (ICCAT), for tunas. 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 a scientific body 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 data at for EU fleets is contained in the Annual Economic Report on the EU Fishing Fleet (AER) [7], where economic indicators are provided on a fleet segment basis. The AER along with other data (fishing effort, catches, landings and biological data) are used 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 of the fishing fleets (i.e., financial and employment indicators of the fishing fleets). This procedure is probably followed to avoid the double accounting. Fisheries involve other economic sectors in their activity having their own economic analysis (i.e. ship building). The sum of the economic performance of these sectors, at individual basis, can be done, although, potentially, can also underestimate the macro-economic consequences of the fisheries policies. Projections of economic variables are also provided by the AER. However, as the STECF [12] notes, the projection models used to forecast are based on the correlations between variables. It implies that are not grounded in any economic 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, fleet segment or metier[1] 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 a hindrance (see Prellezo et al. [15]). 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 (output based regulations) or on the non-linear relationship between the fishing effort and fishing mortality (the so called hyperstability) in the input based regulated systems. 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. However, if the economic aspects of the model are not correctly modeled this feedback process cannot be properly captured.

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

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[1] The fishing activity which is characterised by one catching gear and a group of target species, operating in a given area during a given season, within which each vessels effort exerts a similar exploitation pattern on a particular species or group of species

of most projection models. This is an extremely important issue; given that some projections can be based on strong assumptions in terms of factors availability (except fishing opportunities) and can potentially ignore the likely impact of these factors on stock-rebuilding strategies (or the other way around).

Shortcoming (i) makes the economic results difficult to interpret because of the feedback mechanisms embodied in the models. The general macro-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 different way of thinking to provide economic assessment of 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 households 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 [2]. 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. Furthermore, the definition of core economic concepts (i.e. consumer and producer surplus) using an equilibrium approach –i.e. stationary solutions– and disequilibrium approach –i.e. transitional dynamics– is identical. 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. Overall, equilibrium models can provide disaggregated and aggregated economic and social indicators (wages and household utility), capital indicators (number of vessels[3]) and macro-economic aggregate indicators (gross value added -GVA- and wealth). It considers the heterogeneity of fishing plants; this allows to endogenously consider the capital dynamics. Finally it should be also remarked, that measuring welfare using a disequilibrium approach is complex. For example, during the transitional period towards equilibrium, resource rent (difference between total revenue and total opportunity costs) is constantly changing.

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 plants 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 plants (vessels) of these plants are faced. The idea is that the dynamics of the plant size can be explained by stochastic models of evolution with purely idiosyncratic (plant-specific) shocks. This idea has

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

[3] Plants in the particular model proposed.

been established for a long time in the relevant literature (see Hopenhayn [16] for a general overview and Weninger and Just [17] 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 plants (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 - sub-section 3.5) and the results, considering the steady state (sub-section 4.3.1) and the transitional period (sub-section **??**).

3.1 The household problem

It is assumed that there is a representative household who owns the plants and the plants, supplies labour, produces the intermediate inputs, and consumes the final good, taking prices as given. Households will supply 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 income 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 plants problem

It is considered that fishing firms are composed of individual plants (vessels). The problem of incumbent plants can be defined as follows:

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

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

That is, it is assumed that plants 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 plants 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 fishing plant (vessels) dynamics must be computed. As described in the study of Weninger and Just [17], it is assumed that the abilities of individual plants change over time. Another assumption is that if a plant wants to remain active, then it must pay a fixed cost (c_f). These two assumptions are associated with changes in the individual plants: some of the plants 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 plant 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 plants 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 plants is determined endogenously by the exit decisions made by the plants themselves. Given instantaneous profits, the dynamic of the incumbent plant 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 plant 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 plants 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 plants, $g(z,t)$, that is, the number of plants of productivity z at the period t. The distribution of plants is determined endogenously by exit decisions made by the plants 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 [18][19]) (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 opportunities for each fish stock $(Y(t))$ should follow the next rule (see Da-Rocha et al. [20] for an application of this dynamic):

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

In this case a fleet is considered as group of plants. Ex-vessel (first-sale) prices of each stock and fleet $(P(s,f))$ and catch composition by fleet and stock $(share(f,s))$ are used to generate the value of the catches for each fleet:

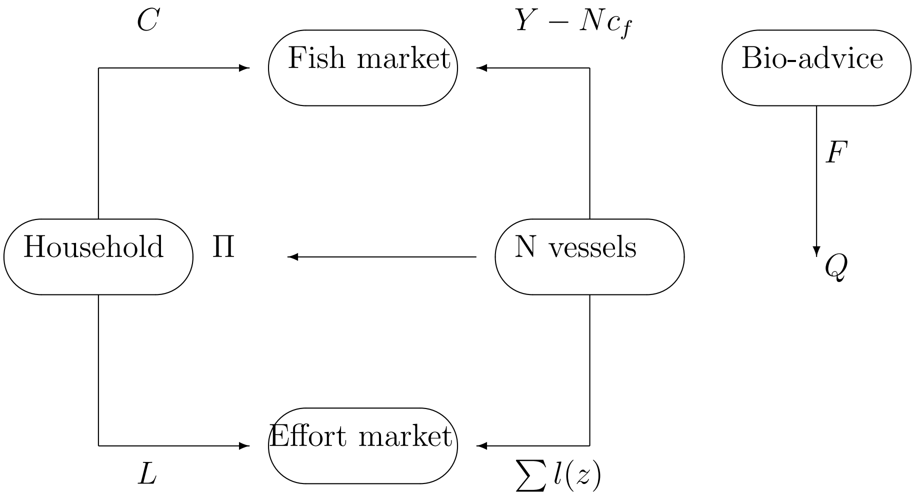
$$Q(t) = \sum_{s_f} P(f,s)share(f,s)Y(s,t), \tag{8}$$

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

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 plants (vessels) and exchanged in the fish market. These plants 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.



do so, the feasibility condition in the labour market is required:

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

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:

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

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

i) Incumbents plants optimization problem and plant measure are satisfied (Eq.(6)).

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 opportunities (Q) and the number of vessels ($N(t)$).

The economy is defined by Equations (6, 10-11).[4] Figure 1 represents this equilibrium graphically and Appendix B mathematically.

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. [21] in where the MEFISTO model is applied to the hake of Catalonia and Maynou et al. [22] in where several management strategies are assessed. Marine protect areas economic assessment has been also performed by Merino et al. [23] and an analysis of effort dynamics can also be found in Merino et al. [24].

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

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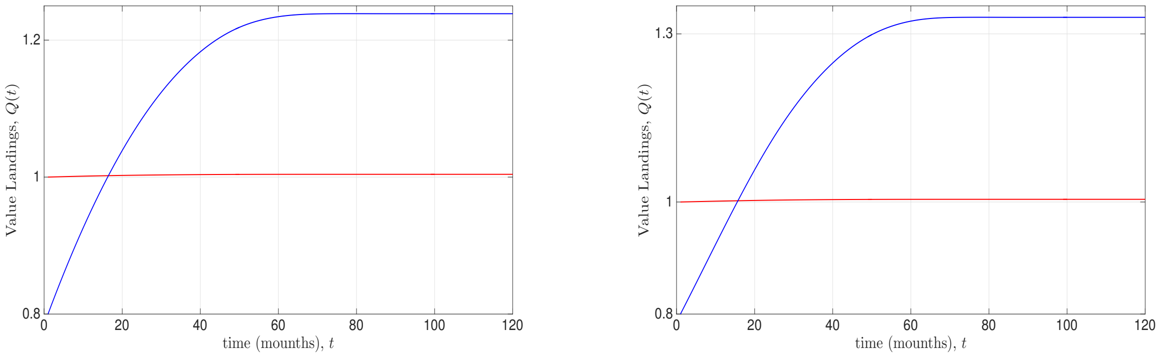
[4] Equation (9) is satisfied by the Walras law. Walras proved that the state of the economic system at any point is the solution of simultaneous equation representing the demand for goods (consumers) the supply of goods the producers and the equilibrium condition that supply equals demand on every market.

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. [25] in Mediterranean European countries, 85% of the assessed stocks are currently over-fished compared to a MSY reference value. As shown in Table **??** this overfishing also occurs in the GSA studied. This implies that a rebuilding is required for the 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 **??**). 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 period, Δt, which is lower than one 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 opportunities (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 **??**). 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 **??**- 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 [17] and its per-unit time volatility ($\sigma_z = 0.01$) from Da-Rocha et al. [26]. The discount rate (ρ) was set to 0.04. This value was obtaining considering that the discount rate has to be above the interest rates (see, for instance, Mehra and Prescott [27]). 4% is, approximately, the Spanish and French average capital input growth rate in the pre-economic crisis period (2006-2008) according to the Organisation for Economic Co-operation and Development[5].

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. The value calibrated for e was 1.5339. 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 plants 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.

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 **??** have been

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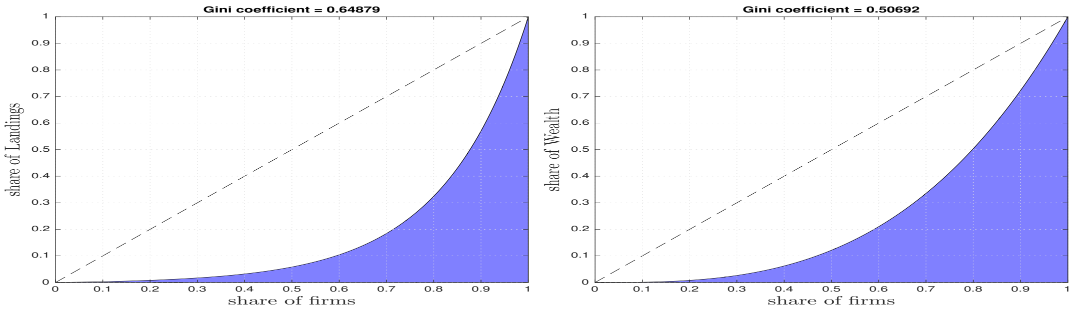
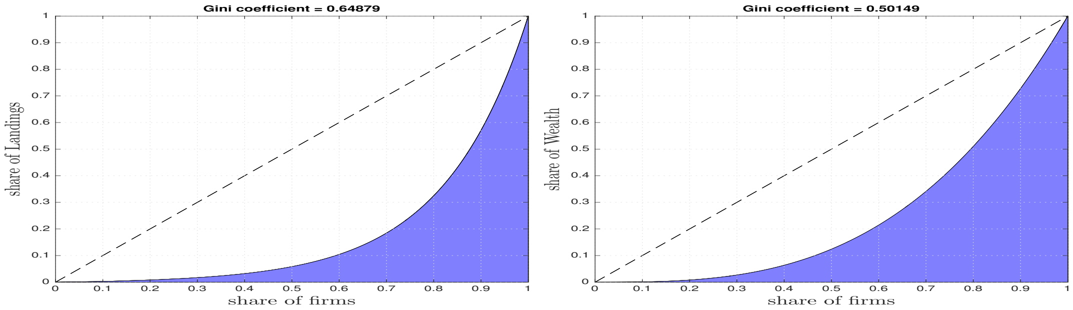
[5] Source: http://stats.oecd.org/.



(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 computed 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).

obtained from the STECF [11]. See the supplementary material for the results of the fittings for each stock.

4.3 Results

4.3.1 The steady state

To evaluate the macro-economic 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 plant;

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

iii) Fleet size (the number of plants, $N(t)$).

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 fleet size ($N(t)$) represents the number of "standardised" plants. The plants have the operating capital and stay active if they find optimal to pay the idling cost, c_f. Note that for the marginal plant (the less efficient plant), there is no difference between paying the idling cost of fishing or exiting the economy. This marginal plant makes negative instantaneous profits, but has a positive opportunity cost of exiting the fishery (see Weninger and Just [17]). Its total expected value of operating the plant 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 plants with higher fixed costs have a higher break-even productivity. In other words, if the plants 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 plants corresponding to each productivity level (Fig. 4).

To understand the differences between the F_{sq} and F_{80} scenarios shown in Table 1 (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 opportunities imply

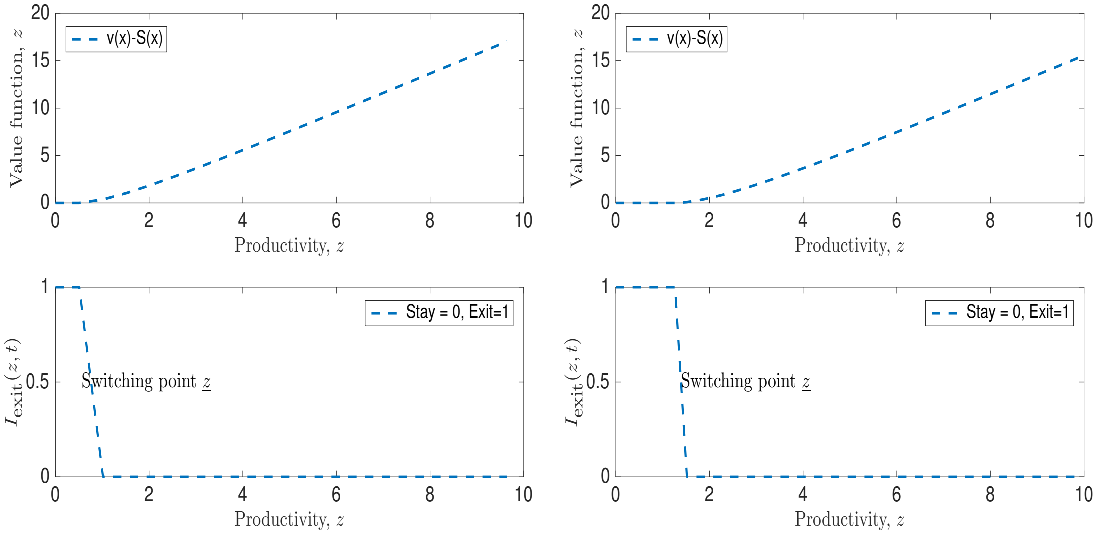
Table 1: Steady-state indicators for French and Spanish fleets under the two scenarios (F_{sq} and F_{80})

France

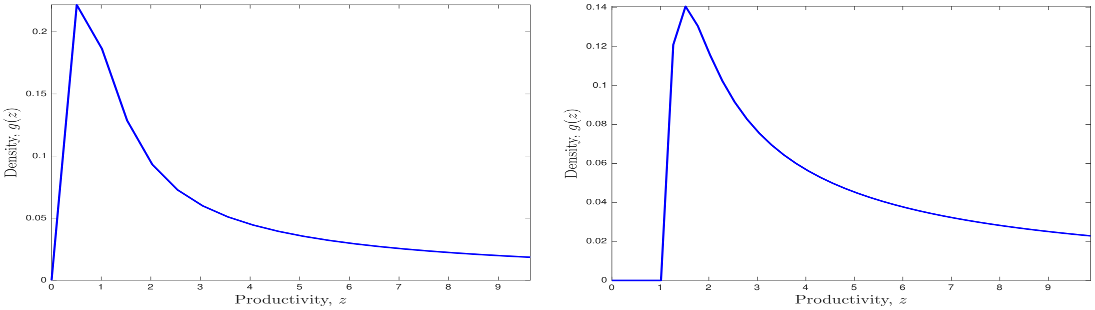
Scenario		F_{sq}	F_{80}
Fleet Size	N	1	1.759
wage	w	1.500	1.980
		Per vessel	
TFP (CPUE per vessel)	$E[y(z)/l(z)]$	3.000	3.960
Days per vessel	$E[l(z)]$	2.004	1.150
Yield per vessel	$E[y(z)]$	6.014	4.556
Profits per vessel	$E[\pi(z)]$	2.874	2.145
Value of vessel	$E[v(z)]$	34.969	25.938
		Inequality	
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)

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 labour for each plant is reduced. On the other hand, the elevated wages induce some plants 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 plant (of more productive plants) generated by higher wages. The process is illustrated in Figure

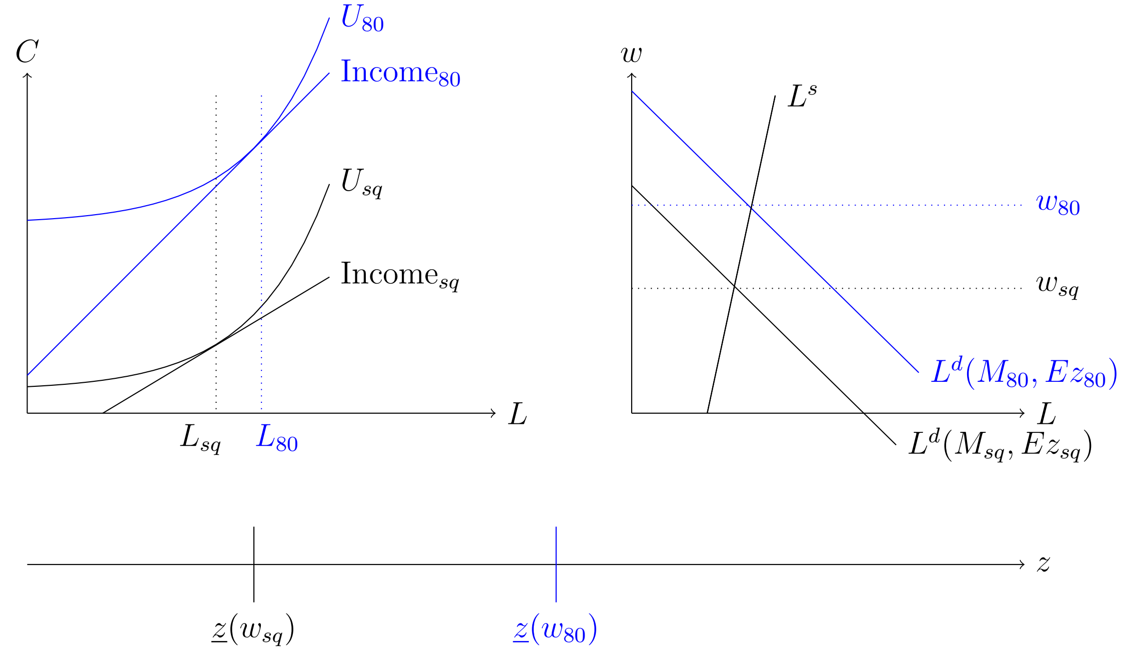


Figure 5: General equilibrium of a stock-rebuilding strategy (F_{sq} to F_{80}). In the steady state the stock-rebuilding strategy (F_{80}) produces higher catches and higher income that increases also the utility (U). Increased wages induce changes in the effort composition making the break even productivity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

5 and the numerical results in Table 1.

The increased fleet size intensifies the competition among the plants and raises the wages. Plants increase the productivity; TFP per plant increases. However, on average, the individual plants spend fewer days at sea, and the total catches per plant are reduced. As a result, the profits per plant and plant value decrease.

Essentially, the increased future catch opportunities will be translated into an increased number of plants 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 plant level, the individual plants would have been benefited from the improved fishing opportunities. This implies that the number of plants shown in Table 1 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 plants). Gross operating surplus is also increased by the recovery program. As far as the social utility of the households is concerned, this surplus is also higher under the F_{80} than under F_{sq} scenario[6]; 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 plants) is highly malleable. Note that at $t = 0$, the capital, $N(0)$, and the measure of plants, $g(z, 0)$ are set. Therefore,

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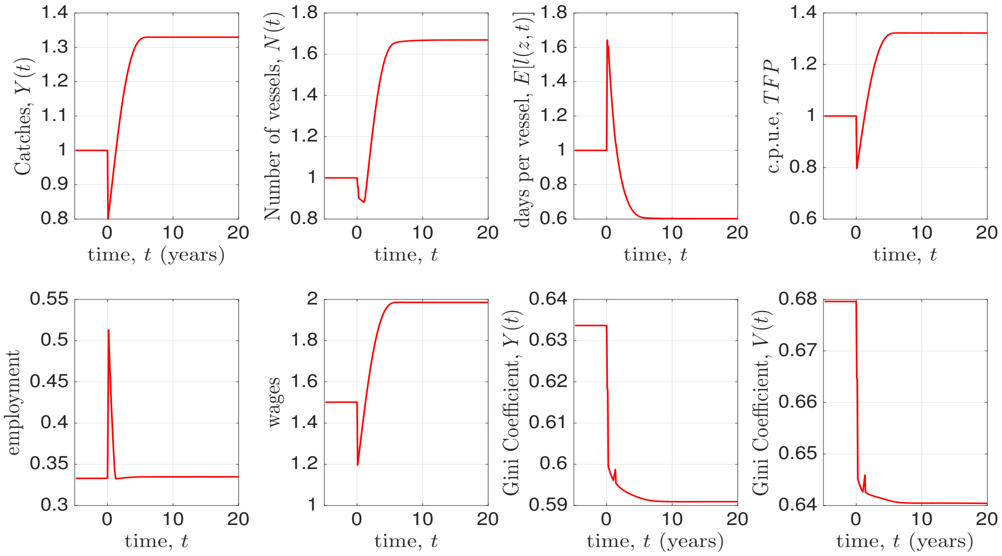
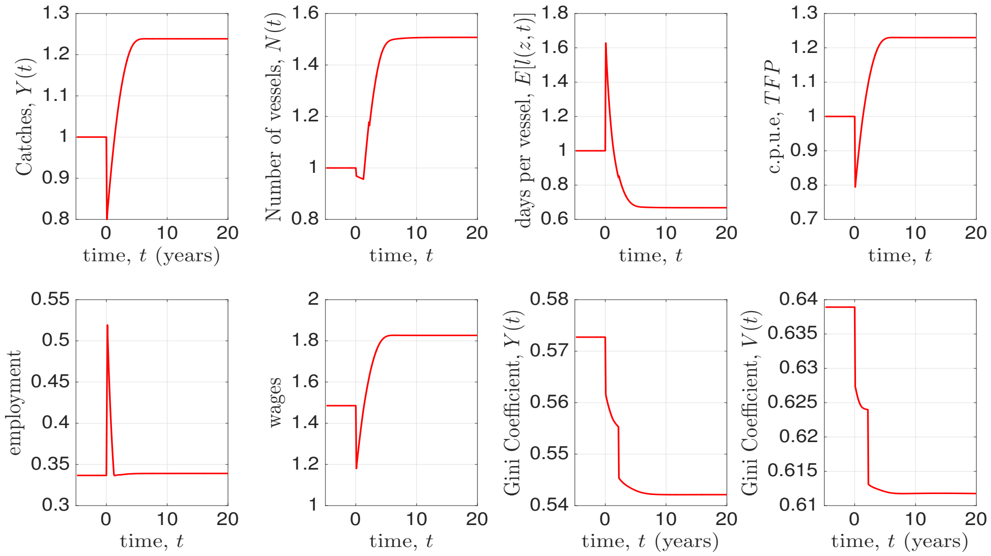
[6] It should be noted that the utility function has to be read in a standard ordinal sense; the higher the better.



(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)).

deteriorated fishing opportunities at $t = 0$ imply a reduced wage compared with the initial conditions. 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 plants, the lower will be the fraction of total fishing opportunities available for each plant. That is, the vessel profitability depends on the individual fishing opportunities rather than on the total ones. Then, the expectations of future individual fishing opportunities are formed. These fishing opportunities have to satisfy Equation (8), in each period.

Therefore, the individual fishing opportunities are the prices, which depend on the scarcity of the fishing opportunities. As in the steady state, the equilibrium is the result of adjustments in three margins: CPUE (per day at sea and per plant), average days at sea per plant and the number of plants.

[**Figure 7 around here**]

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 opportunities 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 plants (vessels) 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 [28]. Some other approaches simply do not use models but are scenario-based [29]. 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 -plants- 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 the 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 plants are considered heterogeneous agents.

When a production factor is heterogeneous (the individual ability, z) intra-marginal plants create a producer surplus (individual profits). The size of these profits is determined by the marginal plant. These plants require a minimum productivity level; below this level, they will exit the fishery, and above it, they will stay. It can be considered as the minimum 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 vessels 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 plants (vessels) are active, it is because they are productive enough in relation to their costs. If they attempt to remain in the fishery, it is because the opportunity cost of exiting is high, even if they face instantaneous negative profits.

Changes in the fishing opportunities due to the rebuilding policy, modify the fleet size and the break-even productivity (the distribution of individual profits). Although, both statistics are equilibrium objects (that are simultaneously determined), changes in the individual distributions (generated by changes in the break-even productivity) can be associated to changes in intra-marginal rents while changes in aggregate statistics (i.e. fleet size, consumer surplus) to changes in resource rents [33]. However, the model (as it is) is not free of limitations. As explained in Section 3.1, households are the owners (producers) of the all the production factors and the buy directly all the production. The former implies that variable costs are not considered explicitly which limits the analysis of changes in, for example, fuel prices, important in the fisheries context. The later will imply to model a retail sector that also considers the difference between the ex-vessel prices and the final price paid by the consumer. However, this will also require to model an external market that considers that the retailer is selling internal (within the fishery) and external goods (imports). This is necessary given that the two economies studied are net importers of fish [**?**].

As pointed out by Clark et al. [31], in cases of overexploited fisheries (as it is the case in our case study), the questions to be tackled are the extent of the rehabilitation and its rate. These authors also gave the answer to this question: it will depend on the initial level of capital. Here, the capital is defined by the number of vessels. The model presented here shows how this rehabilitation trajectory can be computed when entry-exit is an endogenous decision which depends on the initial conditions. 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]. However implementation failures are not considered in the model. On the one hand, any lack of enforcement can induce more effort than that advised; on the other hand, as pointed out by **?** [**?**] 'command and control' management fails if the industry raises its cost by increasing capital. Further work (i.e. allowing plants to invest in capacity) must be done to address these issues.

An important characteristic of the model is that fleet behaviour is modeled taking the rebuilding strategy as given. 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 fishing opportunities 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. It should be noted that the main feature of these type 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 segments 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. It can be acknowledged that 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 Larkin et al. [30] a model that is weak on the biological aspects will attribute all problems to the economics of the fishery and, conversely, a model that is weak on the economic aspects will attribute all problems to the biology whether or not these problems have economic causes. However, the model can be extended to determine the bioeconomic optimum. Note, that in the model individual plants do not internalize that their entry/exit decisions modify the current aggregate catches, which affects the rest of agents through future prices and fishing opportunities. As pointed out by **?** [**?**] a central planner would take this effect into account.

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 (plant) level, the stock effect is not considered (Eq.(4)). The existing reports on the size of the stock effect are ambiguous. According to Hannesson [34], 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 [35], while for the trawl fisheries in Norway, it is significant [30]. As Diekert [36] 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. [24] 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 1) 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 [37], 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 analysed 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 some further empirical work is required for the labour substitution effect 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. Under the described assumptions, the model presented defines endogenously the equilibrium relationship between wages, employment and number of vessels. 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 macro-economic 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 rebuilding strategies are considered as given, that is, the economic consequences of implementing the current (and future) CFP.

7 Acknowledgments

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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 ([18], [19]):

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

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 plants decide to exit.

The distribution of plants is determined endogenously by exit decisions made by plants themselves. To find the measure of plants 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 plants $(g(z,t))$, 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 plants) $g(z,t)$, satisfies the Kolmogorov-Fokker-Planck (Eq.(B.2)).

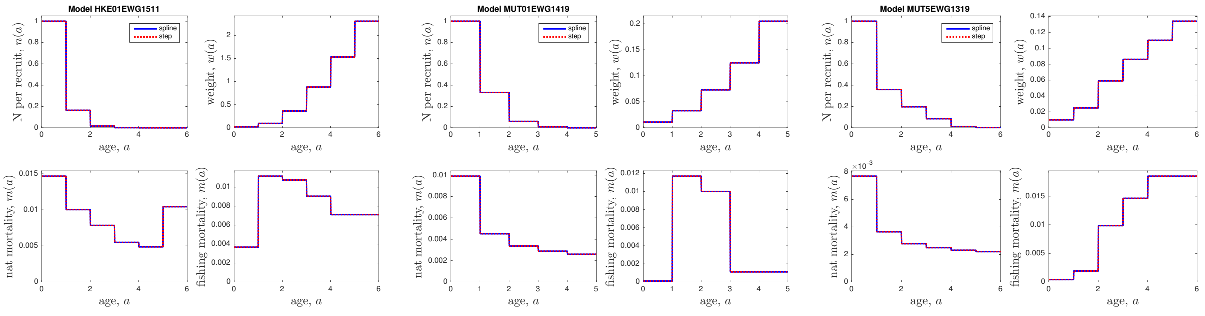
iii) (Market clearing-feasibility) Given individual decision rules and the measure of plants, $w(t)$ and $\underline{z}(t)$, solve Equations (9-10).

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

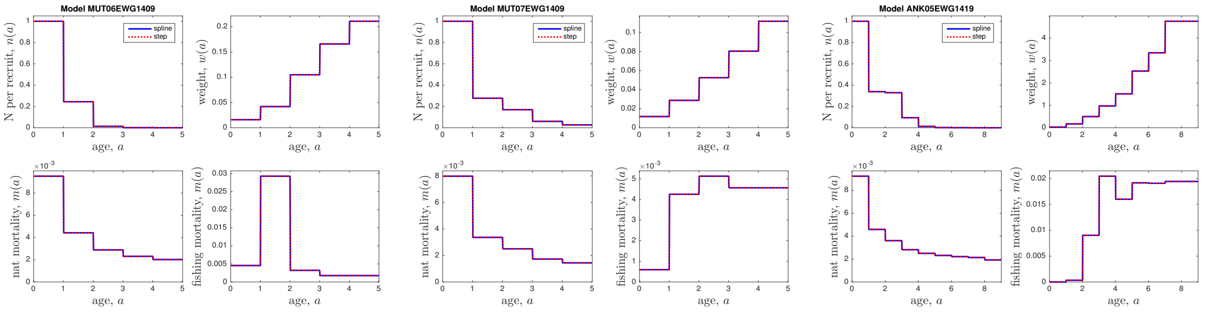
$$\begin{aligned} v(z,t) &= \max_{\tau} E_0 \int_0^{\tau} \pi(z,t) e^{\rho t} dt + S(t) e^{\rho t}, \\ -\partial_z[\mu z g(z,t)] + \frac{\sigma^2}{2}\partial_{zz} g(z,t) - I_{\text{exit}}(z,t) g(z,t) &= \partial_t g(z,t), \\ \int_{\underline{z}(t)}^{\infty} g(z) dz &= N(t), \\ \int_{\underline{z}(t)}^{\infty}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

C Age structured stock dynamics

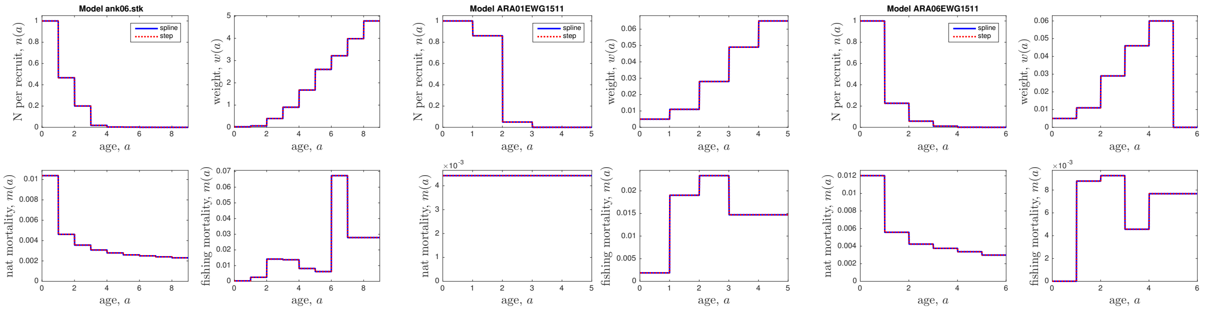
Figure C.1: Age Structured Models. GSA stands for Geographical Sub-Areas.



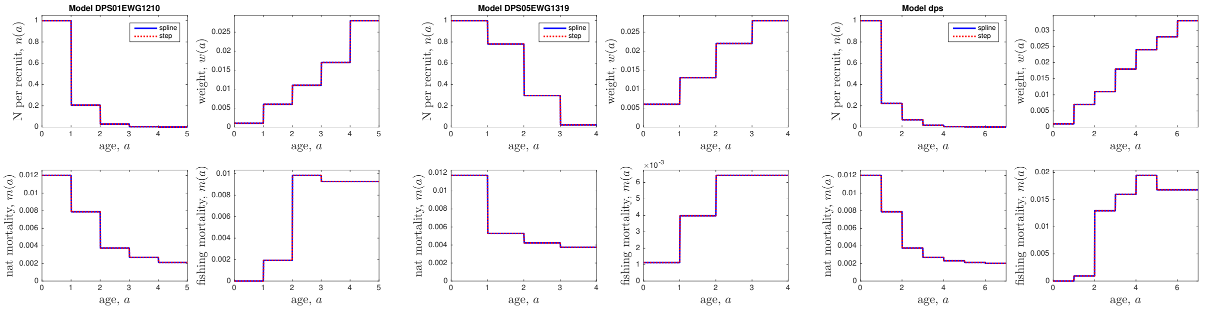
(a) Hake GSA 1 (b) Red mullet GSA 1 (c) Red mullet GSA 5



(d) Red mullet GSA 6 (e) Red mullet GSA 7 (f) Monkfish GSA 1

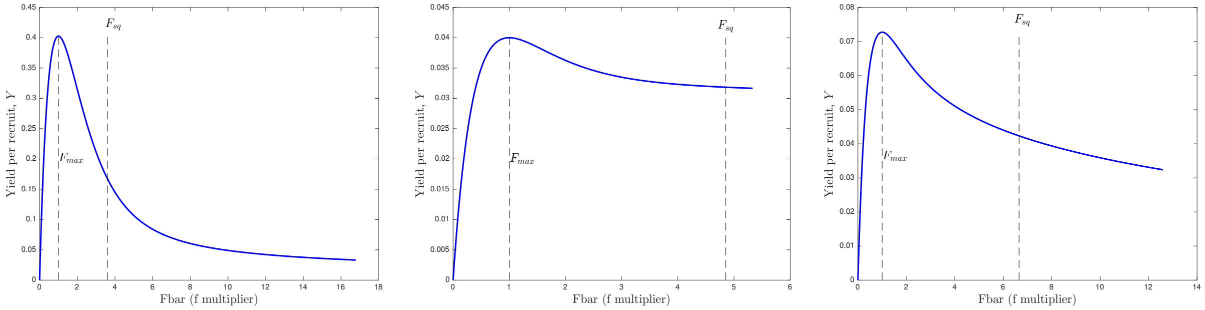


(g) Monkfish GSA 5 (h) Blue and red shrimp GSA 1 (i) Blue and red shrimp GSA 5

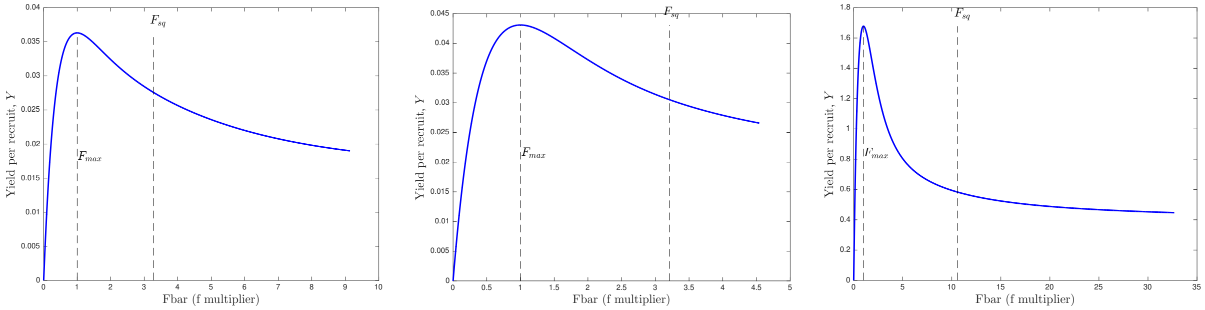


(j) Deep water red shrimp GSA 1 (k) Deep water red shrimp GSA 5 (l) Deep water red shrimp GSA 6

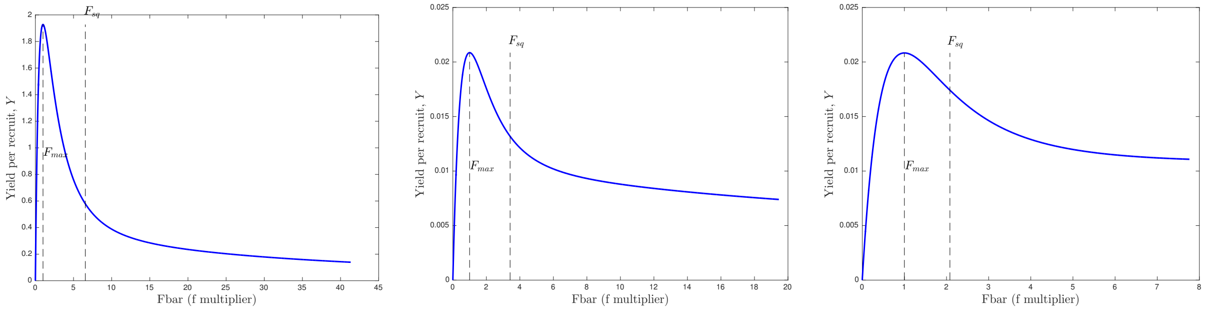
Figure C.2: Target by stock. GSA stands for Geographical Sub-Areas.



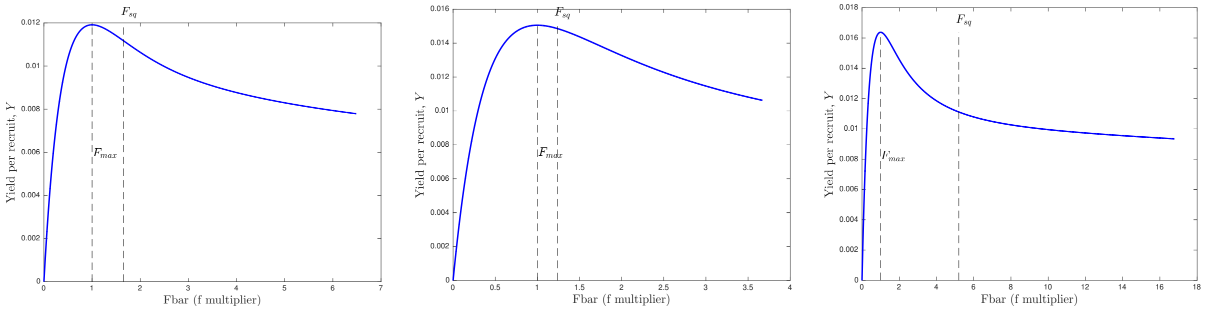
(a) Hake GSA 1 (b) Red mullet GSA 1 (c) Red mullet GSA 5



(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