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Caps on working hours per vessel: A general equilibrium analysis*

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Abstract

General equilibrium analysis shows that regulation based on caps on working hours per vessel affect the entry/exit margin (more low productivity vessels stay in the fishery), wages (a less productive fleet implies lower equilibrium wages) and aggregate employment allocated to the sector. Although the total number of vessels increases, total employment in the fishery is reduced and the aggregate rents generated in the fishery are lower. Moreover, regulatory policies based on input controls also affect capital dynamics across the stock recovery phases. In comparison with a fishery regulated via efficient instruments, we find that those dynamics are characterized by fewer exits of vessels. Finally, using data from the Western Mediterranean Sea, we show that the use of input controls gives rise to a Spanish fleet around 14 percent larger than the one that would result from a non-distortionary instrument.

Keywords: Firm dynamics, Investment, General Equilibrium, Fisheries.

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1 Introduction

Fisheries in the Mediterranean Sea have traditionally been managed via input measures[1], specifically caps on working hours per vessel (see, for instance, Maynou et al. (2006), and Cardinale and Scarcella (2017)). Seminal papers such as Squires (1987) and Kompas et al. (2004), among others, show that policies based on input controls induce fishers to replace regulated inputs by unregulated inputs, generating economic inefficiencies that reduce vessels' productivity.

In this paper we extend the analysis of the impact of input controls to a dynamic general equilibrium framework. In particular, we focus on the effect of input controls on individual firms' decisions. We assume that individual decisions are taken based on rational expectations. This enables us to relate fleet dynamics to the policy instruments used to manage the fishery.

As is done in Da-Rocha et al. (2017b), we consider that the abilities of individual firms follow a stochastic process and that there is a fixed operating cost that firms must incur if they want to remain in the fishery. We use a general equilibrium framework to compute how input controls affect endogenous prices, labour supply and the number, productivity and composition of the fleet.

The general equilibrium analysis presented here provides new insights not offered by a partial equilibrium analysis. When the impact of a given policy is analyzed in a general equilibrium setting, the aggregate effect is the result of several effects that are assessed separately in partial equilibrium models. Therefore, the final result may be different from the one predicted by a partial equilibrium analysis. Some of the main insights regarding these differences are explained below.

[1] In a few cases, e. g. bluefin tuna and swordfish, output measures are used (see, for instance, the summary of the rules used in the Mediterranean Sea in the website of the European Union https://ec.europa.eu/fisheries/cfp/mediterranean/rules_en).

A cap on working hours per vessel generates static input misallocation across heterogeneous vessels that reduces productivity. A constraint on the hours worked per vessel leads more productive firms to produce less than they would optimally produce. In consequence, those firms are not producing at the optimal scale level and their production costs are not minimized, leading to an inefficient allocation. Catches per unit of effort (CPUE) are lower than optimal. Therefore, to produce the same aggregate yield, more vessels are needed under input controls than under a non-distortionary price-based instrument. This static misallocation is also analyzed in Johnson and Libecap (1982), where two fishers facing different marginal costs but symmetrically sharing a globally efficient quota, do not maximize aggregate profits.

In addition to these partial equilibrium insights, general equilibrium analysis also means that the number of fishermen does not remain constant when quotas are not distributed efficiently. In fact, policies also affect the composition of the fleet. Input controls reduce individual profits and also the continuation value of remaining active in the fishery. This reduction in individual profits, affects all the firms in the distribution via prices (and not only those on which the input constraint is binding), affects exit decisions and determines the productivity distribution of the fleet in equilibrium. Input controls mean that more low-productivity vessels stay in the fishery, causing dynamic input misallocation.

A less productive fleet means lower equilibrium wages. Lower wages reduce the attractiveness of working in the fishery. In contrast with what would happen in a partial equilibrium setting, total employment in the fishery is reduced. Therefore, despite the increase in the number of vessels in the fishery, the cap on working hours per vessel does not increase total employment in the fishery (as the total number of working hours is reduced at the fishery level). All these factors mean that, despite the fact that the cap on working hours per vessel induces substitution of labor by capital, the aggregate rents generated in the fishery are lower. The fishery is thus less wealthy.

Regulatory policies based on input controls also have effects on capital dynamics across the stock recovery phases. In comparison with a fishery regulated with efficient instruments, we find that those dynamics are characterized by fewer exits of vessels from the fishery at the initial stages, as the fleet tends to stay in during the initial stages of a fishery rationalization policy (in which present catches are reduced in order to increase the stock of fish with a view to increasing captures in the future). Given that input controls are associated with larger fleets which are less productive, although the average reduction in catches is the same regardless the regulatory instrument used, that reduction represents a lower proportion of the fixed costs and thus induces fewer exits when input controls are used.

Finally, when input controls are used, vessels enter at earlier stages and the fleet is replenished with less efficient vessels than when efficient regulatory instruments are used. Entry occurs earlier because, the low productivity of the entrants means that entry increases capacity more slowly than when an efficient regulatory instrument is used.

The work presented here is related to three strands of literature: the literature assessing the impact of removing constraints, the literature analyzing malleability of capital, and the literature on rational expectations and excess capacity.

In relation to the literature assessing the impact of removing constraints, there are examples of how policies affect the composition of the productivity of a fleet. For instance, Lian et al. (2009) measure the extent of harvesting inefficiency in the Pacific Coast groundfish fishery under the controlled access management program and predict the equilibrium fleet structure, harvesting costs, and fishery rents that are expected to emerge under an individual fishing quota management program (without and with restrictions in transferability). They estimate the savings in cost associated with policies inducing the use of the most efficient cost structure. By explicitly considering an endogenous distribution of firms, our general equilibrium setting enables us to compute the endogenous change in the distribution of productivity due to the use of input controls and compare the results with any other regulatory policy. This is more general than computing the impact of removing distortions by comparing two cost structures. We use calibrated costs to predict the number and type (length class) of vessels.

We explicitly consider individual firms' entry and exit decisions, so our work is closely related to the literature analyzing malleability of capital. In our paper the degree of malleability of capital is endogenous to regulatory policies. Analysis of the dynamics of firms based on individual stay/exit decisions has received much less attention in the economic literature than the analysis of optimal capacity investment paths under the assumption of a sole fleet owner.[2]

Capital at fishery level is closely related to the entry and exit decisions taken by firms, which are based on their expectations as regards current and futures policies. This is especially relevant when changes in fishery management policies are assessed, especially on those which seek higher stock levels. In our model, individual rational decisions are based on the whole transitional dynamic (induced by the instrument used to achieve the stock rehabilitation objective). Individual firms assess the expected value of staying in the industry at each moment and compare it to the present discounted value of profits associated with exiting the industry. Based on this comparison, individual firms decide to stay in or exit the industry. The aggregate behavior of individual firms, and not the decision of a monopolistic fleet owner, determines the dynamic of capital in the industry.

In relation to the literature relating expectations and excess capacity, we highlight the link between rational (forward-looking) expectations and the resultant level of excess capacity. Our results show that, in contrast with modeling frameworks based on myopic expectations such as Rust et al. (2016), vessels will enter the fishery even when the fish stock is lower than

[2]Indeed, in the spirit of Smith (1968, 1969) the literature has mostly focused on models in which capital is assumed to be equal to the number of vessels in fleets composed by homogeneous vessels. Stay/exit decisions have been modeled as investment/disinvestment decisions, and (usually) a sole fleet owner chooses the optimal fleet size, or the capacity utilization under different assumptions on investment cost (Boyce, 1995; Nøstbakken, 2008; Sandal et al., 2007), stock dynamics (Botsford and Wainwright, 1985), stock uncertainty (Hannesson, 1987; Singh et al., 2006; Da-Rocha et al., 2014a) and the strategic effect of irreversible investment decisions in a strategic environment (Sumaila, 1995). For a summary of the literature see Nøstbakken et al. (2011).

its steady state stock level. Therefore, rational expectations on the transitional path have empirically testable implications. If we assume that vessels enter the fishery only when the fish stock is greater than its steady state stock, entry will ever be observed in the course of the fishery recovery process. Moreover, the model predicts that exits will be more numerous and faster when the fishery recovery policy is based on a non-distortionary instrument. This finding is consistent with the fleet decrease observed in the Northeast Multispecies (Groundfish) U.S. fishery after the introduction of the New Management Plan in 2010 which reinforced the use of market instruments.[3]

Finally, in our model malleability is generated by the optimal individual decisions of entering, exiting and staying. These decisions are endogenous to the policy instrument used for the stock recovery and therefore, cannot be predicted by a regression model (e.g. probit or logit models). If the probabilities of entering, exiting and staying are estimated using historical data, as for example in Tidd et al. (2011), exit may be underestimated if there is a structural change in the regulatory regime of the fishery.

2 The Model

As occurs in Terrebonne (1995) and Heaps (2003), we consider a natural resource industry with heterogeneous firms. This industry is output-constrained by a regulatory agency in order to rehabilitate a given stock. Moreover, we assume that entry is allowed only when quota, Q, exceeds capacity.

There are two markets in the economy: The final goods and labor (which is used to produce the final good) markets. Taking output price as the numeraire, we denote wages by $w(t)$. We assume that a continuum of identical households, which own the firms, consume the final

[3] Da-Rocha et al. (2017b) report that after remaining stable from 2007 to 2009, the number of active vessels decreased by 32% in the Northeast Multispecies (Groundfish) U.S. fishery in 2010.

good and supply labor by solving a consumption-leisure maximization problem.

We assume that firms have a finite lifespan and are heterogeneous. Let $g(z,t)$ be the measure of firms over time (i.e. the number of firms with productivity z at time t). The decision rules of incumbent firms at time t depend on z. We denote the optimal choices of output and labor by $y(z,t)$ and $l(z,t)$.

As occurs in Da-Rocha et al. (2017b) , we assume that the abilities of individual firms follow a stochastic process and that there is a fixed operating cost of c_f that must be paid by individual firms that remain active in the industry. These two assumptions mean that individual firms change over time. At each particular moment in time some of them expand production, hiring staff, while others contract production, firing staff, and others exit the industry altogether.

The decision problem of incumbent firms produces two types of decision rules. There are continuous decision rules for the optimal choice of output $y(z,t)$ and labor $l(z,t)$, and there is a discrete decision rule for the optimal stay/exit decision. This implies, on the one hand, that there is endogenous exiting. This decision depends on employment $l(z,t)$ and output $y(z,t)$ in each period. Conditional on the choices in each period, $l(z,t)$ and $y(z,t)$, each firm must assess the expected value of staying in the industry and must compare it to the present discounted value of profits associated with exiting the industry $S(t)$ -a scrap value-. On the other hand, a finite vessel lifespan implies depreciation.

Finally, when managers of fisheries allow *entry*, we assume as does Luttmer (2007) that potential entrants copy incumbents. Overall, this means that the distribution of the productivity of firms, $g(z,t)$, changes over time and is endogenously determined by exiting decisions.

The model is analyzed in three steps. First we solve the individual problems of firms and households. This establishes the relationship between input controls and exit decisions. Then we specify the dynamics of the distribution of firms and the feasibility conditions. Finally we define the equilibrium.

The problem of incumbent firms is as follows. Let $\tau_l(t)$ be a constraint on effort (in particular, $\tau_l(t)$ is the maximum number of working hours per vessel in period t). Conditional on this constraint, firms maximize profits subject to the technology available to them, $y(z,t) = \sqrt{z\ l(z,t)}$.[4] Thus, at time t the intra-temporal profit maximization problem is

$$\begin{aligned}
&\max_{l(z,t),y(z,t)} \quad y(z,t) - w(t)l(z,t) - c_f, \\
&s.t. \quad y(z,t) = \sqrt{z \ \ l(z,t)}, \\
&\qquad\quad l(z,t) \leq \tau_l(t),
\end{aligned}$$

where profits are defined as revenues $y(z,t)$, less labor costs $w(t)l(z,t)$, less fixed operation costs c_f. Note that we assume that fishermen's behavior is not affected by stock variability (so we are not including the stock of fish explicitly in the maximization problem) and that physical capital at vessel level is non-malleable (which means that we can normalize capital per vessel to one).[5] Solving for the first order conditions of this problem, we find that labor demand, given by

$$l(z,t) = \begin{cases} \dfrac{z}{4w(t)^2} & \text{if} \quad z \leq z^c(t), \\ \\ \tau_l(t) & \text{if} \quad z > z^c(t), \end{cases}$$

and profits, given by

$$\pi(z,t) = \begin{cases} \dfrac{z}{4w(t)} - c_f & \text{if} \quad z \leq z^c(t), \\ \\ \sqrt{z\tau_l(t)} - w(t)\tau_l(t) - c_f & \text{if} \quad z > z^c(t). \end{cases}$$

[4] Our technology complies with the fifty-fifty rule, i.e. 50% of net revenues are accounted for by payments to crew members.

[5] In Da-Rocha et al. (2017a) capital is allowed to be an endogenous variable.

both depend on the input constraint.

We assume that the productivity shock z follows a stochastic process with a negative expected growth rate, μ, i.e. $dz = -\mu dt + \sigma_z dW$, where σ_z is the per-unit time volatility, and dW is the random increment to a Weiner process. The dynamic incumbents' problem is a *stopping time problem* defined by

$$\begin{aligned} v(z,t) &= \max_{\tau} E_0 \int_0^{\tau} \pi(z,t) e^{(\rho+\lambda)t} dt + S(t) e^{\rho t}, \\ & s.t. \quad dz = -\mu z dt + \sigma_z dw_z. \end{aligned}$$

where λ is the exogenous death rate of firms[6], τ is the time required by a firm to take a given action and ρ is the discount rate. Let z be such that the firm does not exit. Then the following Hamilton-Jacobi-Bellman (HJB) equation holds:

$$(\rho+\lambda) v(z,t) \; = \pi(z,t) - c_f + \mu z \partial_z v(z,t) + \frac{\sigma_z^2}{2} \partial_{zz} v(z,t) + \partial_t v(z,t).$$

The value matching and smooth pasting conditions at the switching point $\underline{z}$ are $v(\underline{z},t) = S(t)$ and $v'(\underline{z},t) = 0$, respectively. For z lower than the exit threshold, $z \leq \underline{z}$, we have $v(z,t) = S(t)$. The incumbent's problem can also be written as an Hamilton-Jacobi-Bellman (HJB) variational inequality, i.e.

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

where $I_{\text{exit}}(z,t)$ is an indicator function that summarizes the endogenous decision to exit.

Firms operate capital (the vessel) and stay active if they find it optimal to pay the idling cost, c_f. Note that the marginal firm (the least efficient active vessel) is indifferent between paying the idling cost and exiting the market. This marginal firm makes negative instantaneous

[6] The death rate of firms is equal to the inverse of the vessel lifetime.

profits, i.e. $\pi(\underline{z}, t) - c_f = -\frac{\sigma^2}{2}\partial_{zz}v(\underline{z}, t) < 0$, and the total expected value of operating the vessel is zero.[7]

Each representative household solves a static consumption-leisure maximization problem:

$$\max_{C(t),L(t)} \log C(t) - eL(t),$$

subject to the budget constraint $C(t) = w(t)L(t) + \Pi(t)$, where the right-hand side of the budget constraint is given by the wage income $w(t)L(t)$ and the total profits of operating firms, $\Pi(t)$.[8] Wages are determined by

$$w(t) = e[w(t)L(t) + \Pi(t)].$$

For prices to be calculated, the dynamics of firms must be computed. In our economy, the change over time in the distribution of firms is determined endogenously by entry/exit decisions made by the firms themselves. As stated previously, entry occurs when the incumbents are not producing the total quota allowed (i.e. when the quota allowed exceeds the capacity of the fleet). We assume that entrants imitate incumbents in the sense that they are drawn from the incumbents' stationary distribution of productivity. This would close the model because the distribution of the entrants is endogenously generated by the policy in

[7] If the marginal active firm decides to leave the market, it obtains the value $v(\underline{z}) = S = 0$. From the smooth pasting condition and stationarity, $(\partial_z v(\underline{z}, t) = \partial_t v(\underline{z}, t) = 0)$ we have equation (1) $-\pi(\underline{z}, t) + c_f + \frac{\sigma^2}{2}\partial_{zz}v(\underline{z}, t) = 0$.

[8] Controls on inputs/outputs per vessel generate unemployment and (potentially) introduce heterogeneity in households. We apply a convenient technical device developed by Hansen (1985) and Rogerson (1988) to simplify the problem and use a representative household framework to solve it. That is, we assume that there is a lottery such that each household has an equal probability p_n of being selected to work. Therefore, in expected terms, each household will work $p_n L$ hours. Note that the rules of this lottery mean that there is perfect insurance in the sense that every household gets paid whether it works or not. Hence, they will have identical consumption, i.e. $C = wL + \Pi$. Under these conditions, the utility function associated with the lottery is quasilinear in labor.

equilibrium. Formally, $g(z,t)$ follows a Kolmogorov-Fokker-Planck (KFP) equation

$$\partial_t g(z,t) = -\partial_z[\mu z g(z,t)] + \frac{\sigma_z^2}{2}\partial_{zz} g(z,t) - (I_{\text{exit}}(z,t) + \lambda) g(z,t) + g^e(z,t). \tag{2}$$

where entry, when allowed, is given by the distribution $g^e(z,t)$ where

$$g^e(z,t) = \begin{cases} \epsilon(t) g^{\text{ss}}(z) & \text{if} \quad \int y(z,t)(1 - I_{\text{exit}}(z,t) - \lambda) g(z,t) < Q(t), \\ \\ 0 & \text{in} \quad \text{other} \quad \text{case} \end{cases}$$

where the entry rate, $\epsilon(t)$ verifies $\int y(z,t)\left[(1 - I_{\text{exit}}(z,t) - \lambda) g(z,t) + \epsilon(t) g^{\text{ss}}(z)\right] dz = Q(t)$. After entry is calculated, we use the distribution to compute the number of firms, i.e. $N(t) = \int_{\underline{z}(t)}^{\infty} g(z) dz$.

Notice that, in a fishery without ITQs the fact that managers of the fishery allow entry only when quota exceeds capacity means that entry is not regulated by a zero profit condition as in other papers[9].

To close the model we need to define feasibility conditions. The household budget constraint means that the final output market is in equilibrium. That is,

$$C(t) \quad = \quad w(t)L(t) + \Pi(t) \Rightarrow C(t) = \int_{\underline{z}(t)}^{\infty} y(z,t) g(z,t) dz - c_f N(t),$$

where $c_f N(t)$ is the value of output allocated to produce the fixed operating cost.[10] The

[9]For instance Da-Rocha et al. (2017b) assume a zero profit condition for entrants.

[10]Note that $C(t)$ is equal to

$$w(t)L(t) + \Pi(t) = \int_{\underline{z}(t)}^{\infty} w(t) l(t) g(z,t) dz + \int_{\underline{z}(t)}^{\infty} \left(y(t) - w(t) l(t) - c_f\right) g(z,t) dz = \int_{\underline{z}(t)}^{\infty} y(z,t) g(z,t) dz - c_f N(t).$$

manager of the fishery sets the input control such that the individual decisions given by

$$y(z,t) = \begin{cases} y(z,t)^* = \dfrac{z}{2w(t)} & \text{if} \quad z \leq z^c(t) \\ \\ y(z,t)^c = \sqrt{z\tau_l(t)} & \text{if} \quad z > z^c(t) \end{cases}$$

satisfy the quota path, $Q(t)$. Therefore, feasibility conditions in the labor and output markets are given by

$$\int_{\underline{z}(t)}^{\infty} l(z,t)g(z,t)dz = L(t), \tag{3}$$

$$\int_{\underline{z}(t)}^{z^c(t)} y^*(z,t)g(z,t)dz + \int_{z^c(t)}^{\infty} y(z,t)^c g(z,t)dz = Q(t). \tag{4}$$

Note that, given $Q(t)$, equations (3-4) jointly determine $w(t)$ and $z^c(t)$. Moreover, after some manipulation we can write the wage as a function of e, $Q(t)$ and the mass of firms, $N(t)$, i.e

$$w(t) = e\left[Q(t) - c_f N(t)\right],$$

which shows that wages will be lower when $N(t)$ is larger.

Given expectations about prices, in this economy firms solve their individual problems (equation (1)), and decide whether or not to stay in the fishery. Given this decision (summarized by $I_{\text{exit}}(z,t)$), equation (2) enables us to compute the equilibrium distribution of firms and check, using feasibility conditions (3 -4), whether the expectations are "rational". Appendix A.1 provides a formal definition of the steady state and how to compute it.

3 Case study

We apply the model to assess the impact of input controls on the Spanish demersal fleet in the Mediterranean Sea. The data used comes from the Expert Working Group of the Multiannual Plan for demersal fisheries in the Western Mediterranean drawn up by the Scientific, Technical and Economic Committee for Fisheries (STECF, 2016b).

According to STECF (2016a), in 2014, the fleet potentially targeting demersal fisheries covered by the Multiannual Plan numbered around 9,000 vessels with a combined gross tonnage of 56,331 GT and engine power of 473,615 kW. They accounted for 932,798 days at sea, and the estimated employment in these fisheries was 14,119 jobs, corresponding to 10,717 full time equivalent jobs.

The main species caught in the demersal fishery in the Western Mediterranean Sea are hake, red mullet, blue whiting, monkfish, deep-water rose shrimp, giant red shrimp, blue and red shrimp and Norway lobster. In 2014 landings of hake, red mullet, and deep water rose shrimp totaled 10,000 metric tones, accounting for about €69 million (around 25% of the overall demersal output). The leading species in both volume and value was hake, followed by red mullet and deep water rose shrimp. In Geographical Sub Areas (GSA) 1-7, hake is principally targeted by Spanish vessels (which land 58% of the total). The average price of the red mullet, deep water rose shrimp, and hake landed by Spanish vessels are €5.92/kg, €16.15/kg, and €6.68/kg, respectively.

We consider a stock rehabilitation policy associated with a reduction in the fishing mortality level from the status quo to the maximum sustainable yield (MSY) fishing mortality level. Table 1 provides the details of the reduction in fishing mortality for each of the 14 different stocks considered by (STECF, 2016b).

To compute the output constraints faced by the Spanish fleet associated with the stock rehabilitation policy, we use the value added path generated by the age-structured models

Table 1: **Species caught by Spanish demersal fishing vessels in the Mediterranean Sea and reference points**

GSA	3A code	Scientific name	Ref year	FMSY	Fcurr/FMSY
1 7	HKE	Merluccius merluccius	2014	0.39	3.59
1	ARA	Aristeus antennatus	2014	0.41	3.41
1	ANK	Lophius budegassa	2013	0.16	1.56
1	MUT	Mullus barbatus	2013	0.27	4.85
1	DPS	Parapenaeus longirostris	2012	0.26	1.65
5	ARA	Aristeus antennatus	2013	0.24	1.75
5	ANK	Lophius budegassa	2013	0.08	10.50
5	MUT	Mullus barbatus	2012	0.14	6.64
5	DPS	Parapenaeus longirostris	2012	0.62	1.24
6	ANK	Lophius budegassa	2013	0.14	6.50
6	MUT	Mullus barbatus	2013	0.45	3.27
6	DPS	Parapenaeus longirostris	2012	0.27	5.19
7	ANK	Lophius budegassa	2011	0.29	3.34
7	MUT	Mullus barbatus	2013	0.14	3.21
Source: STECF (2016b)					

Table 2: **Species and Prices of Spanish demersal fisheries in the Mediterranean Sea**

		Species				
		hake	red mullet	DW Red Shrimp	Monk fish	blue and red shrimp
country	GSA	HKE	MUT	DPS	ANK	ARA
Spain	1		x	x	x	x
Spain	5		x	x	x	x
Spain	6		x	x	x	x
France /Spain	7	x	x			
		HKE	MUT	DPS	ANK	ARA
Share of each Species	1-7	0.58	1.00	1.00	1.00	1.00
		HKE	MUT	DPS	ANK	ARA
Prices of each Species	1-7	6.68	5.93	16.15	=HKE	=DPS

for each species (see Appendix A.2). Table 2 also provides the ex-vessel prices used.

3.1 Calibration

Table 3: Calibration

Parameter	Value	Statistic	
Q	1	TAC	Normalization
e	1.5339	utility parameter	L=1/3
ρ	0.04	discount rate	Da-Rocha et al. (2014b)
λ	0.04	vessel lifespan	25 years
μ	-0.04	Productivity Drift	Da-Rocha et al. (2014b)
σ^2	0.01	Productivity Drift	Da-Rocha and Sempere (2016)
S	0	Scrap value	No decommissioning scheme
c_f	0.2403	fixed cost	STECF (2016b)

We select the values of μ and σ^2 from Da-Rocha et al. (2014b). Given this stochastic process, it is necessary to calibrate six parameters Q, λ, S, c_f, e and ρ. We start by selecting a value for the annual interest rate of $\rho = 0.04$ which is standard in macroeconomic literature.[11] We set $Q = 1$. We consider a vessel life span of 25 years ($\lambda = 0.04$). We assume that there are no decommissioning schemes, $S = 0$. We use data from structure and economic performance estimates by fleets from EU Member States operating in the Mediterranean & Black Sea regions in 2014 to compute the fixed cost.[12] Finally, we calibrate the utility parameter e by solving the model when the economy is non-distorted in order to match a labor supply of 1/3. This is a standard normalization in macroeconomic literature.

[11]See, for instance Restuccia and Rogerson (2008).
[12]See Table 4.3 of the STECF (2016b).

4 Results

This section is divided into two parts. Part 1 presents the main results regarding the steady state solution of the model. Part 2 presents the results of the analysis of the transitional dynamics implied by stock rehabilitation policies leading to a situation in which all stocks are at their MSY fishing mortality level.

4.1 Steady state solution

Table 4 shows the steady state associated with different levels of effort control τ_l (measured as the % of z constrained). This table illustrates input misallocation across heterogeneous vessels which reduces productivity (CPUE), generates lower equilibrium wages (w), and reduces employment levels (L) in the fishery.

In this economy the total output is given. Therefore, to measure the distortion produced by the use of input controls we use the difference in consumption generated from the same output level under different regulatory policies. From the feasibility conditions, it is possible to write consumption as the difference between output and the resources used to produce the operating costs , i.e. $Q - c_f N$. Our results mean that an economy without distortions allocates 3.2 % of its total resources to operating cost, $c_f N$, while in the most distorted economy considered operating costs are 4.2 %. Therefore, total output is reduced by 1%.

To evaluate the macroeconomic and welfare implications of effort controls (changes in τ_l), the model generates the optimal response in three (management) variables: (1) average catch per unit effort $CPUE = E[y(z,t)/l(z,t)]$; (2) average days at sea per vessel, $E[l(z,t)]$; and (3) the number of vessels, $N(t)$.[13]

[13]Given that

$$Y(t) = N(t) \int_{\underline{z}(t)}^{\infty} \left(\frac{y(z,t)}{l(z,t)} \right) l(z,t) g(z,t) dz.$$

Table 4: **Effects of different levels of control on days**

		Q =1				
Control on Inputs	% of z constrained	0.000	0.187	0.375	0.562	0.750
Fleet Size	N	0.132	0.133	0.138	0.149	0.175
wage	w	1.485	1.485	1.483	1.479	1.469
		data per vessel				
CPUE	$E[y(z)/l(z)]$	2.971	2.970	2.966	2.958	2.939
Employment per vessel	$E[l(z)]$	2.553	2.505	2.348	2.047	1.536
Yield per vessel	$E[y(z)]$	7.583	7.509	7.254	6.724	5.710
Profits per vessel	$E[\pi(z)]$	3.551	3.550	3.532	3.456	3.213
Wealth per vessel	$E[v(z)]$	28.778	28.785	28.764	28.502	27.202
		Inequality: Gini Coeff.				
Revenues	$E[y(z)]$	0.573	0.573	0.573	0.573	0.573
Wealth	$E[v(z)]$	0.624	0.624	0.623	0.620	0.606
		Aggregate Accounts				
Operating Cost	$c_f N$	0.032	0.032	0.033	0.036	0.042
Consumption	$Q - c_f N$	0.968	0.968	0.967	0.964	0.958
Remuneration of employees	wL	0.500	0.495	0.480	0.450	0.395
Gross operating surplus	Π	0.468	0.473	0.487	0.514	0.563
		Days at the see				
Total days at sea	L	0.337	0.334	0.324	0.304	0.269
Impact of effort control	L/L^*	1.000	0.991	0.961	0.904	0.799

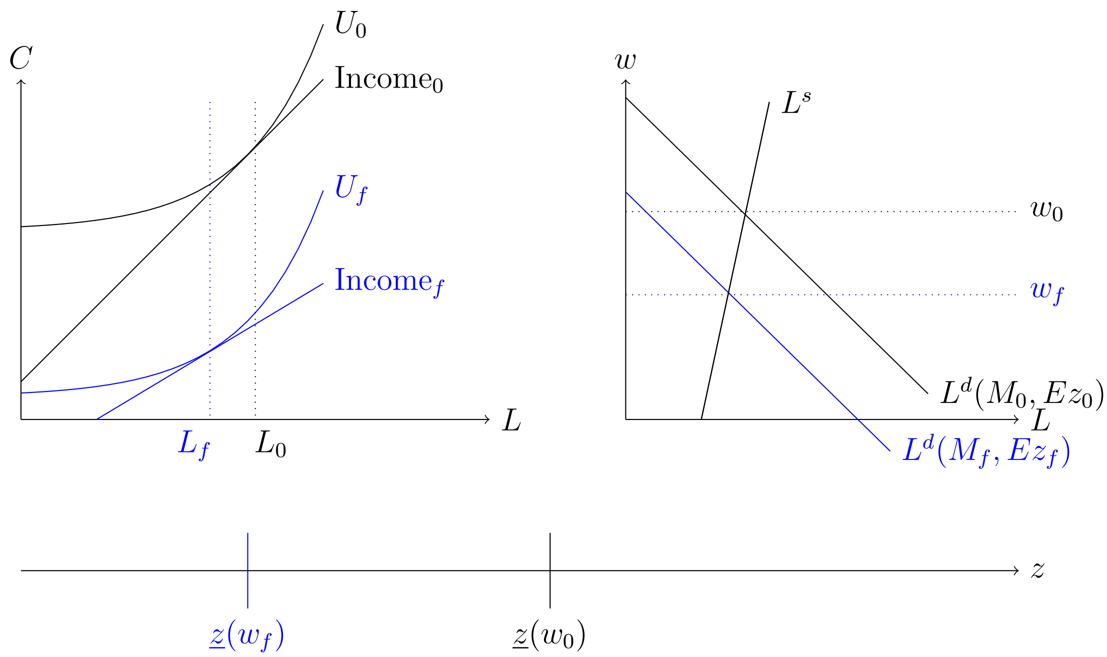


Figure 1: General Equilibrium effects of different levels of control on days in the Steady State

Effort controls –i.e. caps on working hours per vessel– change all three management variables at the same time. First notice that effort controls create lower wages. The intuition of this result is as follows: The constraint on working hours per vessel leads more productive firms to produce less than they would optimally produce, which leads to an inefficient allocation. Therefore catches per unit of effort (CPUE) are lower than optimal so, to produce the same aggregate output, more vessels are needed under input controls than under a non-distortionary price-based instrument. Thus, if there are effort controls in place, more vessels are active for the same quota than if there are not. Notice too that having more vessels means higher operating costs, $c_f N$, and remember from the household problem in Section 2 that higher operating costs mean a lower consumption level $C = [Q - c_f M]$. This lower consumption level increases the marginal utility of labor. Therefore, in equilibrium wages have to decrease so the following equation holds:

$$\partial_C U(C)w(t) = -\partial_L U(L) \Rightarrow \frac{w(t)}{C(t)} = e(t).$$

Note that for the new wage rate (induced by the effort control) the labor supply is lower (the graph at the top left in Figure 1 illustrates this). Lower wages result in changes in nominal effort composition. On the one hand, the demand for labor on each vessel is reduced, i.e. effort control is active and $E[l(z)]$ is lower for each vessel -each vessel spends fewer days at sea- (the graph at the top right in Figure 1 illustrates this). On the other hand, lower wages induce some vessels that would otherwise exit to stay, as $\underline{z}$ decreases and the average productivity of the fleet, $E[z]$ decreases. Therefore an increment in fleet size is compatible with fewer days at sea in total $L(t) = N(t)E[l(z)]$ and lower effort per vessel $E[l(z)]$ generated by effort controls. The graph at the top right in Figure 1 illustrates this last effect.

Summarizing, effort controls give rise to fleets with more vessels. Productivity of vessels (TFP= $E[y(z)/l(z)]$) is reduced, vessels stay at sea for fewer days (lower $E[l(z)]$), and total catches per vessel, $E[y(z)]$, are lower. As a result, both profits per vessel and the value of each vessel ($E[\pi(z)]$ and $E[v(z)]$, respectively) are lower.

4.2 Entry / Exit behavior in a stock rebuilding process

In our model $N(t)$ is equivalent to aggregate capital in period t. Therefore investment in capital, satisfies $N(t + dt) = N(t) + I(t)$, where,

$$I(t) = \int_{\underline{z}(t)}^{\infty} \left[g^e(z,t) - (I_{\text{exit}}(z,t) + \lambda)g(z,t)\right] dz.$$

To assess the impact of input controls (a cap on working hours per vessel) on entry and exit, we need to compute a transition (as in the steady state $I(t) = \int \lambda g(t,z)dz$).

As occurs in Clark et al. (1979) and in Clark et al. (2017), we choose a stock rebuilding process to study the impact of the policy. We compute transitions in fisheries with and without input controls. To minimize the misallocation impact of the cap when total catches must be reduced (i.e. when the instaled capacity is greater than the catches allowed), we use sequences of taxes –a non-distortionary instrument– to induce vessels to harvest less. [14] In our model there is not free entry. However, the existence of depreciation, λ, implies that there is entry to replace capital. Moreover, entry is allowed when total captures must be increased. In both cases, we assume that potential entrants copy incumbents and select a vessel -draw a z- from the stationary distribution (which is an endogenous equilibrium object). See Appendix A.3 for a formal description of the transition.

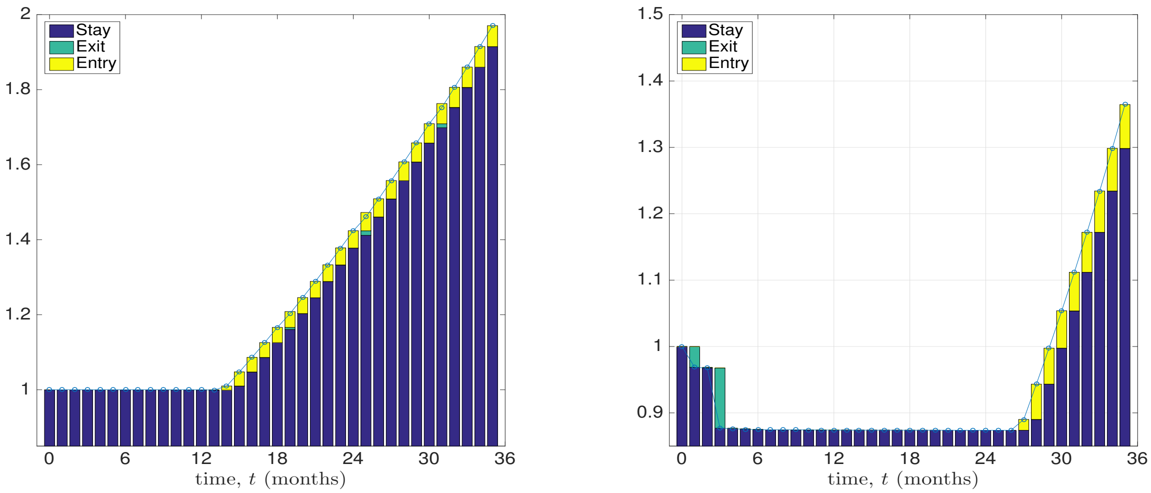
The main findings of the analysis of the transitional dynamics can be summarized as follows:

1. With input controls the adjustment is less drastic and is characterized by fewer exits at the beginning of the stock rebuilding process. Figure 2(a) illustrates this fact and shows that with effort controls there are not exits. However, Figure 2(b) shows for the same period that without effort controls some firms exit in the first few months and firms enter at the end of the period considered.

   The economic reason for this different entry/exit behavior is that even though the percentage of reduction in output is the same in both economies, in the economy with input controls it represents a smaller fraction of the fixed costs of each vessel (as output per vessel is smaller in this economy). This generates fewer exits.

2. With input controls vessels enter earlier and in greater numbers than when non-distortionary policies are used. Figure 3 shows that excess capacity, measured as the difference between measures $g(z,t)$ associated with the different policies for each z and t, is positive for each z and t. This difference is larger for low productivity levels (i.e.

[14] Therefore profits are equal to $\pi(z,t) = (1-\tau(t))y(z,t) - w(t)l(z,t) - c_f$.



(a) with effort controls

(b) without effort controls

Figure 2: Entry- exit behaviour on the stock rehabilitation path,

for z closer to zero). This means that excess capacity is relatively more concentrated in vessels with low productivity.

Therefore, with input controls the fleet is replenished $\lambda g(z,t)$ with less efficient vessels. This means that entry increases capacity more slowly than when non-distortionary policies are used. This is the economic rationale for the different entry patterns in the two economies.

These findings can be summarized by computing the excess capacity associated with the use of input controls. We compute the excess of capacity associated with the distortionary policy as the difference in each period between capital in the fishery regulated with input controls and capital in the fishery regulated with a non-distortionary instrument, as shown in Figures 4(a) and 4(b).

Figure 4(a) represents the number of vessels (in percentage terms) associated with a regulatory policy based on input controls and the number of vessels associated with a policy based on non-distortionary instruments for each moment in time. Figure 4(b) represents the

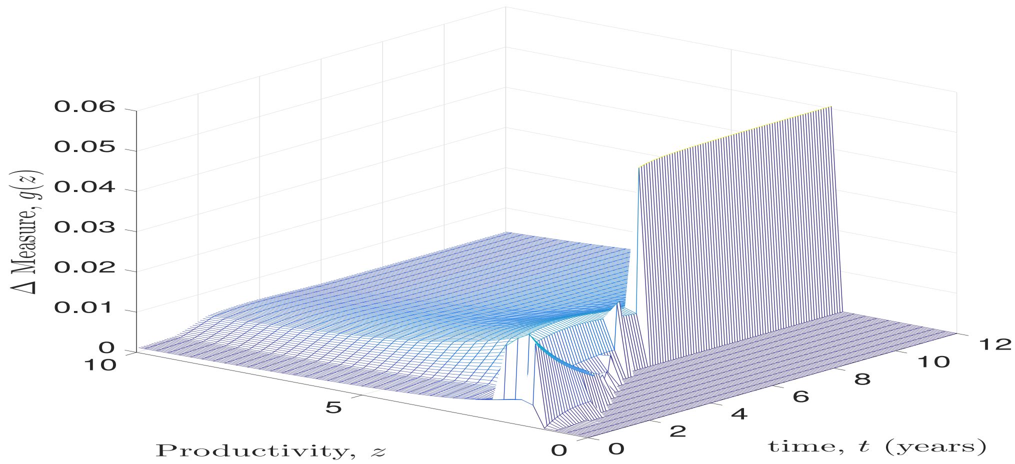
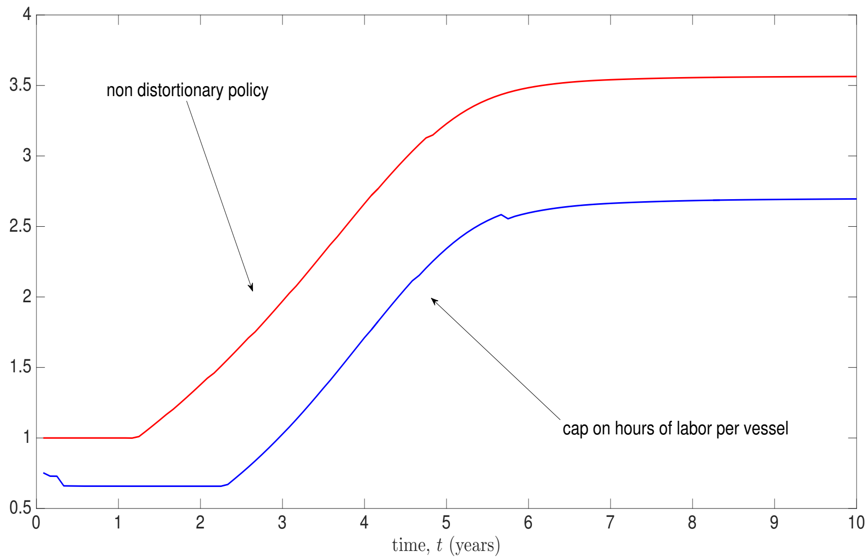


Figure 3: Excess of capacity, measured as the difference between measures $g(z, t)$ associated with the different policies for each z and t,

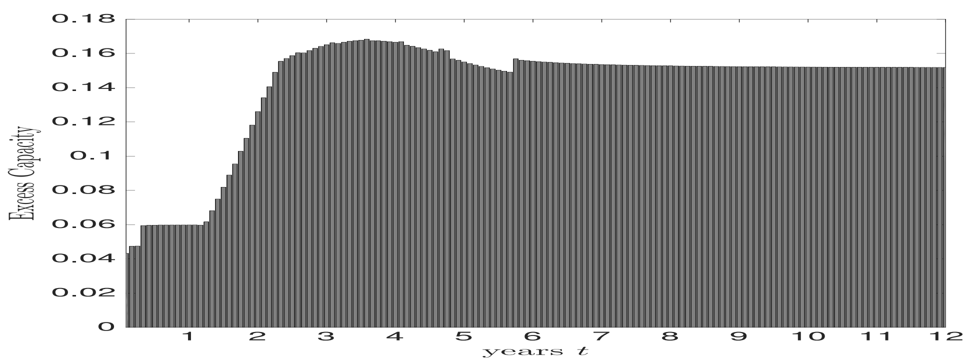
difference between the number of vessels (in percentage terms) associated with a regulatory policy based on input controls and the number of vessels associated with a policy based on non-distortionary instruments for each moment in time. We refer to this number as "the excess of the fleet". The figure shows that the excess of the fleet is always positive. It is increasing in the early periods and is close to 16% in some periods. Later, it remains positive and stabilizes at around 14%.

5 Discussion and conclusions

In a given already overcapitalized fishery a policy of input controls makes the problem even worse as the excess of capital is always positive with respect to that which results from other less distortionary policies. Empirical evidence provided by the Spanish fleet seems to support our findings. The management system in the Mediterranean is mainly based on effort restrictions (limitations on average days at sea and other measures of time per vessel), so our results mean that we should expect more excess capacity in fleets operating in the



(a) $N(t)$



(b) $\Delta N(t)$

Figure 4: Fleet size dynamics

Mediterranean than in fleets operating in the Atlantic. Figure 5 shows the status of the Spanish fleets. The long-term economic profitability of vessels as measured by Return on Fixed Tangible Assets (ROFTA, calculated as Net profit/Capital Value) is plotted on the y-axis and the Sustainable Harvest Indicator (SHI) on the x-axis. SHI measures the degree to which a fleet segment depends on overexploited stocks at levels above MSY for its revenues. SHI values greater than 1.2 indicate that fleets are operating under biological imbalance.

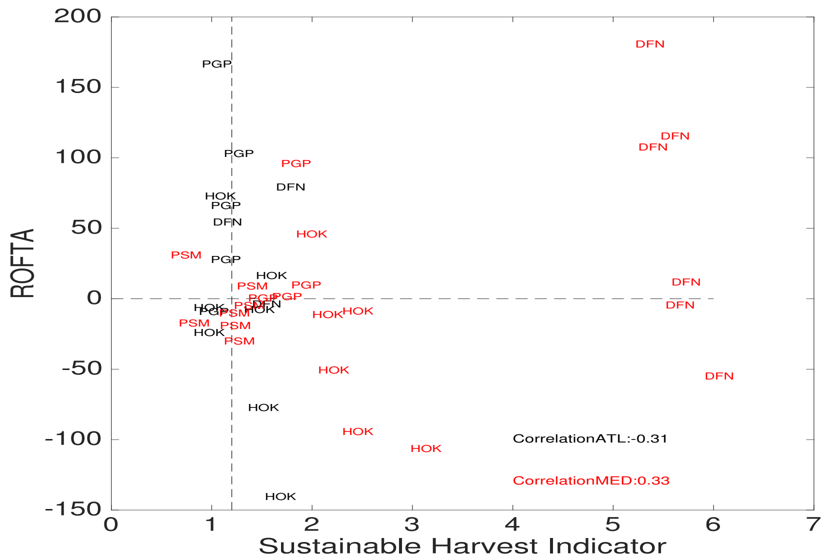


Figure 5: Return on Fixed Tangible Assets (ROFTA) and Sustainable Harvest Indicator (SHI) for Spanish Atlantic Spanish fleet segments (black) and Spanish Mediterranean Spanish fleet segments (red). where PGP, DFN, PSM and HOK, represent different fleet segments. Source: MAAMMA (2014).

Figure 5 shows that Mediterranean fleets do indeed operate under lower ROFTA and greater biological imbalance than Atlantic fleets. This suggests a higher excess capacity in the Mediterranean fleets than in the Atlantic ones. This is consistent with the conclusion drawn from the results. In the modeling framework presented, in the steady state equilibrium a policy of limiting fishing days leads to smaller vessels with lower yields, lower individual profits, and lower wages. The lower wages allow less productive vessels (that would otherwise exit) to stay in the fishery, reducing the average productivity of the fleet. The result of input controls is that more vessels are required to achieve the same biological targets, which means an overcapitalized fleet.

We also characterized the transition dynamics caused by stock rehabilitation policies leading the fishery from a given status quo to a stationary situation where all stocks are at their maximum sustainable yield fishing mortality levels. We show that on the stock rehabilitation path, capital depends on the use (or not) of input controls. We conclude that without input controls firms exit on the transition path and the stock of capital in the fishery is reduced. However, when input controls are used no firms exit on the transition path and the capital is not reduced. Under rational expectations, less productive vessels stay in the fishery and pay the idling cost to wait for better times. In addition, we show that the excess of capacity associated with input controls also produces lower average levels of productivity as it is relatively more concentrated in vessels with low productivity. Furthermore, the excess of the fleet associated with this type of policy is always positive.

From the policy perspective we relax the assumption that fishing firms' form expectations of the productivity of current capital based only on the current level of the biomass in deciding the level of capital investment or disinvestment. In this case rational expectations discount future fishing possibilities so the decision to enter or exit is based on the future evolution of the fishery. This is an extremely relevant modeling characteristic when stock rebuilding policies are assessed, given that firms' behavior can be influenced by the "bright" future coming from the policy. Furthermore, this characteristic is not constrained to the fishery policy itself, but must be considered when dealing with natural regimen shifts that can be caused by, for example, climate change.

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A Appendix

A.1 Steady State

Given an output restriction, $Q(t)$, and an input control τ_l, an equilibrium is a measure of firms $g(z,t)$, wages $w(t)$, value functions of incumbents $v(z,t)$, individual decision rules $l(z,t)$, $y(z,t)$, and a threshold $\underline{z}(t)$, such that:

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

ii) (Firm measure) $g(z,t)$ satisfies the Kolmogorov-Fokker-Planck equation (2).

ii) (Market clearing-feasibility) Given individual decision rules and the firm measure function, $w(t)$ and $\underline{z}(t)$, solve equations (3-4).

The steady state economy can be represented by the following system of equations

$$\begin{aligned}
\min_{I_{\text{exit}}(z)} \left\{ \rho v(z) - \pi(z) + c_f - \mu z \partial_z v(z) - \frac{\sigma_z^2}{2} \partial_{zz} v(z), \quad v(z) - S \right\}, \\
-\partial_z[\mu z g(z)] + \frac{\sigma_z^2}{2} \partial_{zz} g(z) - (I_{\text{exit}}(z) + \lambda) g(z,t) + g^e(z,t) = 0, \\
\int_{\underline{z}}^{\infty} g(z) dz = N, \\
\int_{\underline{z}}^{z^c} y^* g(z) dz + \int_{z^c}^{\infty} y(z)^c g(z) dz = Q, \\
e\left[Q - c_f N\right] = w.
\end{aligned}$$

Finally, note that in a stationary equilibrium $g^e(z) = g(z)$ and $I = 0$.

Following Achdou et al. (2014) Achdou et al. (2015) we use a finite difference method and approximate the fuctions $v(z,t)$ and $g(z,t)$ (equations 1 and 2). We use the shorthand notation $v_i^n = v(z_i, t_n)$ and $g_i^n = g(z_i, t_n)$.

Linear Complementarity Problems (LCP). We approximate (1)

$$\rho v_i^n = \pi_i^n + [\mu_i]^+ \left(\frac{v_{i+1}^n - v_i^n}{\Delta z} \right) + [\mu_i]^- \left(\frac{v_i^n - v_{i-1}^n}{\Delta z} \right) + \frac{\sigma_z^2}{2} \left(\frac{v_{i+1}^n - 2v_i^n + v_{i-1}^n}{\Delta z^2} \right) + \left(\frac{v_i^{n+1} - v_i^n}{\Delta t} \right),$$

where $[\mu_i]^+ = \max\{\mu_i, 0\}$ and $[\mu_i]^- = \min\{\mu_i, 0\}$. Therefore, collecting terms, we have

$$\begin{aligned}
\rho v_i^n &= \pi_i^n + a_i v_{i-1}^n + b_i v_i^n + c_i v_{i+1}^n + \left(\frac{v_i^{n+1} - v_i^n}{\Delta t} \right), \quad \text{where} \\
a_i &= -\frac{\min\{\mu_i, 0\}}{\Delta z} + \frac{\sigma_z^2}{2\Delta z^2}, \\
b_i &= -\frac{\max\{\mu_i, 0\}}{\Delta z} + \frac{\min\{\mu_i, 0\}}{\Delta z} - \frac{\sigma_z^2}{\Delta z^2}, \\
c_i &= \frac{\max\{\mu_i, 0\}}{\Delta z} + \frac{\sigma_z^2}{2\Delta z^2}.
\end{aligned}$$

Note that $a_i + b_i + c_i = 0$. Thus, equation (5) in matrix form is

$$\rho v^n = \pi^n + \mathbf{A} v^n + \frac{1}{\Delta t}\left(v^{n+1} - v^n\right),$$

where (for i=1,2,3,4)

$$\mathbf{A} = \begin{bmatrix} b_1 & c_1 & 0 & 0 \\ a_2 & b_2 & c_2 & 0 \\ 0 & a_3 & b_3 & c_3 \\ 0 & 0 & a_4 & \hat{b}_4 \end{bmatrix}.$$

Boundary conditions: from $\partial_z v(\infty, t) = 0$ we have, $v_I^n = v_{I+1}^n$, then $\hat{b}_I = b_I + \frac{\sigma_z^2}{2\Delta z^2}$ such that $a_I + b_I = 0$.

To solve equation (1) we follow Huang and Pang (1988). They show that the variational inequality problem (the discretized version of equation (1))

$$\min_{I_{\text{exit}}(z,t)} \left\{ \rho v^n - \pi^n - \mathbf{A} v^n - \frac{1}{\Delta t}\left(v^{n+1} - v^n\right), v^n - S^n \right\},$$

can be formulated as Linear Complementarity Problems (LCP), i.e.

$$\begin{aligned} (v^n - S^n) \perp \left(\mathbf{B}(v^n - S^n) + \mathbf{q}^{m+1}\right) &= 0, \\ (v^n - S^n) &\geq 0, \\ \mathbf{B}(v^n - S^n) + \mathbf{q}^{m+1} &\geq 0, \end{aligned}$$

where $\mathbf{B} = \left(\rho + \frac{1}{\Delta t}\right)\mathbf{I} - \mathbf{A}$ and $\mathbf{q}^{m+1} = \mathbf{B} S^n - \pi^n - \frac{1}{\Delta t} v^{n+1}$.[15]

Kolmogorov Forward equation. We approximate the KFP equation (2) using the following approximation for $\partial_z[\mu z v(z,t)]$

$$\partial_z[\mu z v(z,t)] \simeq \left[\left(\frac{[\mu_i]^+ g_i^n - [\mu_{i-1}]^+ g_{i-1}^n}{\Delta z}\right) + [\left(\frac{[\mu_{i+1}]^- g_{i+1}^n - [\mu_{i-}]^- g_i^n}{\Delta z}\right)\right].$$

Therefore, we have

$$\begin{aligned} \left(\frac{g_i^{n+1} - g_i^n}{\Delta t}\right) &= c_{i-1} g_{i-1}^n + b_i g_i^n + a_{i+1} g_{i+1}^n - I_i^n g_i^n + \delta^n, \quad \text{where} \\ a_{i+1} &= -\frac{\min\{\mu_{i+1}, 0\}}{\Delta z} + \frac{\sigma_z^2}{2\Delta z^2}, \\ b_i &= -\frac{\max\{\mu_i, 0\}}{\Delta z} + \frac{\min\{\mu_i, 0\}}{\Delta z} - \frac{\sigma_z^2}{\Delta z^2}, \\ c_{i-1} &= \frac{\max\{\mu_{i-1}, 0\}}{\Delta z} + \frac{\sigma_z^2}{2\Delta z^2}. \end{aligned}$$

Note that (5) in matrix form

$$\frac{1}{\Delta t}\left(g^{n+1} - g^n\right) = \mathbf{A}^T g^n$$

[15] Matlab provides Yuval Tassa's Newton-based LCP solver, downloadable from http://www.mathworks.com/matlabcentral/fileexchange/20952.

where (for i=1,2,3,4)

$$\mathbf{A}^T = \begin{bmatrix} b_1 & a_2 & 0 & 0 \\ c_1 & b_2 & a_3 & 0 \\ 0 & c_2 & b_3 & a_4 \\ 0 & 0 & c_3 & b_4 \end{bmatrix}.$$

and $g^n = I^n_{\text{exit}} g^n$. Finally density is computed as $f_i = \frac{g_i}{\sum_{i=1}^{I} g_i \Delta z}$, where $\sum_{i=1}^{I} g_i \Delta z$ is the mass of firms.

A.2 Age-structured Stock dynamics

For each species we use an age-structured model (see Figure 6) to assess the impact of each *fishing mortality*, $F(t)$, trajectory to Fmsy (see Figure 7) on landings generated by the transitional dynamics of the stocks, $n(a,t)$ (see Figure 8). Let $n(a,t)$ be the number of fish of age a at time t. As in Botsford and Wainwright (1985), the conservation law is described by the following McKendrick-von Foerster partial differential equation:[16]

$$\frac{\partial n(a,t)}{\partial t} = -\frac{\partial n(a,t)}{\partial a} - [m(a) + p(a)F(t)]n(a,t). \tag{5}$$

Equation (5) states that the rate of change in the number of fish in a given age interval, $\frac{\partial n(a,t)}{\partial t}$, 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 $\frac{\partial n(a,t)}{\partial a}$. The rate of deaths at age a is proportional to the number of fish of age a, i.e. $[m(a) + p(a)F(t)]n(a,t)$.

Moreover, in order to pose the model properly, Equation (5) need to be completed with an initial condition at $t = 0$ and a boundary condition at $a = 0$, thus providing the initial number of fishes at each age and the recruitment at each time [17] . Thus we consider:

$$n(a,0) = n_0(a), \qquad n(0,t) = 1 \tag{6}$$

Note that when solving Equation (5) in the interval $[0, A]$ for the ages, we can identify a large enough value of A so that all fishes die (just recovering $n(A,t) = 0$, which cannot be imposed in the model).

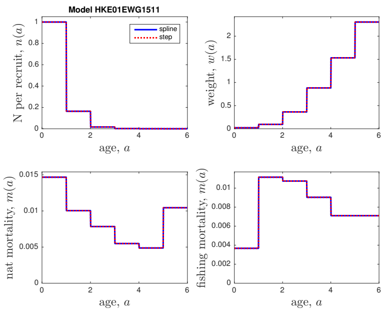
For a given $F(t)$ trajectory, catches at age a are equal to $p(a)F(t)n(a,t)$, therefore $Q(t)$, is equal to

$$Q(t) = \left(\int_0^A \omega(a)p(a)n(a,t)da \right) F(t).$$

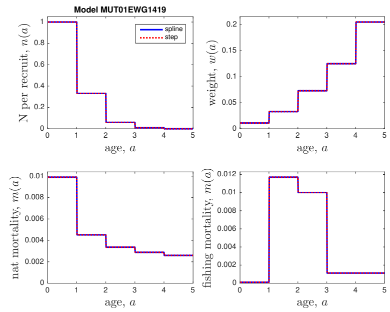
[16]See Von-Foerster (1959) and McKendrick (1926).

[17]A Stock Recruitment relationship can be assumed. In that case, each period, the number of fish at age zero is given by $n(0,t) = \Psi(\int_0^A \omega(a)\mu(a)n(a,t)da)$, where, $\int_0^A \omega(a)\mu(a)n(a,t)da$ is the SSB. See Da-Rocha et al. (2012).

Figure 6: Age Structured Models



(a) HKE



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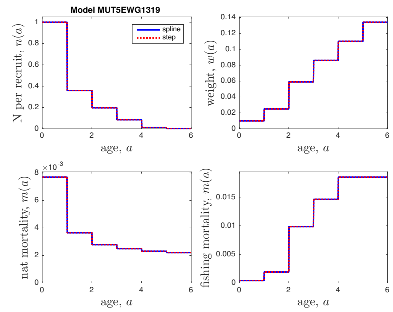

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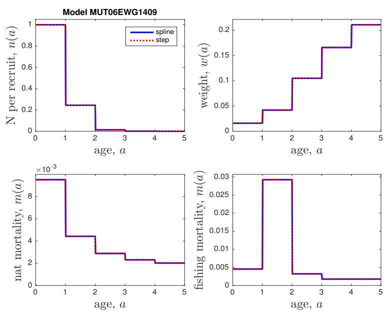

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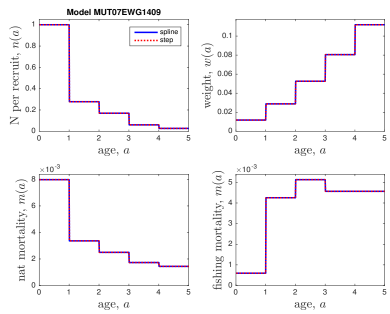

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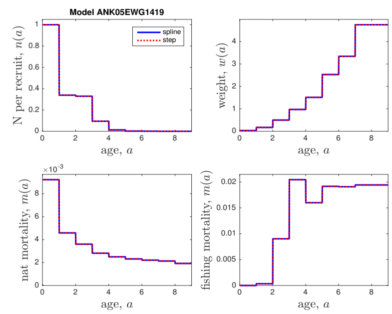

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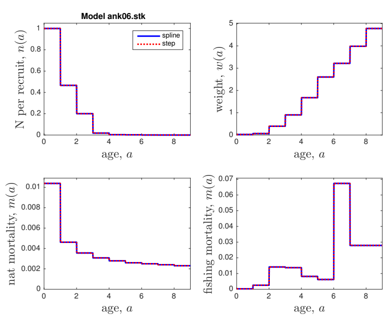

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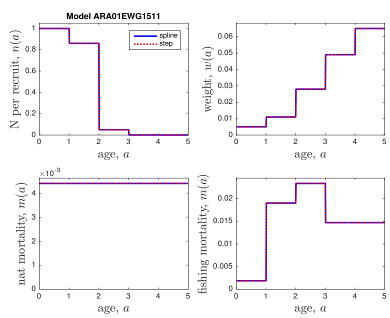

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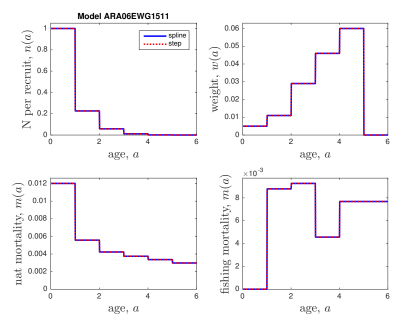

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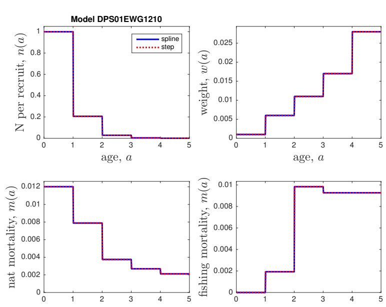

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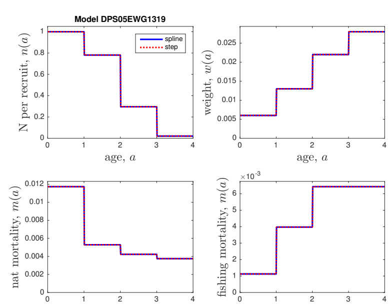

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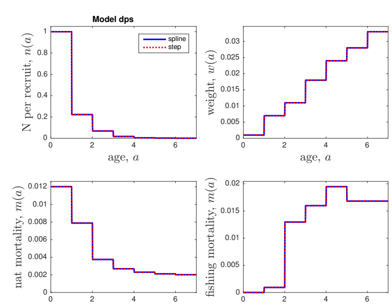

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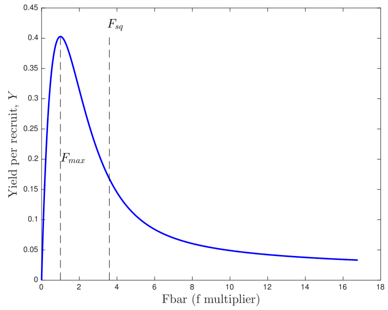
Figure 7: Targets



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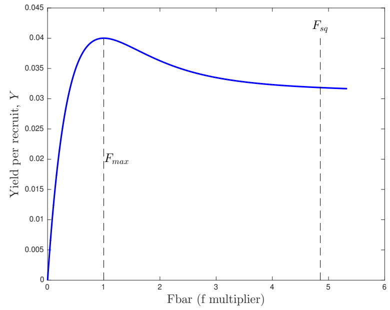

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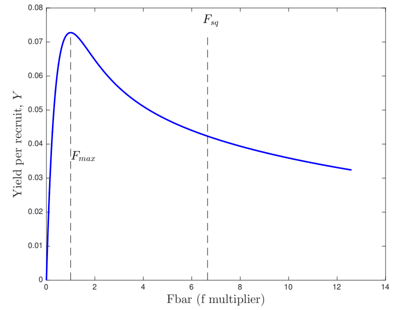

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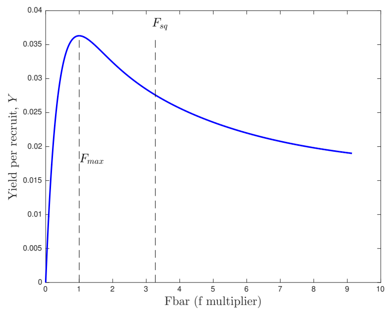

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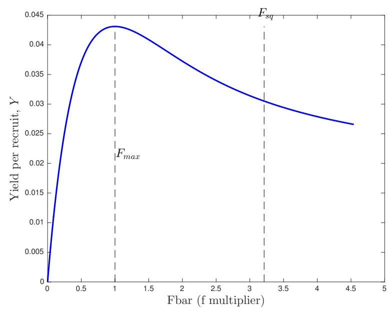

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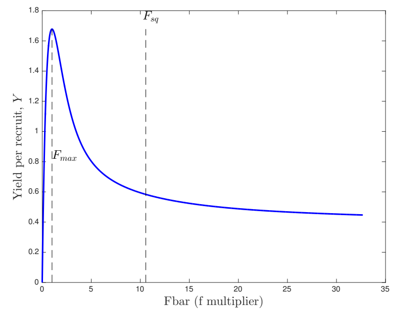

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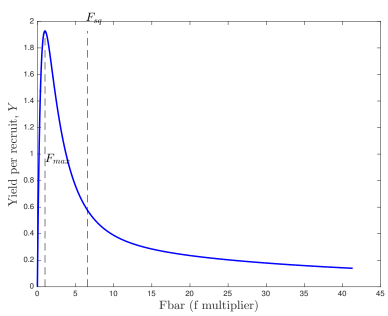

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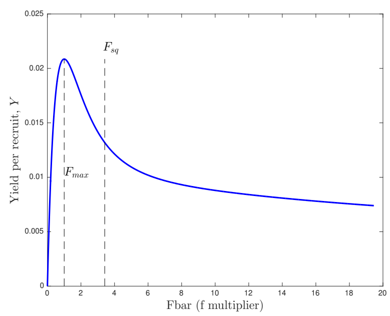
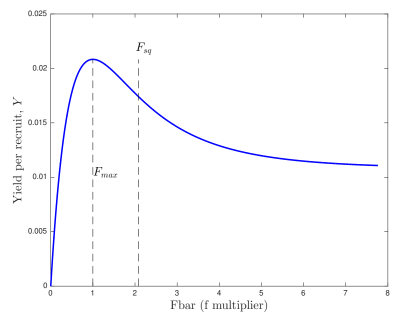


(h) ARA 1



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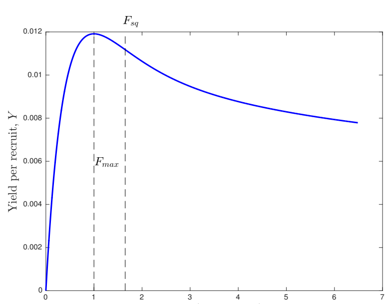

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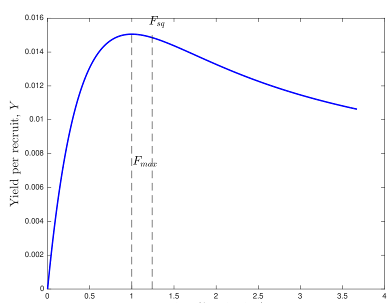

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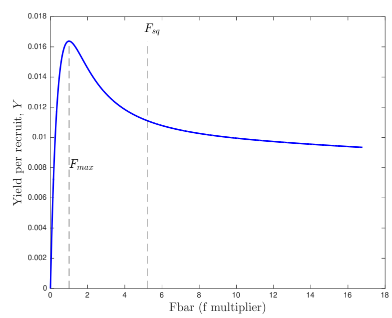
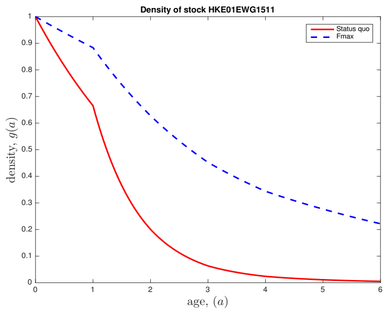
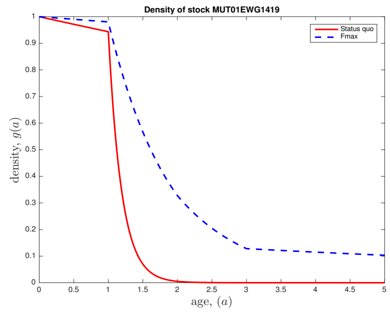


(l) DPS 3

Figure 8: Equilibrium Distributions by age



(a) HKE



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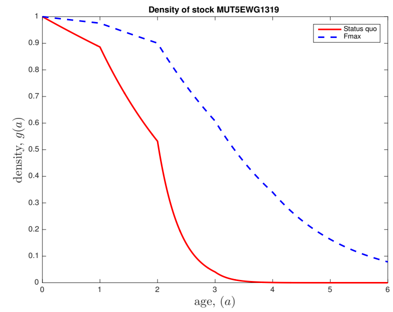

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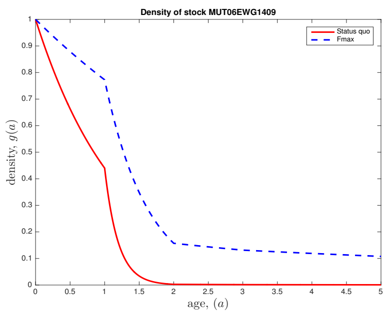

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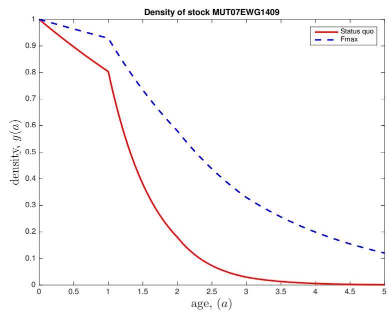

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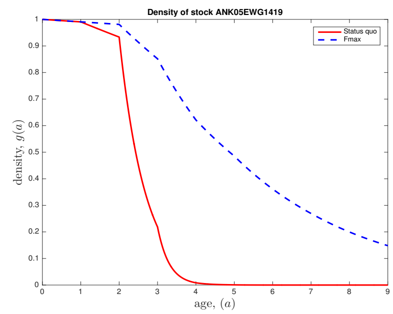
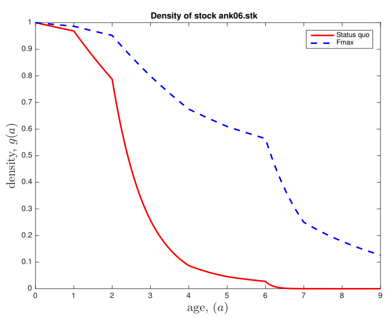


(f) ANK 1



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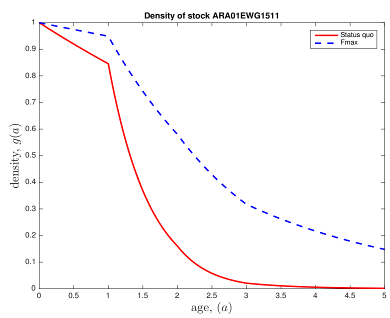
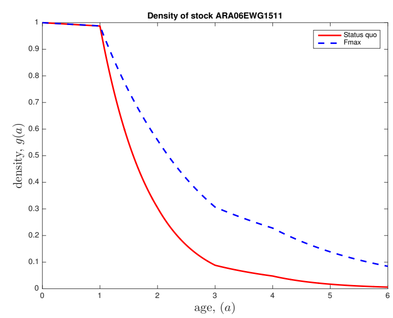


(h) ARA 1



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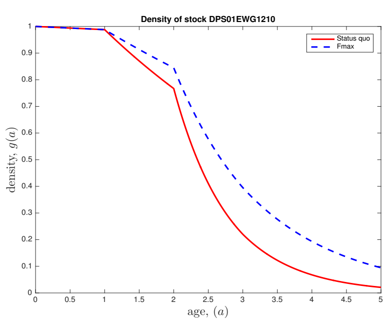

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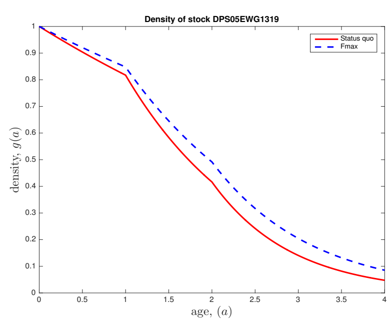

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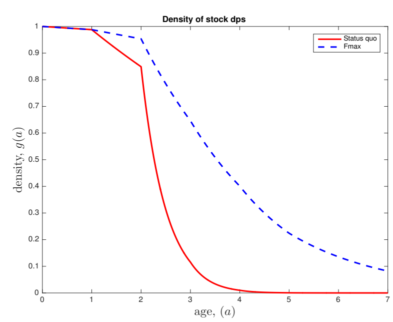

(l) DPS 3

A.3 Transitions

This appendix focuses on characterizing the transition dynamics caused by stock rehabilitation policies leading the fishery from a given status quo to a stationary situation where all stocks are at their maximum sustainable yield fishing mortality levels ($Fmsy$). Our characterization strategy follows two steps. First, we set a drastic reduction of $Fmsy$ for all species in the fishery and compute the value of landings (VA) using the age structured mode (see Appendix A.2). Second, given the VA for the Spanish fleet associated with a reduction to $Fmsy$ for all species, we compute the transition dynamics associated with the non-distortionary instrument $\tau(t)$[18] that drive the fishery from the status quo (the VA associated with fishing mortality in the status quo) to the stationary solution where fishing mortality is $Fmsy$ for all species. We assume that tax revenue is returned to households in the form of a non-distortionary lump sum transfer. Tax revenue is $T(t) = \int_{\underline{z}(t)}^{\infty} \tau(t) y(t) g(z,t) dz$. The transitional dynamics are described by the following system of equations

$$
\begin{aligned}
\min_{I_{\text{exit}}(z,t)} \left\{ \rho v(z,t) - \pi(t) z + c_f - \mu z \partial_z v(z,t) - \frac{\sigma_z^2}{2} \partial_{zz} v(z,t) - \partial_t v(z,t), \quad v(z,t) - S(t) \right\}, \\
-\partial_z[\mu z g(z,t)] + \frac{\sigma_z^2}{2} \partial_{zz} g(z,t) - (I_{\text{exit}}(z,t) + \lambda) g(z,t) + g^e(z,t) = \partial_t g(z,t), \\
\int_{\underline{z}(t)}^{\infty} g(z,t) dz = N(t) \\
\int_{\underline{z}(t)}^{z^c(t)} y^*(t) g(z,t) dz + \int_{z^c(t)}^{\infty} y(t,z)^c g(z,t) dz = Q(t), \\
e\left[Q(t) - c_f N(t)\right] = w(t) \\
\text{Exit}(t) = \int_{\underline{z}(t)}^{\infty} I_{\text{exit}}(z,t) g(z,t) dz
\end{aligned}
$$

We solve this system using the following algorithm.

1. First, we compute the stationary value functions, $v(z|Q)$,and fleet distributions, $g(z|Q)$, associated with the status quo, $Q_0 = 1$, and the stock rehabilitation, $Q_T = 2.407$.
2. Second, we guess a function $\tau(t)$ $\forall t = 1, .., T$, then we follow this iterative procedure:
   (a) Given $w(t)$, compute $v(z,t)$ by solving the HJB equation (7) with terminal condition $v(z|Q_T)$ and also compute $I_{\text{exit}}(z,t)$;
   (b) Given $I_{\text{exit}}(z,t)$, compute $g(z,t)$ by solving the KFP equation (7) using $g(z|Q_0)$ as the initial conditions;
   (c) Given $g(z,t)$, calculate $w^1(t)$ using equation (7) and update $w(t)$. Stop when $w^1(t)$ is sufficiently close to $w(t)$.
   (d) Given $w(t)$, compute $Q(t)$. Allow entry if $Q(t)$ is lower than the VA path associated with the stock rehabilitation policy.
3. Stop when $Q(t)$ is sufficiently close to the VA path. Otherwise update $\tau(t)$

[18] $\tau(t)$ can be interpreted as a tax rate or as the price of an ITQ in a system of fully tradable individual quotas.