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## Endogenous catch per unit effort and congestion externalities between vessels in a search- matching model: Evidence from the French Guiana shrimp fishery

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### Abstract :

This paper aims at explaining the recent rise in profits in the French Guiana shrimp fishery (FGSF) despite the overall fall in activity observed between 1990 and 2009. We develop a stochastic search-matching version of the usual Cobb–Douglas bioeconomic fishery model. In this version catch per unit effort becomes endogenous, decreasing in the ratio of empty vessels to escaped fish, which we call “anthropic pressure” and which is determined by standard profit maximization. We first estimate the stochastic harvest function, which exhibits nearly constant returns to scale. We then show that a decrease in equilibrium anthropic pressure and congestion between vessels may be more than compensated by the consecutive rise in catch per unit effort. This leads to a fall in average harvesting costs and thus, to a rise in profits. In addition, we identify the condition under which a search-matching fishery, working under open access, could reach a maximum economic yield equilibrium, which corresponds to a very particular case. Finally, the model makes it possible to evaluate the actual catch per unit effort and explain how the FGSF changed over the period considered with the help of the open access and maximum economic yield frameworks.

**Keywords** : catch per unit effort, fisheries, matching, search cost

# 1 Introduction

Shrimp is nowadays the most consumed and one of the most internationally traded fishery products in the world, representing 16 % of world fishery exports (FAO, 2008) and a major source of value for French Guiana, where it is the third largest export sector of the country (25% of the total volume). The French Guiana waters are home to numerous species, with shrimp being one of the most harvested for its economic value. Two slightly different species represent the bulk of the harvest in the French Guiana shrimp fishery (FGSF), brown shrimp and pink shrimp (resp. *Farfantepenaeus subtilis* and *Frafantepenaeus brasiliensis*). *F. Subtilis* represents more than 85% of shrimp landings. The FGSF started in the late 1960s with the activity of US and Japanese fleet (Sanz *et al.*, 2017). Since 1992, the entire fleet has been solely made up of French trawlers targeting shrimp on the continental shelf. After twenty years of sustained growth, the FGSF started to experience major difficulties, as indicated in Fig. 1. Shrimp stocks have steadily decreased over the past two decades, though certain management measures in compliance with European legislation have been implemented. First, spatial restrictions in order to limit the impact of trawling on juvenile shrimp have been decided, and trawling is currently forbidden in inshore waters less than 30 meters deep. In addition, a total allowable catch (TAC) of 4108 tons/year was adopted in 1983, although it has only been reached in 1997. Lastly, a license system was introduced in 1991 to limit total fleet size. However, except in 1993, the number of available licenses has never been granted. According to the distinction proposed by Homans and Wilen (1997), the FGSF thus seems to have operated under a kind of restricted-regulated open access regime (FAO, 2008), without the above legal constraints having succeeded in stabilizing shrimp stocks. In order to explain the observed drop in shrimp stocks, Diop *et al.* (2018c, 2018b, 2018a) highlight the role of, respectively, global warming, changes in mangrove surface area, and the combined effects of these two phenomena. However, the most striking fact is that the consecutive marked drop in both fishing effort and harvest did not lead to the expected corresponding decrease in the overall level of profits. On the contrary, profits remained broadly positive over the same period, and have even increased during the last few years (Fig. 1). The way how profit data were estimated is detailed in Diop (2016). Thus, the observed trend in the rent generated by the FGSF over the period 1990-2009 constitutes a kind of paradox that is worth being further investigated and understood.

The fact that technical conditions for harvesting and nominal input and output prices remained largely unchanged in the FGSF between 1990 and 2009 suggests that the recent rise in profits mentioned above, at first glance

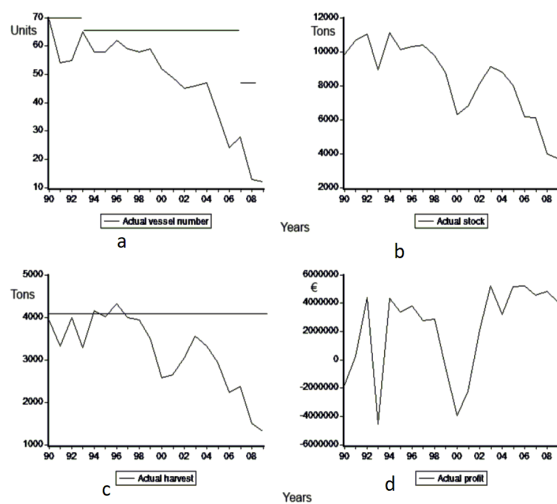


Figure 1: Actual stock, fishing effort, harvest, and profits levels in the FGSF between 1990 and 2009. a- Horizontal lines on the diagram of the trend of the number of vessel symbolize licenses. c-The quota is symbolized by the horizontal line on the diagram of the historical evolution of harvest.

surprising, could be explained by a drop in average harvesting costs and more precisely, in target search costs. Search costs are highly variable since they depend directly on the duration of the search process for fish and thus, on the probability of finding it. Since fish distribution is often patchy within fishing areas, harvests may vary considerably over time. Unlike other natural resources where search effort plays an important role (such as oil exploration), fish harvest is complicated by the movement of fish, that must still be localized precisely even if they are known to be present. The target detection process thus often represents the most time-consuming and therefore the most costly activity when compared with catch *per se*. In addition to the usual cost of fishing effort, which encompasses in particular vessel maintenance and crew wages, fishing firms must often allocate specific resources to the acquisition of information concerning the location, size, and quality of fish. Starting in the early 1980s, several works have underlined the fact that the corresponding expenditures in fuel consumption, investments into detection equipment, *etc.* often represent the largest share of total costs for fishing firms (Mangel and Plant, 1985). Numerous examples of fisheries in which significant effort is devoted to the search activity itself are identified by Mangel and Clark (1983), although, in aquaculture or for some easily locatable species, search activities and their associated costs may be much lower (Bjorndal *et al.*, 1993). Nevertheless, most canonical models used in the economic literature concerning fisheries (Cobb and Douglas, 1928; Gordon, 1954; Beverton and Holt, 1957; Schaefer, 1957; Clark and Munro, 1982) are of deterministic nature and voluntarily neglect the search activity itself, which prevents them from providing an accurate and realistic description of fish harvesting<sup>1</sup>. Among the rare studies on search activity, Mangel and Beder (1984) model search activities as stochastic Poisson processes and determine the optimal allocation of search effort between several historical fishing grounds, taking into account the stochastic fish distributions among them<sup>2</sup>. Some population models explicitly introduce stochasticity faced by fishing firms into standard models, but only with regard to fish stock dynamics and not the harvest process *per se* (*e.g.* Reed, 1978; Sethi *et al.*, 2005; Singh *et al.*, 2006). A parallel line of research focuses on empirically identifying certain latent fishery attributes such as the stock size, but from a scientific or managerial point of view (Zhang and Smith, 2011). This line focuses also on developing spatial models of endogeneous fishing location choice, but in terms of a trade-off between exploitation of the main target

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<sup>1</sup>See *e.g.* Munro (1992) for a survey on mathematical bioeconomic fishery models.

<sup>2</sup>See also McConnell *et al.* (1995) for a use of Poisson processes in the modeling of sportfishing.

and its associated bycatch (*e.g.* Abott and Wilen 2011). As can be seen, studies on the precise role of search activities for a particular target and the related costs are quite old and unsatisfactory. Literature on modelling the economics of fisheries has focused on the analysis of markets for fishery products and on evaluating different fishery management strategies (Clark, 1990; Schaefer, 1954). However, the standard model introduces empirical problems like natural variation on biological dynamics and stochastic shocks on production function. Very little attention has been directed at describing fishing as a complex process that consists of a number of inter-related activities. An extensive theoretical treatment of search in fisheries is given by Mangel (1982), and Mangel and Clark (1983).

This paper aims therefore at explaining the changes in the FGFSF between 1990-2009 by taking into account the time necessary for target detection that characterizes most of fish harvesting activities, and the costs that are associated to it. In order to take into account explicitly catch uncertainty, we adapt the search and matching model of Pissarides (2000), which describes the meeting between workers and firms in the labor market as a result of a stochastic Poisson process, to the case of fisheries. In our version of Pissarides' model, fish are scattered throughout the fishing area, and catch per unit effort (CPUE) depends on the ratio of the number of empty vessels to the number of escaped fish units, which we call "anthropic pressure". Nevertheless the relative abundance of French Guiana shrimp is probably not uniformly distributed in space (Martin *et al.*, 2015). Since the number of empty vessels sent to sea, which represents search effort, is explicitly derived from profit maximizing behavior, anthropic pressure and therefore CPUE are both endogenous. Our framework thus constitutes an important departure from standard fishery models, which consider CPUE as given. Moreover, it makes it possible to highlight the role played by congestion effects between vessels in the FGFSF, which appears to be important in other fisheries such as the North Carolina shrimp fishery (Huang and Smith, 2014). Lastly, the fact that the search process is assumed not to be instantaneous implies that, at any moment in time, there always remain some escaped fish. This makes it possible to determine an equilibrium level of escapement in the fishery and to highlight the factors that influence it, *i.e.* to propose a novel analysis framework for animal resource harvesting. The model also highlights the sensitivity of several variables typical of fisheries - such as the levels of anthropic pressure, search effort, and harvest, the state of stock conservation, the average duration of fishing trips, and fleet size - to exogenous economic, technological, and biological changes. The theoretical model is developed under the open access (OA) and maximum economic yield (MEY) regimes, both of which used to interpret developments in the FGFSF between 1990 and

2009.

The paper is organized as follows. Section 2 presents the basic fishery model. Section 3 determines the equilibrium of the fishery when it operates in an OA environment, where firms seek to maximize their profit in a decentralized manner. This section highlights the sensitivity of the fishery to changes in exogenous parameters in the long run. Section 4 studies the behavior of the fishery when it is managed in a totally centralized way and establishes the condition under which both the OA and MEY equilibria match. Section 5 uses the results obtained in Sections 3 and 4 to interpret the current trend in the FGFSF in light of both reference regimes and presents some concluding remarks.

## 2 The model

In the present model, empty vessels search for fish in a situation of imperfect information about its location. Production is not modeled as a continuous process with varying intensity, but as instantaneous, with searching for fish being considered time consuming. The fishery is made up of fish units (individuals of any size, tons of fish, schools...), and fishing firms each having a single vessel that is either empty, *i.e.* searching for fish, or filled with a unit of fish. At each instant in time, a number  $B$  of new fish, where  $B$  stands for the shrimp stock population growth, arrive into the fishery, and  $H$  fish are met and caught by vessels. We assume that the time required to harvest is negligible relative to the time required to find fish, and thus, that once a unit of fish has been found by a vessel, it is instantaneously caught and removed from the fish pool. Thus, at any moment in time, the total number of available fish units in the fishery,  $X$ , is equal to the sum of the  $H$  found and thus harvested fish units, and the  $U$  uncaught/escaped fish units. In line with the literature about fisheries, variable  $U$  will be called uncaught or "escaped" fish (see *e.g.* Reed, 1978) and be interpreted as an indicator of fish stock conservation status. We also assume that each vessel can only load a single unit of fish. We further suppose that once they have caught a fish unit, vessels must unload it before being able to catch another one. The number of empty vessels,  $E$ , that fishing firms decide to send to sea for a fishing campaign, represents "fishing effort", as in the literature. Only escaped fish units and empty vessels take part in the harvest process; they are randomly selected from the sets  $U$  and  $E$ .

## 2.1 Harvest and CPUE technologies

This first section gives a detailed description of the harvest process, *i.e.* the properties of the harvest function. Moreover, it estimates its parameters with the help of data concerning the FGSE. Finally, it determines equilibrium escapement in the steady state. Following Pissarides (2000), we assume that a Cobb-Douglas harvest function,  $H$ , gives the result of harvest per unit time, *i.e.*, the number of fish units met and thus caught by empty vessels. This harvest function depends on both the  $U$  escaped fish units and the  $E$  empty vessels as follows:

$$H(E, U) = qU^\alpha E^\beta \quad (1)$$

where  $q$  denotes catchability, and  $\alpha$  and  $\beta$ , the elasticities of harvest with respect to escapement and search effort, respectively. Ifremer (French Research Institute for Exploitation of the Sea) provides information about French Guiana shrimp stocks, which are evaluated using the Virtual Population Analysis (VPA) method (Sanz *et al.*, 2017), harvest, and fishing effort (number of days at sea) for the period 1990-2009. This allows escapement to be calculated, since  $U = X - H$ . As far as search effort is concerned, it can be evaluated by assuming that vessels are searching for fish, and hence are remaining empty, as long as they stay at sea, which makes it possible to use the number of days at sea (soak length) as a proxy of the number of empty vessels,  $E$ .

Table 1. Parameter estimates of the harvest function for the FGSE between 1990 and 2009

$H = qU^\alpha E^\beta$	
$\text{Log}(H) = \text{Log}(q) + \alpha \text{Log}(U) + \beta \text{Log}(E)$	
$q$	4.48 (0.054) *
$\alpha$	0.65 (0.000) **
$\beta$	0.29 (0.0022) **
Number of observations 20	Heteroskedasticity Test: White 5.60
$R^2$ : 0.944	$R^2$ adjusted : 0.938
JB (Jarque Bera) : 5.14	P-value in parenthesis, *significant at 95%, **significant at 99%
LM (Lagrange Multiplier) statistic : 1.78	DW (Durbin Watson) : 1.51
Hypothesis test of $\alpha + \beta = 1$	Prob. : 0.31

As shown in Table 1, empirical evidence for the FGSE indicates that returns on fishing effort are quite low, which means that participation externalities, arising from *e.g.* information sharing between vessels about the

location of fish, are rather weak in the FGSF. The parameter have been estimated by a log-log OLS model as specified in Table 1. The LM test statistic for the null hypothesis of no serial correlation indicates no serial correlation in the residuals. The White Test statistics in Table 1 rejects the hypothesis of heteroskedasticity. At last, Hausman test (Hausman, 1978, Sanz *et al*, 2017 ) rejects the endogeneity of the variable  $U$  in the harvest function. Moreover, the results obtained also show that returns to scale in the FGSF are nearly constant. Table 1 details the corresponding results and indicates more particularly that the hypothesis  $\alpha + \beta = 1$  is accepted<sup>3</sup>. The constant returns to scale assumption adopted from the above empirical results has an implication of particular theoretical interest, since it implies that the harvest function is homogeneous of degree one, which makes it possible to write the rate (frequency) at which vessels catch fish units, *i.e.* CPUE, as:  $H(U, E) / E = H(U/E, 1) \equiv m(\theta)$ , where:

$$\theta = \frac{E}{U} \quad (2)$$

From Eqs. (1) and (2), the function  $m(\theta)$  thus has the following form:

$$m(\theta) = q\theta^{-\alpha} \quad (3)$$

where  $\alpha = 1 - \beta$  therefore here stands for the elasticity of CPUE with respect to anthropic pressure. Being equal to the ratio of search effort to escapement, the variable  $\theta$  constitutes an appropriate indicator of the level of anthropic pressure that fishing firms apply on the fish stock. Since, as we shall see,  $\theta$  will be determined by fishing firms' economic decisions, CPUE will also be endogenous. This constitutes the major departure of our framework from the traditional Gordon-Schaefer and Cobb-Douglas models. Moreover, Eq. (3) and the positive estimated value of  $\alpha$  estimated in the case of the FGSF (see Table 1) imply:  $m'(\theta) < 0$ . This means that an increase in anthropic pressure yields a decrease in CPUE in the fishery. More precisely, if the ratio of empty searching vessels to escaped fish increases, the probability of finding fish for the average vessel,  $m(\theta) \delta t$ , decreases (there is stochastic rationing), and the probability of being caught for the average fish,  $\theta m(\theta) \delta t$ , increases, and conversely. Thus, the above results indicate that generally speaking in the FGSF, negative congestion externalities between vessels are stronger than positive participation externalities, which seem to be low, as mentioned above. As this paper will show later, the present model precisely highlights the central role played by congestion effects in the working of the FGSF.

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<sup>3</sup>As in Sanz *et al.* (2017), a problem of simultaneity bias may occur with the function  $H$  since empirically, the stock level may be evaluated on the basis of harvest. Here, the stock series has been corrected in order to avoid this possibility.



## 2.2 Steady state escapement

In this subsection, we focus the analysis on fish conservation, *i.e.* on the determination of steady state escapement,  $U$ . According to the harvest function (1), the process that makes a unit of fish meet a vessel is Poisson process with parameter  $H(U, E) / (U)^4$ . From the homogeneity property of the harvest function,  $H(U, E) / U = (E/U) H(U/E, 1)$ , we have:

$$\frac{H}{U} \equiv \theta m(\theta) \quad (4)$$

By construction,  $\theta m(\theta)$  indicates the rate at which fish is caught by vessels<sup>5</sup>. Hence, the mean number of still uncaught fish that are captured by vessels during a short time interval is:  $H\delta t = \theta m(\theta) U\delta t$ , where  $\theta m(\theta) \delta t$  reads as the fish's transition probability, and  $1 / [\theta m(\theta) \delta t]$ , the period at the end of which fish is being caught. The change in escapement is given by the difference between the number of new safe fish that arrive in the fishery, which corresponds to fish stock natural growth,  $B$ , and the portion of the fish stock that is caught by vessels,  $H$ . Thus we have:  $\dot{U} = B - H$ . In the steady state,  $\dot{U} = 0$ , which implies:

$$H = B \quad (5)$$

Thus, in the steady state, vessels catch all new fish that arrive in the fishery. Inserting Eq. (5) into Eq. (4), and isolating  $U$  yields:

$$U = \frac{B}{\theta m(\theta)} \quad (6)$$

Eq. (6) is the stationary condition and the first key equation of the model. It indicates that, in the steady state, escapement logically increases with natural growth and decreases at the rate at which fish is being caught by vessels. Since, as already stated,  $\theta$  is set from firms' maximizing behavior,  $U$  is also endogenously determined in the model.

## 3 Open access equilibrium

In this section, we determine the OA equilibrium of the fishery, assuming that there is free entry and exit of firms into and out of the fishery.

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<sup>4</sup>The Poisson process is also applied by Clark and Mangel (1984) to animals searching for forage in order to study the role of information in their foraging strategies.

<sup>5</sup>For the sake of clarity, we assume here that found fish are systematically caught and therefore definitively eliminated from the stock. The possibility of discarding behavior by fishermen, although important, is left for future work. Moreover, bycatch phenomena are also voluntarily ignored here.

### 3.1 Firms' decisions and equilibrium anthropic pressure

This subsection is devoted to the determination of the equilibrium level of anthropic pressure,  $\theta$ , which is derived from fishing firms' microeconomic decisions. We assume here that fishing activities are totally decentralized, so that individual firms take the level of aggregate variables, such as escapement, as given when maximizing profits. In our setting, firms decide whether or not they send empty vessels to sea to search for fish. The process that changes the state of an empty vessel is a Poisson process with rate  $H(U, E) / (E) = H(U/E, 1)$ . Written differently:

$$\frac{H}{E} \equiv m(\theta) \quad (7)$$

In Eq. (7), since  $m'(\theta) < 0$ , the catch level per unit effort/empty vessel decreases with the level of anthropic pressure exerted within the fishery. During a short time interval  $\delta t$ , an empty vessel catches fish at a rate  $m(\theta)$ , or with probability of  $m(\theta) \delta t$ , which implies that the mean duration (or "period") during which a vessel remains empty is equal to  $1/m(\theta)$ . Firms maximize profits dynamically, but in a stationary biological environment imposed by Eq. (6). An empty vessel searching for fish costs  $S$  per unit time, and after having found fish, harvests it instantaneously. We assume that  $S$  integrates all the costs that are necessary to equip a vessel for a fishing campaign (crew wages, fuel, *etc.*)<sup>6</sup>. Firms have a positive discount rate,  $r$ , and seek to maximize profits. They have full knowledge of the harvest process, but do not coordinate their actions and consider the catch probabilities as given. Let  $W_E$  and  $W_F$  be the present discounted value of expected flows of future profits from an empty vessel and a full vessel, respectively. After performing several calculations,  $W_E$  and  $W_F$  can be written as (see Appendix A):

$$rW_E = -S + m(\theta)(-W_E + W_F) \quad (8)$$

$$rW_F = r(1 + W_E) \quad (9)$$

In a perfect capital market, the valuation of their vessels by fishing firms is such that, whatever the state of the vessel (empty or full), the capital cost,

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<sup>6</sup>Like Mangel and Clark (1983), we assume here that the search component of fishing operations is the most important stochastic consideration. What fishing firms can do about the uncertainties concerning weather or stock size and quality is negligible in comparison to what they can accomplish in the way of locating fish (see also Mangel and Plant, 1985, on this point).

$rW$ , is exactly equal to the rate of return on the vessel. In Eq. (8), an empty vessel costs  $S$  per unit time and is being filled at rate  $m(\theta)$ , which makes the fishing firm lose the value of an empty vessel,  $W_E$ , and earn the value of a full vessel,  $W_F$ . In the steady state, since the change in vessel status from full to empty is instantaneous,  $W_F$  is independent of the interest rate and is equal to the harvested fish unit, and the value of an empty vessel,  $W_E$ <sup>7</sup>.

We assume that firms maximize profit by sending vessels to sea until the present-discounted value of the expected profit from the last engaged empty vessel is equal to zero ( $W_E = 0$ ). This assumption ensures that all fish production opportunities are exploited by firms. Since each firm only owns a single vessel, this assumption corresponds to a zero-profit condition applied to the fishery as a whole, and thus represents the OA situation. Applying  $W_E = 0$  to Eq. (8) and isolating  $W_F$  gives  $W_F = S/m(\theta)$ : in equilibrium, the number of vessels sent to sea by firms is such that expected profit from a full vessel,  $W_F$ , is exactly equal to the expected cost of an empty vessel, *i.e.* the per unit time search cost,  $S$ , weighted by the rate at which fish is being caught,  $m(\theta)$ . Continuing to use  $W_E = 0$  in Eq. (9) leads to  $W_F = 1$ . Still using  $W_E = 0$  in Eq. (8), dividing all terms by  $m(\theta)$ , and rearranging, leads to:  $m(\theta) = S$ . In equilibrium, firms' instantaneous profit, net of average search cost ( $S/m(\theta)$ ), is equal to zero or, expressed differently, marginal benefit equals marginal cost. Lastly, isolating  $m(\theta)$  gives implicitly the OA equilibrium value of anthropic pressure:

$$m(\theta_{OA}) = S \tag{10}$$

Eq. (10) is the second key equation of the model. It is a marginal condition which indicates that fishing firms send empty vessels to sea until the catching rate,  $m(\theta_{OA})$ , which represents the number of fish units caught per unit time, covers totally the (real) cost of the last vessel sent. Since  $m'(\theta) < 0$ , it also shows that equilibrium anthropic pressure logically decreases with the search cost. Since it is derived from fishing firms' economic decisions, Eq. (10) constitutes the driving force of the model under OA. Furthermore, this is the main innovative feature of the present framework since it implies that CPUE is endogenous. This contrasts with the existing literature concerning fishery economics, where effort,  $E = H/m(\theta)$ , has constant marginal cost, say  $c$ , which immediately implies that  $m(\theta) = c$ , and thus an exogenous CPUE.

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<sup>7</sup>Here, the vessels owned by firms may be interpreted as assets. Eqs. (8)-(9) correspond to what is called in financial economics "Capital Asset Pricing Market" (CAPM) equations. In a more general context, Scott (1955) suggests to treat stocks of natural resources as assets as well.

### 3.2 Overall outcome

The model is made up of a system of five equations (2), (6), (7), and (10), and four unknowns,  $\theta_{OA}$ ,  $H_{OA}$ ,  $E_{OA}$ , and  $U_{OA}$ , whose OA equilibrium values are given by<sup>8</sup>:

$$\theta_{OA} = \left(\frac{q}{S}\right)^{\frac{1}{\alpha}} \quad (11)$$

$$U_{OA} = B \left(\frac{S^{1-\alpha}}{q}\right)^{\frac{1}{\alpha}} \quad (12)$$

$$E_{OA} = \frac{B}{S} \quad (13)$$

$$H_{OA} = B \quad (14)$$

The signs of the effects of changes in the technological, economic, and biological parameters on the endogenous variables of the model under OA are summarized in Table 2:

Table 2: Sensitivity analysis of the OA equilibrium

	$\theta_{OA}$	$U_{OA}$	$E_{OA}$	$H_{OA}$
$q$	+	-	0	0
$S$	-	+	-	0
$B$	+	+	+	+

Equilibrium anthropic pressure increases in catchability and decreases in the vessel cost, the equilibrium number of uncaught fish decreases in catchability but rises logically in the search cost and natural growth, fishing effort is independent from catchability but decreases in the search cost and increases in natural growth, and equilibrium harvest only depends on natural growth in the steady state. Notice that the equation giving OA equilibrium fishing effort can be alternatively written as:  $SE_{OA} = B$ . The latter equation clearly shows that fishing firms send empty vessels to the sea until natural growth covers exactly the cost of all vessels sent. Graphically, the equilibrium of the

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<sup>8</sup>The closing of the model may be undertaken as follows. Using Eq. (3) to isolate  $\theta$  in Eq. (10), one finds the OA equilibrium value of anthropic pressure, which is given by Eq. (11). In addition, inserting Eq. (11) into the steady state escapement equation, Eq. (6), and isolating  $U$  yields the expression of OA equilibrium escapement. Then, recalling the definition of anthropic pressure given by Eq. (2), isolating  $E$  and replacing  $\theta$  and  $U$  by Eq. (11) and (12) respectively leads to equilibrium search effort under OA (Eq. (13)). Now, inserting Eq. (12) and Eq. (13) into Eq. (1) and simplifying make it possible to check the entire model by finding Eq. (14), which is the same as the steady state condition (Eq. (5)).

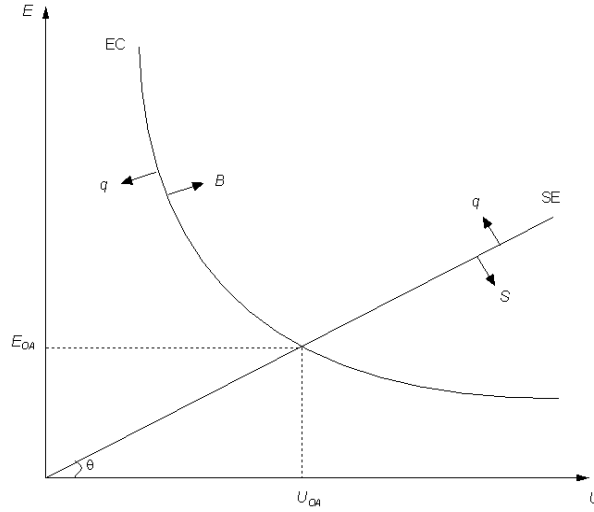


Figure 2: The open access search-matching fishery equilibrium

fishery can be represented by the intersection of two curves, the Escapement Curve (EC) and the Search Effort (SE) curve, given by Eq. (6) and Eq. (10), respectively<sup>9</sup>. The overall situation is depicted in Fig. 2. As can be seen, the EC curve is decreasing and convex in the  $(U, E)$  space. As the number of empty vessels falls along the EC curve, the global harvest level decreases, which mechanically translates into a rise in escapement. In other words, the reduction in search effort,  $E$ , and the simultaneous rise in escapement,  $U$ , make anthropic pressure, and thus the probability for a fish to be caught by an empty vessel,  $\theta m(\theta)$ , decrease. Eq. (6) then indicates that for escapement to remain constant in the steady state, the number of empty vessels engaged in the search must decrease. Conversely, a higher search effort corresponds to lower escapement. As far as the SE curve is concerned, Eq. (10) clearly indicates that it is linear in  $U$ , passing through the origin in the  $(U, E)$  locus, with slope  $\theta$ . An increase in  $U$  leads to a reduction in  $\theta$  which makes CPUE,  $m(\theta)$ , increase ( $m'(\theta) < 0$ ). This in turn makes the cost per unit search,  $S/m(\theta)$ , decrease, which induces firms to increase search effort,  $E$ . As far as the exogenous shocks that may affect the fishery are concerned, neither changes in the catchability parameter,  $q$ , over time nor changes in the search cost,  $S$ , explain the simultaneous falls in fishing effort, harvest, and escapement in the FGSF between 1990 and 2009. Indeed, Table 2 indicates

<sup>9</sup>In the present example, the equations of the EC and SE curves can be obtained respectively by replacing  $\theta$  by  $E/U$  and isolating  $E$  in Eq. (6) and (10), which leads to  $E_{EC} = (B/q)^{1/(1-\alpha)} U^{-\alpha/(1-\alpha)}$ , and  $E_{SE} = (\frac{q}{S})^{1/\alpha} U$ .

that a change in  $q$  has no effect on  $E$  and  $H$ , and that it has a negative impact on  $U$ , whereas a variation in  $S$  lowers  $E$ , has no impact on  $H$ , and raises  $U$ . However, a reduction in natural growth per stock unit,  $B$ , leads simultaneously to the falls in  $E$ ,  $H$ , and  $U$  observed empirically. An exogenous reduction in  $B$  induces vessels to decrease their harvest level in the steady state (Eq. (5)). The reduction in harvest implies that, for profits to remain null under OA, the average cost per unit search ( $S/m(\theta)$ ) must also decrease (Eq. (10)), which implies, for a given search cost,  $S$ , an increase in CPUE,  $m(\theta)$ . This rise in CPUE comes from the weakening of the congestion effects at work within the fishery and corresponds to a reduction in the level of anthropic pressure,  $\theta$  ( $m'(\theta) < 0$ ). It is worth noting here that the rise in CPUE may even occur after a slight reduction in anthropic pressure, if the value of the elasticity of  $m(\theta)$  with respect to  $\theta$ , *i.e.*  $\alpha$ , is sufficiently high. As already shown, this is especially the case in the FGFSF, where  $\alpha$  close to one. From a reduction in  $H$ , coupled with a rise in  $m(\theta)$ , Eq. (7) implies an unambiguous reduction in  $E$ . Finally, since by definition  $U = E/\theta$ , the net effect on  $U$  remains theoretically ambiguous, since it depends on the value of  $\alpha$  (Eq. (6)). This statement can be confirmed by observing Fig. 2, where a reduction in  $B$  is represented by the combined downward movements along the ER and SE curves, which lead to an unambiguous reduction in  $E$  but to an undetermined change in  $U$ . Nevertheless, in the case of the FGFSF, a reduction in  $B$  leads to an unambiguous reduction in  $U$ . This result can be explained with the help of the steady state constraint given by Eq. (6), which indicates that a fall in  $B$ , and thus in  $\theta$ , has an ambiguous impact on  $U$ . However, Eq. (11) clearly shows that a reduction in  $B$  is followed by a stronger reduction in  $\theta$  (since  $\alpha < 1$ ), so that  $U$  should increase in Eq. (12). The only additional mechanism that may lead to an overall reduction in  $U$  is thus necessarily a stronger rise in CPUE,  $m(\theta)$ , resulting from the reduction in anthropic pressure and the congestion effects. In other words, after a negative change in natural growth rate of the stock, the fall in the number of vessels that search for fish allows the remaining vessels to catch fish more easily, which results in reduced escapement.

## 4 Maximum economic yield equilibrium

In this section, we would like to examine the case where the present search-matching fishery works under a MEY regime. In order to do so, we now assume that the fishery is managed in a totally centralized manner by, say, a regulator, who has a positive discount rate,  $r$ , and who maximizes profits. We assume that firms' profit is equal to the number of harvested fish units,  $H$ ,

less the cost of an empty vessel,  $S$ , multiplied by the number of empty vessels,  $E$ . From Eq. (6), we can express the objective function of the regulator as follows:

$$\Omega = \int_0^{\infty} (H - SE) e^{-rt} dt \quad (15)$$

Hence, the regulator maximizes  $\Omega$  with respect to  $\theta$ , subject to the technological constraint given by Eq. (1) and the escapement dynamics,  $\dot{U} = B - H$ . Solving the regulator's program then leads to the following implicit equation for optimal anthropic pressure,  $\theta$  (see Appendix B):

$$1 - \eta(\theta) - \frac{r + \eta(\theta) \theta m(\theta)}{m(\theta)} S = 0 \quad (16)$$

In order to identify the conditions under which the fishery under OA works optimally, Eq. (11) can be rewritten as Eq. (16) in the following way:  $1 - S/m(\theta) = 0$ . This enables to see that  $\theta_{OA} = \theta_{MEY}$  if  $\eta(\theta) = 0$  and  $r = 1$ . Thus the present fishery would work optimally under OA if the elasticity of CPUE with respect to anthropic pressure equalled zero and the regulator had the strongest preference for present. The condition  $\eta(\theta) = 0$  corresponds indeed to the extreme situation where CPUE,  $m(\theta)$ , is independent from anthropic pressure,  $\theta$  (see Eq. (3)). In this a case, congestion effects between empty vessels are non-existent, which allows for reaching the highest CPUE level. The condition  $r = 1$  stems from the fact that the intertemporal value of a full vessel and thus, OA equilibrium anthropic pressure, do not depend on the interest rate which implies that both regimes' equilibria are only comparable when the regulator values the current period only.

## 5 Empirical results

In order to plot the changes over time in the most representative endogenous variables of the model, we follow Martinet and Blanchard (2009), who retain the following logistic-type function for describing the shrimp stock population growth:

$$B(X, i, K) = iX \left( 1 - \frac{X}{K} \right) \quad (17)$$

where  $i$  represents the maximum relative growth or “intrinsic growth rate”, which is related to the studied species, and  $K$ , the carrying capacity, which depends on the characteristics of the species' natural environment, such as the size and the biological productivity of the habitat. Both parameters are assumed to be fixed, and for a biological equilibrium to exist,  $K > X$  and

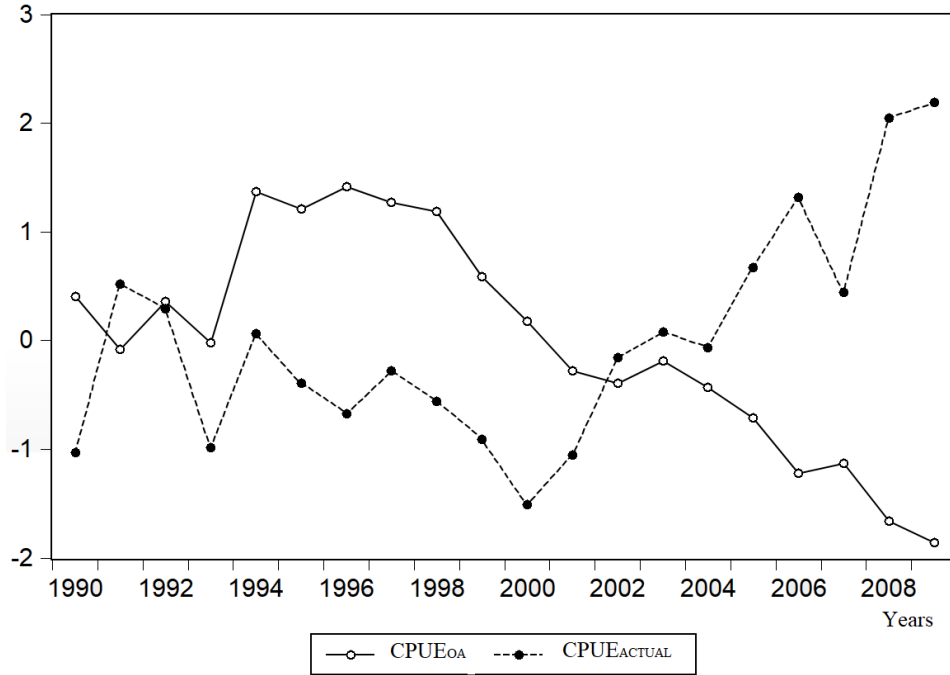


Figure 3: Changes in Actual and OA levels of CPUE

$i > 0$  must be verified. We assume that natural mortality is considered in the growth rate. The values used by the above authors for both parameters are:  $K = 18,5$  tons and  $i = 0.91$ . Total fishing effort is calculated with the help of Eq (13). For escapement,  $U$ , we suppose that it is equal to the difference between the annual shrimp stock and harvest levels, *i.e.*:  $U = X - H$ . Actual and OA CPUE levels are plotted in Fig. 3, using Ifremer data from the period 1990-2009. Parameters  $\alpha$  and  $q$  are estimated in Table 1, with  $\alpha = 0.65$  and  $q = 4.48$ . The values of the exogenous search cost,  $S$ , were collected in Diop (2016) and are expressed in real terms. Lastly, the variable  $B$  is calculated using parameters “ $i$ ” and “ $K$ ” found in Martinet and Blanchard (2009), and the corresponding stock during the same period comes still from Diop (2016). We assume that the price of a shrimp unit is constant for all periods, which seems to be a reasonable assumption on the empirical ground (see Diop, 2016). The variable  $H$ , which denotes the number of meeting between vessels and fish units per unit time, is thus also expressed in real terms.

First of all, Fig. 3 indicates that actual CPUE was low in 1990 but that it strongly increased from 2000. The increase in the average CPUE inside the fishery allowed for the recovering of profit levels at the end of the period studied, that can be observed in Fig. 1. Our results suggest that congestion



effects between vessels and the resulting changes in CPUE have played a major role in explaining the simultaneous evolutions of the fleet size/search effort, catch, and profit levels in the FGSF since 2000. The substantial reduction in the fleet size to about 20 active vessels in 2016, undertaken to concentrate fishing activities over a limited number of profitable vessels (Blanchard *et al.*, 2019), might have substantially decreased congestion effects between them. This seems to have in turn resulted into a strong rise in the CPUE levels that might have more than compensated for the fall in fishing effort and catch, and finally resulted in the rise in profits. Conversely, Fig. 3 shows that if the FGSF had worked under OA, CPUE would have substantially decreased from 1993. Since the FGSF seems to have worked under an open access regulated regime, the above result suggests that such a regime might have allowed for a better working of the FGSF.

## 6 Conclusion

Much of the literature in fisheries economics is based on the Schaefer (1954) framework where the CPUE is considered exogenous. However there has been increasing interest in endogenous CPUE models in recent years (Zacharia *et al.*, 2020; Sweke *et al.*, 2015; Zhang and Smith, 2011; Mardle and Pascoe, 2000). In line with these authors our framework constitutes a departure from standard fishery models, proposing endogenous CPUE. The present paper contributes to the fisheries economics literature by proposing a micro-economic model of the fishing process and thus a micro-foundation for the fishing cost function.

As Bjorndal and Munro (2003) point out, “The economics of fisheries management under uncertainty is currently underdeveloped. Without question, much remains to be done.” In order to explain the recent development in the FGSF, the fishery model proposed in this paper partially fills the above-mentioned gap by explicitly taking into account the fact that fish harvesting is by nature a random activity. It uses search theory to describe the specific economic behavior of fishing firms and highlights its consequences for the overall situation of fisheries. According to our approach, uncertainty and, more precisely, catch stochasticity, play a major role in explaining the economic performance of fisheries. More precisely, our results suggest that congestion effects between vessels should be carefully taken into account when choosing the optimal fleet size of a fishery. Lastly, the present framework could potentially be used to analyze the exploitation of almost any animal species, including land animals.

# Appendices

## Appendix A: Fishing firms' choices and the Bellmann equations (in continuous time)

### Method 1 (formal method)

The present discounted values of expected profit from an empty and a full vessel are given respectively by:

$$W_E = -S\varepsilon \int_0^T e^{-rt} dt + (1 + W_E) \varepsilon (e^{-rT}) \quad (\text{A1})$$

$$W_F = 1 - S\varepsilon \int_0^T e^{-rt} dt + W_F \varepsilon (e^{-rT}) \quad (\text{A2})$$

where  $\varepsilon$  is the mathematical expectation. An empty vessel searching for fish costs  $S$  per unit time between 0 and  $T$ , where  $T$  is the instant at which the vessel finds a fish unit.  $T$  is a random variable that follows a Poisson process, whose parameter is given by the rate at which vessels find fish units,  $m(\theta)$ . Still at date  $T$ , the vessel harvests a single fish unit and sells it in the market instantaneously, also earning the present discounted value of expected profit from an empty vessel,  $W_E$ . A firm with a full vessel sells its fish unit in the market instantaneously and then becomes empty, starting to search for fish between 0 and  $T$ , where  $T$  is a random variable that follows a Poisson process of parameter  $m(\theta)$ . At instant  $T$ , the empty vessel finds a fish unit and regains the status of a full vessel, earning the corresponding expected profit,  $W_F$ .

Let's start by calculating the integral included in Eqs. (A1) and (A2):

Now, if  $T$  is a random variable that follows a Poisson process of parameter  $m$ , we have:  $\varepsilon(e^{-rT}) = \int_0^\infty m e^{-(r+m)T} dT$ . Thus, Eqs. (A1)-(A2) become:

$$W_E = -S\varepsilon \frac{1 - e^{-rT}}{r} + (1 + W_E) \varepsilon(e^{-rT}) \quad (\text{A3})$$

$$W_F = 1 - S\varepsilon \frac{1 - e^{-rT}}{r} + W_F \varepsilon(e^{-rT}) \quad (\text{A4})$$

After calculating the integrals and simplifying, we obtain:

$$W_E = -S \frac{1}{r + m} + (1 + W_E) \frac{m}{r + m} \quad (\text{A5})$$

$$W_F = 1 - S \frac{1}{r + m} + W_F \frac{m}{r + m} \quad (\text{A6})$$

Lastly, solving for  $W_E$  and  $W_F$  leads respectively to Eqs. (8)-(9).

## Method 2 (intuitive method)

According to the assumptions used in our model, the present discounted values of expected profit from an empty vessel and a full vessel can be written respectively as:

$$W_E = \frac{1}{1 + rdt} \{-Sdt + [1 - m(\theta) dt] W_E + m(\theta) dt W_F\} \quad (\text{A7})$$

$$W_F = \frac{1}{1 + rdt} (1 + W_E) \quad (\text{A8})$$

At a discount rate  $r$ , an empty vessel costs  $S$  per unit time and continues yielding the expected value of an empty vessel,  $W_E$ , as long as it remains in this state with probability,  $1 - m(\theta) dt$ . With the complementary probability,  $m(\theta) dt$ , it finds a fish unit and yields the expected value from a full vessel,  $W_F$ , for the firm. A firm with a full vessel, loaded with one fish unit, becomes instantaneously empty and earns the expected profit associated with the state of an empty vessel,  $W_E$ . Multiplying all terms by  $(1 + rdt)$  and rearranging terms if  $dt$  tends to zero leads to Eqs. (8)-(9) in the text.

## Appendix B: The regulator's program (in continuous time)

According to our model, the Hamiltonian corresponding to the regulator's profit maximization program is:

$$\mathcal{H} = (H - SE) e^{-rt} + \mu \dot{U} \quad (\text{B1})$$

where  $\mu$  denotes the co-state variable. From the definition of anthropic pressure (Eq. (2) in the text), the rate at which fish is being caught (Eq. (4)), and the steady state condition given by Eq. (6), the Hamiltonian can be rewritten as:

$$\mathcal{H} = (X - U - S\theta U) e^{-rt} + \mu [B - \theta m(\theta) U] \quad (\text{B2})$$

Therefore, the optimality conditions related to  $\theta$  ( $\partial\mathcal{H}/\partial\theta = 0$ ), and  $U$  ( $\partial\mathcal{H}/\partial U = -\dot{\mu}$ ), give respectively:

$$-S U e^{-rt} + \mu [m(\theta) + \theta m'(\theta)] U = 0 \quad (\text{B3})$$

and

$$e^{-rt} (-1 - S\theta) e^{-rt} + \theta m(\theta) \mu - \dot{\mu} = 0 \quad (\text{B4})$$

Directly calculating the elasticity of the capturability function with respect to anthropic pressure from Eq. (3), *i.e.*  $m'(\theta) \theta / m(\theta) = -\alpha$ , and isolating  $\mu$  in Eq. (B3), yields:

$$\mu = \frac{S}{m(\theta) [1 - \eta(\theta)]} e^{-rt} \quad (\text{B5})$$

The derivative of  $\mu$  with respect to time thus reads:

$$\dot{\mu} = -r \frac{S}{m(\theta) [1 - \eta(\theta)]} e^{-rt} = -r\mu \quad (\text{B6})$$

Combining Eq. (B4) and Eq. (B6), while still taking into account Eq. (B5), and simplifying gives Eq. (16) in the text.

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