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# A search-matching model of fisheries

Nicolas Sanz\*      Bassirou Diop\*

## Abstract

This paper studies the implications of fish search activities on the working of fisheries. We develop a simple fishery matching model in which firms' stochastic search for fish requires specific resources. The equilibrium level of anthropic pressure (number of empty vessels/conserved fish stock) exerted by firms on the fish stock is derived from their individual profit maximizing behavior. Anthropoc pressure determines in turn the rate at which vessels find fish *i.e.* catchability, which is therefore endogenous in our model, and the stock conservation (uncaught fish) rate, through the dynamic equation of the latter. We then show that under open access, equilibrium anthropic pressure, fishing effort and the conservation rate heavily depend on search costs. An empirical study of the French Guiana shrimp fishery confirms the ability of the model to reproduce empirical data.

*Keywords:* fisheries; search costs; bioeconomic matching model

*JEL Classification:* Q22

## 1 Introduction

A particular feature of fish production is that the targets' search process, that it almost always includes, often represents the most time-consuming and costly activity, especially when compared with harvesting *per se*. Next to the "fishing effort" cost, which encompasses notably input prices such as crew wages and catching material costs, fishing firms must often spend additional resources to acquire some information about the location, size, and quality of fish (Mangel and Plant, 1985). The corresponding expenses in fuel consumption, investments into detection materials and so on, may be therefore non neglectable. There are numerous examples of fisheries in which

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significant effort is devoted to the search activity itself (see *e.g.* Mangel and Clark, 1983)<sup>1</sup>. Moreover, environmental variability implies that fish harvesting does not correspond to a deterministic process. Since fish distribution is often patchy within fishing areas, successful fish catches are by definition uncertain and therefore potentially very costly for fish producers. Mangel and Clark (1983) underline the fact that unlike other natural resources where search is also important (such as oil exploration), fish harvest is even more complicated by the movement of fish, which must still be found even if it is known to be present.

Nevertheless, a quite surprising fact is that the effects of search costs on the stocks and harvest levels have rarely been deeply studied in the scientific literature devoted to this subject. Most canonical bioeconomic fishery models such as the Gordon-Schaefer model (Gordon, 1954; Schaefer, 1957) or Clark's model (Clark, 1976) are of deterministic nature and voluntarily neglect search costs, thus preventing the analytical framework they rely on from giving an accurate and complete description of fish harvesting<sup>2</sup>. Only a few contributions have later dealt with the present topic. Mangel and Clark (1983), Mangel and Beder (1984), and Mangel and Plant (1985) explicitly model search activities as stochastic Poisson processes<sup>3</sup>. Since matching between fish and fishermen is not instantaneous, it mechanically generates some costs for the latter. The above authors then determine the optimal allocation of search effort between several historical fishing grounds, taking into account the stochastic fish distributions between them. According to these works, the most important source of uncertainty concerns the location of fish.

In this paper, we start from the idea that search activities for fish often imply the main costs for fishing firms and must for this reason be explicitly taken into account in the economic and biological analysis of fisheries<sup>4</sup>. Moreover, the magnitude of search costs might mainly depend on the probability for a vessel to find fish, which itself relies on the relative number of empty vessels and yet uncaught fish that are simultaneously present within the fishery. In order to proceed, we adapt the search-matching framework developed

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<sup>1</sup>The fisheries retained in Mangel and Clark (1983) are the eastern tropical Pacific tuna-purse-seine fishery, the British Columbia salmon-purse-seine fishery, the Australian Gulf of Carpentaria prawn fishery, and the California-Oregon-Washington shrimp fishery. However, in aquaculture or for some easily locatable species, search activities and their associated costs may be much lower (see *e.g.* Bjørndal *et al.*, 1993, for a discussion on this point in the case of seals or schooling species).

<sup>2</sup>See *e.g.* Munro (1992) for a survey on mathematical bioeconomic models of fisheries.

<sup>3</sup>Clark and Mangel (1984) also use a Poisson stochastic process to describe the behavior of animals searching for forage and the role of information in their foraging strategies. See also McConnell *et al.* (1995) for a use of Poisson processes in the modelling of sportfishing.

<sup>4</sup>For a study of fisheries management costs, see Arnason (2000).

by Sveriges Riksbank prize in economic sciences in memory of Alfred Nobel laureates Peter Diamond, Dale Mortensen, and Christopher A. Pissarides for the analysis of labor markets to the case of fisheries<sup>5</sup>. In our simple bioeconomic matching model, fishing firms explicitly allocate resources to search activities by sending empty vessels to sea. Once a firm has decided to send an empty vessel to sea, the latter starts searching for fish in a situation of imperfect information about the location of fish. The fishing effort function is thus microfounded and derived from firms' profit maximizing behavior. Empty vessels and uncaught fish then meet each other gradually according to a "matching technology". During the matching process and before all unmatched vessel-fish pairs meet, some new fish arrive into the fishery due to natural biological growth, providing a steady flow into the uncaught fish pool. With the above assumptions, there still remain some uncaught fish in the steady state, *i.e.* the uncaught fish rate, defined as the ratio between the uncaught fish and the overall fish stock available in the fishery, remains positive and is derived from the fish's transitions in and out of the fishery. In our model, the uncaught fish rate constitutes an indicator of the species conservation state. The transition probabilities are influenced by both individual fishing firms' decisions and aggregate events that occur at the global fishery level. In particular, the rate at which vessels find fish, which corresponds to the usual "catchability" coefficient in the literature on fisheries, depends on the relative number of vessels with respect to the number of fish units that evolve within the fishery, that we call "anthropic pressure". The fact that anthropic pressure is chosen by firms through their profit maximizing behavior makes the catchability coefficient endogenous, which constitutes an important departure of the present model from existing works that usually consider it as given. Here, harvest efficiency evolves with respect to the ratio between both kinds of participating individuals to the fishing/meeting process. The model then allows for determining an equilibrium rate of uncaught fish, and to highlight the factors that influence it, *i.e.* to develop a theory of natural resources conservation. Lastly, the introduction of a natural growth function into the dynamic equation of the uncaught fish rate also makes it possible to capture some biological parameters usually retained in bioeconomics models, such as the intrinsic growth rate or the carrying capacity of the habitat of the studied species.

The paper is organized as follows. Section 2 presents a simple fishery search-matching model, that gives a detailed description of the meeting process between vessels and fish and the determination of the steady state

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<sup>5</sup>For a general presentation on search-matching models applied to the labor market, see Pissarides (2000).

equilibrium uncaught fish rate of a given species. Section 3 gives the equilibrium of the fishery when the latter is assumed to work under an open access environment, where firms seek to maximize their profit in a decentralized manner. Section 4 provides an illustrative application of the model to the case of the French Guiana shrimp fishery. Lastly, Section 5 summarizes the main findings of the paper and gives some concluding remarks.

## 2 A fishery search-matching model

We assume that “our” fishery entails fishing firms equipped with vessels, and fish units (individuals of any size, schools...). Production is not modelled as a continuous process with varying intensity, but as instantaneous, with the search for fish as time consuming.

### 2.1 The meeting process between vessels and fish

The fishery is made up of a given fish stock,  $X$ , and an endogenous number firms,  $V$ , each equipped with a single vessel. We assume that once a unit of fish has been found by a vessel, it is instantaneously successfully caught and removed from  $X$ . Thus, at any moment in time, the fish stock  $X$  is equal to the sum of the  $F$  found and caught fish and the  $U$  unmatched and thus, uncaught (conserved) fish. We further assume that, after having found and caught it, firms can only load their single vessel with a single unit of fish. Thus the total number of vessels,  $V$ , equals the  $E$  empty vessels plus the  $F$  filled vessels. We assume that only the  $U$  uncaught fish and the  $E$  empty vessels engage in meeting. We use for convenience the corresponding density variables,  $u$  and  $e$ , respectively representing the uncaught fish rate and the empty vessel rate, both with respect to the fish stock, and thus defined by:  $u = U/X$ ;  $e = E/X$ . Since it reflects the conservation state of the stock,  $u$  represents the first main variable of the model. The following matching/catching function gives the number of met and thus caught fish as a function of the  $U$  uncaught fish and the  $E$  empty vessels at any moment in time:  $F(U, E) = F(uX, eX)$ . We assume that  $F$  exhibits the same properties as most of the production functions used in the fisheries science literature, *i.e.* it is increasing and concave in its two arguments (Morey, 1986; Clark, 1990). Moreover, we further suppose that it exhibits constant returns-to-scale. Situations of either decreasing or increasing returns on both the harvest effort and the stock levels may of course be observed in some fisheries and the matching function retained here would need further be empirically estimated. However, such a study is beyond the scope of the presentation

of the basic model. As we shall see, the homogeneity property makes it possible to give a convenient formulation of the model and to present its main qualitative properties in a very simple manner. If  $F$  is homogenous of degree one, it can be expressed in the following way:

$$F(uX, eX) = f(u, e)X \quad (1)$$

where  $f(u, e)$  denotes the matching rate, *i.e.* the fraction of the stock that is caught by vessels per unit time.

## 2.2 The steady state conservation rate

In this subsection, we focus the analysis on the conservation rate of the fish stock. We assume that only empty vessels and uncaught fish take part to the matching process and are thus randomly selected from the sets  $eL$  and  $uL$ . According to the above matching function, the process that makes a unit of fish meet a vessel is Poisson with parameter  $f(uX, eX)/(uX)$ . Still from the homogeneity property of the matching function,  $f(uX, eX)/uX = (e/u)f(u/e, 1) = \theta f(1/\theta, 1) \equiv \theta q(\theta)$ , where  $\theta = e/u$  and  $q'(\theta) < 0$ <sup>6</sup>. By definition,  $\theta$  constitutes an indicator of the anthropic pressure exerted by firms on the fish stock. As will be shown below,  $\theta$  is derived from the firms' profit maximizing behavior, which makes the catchability coefficient,  $q(\theta)$ , endogenous in our model. By construction,  $\theta q(\theta)$  indicates the rate (frequency) at which fish are being found by vessels<sup>7</sup>. Hence, the mean number of uncaught fish that are found by vessels during a small time interval is  $fX\delta t = \theta q(\theta)uX\delta t$ , where  $\theta q(\theta)\delta t$  reads the fish's transition probability, and  $1/[\theta q(\theta)\delta t]$ , the period at the end of which a fish is being caught. The steady state uncaught fish rate is equal to the difference between the rate of new safe fish that arrive into the fishery, which corresponds to the fish stock's (relative) natural growth rate,  $b(\cdot) = B(\cdot)/X$ , and the rate of fish that leave the uncaught fish pool,  $\theta q(\theta)uX$ . In the steady state,  $b = \theta q(\theta)uX$ , which, isolating  $u$ , gives:

$$u = \frac{b}{\theta q(\theta)} \quad (2)$$

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<sup>6</sup>It can be easily shown that the assumptions adopted above for the matching technology imply  $q'(\theta) < 0$ , and that the elasticity of  $q(\theta)$  with respect to  $\theta$  is entailed between 0 and  $-1$ . Hence, empty vessels find fish more easily when there are more fish relative to empty vessels within the fishery.

<sup>7</sup>For the sake of clarity, we assume here that found fish are systematically caught and therefore definitely eliminated from the stock. The possibility of discarding behavior by fishermen, although interesting, is left to later work. More broadly, bycatch phenomena are also voluntarily ignored here.

Equation (2) is the stationary condition of the model and corresponds to its first key equation. It indicates that, at the stationary equilibrium, the uncaught fish rate logically increases with the stock natural growth rate and decreases with the rate at which fish are being caught by vessels.

Whereas  $u$  is clearly decreasing with  $\theta q(\theta)$ , the effect of  $\theta$  itself on  $u$  could seem ambiguous at first sight. This is due to the simultaneous presences of two kinds of externalities that work in opposite directions. On the one hand, the *participation externality* (a higher number of vessels relative to the uncaught fish stock increases the matching rate/the probability for a fish to be caught), explains why the uncaught fish rate partly increases with anthropic pressure through the term  $q(\theta)$  ( $q'(\theta) < 0$ ). On the other hand, the *search or congestion externality* (a higher number of vessels reduces the probability that an isolated vessel finds a fish unit) is reflected by the fact that a rise in  $\theta$  leads directly to a fall in  $u$ . With the functional form of the matching technology that will be retained later for illustration purposes, the first effect dominates the second one, making  $u$  all in all decreasing with  $\theta$ .

### 3 Open access equilibrium

In this section, we assume that fishing activities are totally uncontrolled and that there is free entry and exit of firms into and out of the fishery.

#### 3.1 Firms' fishing effort and equilibrium anthropic pressure

This subsection is devoted to the determination of the equilibrium level of anthropic pressure,  $\theta$ , that firms set on the basis of pure economic considerations. In our setting, the “fishing effort” variable usually encountered in the literature on fisheries has its counterpart through the firms' decision about whether or not to enter the fishery and to send empty vessels to sea for fishing. An empty vessel searching for fish costs  $s$  per unit time, and after having found a fish unit, immediately catches the latter which yields an instantaneous profit  $\pi$ . We assume that  $s$  integrates all the costs that are necessary to equip a vessel for a fishing campaign (crew wages, fuel...). It corresponds here to the usual overall cost of fishing effort. Firms have a positive discount rate,  $r$ , and seek to maximize the present-discounted value of expected profits. They have full knowledge of the matching process but do not coordinate their actions and take the matching probabilities as given.

As long as fishing firms have not found any fish yet, their vessel remains

empty<sup>8</sup>. The process that changes the state of an empty vessel is Poisson with rate  $f(uX, eX)/(eX) = f(u/e, 1) \equiv q(\theta)$ . In other words, during a small time interval  $\delta t$ , an empty vessel finds a unit of fish at a meeting rate (or frequency)  $q(\theta)$ , or with probability  $q(\theta)\delta t$ , which implies that its mean duration (or period) is equal to  $1/q(\theta)$ . Let  $\Pi_E$  and  $\Pi_F$  be respectively the present-discounted value of the flow of instantaneous profit earned by a fishing firm with respectively an empty vessel and a filled vessel. After some calculations,  $\Pi_E$  and  $\Pi_F$  can be written as (see Appendix):

$$r\Pi_E = -s + q(\theta)(-\Pi_E + \Pi_F) \quad (3)$$

$$r\Pi_F = r(\Pi_E + \pi) \quad (4)$$

In a perfect capital market, the valuation of their vessels by fishing firms is such that, whatever the state of the vessel (empty or filled), the capital cost,  $r\Pi$ , is exactly equal to the rate of return on the vessel. In Eq. (3), an empty vessel costs the firm  $s$  per unit time. The empty vessel finds a fish unit and changes state according to a Poisson process with rate  $q(\theta)$ , yielding net return  $(-\Pi_E + \Pi_F)$ . At a stationary state, since the vessel's change in status from filled to empty is instantaneous, the profit from a filled vessel,  $\Pi_F$ , is independent from the interest rate and equals the present-discounted value of an empty vessel plus the profit from the catch,  $\Pi_E + \pi$ <sup>9</sup>.

We assume that firms maximize their 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 ( $\Pi_E = 0$ ). This assumption ensures that all fish production opportunities are exploited. Since each firm only owns a single vessel, it corresponds to a zero profit condition applied at the global fishery level, and thus represents an open access situation. Applying  $\Pi_E = 0$  to (3) and isolating  $\Pi_F$  gives the present-discounted value of the expected profit from a filled vessel under open access,  $\Pi_F = s/q(\theta)$ : in equilibrium, the number of vessels sent to sea by firms is such that the expected profit from a filled vessel,  $\Pi_F$ , is exactly equal to the expected cost of a vacant job, *i.e.* the per unit time search cost,  $s$ , weighted by the rate at which a fish unit is found,  $q(\theta)$ . Now, also setting  $\Pi_E = 0$  in (4) leads to  $\Pi_F =$

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<sup>8</sup>As 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 neglectable in comparison with what they can accomplish in the way of locating fish (see also Mangel and Plant, 1985, on this particular point).

<sup>9</sup>Here, the vessels owned by firms may be interpreted as assets. In financial economics, Eq. (3)-(4) are called "Capital Asset Pricing Market" (CAPM) equations. In a more general context, Scott (1955) already suggested to treat stocks of natural resources as assets as well.

$\pi$ . Replacing  $\Pi_F$  by  $\pi$  in (3), always with  $\Pi_E = 0$ , dividing all terms by  $q(\theta)$  and rearranging implicitly leads to:  $\pi - s/q(\theta) = 0$ . In equilibrium, firms' instantaneous profit yielded by the production of one fish unit,  $\pi$ , net of average search cost,  $s/q(\theta)$ , equals zero. Lastly, isolating  $q(\theta)$  gives implicitly the equilibrium value of anthropic pressure:

$$q(\theta) = \frac{s}{\pi} \quad (5)$$

Since  $q'(\theta) < 0$ , Eq. (5) is the second key equation of the model. It indicates that equilibrium anthropic pressure increases with firms' profit,  $\pi$ , and decreases with the search cost,  $s$ . Since it is derived from fishing firms' economic decisions, it constitutes the driving force of the model.

### 3.2 Global outcome

The model includes three unknowns,  $\theta$ ,  $u$ , and  $e$  and the fishery equilibrium is defined around three equations. Eq. (5) gives implicitly the equilibrium value of  $\theta$ . Though being set at the individual level,  $\theta$  is a global variable and states therefore a bridge between the firms' microeconomic decisions and the global situation of the fishery. For a given  $\theta$ , the uncaught fish rate,  $u$ , is found with help of Eq. (2). Finally, the equilibrium rate of firms with an empty vessel,  $e$ , follows from the definition of  $\theta$ , that implies:  $e = \theta u$ .

Deriving from the above results and the properties of  $q(\theta)$ , the sign of the changes in the exogenous parameters on  $\theta_{OA}$ ,  $u_{OA}$ , and  $e_{OA}$  are summarized in Table 1:

Table 1: Sensitivity analysis of stationnary equilibrium

	$s$	$q$	$b$
$\theta_{OA}$	-	+	0
$u_{OA}$	+	-	+
$e_{OA}$	-	0	+

The equilibrium of the fishery can be represented by the intersection of two curves, the Species Conservation curve (SC) and the Firms' Entry curve (FE), respectively given by Eq. (2) and (5), and the definition of  $\theta$ . The overall situation is depicted in Figure 1. As can be seen, the (SC) curve is decreasing and convex in the  $(u, e)$  space. As the empty vessel rate falls along the (SC) curve, the global harvest level decreases, which mechanically translates into a rise in the uncaught fish rate. In other words, the simultaneous fall in  $e$  and rise  $u$  make anthropic pressure, and thus the probability for a fish to be caught by an empty vessel,  $\theta q(\theta)$ , decrease. Eq.

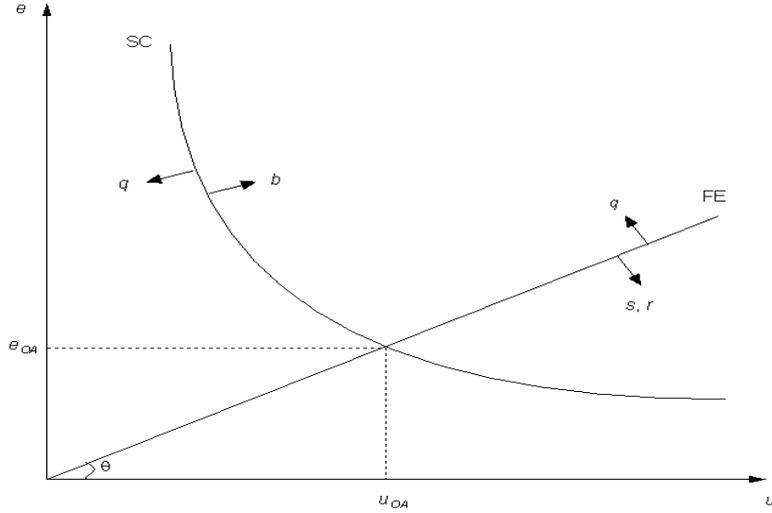


Figure 1: Fish search and equilibrium conservation

(2) then indicates that for the uncaught fish rate to remain constant at the stationary state, the number of empty vessels engaged into search must decrease. Conversely, a higher empty vessel rate corresponds to a lower uncaught fish rate. As far as the (FE) curve is concerned, Eq. (5) clearly indicates that it is linear in  $u$ , going through the origin in the  $(u, e)$  locus, with slope  $\theta$ . An increase in the uncaught fish rate,  $u$ , leads to a fall in anthropic pressure,  $\theta$ , which makes the probability for an empty vessel to capture a fish,  $q(\theta)$ , increase ( $q'(\theta) < 0$ ). This in turn makes the cost incurred by an empty vessel,  $s/q(\theta)$ , decrease, which induces firms to search for fish more intensively, *i.e.* a rise in  $e$ .

An increase in the search cost,  $s$ , lowers expected profit, which logically leads to a fall in the number of empty vessels within the fishery in equilibrium,  $e_{OA}$ , making the (FE) curve rotate clockwise. The move of the (FE) curve along the decreasing (SC) curve leads to a rise in the uncaught fish rate,  $u_{OA}$ . All in all, anthropic pressure increases within the fishery (since  $\theta = e/u$ ). An exogenous increase in the fish's natural growth rate,  $b$ , corresponds obviously to a larger available stock which translates into a higher conservation rate. The rise in  $b$  also allows a higher level of exploitation, since it rises the probability of finding a fish unit and thus expected profit. The resulting changes in  $u_{OA}$  and  $e_{OA}$  are of the same range so that a change in  $b$  has no effect on  $\theta_{OA}$ . An overall improvement of the matching process, illustrated by an exogenous rise in  $q$ , increases other things equal the probability of finding fish, and therefore lowers the average production cost. This translates into

a counterclockwise move of the (FE) curve, and into a rise in the number of vessels searching for fish, which makes the conservation rate fall and results into a rise in anthropic pressure.

The model can be further entirely closed by calculating the equilibrium number of vessels in the fishery. Since by assumption, each vessel can only load a single fish unit, we have:

$$V_{OA} = e_{OA}X + (1 - u_{OA})X \quad (6)$$

Beyond the technical closing of the model, the expression of  $V_{OA}$  is of particular interest since it indicates that it results from two endogenous flows of distinct natures: the flow of empty vessels (first term), which derives from firms' economic decisions, and the flow of harvested fish (second term), which depends on the conservation rate, thus on biological, technological and economic conditions. Furthermore, Eq. (6) will reveal useful for the empirical analysis undertaken in Section 5.

## 4 An example: the French Guiana shrimp fishery

The French Guiana waters entail numerous species and the shrimp constitutes a good example of a species that is exploited for economic purposes. Two shrimp species are mainly exploited in this fishery, the brown shrimp and the pink shrimp (resp. *Farfantepenaeus Subtilis* and *Frafantepenaeus Brasiliensis*). The *Subtilis* represents more than 85% of shrimp landings. The French Guiana shrimp fishery started in the late 60's with the US fleet activity. Since 1992 the whole fleet is only composed with french trawlers targeting shrimp on the continental shelf. One particular interest this fishery presents is that its stock has steadily decreased over years though the effort and harvest levels have followed quite the same trend and some management in compliance with European legislation has been implemented. First a total allowable catch (TAC) of 4108 tons/year was adopted in 1983 and never changed until 2011. Furthermore, a license system was introduced in 1991 to limit the number of vessels. However it did not seem to be, in fact, an efficient resource management tool. Finally there were also some spatial restrictions in order to limit the impact of trawling on juvenile shrimp. Trawling is nowadays forbidden in inshore water less than 30 meters deep. In addition, the profitability has declined in this industry due to growing aquaculture, which results in a lower shrimp price. The economic dynamics of the fishery has been characterized by a diminution of the fleet size, to concentrate the fishing

activities on a reduced number of profitable vessels. All in all, the fleet size is expected to be reduced to about 20 active vessels in year 2016 (Chaboud *et al.*, 2009).

The results obtained to this point enable to highlight some important economic, technological, and biological factors that may influence the conservation of the stock of a given species. The aim of this last section is to illustrate the use of the above search-matching model through the study of the French Guiana shrimp fishery, which might also help to more deeply understand the properties of the model.

## 4.1 Functional forms

In order to close the model explicitly and to be able to calibrate it, we retain the following functional form for the matching function (1):

$$f(u, e) = \omega u^\rho e^{1-\rho} \quad (7)$$

with  $0 < \rho < 1$ , and  $\omega$  the harvest technology parameter. Sanz *et al.* (2013) give some empirical support to the constant-returns to scale hypothesis in the case of the production of shrimp in French Guiana. Following Martinet and Blanchard (2009), we retain the logistic type function proposed by Verhulst (1838) and Pearl (1925) to describe the natural growth rate of the shrimp stock, that we express in stock units:

$$b(X, i, K) = i \left( 1 - \frac{X}{K} \right) \quad (8)$$

where  $i$  represents the maximum relative growth or *intrinsic growth rate*, which is related to the studied species. Parameter  $K$  denotes the carrying capacity, that depends on the characteristics of the natural environment in which the species evolves, 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  $i > 0$  must be verified. Using (1) to isolate  $\theta$  in (5), and assuming that search costs are proportional to production (*i.e.*  $s = sY$ ), one finds<sup>10</sup>:

$$\theta_{OA} = \left( \frac{\omega\pi}{s} \right)^{\frac{1}{\rho}} \quad (9)$$

Eq. (9) gives an explicit expression of equilibrium anthropic pressure in the fishery under open access. Now, inserting (9) into the uncaught fish rate

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<sup>10</sup>Clark and Munro (1975) provide some theoretical foundations to the linear dependence of costs on the harvest level.

equation (2) yields the expression of the equilibrium uncaught fish rate in the fishery under open access:

$$u_{OA} = \frac{i}{\omega^{\frac{1}{\rho}}} \left(1 - \frac{X}{K}\right) \left(\frac{s}{\pi}\right)^{\frac{1-\rho}{\rho}} \quad (10)$$

Lastly, recalling that  $e = \theta u$ , while using (9) and (10), leads to the equilibrium (relative) number of empty vessels within the fishery under open access<sup>11</sup>:

$$e_{OA} = i \left(1 - \frac{X}{K}\right) \frac{\pi}{s} \quad (11)$$

## 4.2 Calibration

Table 2 summarizes the values used for the parameters of the model.

Table 2: Parameters values used in the model

Name	Parameter	Value (French Guiana)
Technological change	$\omega$	1.02
Matching efficiency	$\rho$	0.5
Search cost	$s$	0.55
Intrinsic growth rate	$i$	0.91
Carrying capacity (tons)	$K$	18,5
Stock (tons)	$X$	6,097

In line with the literature on production economics, we assume that the matching function exhibits constant returns-to-scale over its two inputs, *i.e.*  $\rho = 0.5$ . The intrinsic growth rate and the carrying capacity of the habitat are both taken from Martinet and Blanchard (2009). The orders of magnitude for the biomass size are available at the French Guiana office of the Institut Français de Recherche pour l'Exploitation de la Mer (Ifremer). Search cost  $s$  correspond to a mean value of fuel costs and are collected from the French Institut National de la Statistique et des Etudes Economiques (Insee; see Table 3). Lastly, the value of  $\omega$ , about which we do not hold a reliable order of magnitude, is chosen to calibrate the model, *i.e.* in such a way as to obtain conservation rates that are compatible with the data.

<sup>11</sup>In the present example, the equations of the (SC) and (FE) curves can be respectively obtained by replacing  $\theta$  by  $e/u$  and isolating  $e$  in Eq. (2) and (5), which leads to  $e_{SC} = (b/\omega)^{1/(1-\rho)} u^{-\rho/(1-\rho)}$ , and  $e_{FE} = \left(\frac{\omega\pi}{s}\right)^{1/\rho} u$ .

### 4.3 Simulations and results

Table 3 shows the available data that have been collected from the Ifremer and the Insee for the period 2000-2005, and the equilibrium and empirical values of the endogenous variables of the model.

Table 3: Endogenous variables equilibrium and empirical values over the period 2000 and 2005

	2000	2001	2002	2003	2004	2005
$X$ (tons)	6,302	6,809	8,120	9,110	8,778	8,026
Fuel cost ( litres)	182,963	166,897	243,684	239,818	198,966	204,571
Harvest (k€)	326,8	312,4	356,3	365,0	343,0	404,3
Fuel cost per harvested unit	0.56	0.53	0.68	0.66	0.58	0.51
$\theta_{OA}$	3.43	3.31	2.25	2.38	3.09	4
$e_{OA}$	1.11	1.04	0.92	0.83	0.86	0.93
$u_{OA}$	0.32	0.31	0.40	0.34	0.27	0.23
$u = (X - F)/X$	0.59	0.61	0.63	0.61	0.62	0.64
$V_{OA}$	11	12	12	13	14	13
$V$	52	49	45	46	47	36

(Actual variables have no subscript)

Firstly, Table 3 indicates that the stock has increased over the considered period while the harvest has decreased. Secondly, anthropic pressure on the shrimp stock decreases steadily because the rate of conservation (uncaught fish rate),  $u$ , remains almost constant whereas the empty vessel rate falls. Now, comparison between  $u$  and  $u_{OA}$  shows that fishing firms have chosen an insufficient level of anthropic pressure which led to an inflated rate of conservation over the period. This statement is not surprising since the French Guiana shrimp biomass is known to be sufficiently abundant with respect to its exploitation, and quotas have never been reached when they were in force. This suggests that the French Guiana shrimp could be more intensively exploited under the economic viewpoint. As far as the total number of vessels is concerned, direct comparison between  $V$  and  $V_{OA}$  suggests that there were too many vessels in the fishery over the period, some of them being non-profitable. This result could explain the steady decline in the number of vessels evolving within the fishery during the considered period<sup>12</sup>. Lastly, Table 3 shows that fuel costs per harvested unit have decreased from 0.56 to 0.51 between 2000 and 2005, while the shrimp uncaught fish rate has risen from 0.59 to 0.64 over the same period, thus exhibiting an absolute rise of 0.05. Figure 2 draws the evolution of the equilibrium uncaught fish rate with

<sup>12</sup>Several fishing firms have closed over the same period, mainly because of profitability deficiency.

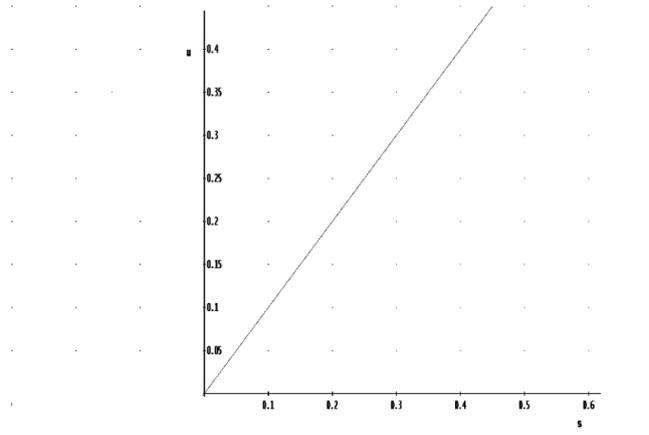


Figure 2: Sensitivity of the shrimp conservation rate with respect to the search cost

respect to the search cost over the studied period. It shows that the model translates the actual fall in the search cost into a decrease in the uncaught fish rate of approximately 0.05 too. The model succeeds quite well in reproducing the evolution of the conservation rate of the French Guiana shrimp on the sole basis of variations in fuel costs. The difference between actual and theoretical values may be due to changes in other components of the cost of effort such as wages, fishing material prices...

## 5 Conclusion

As Bjorndal and Munro (2003) point out, “the economics of fisheries management under uncertainty is currently underdeveloped. Without question, much remains to be done”. The search-matching fishery model proposed in this paper introduces quite directly pure biological features into a stochastic economic framework, while adapting search theory to the specific economic behavior of fishing firms and being based on precise microeconomic foundations. The model therefore exhibits the attractive properties of its original source, making it possible to study the effects of changes in search costs on several variables specific to fisheries. The application of the model to the French Guiana shrimp fishery suggests that catch efficiency, and the costs that are associated with it, play a major role in explaining the evolution of

the conservation of some species. It suggests that changes in search costs *per se* (mainly in fuel consumption) heavily explain the variations in anthropic pressure, fishing effort and the state of shrimp conservation during the period, as well as the evolution of the fishing fleet engaged into the fishery.

Beyond the results obtained here, our framework may be further extended into several directions in order to capture other specific features of the working of fisheries, and seems quite easily tractable for direct empirical analysis. Among the numerous theoretical extensions of the search-matching model that have already been undertaken in the past, some of them, like the endogenization of search effort, could also be considered in our framework to analyze the consequences of the interactions between fishing firms<sup>13</sup>. Additionally, a deeper analysis of the transitional dynamics of the model should also be undertaken in order to improve the explaining power of the latter. Lastly, the integration of bycatch and discard behaviors into the present basic model may also constitute other relevant avenues for future research<sup>14</sup>.

All in all, the use of a search-matching model for the analysis of fisheries seems at first sight at least as natural as its application to *e.g.* labor markets. We thus hope that our framework will help to improve the understanding of the working of fisheries by notably providing a convenient tool suitable for the design of management policies.

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<sup>13</sup>Variable search effort must be related to the question of information sharing (deficiency) among fishermen about the location of productive fishing sites, as in Evans and Weninger (2014).

<sup>14</sup>The present model may be also applied to *e.g.* terrestrial animals hunting.

## Appendix (in continuous time)

### Method 1 (formal method)

The present-discounted values of expected profit from an empty and a filled vessels are respectively given by:

$$\Pi_E = -s\varepsilon \int_0^T e^{-rt} dt + (\pi + \Pi_E) \varepsilon (e^{-rT}) \quad (\text{A1})$$

$$\Pi_F = \pi - s\varepsilon \int_0^T e^{-rt} dt + \Pi_F \varepsilon (e^{-rT}) \quad (\text{A2})$$

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 date at which the vessel finds a fish unit.  $T$  is thus a random variable that follows a Poisson process, whose parameter is given by the rate at which vessels find fish units,  $q(\theta)$ . Still at date  $T$ , the vessel instantaneously yields profit from the catch,  $\pi$ , and the present-discounted of expected profit from an empty vessel,  $\Pi_E$ , to the firm. A filled vessel instantaneously yields profit from the catch,  $\pi$ , becomes empty and search for fish between 0 and  $T$ , where  $T$  is a random variable that follows a Poisson process of the same parameter as above, *i.e.* that is given by the rate at which vessels find fish units,  $q(\theta)$ . At date  $T$ , the empty vessel finds a fish unit and recovers the status of a filled vessel, earning the corresponding present-discounted value of expected profit,  $\Pi_E$ .

Let us start from calculating the integral entailed in Eq. (A1)-(A2), that become:

$$\Pi_E = -s\varepsilon \int_0^T e^{-rt} dt + (\pi + \Pi_E) \varepsilon (e^{-rT}) \quad (\text{A3})$$

$$\Pi_F = \pi - s\varepsilon \int_0^T e^{-rt} dt + \Pi_F \varepsilon (e^{-rT}) \quad (\text{A4})$$

Now, if  $T$  is a random variable that follows a Poisson process of parameter  $q$ , we have:  $\varepsilon (e^{-rT}) = \int_0^\infty q e^{-(r+q)T} dT$ . Thus, Eq. (A3)-(A4) become:

$$\Pi_E = -s \int_0^\infty \left\{ \left[ -\frac{1}{r} e^{-rt} \right]_0^T \right\} q e^{-(r+q)T} dT + (\pi + \Pi_E) \int_0^\infty q e^{-(r+q)T} dT \quad (\text{A5})$$

$$\Pi_F = \pi - s \int_0^\infty \left\{ \left[ -\frac{1}{r} e^{-rt} \right]_0^T \right\} q e^{-(r+q)T} dT + \Pi_F \int_0^\infty q e^{-(r+q)T} dT \quad (\text{A6})$$

After calculating the integrals and simplifying, one obtains:

$$\Pi_E = -s \frac{1}{r+q} + (\pi + \Pi_E) \frac{q}{r+q} \quad (\text{A7})$$

$$\Pi_F = \pi - s \frac{1}{r+q} + \Pi_F \frac{q}{r+q} \quad (\text{A8})$$

Lastly, solving for  $\Pi_E$  and  $\Pi_F$  leads to respectively Eq. (3)-(4).

## Method 2 (intuitive method)

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

$$\begin{aligned} \Pi_E &= \frac{1}{1+rdt} \{-sdt + [1 - q(\theta) dt] \Pi_E + q(\theta) dt \Pi_F\} \\ \Pi_F &= \frac{1}{1+rdt} (\pi + \Pi_E) \end{aligned}$$

At a discount rate  $r$ , an empty vessel costs  $s$  per unit time and go on yielding the expected value of an empty vessel,  $\Pi_E$ , as long as it remains in this state with probability  $1 - q(\theta) dt$ . With the complementary probability  $q(\theta) dt$ , it finds a fish unit, yielding the expected value from a filled vessel,  $\Pi_F$ . Besides, a filled vessel generates instantaneously a profit  $\pi$ . It then becomes also instantaneously empty and yields the expected value associated with the empty vessel state,  $\Pi_E$ . Multiplying all terms by  $(1 + rdt)$  and rearranging terms if  $dt$  tends to zero leads to Eq. (3)-(4) in the text.

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