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# Optimal Selectivity and Effort Cost A Simple Bioeconomic Model with an Application to the Bay of Biscay *Nephrops* Fishery

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*Petit poisson deviendra grand  
Pourvu que Dieu lui prête vie;  
Mais le lâcher en attendant,  
Je tiens pour moi que c'est folie  
Car de le rattraper il n'est pas trop certain [...]  
Le petit Poisson et le Pêcheur, La Fontaine*

**Abstract** *This article investigates the relationship between optimal gear selectivity and effort cost in the fishing industry. We first show that optimal selectivity depends negatively on the level of effort cost, but that this relationship is not continuous. Optimal selectivity switches when real effort cost goes beyond a certain level, and this switch induces a non-marginal reduction in the level of fishing effort. In the second part of this article, we show that the current level of real effort cost in the *Nephrops* fishery of the Bay of Biscay is far below the switch point, which makes high selectivity optimal. The discrepancy between optimal and current selectivity may be explained by the state of the fishery management and also by the fact that selectivity is hardly observable with the type of gear presently used.*

**Key words** Selectivity, effort, technical measure, management tradeoff, *Nephrops* fishery, Bay of Biscay, bio-economic model, social and private benefits and costs, fuel costs.

JEL Classification Codes Q22, Q57, H23.

## Introduction

So-called “technical measures,” aimed at increasing the selectivity of catches in the fishing industry, are an important component of the standard fisheries management toolbox (Suuronen and Sardà 2007). Several social benefits are expected from this increased selectivity (Pascoe and Revill 2004). The most widely acknowledged ones rely on the biological impact of selectivity measures. Selectivity has positive consequences on non-

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commercial species and on the biomass and age-structure of commercial stocks (Beverton and Holt 1957; Kvamme and Frøysa 2004; MacLennan 1995; Salini *et al.* 2000; Stergiou *et al.* 1997; Suuronen and Sardà 2007; VanMarlen 2000; Ward 1994)<sup>1</sup>. Another important social benefit is due to the fact that rights-based systems of fisheries management are easier to implement when fishing is selective; *i.e.*, when unsought joint productions are minimized. Moreover, selectivity may generate some private benefits, such as minimizing time spent by crew sorting catches.

However, selectivity also generates costs that need to be considered when establishing the policy-mix characterizing the management of a fishery. Apart from the possible higher price of selective gears, a major source of costs arises from the use of more selective gears, which often reduce catches of marketable fish per unit of effort (Fonseca *et al.* 2005; Kvamme and Frøysa 2004; Madsen *et al.* 1999; Tschernij, Suuronen, and Jounela 2004; VanMarlen 2000). This feature suggests that net benefits provided by selectivity depend on the level of fishing effort.

In this article, we address this issue with the help of a simple bioeconomic model, which we apply to the case of the French fishery of the Bay of Biscay. The model describes the harvesting of a commercial stock with a poorly selective gear (*e.g.*, trawling). Low selectivity usually results in jointly harvesting individuals belonging to several species, and, for each species, individuals belonging to several size or age classes. In the model, we simplify this feature by assuming that only different age groups of the same species are jointly harvested. Increasing selectivity (*e.g.*, by using larger mesh size) reduces catch per unit of effort (CPUE) for younger age groups, which are also characterized by lower landings prices. The model allows computing the long-run benefits and costs of increasing selectivity for a given level of effort. It also makes it possible to determine the optimal policy-mix between effort and selectivity controls.

In the first part of this article, we describe a simplified version of the model with only two age groups. After presenting the assumptions of the model, we analyze the impact of increasing selectivity on equilibrium catches and landed values for a given level of effort. We then characterize the envelope curve representing landed value as a function of fishing effort, assuming optimal selectivity for each level of effort. Using this envelope enables the definition of the optimal combination of selectivity and effort and to assess the impact of increased fishing costs on this combination.

In the second part of this article, we apply an extended version of the model to a simplified representation of the French *Nephrops* fishery of the Bay of Biscay. We simulate the impact of an increase in fuel cost on the optimal level of fishing effort and optimal selectivity.

Concluding remarks are devoted to a comparison between simulation results, the current state of the fishery, and to the possibility of bridging the gap between private and social net benefits of selectivity.

## Simplified Theoretical Model

In this section, we present a simplified version of the model, assuming the harvest is composed of only two age classes. This simplification is aimed at presenting more clearly the basic mechanisms at work when increasing gear selectivity. The model is run under biological equilibrium conditions; *i.e.*, assuming stabilized fish biomass for each age group in each case. As a result, expressions such as “increasing gear selectivity” are used here only for the sake of brevity; the analysis developed in this section is purely based on comparative static.

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<sup>1</sup> Possible genetic impacts due to selective harvesting of larger individuals have also been investigated (Jennings and Revill 2007; Law 2000). However, these possible long-term effects are not yet fully supported by empirical evidence and will not be considered herein.

### Assumptions

We assume that a single stock composed of two age groups ( $i = 1, 2$ ), is fished by a homogenous fleet making use of a given fishing technique. Time unit is the fishing season, which may be equal to a year, or shorter. Fishing effort ( $E$ ) is held constant over time (*i.e.*, during the whole fishing season and from season to season). For each age group, CPUE is assumed to be proportional to the corresponding fish biomass. As a result, the rate of fishing mortality in each age group ( $F_i$ ) is proportional to fishing effort, and hence is also constant over time:

$$F_i = q_i E \quad (i = 1, 2), \quad (1)$$

where  $q_i \geq 0$  is the catchability coefficient concerning age group  $i$ . The value of this coefficient is conventionally set at 1 for the older group ( $q_2$ ). For the younger group, it is defined as:

$$q_1 = 1 - s \quad (0 \leq s \leq 1), \quad (2)$$

where  $s$  is a parameter characterising the selectivity of the fishing technique. If  $s$  is equal to one, fishing mortality for age group 1 is null, and the fishing technique is said to be fully selective, or, in short terms, selective. If  $s$  is lower than one, joint productions appear: fishing effort generates mortality for both age groups. Cases where  $0 < s < 1$  are described as situations of “imperfect selectivity.” The level of selectivity decreases as  $s$  gets closer to zero. When this parameter reaches zero, the rate of fishing mortality for age group 1 reaches the same level as for age group 2, and the fishing technique is called “non-selective.” For the sake of simplicity, we assume that changes in selectivity do not modify effort costs (*e.g.*, the price and operating cost of a trawl are assumed to be independent of mesh size).

Also for the sake of simplicity, changes in fish biomass owing to recruitment, individual growth, and natural mortality are assumed to occur once a year, at the beginning of the fishing season. Annual recruitment is exogenous.<sup>2</sup> We assume that it is constant and conventionally set the level of yearly recruited biomass at 1. When the stock is not fished, changes in biomass between age groups 1 and 2 are due to individual growth and natural mortality. We use a single positive parameter,  $a$ , to represent the combined impact of these two factors:  $a$  is equal to the biomass of age group 2 at the beginning of the fishing season, assuming age group 1 is not fished. It is larger than 1 if the impact of individual growth overrides the impact of natural mortality, and smaller than 1 in the reverse case.

All catches are supposed to be landed and marketed. Unit-cost of effort ( $c$ ) and ex-vessel unit-prices ( $p_i$ ) for landings of individuals of each age group ( $i = 1, 2$ ) are exogenous, positive, and constant. We assume that:

$$p_2 a > p_1. \quad (3)$$

(Should this condition not be satisfied, non-selective fishing would be optimal in any case.)

<sup>2</sup> The exogenous character of recruitment is a questionable assumption in a model where spawning stock biomass (SSB) is endogenous. However, in many real-world fisheries, no statistically significant relationship between SSB and recruitment may be drawn from available data, which may be explained by the reproductive strategy of a large class of marine commercial (and non-commercial) species. As a result of this strategy, recruitment depends much more on environmental (*e.g.*, hydroclimatic) conditions that prevailed during the prerecruitment stage than on the number of genitors (Chambers 1997; Hilborn and Walters 1992; ICES 2006, 2008). This feature, which fully applies to the stock used as a case study in the second part of this article, makes the simplifying assumption of exogenous recruitment more acceptable.

*Impact of Selectivity on Catches*

Let ( $t = 0$ ) be the beginning of the fishing season and  $X_i(t)$  the biomass of age group  $i$  ( $i = 1, 2$ ) at time  $t$  of the fishing season. Since the only factor of variation of this biomass during the fishing season is fishing mortality, the instantaneous rate of which is held constant, we can write:

$$X_i(t) = X_i(0)e^{-q_i E t} \quad (i = 1, 2). \tag{4}$$

The volume of catches over age group  $i$  during the whole season is given by:

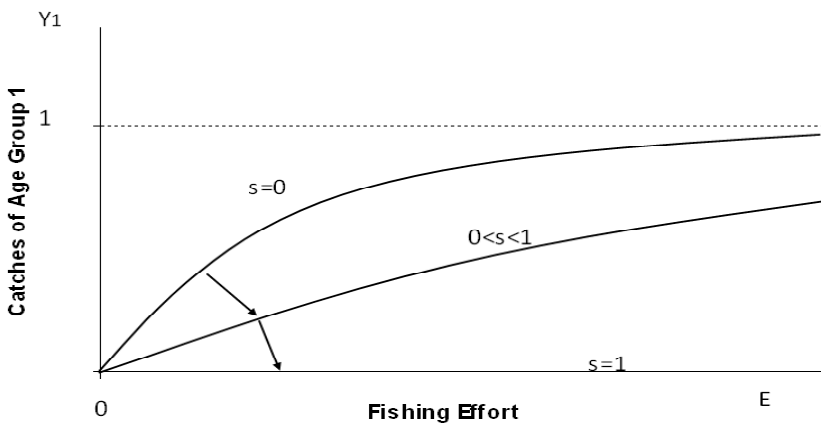
$$Y_i = X_i(0) - X_i(1) = X_i(0)(1 - e^{-q_i E}) \quad (i = 1, 2). \tag{5}$$

Let us now consider this function separately for each age group and assess the impact of a change in the selectivity parameter on the corresponding catches.

For age group 1,  $X_i(0)$  is equal to recruited biomass, conventionally set at 1, and the catchability coefficient is given by relationship (2). Therefore, the above equation becomes:

$$Y_1 = 1 - e^{-(1-s)E}. \tag{6}$$

When fishing is selective ( $s = 1$ ), catches of individuals belonging to age group 1 are null ( $Y_1 = 0$ ). With a selectivity coefficient lower than 1, catches of group 1 are an increasing and concave function of fishing effort, with an asymptotic level equal to recruited biomass as effort increases indefinitely. In this case, an increase in selectivity reduces catches of group 1 for any positive level of effort (figure 1).



**Figure 1.** Catches of Age Group 1 as a Function of Fishing Effort for Different Levels of Selectivity  $s$  (arrows outline increasing selectivity)

For age group 2, the catchability coefficient is conventionally set at 1, and the biomass at the beginning of the fishing season is equal to  $ae^{-(1-s)E}$ . Therefore, equation (5) becomes:

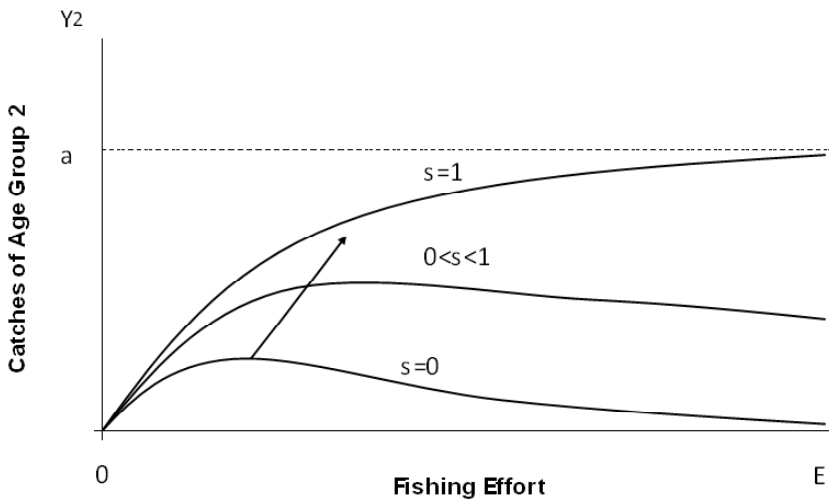
$$Y_2 = ae^{-(1-s)E} (1 - e^{-E}). \tag{7}$$

When fishing is selective, age group 1 is not harvested, and the biomass of age group 2 at the beginning of the fishing season is equal to  $a$ . In this case, catches of age group 2 are a monotonic increasing and concave function of fishing effort, with  $a$  as an asymptote when effort grows indefinitely (figure 2). With a selectivity coefficient lower than 1, the situation is more ambivalent, because an increase in fishing effort (under equilibrium conditions) has two opposite effects on catches of age group 2: a direct positive effect, symbolised by factor  $(1 - e^{-E})$  in relationship (7), and an indirect negative effect, symbolised by factor  $ae^{-(1-s)E}$  in the same equation. The latter is due to the fact that increasing fishing effort with a non-selective or an imperfectly selective gear induces a decrease in the volume of age group 1 biomass at the end of the fishing season and, as a result, in the volume of age group 2 biomass at the beginning of the next season. The direct positive effect is dominant for a low level of fishing effort, but once effort has gone beyond the following threshold:

$$\bar{E} = \ln \frac{2-s}{1-s}, \tag{8}$$

the indirect negative effect becomes dominant, and catches of age group 2 become a decreasing function of fishing effort. These catches tend towards zero as effort increases indefinitely, because this implies that nearly all fish are caught at age 1 (“recruitment fishery”).

The impact of an increase in selectivity on the relationship between effort and catches of age group 2 is depicted in figure 2. For any given level of effort, increased selectivity means increased catches of this group, because it lets a larger number of individuals reach age 2. Moreover, the level of effort corresponding to maximum catches of this age group increases (when  $s$  reaches 1; *i.e.*, when fishing becomes fully selective, this level is infinitely high. As noted before, catches of group 2 are a monotonic increasing function of effort if fishing is selective).



**Figure 2.** Catches of Age Group 2 as a Function of Fishing Effort for Different Levels of Selectivity  $s$  (arrow outlines increasing selectivity)

*Impact of Selectivity on Landed Value*

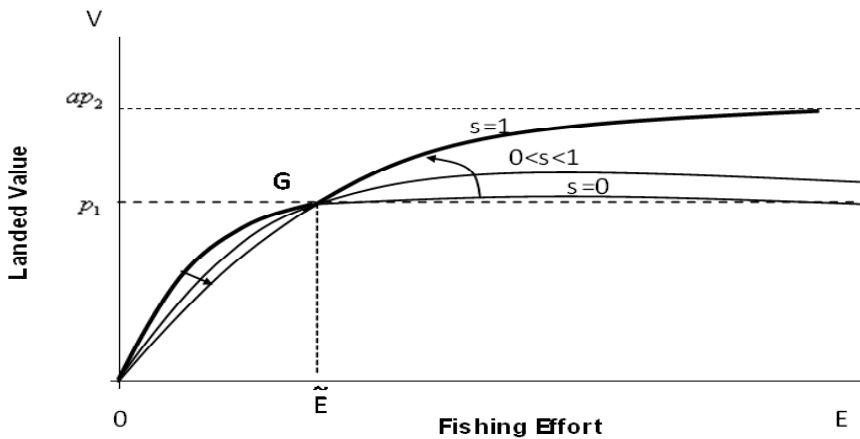
The yearly landed value is defined as:

$$V = p_1Y_1 + p_2Y_2. \tag{9}$$

Combining this relationship with (6) and (7), we get:

$$V = p_1 (1 - e^{-(1-s)E}) + p_2ae^{-(1-s)E} (1 - e^{-E}). \tag{10}$$

For given levels of selectivity and prices, this equation expresses landed value as a function of fishing effort (figure 3).



**Figure 3.** Landed Value as a Function of Fishing Effort for Different Levels of Selectivity (arrows outline increasing selectivity)

In the case of full selectivity ( $s = 1$ ), only individuals of age group 2 are landed, and  $V$  is a monotonic increasing and concave function of  $E$ , tending towards  $p_2a$  as fishing effort increases indefinitely.

If the selectivity coefficient is lower than 1, fishing generates joint productions, and  $V$  becomes a weighted means of catches of age groups 1 and 2. While the former is a monotonic increasing function of fishing effort, we have seen that the latter is an increasing function of effort as long as  $E < \hat{E}$ , and becomes a decreasing function of effort beyond this level, with a zero asymptote as effort grows indefinitely. As a result, provided condition (3) holds, the relationship between  $E$  and  $V$  is not monotonic. For low levels of effort,  $V$  is an increasing function of  $E$ . It is maximum when  $E$  reaches:

$$\hat{E} = \ln \frac{2-s}{1-s} + \ln \frac{p_2a}{p_2a - p_1}, \tag{11}$$

If effort grows beyond that point, landed value starts decreasing. It tends monotonically towards  $p_1$  when effort increases indefinitely, as catches concentrate on age group 1 (recruitment fishery). The maximum value of  $V$ :

$$V(\hat{E}) = p_1 + p_2 a \left(1 - \frac{p_1}{p_2 a}\right)^{2-s} \frac{(1-s)^{1-s}}{(2-s)^{2-s}}, \quad (12)$$

is included between  $p_1$  and  $p_2 a$ , which are the two asymptotic values of  $V$ , respectively, when effort grows indefinitely with imperfect selectivity (or non-selectivity) and full selectivity.

The way selectivity affects landed value varies according to the level of fishing effort. For low levels of effort, the negative impact of poor selectivity on the harvestable biomass of age group 2 is limited, and increasing selectivity merely results in decreased value of landings of age group 1. For higher levels of effort, the negative impact of poor selectivity on the harvestable biomass of age group 2 becomes more severe and may override its positive influence on the landings of age group 1. Consequently, increasing selectivity may result in increasing total landed value. Differentiating (10) with respect to  $s$  shows that landed value is a decreasing function of selectivity for levels of effort that are lower than:

$$\tilde{E} = \ln \frac{p_2 a}{p_2 a - p_1} \quad (13)$$

and becomes an increasing function of selectivity with higher levels of effort. Note that  $\tilde{E}$ , which is the level of effort resulting in  $V = p_1$ , does not depend on  $s$ . In figure 3, the curve representing  $V(E)$  rotates counter clockwise around the point of coordinates  $(\tilde{E}, p_1)$  as  $s$  is progressively increased from 0 to 1; *i.e.*, as fishing technique evolves from non selectivity to full selectivity. During this evolution, the level of effort  $\hat{E}$  maximising  $V$  increases, and so does the corresponding maximum value. When  $s$  tends towards 1,  $\hat{E}$  tends towards infinite, and  $V(\hat{E})$  tends towards  $p_2 a$ .

According to the level of effort in the fishery, selectivity and effort may be regarded as complementary or substitutive factors. For effort levels under  $\tilde{E}$ , increasing selectivity reduces the value of landings *ceteris paribus*, but this effect may be offset by a simultaneous increase in effort; effort and selectivity may be considered as complementary. When effort is between  $\tilde{E}$  and  $\hat{E}$ , landed value is an increasing function of both selectivity and effort, which may then be regarded as substitutes (an increase in one of these factors may be used to balance the consequences of a decrease in the other). If effort goes beyond  $\tilde{E}$ , effort and selectivity become complementary once again. Increasing effort reduces landed value, *ceteris paribus*, but increasing selectivity has the opposite effect, and may be used to offset the negative effect of a higher level of effort.

### Landed Value Envelope Curve

We now describe the envelope curve representing landed value as a function of fishing effort, assuming the level of selectivity is optimal for each level of effort. Let us name  $V_s(E)$  the relationship between fishing effort and landed value for a given level of selectivity  $s$ . For a given level of effort  $E$ , in a situation where no specific cost is attached to selectivity, the best level of selectivity  $s^*(E)$  is the one that maximises landed value. As a result, the envelope curve  $V^*(E)$  is defined as:



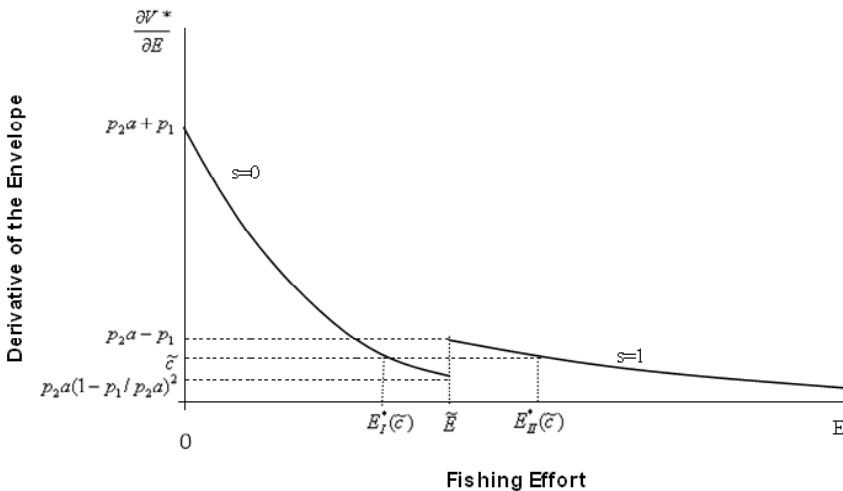
$$V^*(E) = \max_s V_s(E) \quad \forall E; \tag{14}$$

*i.e.*, the relationship between effort and landed value, assuming that for each level of effort the selectivity that maximises landed value is adopted (this envelope is represented by the thick line in figure 3).

As noted before, the sign of the partial derivative  $\partial V/\partial s$  depends on the value of  $E$ . If  $E$  is lower than  $\bar{E}$ , this derivative is negative, which implies that non-selectivity is optimal ( $s^* = 0$ ). When fishing effort is equal to  $\bar{E}$ ,  $\partial V/\partial s$  is null. It becomes positive for values of  $E$  higher than  $\bar{E}$ , which makes full selectivity optimal ( $s^* = 1$ ). Effort  $\bar{E}$  is therefore the switch point where optimal technique changes from non-selectivity to full selectivity. In this model, imperfect selectivity is never optimal, except possibly at the switch point  $\bar{E}$ , where  $s^*$  is undetermined (when  $E = \bar{E}$ , landed value is independent of the level of  $s$ ). Combining these results with (10), we get the following expression for the equation of the envelope curve:

$$V^*(E) = \begin{cases} V_{s=0}(E) = (p_1 + p_2 a e^{-(1-s)E})(1 - e^{-E}) & \text{for } E \leq \bar{E} \\ V_{s=1}(E) = p_2 a (1 - e^{-E}) & \text{for } E \geq \bar{E} \end{cases} \tag{15}$$

The envelope curve is continuous and strictly increasing. When effort grows indefinitely,  $V^*(E)$  tends asymptotically towards  $p_2 a$ . It is differentiable at any point and strictly concave in the neighbourhood of any point, except  $\bar{E}$ . The point of envelope  $V^*(E)$  where  $E = \bar{E}$  is a sharp point (point  $G$  in figure 3), where the left-side derivative of  $V^*$  with respect to  $E$  is lower than the right-side derivative (figure 4).



**Figure 4.** Derivative of the Envelope  $V^*(E)$

Optimal Combination of Effort and Selectivity

The optimal combination of effort and selectivity in the fishery is the vector  $(E^*, s^*)$  that maximises the fishery rent under biological equilibrium conditions:

$$\pi(s, E) = V(s, E) - cE. \tag{16}$$

With the help of the envelope  $V^*(E)$ , this two-variable optimisation problem may be reduced to the following one-variable problem:

Determine  $E \geq 0$   
 such that:  $[V^*(E) - cE] \rightarrow \max.$

If effort  $E^*$  is optimal, it satisfies the first order condition:

$$\frac{\partial V^*}{\partial E} = c. \tag{17}$$

According to this condition, optimal combination of effort and selectivity makes the marginal value of effort on the envelope curve equal to the unit cost of effort. However, due to the shape of the curve representing the relationship between  $\partial V^*/\partial E$  and  $E$ , two local optima, both satisfying condition (17), may occur (see figure 4). This will happen if the unit-cost of effort belongs to the interval:

$$p_2 a \left( 1 - \frac{p_1}{p_2 a} \right)^2 < c < p_2 a - p_1, \tag{18}$$

the lower and upper bounds of which are equal to the values of  $\partial V^*/\partial E$  for  $E = \tilde{E}$ , with the non-selective technique ( $s = 0$ ), and with the selective technique ( $s = 1$ ), respectively.

If unit effort cost  $c$  belongs to the interval defined by (18), the overall optimum may be obtained by comparing rent levels for the two local optima. To this end, let us call “scenario I” the use of a non-selective fishing gear ( $s = 0$ ), and “scenario II” the use of fully selective gear ( $s = 1$ ). For each scenario, there is an optimal fishing effort  $(E_I^*, E_{II}^*)$ , resulting in a maximum level of rent  $(\pi_I^*, \pi_{II}^*)$ . It may be shown that the optimal rent difference between the non-selective scenario and the selective scenario  $(\pi_I^* - \pi_{II}^*)$  is a continuously increasing function  $f$  of unit effort cost  $c$  (see Appendix). In other words, a high cost of effort favours the non-selective technique with respect to the selective technique. More specifically, as  $f(c)$  is negative for the lower boundary of interval (18) and positive for the upper boundary of the same interval, there is an intermediate value,  $\tilde{c}$ , between these two boundaries, such that  $f(\tilde{c}) = 0$ , with  $f(c)$  negative for  $c$  smaller than  $\tilde{c}$ , and  $f(c)$  positive for  $c$  larger than  $\tilde{c}$  (figure 5). This result implies that scenario II (selectivity) is more profitable as long as effort cost,  $c$ , is smaller than  $\tilde{c}$ , while scenario I (non-selectivity) becomes more profitable once  $c$  has gone beyond  $\tilde{c}$ . As a result,  $\tilde{c}$  is the switch point, in terms of effort cost, between the two techniques.

To illustrate the impact of effort cost on selectivity, let us first suppose that  $c < \tilde{c}$ , (figure 4). If the fishery is optimally managed, the technique in use is the selective one (scenario II, with  $s^* = 1$ ). A rise in  $c$ , due to an increase in fuel price (for example), will gradually reduce the optimal volume of effort  $E^*$ , but will not alter the fishing technique

as long as the unit cost of fishing effort has not reached the switch point,  $\tilde{c}$ . Once this point is reached, the optimal technique shifts from selectivity to non-selectivity (scenario I, with  $s^* = 0$ ). This change of scenario at point  $\tilde{c}$  entails a non-marginal reduction of fishing effort, which is visualised in figure 4 by a “jump” from  $E_I^*(\tilde{c})$  to  $E_I^*(\tilde{c})$ . A further increase in  $c$  would result anew in a gradual decrease in optimal effort, keeping the non-selective technique in use (as long as  $c < p_1 + p_2a$ , which is the maximum level of effort cost consistent with a profitable activity; if  $c$  goes beyond this point, the optimal alternative is to stop fishing).

This very simple model suggests that rising fishing costs are likely to discourage the use of selective fishing gears. However, even within the oversimplified framework of the model, it is clear that several factors may offset this tendency. One of them is a change in the structure of ex-vessel prices. It can be seen from the Appendix that a decrease in  $p_1$  relative to  $p_2$  will move the curve representing  $f(c)$  downward, which, in turn, raises point  $\tilde{c}$  where  $f(c) = 0$ . As a consequence, the range of costs where selective fishing is optimal widens.

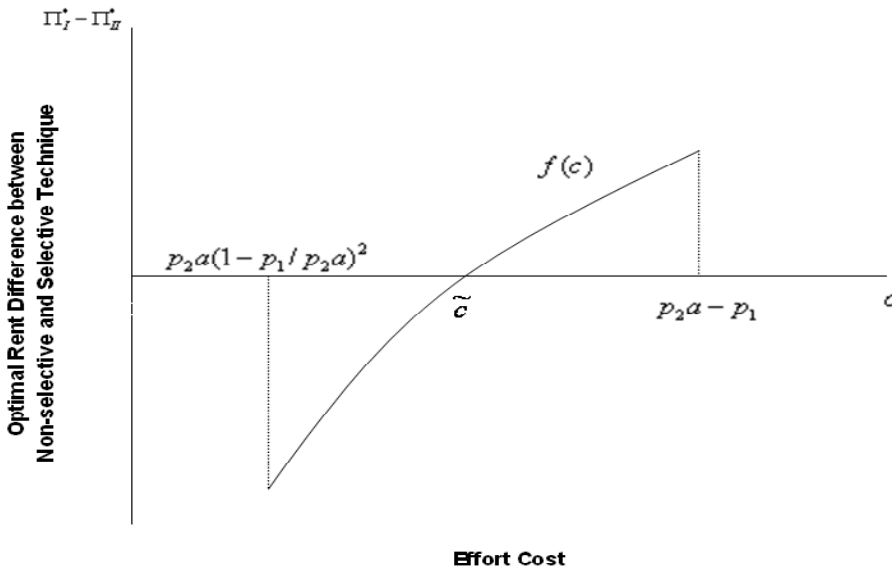


Figure 5. Optimal Rent Difference Between the Non-selective and Selective Technique as a Function of Effort Cost

### Application to the *Nephrops* Trawl Fishery of the Bay of Biscay

In this section, we apply our model to a simplified representation of the French Norway lobster (*Nephrops norvegicus*) trawl fishery of the Bay of Biscay (ICES VIIIa,b) (figure 6). To this end, we extend the theoretical version that was presented in the former section. After a short presentation of the case study, we describe the applied version of our model and the scenarios that are run with its help. Finally, we present the simulation results.

#### Case Study

The *Nephrops* fishery is one of the most important fisheries of the Bay of Biscay. In 2003, its turnover amounted to 33.2 million euros. The fleet is composed of some 250 trawlers

(mainly twin-trawlers) most of them French<sup>3</sup> and represents approximately 25% of the total number of trawlers operating in the area. In 2003, the average length of these boats was 15 meters, with an engine power of 235 kW, an average age of 19 years, and a yearly average of 200 days at sea (IFREMER 2005). A decrease in the number of vessels targeting *Nephrops* in the Bay of Biscay has been observed during the last decades, but it has been largely offset by increased fishing efficiency (Marchal *et al.* 2007).

The management of the fishery mainly relies on conservation measures: a total allowable catch (TAC) revised each year, a minimum landing size (MLS, 9 cm corresponding to *Nephrops* younger than age group 3), and a minimum trawl mesh size (70 mm). In regards to access regulations, a limited entry license system has been enforced since 2005. However, it does not include individual limitations of effort or catches.

The fishery is characterized by high levels of bycatch and discards (ICES 2006). Discards of *Nephrops* affect mainly small individuals. Respectively 96, 75, and 28% of the *Nephrops* catches of age groups 1, 2, and 3 (in weight) are discarded, with a minimum 70% rate of mortality (Guéguen and Charreau 1975). Since 2000, fishers have developed a program intended to improve selectivity, with technical assistance from IFREMER. Several selective devices have been tested: square mesh panel to enable hake escapement, *Nephrops* grid, and mesh size increase. In 2005, the use of a square mesh panel became compulsory.



**Figure 6.** Nephrops Fishery in ICES Divisions VIIIa,b

<sup>3</sup> The French quota represents 94% of the annual TAC set by the EU.

*Applied Model*

Compared to the theoretical model presented in the first part of this article, the applied model we use to analyse the case study provides a more realistic description of the fishery. An extended bio-economic model of the Bay of Biscay *Nephrops* fishery is described in (Macher *et al.* 2008). Several groups of vessels are considered to differentiate between two fishing strategies (a Northern fleet, targeting *Nephrops* most of the year, and a Southern fleet, targeting *Nephrops* occasionally) and various cost structures linked to vessel length categories. The age-structured biological component describes the dynamics of the nine *Nephrops* age group. Discards are taken into account. For the sake of the present application, a simplified version of this model is considered. The main simplifications are that the *Nephrops* fleet is described as a whole and that age-groups are aggregated into two main categories—"small *Nephrops*," which correspond to age groups 1 to 4 and "large *Nephrops*," which correspond to age groups 5 to 9—to be better linked to the model described in the former part of the article. The model is comprised of three components: biological, technical, and economic. Inputs are detailed in table 1.

**Table 1**  
Parameters of the Applied Model

Indices	
Small <i>Nephrops</i> Age Groups 1 to 4	1
Larger <i>Nephrops</i> Age Groups 5 to 9 <sup>+</sup>	2
Stock Parameters	
Recruitment	354,041
a	0.7111
Mean weight (kg/individuals)	
w1	0.0139
w2	0.0432
Catches (tonnes)	
Y1	4,056
Y2	1,719
Discard Rate (% in weight)	
D1	37
D2	3
Catchability	
q1	3.6221E-05
q2	5.0167E-05
Price Parameters Euros/kg	
p1	7.4
p2	13.2
Fleet Parameters	
Nb of vessels	237
Mean Nb of days at sea per vessel	204
<i>Nephrops</i> gross revenue (millions euros)	41
Total gross revenue (GR) (millions euros)	85
Landing costs (% of total GR)	5
Fuel costs (euros/days at sea)	225
Food costs (euros/days at sea)	31
Ice costs (euros/days at sea)	9

The biological component describes the *Nephrops* stock dynamics. Annual recruitment is assumed to be constant as is mean weight per category.<sup>4</sup> Stock, catches, discards, and catchability parameters were derived from the *Nephrops* fishery model results at equilibrium using 2004 stock assessment (ICES 2004).

The main features of the technical component may be described as follows. For each category, CPUE is assumed to be proportional to biomass, and catchability is held constant over time. Selectivity scenarios are assumed to modify catchability as described in the theoretical section. On the basis of fishing mortality, the model calculates catches, landings, and discards per category.<sup>5</sup>

In regards to the economic component of the model, the IFREMER fisheries information system provided cost data for the *Nephrops* fleet (IFREMER 2005). Variable costs (fuel, ice, food, etc.) are assumed to be proportional to fishing effort.

*Nephrops* ex-vessel prices come from auction markets statistics. Annual mean prices are assumed to be exogenous and constant.<sup>6</sup> Small *Nephrops* obtain a mean ex-vessel price of 7.2 euros/kg, and “large *Nephrops*” obtain a higher price (13.2 euros/kg).

*Nephrops* gross return is calculated from landings and prices. Revenues provided by species other than *Nephrops* are assumed to be constant. Net gross return is equal to total gross return minus landing taxes.

According to the so-called “share system,” enforced in French small-scale fisheries, the net return to be shared is obtained by subtracting so-called “shared costs” from boat net turnover (shared costs are those variable costs that may be isolated on a trip basis, such as fuel or ice).<sup>7</sup>

## Scenarios

The applied model is a simulation model, with exogenous levels of selectivity and effort. The model is fit for explicit optimization and also enables us to test a variety of selectivity scenarios and to run simulations for each of them that cover a range of effort levels.

Two scenarios have been designed. Both assume equilibrium conditions (comparative static). The first scenario, denoted  $S_I$ , assumes current selectivity. The second scenario, denoted  $S_{II}$ , assumes a higher selectivity such that the catchability for age group 4 and younger age groups is null, while catchability for elder age groups remains unchanged (*i.e.*, at the same level as in  $S_I$ ). This scenario implies that only individuals belonging to the “large *Nephrops*” commercial grade are caught.

As in the theoretical model, we assume that the only cost of greater selectivity is the decrease in catches of smaller individuals.

We first analyse the potential impact of each scenario on the equilibrium gross revenue for various levels of effort. We then test the impact of a range of hypothetical increases in effort cost on the relative profitability of these two scenarios in terms of return to be shared.

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<sup>4</sup> The assumption of constant mean weight per age group disregards the potential impact of selectivity on growth parameters (Schirripa and Trexler 2000).

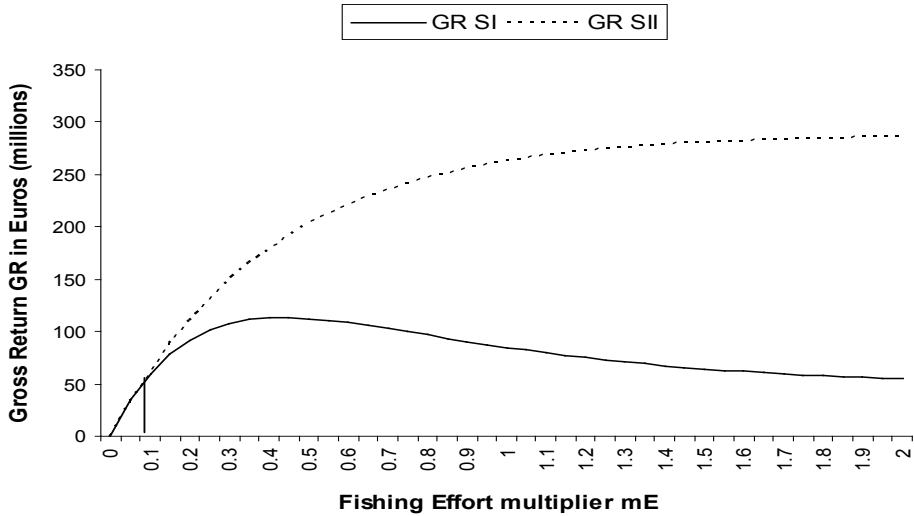
<sup>5</sup> Some discards are motivated by legal considerations (when individuals under the minimum landing size are caught, they are required to be discarded). Technical and economic reasons also motivate discards, as sorting catches on the deck is a time-consuming and uncomfortable operation, which results in discarding some of the less valuable individuals.

<sup>6</sup> The exogenous character of landing prices is justified by the fact that the fishery under survey provides only a minor part of the supply on the market for the considered species.

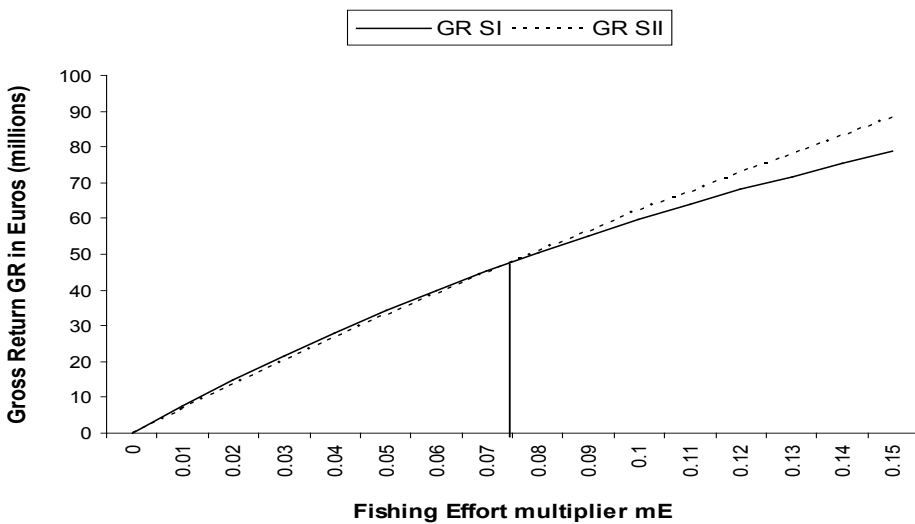
<sup>7</sup> The net return to be shared is split into two parts, determined by a pre-established key, to obtain the crew and owner shares.

Simulations Results

Figure 7 (a,b) summarizes aggregated simulation results, assuming the current level of unit effort cost. Aggregated effort is normalized so that ( $mE = 1$ ) corresponds to the mean level that was observed over 2001–2003 (“actual effort”).



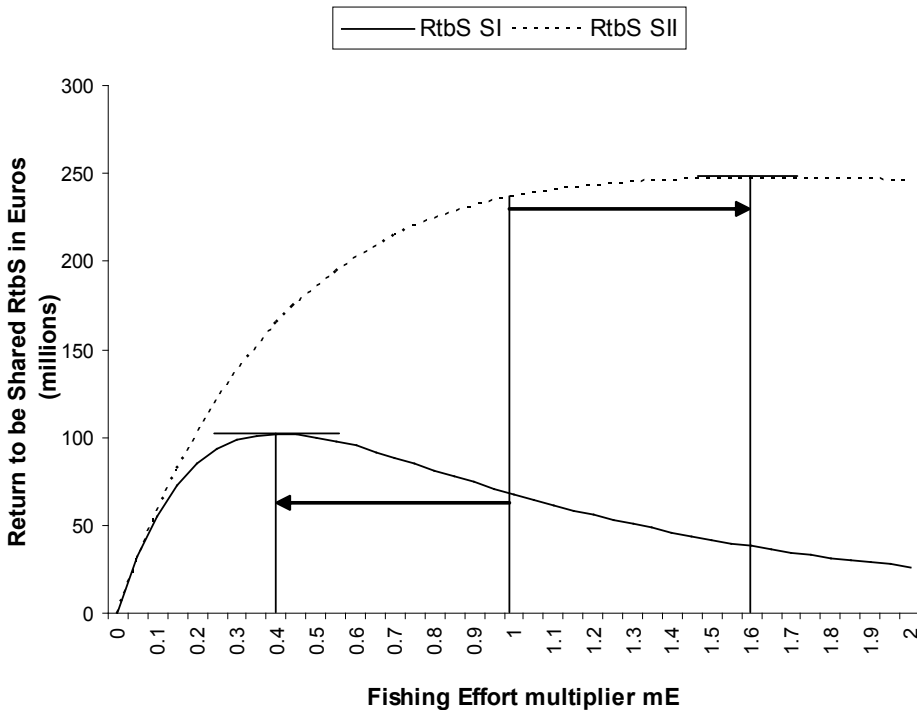
**Figure 7a.** Equilibrium Gross Revenue (GR) as a Function of Selectivity (SI non selective scenario, SII: selective scenario) and Fishing Effort (expressed as a multiplication factor of the effort) for Actual Prices and Costs



**Figure 7b.** Focus on the Switch Point Effort Area of the Equilibrium Gross Revenue (GR) as a Function of Selectivity (SI: non selective scenario, SII: selective scenario) and Fishing Effort for Actual Prices and Costs

According to our simulations, under the current level of effort ( $mE=1$ ), scenario  $S_{II}$  is optimal. For effort levels below the switch point ( $\bar{E}$ ) depicted in the first section, scenario  $S_I$  becomes the most profitable, while for any permanent level of effort beyond that point, scenario  $S_{II}$  (where only individuals belonging to the higher commercial grade are caught) is the most profitable (Figure 7a,b). The effort corresponding to the switch point ( $E$ ) is approximately 7% of the present level. Analyses of the fishery return to be shared (RtbS) provided in figure 8 show that under scenario  $S_I$ , the actual level of effort is too high, assuming unchanged selectivity, a reduction in fishing effort by 40% could raise the RtbS by 50%. Under scenario  $S_{II}$ , RtbS is maximised with an effort 60% higher than the current one, and the simulations suggest that it could be 5% higher than it is now. Improving selectivity could be profitable to the fishery without requiring a reduction in fishing effort.

In order to check the impact of effort cost on optimal selectivity, a range of increase in fuel price was simulated (table 2). In this simulation, scenarios  $S_I$  and  $S_{II}$  were run assuming a fuel price multiplier of the average 2001-2003 price level. An increase would naturally impact fishery rent negatively for all levels of effort scenarios. The results show that  $S_I$  becomes optimal only for very high fuel price increases. Assuming best selectivity, increasing fuel cost tends to reduce the optimal effort level. However, possible fuel cost increases would lead to optimal effort levels still significantly beyond the switch point, and, as a result, the best selectivity scenario would still be  $S_{II}$ . Associating the rise in fuel price with a change in the relative price of large and small *Nephrops* could change this situation. As demonstrated in the appendix, such a change modifies the level of unit effort cost that induces a shift in optimal selectivity.



**Figure 8.** Equilibrium Fishery Total Return to be Shared (RtbS) as a Function of Selectivity and Fishing Effort for Actual Prices and Costs



**Table 2**  
Impact of a Range of Increase in Fuel Cost on the Optimal Level  
of Fishing Effort and Optimal Selectivity

Fuel Cost Multiplier	mE*	Smax	RtbS max
1	1.628	SII	247
5	1.017	SII	193
10	0.738	SII	146
15	0.573	SII	111
20	0.456	SII	83
25	0.364	SII	61
30	0.290	SII	43
35	0.226	SII	29
40	0.172	SII	18
45	0.123	SII	10
50	0.054	SI	5
55	0.038	SI	3
60	0.023	SI	1

## Conclusion

The simple theoretical model presented in the first part of this article highlights the fact that optimal selectivity depends on fishing effort and, therefore, on prices and costs. One of the conclusions that can be drawn from the model is that, assuming an optimally managed fishery, higher fishing effort costs favour lower selectivity. However, this process is not continuous. As long as unit cost of effort is kept below a critical level, the hierarchy of techniques remains unaltered. It reverses beyond this level, which acts as a switch point. This technical switch goes with a non-marginal reduction in the level of optimal effort.

The second part of the article presented an empirical application of the model to the *Nephrops* fishery of the Bay of Biscay. According to the simulations that were run, the current state of the fishery is far from optimal in terms of effort, as well as selectivity. Keeping selectivity unchanged, rent could be increased by significantly decreasing effort, but the increase in rent could be even higher if selectivity was increased, and this would not necessarily require a decrease in global effort.

With respect to present conditions, simulations also suggest that reaching the technical switch point would require a very high increase in effort costs. At first sight, this result may be regarded as a paradox when considering the current state of the fishery, since the current technique appears to be the least profitable one, even with provision for significantly increasing fuel costs. The explanation is twofold. First, the fishery is not optimally managed in terms of effort. Second, costs and benefits of selectivity do not belong to the same category. While the former are purely private, the latter are mainly social; *i.e.*, operate at the scale of the fishery, not at the scale of the individual fisher. It is true that this discrepancy is not specific to selectivity; being rooted in the common-pool nature of the fish stocks, it also concerns fishing effort. However, it is likely to be more acute with selectivity than with effort for two reasons; while decreasing effort normally reduces social costs, it also reduces private costs, although to a lesser degree.

Contrasting with this situation, the benefits of increasing selectivity are in most cases purely social; the probability that an individual fisher catches a large fish which he refrained from catching when it was small is close to zero. This problem is often worsened by the fact that under many circumstances current selectivity is non-observable. It makes it relatively easy to circumvent apparent improvements in selectivity (*e.g.*, grids, change in mesh size or shape).

This factor may powerfully boost temptations for individual fishers to act as free riders, making non-selective use of apparently selective techniques. A solution to this problem might be a drastic change in the type of gear; e.g., a shift from trawl to pot in the case of the *Nephrops* fishery. The private costs of such a change, which might seriously decrease in the context of a long-term increase in fuel price, should be balanced by a thorough consideration of its social benefits, which are obviously broader than the ones considered in this article.

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## Appendix

### Optimal Profitability Gap between Non-selective and Selective Fishing as a Function of Unit Effort Cost

Let  $\pi_I$  and  $\pi_{II}$  be the fishery rents when fishers use the non-selective technique and the selective technique, respectively. Combining (10) and (16) alternatively for ( $s = 0$ ) and ( $s = 1$ ), we get:

$$\pi_I = (p_1 + p_2 a e^{-E})(1 - e^{-E}) - cE \quad (1a)$$

$$\pi_{II} = p_2 a (1 - e^{-E}) - cE. \quad (2a)$$

Maximising the rent for  $E$  in each scenario gives:

$$\left. \begin{aligned} \pi_I^* = \frac{p_2 a}{8} \left[ \left( \frac{p_1}{p_2 a} \right)^2 + 6 \frac{p_1}{p_2 a} + 1 + \sqrt{\Delta} \left( 1 - \frac{p_1}{p_2 a} \right) \right] - c \left[ \frac{1}{2} + \ln \frac{4}{1 - \frac{p_1}{p_2 a} + \sqrt{\Delta}} \right] \\ \text{with } \Delta = \left( 1 - \frac{p_1}{p_2 a} \right)^2 + 8 \frac{c}{p_2 a} \end{aligned} \right\} \quad (3a)$$

$$\pi_{II}^* = p_2 a - c \left( 1 + \ln \frac{p_2 a}{c} \right). \quad (4a)$$

Let us now express the difference between these two optimal rents as a function of unit effort cost:

$$\pi_I^* - \pi_{II}^* = f(c). \tag{5a}$$

This function is defined, continuous, and differentiable over the whole interval delimited by (18). Combining (3a), (4a), and (5a) we get:

$$f'(c) = \ln \frac{p_2 a}{c} - \ln \frac{4}{1 - \frac{p_1}{p_2 a} + \sqrt{\Delta}}. \tag{6a}$$

As this derivative is strictly positive,  $(\pi_I^* - \pi_{II}^*)$  is an increasing function of  $c$ . Moreover, when  $c$  is equal to the lower boundary of interval (18), this function has the following value:

$$\pi_I^* - \pi_{II}^* = -\frac{(p_2 a - p_1)^2}{p_2 a} \left( \frac{p_1}{p_2 a - p_1} - \ln \frac{p_1}{p_2 a - p_1} \right), \tag{7a}$$

which is strictly negative. Symmetrically, when  $c$  is equal to the upper boundary of interval (18), the same function has the following value:

$$\left. \begin{aligned} \pi_I^* - \pi_{II}^* &= (p_2 a - p_1) \left[ \frac{1}{2} \left( k + \frac{p_1}{p_2 a} \right) + \ln \left( 1 + \frac{k/4}{1 - p_1/p_2 a} \right) \right] \\ \text{with } k &= \sqrt{\Delta} - 3(1 - p_1/p_2 a) \end{aligned} \right\} \tag{8a}$$

which is strictly positive. As a result, there is one and only one value  $\tilde{c}$  inside interval (18) such that  $f(\tilde{c}) = 0$  (see figure 5). For any  $c$  lower than  $\tilde{c}$ ,  $f(c)$  is negative, which means than selective fishing is more profitable than non-selective fishing. If  $c$  becomes higher than  $\tilde{c}$ ,  $f(c)$  is positive, which means than non-selective fishing is more profitable than selective fishing.

The position of the curve representing  $f(c)$  on figure 5 depends on various parameters, including ex-vessel prices of each age group ( $p_1, p_2$ ). The easiest way to analyse the influence of the relative price of landings of these two groups on the relative profitability of the two fishing techniques is to consider the impact of a change in  $p_1$  on  $f(c)$ , *ceteris paribus*. The partial derivative of  $(\pi_I^* - \pi_{II}^*)$  with respect to  $p_1$  is:

$$\frac{\partial (\pi_I^* - \pi_{II}^*)}{\partial p_1} = \frac{1}{4} \left( \frac{p_1}{p_2 a} + 3 - \sqrt{\Delta} \right). \tag{9a}$$

This expression is strictly positive, which implies that a rise in  $p_1$  will increase  $f(c)$  for any value of  $c$  belonging to interval (18). As a result, the curve representing  $f(c)$  in figure 5 will move upward, and point  $\tilde{c}$  where this curve crosses the horizontal axis ( $f(c) =$

0) will move to the left. An increase in  $p_1$ , *ceteris paribus*, narrows the range of effort cost where the selective technique is more profitable than the non-selective one. The opposite result is obtained in the case of a decrease in  $p_1$ .