

## Effort dynamics in a fisheries bioeconomic model: A vessel level approach through Game Theory

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**SUMMARY:** Red shrimp, *Aristeus antennatus* (Risso, 1816) is one of the most important resources for the bottom-trawl fleets in the northwestern Mediterranean, in terms of both landings and economic value. A simple bioeconomic model introducing Game Theory for the prediction of effort dynamics at vessel level is proposed. The game is performed by the twelve vessels exploiting red shrimp in Blanes. Within the game, two solutions are performed: non-cooperation and cooperation. The first is proposed as a realistic method for the prediction of individual effort strategies and the second is used to illustrate the potential profitability of the analysed fishery. The effort strategy for each vessel is the number of fishing days per year and their objective is profit maximisation, individual profits for the non-cooperative solution and total profits for the cooperative one. In the present analysis, strategic conflicts arise from the differences between vessels in technical efficiency (catchability coefficient) and economic efficiency (defined here). The ten-year and 1000-iteration stochastic simulations performed for the two effort solutions show that the best strategy from both an economic and a conservationist perspective is homogeneous effort cooperation. However, the results under non-cooperation are more similar to the observed data on effort strategies and landings.

**Keywords:** effort dynamics, game theory, fisheries bioeconomics, simulation models, red shrimp, Northwestern Mediterranean.

**RESUMEN:** DINÁMICA DE ESFUERZO EN UN MODELO BIOECONÓMICO PESQUERO: APROXIMACIÓN A NIVEL DE BARCO A TRAVÉS DE TEORÍA DE JUEGOS. – La gamba rosada, *Aristeus antennatus* (Risso, 1816) es uno de los más importantes recursos para las flotas de arrastre de fondo del Mediterráneo noroccidental, tanto en términos de capturas como de valor económico. Se propone un modelo bioeconómico simple que introduce la Teoría de Juegos para la predicción de dinámicas de esfuerzo pesquero a nivel de barco. El juego se presenta entre doce barcos que explotan la gamba rosada en Blanes. Se presentan dos soluciones dentro del juego: no cooperación y cooperación. La primera se propone como método realista para la predicción de estrategias de esfuerzo pesquero a nivel individual, mientras que la segunda permite ilustrar el potencial de beneficios de la pesquería. La estrategia de esfuerzo pesquero de cada barco es el número de días en el mar durante un año, y se asume que su objetivo es maximizar beneficios, individuales para el caso no cooperativo y totales para el caso cooperativo. En el análisis que se presenta los conflictos estratégicos entre los barcos son resultado de las diferencias en su eficiencia técnica (coeficiente de capturabilidad) y su eficiencia económica (definida en el trabajo). Las proyecciones estocásticas de diez años y 1000 iteraciones para las dos soluciones de esfuerzo demuestran que la mejor estrategia, tanto a nivel económico como conservacionista, es la cooperación. Los resultados bajo la condición de no cooperación se asemejan mejor a la realidad observada en datos de estrategia de esfuerzo y desembarcos.

**Palabras clave:** dinámica de esfuerzo, teoría de juegos, bioeconomía pesquera, modelos de simulación, gamba rosada, Mediterráneo Noroccidental.

### INTRODUCTION

The red shrimp, *Aristeus antennatus* (Risso, 1816), is one of the most important resources for the bottom-trawl fleets in the northwestern

Mediterranean, in terms of both landings and economic value (Demestre and Lleonart, 1993; Demestre and Martin, 1993; Maynou *et al.*, 2006). One of the ports obtaining the highest yields in the area is that of Blanes (Irazola *et al.*, 1996; Bas,

2006). The bottom-trawl fleet of Blanes is composed of twelve vessels that operate near the Blanes submarine canyon from 400 to 800 m depth (Demestre and Lleonart, 1993; Demestre and Martin, 1993; Bas *et al.*, 2003). Recent studies on population dynamics and assessments of Spanish Mediterranean stocks of *A. antennatus* (Carbonell *et al.*, 1999; Carbonell *et al.*, 2003) have shown that this species is slightly overexploited. The data series of red shrimp landings at Blanes port report values around 60 t annually from 1997 to 2004.

Exploitation of renewable resources such as fish stocks shared by a limited number of agents introduces the so-called *stock externality* (Mesterton-Gibbons, 1993; Grønbaek, 2000) and strategic interactions are consequently involved (Hannesson, 1997). Game Theory is a formal tool for analysing the strategic interactions between a finite number of agents sharing an exploited resource (Sumaila, 1997). Strategic interaction in fisheries is interpreted as the way in which the harvest by one agent highly affects the fishing strategy of other agents (Grønbaek, 2000). Game Theoretic models have been applied to different cases in fisheries, such as equilibrium global models with symmetrical agents (Hannesson, 1997), dynamic age-structured models in fleet conflicts (Sumaila, 1997), countries sharing migratory species (Arnason *et al.*, 1999), and suitability of cooperative and non-cooperative behaviours in the management of shared fisheries (Hannesson, 1995).

These previous works on Game Theory applied to fisheries assumed that fleets or countries were the main decision makers (agents or players). However, it is reported that the Mediterranean fisheries have some particularities (see e.g. Lleonart and Maynou, 2003 for a recent review) that make it necessary to conduct the economic analysis at vessel level for the correct assessment and management of the resources (Lleonart and Maynou, 2003; Lleonart *et al.*, 2003). The model proposed here aims to determine the effort strategy adopted by each vessel under two assumptions: i) each vessel strives to maximise its profits for the non-cooperative solution, and ii) vessels maximise overall profits for the cooperative solution. We propose that differences among individual vessels are reflected in their catchability and costs of activity.

The bioeconomic model includes some Mediterranean particularities, such as the economic balance that includes the part for the owner and the

income from secondary species (Lleonart *et al.*, 2003). Secondary species are expressed as a pool of by-catch that adds significant economic revenue to the fleet. Data series from the Blanes Fishers' Association allowed us to estimate the empirical relationship of secondary and target species landings. The annual revenues from secondary species were equivalent to the revenues from red shrimp in the analysed case study. An average price of the secondary species is also estimated.

Non-cooperative and cooperative solutions reflect the fishermen's behaviour in making decisions. For the former, we assumed that each fisherman strives to maximise his profits with an individual effort strategy. It is assumed that there is no agreement between the players and that their behaviour is "self-regarding" (Camerer and Fehr, 2006). For the latter, some agreement between the fishermen is considered. The players agree to maximise the profits from the exploitation subject to some conditions. The agreement in our case is related to the application of the same effort level by each fisherman. In both solutions the profits for each vessel will thus be related to their individual costs of fishing and their catchability coefficient.

Cooperative and non-cooperative behaviours are compared with real target species landings and effort data. This paper therefore has two main objectives: i) to test a non-cooperative game as a realistic approach to Mediterranean fisheries, and ii) to compare the profitability of a Mediterranean fishery under cooperation and non-cooperation. All the analyses were carried out with realistic constraints for the minimum and maximum effort levels.

## MATERIAL AND METHODS

### The model

The description of the model is divided into four parts: The profits, the population dynamics, the dynamics of catchability and the construction of the game.

#### *The profits*

Individual profits are the evaluation function for the non-cooperative solution, while the sum of the individual profits is the evaluation function for the cooperative solution. A simple bioeconomic model

is constructed by balancing the revenues from the sale of the product and the costs, and relying upon the level of the biomass  $B_t$  whose dynamics are described. For each fisherman, the net profits ( $\pi_v$ ) at time  $t$  are:

$$\pi_{v,t} = p \cdot y_{v,t} + ps \cdot y_{s,v,t} - C_{v,t} \quad (1)$$

where  $p$  is the constant price of target species,  $y_{v,t}$  is the catch of the target species per vessel  $v$  at time  $t$ ,  $ps$  is the constant price of secondary species,  $y_{s,v,t}$  is the catch of secondary species and  $C_{v,t}$  is the total cost for each vessel  $v$  at time  $t$ . The catch of target species by vessel  $v$  is given by (Schaefer, 1954):

$$y_{v,t} = q_{v,t} \cdot f_{v,t} \cdot B_t \quad (2)$$

This model describes the catch of target species of a vessel as a function of its catchability coefficient  $q_{v,t}$ , its effort strategy  $f_{v,t}$  at each time and the available biomass of the exploited stock  $B_t$ . The catchability coefficient  $q_{v,t}$  is the mortality generated by each vessel with a unit of effort at each time interval and its dynamics are explained later. The yield of secondary species in time  $t$  for each vessel ( $y_{s,v,t}$ ), following Lleonart *et al.* (2003), is related linearly to the target species landings as:

$$y_{s,v,t} = \mu + \nu \cdot y_{v,t} \quad (3)$$

where  $\mu$  is the catch of secondary species in the absence of target species and  $\nu$  is the catch of secondary species for each catch unit of target species. These parameters are estimated empirically using the data from the Fishermen's Association and are considered to be the same for the entire fleet. The assumption of the secondary species equation implies accepting that its population dynamics is linearly related to that of the target species. This simplification arises from the need to consider the income from secondary species that balances the actual income obtained by each vessel, while avoiding building population dynamics models for each bycatch species.

The costs of the activity are divided into three:  $c_v$  is the cost of unit of effort of a vessel  $v$ ;  $fixed_v$  are the annual fixed costs for a vessel  $v$  (insurances, license and other fixed costs);  $comm$  are the sales commissions (commercialisation costs).

Combining Equations 1 and 3 and introducing the owner's share of the profits and the costs structure, the profits per vessel  $v$  at time unit  $t$  are:

$$\pi_{v,t} = (1 - g) \cdot ((1 - comm) \cdot$$

$$\cdot (p \cdot y_{v,t} + ps \cdot (\mu + \nu \cdot y_{v,t}) - c_v \cdot f_{v,t})) - fixed_v \quad (4)$$

where  $(1 - g)$  is the owner's share of the profits.

### Stock dynamics

Players (vessel owners) in the game are jointly constrained by the dynamics of the target species stock. "What one user appropriates is unavailable to other users" (Oakerson, 1992). We assume that we have  $N$  (later on  $N=12$ ) vessels exploiting the fish stock that is considered their common property (Hardin, 1968; Grønbaek, 2000): a single stock exploited by  $N$  vessels sharing a fishery. The dynamics of the stock are described by the Schaefer's (1954) surplus production model:

$$dB / dt = r \cdot B_t \cdot (1 - B_t / K) - Y_t \quad (5)$$

$$Y_t = \sum_{v=1}^N y_{v,t} \quad (6)$$

where  $r$  represents the intrinsic growth rate of the stock,  $K$  represents the carrying capacity,  $N$  represents the number of vessels exploiting the main stock,  $Y_t$  is the total catch of the target stock at time  $t$ , and  $y_{v,t}$  is the catch of the target species of vessel  $v$  at time  $t$  (Eq. 2).

The biomass dynamics was modelled using the difference equation (Hilborn and Walters, 1992) for 10000 time steps and the bioeconomic loop was completed at each time step. However, the results were produced at year level, summing the results of the 10000 time steps included in a year (Merino, 2006).

The target stock variations can be modelled by Equation 5, taking into account that  $Y_t$ , the sum of the catches of target species by all the vessels at each time step, can be written as a function of the efforts by means of Equation 7, derived from Equations 2 and 6.

$$Y_t = \sum_{v=1}^N y_{v,t} = \sum_{v=1}^N q_{v,t} \cdot f_{v,t} \cdot B_t \quad (7)$$

The time horizon for the dynamic game is 10 years, and the evolution over time is easily predicted, with a dynamics for the catchability coefficient  $q_{v,t}$  (Eqs. 8a, b, c) and a set of effort strategies,  $f_{v,t}$ . The estimation of the initial biomass  $B_0$  and the biological parameters is explained below (see *Parameter estimation*).

### The dynamics of the catchability coefficient

The catchability coefficient of a vessel  $v$  at time  $t$  is defined as the mortality generated in the target species by one unit of fishing effort by vessel  $v$ . It is described by Equation 8a, where  $\lambda$  is the annual rate of catchability increase.

$$dq_v / dt = \lambda \cdot q_v \quad (8a)$$

The solution of the differential equation is Eq. 8b, with the initial condition  $q_{v,t_0}$ , the catchability coefficient at time 0 for vessel  $v$ .

$$q_{v,t} = q_{v,t_0} \exp(\lambda(t - t_0)) \quad (8b)$$

A discretisation was made for the catchability dynamics, where catchability is assumed constant throughout the year and increased every time interval  $\tau$  (yearly). It can be approximated by Equation 8c.

$$q_{v,\tau} = q_{v,\tau_0} \cdot (1 + \lambda)^{\tau - \tau_0} \quad (8c)$$

### The Game

The effort strategies simulate two different behaviours: non-cooperation and cooperation. In the first case, where fishermen are supposed to maximise their own benefits without considering any cooperation other than the residual information related to their activity and characteristics, Nash's non-cooperative solution was found (Nash, 1951). For the second case, a constrained cooperative solution was used, with the condition that all fishermen apply the same effort, i.e. each fisherman fishes for the same number of days.

#### Non-cooperation

The non-cooperative solution concept is proposed in the present document as a realistic method for predicting effort dynamics in Mediterranean fisheries. It allows us to simulate the effort to be made by each vessel owner.

The biomass of the stock follows the dynamics described in Equation 5, starting from the estimated initial biomass  $B_0$ . The aim of the calculations under the non-equilibrium assumption is to fix a ten-year fishing effort strategy for each vessel, and it will consider that this strategy is constant over time ( $f_{v,t} = f_v$ ). The aim of this hypothesis is to avoid ideal solutions of infinite intervals, i.e. not leading the system to a

short-term analysis in which profits would be maximised by removing all the stocks from the ecosystem. Moreover, the observations on this fishery allow us to assert that vessel owners design their plans for an average period of about ten years (Esgleas, *pers comm.*). Some authors (Sumaila, 1999; Grønbaek, 2000) have noted that the assumption of constant strategy can likewise be used due to the difficulties of computing dynamic strategies. In the present study, the effort solutions represent an attempt to describe the usual fishing behaviour of the vessels, i.e. they describe vessels as intense, medium or occasional exploiters of the analysed stock. Some heterogeneity in vessel characteristics and fishing behaviour is reported in Mediterranean fisheries (Lleonart and Maynou, 2003; Merino, 2006).

As noted above, the profit of each owner depends upon his own effort strategy, but also upon the strategies of the other owners. Hence, we are faced with an  $N$ -player (the  $N$  vessel owners), non-zero sum game (Luce and Raiffa, 1989; Fudenberg and Tirole, 1991; Basar and Olsder, 1999). The solution concept used is the Nash equilibrium (Nash, 1951), defined as a set of strategies satisfying that each player's strategy is the best response to the equilibrium strategies of the others. It provides us with strategies such that none of the players will benefit from unilateral deviation. The effort strategies vector  $(f_1^*, f_2^*, f_3^*, f_4^*, \dots, f_N^*)$  will be called a *Nash equilibrium* if the following expression holds true:

$$\sum_{t=0}^T e^{\delta t} \pi_{v,t}(f_1^*, f_2^* \dots f_v^* \dots f_N^*) \geq \sum_{t=0}^T e^{\delta t} \pi_{v,t}(f_1^*, f_2^* \dots f_v \dots f_N^*), \text{ for every } v \in N \quad (9a)$$

where  $e^{\delta t}$  is the discount rate.

Equation 9 provides us with actions such that none of the players will benefit from unilateral deviation (Fudenberg and Tirole, 1991; Basar and Olsder, 1999).

Some constraints are included in the form:

$$f_{\min} \leq f_v^* \leq f_{\max}$$

For the purpose of the analysis,  $f_{\min} = 0$  and  $f_{\max} = 240$  days. The maximum effort level of 240 days is proposed as a realistic constraint derived from the regulation of Spanish Mediterranean fisheries, where fishing is permitted only from Monday to Friday with the exception of public holidays.

According to these assumptions, once the agents reach the effort strategy given by Equation 9, they have no incentive to deviate from that choice (Luce and Raiffa, 1989).

Nash's non-cooperative solutions were obtained with a successive approximation method to iteratively approximate solutions for the twelve equilibrium equations.

### Cooperation

Agents playing a cooperative strategy act jointly as a single harvester maximising aggregated profits (Grønbaek, 2000). A cooperative game is one in which players are able to make enforceable contracts (Shor, accessed 2006). The cooperation concept with Nash's bargaining solution (Nash, 1950) implies the maximisation of the whole fishery with some constraint related to the bargain between the agents (Sumaila, 1997). If the agents sharing a common resource have identical management goals, the optimisation problem is straightforward: that is, choosing the strategy as a sole-owner and bargaining then takes place over the division of the net economic returns (Munro, 1990; Grønbaek, 2000). In our case, the bargain is related to the amount of effort to apply. Vessel owners decide to maximise the income from the fishery by applying the same effort, which is more realistic according to the Mediterranean management structure, where effort is regulated with maximum days allowed for fishing and fishermen's associations may act as single agents. The agreement is thus reached before the maximisation of the economic return and it acts as a constraint to that maximisation. It accounts for the strategic interactions between fishermen, as differences in vessels will bring different profits to each one. It may be stated that the decision is first reached on effort shares and attention is then turned to maximising profits. Realistically, this simulates that fishermen, aggregated in the Fishermen's Association, make the decision with this constraint. We may call this cooperative solution "a homogeneous strategy cooperative solution" (Eq. 10).

A minimum and a maximum effort level are defined again.

$$\sum_{t=0}^T e^{\delta t} \sum_{i=1}^N \pi_{v,i}(f_1^o, f_2^o \dots f_v^o \dots f_N^o) \geq \sum_{t=0}^T e^{\delta t} \sum_{i=1}^N \pi_{v,i}(f_1, f_2 \dots f_v \dots f_N), \text{ for every } v \in N \quad (10)$$

$$f_{\min} \leq f_v^o \leq f_{\max} \quad \text{and} \quad f_i^o = f_j^o.$$

The cooperative solutions were obtained with the genetic algorithm *pikaia* (Charbonneau, 2002) for global maximisation.

### The data

Landings and effort data series from 1997-2004 at vessel level were provided by the Blanes Fishermen's Association and were used to estimate the catchability coefficients of each vessel and the biological parameters of target species and their relation to secondary species.

The technical description of the vessels and their economic parameters (including fuel consumption, insurance, variable costs and other daily costs) were obtained during the COCTEL project ("Analysis of the Mediterranean (including North Africa) deep-sea shrimp fishery: Catches, effort and economics", European Commission DG XIV) (Sardá, 2000; Maynou *et al.*, 2006) and were used here to calculate the cost of unit of effort as well as fixed costs for every vessel. The technical and economic characteristics of an average vessel of the fleet are presented in Table 1. Economic parameters such as the price of red shrimp and fuel, together with the costs and revenue structures, which includes a share system to pay the workers' wages, sales commissions and revenues from secondary species, were obtained during the BEMMFISH project ("Bio-economic modelling of Mediterranean Fisheries", European Commission DG FISH) and are also shown in Table 1.

TABLE 1. – Economic and technical parameters for the Blanes trawling fleet targeting red shrimp (*Aristeus antennatus*). Estimated from (Sardá, 2000) and (Merino, 2006).

Fuel consumption (l/day)	116.8
Trawlers' average fuel consumption	1116.8 l/day
Trawlers' average gross tonnage	87 t
Trawlers' average fixed costs	59473 euro/year
Trawlers' average cost of effort unit	335.2 euro /day
Price of target species (p)	29.75 euro/kg
Price of secondary species (ps)	5.091 euro/kg
Secondary species for target landed unit (v)	4.82 kg/kg of target sp.
Fixed secondary species landings when no target landed (μ)	76342 kg
Commercialisation tax	0.07%
Part of the profits for the owner (1-g)	0.5 (50%)
Discount factor	(96%)
Effort costs (euro/day)	335.2



## Parameter estimation

### Biological parameters

A series of eight years for the total landings of red shrimp and specific effort was used to estimate the target stock biomass the first year of the data series  $B_0$ , its intrinsic growth rate  $r$  and its carrying capacity  $K$ , as well as the average catchability  $q_m$  of a vessel during the period of the data set, following Prager (1994). The function to minimise is related to the difference between observed and estimated landings (Eq. 11). The minimisation was held with the genetic algorithm *gafortran* (Carroll, 2001).

$$\min \sum_{t=1}^T \log \left( \frac{Y_{obs,t}}{Y_{est,t}} \right)^2 \quad (11)$$

After fitting the model to the data series with a constant catchability coefficient, estimation was improved by adding dynamic catchability and tuning the empirical fit of the estimation based on the literature (Lindebo, 1999).

### Vessels catchability coefficients

Fleet's heterogeneity is reflected by the vessels' fishing capacity or catchability coefficient and their fishing costs, or more exactly by their  $q_v/c_v$  ratio.

The biomass dynamics parameter estimation is performed with total catch ( $Y$ ) and effort ( $E$ ) data series of the target species, and as a result, fishing mortality ( $F$ ) can be expressed as:

$$F = q \cdot E = q_m \cdot \sum_{v=1}^N E_v \quad (12)$$

where  $q_m$  is the average catchability of a vessel of the fleet under study. To estimate the vessels' catchability coefficients the following method was used: The catchability of each vessel was related to the catchability of an average vessel at initial time, making the following assumptions for each year, and to the landings and effort data at vessel level:

1) First, each vessel's catch per unit effort ( $cpue$ ) of target species is related to a reference vessel, which can be the vessel with highest  $cpue$ , for instance vessel 1 (Eq. 13).

$$cpue_v = C_v / E_v = \eta_v cpue_1 = \eta_v q_1 B \quad (13)$$

2) As the  $cpue_1$  and  $cpue_v$  are known, we obtain the relative  $\eta_v$  values that allow the relation between

vessels'  $cpue$ . We demonstrate that the relative  $\eta_v$  values between  $cpues$  are also relative differences between catchability coefficients (Eqs. 14 and 15):

$$\begin{aligned} cpue_m &= \frac{\sum_{i=1}^N cpue_i}{N} = \frac{\sum_{i=1}^N \eta_i cpue_1}{N} = \\ &= \frac{cpue_1 \sum_{i=1}^N \eta_i}{N} = \frac{q_1 B \sum_{i=1}^N \eta_i}{N} \end{aligned} \quad (14)$$

$$\frac{cpue_m}{B} = q_m \rightarrow q_m = \frac{q_1}{N} \sum_{i=1}^N \eta_i \quad (15)$$

The only unknown in Equation 15 is the reference catchability parameter  $q_1$ .

3) After solving Equation 15 and obtaining  $q_1$ , we easily calculate vessel level catchability coefficients:

$$q_v = \eta_v q_1, \text{ for every } v \in N \quad (16)$$

A similar method of vessel description or characterisation was performed by Sparre and Willman for their BEAM 4 model, though they relate the standardisation of fishing effort at vessel level through differences in fishing power (Sparre and Willman, 1993a, b).

### The uncertainty

Some uncertainty was added to the landings and effort equations (Equations 17 and 18). Using normal and lognormal distributions of errors, the simulated target species' catch was generated by adding noise to the Schaefer model:

$$(y_{v,t})_{sim} = y_{v,t} \cdot L(Ln(m_1), 0) + N(h_1, \sigma_1^2) \quad (17)$$

The uncertainty for the non-cooperation effort solutions was similarly introduced as:

$$(f_{v,t})_{sim} = f_v \cdot L(Ln(m_2), 0) + N(h_2, \sigma_2^2) \quad (18)$$

where  $m$  is the slope of the linear regression relating estimated to observed values,  $h_i$  is the mean error observed and  $\sigma^2$  is the standard error. Note that after the introduction of the uncertainty, the effort is not necessarily constant each time interval.

The values of these parameters for the target species' catch equations and for the non-cooperative effort solutions were obtained after linear regressions (see below).

For the cooperative solution, the uncertainty represents the impossibility of assuring that fishermen will fish the indicated number of days. It was approached with an additive variability of 5% days imposed, which is considered to be caused by *implementation uncertainty* (Hauge, 2005; Merino, 2006).

## RESULTS

The first result to highlight is the parameter set describing the population dynamics of the target species, red shrimp, with the Schaefer's model (Table 2). Figures 1 and 2 show the temporal fit of the data and the correlation between catch and *cpue* estimates and observations. The slope of the function that relates estimated to observed landings of red shrimp was 0.9753, with a standard error of 0.04204 and a significance of  $p(\eta) < 10^{-5}$ .

Vessels' catchability coefficients in 1997 and their economic efficiency parameters are shown in Table 3, jointly with their economic efficiency

TABLE 2. – Estimated red shrimp biological parameters (intrinsic growth rate ( $r$ ), carrying capacity ( $K$ ), initial biomass at 1997 ( $B_0$ )), average catchability coefficient ( $q$ ) and annual increase in catchability ( $\lambda$ ) of the Blanes bottom-trawl fleet exploiting red shrimp.

$r$ (days <sup>-1</sup> )	$K$ (t)	$B_0$ (t)	$q$ (day <sup>-1</sup> )	$\lambda$
0.9626	327.0	75.2	0.0004805	0.03 (3%)

TABLE 3. – Catchability parameter ( $q_v$ ) and economic efficiency ratios ( $q_v/c_v$ , mortality generated by a unit cost of effort) of the twelve trawlers of the Blanes fleet targeting red shrimp in 1997 and corresponding effort strategies directed at red shrimp (days at the sea) for cooperative and non-cooperative solutions.

Vessel	Catchability ( $q_v$ )	Economic efficiency ( $q_v/c_v$ ) $10^{-6}$	Effort of non-cooperation (days)	Effort of cooperation (days)
v-1	0.00015	0.7	0	71
v-2	0.00086	1.52	19	71
v-3	0.00080	2.13	216	71
v-4	0.00105	2.74	240	71
v-5	0.000369	1.14	0	71
v-6	0.00115	2.25	168	71
v-7	0.00068	1.76	135	71
v-8	0.00091	3.31	240	71
v-9	0.00032	2.74	240	71
v-10	0.00119	2.41	183	71
v-11	0.00037	1.30	0	71
v-12	0.00111	2.57	215	71
Total	-	-	1656	852

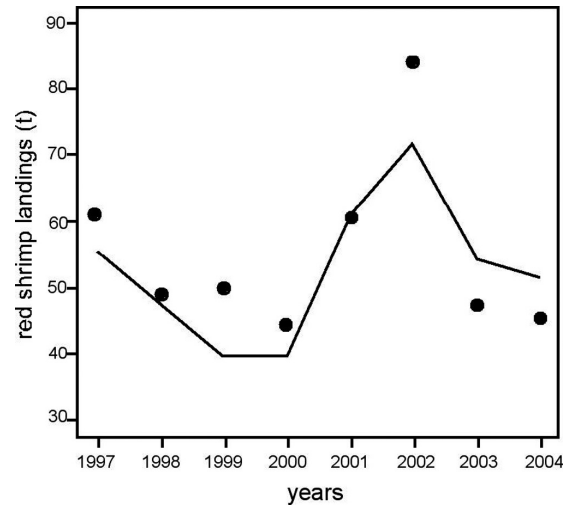


FIG. 1. – Fit (line) to the observed landings (points) with the estimated set of biological parameters for the red shrimp landings series from 1997 to 2004 in Blanes.

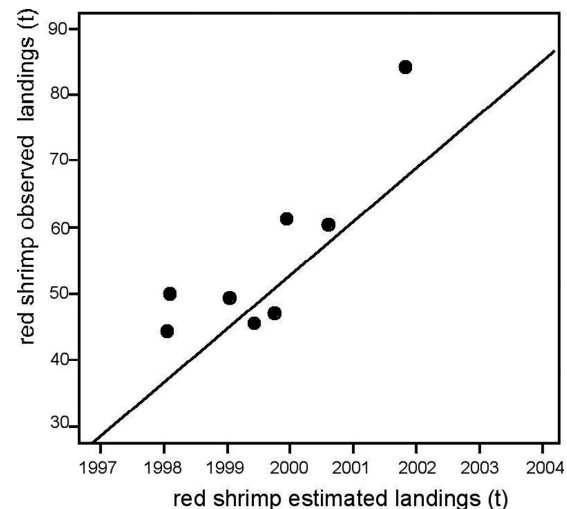


FIG. 2. – Observed red shrimp landings from 1997 to 2004 in Blanes and estimated landings with parameters shown in Table 2 and the Schaefer model. Standard error = 0.04204 and significance of  $p(\eta) = 5.387 \cdot 10^{-7} < 10^{-5}$ .

parameters and their corresponding cooperative and non-cooperative strategies. Non-cooperative effort solutions are proposed as a realistic approach to the observed effort dynamics in Mediterranean fisheries. Figure 3 relates the estimated individual effort strategies to the observed average effort level of vessels in the period 1997-2004. It allows vessels to be classified into three groups: vessels that fish red shrimp all the year, medium-intensity exploiters and occasional exploiters. As is observed, Nash's solutions provide a suitable identification of the vessels that fish red shrimp most frequently and the ones that fish occasionally. The model also identifies a group of vessels that exploit in a medium-intensity

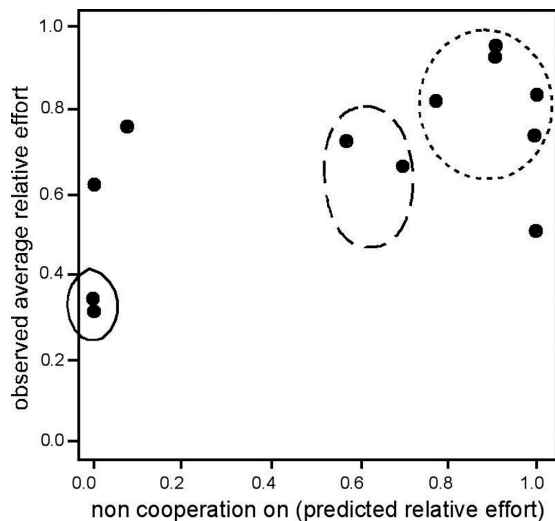


FIG. 3. – Observed relative effort strategies for the twelve vessels in the Blanes red shrimp fishery and their respective non-cooperative solutions. Note that the solution to the proposed non-cooperative game simulates high intensity (pointed circle), mid intensity (dotted lined circle) and occasional (lined circle) fishermen targeting red shrimp. Pearson coefficient = 0.56.

effort strategy. Three vessels that the model estimates as occasional and intense were not appropriately estimated.

The  $R^2$  parameter estimation has been observed to be controversial for the regressions crossing the point (0, 0) (Cade and Terrell, 1997; Merino, 2006) and is not displayed. The positive Pearson correlation between the estimated and observed effort strategies was 0.56. The statistical parameters relating observed and estimated effort strategies were used to build the simulated effort solutions ( $m_2 = 0.662$ ,  $h_2 = -15.24$ , ).

Simulations from 1997 to 2006 were performed for the two solutions to compare the effects of non-cooperative and cooperative strategies over a ten-year horizon. The simulations were performed with 1000 iterations and the uncertainty associated with the parameter estimation process and the effort dynamics derived from the regressions in Figures 2 and 3 (Eqs. 17 and 18). The simulations (Figs. 4, 5, 6 and 7) are displayed through the mean and the 5 and 95% confidence intervals for all the bioeconomic indicators.

The results displayed are target species' biomass level, total catch, fishing mortality and discounted profits. The non-cooperative scenario is represented

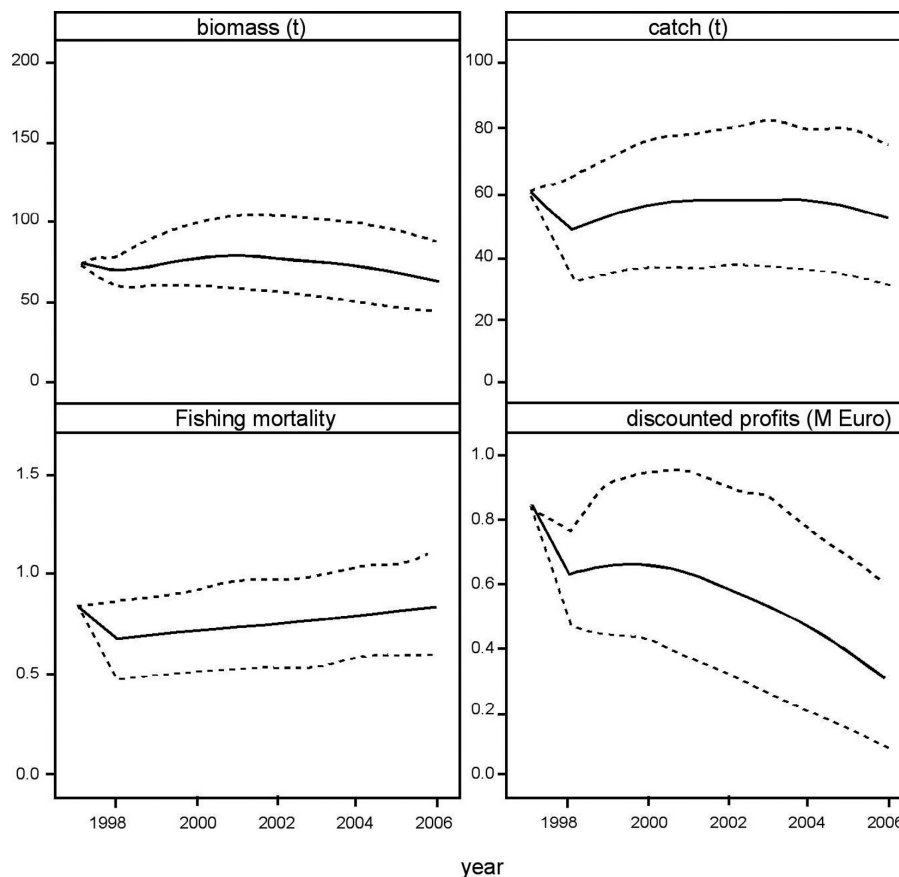


FIG. 4. – Simulation of the global bioeconomic indicators in a non-cooperative system of the Blanes red shrimp fishery from 1997 to 2006. The bioeconomic variables of the activity are represented through their mean values and their 5 and 95% confidence intervals.



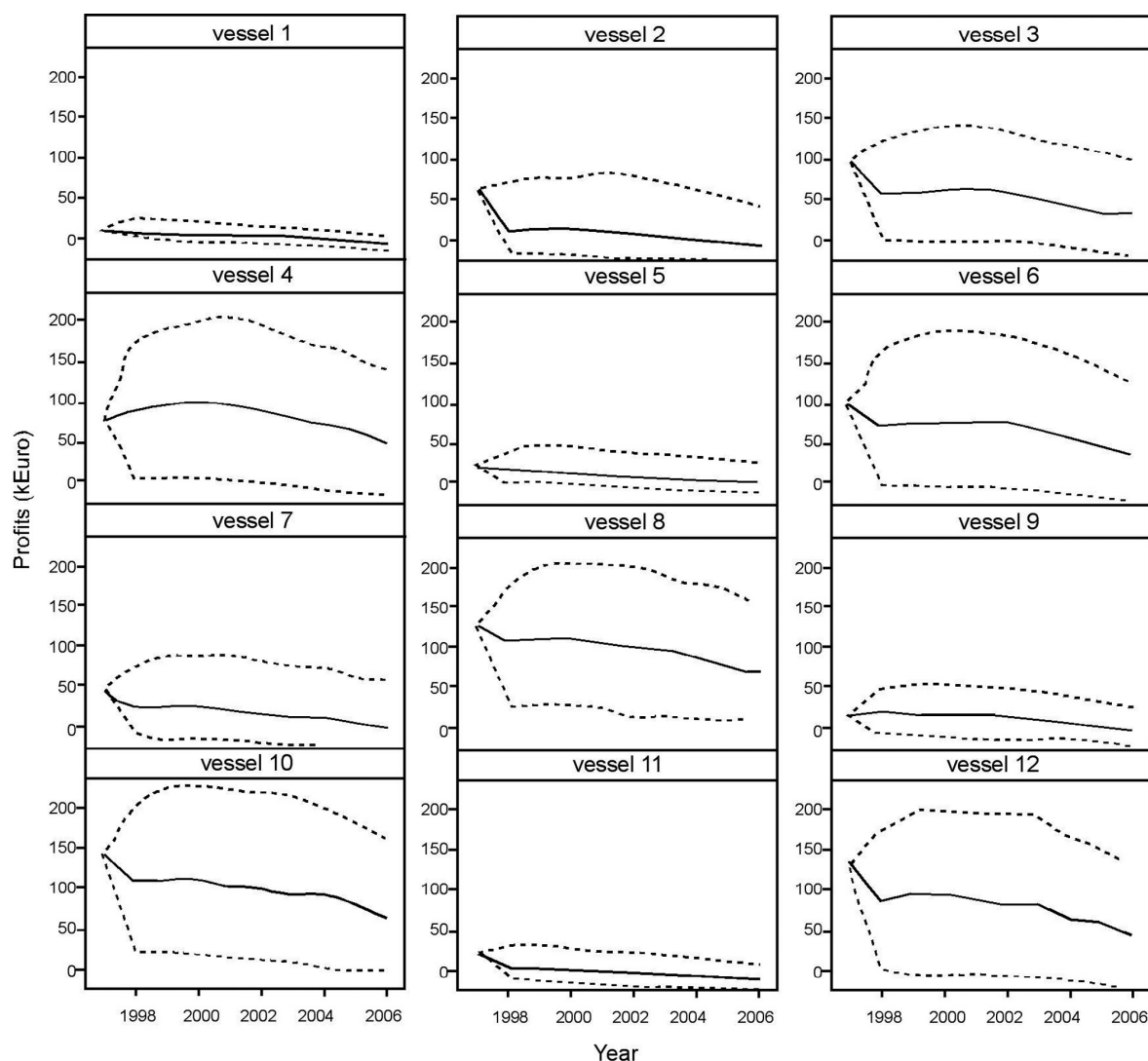


FIG. 5. – Simulation of the discounted profits of the twelve vessels in a non-cooperative system. Note that the vessels' profits are related to both their catchability and their economic efficiency coefficients. Profits of the twelve trawlers targeting red shrimp in Blanes are represented by their mean and their 5 and 95% confidence intervals.

with the simulations in Figures 4 (total level) and 5 (vessel level). Figure 4 shows a slight recovery of the population due to a predicted slight decrease in effort. The population is simulated to be sustained around 70 t level, which represents 21% of its carrying capacity. Landings are simulated to fluctuate around the 50 t level. Fishing mortality decreases slightly due to this effort reduction but the constant increase in catchability is predicted to return it to the levels in 1997. The discounted profits of the activity in a non-cooperative system are predicted to be maintained initially near 0.6 M euro but constantly decreasing due to the discount factor (Table 1).

Regarding the vessels' economic return, it can be observed that the expected profits are related to

the vessels' technical characteristics. The vessels that obtain the highest profits from the red shrimp fishery (3, 4, 6, 8, 10, 12) are those with the highest catchability and economic efficiency parameters, with two exceptions. Vessel 2 has a high catchability coefficient (it generates a high fishing mortality with a unit of effort) but it has a low economic efficiency parameter. On the other hand, Vessel 9 is an economically very efficient vessel (it generates a high fishing mortality for each euro invested) but it has a low catchability coefficient. These two vessels obtain very low profits from their activities. To sum up, vessels' competitiveness is related to both their catchability and their economic efficiencies.

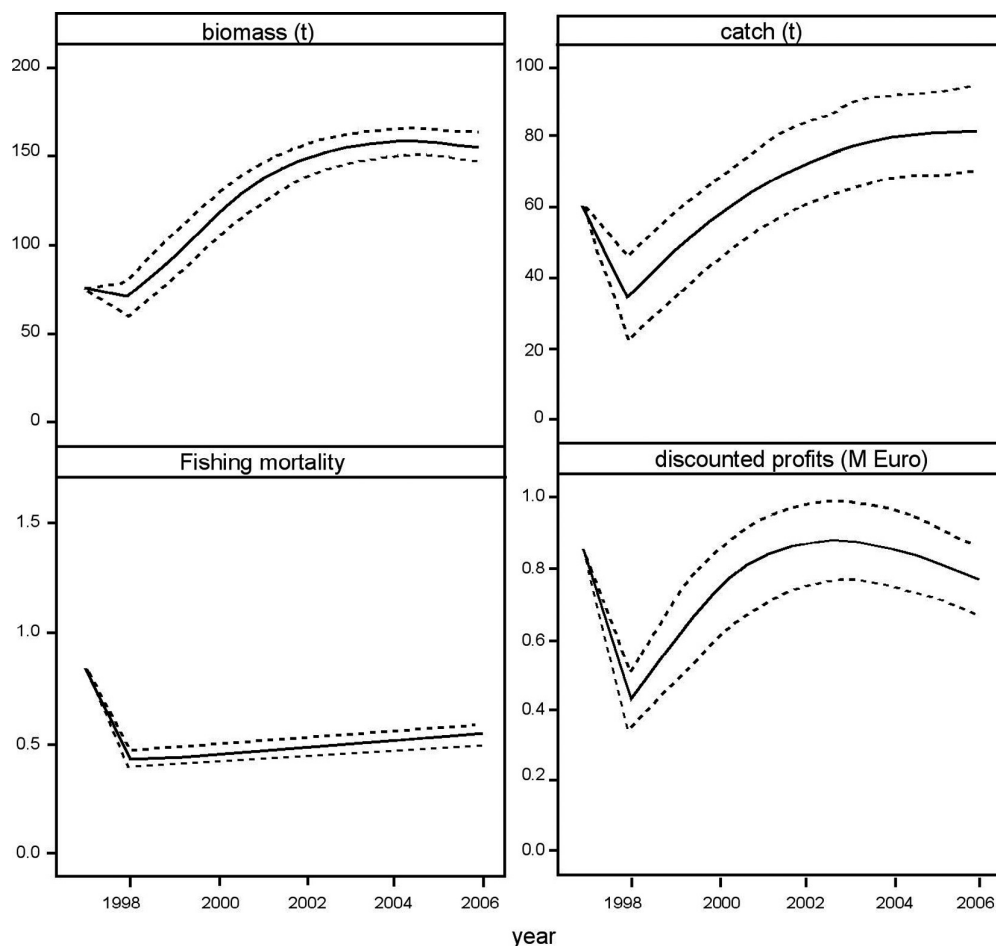


FIG. 6. – Simulation of the overall bioeconomic indicators in a homogeneous effort cooperation scenario for the Blanes red shrimp fishery. The bioeconomic variables are represented through their mean values and their 5 and 95 % confidence intervals.

The homogeneous cooperative effort scenario (Fig. 6) would bring about a considerable reduction in fishing effort (Table 3). This should lead to a significant recovery in the population level, which would reach 150 t, which represents 45% of its carrying capacity. Landings would initially decrease due to the effort reduction but the population's recovery would bring the total landings to previous levels in the medium term. In the long run, landings should increase to 80 t. The increase in landings and the reduction in the costs of the activity should lead the overall economic profitability of the exploitation to a medium-term equilibrium around 0.9 M euros.

At vessel level, cooperation would bring positive results to all the vessels sharing the red shrimp exploitation (Fig. 7). Table 4 reflects the change in the vessels' profits in a cooperative strategy. As it is straightforward, all the vessels should consider the change to a cooperative system as individually rational (Camerer and Fehr, 2006).

The differences in the overall bioeconomic indicators are displayed in Figure 8. The variables show higher values for cooperation (black area) or for non-cooperation (grey area) during the simulation

TABLE 4. – Economic return of individual vessels if homogeneous effort cooperative strategy was adopted instead of the current non-cooperative strategy currently described for the trawlers targeting red shrimp in Blanes.

Vessel	Return of changing to cooperation (euro)
v-1	61388.81
v-2	494315.79
v-3	115578.30
v-4	38239.08
v-5	208598.72
v-6	316599.53
v-7	249949.01
v-8	20937.04
v-9	5600.96
v-10	249268.02
v-11	194593.27
v-12	133512.77

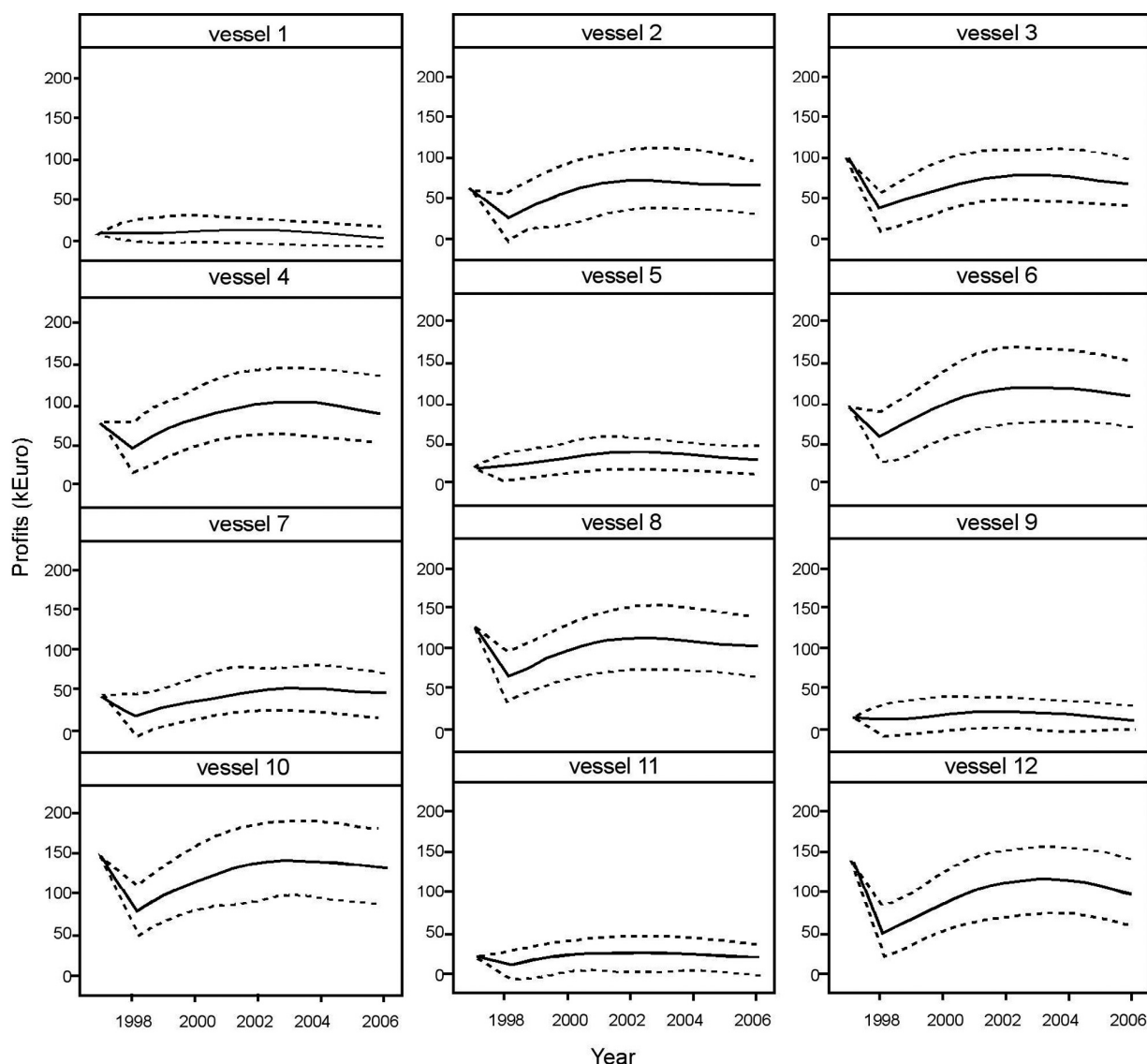


Fig. 7. – Simulation of the discounted profits of the twelve vessels in a cooperative system. Note that the trawlers' profits are related to both their catchability and their economic efficiency coefficients. Profits of the twelve vessels targeting red shrimp in Blanes are represented by their mean and their 5 and 95% confidence intervals.

time. From a conservationist perspective it is obvious that cooperation allows the population to reach secure levels and the medium-term profits are also higher with cooperation. The cooperative behaviour would bring higher landings and higher profits to the activity in the medium term after the population's recovery (3 years).

## DISCUSSION

Biological parameters are the first result obtained in the present work and show values that are significantly different from the parameters obtained previously by other authors for the same species

(Demestre and Lleonart, 1993; Demestre and Martin, 1993; Carbonell *et al.*, 1999; Carbonell *et al.*, 2003).

Simulations performed for non-cooperation and homogeneous effort cooperation suggest interesting conclusions about exploitations described as shared resources.

Apparently, under a non-cooperative regime, the red shrimp fishery will be sustained in a moderately exploited situation, which is concordant with the assessments of this species along the northwestern Mediterranean (Sardá *et al.*, 2003).

In the current management scheme for red shrimp, non-cooperation would decrease the profitability of the system, due to both the common

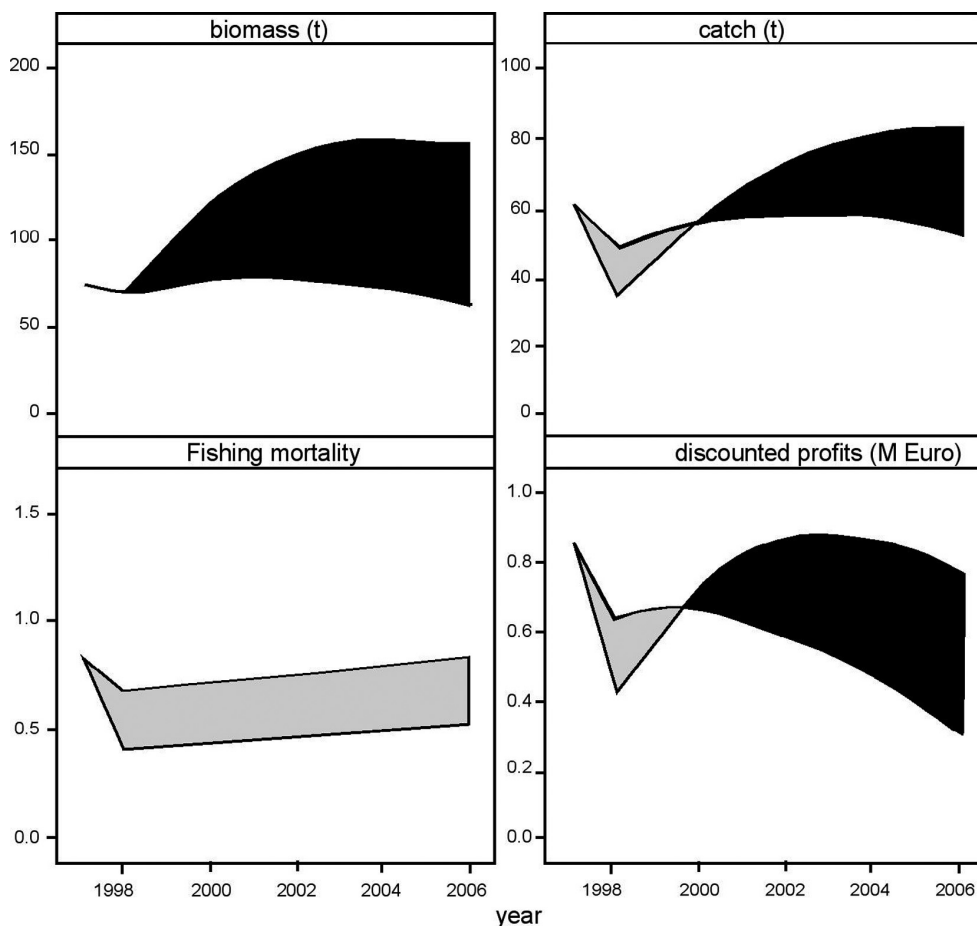


FIG. 8. – Mean values of the bioeconomic indicators of the Blanes red shrimp fishery under cooperative and non-cooperative behaviours. The grey and the black areas represent the difference between the values in a non-cooperative and cooperative regime in the bioeconomic indicators. In grey, values that are higher in the non-cooperative scheme; in black, values that are higher in the cooperative scheme.

property distortion (Hardin, 1968; Arnason, 1998) of the system and the increase in catchability or overcapitalisation.

Non-cooperative behaviour compared favourably with the observed data (Fig. 3) and, under the assumption of non-cooperation, profits would show a slight but constant decrease.

Maximum economic income over a ten-year period is reached under cooperative behaviour. The characterisation of the fleet at vessel level showed the differences in economic efficiency between the vessels. This characterisation has been demonstrated to be necessary for the prediction of effort dynamics and profitability estimates for decision making related to both investments in technology (increase of  $q$ ) and reducing costs ( $c$ ).

The fishery is subsidised, with effort subsidies (exemption of fuel tax, which means that the fuel price paid by fishermen is around 50% of the retail price) introducing a distortion in the system

(Arnason, 1998). As a consequence, it is not possible to say whether the fishery could regulate the effort adequately to the resource. The current regulation may be described as non-cooperative behaviour with the constraints of no fishing during weekends and public holidays. Moreover, climatologic conditions also constrain the number of fishing days. Our results agree with those of other authors who state that cooperation is the economically best management regime and with theoretical results on the management of shared resources (Hardin, 1968; Munro, 1979; Sumaila, 1997).

The individualisation of the decision to establish an effort strategy appears to be a good tool for predicting the evolution of the system under any new regulation proposed for the optimisation of the system. Research under these assumptions is an open field, in which the results of completely liberalising the effort strategies with no subsidies or the decision to leave the fishery may be investigated.

# CONCLUSIONS

Our study has shown that there are vessel level management options for improving the long-term regulation of red shrimp (*Aristeus antennatus*) trawl fisheries. The method presented can be used to characterise the fleet with catch and effort data for the target species at vessel level. A management option based on cooperation would help to maximise the profits generated by the resource and to conserve the target species. Nevertheless, the analysed fleet's effort dynamics are suitably approximated with a non-cooperative scheme.

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