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Bioeconomic model of the dynamics of fisheries facing global economic and environment changes: the French Guyana shrimp fishery

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Abstract: . In the past two decades, the French Guyana shrimp fishery has known dramatic evolutions, largely driven by global changes. On the economic side, two major driving factors are the globalization of the shrimp market, with a decreasing trend in real prices, and the long-term increase in fuel prices worldwide. On the environmental side, recruitment of the two main species of shrimp targeted in the fishery seems to have decreased over the last decade. This decrease is probably related to hydroclimatic modifications linked to global change. It is important to assess the adaptive capacity of the fishery facing such changes, as well as the relevance of past and future public policies to improve this capacity.

A key component of this adaptive capacity is the way in which fishing firms assess tradeoffs and make decisions regarding alternative fishing strategies. In the French Guyana shrimp fishery, of particular interest is the comparison which firms make between maximizing catch volume and maximizing catch value. Because of the strong relationship between size and price per kg for shrimps, a maximum value strategy leads to significantly different exploitation choices than the maximum catch strategy, in terms of effort allocation in space and time, and of gear selectivity. The existence of a volume-based subsidy in the fishery however influences this tradeoff, as it creates an incentive to maximize catch volume rather than catch value.

A bio-economic model of the French Guyana shrimp fishery was developed in order to analyze the dynamics of the fishery. The aims of the modeling exercise were: 1) to account for the changes observed in the fishery over the past ten years and major drivers of those changes; 2) to simulate possible responses of the fishery to economic changes but also to environmental perturbations or regime shifts; and 3) to assess the consequences of past and possible future public policies on the bioeconomic viability of the fishery.

The aim of this paper is to present the key results derived from this modeling exercise, as regards assessment of the adaptive capacity of the fishery to global changes, and the role of public policies in this respect. The paper is structured as follows. Section 1 provides a brief introduction to the shrimp fishery and its evolution over the past decade. Section 2 presents the general characteristics of the simulation model. Section 3 presents the adjustment of the model to historical data and the probable future trends in the fishery given the current status of major driving factors, showing that strong adaptations are necessary in the fishery if the recent trends in economic parameters still hold in the future. Section 4 assesses the role of harvesting strategies in explaining the changes observed and the influence of public policies on these strategies. Section 5 discusses these results, in the light of alternative public policies which could facilitate adaptation of the fishery to its changing environment, and concludes.

This research was carried out as part of the “Chaloupe” program (http://www.projet-chaloupe.fr) funded by the French National Agency For Research (ANR). The objective of the program is to study the adaptation capacity of exploited marine communities and fisheries, facing environmental and economic global changes, based on the comparative analysis of different case studies.

Keywords: *bioeconomic modeling, fishery management, subsidies, shrimp, French Guyana*

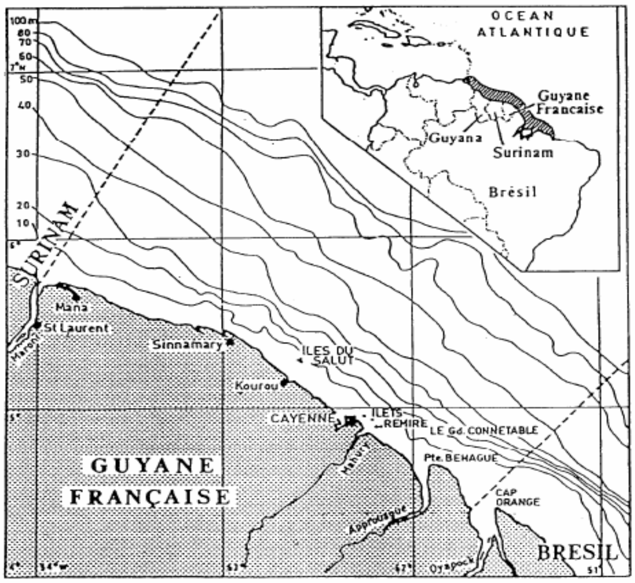
1. INTRODUCTION

Major changes are currently being observed in marine ecosystems and in the human activities that depend upon them. This raises growing concerns, in terms of both the capacity of the ecosystem to absorb these changes without being radically transformed, and the sustainability of fisheries that rely on the ecosystems. A central issue in this respect is to better understand the adaptive ability of fisheries facing such changes, and the role of past and future public policies in strengthening or weakening this ability.

During the past twenty years, the French Guyana shrimp fishery has faced dramatic changes, leading to strong evolutions of its biological and economic status. On the economic side, two major driving factors are the globalization of the shrimp market, with a decreasing trend in real prices, and the long-term increase in fuel prices worldwide. On the environmental side, recruitment of the two main species of shrimp targeted in the fishery seems to have decreased over the last decade. This decrease is probably related to hydroclimatic modifications linked to global climate change. Adaptation to these modifications in the fishery’s environment involve micro-economic decisions by fishing firms as regards (dis)investment in the fishery, and the selection of harvesting strategies. Existing public policies regarding the sector’s regulation and support have had a strong influence on these decisions.

The aim of this paper is to model the changes observed in the French Guyana shrimp fishery and their key driving factors, to analyze the micro-economic strategies which have at least partly determined theses changes, and to assess the influence of public policies on these strategies. The paper is structured as follows. Section 1 provides a brief introduction to the shrimp fishery and its evolution over the past decade. Section 2 presents the general characteristics of the simulation model. Section 3 presents the adjustment of the model to historical data and the probable future trends in the fishery. Section 4 assesses the role of harvesting strategies in explaining the changes observed and the influence of public policies on these strategies. Section 5 discusses these results, in the light of alternative public policies which could facilitate adaptation of the fishery to its changing environment, and concludes.

Figure 1. Map of the French Guyana shrimp fishery



1.1. Rise and fall of the French Guyana shrimp fishery

The exploitation of the Guyana shrimp stocks[1] began during the 1960’s when US shrimp fishing boats extended their fishing zones to the continental shelf of Guyana, between Venezuela and Brazil (fig. 1). During nearly 20 years, Cayenne (French Guyana) and Paramaribo (Surinam) were used as local landing sites by more than 400 US shrimp boats for transhipment of their landings of up to 20 000 tons (maximum observed) to the US market. Japanese boats also entered the Guyana fishery. The implementation of 200 miles Economic Exclusive Zones (EEZ) in 1977 gave control of Guyanese living resources to the coastal states of Surinam, Guyana, France and Brazil.

[1] Composed mainly of two species *Farfantepenaeus subtilis* (brown shrimp) and *Farfantepenaeus brasiliensis* (pink shrimp).

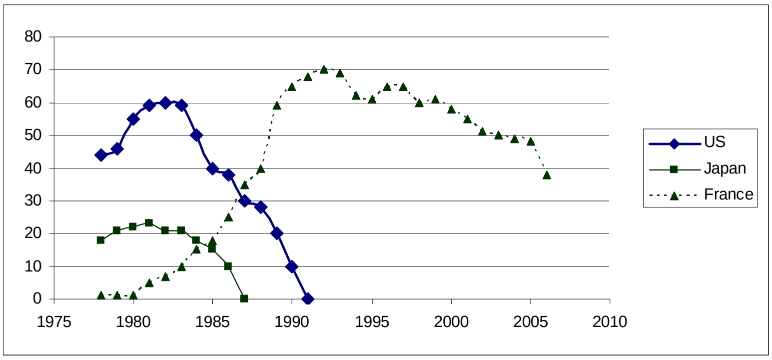


Figure 2. Evolution of the number of boats in the French Guyana shrimp fishery

In French Guyana the objective during the 1980's was to promote the development of a national fleet in place of the foreign vessels still in operation in the French EEZ. This so-called "francisation" of the fishery was supported by strong intervention of the State through subsidies and infrastructure building. In 10 years the French shrimp trawler fleet increased from nil to 70 units (fig. 2), while the number of US trawlers decreased to 0. This rapid development of the French Guyana fishery was also related to the expansion of the international market for tropical peneid shrimps. French Guyana, like most other French overseas territories, suffered from a weak local economy with limited industrial development and high labour costs, compensated by strong economic support from the mainland. Given the apparent abundance of the resource and promising external marketing conditions, the shrimp fishery was considered as a key sector for the future of the Département.

The success story of the 80's was short-lived. Since the beginning of the 90's, the sector entered a period of economic hardship. In 1993, three important fishing firms were closed. From 1993 to 2006 landings showed a decreasing pattern (fig 3), as well as the number of trawlers. During the "francisation" of the fleet and up to 1995, fishing effort concentrated in shallow waters, where the biomass of *F. subtilis* is high but mainly composed of small individuals. In the past 15 years, landings became increasingly dominated by small brown shrimp. This probably made the fishery more vulnerable to recruitment failures and environmental variability. On the economic and social side the fishery experienced two main crises: 2000-2001 and 2006 onwards (see infra) which resulted in a reduction of fleet size and concentration of fleet ownership due to the closure of smaller firms, and the reduction of vessel numbers in those firms that remained active. Today only three fishing firms remain in the sector, one of them holding more than half the total fishing capacity. In 2008, this main fishing firm withdrew 9 trawlers because of economic losses, and the total fleet capacity of the fishery was reduced to 23 fishing units. At the beginning of 2009 the situation had worsened, with only 15 active fishing units remaining in the sector.

1.2. Drivers of change

Drivers of the changes observed can be sought in the economic, the environmental and the regulatory domains. On the economic side, a key driver has been the evolution of the world shrimp market. After 1980, most landings by the French fishing fleet were exported to the French domestic market. From the mid 1990's, the shrimp world market has been characterized by the rapid development of aquaculture. This has entailed a drop in the international market prices for shrimp. According to FAO international trade data, the unit price for shrimp in current terms decreased since 1995. In 2003, the current price (6.5 US $ / kg) was thus lower than the price observed in 1986 (7 US $ / kg). In addition to this decrease in the potential value of shrimp landings, the rise of fuel costs observed in the past few years heavily impacted the already depressed economic status of the shrimp fishery.

On the resource side, a general decreasing trend in shrimp biomass has been observed at the regional level since 1995-96 (Dintheer and Kalaïdjian, 2001). In French Guyana, based on virtual population analysis (VPA) of 1994-2006 data, Ifremer scientists also identified two periods of low recruitment for the main target species (*F. subtilis*): 2000-2001 and 2006. For the second species *F. brasiliensis,* VPA results also indicated a reduction in biomass which could be explained by overexploitation in neighbouring Surinam waters. Other environmental drivers have been considered as potential drivers of the changes in the biological condition of the stock: for example, the increase of sea surface temperature observed over the past decades in the waters of French Guyana (Blanchard and Thébaud, 2007) could also have induced changes in growth or mortality parameters.

A third set of factors driving the observed changes in the fishery relates to its management. This has been carried out in accordance with European legislation, with the progressive creation and implementation of management regulations after the establishment of the EEZ. Key features of the management system include:

- a total landings limitation (LL) of 4 108 tons was adopted in 1983, but was never reached, with catches averaging 2 930 tons between 2000 and 2006. The limit has not been changed until today, despite decreasing landings and estimated biomass. It has thus not been used as an active management tool;
- a licence system (without fees), introduced in 1991 for shrimp fishing, with the stated objective to protect the resource. The Préfet of the Guyana region (representing the central state) is responsible for determining the total number of fishing licences and their allocation on an annual basis. The initial number of licences, 69 in 1991, was reduced to 68 (1994) and 63 (1999), but was always greater than the number of active fishing units. Hence, the licence system was never used as a tool to preserve the resource (which would be difficult given the lack of clear relation between fishing effort and the annual abundance of shrimp, which is mainly correlated to recruitment), nor to improve economic results of the active vessels;
- a minimum mesh size equal to 45 mm, which is an important technical measures in shrimp fisheries, for both biological and economic reasons (see infra);
- a spatial restriction to fishing, with trawling forbidden in coastal waters less than 30 meters depth, aimed at limiting the impact of trawling on juvenile shrimp in shallow waters, and avoiding conflicts with coastal small-scale fishers.

Overall, the creation of the EEZ in 1977 permitted the development of the French fishery, but created favourable conditions for the development of excess fishing capacity as access regulations were never effectively restrictive for French firms wishing to invest in the fishery. This investment was fostered by fiscal and investment incentives. The economic support granted by the European Union to ultra-peripheral regions to offset the costs induced by their distance from main EU markets also had a strong influence on the evolution of the fishery. For the French Guyana fishery this support was granted in 1993; an amount of 1.1 € was given per kg of shrimp exported to the EU market, with a maximum limit of 4 200 t per year. Since 2003, this limit has been reduced to 3 300 t. This subsidy has contributed to maintaining fishing capacity at high levels and has also been questioned as an incentive to maximise catch volume rather than value (see infra).

Clearly the management system has not anticipated or even reacted efficiently to the ecological and economic changes faced by the shrimp fishery. The biological and economic problems were however addressed in many scientific reports. Since the 1980's scientific monitoring of catch and effort has been conducted by Ifremer on a regular basis, and completed by occasional economic analyses. The assessments produced based on this information all provided early warnings about the growing difficulties of the fishery.

2. BIOECONOMIC MODEL OF THE FISHERY

A model of the French Guyana shrimp fishery was developed with the following objectives:

1. Represent the past dynamics of the fishery over the 1994-2006 period and allow projections for up to ten years in the future. The 1994-2006 period was chosen because of the availability of good data concerning fishing effort. Simulations were carried out for two periods. During the first period recruitment (estimated via Virtual Population Analysis) and fishing effort were set equal to the observed historical values. During the projection period (after 2006) recruitment was modelled as a stochastic variable, and effort was used as a control variable.
2. Simulate the impact of exogenous changes on the fishery. These changes can be economic (mainly shifts in world shrimp prices and fuel cost), or environmental, using shrimp recruitment as a proxy of environmental variability.
3. Evaluate the consequences of public policies on the economic viability of the fishery. This concerned policy instruments already used in the fishery, but also included simulating the impact of alternative management measures such as the adoption of selective gear to limit fish and turtle by-catches.

2.1. Model Structure and characteristics

The model was developed using the VENSIM software[2]. It is composed of different linked modules, of which a brief description is provided below.

- **Shrimp stocks dynamics and catch module**: this module uses an age-structured model for the two target species (brown and pink shrimp), with monthly cohorts of males and females[3]. Two types of fishing strategies have been distinguished: coastal (from 30 to 50m depth) and off-shore (more than 50m depth). The strategies are characterized by different catchabilities for the two target species. Computation of catch is carried out at each time step for each cohort per species and sex, and instantaneous total catch is obtained by summation over the cohorts.
- **Current economic results module**: at each time step current economic results (revenue and variable costs) are computed, based on a set of exogenous economic parameters. These include price of shrimp per commercial category, per species, and fixed and variable cost parameters.
- **Fishing capacity adjustment module**: during the simulation projection period, the number of vessels each year can be defined as a function of the previous year's economic results (Smith, 1969), or can be maintained at a fixed level during a chosen period.
- **Management decisions module**: a variety of management decisions were modeled including existing measures, and possible new measures. Measures considered in the model include licenses, taxes, subsidies, gear regulation, time closure, spatial regulation.
- **Annual economic results module:** at the end of each simulated year, synthetic economic results are computed, including profit per vessel, per fishing strategy, total fishery profit, fishery rent, and net contribution to state incomes. In the model profit is considered to represent the perspective of private firms involved in the fishery: they incorporate the net contribution of public subsidies to the fishery sector (subsidies less taxes). On the contrary, economic rent represents wealth creation from the collective point of view and is equal to profit plus taxes less subsidies.

3. GOODNESS OF FIT AND PROJECTIONS

The quality of fit on the past period 1995-2005 is quite good for total shrimp catch (fig.4), while catch per unit of effort were less well adjusted. For shrimp biomass, comparison between Virtual Population Analysis estimates and model simulation results shows that the model slightly over-estimates biomass. A closer look at the results shows that fit is good for the most important species (*F subtilis*), but less satisfactory for the second target species (*F. brasiliensis*).

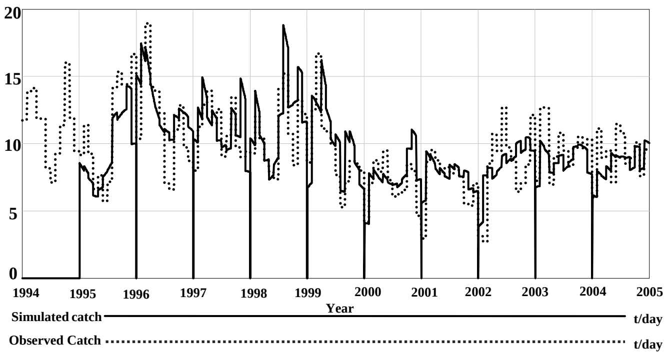


Figure 3.- Simulated vs observed shrimp catches

Projections were made for up to ten years in order to assess the current ability of the fishery to face exogenous changes affecting both ecological and economic parameters. Simulations were carried out assuming two alternative scenarios as regards key economic variables (scenario 1 which we considered pessimistic when the analysis was carried out, while scenario 2 was more optimistic), while shrimp recruitment was modelled assuming the average pattern observed during the 2004-2007 period (poor recruitment levels). The following exogenous shocks were tested (parameter values for scenario 1 followed in parenthesis by parameter values for scenario 2):

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[2] http://www.vensim.com/

[3] In the model, monthly recruitment takes place the first day of each month.

i) change in shrimp prices according to commercial category[4]: decrease by 4 % (3 %) per year for small shrimps (40/60 to 120-up categories), and 1 % (0 %) per year for medium shrimp (30/40 category); and increase by 2 % per year for big shrimp (20/30 and 10/20 categories).

ii) decrease of the marketing subsidy: by 50 % (25 %). Such a reduction in this subsidy seems realistic given of current international orientations through World Trade Organization to suppress trade distortions.

iii) increase in fuel prices: by 15 % (10 %) per year. This seemed optimistic in comparison with the situation on the world oil market when the project was carried out, in 2008. However, a trend based on years 2007 and 2008 variations would rapidly lead to a non-viable fishery.

Taking these changes simultaneously into account leads to a reduced fleet of 18 (respectively 10) active vessels in year 2016 (fig. 5). The self-regulating behaviour of the fishing fleet allows a very important recovery of the shrimp resource because of the strong decrease in fishing effort and despite the bad recruitment regime assumed here. This result stresses the possibility that the fishery will become economically unviable in a close future, despite resource recovery, if current trends in shrimp and fuel prices are not stabilized or inverted, given the harvesting regime in place. To avoid the collapse of the fishery would require developing public policies clearly aimed at improving the economic results of fishing firms.

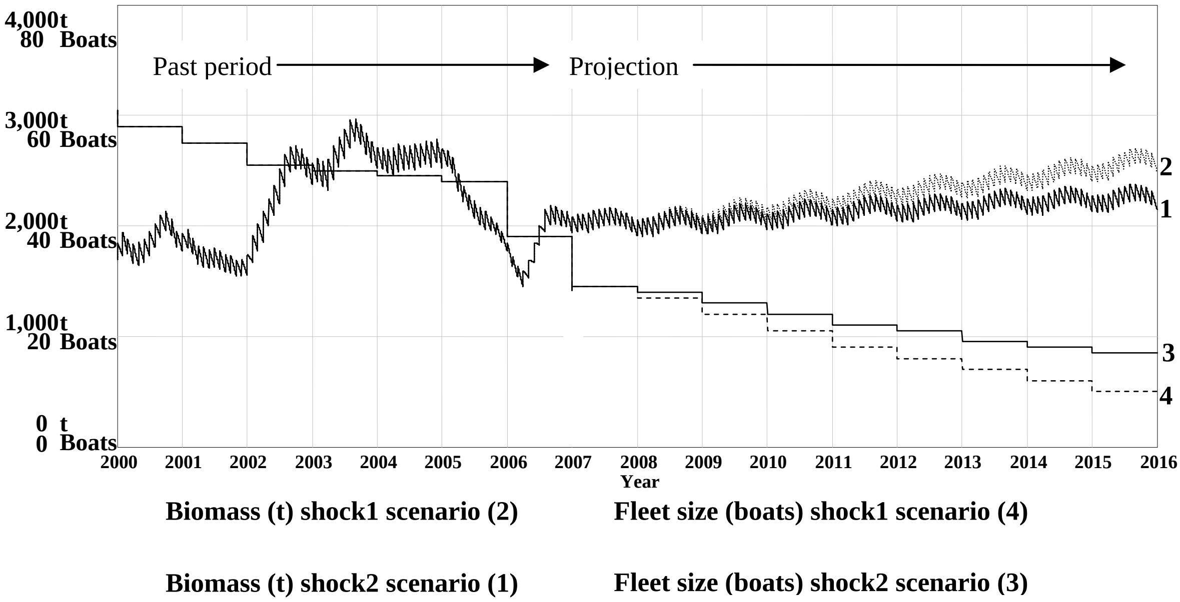

Figure 4. Ten years projections for fleet and biomass, based on recent period (2004-2007) recruitment and two scenarios for shrimp prices, fuel price, and European Poseidom subsidy.

4. HARVESTING STRATEGIES: THE PRICE/VOLUME TRADE-OFF

Peneid tropical shrimps are characterized by a very rapid growth and a positive relationship between market price and individual shrimp weight. Fig. 6 shows the 2006 French Guyana shrimp prices per commercial categories (defined by the number of head-on shrimps per kg). Because of this specific shape of the price vector for shrimps, it would appear rational to develop catch strategies targeted towards larger shrimp, as this allows much higher individual values for catch.

Fig 7 shows the growth in weight and in value (in relative terms) for *F. subtilis*, from age 150 (in days). Between days 150 and 400, weight is multiplied by 5 but value by 28. The gross return obtained by postponing the catch of shrimp to allow it to grow can easily be assessed: if natural mortality is equal to 0,2 per month, growth in weight and value between the two dates are 102% and 590 % respectively.

[4] For head-on shrimps, the standard commercial categories are defined by the number of individuals per kg.

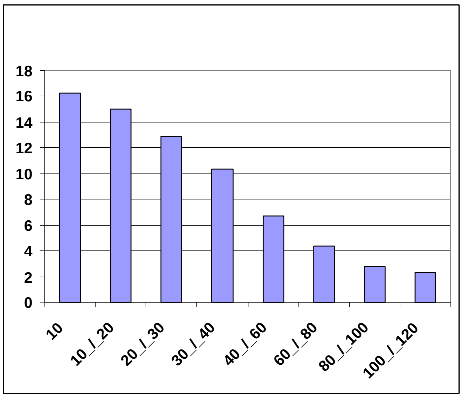

Figure 5. Shrimp price (*y* axis, €/kg) per commercial category (*x* axis)

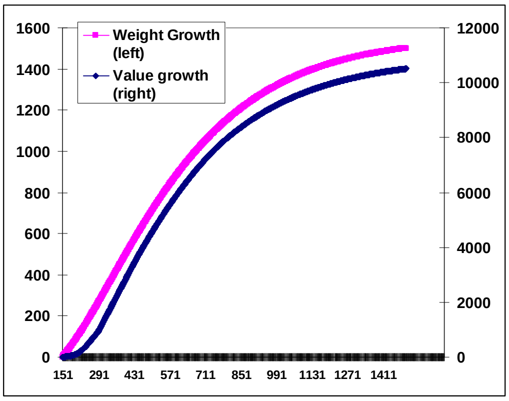

Figure 6. Percent growth of shrimp individual weight (left *y* axis, in %) and value (right *y* axis, in %), from age 150 (*x* axis, in days).

Two alternative strategies are available to Guyanese fishing firms: maximize the volume of lower valued shrimp, or maximize the price of landings by targeting less but bigger and better priced shrimps. Such choices imply a different spatial distribution of fishing effort, because high levels of biomass of small and medium sized shrimp are mostly located between the 30 and 50 meters isobaths (coastal fishing strategy), while the large sized shrimp are mostly located in more than 50 meters depth (the offshore fishing strategy).

This trade-off is strongly affected by the landings subsidy, as this adds a premium to the market price which is independent of the size category of shrimp. All else equal, this subsidy could be expected to have reinforced incentives to land larger volumes, hence to fish smaller shrimp in coastal waters.

4.1. Assessing the impact of Poseidom subsidy

Simulations were carried out with variable proportions of the coastal fishing strategy in total effort, from 0 to 1, from year 2006 up to year 2013. The total number of boats was held constant (30 boats) in all simulations and economic parameters were maintained at their 2006 values. The results (figure 8) show that optima for rent and for net private profit (NPP) are obtained for different proportions of the coastal strategy: 0.7 and 0.5 respectively, illustrating the difference between the private firm's and the social perspective on adequate harvesting strategies, if the objective in the fishery is to maximize economic returns. This result can be compared to the proportion of the coastal strategy actually observed in the fishery over the 1994-2006 period, which is 0.79 .The value of the observed proportion is much closer to the optimal value for NPP obtained by simulation. This result shows that the landings subsidy, which explains most of the difference between rent and NPP, has clearly worked as an incentive encouraging fishing units to concentrate their effort on coastal fishing. The ensuing structure of landings, dominated by smaller shrimp, has probably increased the sensitivity of the fishery to the downward trends in world market prices, as competition from aquaculture shrimp over the period has been stronger for small to medium sized shrimp.

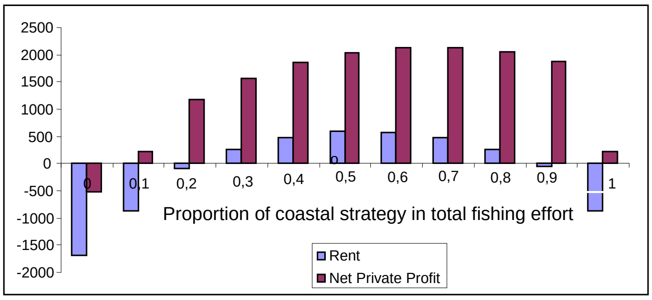

Figure 7. Impact of coastal strategy proportion on economic rent and net private profit

5. DISCUSSION AND CONCLUSIONS

The model was used to evaluate a wide range of alternative policies which could be envisaged in an attempt to avoid the economic collapse of the fishery. Most of the simulation results obtained show that economic results could be improved on the basis of shrimp recruitment pattern of the 2000-2005 period, and year 2006 economic parameters. In particular, the following additional simulations were carried out, of which we only summarize the key results:

- **Reduction of excess capacity:** the results show clear economic overcapacity of the fishery in the reference situation. The level of effort which maximizes net private profit is obtained with 20 boats vs. 51 in the reference situation. The fleet which maximizes economic rent is 10 boats. The difference between the two optima is explained by the levels of subsidies and taxes on profit in the fishery. These optimum fleets levels would be even more strongly reduced with increasing fuel price and decreasing shrimp prices. Achieving these levels of capacity would require regulating individual access to the fishery more strictly than is currently practised. This would allow firms to take better advantage of the favourable years in economic terms, which could at least partly offset the losses due to bad years, particularly as regards recruitment.
- **Closed seasons:** seasonal closures are often used in shrimp fisheries to allow the young individuals (recruits) to grow in weight and obtain a higher market value. Closed seasons also allow cuts in variable costs. *F. subtilis* recruitment data, from 1989 to 2006, follows an average seasonal pattern, with higher numbers of recruits from April to June. We simulated a seasonal closure for these months, from year 2007 onwards, compared to a reference simulation based on years 1989-2006 recruitment and year 2006 prices and costs. In this scenario economic results rapidly improve, but due to induced increases in fleet capacity when it is not regulated, improvements due to closures were dissipated at the end of the simulation. To be efficient in medium and long terms, seasonal closures would thus need to be associated with access regulations.
- **More selective fishing:** tropical shrimp fisheries have important impacts on marine biodiversity through fish by-catch and accidental catch of sea turtle. These impacts have a high environmental cost, in terms of ecosystem resilience and existence value for emblematic and endangered species. A related question concerns access to markets for products not compliant with conservation and sustainable fishing norms. Eco-labelling, defined as a way to differentiate environmentally safer fishery products on competitive markets, implies the adoption of gear technology limiting by-catches. In French Guyana, experiments of Turtle Excluding Devices (TED) and By-catch Reducing Device (BRD) have been tested. Their adoption entails a loss of shrimp catchability of 10% for both TED and BRD. Simulations were carried out with the assumption of a combined simultaneous loss of 19 % of catchability, due to the adoption of the two technologies, with no change assumed in cost or price parameters. The recruitment pattern of the 2000-2005 period, and year 2006 economic parameters were used for projection. The immediate decrease of fishing mortality due to decrease in shrimp catchability has a positive effect on biomass. In simulation year 2016, the fleet loses 3 boats (32 vs. 35) because of temporary economic losses after new technology adoption in year 2009. Four years after adoption, the global economic results hold constant, due to fleet and costs reduction, but also because of a slight improvement in the catch structure per size and in the associated average landing price (7.7 vs. 7.3 €/kg in 2016). Adoption of TED and BRD thus looks economically acceptable, if an adjustment of the number of boats permits to offset the decrease in catch and revenues.

Bio-economic modelling, if carried out beyond the development of qualitative representations, is often costly in time and data. To build a good bio-economic simulation model requires good estimations of biological (growth, natural and fishing mortality), economic (prices, costs) and institutional parameters (management rules and more general public policy tools impacting the fishery sector). Despite these requirements, such models are of great interest in the case of shrimp fisheries, because of the important economic value of shrimp and of the short-term response of shrimp fisheries to alternative management scenarios. Indeed, changes in management decisions can be followed by rapid effects, due to the rapid growth and short life span of shrimps, and the potential rent which can be extracted from such fisheries is high.

The example of the French Guyana shrimp fishery shows the importance of micro-economic harvesting strategies in determining the adaptability of fisheries to global changes. In this fishery, of particular importance if the trade-off between catch volume and catch value maximisation. Maximum yield value can be obtained by increasing average catch size with limited effort or the selection of an alternative fishing strategy (offshore vs. coastal). In this case economic results improvements are compatible with a reduction in environmental costs.

This case shows also how public policies initially aimed to support the development of fishing activity or to improve its competitiveness can alter the medium and long term viability of the sector. Changes are needed but often fishery public and private managers are hardly convinced of the potential positive outcomes of changes. Bio economic modelling may be a useful tool to help communicate the potential benefits of altering management strategies to improve the long-term viability of fisheries.

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