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Evaluation of selectivity and bycatch mitigation measures using bioeconomic modelling. The cases of Madagascar and French Guiana shrimp fisheries

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Abstract – Tropical shrimp fisheries are characterized by various interactions with their natural environment and with other fisheries. These latter interactions can be explained by the high quantity of bycatch taken by industrial trawler fleets, which has a significant impact on fish populations associated with shrimps and thus also on finfish fisheries. Bycatch also includes emblematic species, which are subject to strict conservation measures decided by the international community. It seems important to identify and assess the biological and economic consequences of different mitigation measures (increase of mesh size, turtle excluder devices and bycatch reducing devices). This communication is based on case studies undertaken on the Indian white prawn (*Fenneropenaeus indicus*) and speckled shrimp (*Metapenaeus monoceros*) fisheries in Madagascar and on the brown shrimp (*Farfantepenaeus subtilis*) and pink spotted shrimp (*Farfantepenaeus brasiliensis*) fishery in French Guiana. A review of the impacts of these fisheries on resources and ecosystems is made and some results of experiments on mitigation devices given. Finally, the results of simulations obtained using a multi-species, multi-fleet, age-structured bioeconomic model, including modifications of catchability and costs related to the adoption of these devices, is presented and discussed.

Key words: Shrimp fisheries / Selectivity / Bycatch / Mitigation / Bioeconomics / Modelling

1 Introduction

Tropical shrimp fisheries are well known to have a number of different impacts on ecosystems, biodiversity, species associated with the targeted shrimp and other fisheries (Alverson et al. 1994; Kelleher 2005, 2008). These impacts are negative and some incur serious costs that must be paid by society in general or by specific sectors like fisheries. Mitigation actions are one solution proposed to limit these impacts (Foster et al. 2010), and the question of their economic assessment is important in the context of increasing economic constraints. After a general presentation of the different impacts of tropical shrimp fisheries and the proposed mitigation actions, a more detailed analysis will be proposed with two case studies: the shrimp fisheries of Madagascar and of the French Guiana. The impacts of mitigation on resources and economic results were assessed using bioeconomic modelling. The bioeconomic simulation results will be presented and discussed, taking in account the economic and biological constraints of the two fisheries. These results and the limitations of bioeconomic modelling will also be discussed, including the important question of non-modelled impacts.

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General considerations

The general pattern of interactions within shrimp fisheries is presented in a simplified manner (Fig. 1). We consider the case of two fleets exploiting the same shrimp stock and impacting non-target species (bycatch). The first interactions considered are the reciprocal effects on catch volume and structure of each fleet, and on their subsequent revenues (here the shrimp price-per-size vector is assumed constant). The fishing effort and selectivity parameters of each fleet influence the total shrimp biomass and age structure. A particular case is sequential fishing, when a fleet targets the first age classes, generally using poorly selective gears, but also impacts the other fleets that are targeting adult shrimps, without reciprocal influences from the second fleet on the first. This particular situation has been described in many tropical shrimp fisheries, for instance in Ivory Coast (Garcia and Le Reste 1981) and Madagascar (Rodellec du Porzic and Caverivière 2008). The other main interactions concern non-target species (bycatch) which may or not be kept on board. Because of the high market value of shrimp, most bycatch species are discarded. This bycatch consists mainly of finfish, but also of emblematic species like turtles. As finfish is mainly discarded dead, this bycatch

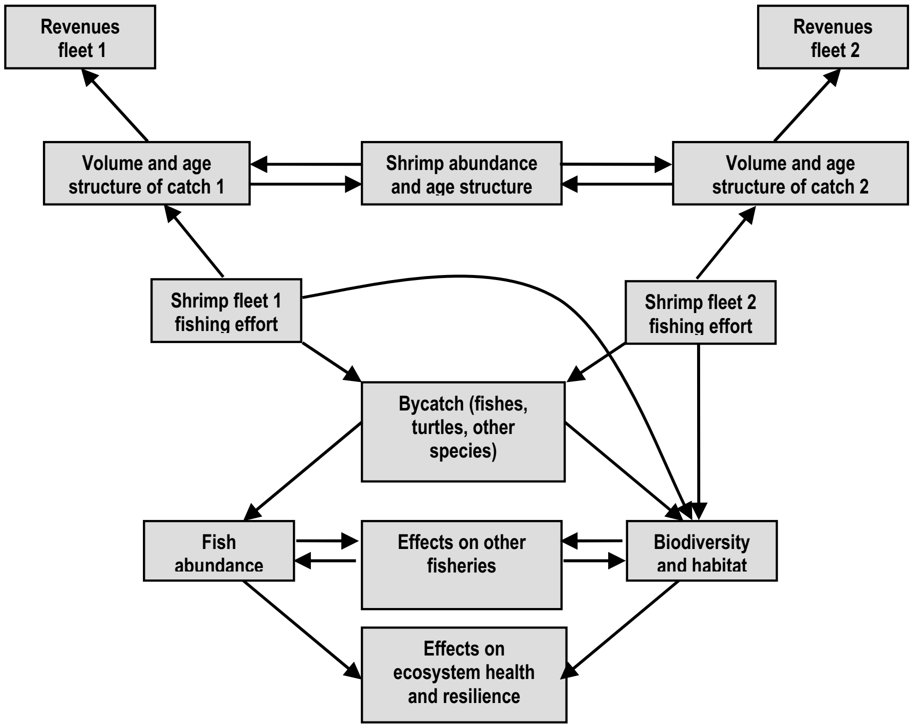

Fig. 1. Interactions in shrimp fisheries.

obviously impacts fleets targeting finfish, but it also has a more general effect on marine populations, habitats and biodiversity.

Tropical shrimp fisheries are characterised by the highest discard rate (ratio of discards to total catches) of all the world's fisheries. A global assessment of bycatch and discards in the world's fisheries (Alverson et al. 1994), covering mainly the 1980s, estimated that shrimp fisheries discards (9.51 Mt) represented 84% of their total catch and one third of all fisheries discards worldwide. For the same period, the overall discard ratio of world fisheries was estimated at 26%. Among the twenty fisheries with the highest recorded discard ratios (discard weight per landed target catch), fourteen were tropical shrimp fisheries.A more recent study (Kelleher 2008) showed a general decrease in the discard ratio of world fisheries (8%), but also showed that shrimp trawl fisheries still have the highest discard ratio (62%). In absolute value, their discards are estimated at 1.86 Mt and are still the single greatest source of discards.

NGOs (Environmental Justice Foundation 2003) and some producer and consumer states like USA considered that the environment and societal costs of shrimp trawl fisheries resulting from their impact on non-target species and marine habitats have to be greatly reduced. Mitigation devices were initially used to reduce mortality in sea turtles, now considered as highly endangered emblematic species. Turtle excluder devices (TED) have been progressively introduced into trawl fisheries since the eighties, after the first experience in the Gulf of Mexico fishery (Watson and Seidel 1980). Since 1989, US legislation (section 609 of United States Public Law 101–162 enacted in 1989) banned shrimp imports from countries where TED were not used (Gillett 2008). Bycatch reducing devices (BRD) were designed to reduce fish bycatch (Crawford et al. 2001; Eayrs 2007). Technologically, a BRD is an opening in the shrimp trawl net to allow finfish or other accidentally-captured aquatic animals to escape while the targeted shrimps are directed towards the tail bag or codend of the net. BRD design has been developed in conjunction with normal bottom trawling practices using trawl nets fitted with a TED. Since 1998, US shrimp trawlers of the Gulf of Mexico and South Atlantic regions were required to insert and use BRD in their nets and this technology has been progressively adopted by other countries (Brewer et al. 2006; Silva et al. 2010). Improving fishing selectivity through mitigation actions is often seen as a component of ecosystem-based fisheries management (FAO 2003).

The use of mitigation actions has potential effects on catches, revenues, costs and profits (Fig. 2), as they modify the catchability of shrimp and fish. While mitigation actions can increase the proportion of large shrimp in the catch and improve prawn product quality (FAO 2001), the impact on total shrimp catch is not so clear: the increase in catch for medium or large shrimp may not offset the losses for small shrimp. For fish, it can be conventionally assumed that the decrease in fish bycatch will improve fish biomass and biodiversity. The variation of revenues from fish is not always positively linked to that of fish catches: a reduction in fish bycatch in shrimp fisheries may not lead to a decrease in fish revenues of shrimpers if a greater share of fish is kept on board and sold. As regards possible cost effects, it is generally accepted that mitigation devices allow a reduction in energy costs due to improvement in the hydrodynamic characteristics of gears and a reduction in the drag exerted on the vessel (Rico Meija et al. 2007). The positive influence on prices resulting from consumer willingness to pay more for "eco-friendly" or eco-labelled products,

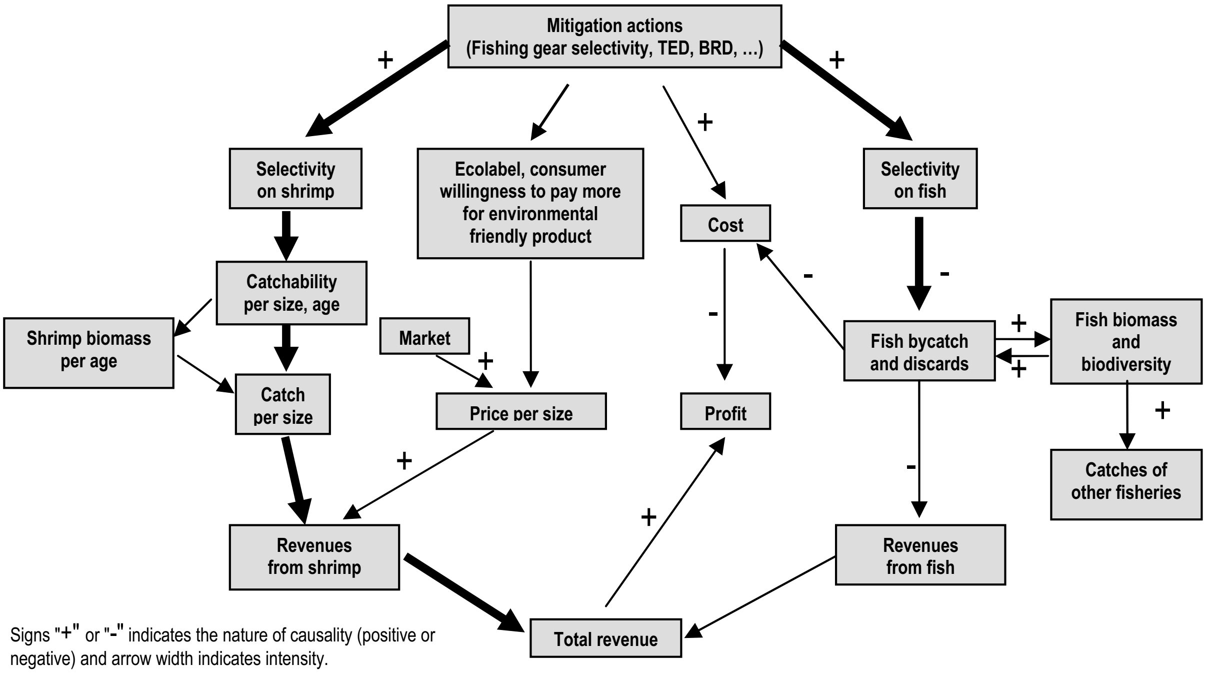

Fig. 2. Potential impacts of mitigation tools.

and the market price differential for larger individuals, may increase revenues gained from shrimp fisheries. However, the shrimp market is becoming increasingly dominated by cheap aquaculture products and the existence of a price premium for eco-labelled shrimp is still a matter of debate.

2 Case studies

Two tropical shrimp fisheries case studies are presented in this paper: those of Madagascar and French Guiana (Figs. 3 and 4).

The Malagasy industrial trawl fishery (vessels with engine power between 50 and 500 hp) began to exploit coastal shrimp stocks in the 1960s and its development stage lasted until the middle of the 1990s, when the total boat number was close to 80 units (Fig. 5a). According to the national legislation, two other sub-sectors exist in the shrimp fishery: "artisanal" (small motorized trawlers less than 50 hp) and "traditional" (non motorized canoes) whose fishing zones partially overlap the industrial fishing grounds. The development of an industrial trawl fishery was strongly supported by foreign investment (mainly French and Japanese) in local fishing firms and shrimp are mainly sold to foreign markets (Europe and Japan). The industrial fishery operates in shallow waters near mangroves zones and there are strong technical interactions with artisanal and traditional fishing units. Since 2003, the fishery has faced serious difficulties: catches fell to less than 4000 t in 2009, compared with a mean catch of 8300 t during the 1995–2003 period, and the industrial fleet was reduced to 42 boats. During the last decade, different management measures have been implemented in Madagascar concerning fishing capacity and reduction of bycatch (Chaboud et al. 2008; Fennessy et al. 2008). These include an increase in trawl codend mesh size (from 40 to 50 mm), a reduction in trawl gear size, the extension of the closed fishing seasons and a reduction in night trawling. Adoption of TED and BRD for industrial trawlers was legally decided in 2003 after experiments and discussion among stakeholders. In 2005, an evaluation of industrial trawler bycatch (Randriarilala et al. 2008) showed that the bycatch ratio and discard ratio (respectively 72% and 48% of total catch) for Madagascar (Fig. 6) were close to the international estimates (Kelleher 2005).

The exploitation of the shrimp stocks of the Guiana continental shelf began at the end of the 1950s when US shrimp fishing boats extended their fishing operations to the area located between the Gulf of Paria in Venezuela and the river Rio Pará in northern Brazil. US companies were established in French Guiana in 1960 (Dintheer et al. 1991). For nearly 20 years, Cayenne (French Guiana) and Paramaribo (Surinam) were used as local landing sites by more than 400 US shrimp boats for transshipment of their landings of up to 20 000 t to the US market. Japanese boats also entered the French Guiana fishery. The implementation of 200 miles of exclusive economic zones (EEZ) in 1977 by Surinam, Guyana, France and Brazil gave these countries full control of their aquatic marine living resources.

For French Guiana (Fig. 5b), the objective was first to promote the development of a national fleet to replace the foreign vessels in the French EEZ. This so-called "*francisation*" was supported by strong State intervention through subsidies and infrastructure building. In 10 years, the French shrimp trawler fleet increased from nil to 70 units, while the number of US trawlers decreased to zero. This rapid development of the French Guiana fishery was also related to the expansion of the international market for tropical penaeid shrimps. The

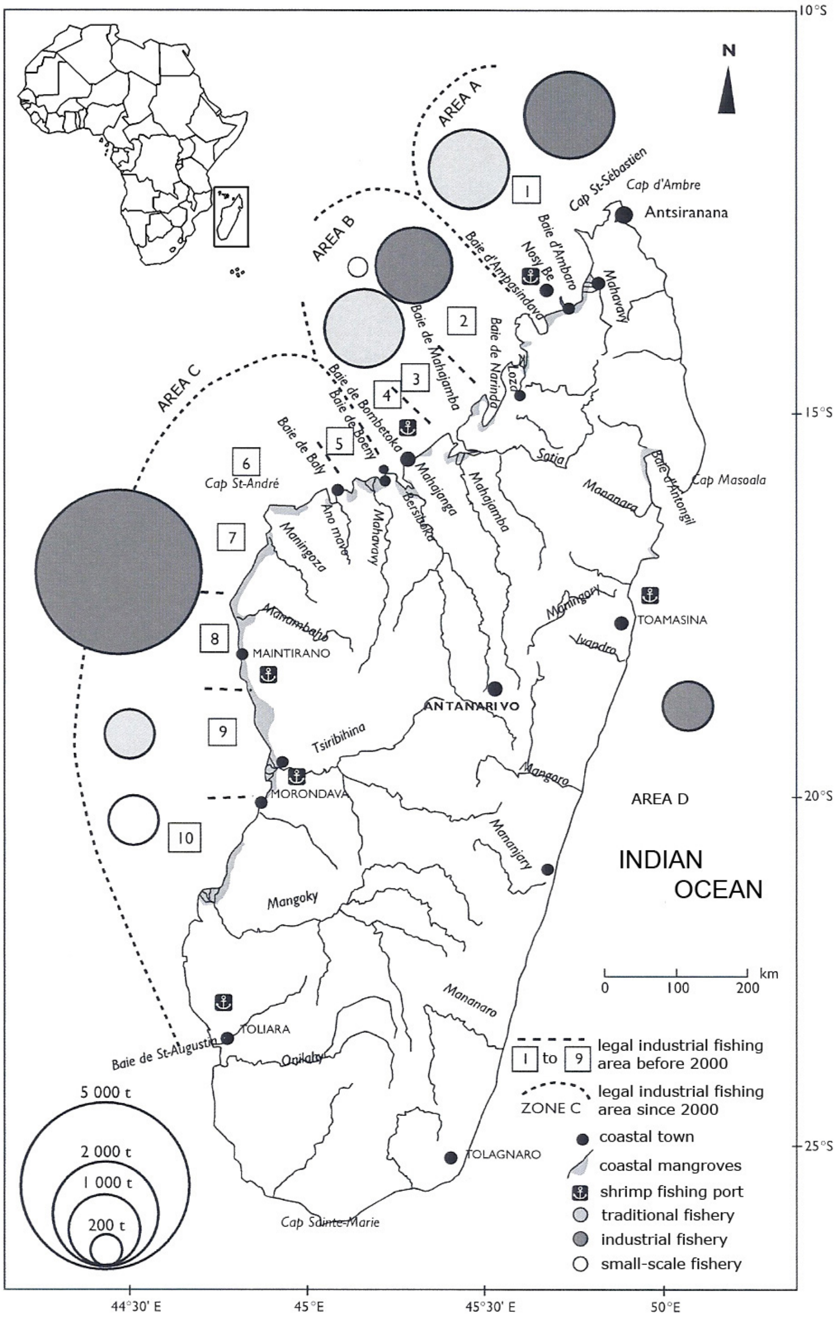

Fig. 3. Madagascar fishing areas.

success story of the 1980s was, however, short-lived. Since the beginning of the 1990s, the sector entered a period of economic hardship (Charuau and Vendeville 2008) and, in 1993, three important fishing firms were closed. Since 1999, landings have shown a decreasing pattern, as has the number of trawlers (Vendeville et al. 2008). During the *francisation* of the fleet and up to 1995, fishing effort concentrated in shallow waters where the biomass of *Farfantepenaeus subtilis* (brown shrimp), the main target species, is high but mainly composed of small individuals. In the past 15 years, landings have become increasingly dominated by small brown shrimp (Charuau 1999, 2000). From economic and social perspectives, the fishery experienced two main crises, in 2000–2001 and 2006 onwards, which resulted in a reduction of fleet size and the closure of smaller firms, as well as a reduction of vessel numbers in those firms that remained active. By the beginning of 2009 the situation had worsened, with only 15 active fishing units remaining in the sector. An important factor in these dynamics is the contribution of the European subsidy (proportional to shrimp landings) to the short run economic viability of the sector and its negative effects in terms of overcapacity and fishing strategy choices (Chaboud and Thébaud 2009).

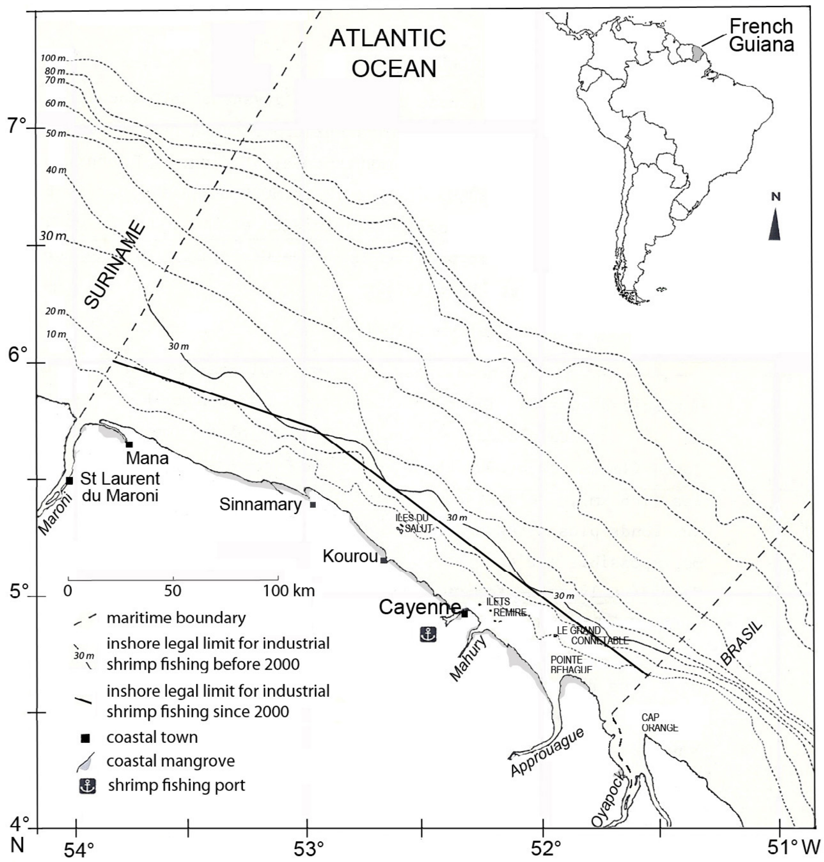

Fig. 4. French Guiana fishing area.

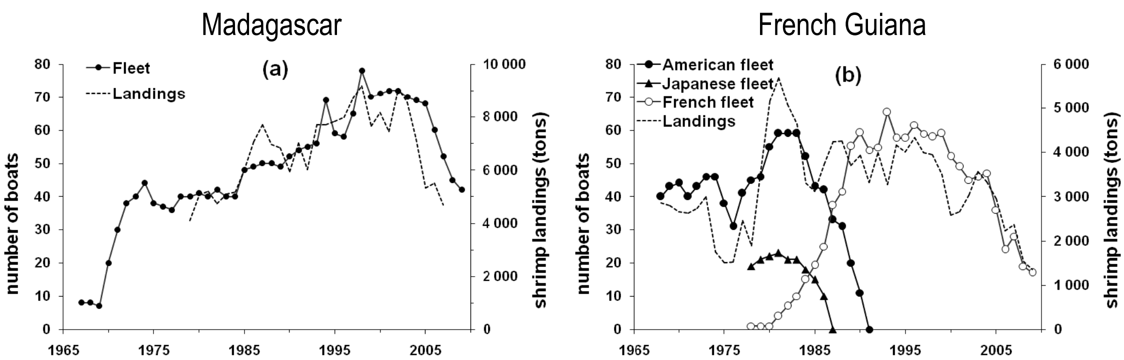

Fig. 5. Shrimp fishery development in Madagascar (a) and French Guiana (b).

Since 1980, French scientists have studied the shrimp bycatch question (Lemoine et al. 1982; Vendeville 1984). In 2005 the bycatch and discard ratios for French Guiana (Fig. 6) were estimated at 85% and 78%, respectively (Vendeville et al. 2008). These high levels of discards, compared to international estimates, may be explained by European legal restrictions on bycatch landings.

For these two case studies, the adoption of mitigation devices for bycatch and mesh size increase took place in a context of economic difficulties due to falling international shrimp prices and increasing energy costs. It therefore seems important to assess the economic consequences of mitigation, as well as effects on biomasses and catches.

3 Methods

3.1 Model specifications

For the two case studies, bioeconomic models (Chaboud 2008; Chaboud and Thébaud 2009) were proposed to assess the viability of the fisheries and to produce scenarios based

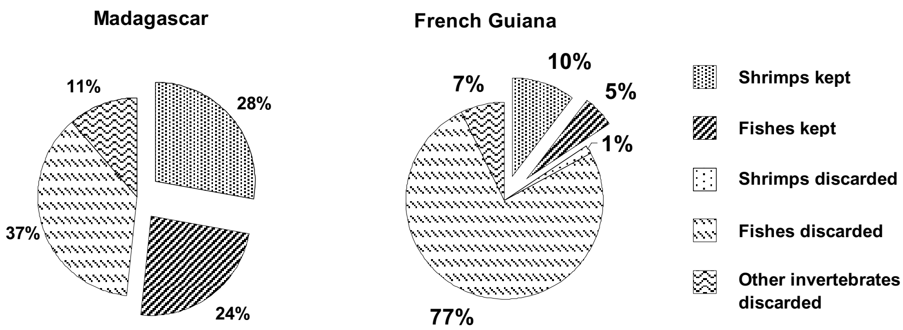

Fig. 6. Bycatch in tropical shrimp trawl fisheries – Madagascar and French Guiana.

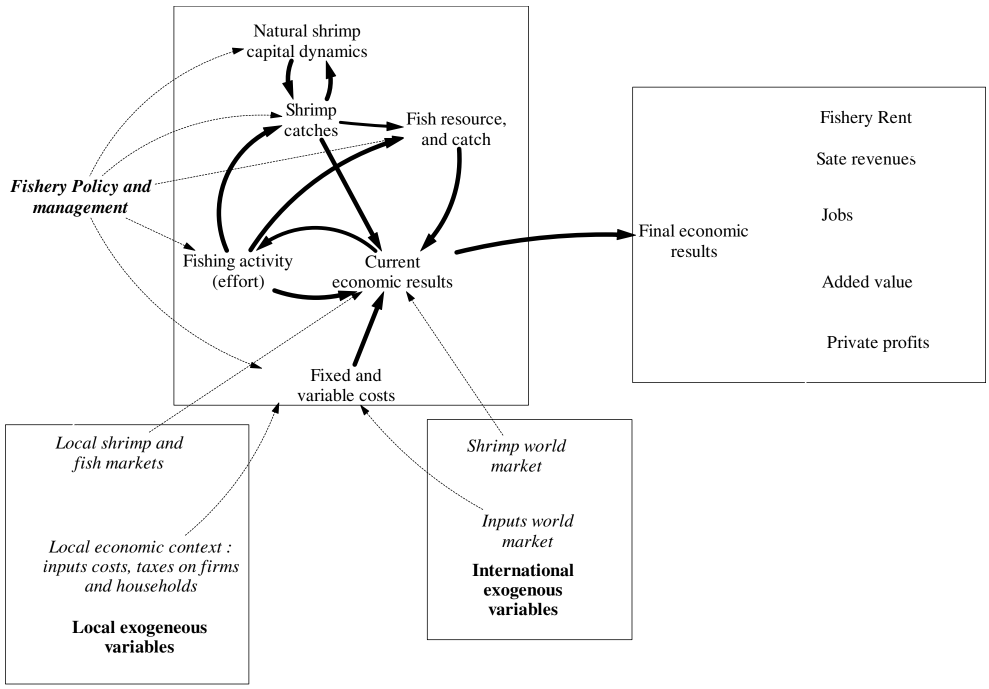

Fig. 7. General structure of bioeconomic models used in this study.

on different management options (capacity control, seasonal closures and taxation) and regulations (gear characteristics). These models are based on the same general structure (Fig. 7). A central module includes the shrimp and fish population dynamics and current economic results calculations. It is fed by three exogenous modules: (I) management decision tools, which can be determined at the beginning or during the simulation; (2) labour and inputs costs; and (3) international shrimp market parameters.

Apart from this common general structure, each of the models has some specific aspects (Table 1). Two main differences exist. The first concerns the simulation time span. The Malagasy model produces one year simulations based on year 2003 parameters values and the recruit values input into the projection are the values assessed for this year using aged-based virtual population analysis (VPA) from the period 2002–2005 (Caverivière and Razafindrakoto 2008a, 2008b). The French Guiana model makes long term simulations, covering the 1994–2006 past period (adjustment to observed data) and a projection period of ten years from 2007 onwards, where recruit values are the monthly means of recruits assessed using aged-based VPA between 2000 and 2005 (Vendeville et al. 2008). The Malagasy model parameters are kept constant during the simulations of one year, whereas the parameters in the French Guiana model can be modified during the projection period.

3.2 Simulation objectives

The two models were used to assess the impact of mesh size increase and adoption of mitigation devices (TED and BRD) on shrimp and fish biomasses, catches and, more generally, fisheries economic results from the points of views of private boat owners (companies) and society. This last distinction is likely to be important because of the role of subsidies to French Guiana's fishery and of fishing license duties in Madagascar. The main indicators used were private profits for boat owners, economic rent and state revenues for the society.

Table 1. Characteristics of the two bioeconomic models.

	MADAGASCAR	FRENCH GUIANA
Shrimp species	*Fenneropenaeus indicus* and *Metapenaeus monoceros*	*Farfantepenaeus subtilis* and *Farfantepenaeus brasiliensis*
Fish species	1 fish stock representing all impacted fish species	1 fish stock representing all impacted fish species
Fleet	12 types of fishing units (2 industrial, 1 small-scale, 9 traditional) Fleet numbers are defined before simulation.	Homogeneous industrial fishing fleet with: Two fishing strategies: coastal (between 30 and 50 m isobaths) and deep water (>50 m isobath); Endogenous fishing capacity (over projection period) depending on last year private profits; Possibility to maintain the boats number at a given level during the projection period; Economic module calculating annual performance from firm & social perspectives.
Fishing zones	4 areas (A,B,C,D)	2 areas (30–50 m and 50–100 m)
Simulation time step	Day	Day
Main parameters	Monthly recruits estimated by aged-based VPA, growth, mortality, catchability per fishing type/species, price per commercial category, input costs, subsidies, taxes Parameter values were kept constant during simulation	Monthly recruits estimated by aged-based VPA , growth, mortality, catchability per fishing strategy/species, price per commercial category, inputs costs, subsidies taxes. Parameters values could be modified during the projection period.
Simulation time span	One year	Simulation of long-terms adjustments: over the past period 1994–2006 followed by a ten-year projection period.
Economic parameters base year	2005	2006

The consequences of mesh size increase were modelled by the mean of shrimp selection curves (Fig. 8). For French Guiana, three selectivity curves were used, obtained from selectivity experiments and corresponding to three different mesh sizes: 40, 45 and 50 mm (Vendeville et al. 2008). The 45 and 50 mm mesh size selectivity curves were used during the projection simulation period, from the beginning of year 2008, and the 40 mm selectivity curve was used as a reference value over the total simulation period. Selectivity results were not available in Madagascar. Instead, two curves were proposed, corresponding to L_{50} values of 21.5 and 24 mm (cephalothoracic length), and based on selectivity curves estimated for *Farfantepenaeus notialis* in Sénégal (Garcia and Le Reste 1981).

Table 2. Simulations hypothesis concerning impact of TED and BRD adoption.

	Hypothesis 1 %	Hypothesis 2 %	Hypothesis 3 %
Effect on shrimp catchability	–5	–5	–5
Effect on fish bycatch	–38	–38	–38
Effect on fuel cost	0	–5	0
Effect on market price	0	+5	+5

Different simulations were undertaken for the two fisheries using three sets of hypotheses (Table 2) about the impact of TED and BRD adoption on shrimp and fish catchability, fuel costs and shrimp market price. The proposed parameter values for TED and BRD adoption impact on catchabilities came from experiments made by Ifremer's fishery technology teams in the two countries (Vendeville et al. 2008), with the collaboration of professional fishers. These values are consistent with experiments made in other fisheries. The important point here is that TED and BRD did not induce a significant loss of shrimp, as confirmed by the literature on other fisheries (Rico Meija and Rueda 2007). The value chosen for reduction in fish catchability appears quite conservative (–39%) compared with the more significant effect observed in other cases.

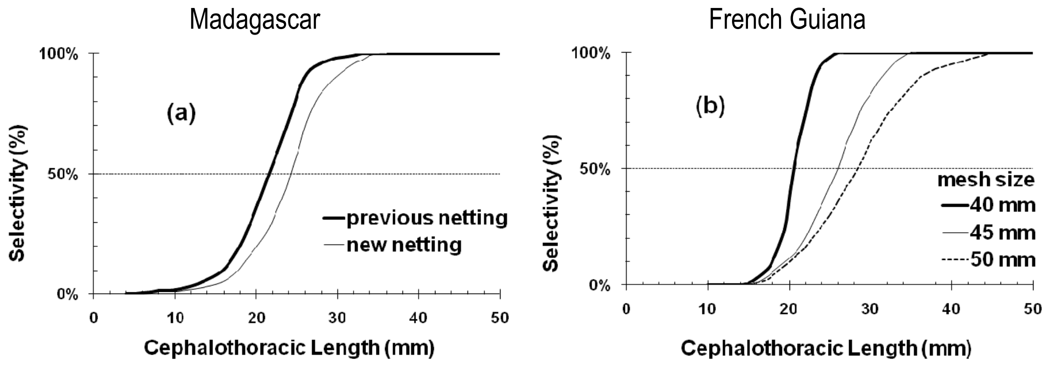

Fig. 8. Selectivity in Madagascar (a) and French Guiana (b).

4 Results

4.1 Consequences of mesh size changes

The two bioeconomic models were first used to simulate the consequences of mesh size changes for industrial trawlers using the selectivity curves presented earlier (Fig. 8), and improvements in shrimp biomass (Fig. 9) were significant. In Madagascar, the shrimp biomass had increased by 21% (compared with the base run value) at the end of the simulation year. In French Guiana, at the end of the ten-year projection period, the improvements in biomass were 21% and 30% for the 45 and 50 mm mesh, respectively, compared with the results obtained for the initial 40 mm mesh. These results underline the contribution of selectivity measures to improve the sustainability of resource exploitation.

The effects on catch and general economic results are given in Tables 3 and 4. In Madagascar, mesh increase led to a slight reduction in total shrimp catch of –1.4%. The greatest catch reduction for the industrial fleet (–7.8%) was offset by an improvement for artisanal (+19.7%) and traditional (+10.9%) fleets, whose gear characteristics were considered unchanged. The artisanal fishery, which uses the same fishing grounds, was the principal beneficiary of the decrease of industrial fishing mortality. In French Guiana, the shrimp catch variation (between –8% and –20%) was very close to the Malagasy estimate for the 45 mm mesh. When the 50 mm was used, the simulated total catch was further reduced (–20%). This result underlines the importance of experiments and a gradual approach to the implementation of trawl mesh size changes in shrimp fisheries, but is based on the assumption that there were no multispecies effects such as feeding interactions.

The effects on shrimp catch per commercial grade (number of shrimps per kg) are presented for the main target shrimp species in Figure 10. Mesh size significantly modified the partition per grade in volume and, more importantly, in value, because price increases with individual size. The contribution of small commercial grade shrimp (less than 40 to 60 individuals per kg) was less for both countries after a mesh size change.

For the Malagasy case study, mesh size changes also led to profit redistribution between subsectors. The overall private profit of the fishery improved slightly (+3%), but with contrasted results between subsectors: industrial (–8%), artisanal (+28%) and traditional (+16%), due to the catch redistribution

Table 3. Impact of trawl mesh change in Madagascar.

Madagascar			
L_{50} (mm CL)	21.5	24	
Shrimp catch (ton)	11 860	11 699	
	Value	Value	Δ (%)
Total firms revenues (M MGA)	90 842	91 734	+1
– Industrial	68 157	66 596	–2
– Artisanal	8 307	9 389	+13
– Traditional	4 318	4 561	+6
Total private profits (M MGA)	–3 842	–3 717	+3
– Industrial	–6 351	6 871	–8
– Artisanal	–973	2 565	+28
– Traditional	505	588	+16
State revenues (M MGA)	11 046	11 022	+2
Economic rent (M MGA	7 091	7 575	+7
Valorisation per kg (MGA/kg)	6 530	6 676	+2

CL: Cephalothoracic Length; M MGA: millions of Malagasy Ariary.

Table 4. Impact of trawl mesh change in French Guiana.

French Guiana					
Mesh size	40 mm	45 mm		50 mm	
	Value	Value	Δ (%)	Value	Δ %
Shrimp catch (T)	2 500	2 300	–8	2 000	–20
Firms revenues (10^3 €)	14 800	15 700	+6	15 100	+4
Private profits (10^3 €)	1 450	2 011	+39	1 600	+10
State revenues (10^3 €)	–1 627	–1 155	+20	–1 109	+32
Economic rent (10^3 €)	–783	–285	+375	62	+108
Valorisation per kg (€/kg)	5.6	6.6	+18	7.0	+25

previously noted among fleets whose fishing zones partially overlap. Societal economic results (state revenues and economic rent) also improved. In this case, mesh change in the industrial fleet is economically viable from the point of view of society, but some compensation could redistribute the benefits to make it more acceptable for industrial boats owners.

For French Guiana, the adoption of the 45 mm mesh led to better results than with the 50 mm one (Table 4. Despite the significant decrease in catch, we observed an improvement in revenues (6% and 4% respectively) and profits (39% and 10%) due to the greater valorisation of larger landed shrimps. The state net revenues were always negative but were improved by the two alternatives. The best result was obtained, as for

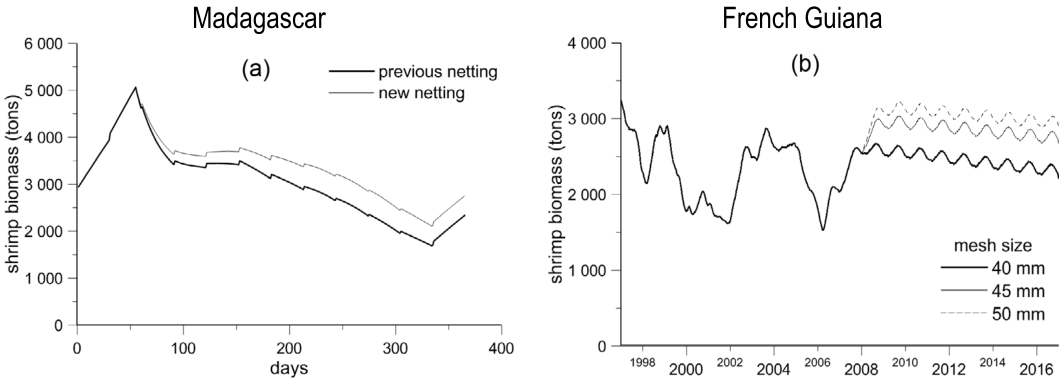

Fig. 9. Impact of a mesh size change on shrimp biomass in Madagascar (a) and French Guiana (b).

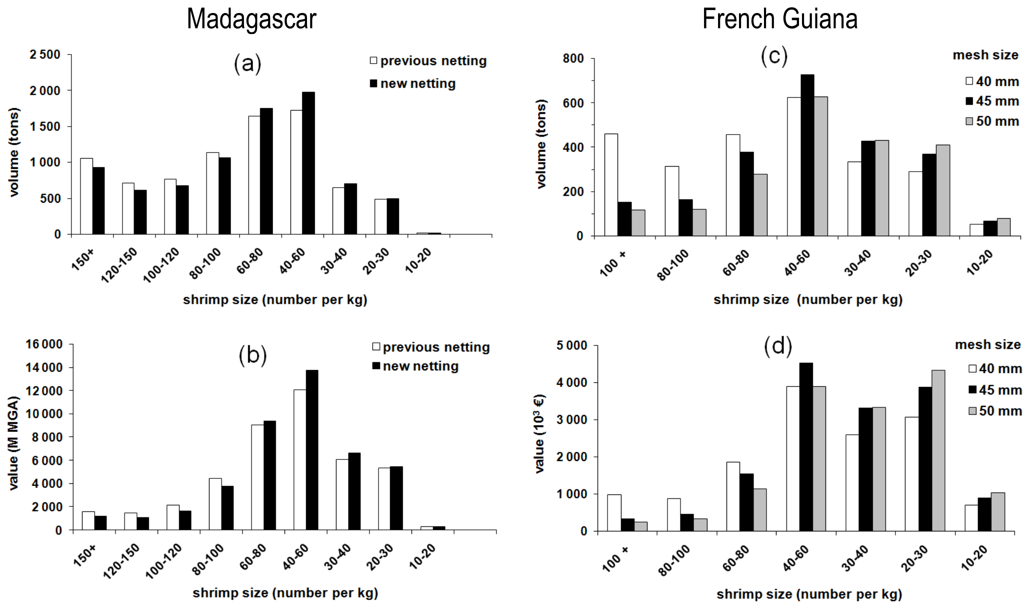

Fig. 10. Impact of a mesh size change on annual volume and value per commercial grade in Madagascar (a, b) and French Guiana (c, d).

economic rent, with the larger mesh (50 mm), and was linked to the decrease of subsidies (a negative state revenue), whose value is proportional to shrimp landings.

4.2 Consequences of TED and BRD adoption

These consequences were estimated by simulation using the set of hypotheses (on catchability, costs and prices, Table 2).

The shrimp biomass levels slightly improved in the two case studies (Fig. 11), but the fish biomass responded more significantly (Fig. 12): +8% in Madagascar and +6% in French Guiana. The total shrimp catch decreased in French Guiana but remained constant in Madagascar, where the improvement of the catches of the artisanal and traditional sub sectors (not concerned by mitigation decisions) offset the industrial losses.

Economic impacts are shown in Tables 5 and 6. When TED and BRD adoption by industrial trawlers only had catchability effects (hypothesis 1), private profits decreased for Madagascar (–8%) and French Guiana (–9%). In Madagascar, profit improved for the artisanal (14%) and traditional (11%) sub sectors, which are the beneficiaries of the positive changes in fish and shrimp biomass levels. When hypothesis 2 and 3 were used, industrial trawlers for the two cases and other sub sectors in Madagascar produced better economic results. These results particularly show the importance of a positive market response to support mitigation initiatives. For the two countries, state revenues and economic rent significantly improved when hypotheses 2 and 3 were used. The relative variations were greater in French Guiana than in Madagascar, where a large part of state revenues and economic rent (industrial fishing licenses) is not impacted by mitigation decisions.

5 Discussion

Two main discussion points can be raised regarding the positive biological and economic results obtained with mesh size increase. First, a critical implicit assumption is the survival of shrimp escaping through larger meshes. A large fraction of

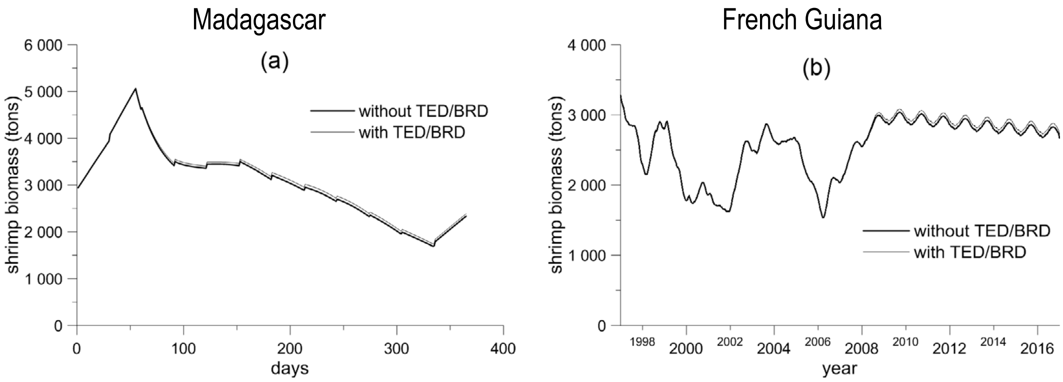

Fig. 11. Impact of Turtle excluder devices /Bycatch reducing devices (TED / BRD) adoption on shrimp biomass in Madagascar (a) and French Guiana (b).

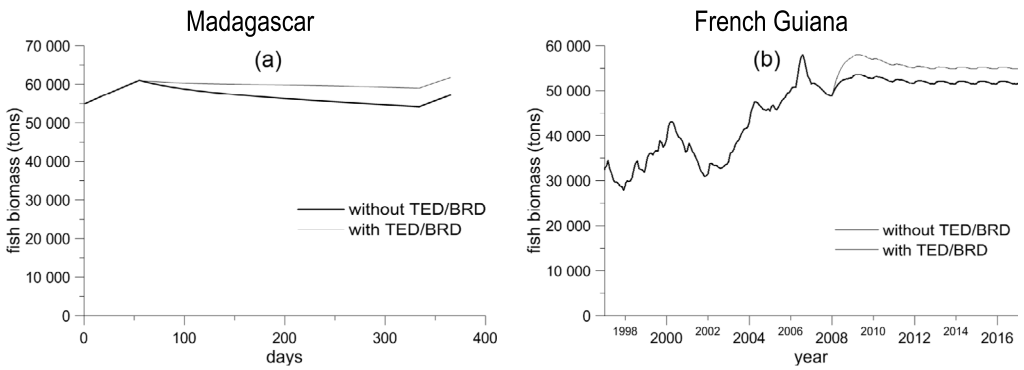

Fig. 12. Impact of TED/BRD adoption on fish biomass in Madagascar (a) and French Guiana (b).

Table 5. Impact of TED and BRD adoption in Madagascar.

	Base	Hyp. 1		Hyp. 2 (cost and price effects)		Hyp. 3 (price effect only)	
	Value	Value	Δ (%)	Value	Δ (%)	Value	Δ (%)
Shrimp catch (t)	11 860	11 832	0	11 832	0	11 832	0
Fish catch (t)	37 182	30 458	–18	30 458	–18	30 458	–18
Total firms revenues (M MGA)	80 784	80 781	0	84 144	+4	84 144	+4
– Industrial	68 157	67 430	–1	70 374	+3	70 374	+3
– Artisanal	8 307	8 838	+6	9 118	+10	9 118	+10
– Traditional	4 318	4 512	+4	4 651	+6	4 651	+6
Total private profits (M MGA)	–3 842	–4 011	–4	–655	+83	–1 201	+69
– Industrial	–6 351	–6 859	–8	–3 724	+41	–4 250	+33
– Artisanal	2 003	2 285	+14	2 466	+23	2 466	+23
– Traditional	505	563	+11	603	+19	603	+19
State revenues (M MGA)	11 146	11 140	+1	11 582	+5	11 536	+4
Economic rent (M MGA)	7 091	7 060	0	10 856	+53	10 258	+45
Valorisation per kg (MGA/kg)	5 690	5 694	0	5 968	+5	5 968	+5

M MGA: millions of Malagasy Ariary.

escaping shrimp supposedly becomes available again for fishing after escaping, given the overall natural mortality. If we choose the alternative assumption, that a proportion of escaping shrimps are subject to additional mortality due to death or injuries when escaping, then the results concerning the technical and economic efficiency of mesh size should be reconsidered. The second point of concern is the selectivity efficiency when high yields per tow may create clogging of codend meshes. This question seems more relevant for the Malagasy fishery where high yields per tow are observed at the opening of the fishing season.

Regarding the biological impact of mitigation, a number of other important questions are not addressed by the bioeconomic models used here. Some authors have discussed the consequences of reducing shrimp fisheries bycatch, taking into account the trophic relationships between all species directly or indirectly impacted by shrimp fishing (Zhou 2008). An important question here is the feedback effect of reduced

Table 6. Impact of TED and BRD adoption in French Guiana.

	Base	Hyp. 1		Hyp. 2 (cost and price effects)		Hyp. 3 (price effect only)	
	Value	Value	Δ (%)	Value	Δ (%)	Value	Δ (%)
Shrimp catch (t)	2 352	2 288	–3	2 288	–3	2 288	–3
Firms revenues (10^3 €)	15 721	15 390	–2	16 159	+3	16 159	+3
Firms profits (10^3 €)	2 011	1 828	–9	2 554	+27	2 262	+32
State revenues (10^3 €)	–1 155	–1 168	–1	–921	+20	–985	+14
Economic rent (10^3 €)	285	96	–66	989	+247	715	+151
Valorisation per kg (€/kg)	6.6	6.7	+2	7.0	+6	7.0	+6

bycatch on shrimp biomass (Crowder and Murawski 1989). This effect can be negative if shrimp predators constitute a significant component of the bycatch. Gribble (2003) used an ECOPATH II and ECOSIM ecosystem models to evaluate the consequences of different management scenarios for the Great Barrier Reef shrimp fishery in Australia. He showed that increased predation and/or competition of bycatch species following mitigation device adoption contribute to decreasing prawn biomass. In the Caribbean Sea Columbian shrimp fishery, using the same trophic models, Criales-Hernandez et al. (2006), showed significant rebuilding of biomass of croakers (scianids), ray, shark, snappers, and overall biomass of middle-low trophic level consumers that constitute most of the bycatch, without any negative effect on shrimp biomass. For Madagascar and French Guiana, data are not yet available to allow such ecosystem models to be built, and the bioeconomic model used was not able to take into account feedback ecosystemic interactions like those studied by Gribble (2003).

A last discussion point concerns the costs of shrimp fishing. In our bioeconomic models, only direct monetary (or market) costs are taken into account. The shift of management from optimizing the economic yield of a fishery (as most bioeconomic models do) to sustainable development objectives should include externalities (negative impacts on others users) and non-market environmental costs. In Madagascar, externalities from shrimp fisheries on traditional and artisanal fish fisheries look significant, but data were not available to include them in our model. In French Guiana there are no significant interactions (among those tested here) between shrimp trawling and small coastal gill net fishery operating in very shallow waters. A more important question is that of non-market environmental costs or values. Some species like sharks, ray, and turtles are, or are becoming, emblematic. They have a high existence value, which, although attested by the international effort to protect them, is still not estimated. Thus, we have to considerer that some benefits for mitigation are under-evaluated in our models.

6 Conclusion

The economic feasibility of better gear selectivity and mitigation device adoption in industrial trawl fisheries has been positively demonstrated by bioeconomic simulations assuming no negative ecosystemic feedback through increased predation. The possibility of cost reductions and price increases make a slight improvement of profits achievable. Where fishery sub sectors are in competition for a resource, as in Madagascar, some profit redistribution may occur in favour of fishery segments that are unaffected by mitigation. From the societal point of view, direct economic results (state revenues or economic rent) are always improved by mitigation. These results do not, however, take into account some possibly important feedback effects, like the increase of predation on shrimps when predator removal through bycatch is reduced by mitigation. The incorporation of ecosystemic feedback effects could, therefore, be the next step to a better evaluation of the interest of mitigation tools. The positive evaluation of mitigation could be more persuasive if the existence value of emblematic endangered species was explicitly taken into account. From this perspective, the mobilization of environmental evaluation economic methods in addition to more traditional bioeconomic approaches may also contribute to go further in the evaluation of the contribution of selectivity and mitigation tools to the sustainable management of tropical shrimp fisheries.

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References

Alverson L.A., Murawski S.A., Pope J.G., 1994, A global assessment of fisheries, bycatch and discards. FAO Fish. Tech. Pap. Rome 339.

Brewer D., Heales D., Milton D., Dell Q., Fry G., Venables B., Jones P., 2006, The impact of turtle excluder devices and bycatch reduction devices on diverse tropical marine communities in Australia's northern prawn trawl fishery. Fish. Res. 81, 176–188.

Caverivière A., Razafindrakoto H., 2008a, Dynamique des populations des crevettes *Fenneropenaeus indicus* dans les quatre zones d'aménagement à Madagascar. In: Caverivière A. Chaboud C., Rafalimanana T. (eds.). Les crevettes côtières de Madagascar. Biologie, exploitation, gestion. Marseille, IRD Editions, pp. 169–225.

Caverivière A., Razafindrakoto H., 2008b, Dynamique des populations des crevettes *Metapenaeus monoceros* dans les trois zones d'aménagement à Madagascar. In: Caverivière A., Chaboud C., Rafalimanana T. (eds.). Les crevettes côtières de Madagascar. Biologie, exploitation, gestion. Marseille, IRD Editions, pp. 226–236.

Chaboud C., 2008, modélisation bioéconomique de la pêcherie crevettière malgache. In: Caverivière A. Chaboud C., Rafalimanana T. (eds.). Les crevettes côtières de Madagascar. Biologie, exploitation, gestion. Marseille, IRD Editions, pp. 261–310.

Chaboud C., Rafalimanana T., Razadindrakoto H , 2008, Evolution du système d'aménagement, relations avec la dynamique de l'exploitation et de son contexte. In: Caverivière A., Chaboud C., Rafalimanana T. (eds.). Les crevettes côtières de Madagascar. Biologie, exploitation, gestion. Marseille, IRD Editions, pp. 327–344.

Chaboud C., Thébaud O., 2009, Bioeconomic model of the dynamics of fisheries facing global economic and environmental change: the French Guyana shrimp fishery. In: Anderssen R.S., Braddok R.D., Newham L.T.H. (eds.). 18 th world IMACS congress and MODSIM09 international congress on modelling and simulation, Canberra, Bruxelles: MSSANZ, IMACS.

Charuau A., 1999, Western Central Atlantic Fishery Commission national reports presented and stock assessment reports prepared at the CFRAMP/FAO/DANIDA stock assessment workshop on the shrimp and groundfish fisheries on the Guiana-Brazil shelf, Port-of-Spain, Trinidad and Tobago, 7–18 April 1997. FAO Fish. Rep. Rome, 600.

Charuau A., Die D. 2000, The fishery for brown shrimp (*Penaeus subtilis*) in French Guiana. In: FAO/Western Central Atlantic Fishery Commission. Report of the third Workshop on the Assessment of Shrimp and Groundfish Fisheries on the Brazil-Guianas Shelf. Belém, Brazil, 24 May-10 June 1999. FAO Fish. Rep. Rome, 628, pp. 53–71.

Charuau A., Vendeville P., 2008, Le secteur de la pêche en Guyane. Atlas illustré de la Guyane. 4éme edn., J Barret, Laboratoire de Cartographie de la Guyane, IESG- ARUAG, pp. 72–77.

Crawford C.R, Steele P., McMillen-Jackson A.L., Bert T.M., 2011, Effectiveness of bycatch reduction devices in roller-frame trawls used in the Florida shrimp fishery. Fish. Res. 108, 248–257.

Criales-Hernandez M.A., Douarte L.O., Garcia C.B., Manjarrés L., 2006, Ecosystem impacts of the introduction of bycatch reduction devices in a tropical shrimp fishery: insights through simulation. Fish. Res. 77, 333–342.

Crowder L.B., Murawski S.A., 1998, Fishery bycatch: implications for management. Fisheries. 23, 8–17.

Dintheer C., Gilly B. , Le Gall J.-Y., Lemoine M., Rosé J., 1991, La recherche et la gestion de la pêcherie de crevettes pénéides en Guyane Française de 1958 à 1988: trente années de surf. In: Durand J.R., Lemoalle J., Weber J. (eds.). Symp. Int. La Recherche face à la Pêche artisanale, ORSTOM-IFREMER, Montpellier France, 3–7 juillet 1989, Paris ORSTOM, tome II, pp. 859–870.

Eayrs S., 2007, A Guide to bycatch reduction in tropical shrimp-trawl fisheries. Revised edition. Rome, FAO.

EJF, Environmental Justice Foundation, 2003, Squandering the seas. How shrimp trawling is threatening ecological integrity and food security around the world. EJF, London. www.ejfoundation.org.uk

FAO, 2001, Tropical shrimp fisheries and their impact on living resources. Tropical shrimp fisheries and their impact on living resources. Shrimp fisheries in Asia: Bangladesh, Indonesia and the Philippines; in the Near East: Bahrain and Iran; in Africa: Cameroon, Nigeria and the United Republic of Tanzania; in Latin America: Colombia, Costa Rica, Cuba, Trinidad and Tobago, and Venezuela. FAO Fisheries Circular, Rome, No. 974.

FAO, 2003, Fisheries management 2: the ecosystem approach to fisheries. FAO Technical Guidelines for Responsible Fisheries No. 4, Suppl. 2.

Fennessy S.T., Vincent X., Budeba T., Mueni E.M., Gove D.Z., 2008, An update on initiatives to reduce prawn trawl bycatch in the western Indian Ocean. Western Indian Ocean J. Mar. Sci. 7, 317–222.

Foster S.J., Vincent A.C.J., 2010, Tropical shrimp trawl fisheries: Fisher's knowledge of and attitudes about a doomed fishery. Mar. Policy 34, 437–446.

Garcia S., Le Reste L., 1981, Cycles vitaux, dynamique, exploitation et aménagement des stocks de crevettes pénaeides côtières. FAO Doc. Tech. Pêche Rome, 203.

Gillett R., 2008, Global study on shrimp fisheries. FAO Fish. Tech. Pap. 475, Rome.

Gribble, N.E., 2003, GBR-prawn: modelling ecosystems impacts of changes in fisheries management of the commercial prawn (shrimp) fishery in the far northern Great Barrier Reef. Fish. Res. 65, 493–506.

Kelleher B., 2005, Discards in the world's marine fisheries. An update. FAO Fish. Tech. Pap. Rome, 470.

Kelleher K., 2008, Les rejets des pêcheries maritimes mondiales. Une mise à jour. FAO Doc. Tech. Pêches Rome, 470.

Lemoine M., Vendeville P., Ladurelle C., 1982, Examen des prises accessoires de la pêcherie de crevettes pénéides du plateau continental de la Guyane Française. Science et Pêche, Bull. Inst. Pêches Marit. 324, 1–11.

Randriarilala F., Rafalimanana T., Caverivière A., 2008, Les captures accessoires des crevettiers industriels et artisanaux. In: Caverivière A. Chaboud C., Rafalimanana T. (eds.). Les crevettes côtières de Madagascar. Biologie, exploitation, gestion. Marseille, IRD Editions, pp. 237–257.

Rico Meija F., Rueda M., 2007, Evaluación experimental bioeconomica de cambios en la tecnología de captura de camaron con redes de arrastre en aguas someras del pacifico colombiano. Bol. Invest. Mar. Cost. 36, 79–109.

Rodellec du Porzic A., Caverivière A., 2008, Principaux engins de la pêche traditionnelle et leur sélectivité sur la côte nord-ouest de Madagascar (Baie d'Ambaro). In: Caverivière A., Chaboud C., Rafalimanana T. (eds.). Les crevettes côtières de Madagascar. Biologie, exploitation, gestion. Paris, IRD Editions, pp. 121–142.

Silva A.C.C.D., Castilhos J.C., Santos E.A.P., Brondizio L.S., Bugoni L., 2010, Efforts to reduce sea turtle bycatch in the shrimp fishery in Northeastern Brazil through a co-management process. Ocean Coast. Manage. 53, 570–576.

Vendeville P., 1984, La pêcherie de crevettes tropicales de Guyane française. Le problème des captures accessoires: estimation et implications. Unpublished Ph.D. thesis, Inst. Polytech. Toulouse.

Vendeville P., Rosé J., Viéra A., Blanchard F., 2008, Durabilité des activités halieutiques et maintien de la biodiversité marine en Guyane. Rapport final de convention, CPER-Docup 2000–2006. Conv. 05/1215640/F - 05/1215614/F. Rapp. Ifremer Guyane. DCM/HMT/RHGUY 2008-1.

Watson Jr. J.W., Seidel W.R., 1980, Evaluation of techniques to decrease sea-turtle mortalities in the southeastern United States shrimp fishery. ICES CM/B 31.

Zhou S., 2008, Fishery bycatch and discards: a positive perspective from ecosystem-based fishery management. Fish Fish. 9, 308–315.