



Linking fishery management and conservation in a tropical estuarine lagoon: biological and physical effects of an artisanal fishing gear

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Received 21 November 2001; received in revised form 15 April 2002; accepted 17 April 2002

Abstract

Information coming from fishery monitoring, surveys and experimental fishing with participation of fishers was employed to determine the impact of an artisanal gear, ‘boliche’, on the biodiversity of the Ciénaga Grande de Santa Marta (CGSM), an estuarine lagoon on the Caribbean coast of Colombia. Fishery monitoring (catch data) included landings before (1968 and 1978) and after (1994–1996) the introduction of the boliche in the CGSM (1985), whereas surveys were conducted seasonally during 1993–1994. Fishing experiments involved evaluating different mesh sizes and the short-term effect of physical disturbance by the boliche. Monitoring suggested potential trophic effects of this fishing gear: the catch of large, long-lived, carnivorous species declined after the introduction of the boliche in the CGSM, whereas catch rates of smaller, shorter-lived, and lower trophic level species increased. Surveys revealed that the boliche retained 41 species. The by-catch made up 62% of the total catch and the remaining 38% involved the three target species *Eugerres plumieri*, *Mugil incilis* and *Cathorops spixii*. Selectivity experiments showed that 2.5 in. stretched mesh size gill nets caught more species than the 3.0-in. mesh. The smaller mesh also increased the risk of a critical reduction in the spawning stock of target species (notably *E. plumieri*); a situation that could affect the fish community if mesh sizes lower than 2.5 in. were intensively used. Suspended particulate matter significantly increased after fishing activity, with higher resuspension on mudshells and mud substrata, whereas dissolved oxygen showed no appreciable changes after fishing operations. Notwithstanding, the activity of the boliche would generate sediment resuspension between 382 and 470 t day⁻¹, which could lead to potential cascade impacts on water quality. We propose a framework of redundancy in management measures in order to simultaneously reach management and conservation goals.

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Keywords: fishing effects; artisanal fishing; tropical estuaries; Colombia

1. Introduction

Direct and indirect effects of fishing have been widely reported on many marine ecosystems (Tegner & Dayton, 1999 and references therein; Watling & Norse, 1998). Much of this work has been focused on industrial fisheries with emphasis on mobile fishing gears, whereas little is known about the quantitative effect of fishing gears intensively used in tropical estuaries. The ecological, economic and social importance of estuaries transcends their frontiers into the broader context of human impacts

(Blaber et al., 2000; Whitfield, 1999). Therefore, an understanding of the processes that affect ecological functions, including the role of fishing, is needed to develop conservation programmes in an integrated fisheries management context. In an attempt to synthesize the effects of fishing on estuaries and nearshore systems, Blaber et al. (2000) defined eight process-orientated categories according to the nature and extent of the fishing impact: target organisms, non-target organisms, nursery functions, trophic effects, habitat change, reduction of water quality, human environment and extinctions.

The Ciénaga Grande de Santa Marta (CGSM) is an estuarine lagoon located on the Caribbean coast of Colombia. It was decreed a Natural Park and Sanctuary in 1969 and Biosphere Reserve by the UNESCO

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(UNESCO, 2000), because of its ecological and social value (a habitat for wide diversity of flora and fauna and source of both food and income for 20,000 persons which depend on fishing activities). Its artisanal fishery is one of most important of Colombia, with 3500 fishers, 1300 canoes and a catch of 5334 t in 1994, which contributed to more than 60% of the nation's landings from the Caribbean in the same year (Santos-Martínez & Viloria, 1998). The fleet consists of motorized and non-motorized canoes ranging from 6 to 8 m in length, which use six types of gears: gill nets, catsnets, hooks and lines (for fishes), and trawls, traps and diving (for shellfish). These gears have been used since 1960s, with the exception of the encircling gillnet called 'boliche', which was introduced to the CGSM in 1985 (Rueda, 1995).

The ecosystem has been systematically degraded due to anthropogenic activities (e.g. increased fishing pressure), since 1956. Poor implementation of ineffective management and conservation schemes prior to the 1990s led to a marked decrease in biodiversity, availability of fishery resources and a deterioration in the quality of life for coastal human populations. During the 1990s, the PRO-CIÉNAGA project (Botero & Salzwedel, 1999) addressed rehabilitation of the system, putting special emphasis on monitoring water quality, mangroves, and the fishery. Based on the findings of this project, current research programmes are intended to end the traditional view that management and conservation are 'contradictory/antagonizing issues' (sensu Castilla, 2000). In this context, cases studied in Latin America benthic shellfisheries (Castilla & Defeo, 2001) have exemplified the potential role of experimental protocols aimed at improving linkages between marine conservation, fisheries management and social sciences.

Given this motivation, the present study aimed to determine the impact of fishing in the CGSM in order to develop conservation and management guidelines. Observational and experimental approaches were employed in a framework that explicitly considers risk and uncertainty (Fig. 1). The approaches followed were: (1) fishery monitoring; (2) fishing surveys; and (3) experimental fishing with the incorporation of resource-users. The CGSM fishery is multispecific, although it is mainly based on the exploitation of *Eugerres plumieri*, *Mugil incilis* and *Cathorops spixii* (more than 80% of commercial landings; see Santos-Martínez & Viloria, 1998), targeted using the boliche (Rueda, 1995). Thus, data coming from (1) and (2) were used to evaluate the effects of the boliche in the trophic structure of the fish assemblage and in the relative composition of the by-catch. The impact of the boliche was quantified through: (a) mesh selectivity experiments; and (b) the short-term effect (i.e. comparing conditions before and after fishing) of physical disturbance caused by the boliche on sediment resuspension and concentrations of dissolved oxygen (DO) in the water column.

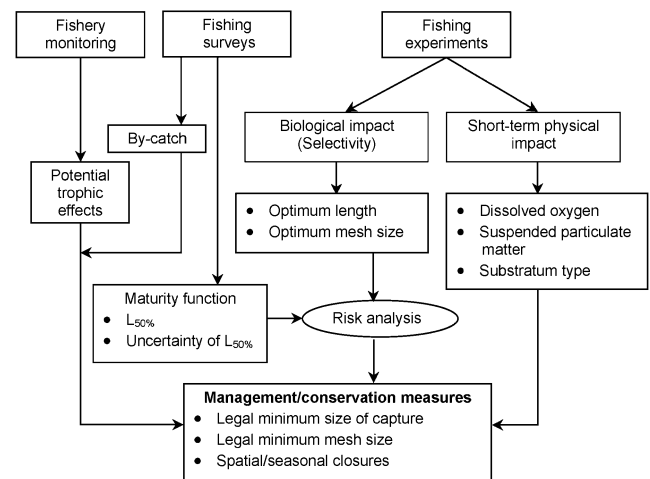


Fig. 1. Hierarchical schematic diagram describing the linkage between management and conservation in the CGSM fishery, using different information sources. $L_{50\%}$ is the average size at sexual maturity defined by Eq. (2).

2. Materials and methods

2.1. Fishery monitoring and fishing surveys

2.1.1. Trophic effects

Potential changes in trophic structure of the fish assemblage caused by the boliche were tested by comparing the relative composition of commercial catches gathered before (all gears without the boliche) and after the introduction of the boliche fishing method in the CGSM in 1985 (Rueda, 1995: all gears including the boliche). We assumed that changes in species composition of landings reflect changes in the fish community structure at specific trophic levels. The 'before' scenario was represented by landings statistics compiled for 1968 and 1978 (Pedraza, Suarez, & Julio, 1979), whereas the 'after' scenario was defined by a fishery monitoring programme conducted between 1994 and 1996 (Santos-Martínez & Viloria, 1998). Because of the lack of time series of commercial catch and diet composition data, we tested changes in the proportion of non-carnivorous to carnivorous fishes before and after the introduction of the boliche through χ^2 goodness of fit test, using the Yates correction for continuity (Zar, 1996).

2.1.2. By-catch and size at sexual maturity

To analyze the composition of the catch, we used information collected between 1993 and 1994 in four seasonal fishing surveys using a standard boliche (mesh size of 2.0 in.), based on a systematic sampling of 115 stations covering the whole CGSM area (450 km²) (see Rueda, 2001 for details). Data on individual length, sex, and maturity of target species were used to estimate the

average size at sexual maturity ($L_{50\%}$), derived from the following logistic function (Restrepo & Watson, 1991)

$$P(L) = \frac{\beta}{1 + \exp(\alpha_1 - \alpha_2 L)} \quad (1)$$

where $P(L)$ is the proportion of mature females at length L and β , α_1 and α_2 are parameters. The function was fitted by non-linear least squares, using the quasi-Newton algorithm. The Monte Carlo resampling method was applied to generate 5000 data sets for the maturity function, which allowed us to estimate confidence intervals for the size at which 50% of the population is sexually mature

$$L_{50\%} = -\alpha_1/\alpha_2 \quad (2)$$

Monte Carlo 95% confidence intervals (CI 95%) for $P(L)$ were defined by the 2.5th and 97.5th percentile values. This procedure was carried out with Matsim program version 1.3 (Roa, Ernst, & Tapia, 1999), which requires growth parameters to be estimated for each of three target species (Rueda & Santos-Martínez, 1999; Sánchez, Rueda, & Santos-Martínez, 1998; Tijero, Rueda, & Santos-Martínez, 1998) as inputs to the program.

2.2. Experimental fishing

2.2.1. Size selectivity

The biological impact of the fishing gear was assessed through selectivity experiments. To this end, the length composition of the catch and selectivity parameters were estimated for the three target species (*E. plumieri*, *M. incilis* and *C. spixii*) collected by a boliche with two mesh sizes ($m_1 = 2.5$ and $m_2 = 3.0$ in.). The experimental boliche followed the original design used in the CGSM fishery, and had four panels each of 124 m², and a hanging ratio of 0.40. Twenty experimental trips were carried out between October 1993 and April 1994 on traditional fishing areas, with the active participation of fishers throughout the experiment. Each trip involved 16 hauls of 15 min, conducted simultaneously with panels of different mesh size interposed in different parts of the gear to reduce the effect of any possible preference of fish for a particular area of the boliche. The number of individuals collected per species, and individual information on wet weight and total length, were recorded separately for each haul and mesh size. Because of the low number of fishes collected per haul, data were pooled per trip in order to compare catches in number and weight by one-way ANOVA.

Contact-selection curves (Millar & Fryer, 1999) were estimated by a linear relationship between the number of fishes C_1 and C_2 collected by mesh sizes m_1 and m_2 and the corresponding individual length L (Holt, 1963)

$$L_n \left(\frac{C_2}{C_1} \right) = a + bL \quad (3)$$

where a and b are the intercept and slope of the linear regression, respectively. Although the boliche moves rapidly during fishing operations, many fishes were caught by gillnetting and wedging and hence a normal curve of selection was assumed:

$$r(L) = \exp \left[-\frac{(L - L_m)^2}{2SD^2} \right] \quad (4)$$

where $r(L)$ is the retention probability for a given length L in a boliche with mesh size m . SD is the common standard deviation for the curves from each mesh size m_1 and m_2 (Sparre & Venema, 1995):

$$SD = \sqrt{\frac{-2a(m_2 - m_1)}{b^2(m_2 + m_1)}} \quad (5)$$

where a and b were defined in Eq. (3). The optimum lengths for mesh size L_{m1} and L_{m2} were estimated from the relationships

$$L_{m1} = -2 \frac{am_1}{b(m_1 + m_2)} \quad (6)$$

$$L_{m2} = -2 \frac{am_2}{b(m_1 + m_2)} \quad (7)$$

and the species-specific selection factor was

$$SF = \frac{-2a}{b(m_1 + m_2)} \quad (8)$$

Selectivity parameters estimated for each target species were used to quantify the risk of the optimum lengths of capture per mesh size (L_{m1} and L_{m2}) falling below an undesirable threshold defined by a specific individual length below which the spawning stock could be threatened. Thus we considered: (1) the average size at sexual maturity $L_{50\%}$; and (2) the upper CI 95% level of $L_{50\%}$, as limit reference points (LRPs) representing two scenarios of fishery status. Scenario 1 could be considered risk neutral, whereas scenario 2 is risk averse. Monte Carlo analysis was used to explicitly account for the uncertainty associated with the selection factor SF (Sparre & Venema, 1995)

$$L_m = SFm \quad (9)$$

where L_m is the optimum length for a given mesh size (m). SF was randomly generated with a normal probability function, since this was that which best-fitted observations of the random variable (Seijo & Caddy, 2000). Twelve Monte Carlo runs of 1000 simulation trials were conducted for each of the three target species, the two mesh sizes and the two LRPs.

2.2.2. Physical impact

Among the fishing gears employed in the CGSM, the boliche is the only one that requires a certain degree of

fishing technology (use of outboard engines, Rueda, 1995). A normal haul involves the participation of three fishers, who set the boliche in a circle from a canoe in motion. After that, the canoe rotates within the circle, while the fishers hit the water surface with poles (1.2 m in size) during 5–10 min, causing physical disturbance on a water column of ca. 1.5 m depth. In order to evaluate this physical impact, suspended particulate matter (SPM) and DO concentrations were measured before and after a haul. Short-term changes were assessed for 70 hauls performed by fishers between April and July 1994, using a standard boliche. The hauls were carried out on mixed ‘mud-shells’ (41%), mud (40%) and fine sands (19%), covering the main substratum types in the CGSM (Rueda, 2001). SPM was obtained from water samples taken to a depth of 50 cm using a 1-l Ruttner bottle, whereas DO was measured in situ to the same depth using a WTW OXI 92 oxymeter. The gravimetric method was applied to determine SPM (Greenberg, Trussell, & Clesceri, 1985). Temporal (before and after fishing operations) and spatial (substratum type) differences in SPM and DO concentrations were tested by two-way ANOVA's with unequal replication (Zar, 1996).

3. Results

3.1. Fishery monitoring and fishing surveys

3.1.1. Trophic effects

The proportion of non-carnivorous to carnivorous fishes was significantly lower before (1.5:1) than after (2.5:1) the boliche introduction (χ^2 test: $P < 0.001$). The relative composition of the catch of large, long-lived, and carnivorous species like *Centropomus undecimalis*, *Arius proops*, *Tarpon atlanticus* and *Elops saurus*, declined after the introduction of the boliche in the CGSM, whereas the catch of smaller, shorter-lived, and lower trophic level species tended to increase (Fig. 2). The long-term analysis showed that, after the introduction of the boliche: (1) the relative contribution of the iliophagous *Mugil incilis* increased from 18 to 44%; (2) some planktivorous engraulids appeared in the catches for the first time (4% of the total catch); (3) *E. saurus* decreased 4%; and (4) *C. undecimalis* and *A. proops* drastically decreased from 14 to 0.5% and from 20 to 0.1%, respectively.

3.1.2. By-catch and size at sexual maturity

About 8992 individuals belonging to 41 species were collected during the four fishing surveys, of which only 38% involved the three species primarily targeted by the boliche: *E. plumieri*, *M. incilis* and *C. spixii* (Fig. 3a). The remaining 62% made up the by-catch, of which only eight species had an abundance greater than 20 ind

0.005 km^{-2} . Abundance significantly differed among species, including both target and non-targeted (root transformed data, ANOVA $F_{10,33} = 10.5$; $P \ll 0.01$, Fig. 3b). The most abundant species (mean $\pm$ SD, Newman–Keuls test: $P < 0.05$) were the non-targeted *Diapterus rhombeus* (619 ± 191 ind 0.005 km^{-2}) and *E. plumieri* (417 ± 198 ind 0.005 km^{-2}), whereas the other two primary targets *M. incilis* and *C. spixii* were clustered in an homogeneous group with *Anchovia clupeioides*, *Bairdiella ronchus*, *Elops saurus* and *Micropogonias furnieri* (Newman–Keuls test: $P > 0.05$), significantly differing from *Mugil liza*, *Oligoplites palometa* and *Cetengraulis edentulus* (Newman–Keuls test: $P < 0.05$).

The maturity–length relationship for each of three target species was successfully explained by the logistic function (Fig. 4). In all cases 100% mature females were found in the largest fish, giving asymptote β -values of 1. The steepest maturity curve for *M. incilis* suggests an abrupt transition to maturity between 24 cm (30%) and 27 cm (80%). This species had also the narrowest CI 95% for $P(L)$, with $L_{50\%}$ (25.2 cm) ranging from 24.8 to 25.6 cm. On the contrary, *E. plumieri* ($L_{50\%} = 21.8$ cm) and *C. spixii* ($L_{50\%} = 24.1$ cm) had wider CI 95%: 20.1–23.8 cm and 22.4–26.1 cm, respectively.

3.2. Experimental fishing

3.2.1. Size selectivity

About 9281 individuals (1285 kg) belonging to 18 species were collected by the experimental boliche. Of them, 17 were retained by mesh size m_1 (2.5 in.) and 14 species by mesh size m_2 (3.0 in.). Mean catch per trip using mesh size m_1 (710.3 kg and 5866 ind) was higher than for m_2 (574.4 kg and 3415 ind). These differences were significant both for catch in numbers (root transformed data: ANOVA $F_{1,38} = 35.1$; $P < 0.01$) and weight (ANOVA $F_{1,38} = 4.3$; $P = 0.045$).

Contact-selection curves were successfully explained by the retention probability at length (Eq. (4)) for *E. plumieri*, *M. incilis* and *C. spixii*. The linear model of Holt (1963) was highly significant ($r > 0.94$ and $P < 0.01$, in all cases) and the optimum lengths L_{m1} and L_{m2} were proportional to the mesh sizes (Fig. 5). Selection curves of *M. incilis* and *C. spixii* were truncated (specifically those of the mesh m_2), because lengths above 40 and 32 cm, respectively, were not well represented. The selection factors varied with fish shape. Indeed, *E. plumieri*, with a deep body, had the lowest SF and optimum lengths, whereas *M. incilis*, with an oblong body, had the highest values (Fig. 5). The same pattern was found for the common SD (Fig. 5), indicating that *M. incilis* was the most vulnerable species to the boliche, followed by *C. spixii* and *E. plumieri*. L_{m2} was higher than $L_{50\%}$ for the three species, although this difference was small in *E. plumieri* (Fig. 5), and, considering the

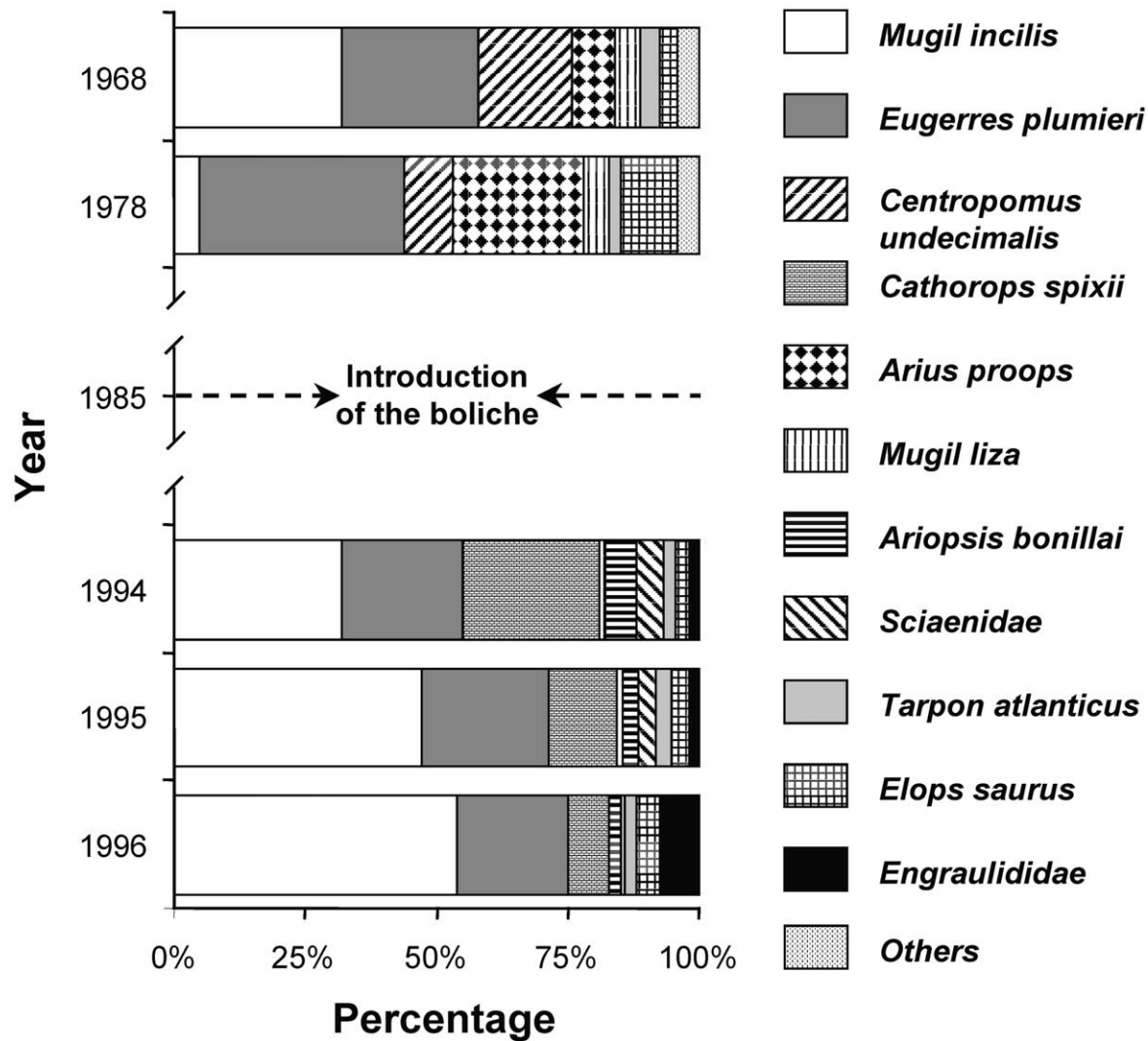


Fig. 2. Relative composition of the catch of fish species before and after the introduction of the boliche in the CGSM fishery in 1985.

upper CI 95% level of $L_{50\%}$, only for this species L_{m2} does fall into this interval. In contrast, L_{m1} was much lower than the CI 95% of $L_{50\%}$ in *E. plumieri*, it was slightly higher than the upper CI 95% of $L_{50\%}$ in *M. incilis*, whereas for *C. spixii*, L_{m1} and $L_{50\%}$ were almost identical. In agreement with these results, risk analysis consistently revealed higher probabilities of L_{m1} of falling below the two LRP scenarios than with L_{m2} (Table 1). Such risk was always high (from 0.80 to 0.90) even when the risk averse scenario was considered for the 2.5-in. mesh size, which retained high proportion of juveniles of *E. plumieri*. A less dangerous situation was evident for *C. spixii* and *M. incilis*, with intermediate probabilities (from 0.51 to 0.68 and from 0.38 to 0.45, respectively) of falling below the LRPs.

3.2.2. Physical impact

Mean SPM concentration (log transformed data) within the water column significantly increased after

boliche hauls (ANOVA $F_{1,92}=7.67$; $P < 0.01$; Fig. 6), irrespective of substratum type. Nevertheless, the substratum type effect was also significant ($F_{2,92}=4.01$; $P = 0.021$), SPM concentrations over mud-shells and mud being higher than over fine sand (Newman-Keuls test: $P < 0.05$). Mean OD concentrations (root transformed data) within the water column did not differ before and after fishing operations ($F_{1,134}=0.013$; $P > 0.10$) and substratum types ($F_{2,134}=1.31$; $P > 0.10$, see Fig. 6).

4. Discussion

4.1. Biological impact

The marked decline in the commercial catches of carnivorous species and the increasing trend of species low in the food chain could suggest potential trophic

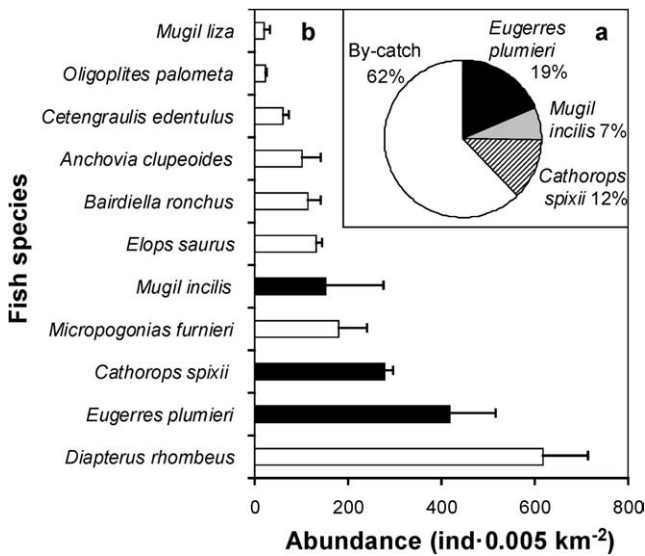


Fig. 3. CGSM fishery. (a) Relative composition of the total catch (in numbers) of the boliche. (b) Abundance (mean $\pm$ SE) of the main target (filled bars) and non-target (empty bars, ≥ 20 ind 0.005 km^{-2}) fish species caught by the boliche. All data were collected during four seasonal surveys during 1993–1994.

effects of the boliche caused by the concurrent increase in fishing technology and effort in the CGSM fishery. This agrees with the global patterns observed in fisheries (Pauly, Christensen, Dalsgaard, Froese, & Torres, 1998), where changes in fishing technology have played a crucial role (Caddy, 1999). In fact, the introduction of the boliche in the CGSM fishery, involving the active use of an outboard engine, resulted in a significant increase in fishing power when compared with other traditional gears (e.g. catsnest, gill nets, lines, traps). Fishing surveys revealed that the amount of incidental catch was significantly higher than the catch of target species. This effect can be explained by progressive improvements in the design and operation (fishing power) of the boliche since its introduction, such as changes in elastic stretching of the net and the hanging ratio (Rueda, 1995). Additionally, the relative increase in incidental catches in the CGSM fishery could be caused by cascade effects and/or sequential depletion of primary targets. Our finding is strongly supported by the significant increase in the catch of non-target species during the 1990s (Santos-Martínez & Viloria, 1998).

Selectivity experiments indicated that higher number of species, catch in weight and number of individuals per trip were retained by the 2.5-in. mesh size than by the 3.0-in. mesh. Differences in weight caught between mesh sizes was due to the predominance of smaller individuals caught by the 2.5-in. mesh size, thus increasing the risk of a critical reduction in the spawning stock, especially for *E. plumieri*. Santos-Martínez and Viloria (1998) also showed that the intensive use of mesh sizes lower than 2.5 in. (e.g. 2.0 in.) affected the target species and thus

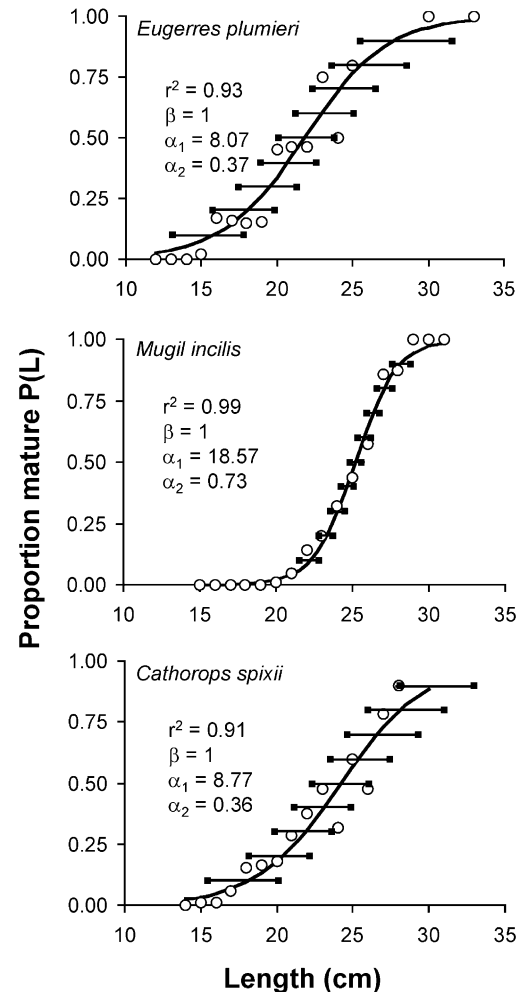


Fig. 4. Maturity functions and related statistical results (non-linear regression) for three target fish species of the CGSM. Closed squares are Monte Carlo confidence intervals for maturity proportions ($P(L)=0.0-1.0$ in steps of 0.1). All parameter estimates were highly significant in the three cases ($P < 0.0001$).

the nursery function of this ecosystem. The risk averse scenario, considering the 3.0-in. mesh size, is suitable for the conservation of the three target species, but allows the escapement of large and marketable individuals of *M. incilis* and *C. spixii* over the size at sexual maturity. Therefore, an appropriate mesh size for the whole fishery should be intermediate between those used in the experiment.

4.2. Physical impact

Most effects of fishing on water quality are local and short-term (Blaber et al., 2000). In agreement with this short temporal scale, our results showed that the operation of the boliche significantly increased the SPM, irrespective of the substratum type on which the haul was carried out. However, higher resuspension

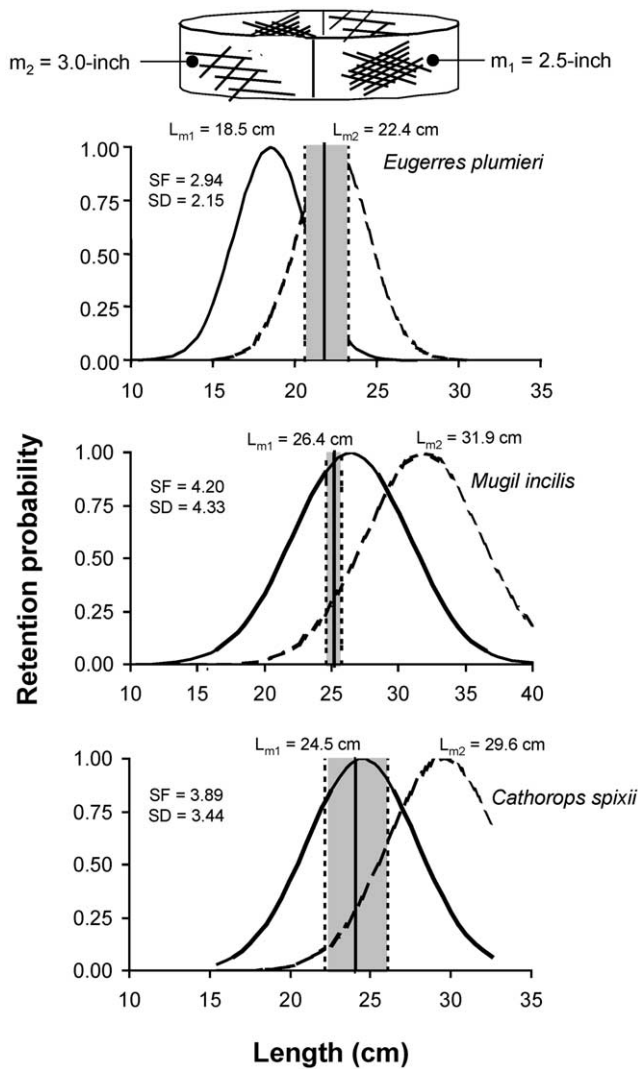


Fig. 5. Estimated contact-selection curves for the three target species for the (—) 2.5 and (---) 3.0 in. mesh sizes of the boliche in the CGSM. The shaded zones bounded by dotted vertical lines represent Monte Carlo confidence intervals for $L_{50\%}$ provided by maturity functions. Selectivity parameters and a scheme of the selectivity experiment are also shown (see details in Section 2).

Table 1
Risk analysis

Species	Mesh size			
	2.5 in.	3.0 in.		
	$L_{50\%}$	$L_{97.5}$	$L_{50\%}$	$L_{97.5}$
<i>E. plumieri</i>	0.80	0.90	0.42	0.54
<i>M. incilis</i>	0.38	0.45	0.07	0.09
<i>C. spixii</i>	0.51	0.68	0.10	0.22

Probability of the optimum length of capture per mesh size of falling below the LRP defined by: (1) the average size at sexual maturity ($L_{50\%}$: risk neutral scenario); and (2) the 97.5th percentile of $L_{50\%}$ ($L_{97.5}$: risk averse scenario), based on 1000 Monte Carlo simulation trials for the three target species.

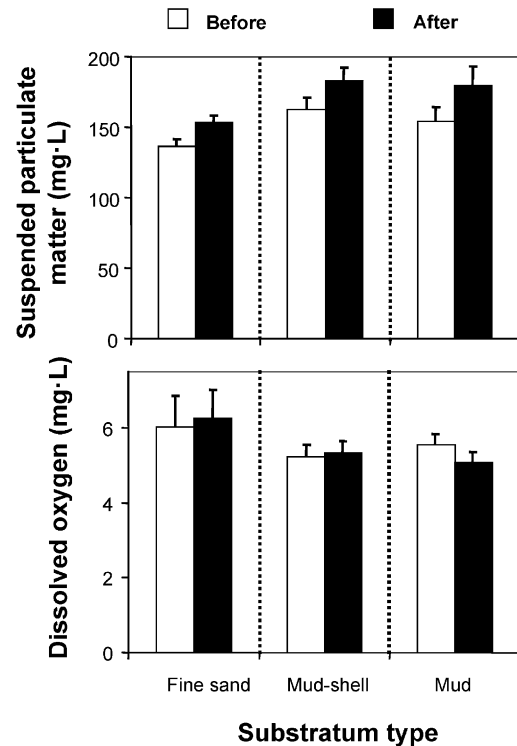


Fig. 6. Short-term changes in SPM and DO in the CGSM generated by boliche operations.

occurred on mud-shells and mud substratum than on fine sands. Changes in SPM may have negative direct effects on fishes, expressed by gills obstruction and reduced oxygen intake, which would make them more vulnerable to fishing (Arias, 1988). This could also explain the progressive eutrophication of this system (Botero & Salzwedel, 1999), which can lead to cascade impacts. Taking into account resuspension estimates obtained in this paper, together with the volume encircled by the boliche and the total number of hauls conducted in the CGSM by the commercial fleet, boliche operations would generate a daily resuspension of sediment between 382 and 470 t day^{-1} , producing anoxic conditions in the sediment and increasing the availability of nutrients within the water column (especially phosphorous). This, together with additional inputs by runoff, may have contributed to noxious phytoplankton blooms and consequent low oxygen concentrations that gave rise to several mass mortalities during 1994 (Botero & Salzwedel, 1999).

4.3. Linking fishery management and conservation

Experimental fishing, surveys and fishery monitoring involving the active incorporation of fishers during the experiments, provided useful information for linking conservation and management issues in the multispecific CGSM fishery. Strategies may be applied in a framework of management redundancy (Caddy, 1999), which

is defined as the implementation of operational and institutional management instruments directed to achieve the common long-term goal of sustainable exploitation (sensu Castilla & Defeo, 2001). In this sense, such framework could consist of a mixture of measures incorporating selectivity criteria and fishing closures within specific area–season windows. Minimum sizes at first capture could be established from the upper CI 95% level of $L_{50\%}$. Thus, the legal minimum sizes for *E. plumieri*, *M. incilis* and *C. spixii*, should be 23.8, 25.6 and 26.1 cm, respectively, which can be achieved if the minimum mesh size is established at 2.75 in. Concerning spatially explicit management measures, the perimeter adjacent to the lagoon borders (e.g. within 1 km from shore) should be permanently closed to fishing, because of resuspension of particulate matter during fishing operations and impacts on the mangrove nursery and on protected areas. This requirement for management redundancy will not be achieved, however, if institutional framework constraints (e.g. social and political instability, poor implementation and enforcement of management/conservation tools) persist (in Colombia), and if experimental management does not involve the active participation of fishers (Castilla & Defeo, 2001).

Acknowledgements

This paper is part of the PhD thesis of M.R. at CINVESTAV-IPN U. Mérida. The INVEMAR and COLCIENCIAS (Grant no. 2105-09-028-94) provided logistical and financial support for fieldwork. We thank Prof. J. Caddy for useful suggestions. The first author would like to thank to the 'CGSM's Fisheries Group' of the INVEMAR and fishers of the CGSM for laboratory and field assistance, respectively.

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