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Effects of mesh size and towing speed on the multispecies catch rates of historical swept area surveys

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ABSTRACT

The use of different trawl nets is a factor to be considered when analysing historical swept-area research surveys aimed to characterize temporal variations in the relative abundance of demersal resources. If factors that may affect the performance of the bottom trawls were considered, more reliable temporal trends could be established. Due to the high species diversity that characterizes tropical areas, this kind of analysis is often carried out at the multispecies level. Therefore, the objective of this study was to establish the effect of two technical factors, mesh size and towing speed on the multispecies catch rates obtained in different demersal surveys carried out in the Colombian Caribbean Sea between 1988 and 2001, using two generalized linear models: one covering the entire study area and another restricted to one eco-region. For the global model, the effect of the mesh size on the multispecies catch rates was marginally significant ($p < 0.10$), unlike the towing speed, whose effect was not significant ($p > 0.10$). In contrast, for the eco-region model, the effect of mesh size was not significant ($p > 0.10$), while towing speed had a significant effect ($p < 0.05$). Size structure analysis showed escapement mainly through the codend meshes for the larger mesh size evaluated (50.8 mm), confirming the appropriateness of considering mesh size when analyzing historical data of swept area surveys. The effect of the towing speed, beyond the clear incidence on the area actually swept, point to the complexity of the relationship between speed and catch rates. In brief, the results showed that, when assessing historical databases, indices of relative abundance of tropical demersal resources can be improved by including mesh size and towing speed factors.

1. Introduction

In general, research survey cruises for assessing demersal fish stocks follow specific protocols that try to minimize the effect of the variables that are not considered in the calculations inherent to the swept area method. It is, however, relatively common that some technical and operational characteristics vary between historical surveys in a region. One of these technical variables is the mesh size used at the codend of the net. This variable is crucial in determining the escape or loss of fish through the nets (Ragonese et al., 2001; Weinberg et al., 2002; Weinberg and Kotwicki, 2008). A second operational variable to take into account is towing speed (Dahm et al., 2002; Weinberg et al., 2002), which may vary significantly over a survey, due to many uncontrollable factors, generally environmental, that modify the functioning of the net (Weinberg et al., 2002; Herrmann, 2005a,b; Duarte and Cuello, 2006). The impact of this variable, as well as that related to the calculation of the swept area, is essential in three basic processes of bottom trawling: (i) horizontal herding, stimulated by sand clouds and the bridles; (ii) vertical herding, in response to stimuli such as the headrope or boat noise; and (iii) fish loss or escapement under the footrope (Weinberg et al., 2002; Weinberg and Kotwicki, 2008). Generally, the effect of these aspects is analysed by a video camera attached to the trawl (Somerton and Weinberg, 2001), since it is difficult to define a measurable variable that can, by itself, reflect the effect of the horizontal herding or the vertical herding.

Other factors that generally vary between historical surveys are tow duration and net size. Although tow duration is a variable considered in the swept area method (Ye et al., 2005; Catalán et al., 2006), it has been proposed that this variable also has an influence on the size structure of the catch, on the basis that the largest individuals are able to swim ahead of the net for longer periods of time

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(Sparre and Venema, 1998). However, several studies have failed to find a significant relationship between tow duration and catch size distribution (Godo et al., 1990; Walsh, 1991; Somerton et al., 2002). According to Godo et al. (1990), this is due to the fact that at the beginning of the tow, before a school is established at the mouth of the net inducing an alert reaction in the fishes, the effect of exhaustion is less important than that of surprise.

With respect to net size, the horizontal opening of the trawl net is considered through the calculation of the swept area (Ye et al., 2005; Catalán et al., 2006; Bergstad et al., 2008). Regarding the vertical opening of the trawl net, in controlled experiments with two different heights of vertical opening, Johnson et al. (2008) did not find statistically significant differences in the number of individuals of the main fish taxa that were caught, or the structure and composition of the assemblages. In contrast, the mean catch per unit effort (CPUE) was greater in the net with a larger opening height, though this trend was most clear for certain pelagic fish taxa that form large shoals.

The ability to use fish catch rates obtained from scientific surveys as relative abundance indices depends on the feasibility of removing effects other than abundance, a process that has been described as “standardization of catch/effort” (Maunder and Punt, 2004). Therefore, we should analyze the effect on the catch rates of those factors that influence the trawl performance as a prerequisite for properly calculating estimates of relative abundance that reflect changes in population distribution and density (Weinberg and Kotwicki, 2008).

It is known that behaviour and swimming performance of different species can vary greatly (Winger et al., 2004; Queirolo et al., 2012) and therefore it would be recommendable to analyse the effect of the mesh size and towing speed at the species level. However, it is also known that analysis of the status of tropical demersal fish resources is usually made at multispecies level, supplemented with analysis of species composition, due to the extremely high species diversity that characterizes this type of surveys in tropical areas (Blaber et al., 1994; Sparre and Venema, 1998). In fact, the fish bycatch of the shrimp trawl fishery operating in the Colombian Caribbean Sea (CCS) is composed of 175 taxa distributed in 58 families (Viaña et al., 2004), while the database of the surveys carried out in the CCS between 1988 and 2001 reports a total of 311 taxa of demersal fish (Duarte and Cuello, 2006). Therefore, the objective of this study was to analyze the effect of the mesh size and towing speed on the multispecies catch rates in historical demersal fish assessment surveys performed in the CCS. Both generalized linear models (GLMs) and generalized additive models (GAMs) offer a powerful tool for achieving this objective, since these models allow more flexible linear predictors as well as automatically control the parametric complexity (Venables and Dichmont, 2004). However, we chose GLMs because a significantly better fitting was not obtained using GAM models, in spite that this technique includes local smoothers as terms.

2. Materials and methods

2.1. Data sources

We used data collected from eight fishery-independent trawl surveys for the assessment of demersal fish stocks conducted in the CCS during the period 1988–2001, which were all based on the swept area method. Specifically, the study was based on the four surveys carried out in 1988 under the framework of the NORAD-UNDP/FAO programme (Strømme and Sætersdal, 1989), the three in 1995 and 1996 under the INPA-VECEP/UE programme (Manjarrés et al., 2005a,b,c) and the survey in 2001 under the INPA-COLCIENCIAS programme (Duarte and Cuello, 2006) (Table 1). A total of 333 fish taxa were found in the 331 hauls carried out in the eight cruise surveys (18 taxa per haul in average, coefficient of variation 73.5%, maximum number of taxa per haul, 79). A total of 21 taxa accounted for 70% of the total catch by weight, the most abundant species being three lutjanids (*Lutjanus synagris*, *Lutjanus analis*, and *Rhomboplites aurorubens*).

As well as the catch rates, the following information was available for each haul: date and time, initial and final latitude and longitude, initial and final sampling depths, tow duration (minutes), average towing speed (Table 1) and basic characteristics of the trawl net used (Table 2). For all surveys, the protocol for determining initial and final latitude and longitude data was based on the navigator’s estimate of the position when the gear made bottom contact after shooting and when gear began to be hauled by the winch, respectively (Sætersdal et al., 1999; Manjarrés et al., 2005a,b,c).

For all surveys net spread (wing tip to wing tip) was used as a measure of the horizontal opening required for estimating swept area. However, in none of the various reports on UNDP-FAO-NORAD survey cruises the methodology for establishing horizontal opening is mentioned. For INPA-VECEP/UE and INPA-COLCIENCIAS surveys (cruisers made by our research group), a model of the relationship between warp length and depth was made, based on a horizontal opening goal of 60% (as recommended by the manufacturing company of these trawls). Both during the previous calibration and for some hauls of the cruises, the horizontal opening was estimated by applying the trigonometric method used for stern trawlers (Okonsky, 1972). In this method, first the distance between otterboards is calculated by relating the distance between the towing blocks and the distance between the towing warps at a fixed distance from the towing blocks. Then, the approximate horizontal opening of the headline is estimated by applying the formula of similar triangles that involves the following measures: distance between otterboards, length of sideline, length of wing bridles (legs) and length of ground bridles. The model showed a good performance in those hauls where the Okonsky’s method was again applied during the surveys (at different depths), in the sense of obtaining a horizontal opening of about 60%.

Target speeds were the same for INPA-VECEP/UE and INPA-COLCIENCIAS surveys (3.5 knot), although, as it is common in demersal surveys, towing speed ranged between 1.5 and 4.5 knot (Manjarrés et al., 2005a,b,c; Duarte and Cuello, 2006). Documents related to UNDP-FAO-NORAD surveys do not specify a target speed. What is only possible to state is that UNDP-FAO-NORAD survey speeds ranged between 0.6 and 4.5 knot (Strømme and Sætersdal, 1989).

2.2. Pre-processing of data

A database editing and screening stage was carried out prior to the modelling stage, for quality assurance. The original database comprised a total of 313 hauls (Table 1), but 18 hauls were eliminated due to very short towing durations (<0.2 h) and 6 more hauls were excluded due to low towing speeds (<1.5 knot), which may mean the risk of otterboards malfunctioning. This prep stage also included the standardization of the scientific names across surveys, given the time elapsed between the different cruises.

Because the data came from cruises conducted with trawl nets of different sizes (Table 2), catches were normalized to a standard area (SA) of 0.04 km^2 to be able obtain the catch per standard area (CPSA) (Rogers and Ellis, 2000; Helser et al., 2004; Ye et al., 2005; Catalán et al., 2006; García et al., 2007; Bergstad et al., 2008). The SA was calculated on the basis of the shortest horizontal spread in the surveys (12.6 m), an effective tow duration of 30 min and a towing speed of 3.5 knot. In this way, potential bias associated with spatial extrapolation was avoided (Kirchner and McAllister, 2002).

Table 1
Original data of the eight demersal fish survey cruises considered in this study (previous to the database editing and screening stage).

Year	Date	Survey cruise	*n*[1]	Research vessel	Bottom trawl code[2]	Towing speed (knots)	Towing duration (h)	Depth range (m)	References
1988	Mar. 4–10	198803 UNDP-FAO-NORAD	35	Fridtjof Nansen	005	10–3.5	0.2–0.5	9–75	Strømme and Sætersdal (1989)
	Jun. 15–21	198806 UNDP-FAO-NORAD	51	Fridtjof Nansen	005	0.6–4.4	0.1–1.0	11–455	Strømme and Sætersdal (1989)
	Sep. 16–22	198809 UNDP-FAO-NORAD	48	Fridtjof Nansen	005	1.2–4.5	0.2–1.0	17–493	Strømme and Sætersdal (1989)
	Dec. 7–10	198812 UNDP-FAO-NORAD	29	Fridtjof Nansen	005	1.2–3.8	0.3–1.0	11–503	Strømme and Sætersdal (1989)
1995	Jul. 11–22	199507 INPA-VECEP/UE	38	B/I Ancón	001	1.8–4.5	0.2–0.6	11–166	Manjarrés et al. (2005c)
	Oct.20–Nov.4	199510 INPA-VECEP/UE	47	B/I Ancón	001	1.5–4.4	0.1–0.6	11–130	Manjarrés et al. (2005a)
1996	Apr. 9–20	199604 INPA-VECEP/UE	26	ARC Malpelo	004	1.7–3.8	0.5–0.6	11–105	Manjarrés et al. (2005b)
2001	Nov.19–Dec.7	200112 INPA-COLCIENCIAS	39	B/I Ancón	001	1.5–4.5	0.5	10–88	Duarte and Cuello (2006)

[1] *n* Means number of hauls carried out in each survey cruise.
[2] Code assigned by the "Sistema de Información Evaluación y Ecología Pesquera"—SIEEP (Duarte et al., 2005; Duarte and Cuello, 2006).

Table 2
Features of the bottom trawls used in the demersal fish survey cruises conducted in the Caribbean Sea of Colombia between 1988 and 2001.

Feature	Trawl code		
	001	004	005
Trawl type	Fish bottom trawl	Engel fish bottom trawl	Fish bottom trawl
Head rope/footrope (m)	20.6/25.6	33.3/41.6	31.0/47.0
Codend mesh (mm)	45.0	50.8	20.0
Foot rope design	80 mm Ø rubber bobbins/11 mm Ø iron chain	350 mm Ø rubber bobbins	400 mm Ø rubber bobbins
Other mesh sizes (mm) (wings/square/body/presack)	120/90/57/45	180/180/160/120	40/30/20/20
Optimal vertical opening (m)	*	3.5	6.0
Otterboard style/material/dimensions (m)	Model V/iron/1.35 × 0.90	Oval/steel/3.10 × 1.8	Thyborøn doors/steel/7.9 m^2
Otterboard weight (kg)	172	1200	700
Bridles at each wing/bridles + sweep length (m)	2/20 m	3/60 m	2/40 m
References	Zúñiga (pers. comm.), Higuera (pers. comm.)	Quintero (1992), Zuñiga (pers. comm.)	Strømme and Sætersdal (1989), Engås et al. (2000)

* Not information available.

Given that some previous studies have noted that some pelagic taxa are occasionally caught with demersal fish trawl nets (Johnson et al., 2008), and the widely reported fact that these species are not quantitatively sampled by these types of nets (Massutí and Reñones, 2005; García et al., 2007; Catalán et al., 2006; Labropoulou and Papaconstantinou, 2004), we only included in the analysis fish species classified as demersal, benthic and benthopelagic, according to the FishBase database (Froese and Pauly, 2011).

Other aspects considered in the pre-processing of data were the geographical, bathymetric and temporal differences among the historical surveys (Table 1). Geographical stratification was based on the eco-region classification of the Colombian National Research Program on Marine and Coastal Biodiversity (PNIBM; Díaz-Merlano and Gómez-López, 2000) (Fig. 1). Bathymetric stratification was based on the average depth of the haul and the following depth strata (Manjarrés-Martínez et al., 2012): 10–30 m (inner continental shelf), 31–50 m (mid continental shelf), 51–100 m (outer continental shelf), 101–200 m (upper continental slope) or >200 m (intermediate continental slope). Temporal stratification was based on two main climatic seasons of the CCS: a calm season (May–November), with predominantly rainy weather, when the Intertropical Convergence Zone is positioned farthest north; and a windy season (December–April), with mostly dry weather, when this zone is positioned farthest south (Schmidt et al., 2004; Andrade and Barton, 2005).

2.3. Construction and evaluation of the GLMs

Two GLMs were selected: one for the entire study area (model 1) and the other only for the Guajira eco-region (GE) (model 2)

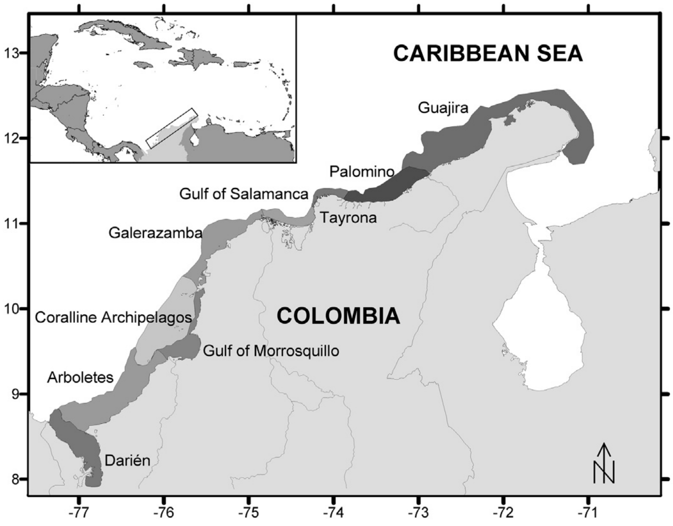

Fig. 1. Study area, showing the eco-regions used for the geographical stratification of the samples.

Table 3
Generalized linear models (GLMs) applied to measure the effect of different factors on catch per standard area (CPSA) of demersal fishes. Spatio-temporal coverage and sampling effort (n) is indicated for each model.

Model code	Model configuration	Temporal coverage			Geographical coverage	n
		1988	1995/1996	2001		
1	ln(CPSA) ~ year + season + eco-region + depth stratum + mesh size + towing speed	X	X		Total area	260
2	ln(CPSA) ~ year + season + depth stratum + mesh size + towing speed	X	X	X	Guajira eco-region	170

(Table 3). A third annual period (2001) was added for model 2, as the 200112 INPA-COLCIENCIAS cruise only covered the northwestern part of the CCS (GE). In both cases, the two main variables of interest, mesh size and towing speed, were treated as continuous variables. Further, with the aim of both (i) considering variables that could theoretically affect catchability (Maunder and Punt, 2004; Quiroz et al., 2005) and (ii) including variables for which there was complete and reliable data, model 1 also included four categorical variables, namely, year, season, eco-region and depth strata, all treated as fixed effects in the model. These were also included in model 2, except for eco-region, given that this model was only applied to the Guajira region.

It is worth noting that two other models with interaction terms were assessed: (1) the first one with the interaction year × ecoregion, at the CCS level, and (2) another with the interaction year × depth stratum, at the Guajira ecoregion level. However, several samples had to be eliminated for achieving convergence, due to strong matrix imbalance (Gatica and Hernández, 2003; Wiff et al., 2005). Furthermore, both explained deviance and Akaike information criterion (AIC) for these models were practically the same that those obtained for the only main effect models.

In terms of the mean catch rate expected in year t, season s, depth strata d, eco-region e, and haul i (μ_{tsedi}), the selected model at CCS level can be formulated as follows (Hilborn and Walters, 1992; Punt et al., 2000; Ye et al., 2001):

$$\ln\ (\mu_{tsedi}) = U_{1111} + \alpha_t + \gamma_e + \beta_s + \tau_d + \theta_1\varphi_i + \theta_2\delta_i \tag{1}$$

where U_{1111} represents the mean catch rate (CPSA) obtained in 1988 during the calm season on the inner continental shelf; α_t, β_s, γ_e and τ_d are scale factors for the expected catch rate for year t compared to 1988, for the windy season relative to the calm season, for the eco-region e relative to the EG, and for the depth d relative to the inner shelf; θ_1 and θ_2 are the expected changes in the natural logarithm of the catch rate per unit of, respectively, mesh size and towing speed used in haul i; and φ_i and δ_i are the mesh size and towing speed used in the haul i, respectively. Model 2 was the same except that it did not contain the factor describing the eco-region effect.

The choice of a probability distribution for the response variable of a GLM involves the specification of the dispersion relating the variance to the expected mean of the response variable, in terms of a constant, ϕ (Maynou et al., 2003; Maunder and Punt, 2004), commonly called the scaling factor (Guisan et al., 2002; Venables and Dichmont, 2004). The CPUE data were strongly positively skewed, suggesting that they should be log transformed. Analysing the logarithmic regression of the variance against the log of the mean demonstrated the validity of using a linear model for this relationship ($p < 0.05$). For both sets of data, the confidence interval of the regression coefficient included the value 2 and, hence, we used a log-gamma function for both models (Milessi and Defeo, 2002; Stefânsson, 1996; Goñi et al., 1999; Punt et al., 2000; Quiroz et al., 2005).

The models were built using both STATISTICA® v. 7.0 and the R STATS package (R Development Core Team, 2009), keeping the same input order of the factors as well as their respective levels. Initially, the significance of the effects explored were assessed with STATISTICA® by two different methods: the Wald statistic, an approximation of the Z statistic for a normal distribution (Dobson, 1990), and likelihood ratio test using type 1 sums of squares, which yields a statistic based on the chi-square distribution (Dobson, 1990; Venables and Dichmont, 2004). Subsequently, the parameters for each model were estimated by iteration of maximum likelihood algorithm and their significance was determined using the Wald test.

The model was evaluated using the *glm* function in R by two methods: Pearson or deviance residuals and a goodness-of-fit test (Maynou et al., 2003; Venables and Dichmont, 2004). Standard residuals were plotted against the fitted values of the model to test for heteroscedasticity. Further, quantile–quantile (QQ) plots were used to check the specification of the model (Maunder and Punt, 2004; Venables and Dichmont, 2004).

To assess the relative advantages of analysing the effect of mesh size using GLMs, catch rates obtained with each of the mesh sizes used were compared in two ways: (i) by plotting medians and 95% confidence intervals for the catch rates, and (ii) by applying Mood's median test using Statgraphics®. Similarly, we compared the median towing speed corresponding to the various different levels of the categorical variables included in the GLMs (year, season, eco-region and depth strata), using Mood's median test. We also plotted the respective medians with 95% confidence intervals. Fig. 2 summarizes the sequence of steps taken to complete data processing (including pre-processing of catch rates).

2.4. *Processing of the catch sizes*

Given that the mesh sizes varied from 20 to 50.8 mm, it could be expected that the selectivity of the smallest species would be different (Rogers and Ellis, 2000). Hence, to analyze the relative impact of these differences on the size-selectivity, we constructed and compared multispecies curves of cumulative relative frequencies of the sizes recorded in the historical surveys. For this, a self-starting four-parameter logistic function was used, implemented using the STATS package (SSfl routine) in R vers. 2.10.1 (R Development Core Team, 2009). The data then corresponded to the nets 001, 004 and 005 (Table 1), for which the codend had mesh sizes of 45, 50.8 and 20 mm, respectively (Table 2).

The four-parameter logistic model is defined by the following equation:

$$\eta\left(x, \theta\right) = b1 + \frac{b2 - b1}{1 + \exp\ \left\{(b3 - x)/b4\right\}} \tag{2}$$

To compare the multispecies ogive curves for the different mesh sizes, the species included were those for which there were size records for all the mesh sizes. On this basis, it was possible to make two comparisons: (i) between the 45 mm (9544 records) and 50.8 mm (4038 records) meshes, including a total of 60 species; and (ii) between all three mesh sizes (20, 45 and 50.8 mm), considering only 7 species (3124, 3653 and 2840 records, respectively). The cumulative relative frequency curves generated were also compared with the Kolmogorov–Smirnov test applied for each of the available time periods (1988, 1995/1996 and 2001), to consider the possible effects of changes over time in the size structure of the respective populations.

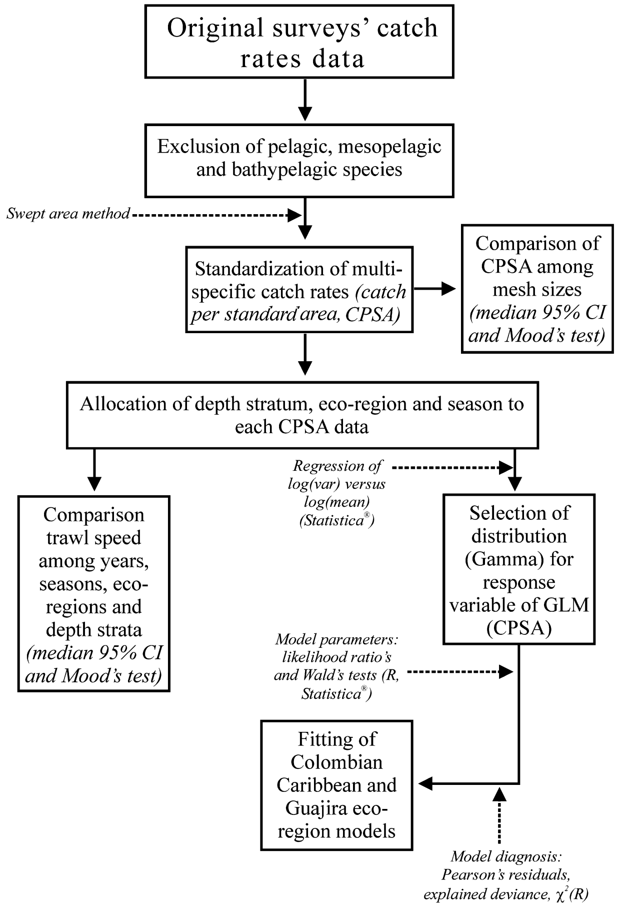

Fig. 2. Simplified flowchart of the sequence of steps taken to complete data processing (including pre-processing of catch rates).

3. Results

3.1. Effects of the mesh size and towing speed

The variables mesh size and towing speed had a minimal effect on the multispecies catch rates of demersal fish, compared to the spatial and temporal variables considered in the models. The combined relative contribution of these two variables to the overall deviance (49.10% in model 1 and 37.01% in model 2) was no more than 3% in either case. In model 1, the deviance explained by mesh size was even less than that explained by towing speed, the reverse being true in model 2 (Table 4). Both the Wald and the chi-square tests showed that the variable mesh size was marginally significant ($p < 0.10$) in model 1, but was not statistically significant in model 2 ($p > 0.10$) (Table 5). The value of the corresponding parameter (−0.0167) multiplied by the difference in size between the 50.8-mm mesh and the reference mesh (20 mm), indicates a reduction of 0.5143 in the natural logarithm of the catch rate using the largest mesh (≈1.67 kg/SA, where SA = 0.04 km^2). Similarly, the log of the catch rates was 0.4175 lower with the 45-mm mesh (≈1.52 kg/SA).

The variable towing speed had a significant effect in model 2 ($p < 0.05$), but not in model 1 ($p > 0.10$) (Table 5). Using the average speed for all the hauls (3 knot) as the reference and the value of the corresponding parameter in model 2 (−0.3791), we obtain that the natural logarithm of the catch rates was 0.1896 lower in the samples taken at 3.5 knot (≈1.21 kg/SA) and 0.1896 higher in those taken at 2.5 knot (≈1.21 kg/SA).

The goodness-of-fit tests based on the residual deviance indicated a good fit of the GLMs to the multispecies catch rates (model 1: $df = 245$, $p = 0.61$; model 2: $df = 160$, $p = 0.60$). In addition, the variance of the residuals tended to be uniform across all levels of the variables considered. The QQ plots did not show deviations from the diagonal that would reveal that the residuals were not normally distributed, though the fit was better with model 2 (Fig. 3).

Table 4
Deviance explained by each factor included in the GLMs fitted to the catch rates (kg/0.04 km^2) of demersal species in swept-area research surveys carried out in the Colombian Caribbean. A log-gamma function was used. The respective models are specified in Table 3. Hyphens indicate that the term is not included in the model.

Factor	Model 1		Model 2	
	Deviance	Deviance explained (%)	Deviance	Deviance explained (%)
Year	120.65	25.80	57.99	23.57
Season	38.70	8.28	22.60	9.19
Eco-region	59.66	12.76	–	–
Depth	7.25	1.55	4.97	2.02
Mesh size	2.23	0.48	1.08	0.44
Towing speed	1.07	0.23	4.41	1.79
Totals/deviance expl. (%)	229.56	49.10	91.05	37.01

Table 5
Statistical significance of the effect of technical factors (Wald and chi-square statistics) and estimation and significance of the respective parameters in the MLZs fitted to the dependent variable "catch rates of demersal fish" (kg/0.04 km^2). Log-link function and gamma distribution were used. Reference levels for categorical variables were: Year 1988, Guajira eco-region, shallow depth stratum and calm season. The two models are specified in Table 3.

Model code	Statistic	Model effects		Parameters (log value)	
		Mesh size	Towing speed	Mesh size	Towing speed
1	Wald	3.54[†]	1.31	−0.0167[†]	−0.1316
	Chi-square	2.72[†]	1.32		
2	Wald	2.18	5.62[*]	0.0906	−0.3791[*]
	Chi-square	1.30	5.38[*]		

[*] $p < 0.05$.
[†] $p < 0.1$.

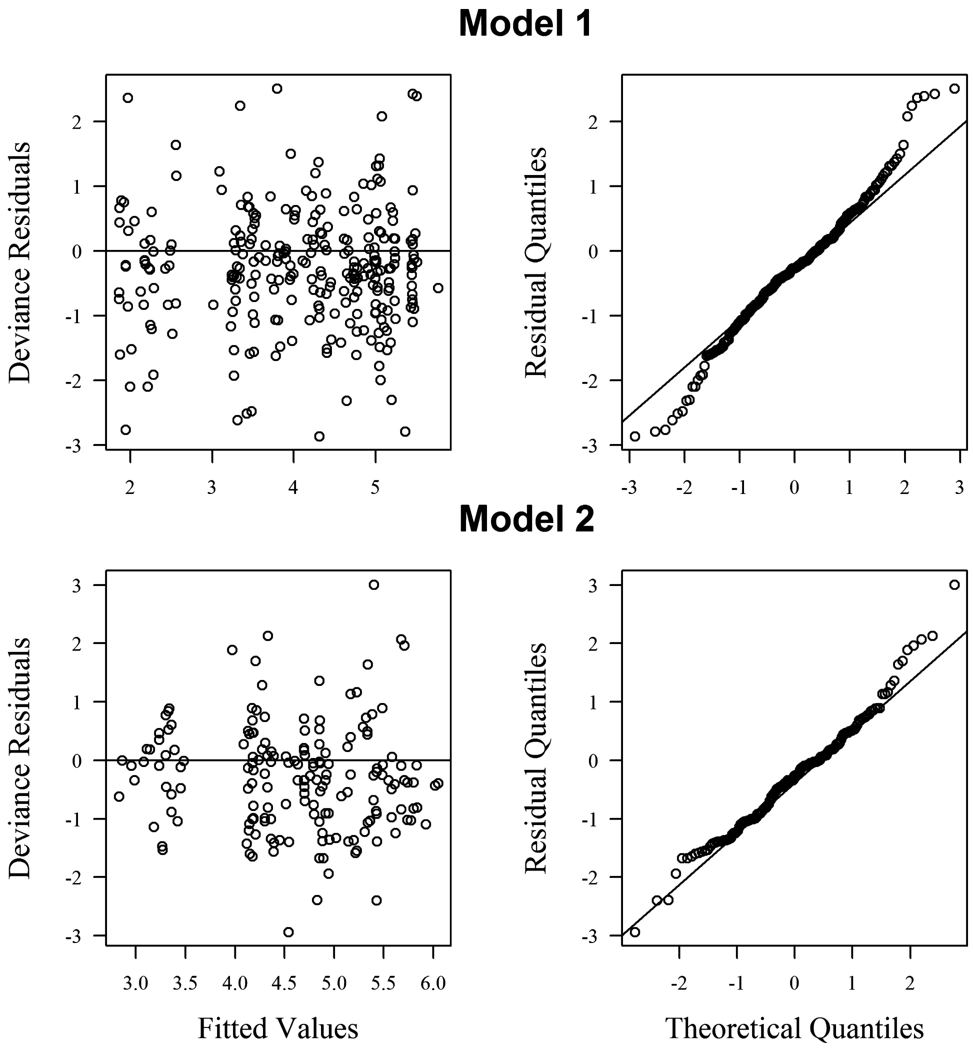

Fig. 3. Deviance residuals versus forecasted values and QQ plots for the two models fitted to the catch rates of demersal species (kg/0.04 km^2). The respective models are specified in Table 3.

3.2. *Independent analysis of the mesh size effect*

If the effect of the remaining variables included in the GLM were not considered, the mesh size would have a non-monotonic effect on the multispecies catch rates in both models (Fig. 4). Even Mood's median test would show a highly significant difference ($p < 0.001$) between the catch rates with the various different mesh sizes, in contrast with when we analyze together the effect of various different factors, using the GLMs.

3.3. *Independent analysis of the towing speed effect*

From the data used in model 1, Mood's test revealed significant differences in towing speed between years ($p < 0.001$), seasons ($p < 0.05$), eco-regions ($p < 0.001$) and depth strata ($p < 0.01$). High towing speeds (3.4–3.5 knot) were more common in the period 1995–1996, while lower ones (2.5–2.8 knot) prevailed in 1988 (Fig. 5a). In addition, the hauls made in calm weather were mostly faster than those in the windy season (Fig. 5b), due to the strong currents occurring in the latter conditions. With respect to eco-regions (Fig. 5c), the most noticeable differences were observed between the GE, where hauls were made at lower speeds (2.7–3.0 knot), and the Salamanca Gulf, Galerazamba and Archipiélagos Coralinos eco-regions, where higher towing speeds were used in most cases (>3.0 knot). Regarding the depth strata (Fig. 5d), there was a marked tendency towards faster towing speeds (3.0–3.4 knot) on the inner and mid continental shelf, than on the outer shelf (2.7–3.1 knot).

Based on model 2 (fitted to the GE catch rates), the most notable differences with Mood's test were between years ($p < 0.001$). There were also marginally significant differences between seasons ($p < 0.10$) and between depth strata ($p < 0.10$). As in the CCS (model 1), the data for the GE were collected at higher speeds in the period 1995–1996 (mainly 3.2–3.6 knot) than in 1988 (Fig. 6a). Towing speeds for the hauls in 2001, although not significantly different from those in 1995/96, were less uniform and tended to be faster (3.2–3.3 knot). Hauls during the calm season were generally made at a speed of 2.9–3.0 knot, while a wider range corresponded to the windy season (Fig. 6b). The speeds used at the different depth strata in the GE showed a similar pattern to that described for the entire CCS: relatively fast and uniform towing speeds in the three strata of the continental shelf and less uniform ones on the intermediate continental (Fig. 6c).

3.4. *Relative effect of the mesh size on fish size structure*

The logistic curves fitted to the size data for 60 species (Fig. 7) showed a good fit to the observed data, both for the 45-mm (Fig. 7a)

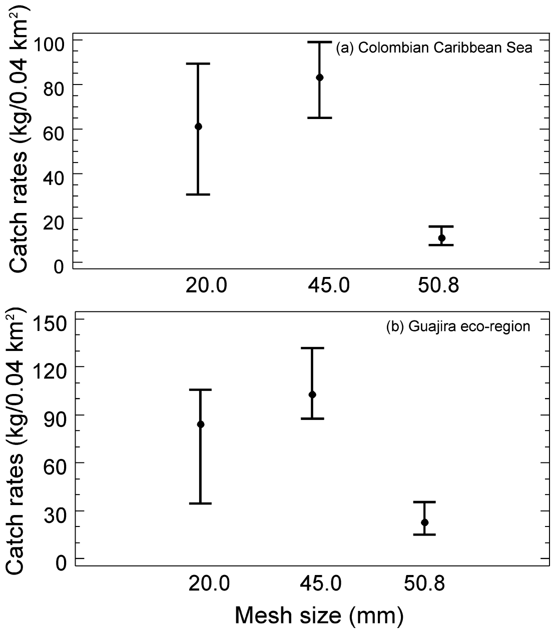

Fig. 4. Medians and 95% confidence intervals of the catch rates of demersal species (kg/0.04 km^2) per mesh size, both for the Colombian Caribbean Sea (a) and Guajira eco-region (b).

and the 50.8-mm (Fig. 7b) meshes. Superimposing the two curves (Fig. 7c) highlights the differential effect for the smaller sizes (<7 cm in total length, TL), these only being caught with the 45-mm mesh net. This relative selectivity of the 50.8-mm mesh net means that cumulative frequencies for larger size fish are higher with this net, the effect being strong enough that the Kolmogorov–Smirnov statistic indicates strongly significant differences between the size distributions obtained with the two nets ($p < 0.001$).

Considering the three logistic curves fitted to the size data for the seven species, the 45- and the 50.8-mm mesh sizes produced similar distributions to those based on data for 60 species (Fig. 7a). The effect of selectivity with the 50.8-mm compared to the 45-mm mesh was clearer, however, in the curves fitted for these seven species (Fig. 7b). In contrast to these two curves, that for the 20-mm mesh size (Fig. 7b) highlights the limited number of records obtained for the smallest size fish in the 1988 survey; indeed, it is not possible to fit the corresponding logistic curve to these data and, hence, this comparison is not possible.

4. Discussion

4.1. Effect of the mesh size on the catch rates

The assessment of the effect of the mesh size using GLMs led to different results to those obtained by an independent assessment of the effect of this variable, confirming the importance of taking into account the combined effect of all factors that may potentially influence catch rates. Using GLMs, we found that the mesh size does not have a very strong effect on the multispecies catch rates from the demersal fish surveys carried out over the last two decades in the CCS. Specifically, the GLMs gave negative parameters for this variable, suggesting a decrease in the multispecies catch rates with an increase in mesh size, but mesh size was only found to be marginally statistically significant in the CCS model. A similar marginal significance was found by Murawski (1996) for the bottom trawl fleet in New England waters ($p = 0.05$). Similarly, Ragonese et al. (2001), in their study on shrimp trawls, found that the differences were only noticeable for meshes ≥45 mm, while comparable mesh sizes (20–28 mm) did not yield statistically different catch rates. It can, therefore, be deduced that the effect of this variable tends to be noticeable only for substantially larger mesh sizes.

The inverse relationship observed between multispecies catch rates and mesh size could be expected, given the theoretical selectivity attributable to bottom trawl nets. One of the factors that determine the catch efficiency of a trawl net is the loss or escape of fish through the codend meshes (Weinberg et al., 2002; Weinberg and Kotwicki, 2008). In demersal fish communities in the CCS, a relatively high percentage of individuals are 3 to 10 cm TL (Duarte et al., 2006; Manjarrés et al., 2008). This predominance of small-sized species of little or no commercial value is also reflected in the percentage of discards (74%) in the commercial shrimp trawl

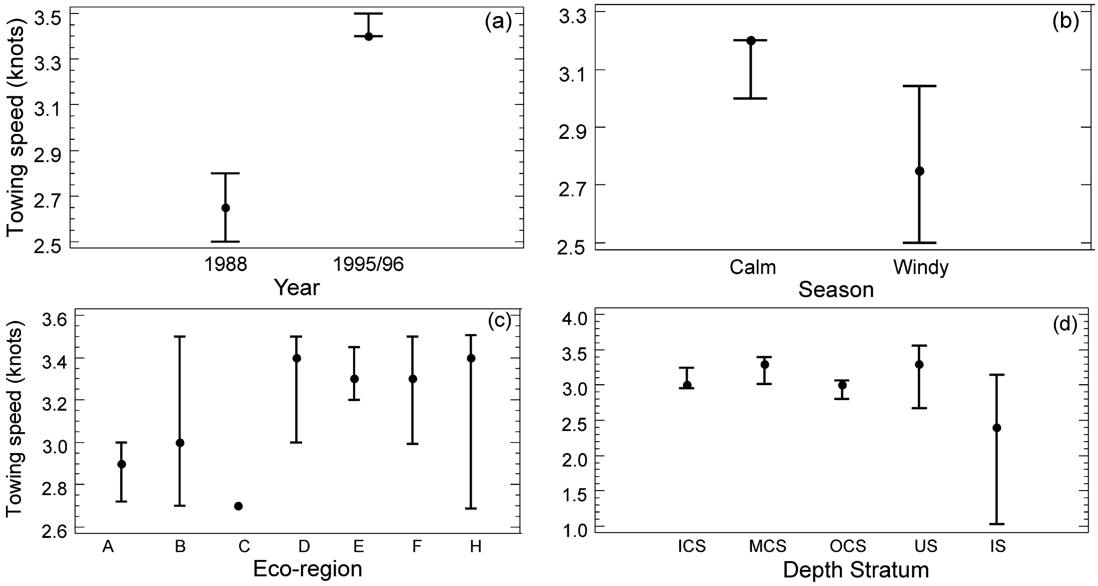

Fig. 5. 95% confidence intervals for the medians of the towing speed at each level of the categorical variables included in the GLMs fitted to the multispecific catch rates recorded in the demersal fish survey cruises conducted in the Caribbean Sea of Colombia between 1988 and 1996 (Model 1). The abbreviations used here are as follows: For eco-regions, a = Guajira, b = Palomino, c = Tayrona, d = Salamanca Gulf, e = Galerazamba, f = Archipiélagos Coralinos, and h = Arboletes; for depth strata, ICS = inner continental shelf, MCS = mid continental shelf, OCS = outer continental shelf, US = upper slope, IS = intermediate slope.

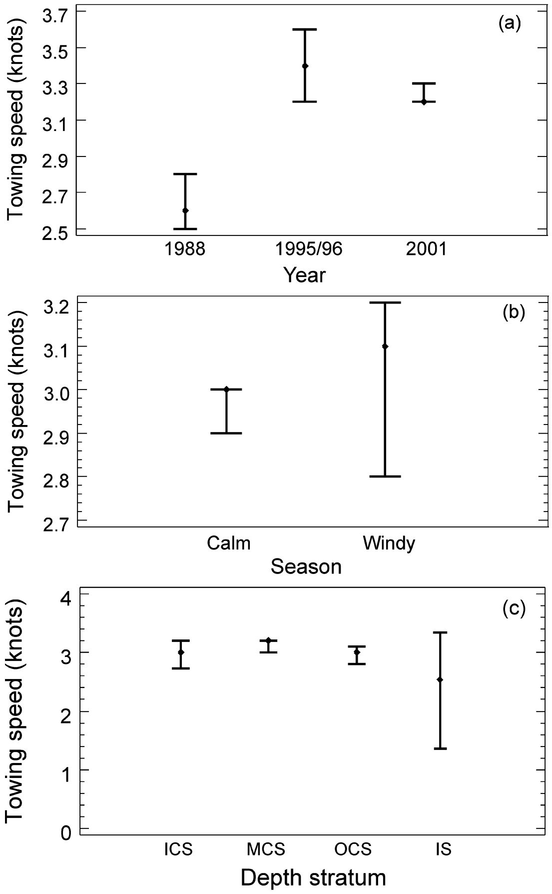

Fig. 6. 95% confidence intervals for the medians of the towing speed at each level of the categorical variables included in the GLMs fitted to the multispecific catch rates recorded in the demersal fish survey cruises conducted in the Guajira eco-region between 1988 and 2001 (Model 2). Abbreviations are the same as in Fig. 5.

fisheries in the region (Viaña et al., 2004), the codend mesh size of 12.5 mm (Viaña and Manjarrés, 2004) being much smaller than those used in the fish resource surveys analyzed in this study (20, 45 and 50.8 mm). Indeed, as many as 88 different fish taxa have been recorded in the discards of the shrimp trawl fleet (Viaña et al., 2004), representing 40% of the total number of taxa in catches by this fleet (Duarte et al., 2006).

Another evidence of the escapement through the codend of some of the demersal fish trawled in these research surveys is provided by the multispecies cumulative relative frequency curves for the fish sizes recorded in the surveys with each of the mesh sizes. These “pseudo-selectivity” curves indicate indirectly that there is some fish size selectivity attributable to mesh size and, given the abundance of small species in the demersal fish communities in the CCS, this is translated into an overall trend of falling multispecies catch rates with increasing mesh size, even though the effect does not reach a high level of significance.

4.2. Effect of the towing speed on catch rates

The need to include towing speed among the predictors in these models is supported by the significant differences observed for this variable between years, seasons, eco-regions and depth strata, as well as by the significance of its effect in one of the GLMs assessed. The way in which towing speed affects the performance of the net is complex and the overall impact is often unclear (Somerton and Weinberg, 2001; Dahm et al., 2002). Some authors have attempted to simplify the analysis by assuming that the differences in towing speed have a little effect on the catch efficiency in most demersal fish species (Rogers and Ellis, 2000), while others (Greenstreet and Hall, 1996) have considered that a towing speed of 2–2.5 knot is sufficient for catching all but the largest and fastest demersal fish species. On the other hand, some studies have found that variations in towing speed may well affect the selectivity of the trawl nets, probably due to geometrical changes, in particular an increase in the opening of the lateral meshes at the codend (O’Neill, 1997; Dahm et al., 2002; Herrmann, 2005a), and/or a greater/lesser ability to escape (Dahm et al., 2002), as well as swimming ability of these species (Videler and Wardle, 1991; Somerton and Weinberg, 2001; Dahm et al., 2002).

Although it is recognized to be difficult to assess the effect of towing speed on selectivity and hence on catch rates using trawl nets, there is a consensus that towing speed influences two important operational characteristics of the net: the wing spread, which is determined by the opening of the net (Helser et al., 2004), and footrope contact with the seabed (Somerton and Weinberg, 2001; Weinberg et al., 2002; Weinberg and Kotwicki, 2008). However,

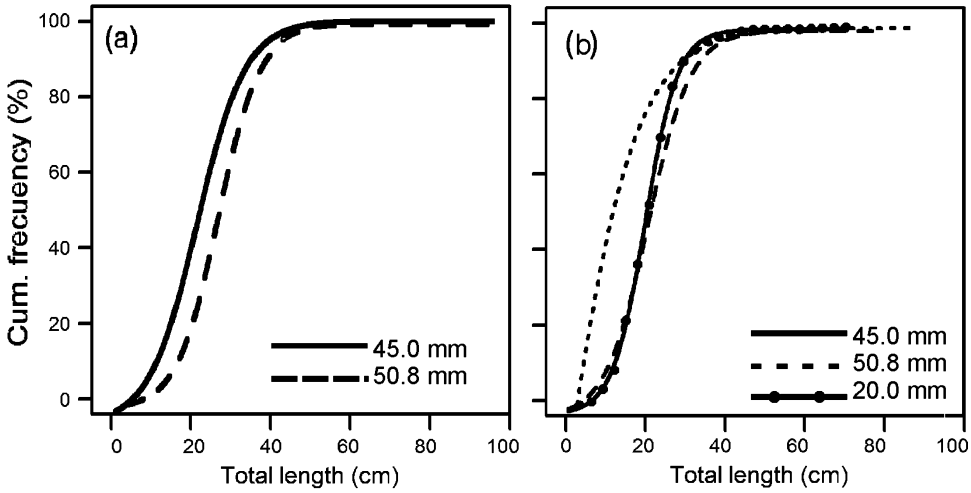

Fig. 7. Cumulative relative size frequency curves for the catches of the bottom trawl nets used in the demersal fish survey cruises conducted in the Caribbean Sea of Colombia between 1988 and 2001, belonging to (a) 60 species that were captured by the 45 and 50.8 mm codend mesh and (b) 7 species that were captured by the 45, 50.8 mm, and 20 mm codend mesh.

given the inverse relationship between towing speed and catch rate found in the GE, it could be argued that in this case the effect of towing speed on the contact with the seabed may be more important than that on wing spread.

The impact of escapement under the footrope on the performance of trawl nets has also been demonstrated in previous studies (Somerton and Weinberg, 2001; Piasente et al., 2004; Weinberg et al., 2002). Contact with the seabed may also explain why the effect of towing speed was only significant for the GE. The effect of the degree of contact with the seabed varies significantly between fish species, and in some cases, even between different sizes of the same species (Weinberg et al., 2002). Given the differences in species composition of the communities between some ecoregions (Manjarrés et al., 2001), it is reasonable that the statistical significance of the effect of the towing speed varies as a function of study area. However, in order to have established with certainty the factors underlying the differences observed between the CCS and the GE, it would have been necessary to collect information on other variables that also influence footrope contact with the seabed, such as sediment particle size (Weinberg and Kotwicki, 2008).

4.3. Goodness-of-fit of the models versus standardization of catch rates

Assessment of historical changes in abundance indices calculated from different surveys of demersal fish resources should ideally be based on standardized catch rates, which means removing most of the annual variation in the data that is not attributable to changes in abundance (Maunder and Punt, 2004). In this study, although the GLM methodology demonstrated its usefulness for exploring the effect of two technical characteristics not generally considered when assessing changes in abundance over time, it is necessary to acknowledge that a considerable fraction of the residual variance in the catch rates in the CCS and the GE could not be explained by the variables considered in the models.

Various authors have noted that the amount of variance explained using GLMs tends to be low (Ye et al., 2001; Gatica and Hernández, 2003). The situation is, however, different when analysing data on commercial single-species fisheries, in which the fishing tactics are specifically focused on catching a given species; therefore, the fleet normally operates in the areas with highest abundance of the target species (Maynou et al., 2003; Guisan et al., 2002). For example, Goñi et al. (1999) found that 63% of the variance was explained in gamma GLMs fitted to the catch rates of the commercial trawl fleet in the Western Mediterranean Sea. Nevertheless, Maynou et al. (2003) found explained variances of 13.1 and 52.4% in GLMs fitted to CPUE for Norway lobster (*Nephros norvegicus*) and red shrimp (*Aristeus antennatus*), respectively, while Wiff et al. (2005) found a explained variance of 37% in a study by using GLMs to standardize catch rates of cardinal fish (*Epigonus crassicaudus*) in Chile. Therefore, it should be noted that the level of the deviance explained in the multispecies gamma models (37 to 51%) is within the top quartile of the results commonly obtained in studies focused on standardising catch rates using GLMs.

There are several potential reasons for variations not being explained by the model (residual variance), most of which relate to uncontrollable factors. When analysing data from historical surveys, it is common that the limited number of samples available makes it difficult to achieve a balanced design and, hence, to evaluate interaction terms that could reduce the residual variance of the model. On the other hand, various authors (Maynou et al., 2003; Guisan et al., 2002) have suggested that, given the high species diversity in bottom trawl research surveys, the random component in the sampling process itself means that the variability in catch rates with different types of fishing gear is governed by a complex and intertwining network of relations between biological, environmental and technical variables, as well as diel variations in the vertical distribution of fish species.

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