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Research Article

Quantifying the morphology of key species caught in the southern Brazilian penaeid-trawl fishery as a precursor to improving selection

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ABSTRACT. Penaeid trawls are poorly selective fishing gears; contributing towards approximately 27% of global marine fisheries discards. Various options are available for mitigating penaeid-trawl bycatch, including gear modifications such as 'bycatch reduction devices' (BRDs) or codend mesh-size regulations. A precursor to developing modifications is information about the key target and bycatch species in terms of their sizes and morphology. Here we describe the relationships between these characteristics for the southern Brazilian industrial penaeid-trawl fishery within a broader objective of proposing more selective trawl configurations. Catches were sampled during 37 tows. Fifty-two species were caught, including two loggerhead turtles, *Caretta caretta*, one green turtle, *Chelonia mydas*, as well as 61 individuals of seven ray species classified as Endangered or Critically Endangered. One penaeid (*Pleoticus muelleri*) and 11 teleosts were assessed for various morphological relationships. The data demonstrated that both the existing conventionally used 26 mm (stretched mesh opening; SMO) mesh and a legislated size of 30 mm SMO are too small. Using morphological relationships, we propose testing a minimum diamond-shaped mesh size of at least 35 mm and a square-mesh window in the top of the codend comprising at least 48 mm mesh. Such a configuration would probably retain penaeids and larger teleosts, but allow many small teleosts to escape. Anteriorly located grids are also required to reduce the bycatch of charismatic species like turtles and rays. Wide-scale use of such BRDs should considerably reduce bycatches and the ancillary impacts of regional penaeid-trawl fisheries.

Keywords: mesh size, morphology, bycatch, penaeid trawl, square-mesh, selectivity.

INTRODUCTION

Determining ideal mesh sizes for penaeid-trawl fisheries is a critical regulatory process within a broad objective of controlling size selectivity, and ultimately the mortality of target and non-target species (assuming adequate survival of escapees, Pope *et al*., 1975). Most penaeid-trawl codends comprise diamond-shaped meshes with stretched mesh openings (SMO) between 30 and 50 mm (Eayrs, 2012). During towing, these small meshes are pulled tight, with lateral openings in codends typically < ~35% of the stretched mesh length (Robertson, 1986). It is only during haulback when the vessel speed slows down to engage the winches and retrieve the nets that codend lateral-mesh openings increase beyond ~35% (Watson, 1989; Broadhurst *et al*., 1996).

Penaeid trawling accounts for nearly 27% of the annual discards (most recently estimated at <10 million ton yr^{-1}; Zeller *et al*., 2018) from global marine fisheries (Kelleher, 2005); a value related to the small mesh sizes used in trawls fished in highly biodiverse and productive near-shore areas. This bycatch often comprises many small teleosts (<20 cm total length; TL), some of which are juveniles of species that, when larger, are an important source of income, either in other fisheries or as retained so-called 'by-product' in the same fishery (Alverson *et al*., 1994; Eayrs, 2012). There are various other broad, cascading ecological concerns associated with discards and the unaccounted fishing mortality of large quantities of species; all of which support developing more selective trawling (Hall & Mainprize, 2005).

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The conventional approach to reduce penaeid-trawl bycatch is to apply technical modifications that typically include bycatch reduction devices (BRDs), and often involve strategic square-mesh panels and escape windows to exclude small teleosts, or grids to exclude turtles and other large animals (Broadhurst, 2000). Such devices exploit either the swimming behavior, morphology or size of unwanted species to promote their escape and have been adopted with varying levels of success among many penaeid-trawl fisheries around the world (Broadhurst, 2000; Eayrs, 2012).

While BRDs can effectively reduce unwanted catches (typically by 30-90%; Broadhurst, 2000), often there are issues associated with adoption and acceptance by fisheries. In many cases, such issues arise from a perceived loss of the targeted penaeids, often exacerbated by technical problems associated with BRD rigging. As a starting point to overcome such issues, it is essential to obtain sufficient fishery-related information, and especially data describing the sizes and morphology of the key species. In some cases (for key species of concern), it might be possible to merely regulate mesh size and/or shape in the trawl as a mechanism for improving selectivity and reducing bycatch. Simple changes to meshes within existing trawl configurations, including readily available diamond-shaped mesh and/or alternative mesh shapes at strategic locations in the codend, might be more accepted than complex modifications.

In Brazil, both small-scale and industrial penaeid-trawl fisheries are characterized by similar bycatch problems as elsewhere, but with different challenges for resolution (Silva *et al*., 2013). One of main regional, industrial fisheries involves up to 276 vessels, trawling along the southern coast (UNIVALI/CTTMar, 2013). Existing legislation prescribes a minimum SMO of 30 mm (Ordinance SUDEPE Nº55, 20th December 1984), which was originally mandated for targeting pink shrimp (*Penaeus paulensis*). However, with the collapse of *P. paulensis* stocks over the past two decades, fleets began targeting the smaller Argentine red shrimp (*Pleoticus muelleri*), and Argentine stiletto shrimp (*Artemesia longinaris*) without any legislated minimum mesh size. Operators typically use 26 mm SMO in the codend and in addition to penaeids, retain large individuals (typically ≥22 cm; TL) of key fish as by-product, including the southern king weakfish (*Macrodon atricauda*), stripped weakfish (*Cynoscion guatucupa*) and Brazilian codling (*Urophycis brasiliensis*) (Haimovici & Mendonça, 1996; D'Incao *et al*., 2002; Duarte, 2013; Pezzuto & Benincà, 2015).

The small mesh and lack of any BRDs are problems throughout all Brazilian penaeid-trawl fisheries, and as a consequence, southern Brazilian penaeid trawlers discard at least ~1.5 kg of bycatch for every 1 kg of penaeids and assorted by-product (Duarte, 2013). Ideally, large numbers of unwanted individuals would escape during fishing, while individuals larger than minimum size at first maturity might be retained for sale. Considering the above, and as a precursor to developing BRDs that might address some of the bycatch issues in the southern Brazilian penaeid-trawl fishery, here we sought to describe various morphometric relationships for the key teleost and one penaeid species (*P. muelleri*), and then use these data to assess the likely impacts on catches of different, regionally available, sizes of diamond mesh throughout the codend and BRDs comprising strategic square-mesh windows.

MATERIALS AND METHODS

Teleost and penaeid samples were obtained from 37 tows during one commercial (February 2014) and two scientific penaeid-trawl cruises (R/V Atlântico Sul, September 2015) across conventional fishing areas between Solidão Lighthouse and Rio Grande city (Fig. 1). The spatio-temporal sampling distributions were designed to encompass the range of bycatch typically caught on the fishing grounds (Dumont & D'Incao, 2011). Scientific observers collected all data, and with a Brazilian government license (SISBio Nº42311-2).

The commercial vessel (18 m length) was double rigged with paired otter boards attached to 2.20 m sweeps. The research vessel (36 m length) had a single rig with paired otter boards attached to 2.20 m sweeps. The trawls towed by each vessel were identical two-seam local designs (19 m headline lengths; Fig. 2). Each trawl comprised mesh sizes of 40 mm SMO made from 1.3 mm diameter polyethylene (PE) twine in the body, and 26 mm SMO polyamide (PA) twine in the codend. Each codend measured 197 meshes in the normal direction (N) and 156 meshes in the transverse (T) direction (Fig. 2). Trawls were diurnally deployed in depths of 17 to 22 m for 4 h by the commercial boat and 30 min by the research vessel.

At the end of each deployment, representative samples of the most abundant teleosts and penaeids were separated from the catch, stored on ice and eventually measured in a laboratory (±1 mm). For each teleost, measurements of the total length (TL) and maximum height (MH) were recorded using a ruler, while maximum perimeter or girth (MG) was measured using a piece string (and then a ruler). Body width (BW) was estimated from the MH and MG via the ellipse formula (Khan, 2013) as follows:

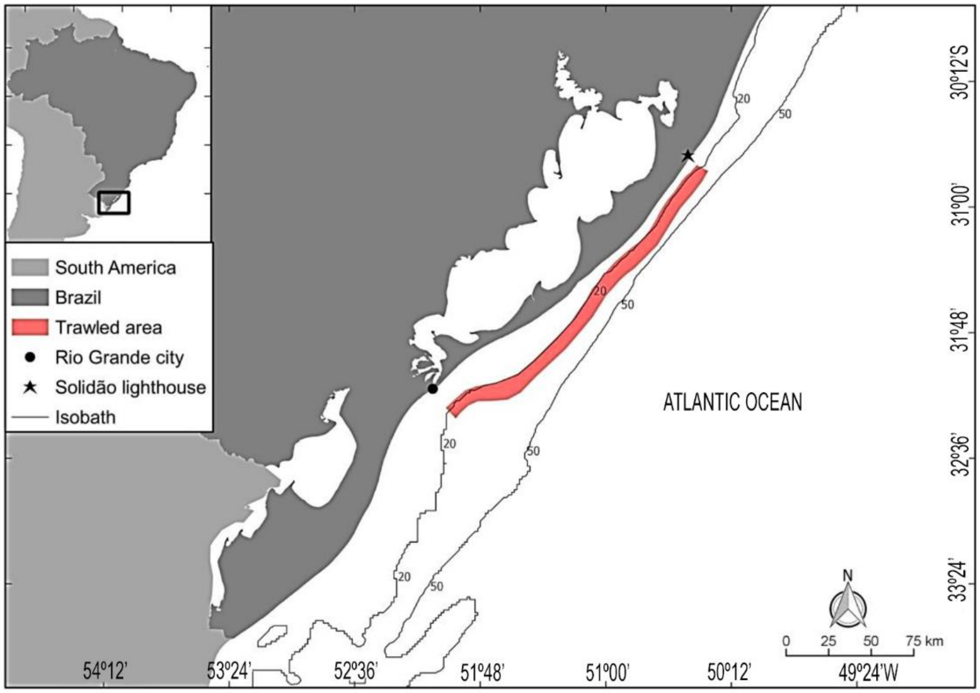

Figure 1. Study area in southern Brazil. The red area represents the fishing grounds used by the double-rigged trawling fleet. The red line represents the extremes of the sampling area.

$$BW = \sqrt{(2 \times \frac{MG^2}{\pi^2} - MH^2)}$$

All teleosts were then weighed (Wt ± 0.1 g). For the penaeid *Pleoticus muelleri*, measurements of TL, carapace length (CL), MG, and MH were similarly recorded as above (±1 mm) and each was weighed (±0.1 g). The same formula as above was used to calculate BW. Insufficient quantities of other penaeids did not allow meaningful analyses.

Linear-regression analyses were used to investigate the relationships between TL and the remaining measures (MH, MG, and BW) for key species. A potential model was fitted to the TL-weight data as follows: $Y = A \times X^B$, where Y is TL and X is Wt (Zar, 2010). The ratio (R) between teleost MH and BW was obtained by dividing the latter into the former to categorize general shape as being either: fusiform: R= 1-2, dorsally compressed: R<1, or ventrally compressed: R>2.

The absolute opening for diamond-shaped codend meshes during towing was assumed to be a maximum lateral distance of 35% of the SMO (Robertson, 1986). Based on this 'fractional' opening, the conventional 26-mm diamond mesh would be reduced to a maximum of 24.34 mm length × 9.10 mm width, while the 30 mm diamond mesh would be reduced to 28.10 × 10.50 mm. By comparison, the fractional-mesh openings for square-shaped meshes in the codend during towing were assumed to be the bar lengths (and with the largest distance across the diagonal). During haulback, both mesh shapes might be opened to their full size (perimeter).

Using the collected morphometric data (MH and MG), we estimated the maximum TLs of key teleosts and penaeids that might escape through the two different sizes of diamond-shaped (*i.e*., conventionally used 26 and 30 mm) and square-shaped meshes (made by hanging 48- and 58 mm mesh on the bar, providing lengths of 24 and 29 mm) in the codend during (1) towing (assuming fractional mesh openings as above during loading) and (2) haulback (when meshes open, and there is no load). The square-mesh size was chosen based on the locally available mesh (there are very few available mesh sizes in Brazil) and assuming that it would be located at a strategic window in the top of the codend. Escape sizes of teleosts during towing were calculated assuming meshes were under load (35% lateral opening for diamond-shaped meshes).

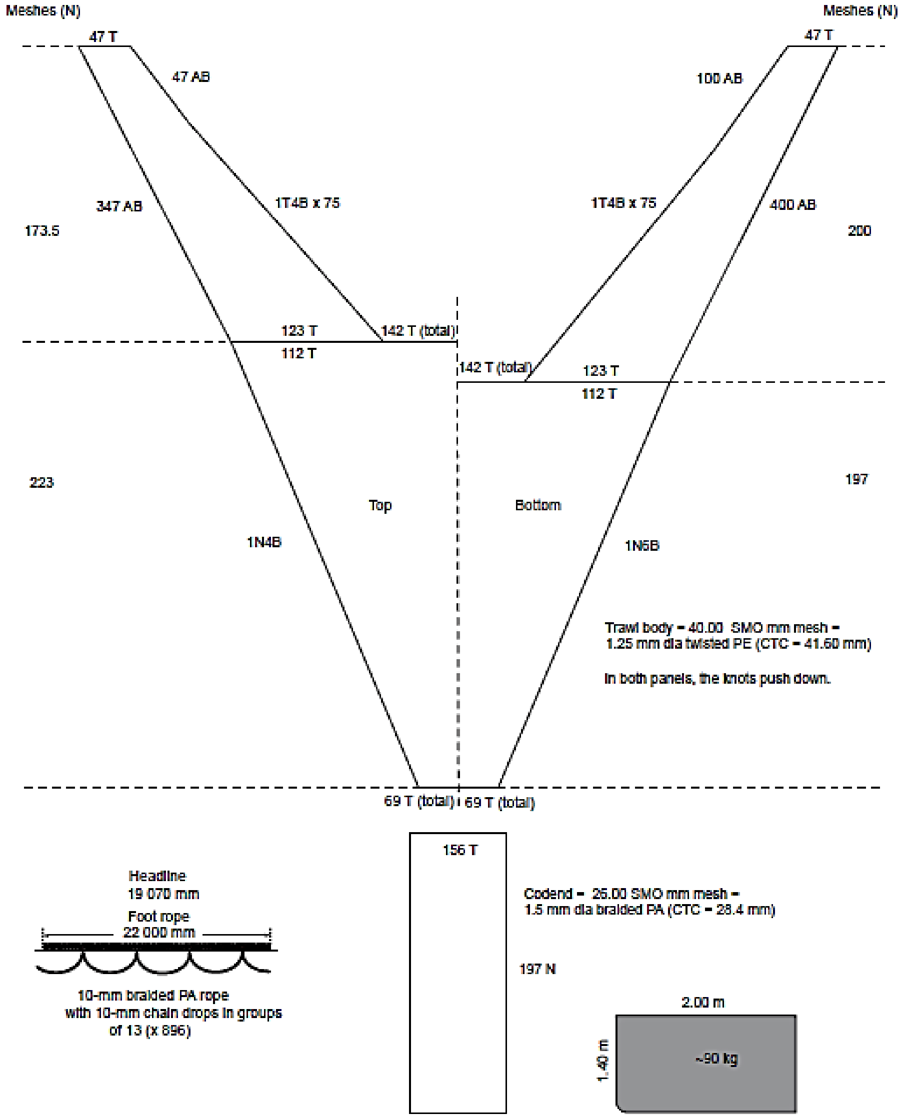

Figure 2. Plan of the trawls used in the present study. N: meshes in the normal direction, T: meshes in the transverse direction; AB: all bars, B: bars, PE: polyethylene, SMO: stretched mesh opening, CTC: center-knot-to-center knot, PA: polyamide.

RESULTS

In total, at least 52 species, including 16 decapod crustaceans, one mollusk genus, 33 fish including seven endangered ray species, two loggerhead turtles (*Caretta caretta*) and one green turtle (*Chelonia mydas*) were sampled from the catches of the vessels (Table 1). Both loggerhead turtles were released alive, but the green turtle died. Approximately 50 kg of penaeids were caught each tow, with *Pleoticus muelleri* the most abundant species (1.17 kg in total were sampled) and only very few *Artemisa longinaris*. Two genera (*Genidens* and *Menticirrhus*) each comprised two similar species (*Genidens barbus* and *G. planifrons*; and *Menticirrhus americanus* and *M. littoralis*, respectively), which were not separated.

We assessed the morphometric relationships of the 12 most abundant species (Table 2). These key species had variable minimum and maximum sizes, but most were 14-350 mm TL and immature (Table 2). Based on the R ratio, the importance of each species' size in terms of being able to pass through meshes during towing varied between their MH and BW. Specifically, *Symphurus jenynsii* was classified as dorsally comprissed; *Paralonchurus brasiliensis*, *Macrodon atricauda*, *Genidens* spp., *Porichthys porosissimus*, *Menticirrhus* spp., *Cynoscion guatucupa*, and *Urophycis brasiliensis* were fusiform, and *Trichiurus lepturus*, *Stephanolepis hispidus*, and *Peprilus paru* were ventrally compressed (Fig. 3).

Table 1. List of taxonomic groups and species as well as the number sampled from catches of penaeid trawlers during 37 tows off the coast of Rio Grande do Sul, Brazil. *Species marked are commercially retained at large sizes (termed 'by-product'). Conservation status (IUCN 2017): CE (Critically Endangered), EN (Endangered), VU (Vulnerable), LC (Least Concern), DD (Data Deficient) and NE (not evaluated). The species in bold were used for morphometric data analyses. [A]*Genidens* spp.: genus comprised two morphologically similar species *Genidens barbus*, and *G. planifrons*. [B]*Menticirrhus* spp.: genus comprised two morphologically similar species *Menticirrhus americanus*, and *M. littoralis*.

Specific name	Common name	Number sampled	Conservation status
DECAPODS			
Achelous spinimanus	Blotched swimming crab	36	LC
Achelous spinicarpus	Longspine swimming crab	36	NE
Arenaeus cribrarius	Speckled swimming crab	19	NE
Artemesia longinaris	Argentine stiletto shrimp	140	NE
Callinectes danae	Blue crab	4	NE
Callinectes sapidus	Blue crab	16	NE
Callinectes ornatus	Blue crab	120	NE
Dardanus insignis	Hermit crab	2	NE
Hepatus pudibundus	Flecked box crab	36	NE
Libinia spinosa	Spider crab	32	NE
Loxopagurus loxochelis	Hermit crab	2	NE
Nanoplax sp.	–	1	NE
Penaeus paulensis	Pink shrimp	3	NE
Persephona mediterranea	Mottled purse crab	6	NE
Pleoticus muelleri	Argentine red shrimp	175	NE
Porcellana sayana	Spotted porcelain crab	1	NE
MOLLUSKS			
Loligo spp.*	–	45	NE
PISCES			
*Balistes capriscus**	Grey triggerfish	3	VU
Chloroscombrus chrysurus	Atlantic bumper	15	LC
Citharichthys spilopterus	Bay whiff	2	LC
*Conger orbignianus**	Argentine conger	3	NE
Cynoscion guatucupa*	Stripped weakfish	79	NE
*Cynoscion jamaiscensis**	Jamaica weakfish	13	NE
Engraulis anchoita	Argentine anchovy	35	NE
Genidens* spp.[A]	White sea catfish	152	LC
Gymnura altavela	Spiny butterfly	1	VU
Macrodon atricauda*	Southern king weakfish	195	NE
Menticirrhus* spp.[B]	Southern king croaker	45	LC
*Micropogonias furnieri**	Whitemouth croaker	4	LC
Myliobatis goodie	Southern eagle	3	DD
Ophichthus gomesii	Pallid snake eel	1	LC
*Paralichthys orbignyanus**	Flounder	4	NE
Paralonchurus brasiliensis	Banded croaker	342	LC
Peprilus paru*	American harvestfish	42	LC
Porichthys porosissimus*	Midshipman	41	NE
*Prionotus punctatus**	Bluewing searobin	35	LC
Pseudobatos horkelii	Brazilian guitarfish	8	CE
Selene setapinnis	Atlantic moonfish	4	NE
Selene vomer	Atlantic lookdown	1	LC
Serranus auriga	Long finned dwarf seabass	6	NE
*Stellifer rastrifer**	Rake stardrum	2	LC
Stephanolepis hispidus*	Planehead filefish	40	LC
Squatina guggenheim	Angular angel shark	6	EN
Squatina occulta	Hidden angel shark	4	EN
Symphurus jenynsii	Tonguefish	51	NE
Sympterygia acuta	Bignose fanskate	27	VU
Sympterygia bonapartii	Smallnose fanskate	12	DD
*Trachinotus marginatus**	Plata pompano	3	NE
Trichiurus lepturus*	Largehead hairtail	126	LC
Urophycis brasiliensis*	Brazilian codling	88	NE
REPTILES			
Caretta caretta	Loggerhead turtle	2	VU
Chelonia mydas	Green turtle	1	EN

Table 2. The sample size (n), minimum (min), maximum (max) and mean (±SD) total length (TL; all in mm), and size at first maturity (SFM; with references) of key teleost and one penaeid species caught in southern Brazilian penaeid trawls. NA: not available. *Indicates species commercially retained at large sizes (termed 'by-product').

Species	Total length (TL)					Reference
	n	Min	Max	Mean ± SD	SFM (mm)	
Penaeid						
*Pleoticus muelleri**	175	82	142	109.45 ± 14.12	121	Segura & Delgado (2012)
Teleosts						
*Cynoscion guatucupa**	79	37	470	95.04 ± 75.48	290	Haimovici & Miranda (2005)
Genidens spp.*	152	75	280	131.6 ± 45.31	400 ♀/430 ♂	Reis (1986)
*Macrodon atricauda**	195	25	360	211.5 ± 77.94	230	Haimovici *et al.* (2006)
Menticirrhus spp.*	45	95	350	211.47 ± 67.42	230	Braun & Fontoura (2004)
Paralonchurus brasiliensis	272	45	240	150.2 ± 39.82	150	Branco *et al.* (2005)
*Peprilus paru**	42	45	220	78.6 ± 29.15	120	Haimovici (1998)
*Porichthys porosissimus**	41	50	300	187.87 ± 58.53	NA	
*Stephanolepis hispidus**	40	14	220	61.43 ± 42.17	140 ♀/150 ♂	Mancera-Rodríguez & Castro-Hernández (2015)
Symphurus jenynsii	51	20	350	172.5 ± 39.4	NA	
*Trichiurus lepturus**	126	85	1100	488.08 ± 245.96	700	Martins & Haimovici (2000)
*Urophycis brasiliensis**	88	77	460	161.44 ± 49.23	400 ♀/290 ♂	Cavole (2014)

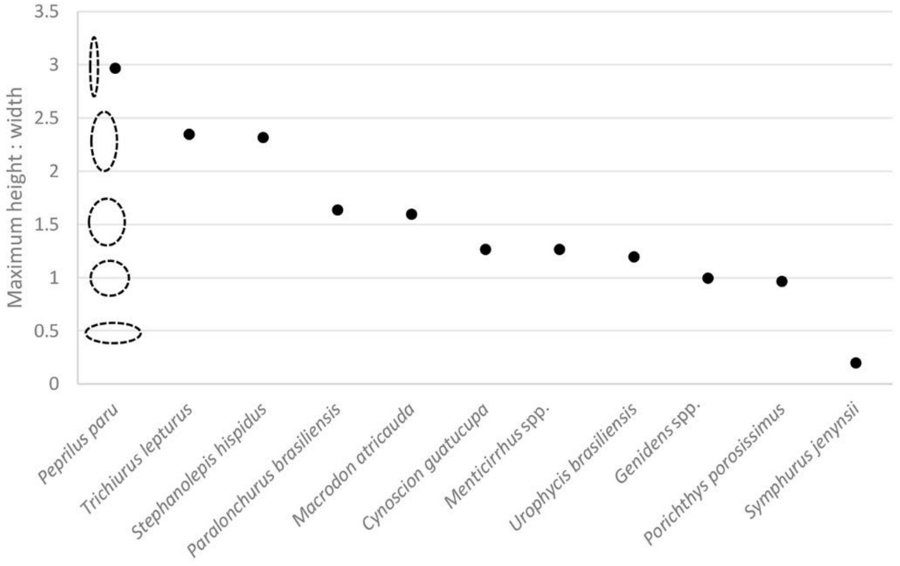

Figure 3. The ratio between maximum body height and width estimated for key teleosts caught in southern Brazilian penaeid trawls, with fish shapes (transverse sections) illustrated by ellipses.

It is possible to postulate the sizes of individuals that might pass through meshes within their hypothesized fishing geometry. In particular, during fishing (when meshes are under load) juveniles of commercial species, such as *C. guatucupa*, *Genidens* spp., *M. atricauda*, *Menticirrhus* spp., and *U. brasiliensis* will only escape at sizes between <59 and 164 mm TL. If the codends had windows/panels of square-shaped mesh with bar lengths of 24 and 29 mm, respectively, the diagonal openings would be 34 and 41 mm, and the same species would escape at sizes <233 mm TL (Table 4).

Assuming teleosts could squeeze though meshes with force (*e.g.*, during haulback when meshes are convoluted and without load, so they open fully), escape would be dictated by MG in relation to the mesh perimeter. The mesh perimeter of the conventional 26 mm mesh is 52 mm, while the 30 mm mesh has a perimeter of 60 mm and the two sizes of square meshes have perimeters of 96 and 116 mm, respectively (Table 4). Many teleosts caught in the diamond meshes were immature, and with quite a few smaller than 100 mm TL. Regarding the two sizes of square mesh, most of

Table 3. Linear and potential relationships of key species caught in southern Brazilian penaeid trawls. TL, total length; CL, carapace length; MH, maximum height; MG, girth; BW, body width; Wt, weight. n = 12–143 for all species.

Species		r^2	Species		r^2
Cynoscion guatucupa	TL = 12.80 + 4.11 MH	0.88	*Porichthys porosissimus*	TL = 29.85 + 5.16 MH	0.91
(37-155 mm TL)	TL = -2.12 + 1.71 MG	0.97	(50-300 mm TL)	TL = 45.20 + 1.40 MG	0.88
	TL = 20.02 + 4.31 BW	0.62		TL = 69.42 + 3.50 BW	0.77
	TL = 44.86 Wt$^{0.33}$	0.95		TL = 54.65 Wt$^{0.30}$	0.69
Genidens spp.	TL = 55.51 + 3.68 MH	0.56	*Symphurus jenynsii*	TL = 26.91 + 15.84 MH	0.84
(75-280 mm TL)	TL = 27.03 + 1.60 MG	0.94	(70-225 mm TL)	TL = 39.56 + 1.40 MG	0.83
	TL = 27.32 + 5.03 BW	0.90		TL = 41.61 + 3.14 BW	0.82
	TL = 58.78 Wt$^{0.28}$	0.98		TL = 60.09 Wt$^{0.30}$	0.96
Macrodon atricauda	TL = 11.52 + 5.05 MH	0.72	*Stephanolepis hispidus*	TL = 3.91 + 2.27 MH	0.99
(100-330 mm TL)	TL = 51.46 + 1.47 MG	0.69	(14-220 mm TL)	TL = -2.09 + 1.01 MG	0.99
	TL = 176.1 + 1.88 BW	0.32		TL = -12.58 + 6.75 BW	0.52
	TL = 5.15Wt$^{1.00}$	0.73		TL = 39.77 Wt$^{0.32}$	0.98
Menticirrhus spp.	TL = 16.54 + 4.78 MH	0.90	*Trichiurus lepturus*	TL = 98.09 + 14.83 MH	0.95
(95-330 mm TL)	TL = 4.05 + 1.79 MG	0.96	(175-950 mm TL)	TL = 75.69 + 6.29 MG	0.95
	TL = 21.17 + 5.87 BW	0.89		TL = 222 + 21.52 BW	0.46
	TL = 54.58 Wt$^{0.29}$	0.99		TL = 16.06 Wt$^{0.28}$	0.97
Paralonchurus brasiliensis	TL = 40.35 + 3.43 MH	0.93	*Urophycis brasiliensis*	TL = 63.28 + 4.15 MH	0.72
(70-220 mm TL)	TL = 35.82 = 1.33 MG	0.91	(77-265 mm TL)	TL = 32.63 + 1.80 MG	0.85
	TL = 80.60 + 3.41 BW	0.49		TL = 89.51 + 3.39 BW	0.38
	TL = 58.57 Wt$^{0.27}$	0.95		TL = 62.11 Wt$^{0.28}$	0.93
Peprilus paru	TL = 12.55 + 1.66 MH	0.85	*Pleoticus muelleri*	TL = 32.46 + 5.44 MH	0.77
(60-85 mm TL)	TL = 11.19 + 0.71 MG	0.88	(82-142 mm TL)	TL = 23.73 + 2.03 MG	0.84
	TL = 59.36 + 0.93 BW	0.20		TL = 24.7 + 6.74 BW	0.81
	TL = 37.39 Wt$^{0.34}$	0.91		TL = 25.04 + 3.02 CL	0.84
				TL = 54.18 Wt$^{0.30}$	0.86

the 11 teleost species would escape if they were <157 and 181 mm TL, respectively (Table 4).

For the 26 and 30 mm SMO diamond-shaped meshes, *P. muelleri* could escape at sizes up to 86 and 95 mm TL, respectively. However, the estimated MGs implied that if windows of both sizes of square mesh were located in a position when penaeids made contact, then most penaeids might escape (Table 4). Note these calculations are based on penaeids passing through longitudinally and should be considered maximums (*e.g.*, individuals are likely to assume a range of convex positions during mesh contact, which might limit the escape of many smaller than the mesh).

DISCUSSION

Species composition and general morphology

Penaeid trawling is postulated to threaten the sustainability of marine fisheries resources (Broadhurst, 2000), primarily because of high discard mortalities (Aramayo, 2015). The data here reiterate such impacts with turtles and ~60 rays (comprising five species listed as critically endangered and two as endangered) (ICMBio/MMA, 2016; IUCN red list, 2017) caught during 37 tows in the studied area. Although the spatiotemporal data are limited, such a rate (*e.g.*, ~0.1 turtles and ~20 rays per deployment) reiterates the urgent need for BRDs involving grids in this fishery, which could be configured to allow most by-product to pass through (*e.g.*, 100 mm bar spaces; Broadhurst, 2000).

In terms of other species, and within the objectives of the study, the conventionally used 26 mm diamond-shaped mesh clearly retained large numbers of small penaeids and teleosts, including unwanted individuals and juveniles of commercial interest. Key examples were *Genidens* spp. and *M. atricauda*, which were caught at minimum TLs of 75 and 25 mm, respectively, and well below their sizes at first maturity and economic value (Reis, 1986; Cardoso & Haimovici, 2014). The large diversity of species and sizes observed here supports previous studies describing the bycatch of other regional inshore artisanal penaeid-trawl fisheries, which despite having entirely different gears (size and configurations) used the same minimum mesh sizes (Dumont & D'Incao, 2011). Considering this consis-tency, any wide-scale changes to mesh sizes and/or shapes identified here that reduce the una-

Table 4. The maximum total lengths (TL in mm) of key species (calculated using linear regressions of relationships between TL and maximum height, body width and girth) that could escape through each of the two diamond- and square-shaped meshes during (1) fishing (*i.e.*, hypothesized maximum openings of 35% of the total stretched mesh opening for diamond meshes and diagonally for square mesh), and (2) with no load during haulback (when, irrespective of mesh shape, the mesh perimeter relative to the maximum girth of the animal determines escape). SMO, stretched mesh opening; B, bar, dia, diamond-shaped mesh; square, square-shaped mesh.

Species	Mesh size/shape during fishing				Mesh size/shape during haulback			
	26 mm SMO dia	30 mm SMO dia	24 mm B square	29 mm B square	26 mm SMO dia	30 mm SMO dia	24 mm B square	29 mm B square
Penaeid								
Pleoticus muelleri	86	95	217	256	52	146	219	259
Teleosts								
Cynoscion guatucupa	59	65	167	197	87	100	162	196
Genidens spp.	73	80	181	206	110	123	181	213
Macrodon atricauda	134	153	183	219	128	140	193	222
Menticirrhus spp.	75	83	179	213	97	111	176	212
Paralonchurus brasiliensis	112	116	157	181	105	116	164	190
Porichthys porosissimus	97	101	173	194	118	129	180	208
Peprilus paru	53	59	69	81	48	54	79	94
Symphurus jenynsii	118	130	148	170	112	124	174	202
Stephanolepis hispidus	59	68	81	97	50	59	95	115
Trichiurus lepturus	418	448	602	706	403	453	680	805
Urophycis brasiliensis	164	180	204	233	126	141	205	241

ccounted fishing mortality of juveniles of various species are likely to benefit other competing fisheries that target adults.

Notwithstanding the need for grids to reduce turtle and ray mortalities, and beyond contributing toward understanding the biology of the different bycatch species (*e.g.*, the length-weight and length-body shape relationships), the morphological data collected here for the various species and their sizes represent an essential and inexpensive first step for proposing mesh-size changes. More specifically, by considering the transverse morphology, it is possible to postulate the effects of different mesh sizes on the retention of targeted penaeids and the escape of unwanted teleosts (Pope, 1975, Tosunoğlu *et al.*, 2003; Broadhurst *et al.*, 2006; He & Balzano, 2012). Certainty such estimation is facilitated by clear, strong linear relationships among morphometric relationships for most teleosts and *Pleoticus muelleri*.

Appropriate mesh sizes and shapes

Prior to discussing the implications of our results, it is important to reiterate that appropriate mesh sizes, shapes and/or their openings in the posterior section of trawls represent only one component of any model defining selectivity. Equally important is the probability of an animal encountering an opening. Generally, because the catch accumulates in the codend, this area is associated with the most opportunity for animals to contact openings, but various factors affect such probabilities, including excessive catch volumes, large-sized animals and/or debris; all of which can mask meshes. Such characteristics mean that formal (and more expensive) selectivity studies (*e.g.*, involving paired gears or covered codends) are required to validate any suggested modifications to trawls based on morphological data (Broadhurst, 2000).

Notwithstanding the above-mentioned caveat, when an animal contacts a mesh, its body shape (along with behavior and swimming speed) is an important characteristic that dictates the likelihood of its escape through the mesh opening. During towing, when meshes are closed, species with substantial morphological discontinuities, such as penaeids, might be retained in large numbers, while species with more regular bodies or smooth shapes can more easily escape through the same size meshes (Watson, 1989; King, 2007). Our study revealed that most of the key bycaught teleosts have a fusiform shape (*i.e.*, an R = 1 to 2), which might be more amendable for escape from the square- rather than diamond-shaped meshes.

The conventionally used diamond-shaped mesh (26 mm SMO) caught *P. muelleri* starting at 82 mm TL. Such sizes are well below the size at first maturity (~121 mm TL) for this species, and also those sizes that are typically considered commercially acceptable (>150 mm TL; Duarte, 2013). Increasing the diamond-shaped mesh throughout the codend to 35 mm (or even larger) would be a more appropriate minimum size.

If the sizes of square mesh postulated in the present study were used throughout the codend, they would allow large numbers of unwanted sizes of fish to escape, but also many penaeids. Specifically, even the smaller 24 mm mesh hung on the bar might allow most *P. muelleri* to escape. However, penaeid loss might be circumvented by placing larger mesh only at strategic positions, such as in the top of the codend and sufficiently close to the end (*i.e*., in 'behavioral-type' BRDs; Broadhurst, 2000). Doing so might facilitate the upwards escape of some small teleosts (but not by-product), while still maintaining catches of penaeids that tend to orientate towards the bottom (Watson, 1989; Broadhurst, 2000).

More specifically, if 48 mm mesh hung on the bar (24 mm bar length) was used, and assuming that fishes were able to contact meshes physically, individuals of all species would escape at sizes 69 to 241 mm longer. Individuals larger than these sizes would still be retained as a by-product.

According to the morphometric equations, using the square mesh (24 or 29 mm bar length) in a strategic behavioral-type BRD might increase the probability of two species (*P. brasiliensis* and *Trichiurus lepturus*) being caught at sizes larger than their first maturation, and three species (*Menticirrhus* spp. and *M. atricauda*) caught at sizes near their first maturation (Table 2). Assuming low escape mortalities (which is typically the case for many species, and certainly less than for discards; reviewed by Broadhurst *et al*., 2006b), such mesh sizes might contribute toward subsequent stocks targeted in other competing fisheries.

Future considerations and conclusions

Juveniles represented all of the teleost species caught in conventional trawls in our study and most are targeted at larger sizes in other fisheries (Haimovici *et al*., 2006; UNIVALI/CTTMar, 2013; Pezzuto & Benincà, 2015). The contribution of discard mortality towards overexploited fishing stocks is widely recognized and may be an important factor explaining the collapse of several valuable resources (Graham, 2010). It is known that simple modifications to trawls, including determining appropriate mesh size and shape as well as installing BRDs can substantially reduce impacts (Broadhurst, 2000; Broadhurst *et al*., 2014). As one example, Zeller *et al.* (2018) attributed at least some of the recent historical decline in discarding (from 19 million ton in 1989 to <10 million ton now) to more selective trawls.

The need to increase mesh size in Brazilian penaeid trawls is reiterated when compared to the minimum mesh sizes allowed in similar trawls targeting the same-sized penaeids in other countries, such as Australia (typically 42 mm SMO; Broadhurst *et al*., 2006a, 2012), Mexico (51 mm) and the United Republic of Tanzania (50-55 mm) (FAO, 2001). The National Management Plan for the sustainable use of penaeids in Brazil (Neto, 2011) suggests improving the technological features of trawls, including the use of square-shaped mesh and BRDs that help protect vulnerable species. Clearly, size-separating (grids) BRDs designed to exclude turtles and rays from trawls such as those proposed by other studies (Willems *et al*., 2016) should immediately be adopted and enforced throughout the fishery. However, the high diversity of other catches (including retained and discarded sizes across various species) presents a challenge to determine adequate selectivity using a single mesh size or shape. As a first step to promote the concept of more selective fishing, we suggest various simple changes involving mesh sizes and shapes might be tested not only throughout the codend but also in relevant behavioral-type BRDs (Tokaç *et al*., 1998; Parsons *et al*., 2012).

The data presented here are likely to be important in terms of future management decisions concerning regional penaeid-trawl fisheries. In addition to better attempts at enforcing the use of BRDs with grids designed to reduce turtle and rays catches and, although not yet commercially available in Brazil, we encourage the use of a minimum diamond-shaped mesh of 35 mm throughout the codend.

As a next step, and using the data collected in the present study, various behavioral-type BRDs, including those involving strategic panels of at least 48 mm square-shaped mesh, might be installed in codends and tested throughout the fishing fleet. Such work requires close industry consultation to demonstrate no adverse impacts on retained catches (both penaeids and by-product). There are many technical solutions available to improve penaeid-trawl selectivity, and following their adaptation to local conditions, dedicated applied extension work is required to facilitate future acceptance and use (McHugh *et al*., 2017).

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