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Research Article

The evolution of the industrial trawl fishery footprint off southeastern and southern Brazil

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ABSTRACT. This study established the spatial footprint of the industrial trawl fishing fleet operating off southeastern and southern Brazil between 2003 and 2011. It also provides estimates of the area swept by this fleet and the correspondent Utilization Index (swept area/available area) as measures of impact over the benthic ecosystem. Lastly, costs/benefits of trawling were addressed by the cumulative biomass landed during the study period expressed as a proportion of the cumulative swept area (Biomass-Swept Area Index). These variables were mapped and their patterns of spatial-temporal variability were associated with fishing strategies (shrimp trawling, slope trawling and pair trawling), latitudinal strata, depth strata, and substrate types. The trawl fishery footprint during the study period comprised 502,190 km^2. The total area swept by trawling operations was 680,697.5 km^2, 1.4 times the available area. Trawling impacts on the substrate were primarily produced by the dominant shrimp trawling strategy. In comparison with other strategies, these vessels used the most extensive shelf area, and disturbed more sand/mud habitat surface to obtain less landed biomass. Delimiting the trawl fishery footprint off southeastern and southern Brazil and its main core areas comprised a first step towards in evaluating impact on such areas, providing preliminary information for future ecosystem-based fisheries management and marine spatial planning strategies.

Keywords: spatial footprint, swept area, trawling, southeast and south of Brazil.

Evolución de la huella espacial de la pesca de arrastre en el sureste y sur de Brasil

RESUMEN. Este estudio estableció la huella espacial de la flota de pesca de arrastre industrial que opera en el sureste y sur de Brasil entre 2003 y 2011. También proporciona estimaciones del “área de barrido” de esta flota y su correspondiente Índice de Utilización (área barrida/área disponible) como medidas de impacto sobre el ecosistema bentónico. Los costos/beneficios de la pesca de arrastre fueron estimados por la biomasa acumulada desembarcada durante el período de estudio expresada como una proporción del área barrida acumulada (Biomasa-Índice de Área Barrida). Estas variables fueron asignadas y sus patrones de variabilidad espacio-temporal se asociaron con las estrategias de pesca (pesca de arrastre de camarón, pesca de arrastre en el talud y de arrastre en pareja), intervalos de latitud, estratos de profundidad y tipos de sustrato. La huella de la pesquería de arrastre durante el período de estudio comprendió 502.190 km^2. El área total barrida por las operaciones de pesca de arrastre fue de 680.697,5 km^2, 1,4 veces la superficie disponible. Los impactos de la pesca de arrastre en el sustrato se produjeron principalmente por la estrategia de la pesca de arrastre de camarón. En comparación con otras estrategias, estas embarcaciones utilizaron una extensa área de la plataforma continental, por lo que perturban mayor superficie del hábitat de arena/fango, pero a la vez obtienen menor cantidad de biomasa desembarcada La delimitación de la "huella" de la pesca industrial de arrastre en el sureste y sur de Brasil y sus áreas "centrales" corresponde a una primera etapa para evaluar el impacto en esas zonas y proporcionar información preliminar para futuras acciones de gestión del ecosistema pesquero y de estrategias de ordenamiento de territorio marino.

Palabras clave: huella espacial, área de barrido, pesca de arrastre, sureste y sur de Brasil.

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INTRODUCTION

Along with various human activities that interact with the seabed, bottom fishing impacts benthic ecosystems in proportion to both intensity and spatial distribution of fishing effort (Halpern *et al*., 2008). Biomass removal of targeted and non-targeted species, physical modification of bottom substrates, disturbance of benthic communities and addition of pollutants to the sea water and the atmosphere, are considered "outputs" of bottom fishing whose geographic spread define its "spatial footprint" (*i.e.*, but not the "ecological footprint" *sensu* Swartz *et al*., 2010). Bottom trawling produces a clearly defined footprint by operating nets that are dragged over the seafloor and 'sweep' variable area extensions as one or more benthic/benthopelagic species are captured for commercial purposes. These nets are rigged with heavy otter doors, cables and ground ropes (sometimes with chains or bobbins) designed to aggregate and/or "detach" fish and shellfish from the seafloor. By doing so they disturb bottom substrates and produce modifications whose ecological consequences are habitat-specific and particularly severe in pristine or little impacted areas (Kaiser *et al*., 2002, 2006).

Assessing the impact produced by a given bottom trawl fishery in the marine ecosystem initially requires delimiting its footprint, for example by merging the area swept by a number of trawl operations carried on in a fishing area during a certain period of time (*e.g.*, Benn *et al*., 2010; Jennings *et al*., 2012; Gerritsen *et al*., 2013; Penney & Guinotte, 2013). Within the delimited footprint, the actual impact of trawling vary according to fishing effort intensity and the sensitivity of the affected habitats to disturbance, usually assessed by the amount of change in benthic communities abundance, production, organisms size and diversity, and the amount of time required for ecosystem recovery (Kaiser *et al*., 2002, 2006; Lambert *et al*., 2011).

Combined, these approaches have become increasingly relevant in the provision of data on wider ecological effects of fishing, as scientific subsidies to the process of implementing ecosystem-based management measures (*i.e.*, position, area extent and design of Marine Protected Areas) (Jennings *et al*., 2012) and in efforts to conciliate bottom fisheries with other seabed human activities (Halpern *et al*., 2008). For example, in the Northeast Atlantic the spatial footprint of bottom trawling was found to be orders of magnitude greater than that of other ocean-based activities including: submarine communication cables, waste disposal and oil and gas extraction (structures, wells and pipelines) (Benn *et al*., 2010). Off New Zealand, the current spatial closure regime applied to trawl fisheries in the high-seas was evaluated by delimiting the fisheries footprint and determining the probabilities for interaction with deep-sea coral areas. In addition, commercial stocks may exhibit particular age-related distribution patterns in time and space, which strongly influence the dynamic behavior of fishing fleets. Establishing a fishery footprint, and its temporal evolution, allows the definition of essential and marginal areas for its economic sustainability, and the incorporation of spatial measures in stock-oriented management plans.

Bottom trawling is responsible for most landings of marine demersal resources in the Brazilian coast. The activity developed in the early 1960´s off the south-eastern and southern coast, when it was initially confined to the inner continental shelf area and sustained by few resources, such as the pink-shrimp (*Farfantepenaeus* spp.). Since then, the trawl fleet expanded continuously attaining, by the end of the 1990's and throughout the 2000's, over 650 vessels operating in a wide latitudinal area (19°-34°S) and depth range (20-1000 m). In recent years their annual landings oscillated around 89,000 ton, approximately 1/3 of all fish and shellfish biomass landed in the region (Perez *et al*., 2001; Valentini & Pezzuto, 2006). Overfishing of the targeted stocks has been the main impact established by various assessments, as a direct consequence of the growing levels of effort exerted by the trawl fleet over time (Haimovici, 1997; D'Incao *et al*., 2002; Haimovici *et al*., 2006; Perez *et al*., 2009a). Yet the spatial distribution of such impacts on commercial stocks and on the marine ecosystem as a whole has not been generally addressed, partially because of the paucity of geo-referenced effort data. That in turn prevented most management regimes from incorporating spatial measures or when they did (*e.g.*, no take areas in coastal zones and in the vicinity of oil platforms, and marine protected areas) their disconnection with the actual spatial patterns of the trawl fleet have hampered their acceptance and compliance by the fishing industry.

That scenario has gradually changed over the past decade, as Vessel Monitoring System (VMS), observers and wide-spread skipper's interview programs have been implemented, and a geo-referenced data base of the trawl fleet operations has become available (*e.g.*, UNIVALI/CTTMar, 2010). This has provided an opportunity to analyze the spatial distribution of trawl fishing effort over nearly a decade in the southeastern and southern Brazilian coast along with a number of derived proxies that describe ecosystem impacts other than stocks overfishing. Using a 9-year data series, the present study is a primary attempt to delimit the recent spatial footprint of the trawl fishery and estimate the extension of the trawled/impacted area in relation to benthic substrates, latitude and depth ranges of southeastern and southern Brazil. Along with a previous assessment of total oil consumption and greenhouse gas emissions produced by these trawlers (Port *et al*., 2016), this analysis is intended to enhance the current understanding on the impact exerted by bottom fisheries on the continental margin benthic ecosystems as a contribution to ecosystem-based management regimes and marine spatial planning initiatives.

MATERIALS AND METHODS

During the past decade over 650 trawlers have operated on the continental shelf and slope (~10 to 800 m) from Espírito Santo State (19°S) to the southern border of Brazilian EEZ (34°S) (Perez *et al*., 2001). Throughout this period, fishing operations have not been homogeneous, varying according to the trawling system used (double-rig, pair, and stern trawling) and at least three major fishing "strategies" (Dias & Perez, 2016; Dias unpublished data). This study addressed the effects of the trawl fishery as a whole as well as those produced by each fishing strategy defined below.

Shrimp trawling (ST) has been by far the most frequent fishing strategy in the region and conducted by double-rig trawlers. These trawlers operate on the inner-middle shelf concentrating in two distinct fishing grounds; one, between 24°-29°S, directed mainly at pink (*Farfantepenaeus* spp.) and bobtail shrimps (*Xyphopenaeus kroyeri*) and a second, south of 29°S, directed at other coastal shrimps (*Artemesia longinaris* and *Pleoticus muelleri*) and a group of demersal finfish that include *Umbrina canosai*, the sea robin (*Prionotus punctatus*) and flatfishes (*Paralychthys* spp.). Slope trawling (SLT) is carried on by double-rig and stern trawlers that operate on the slope areas (250-400 m depths) aiming principally at the Brazilian codling (*Urophycis mystacea*), Argentine hake (*Merluccius hubbsi*) and monkfisk (*Lophius gastrophysus*) (Dias & Perez, 2016). Pair trawling (PT) concentrates on the inner shelf and aim at a variety of sciaenid fish species, including *U. canosai*, *Micropogonias furnieri*, *Cynoscion guatucupa*, *C. acoupa* and *C. jamaicensis*.

The analyzed data set comprised information on catch, effort and fishing areas of 10,144 fishing trips (double rig trawlers = 8,012 trips; stern trawlers = 949 trips; pair trawlers = 1,183 trips) that landed their catch in the harbors of Santa Catarina State between 2003 and 2011 (Port *et al*., 2016) (Table 1). These comprised approximately 70% of total landings in Santa Catarina (UNIVALI/CTTMar, 2004, 2006, 2007a, 2007b, 2008, 2009, 2010, 2011, 2013) and were highly representative of the trawl fishing activity conducted off southeastern and southern Brazil; the state harbors nearly 60% of all operating trawlers and records annually 50-70% of the trawl fishing landed biomass (Perez *et al*., 2001).

Data were reported by skippers in log books or during interviews at the time of the landings, following a sampling protocol established by Santa Catarina State industrial fishing statistical service (Perez *et al*., 1998; www.univali.br/gep). All reported information was criticized by experienced analysts based on long term trends of the trawl fishery (fishing areas, depths, common species in the catch, catch values, trip duration, etc.) and only fishing trips whose information was considered 'reliable' were retained in the analyzed database.

Assessing the trawl fleet footprint was preceded by estimation of the area swept during each assessed fishing trip. Because most reported data did not include precise start – end positions of each trawl, the total area swept (Sa) by a trawler (*i*) during a fishing trip (*j*) was estimated considering the total time spent trawling and mean trawl velocity, according to the equation adapted from Sparre & Venema (1998):

$$Sa_{ij} = n_{ij} \cdot \bar{d}_{ij} \cdot \bar{v} \cdot HRl_i \cdot x$$

where *n* and *d* are the total number of trawls and the mean trawl duration (in hours), as reported by the skipper after a fishing trip, respectively. A constant mean trawl velocity (v) of 3.0 knots (5.56 km h^{-1}) was assumed in accordance with previous studies conducted in the region by Simões *et al*. (2003), Klippel *et al*. (2005) and Santos *et al*. (2009). The length of the head rope (HRl, in meters) of the nets utilized during each fishing trip considered mean values previously known for each trawl type (stern, pair and double-rig) (Correia, 2008). Finally *x* was the fraction of HRl which is equal to the horizontal spread of trawl net. A constant value of 0.56 was adopted following general considerations about trawl net operating performances (Sparre & Venema, 1998) and previous studies in the area (Haimovici, 2007; Sant'Ana, 2013). In the case of double-rig trawlers, which trawl two identical nets simultaneously, the swept area calculated for a single net was subsequently multiplied by two.

Because precise latitude/longitude information of fishing trawls were rarely available, the distribution of the area swept during each fishing trip in geographic space was determined using latitude and depth ranges of fishing operations as reported by skippers. These references allowed the allocation of each fishing trip in a 30 min latitude/longitude block grid delimited by latitudes 19° and 35°S and offshore by the 2000 m isobath (Fig. 1). Such spatial resolution (30x30) has been standard for the description of all activities of fishing fleets operating off Santa Catarina and the one that best conciliated the information about fishing areas,

Table 1. Summary of trawl fleet and fishing operations monitored in the harbors of Santa Catarina State, southern Brazil, between 2003 and 2011. The data are aggregated by type of vessel and year.

Type of trawler	Year	Vessels	Fishing trips
Double-rig	2003	275	1133
	2004	271	1021
	2005	293	1096
	2006	315	1300
	2007	320	1577
	2008	288	1409
	2009	325	1570
	2010	277	1215
	2011	268	1187
	Mean ± SD	292.4 ± 22.2	1278.7 ± 201.5
Stern	2003	26	151
	2004	25	98
	2005	39	108
	2006	23	105
	2007	25	112
	2008	28	101
	2009	26	175
	2010	33	230
	2011	29	204
	Mean ± SD	28.2 ± 5.0	142.7 ± 49.7
Pair	2003	46	292
	2004	46	203
	2005	48	217
	2006	45	214
	2007	39	294
	2008	33	205
	2009	27	195
	2010	24	166
	2011	26	141
	Mean ± SD	37.1 ± 9.7	214.1 ± 50.8
All vessels (2003-2011)	Mean ± SD	357.8 ± 23.6	1635.4 ± 217.7
	Total	-	14719

as reported by the interviewed skippers throughout the 9-year period considered. When the reported latitude and depth ranges exceeded a single block, the estimated swept area (and consequently the landed catch) was divided equally among all visited blocks (UNIVALI/CTTMar, 2010).

The trawl fisheries footprint, *i.e.* the total area actually affected by the monitored trawl fishing activity during the study period (Penney & Guinotte, 2013), was delimited by the distribution of all blocks with allocated swept areas, not considering the spatial overlaps among fishing operations. The "total area available" (AA) and that delimited by the trawl fishery footprint were estimated using the software ArcGIS® (ESRI-Environmental Systems Research Institute, Inc.).

Within each block, the Utilization Index (UI) was calculated considering the cumulative area swept by trawlers throughout the study period divided by the block area. This index was interpreted as a spatial measure of intensity of the trawl net disturbance. The UI of the overall trawl fishery footprint (UI_f) was estimated as:

$$UI_f = \frac{\sum_{q=1}^{Q}\sum_{i=1}^{I}\sum_{j=1}^{J} Sa_{ijq}}{\sum_{q=1}^{Q} AA_q}$$

where J, I and Q are the total number of fishing trips (j), trawlers (i) and blocks (q), respectively.

As a measure of costs/benefits of trawling in each block (q) the cumulative landed biomass (LB) was expressed as a proportion of the cumulative swept area

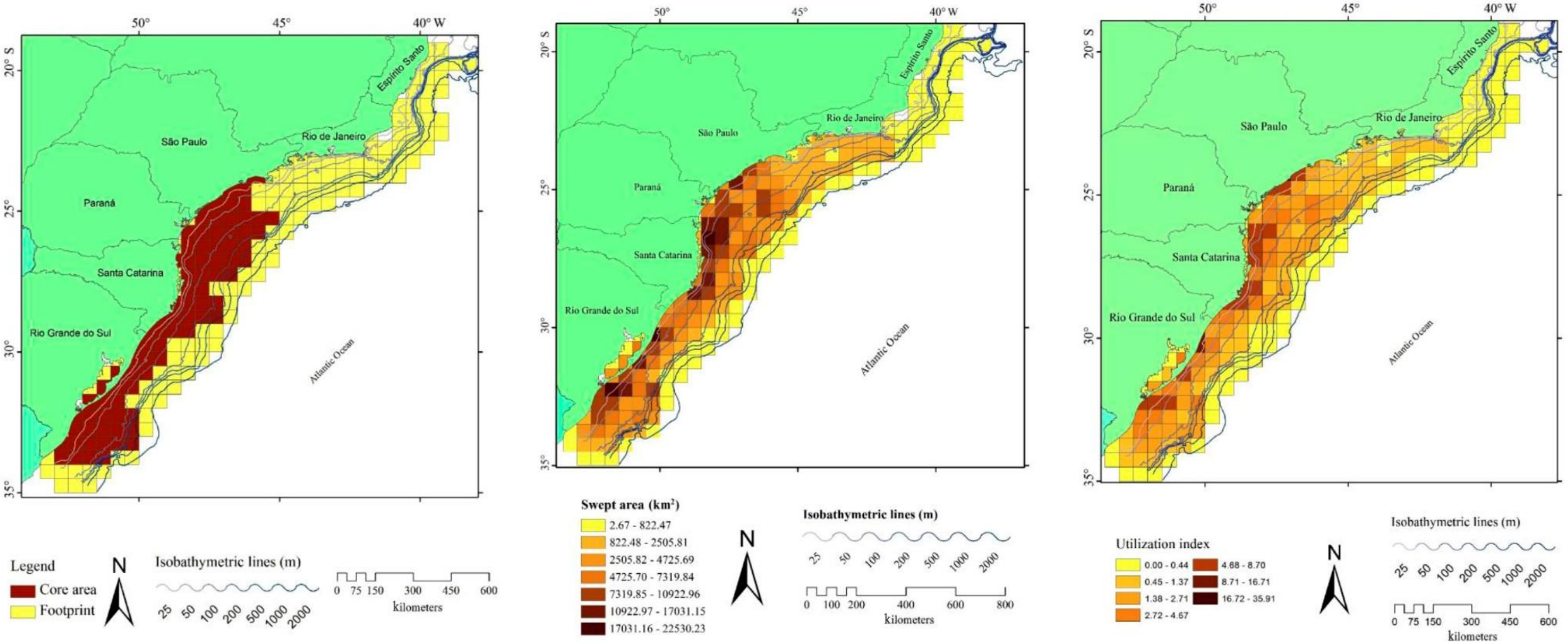

Figure 1. Spatial distribution of the bottom trawl fisheries footprint, swept area and Utilization Index (UI = swept/available area) off southeastern and southern Brazil from 2003 to 2011. Footprint is defined as the area of all 30 min latitude/longitude blocks where trawling activity was recorded during the study period (UI > 0); "Core Area" is defined as the area of all blocks swept more than once (UI > 1).

(Biomass-Swept Area Index, BSA_q). Within the entire footprint BSA was estimated as:

$$BSA_f = \frac{\sum_{q=1}^{Q}\sum_{i=1}^{I}\sum_{j}^{J} LB_{ijq}}{\sum_{q=1}^{Q}\sum_{i=1}^{I}\sum_{j=1}^{J} Sa_{ijq}}$$

The trawl fisheries footprint, UI and BSA were calculated for the entire study period and yearly from 2003 to 2011. These variables were mapped and their patterns of variability were associated to (a) fishing strategies (shrimp trawling, slope trawling and pair trawling), (b) latitudinal strata (North, 19°-25°S; Center, 25°-29°S; South, 29°-34°S), (c) depth strata (<50 m, 50-100 m, 100-200 m, >200 m) and (d) substrate types. The latter followed the spatial distribution of bottom substrates produced by Bizzi *et al.* (2003). Within the area delimited by each block, the proportion covered by each depth strata and substrate type was estimated and multiplied by the footprint, accumulated swept area, UI and BSA. When statistical assumptions were satisfied, the effect of these factors was tested using one-way ANOVA. Otherwise the non-parametric Kruskal-Wallis test (Day & Quinn, 1989; Zar, 2010) was applied.

RESULTS

The total extent of the continental margin off south-eastern and southern Brazil, down to 2000 m depths, is 502,190 km^2; 45.9% of this area is distributed north of 25°S (North), 25.4% between parallels 25°-29°S (Center), and 28.7% south of 29°S (South). The most extensive areas lie above 75 m and below 200 m depths; the area within intermediate depth strata (75-200 m) is less available and wider in the northern sector (Table 2). Over 99% of the area is covered by soft substrates, therefore almost fully available for bottom trawling. The northern sector is comprised of a higher variety of sediment types whereas sand and mud largely dominate the central and southern sectors.

The trawl fishery footprint during the study period comprised 100% of the available area (all blocks included records of swept areas) and the total area swept by trawling operations was 680,697.5 km^2, 1.4 times the available area (Fig. 1, Table 2). Over 60% of the blocks (118) had their fishing areas swept between 1 and 2 times and only 18 blocks (8.1%) were not fully utilized during the study period (UI < 1) (Fig. 2). The "core" of trawling activity, as defined by those blocks whose total available areas were swept more than once (UI > 1), extended over 40.5% of the entire footprint (203,120.3 km^2), mostly south of 25°S and in areas shallower than 100 m depth (Fig. 1).

Over 74% of the area swept by trawlers was distributed in the South (36.7%) and Center (37.6%) sectors (Table 2). These sectors had their areas swept 1.7 and 2.0 times, respectively, whereas areas of the northern sector were less trawled and not fully swept (UI = 0.8) (Fig. 3). Trawling activity was concentrated in areas shallower than 75 m (61% of the swept area, UI = 2.35) and covered only a small fraction of the largely available slope grounds (>200 m: 10.7% of swept area, UI = 0.37) (Table 2, Fig. 3).

Almost 60% of the cumulative swept area (398, 913.7 km^2) affected substrates comprised of muddy sand and mud (Table 2, Fig. 3). Fine and medium sand were substrates affected by 29.3% of the remaining swept area. Slope sediments and gravel substrates were also highly available in areas below 200 m and the northern sector, respectively, but little impacted by the trawl fishery (Table 2, Fig. 3).

The trawl fisheries landed 342,297.6 ton in the harbors of Santa Catarina during the entire study period. Nearly 70% of this biomass was landed after the area swept by all trawlers combined was equivalent to the total footprint area (UI = 1, Fig. 4). On average, 0.5 ton was landed per km^2 (Table 3). The southern sector was the most productive (0.76 ton km^{-2}), followed by the central (0.43 ton km^{-2}) and the northern sectors (0.25 ton km^{-2}).

Nearly 63% of the landed biomass originated from areas covered by muddy sand and mud, where 0.52-0.56 ton were landed, on average, per km^2. In the southern sector these indices raised to 0.74 and 0.87 ton km^{-2}, respectively (Table 3). Slope sediment areas particularly of the southern sector produced, on average, 0.82 ton km^{-2} during the study period. Because these areas were relatively less trawled (6% of total area swept by trawlers, Table 2), however, their contribution to total landings were small (7% of the landed biomass, Table 3).

Trawl footprint by fishing strategy

Shrimp trawling extended along the entire latitudinal range considered down to 100 m depths (Fig. 5). Its footprint reached 78.9% of the total trawl fisheries footprint (396,333.9 km^2) (Table 2). These fishing operations were responsible for over half of the total area swept by trawlers in the study period (57.6%), mostly distributed in shallow areas (<75 m) of central and southern sectors (Table 4). These latitudinal and depth strata were swept 0.9 to 1.7 times during the study period (Fig. 6) and peaks of utilization (UI > 6) were established in coastal areas off Santa Catarina State, southern São Paulo and southern Rio Grande do Sul states (Fig. 5). Shrimp trawling affect principally areas covered by muddy sand, mud, fine and medium sand (Table 4). The areas comprised by these habitats were swept at least once by this fishing strategy with fine

Table 2. Available area and swept area by type of substrate, latitude strata and depth range, of the continental margin of southeast/south of Brazil.

Substrate type	Available area (km^2)	%	%			Swept area (km^2)	%	%		
			North 19°-25°S	Center 25°-29°S	South 29°-34°S			North 19°-25°S	Center 25°-29°S	South 29°-34°S
Slope	142871.1	28.5	13.1	9.4	6.0	40606.6	6.0	1.0	3.4	1.6
Muddy sand	105881.9	21.1	8.9	5.5	6.7	200253.6	29.4	6.7	11.5	11.2
Mud	85839.3	17.1	3.3	5.9	7.9	198560.1	29.2	3.4	14.2	11.6
Gravel	52766.1	10.5	10.5	0.0	0.0	14589.5	2.1	2.1	0.0	0.0
Medium sand	49777.1	9.9	3.6	3.2	3.1	74417.2	10.9	2.1	5.3	3.5
Fine sand	44886.8	8.9	5.0	0.8	3.1	124941.6	18.4	9.0	2.0	7.3
Reef	2791.1	0.6	0.6	0.0	0.0	40.3	0.0	0.0	0.0	0.0
Coarse sand	1627.3	0.3	0.3	0.0	0.0	1546.9	0.2	0.2	0.0	0.0
Muddy gravel	1437.7	0.3	0.1	0.2	0.0	3905.8	0.6	0.3	0.3	0.0
Not classified	13681.6	2.7	0.5	0.4	1.9	21825.2	3.2	0.8	0.8	1.5
<75 m	176924.2	35.2	15.5	6.9	12.8	415098.9	61.0	12.5	20.1	28.4
75-100 m	33172.7	6.6	4.1	1.5	1.0	68864.6	10.1	3.9	4.4	1.9
100-200 m	95843.18	19.1	8.0	6.5	4.5	124107.1	18.2	5.1	9.3	3.8
>200 m	196249.9	39.1	18.2	10.5	10.4	72626.9	10.7	4.2	3.9	2.6
Total area	502190.0		230322.2	127204.6	144033.2	680697.5		174770.9	255880.6	250035.2
%			45.9	25.3	28.7			25.7	37.6	36.7

<5% 5-10% 10-20% >20%

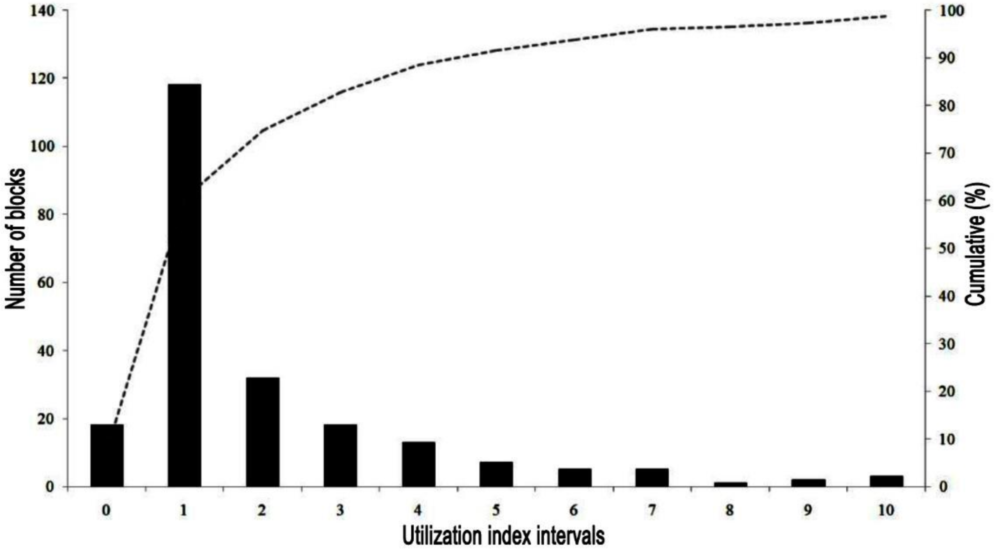

Figure 2. Intensity of bottom trawling activity off southeastern and southern Brazil from 2003 to 2011. 30-minute latitude/longitude blocks were grouped by Utilization Index (UI = swept/available area) intervals, where UI = 1 correspond to blocks whose area was swept once during the study period.

sand substrates being swept more than twice (Fig. 6). The "core" area for this strategy (UI > 1) was estimated in 115,852.7 km^2, 29.2% of its footprint in the period considered.

Pair trawling exhibited the least extensive footprint (3.2% of total trawl fisheries footprint) and represented only 8.2% of the total area swept by trawlers (Table 4, Fig. 5). Spatial patterns generally paralleled those exhibited by shrimp trawling (Table 3) except for a higher concentration of trawling activity in the southern (61.2% of the area swept) and central (32.8%) sectors. Utilization of this footprint in the study period was mar-

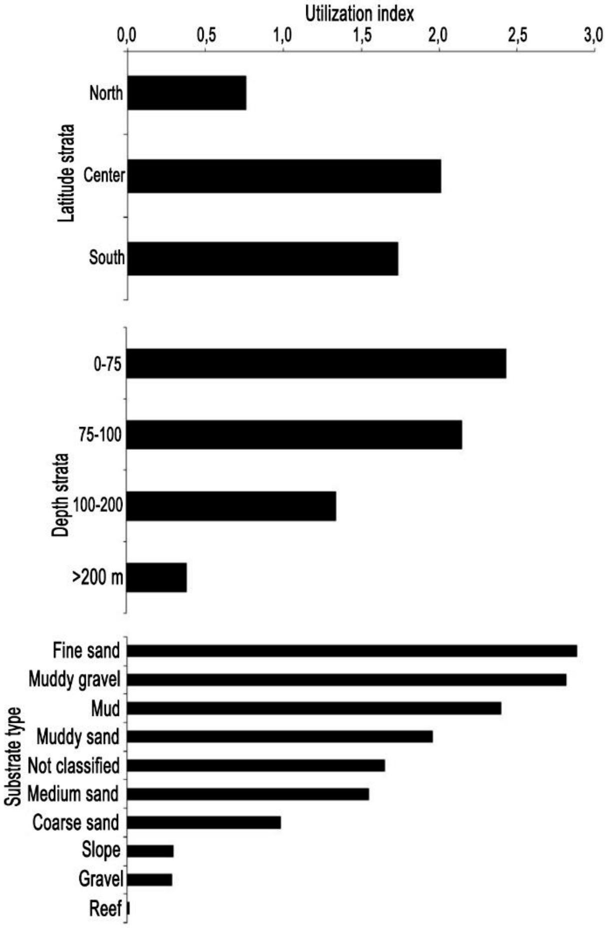

Figure 3. Bottom trawl fishing utilization (UI = swept/available area) of areas within different latitude and depth strata, and substrate types off southeastern and southern Brazil from 2003 to 2011. UI = 1 correspond to strata whose entire area was swept once during the study period.

ginal (UI = 0.11, Fig. 6) and highly concentrated in its "core" area (UI > 1) estimated in 8,192.3 km^2, 3.2% of its footprint.

Slope trawling concentrated in areas deeper than 100 m (63.6% of the swept area) (Table 4). Because this strategy was often mixed with shrimp trawling (*e.g.*, the same fishing trip conducting trawls on the slope and inner continental shelf) its footprint extended inshore reaching 96.6% (485,321.1 km^2) of the total trawl fisheries footprint (Table 4, Fig. 5). The total area swept by slope trawlers was nearly half of the area enclosed in the total footprint (UI = 0.46) and peaks of area utilization (UI = 1-6) occurred between southern São Paulo and Santa Catarina states and off central Rio Grande do Sul (Fig. 5, Fig. 6). Areas between 75 and 200 m isobaths were almost fully swept during the study period (UI = 0.83-0.87) and the most impacted areas included habitats covered mud (UI = 0.80), muddy gravel (UI = 2.06) and coarse sand (UI = 0.83). These two latter substrate types were mostly available in limited areas of the central and northern sectors (Fig. 6). Estimated "core" area was 54,881.6 km^2, 11.3% of its footprint in the study period.

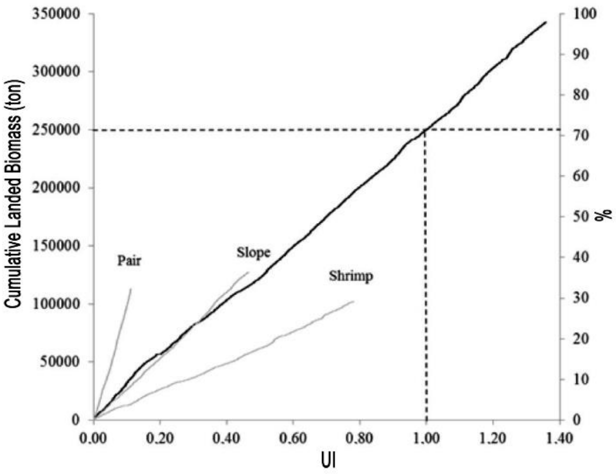

Figure 4. Cumulative biomass landed by bottom trawl fishing operations as a function of area utilization (UI = swept/available area) off southeastern and southern Brazil from 2003 to 2011. Grey lines represent partial contributions of pair, shrimp and slope trawling to the overall activity. UI = 1 (dotted line) correspond a scenario where the entire footprint area was swept once during the study period.

Pair trawling landed 2.03 ton km^{-2}, on average, largely exceeding slope (0.55 ton km^{-2}) and shrimp (0.26 ton km^{-2}) trawling strategies. This pattern was retained in all latitudinal strata, although productivity increased consistently from north to south (Fig. 7). Shrimp trawling operations involved spatial impacts considerably higher than those associated to other trawling strategies; for example, in order to land 50,000 ton, shrimp trawlers swept an area 2.2 and 7.6 times greater than slope and pair trawlers, respectively (Fig. 4).

Footprint evolution

The estimated footprint of the trawl fisheries of southeastern and southern Brazil oscillated annually between 353,390 and 448,812 km^2 with no significant temporal trend (P = 0.51; Fig. 8a). Much of this variability was a direct consequence of expansions and contractions of the slope trawling strategy footprint. Slight increasing and decreasing annual trends were noticed in shrimp and pair trawling footprint, respectively, although none of these were found to be significant (P > 0.10 and P > 0.22, Fig. 8a). Pair and slope trawling, on the other hand, exhibited significant decreasing and increasing trends in the swept area, res-

Table 3. Landed biomass and biomass-swept area index (BSA), by type of substrate, latitude strata and depth range, of the continental margin of southeast/south of Brazil.

	Landed biomass		BSA			Total
	(ton)	%	North	Center	South	
Slope	23596.0	6.89	0.47	0.50	0.82	0.58
Muddy sand	104275.7	30.46	0.25	0.47	0.74	0.52
Mud	111142.3	32.47	0.25	0.38	0.87	0.56
Gravel	5850.3	1.71	0.40			0.40
Medium sand	35290.0	10.31	0.19	0.43	0.71	0.47
Fine sand	47597.1	13.91	0.19	0.23	0.66	0.38
Reef	3.0	0.00	0.08			0.08
Coarse sand	618.4	0.18	0.40			0.40
Muddy gravel	1354.9	0.40	0.32	0.37		0.35
Not classified	12569.8	3.67	0.21	0.76	0.67	0.58
<75 m	193363.9	56.49	0.20	0.29	0.70	0.47
75-100 m	33168.6	9.69	0.26	0.47	0.97	0.48
100-200 m	69828.7	20.40	0.29	0.51	1.05	0.56
>200 m	45936.3	13.42	0.31	0.87	0.81	0.63
Total	342297.6		42885.2	108853.2	190559.3	
%			12.5	31.8	55.7	
BSA (ton/km^{-2})	0.50		0.25	0.43	0.76	

<5% 5-10% 10-20% >20%

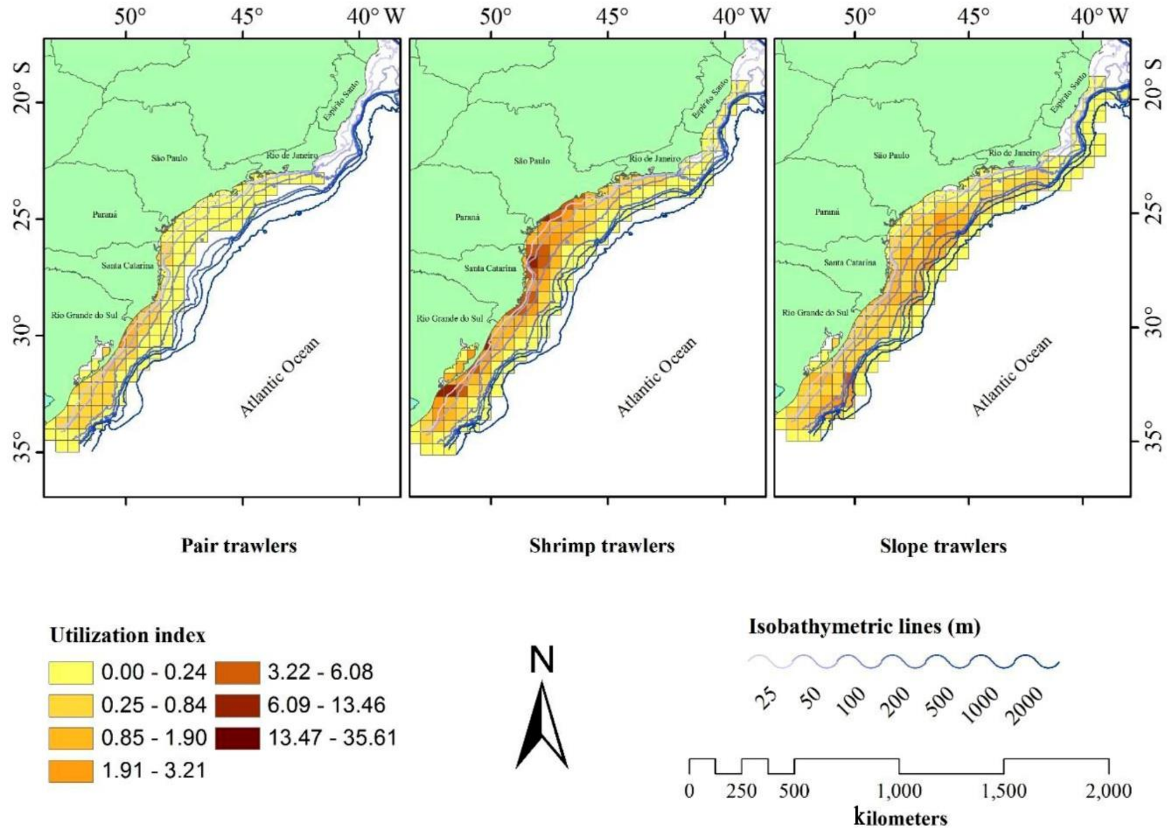

Figure 5. Area utilization (UI = swept/available area) of pair, shrimp and slope trawling strategies off southeastern and southern Brazil from 2003 to 2011.

Table 4. Swept area by fishing strategy (pair trawlers; shrimp trawlers; slope trawlers), substrate type, latitude strata and depth range, of the continental margin southeast/south of Brazil.

	Pair area	%	North	Center	South	Shrimp area	%	North	Center	South	Slope area	%	North	Center	South
Slope	171.7	0.31	0.00	0.00	0.30	1301.2	0.33	0.04	0.15	0.15	39133.6	16.79	2.76	9.65	4.38
Muddy sand	18535.6	33.35	1.64	13.14	18.58	112312.2	28.64	5.81	11.78	11.05	69405.8	29.79	9.36	10.74	9.69
Mud	19224.7	34.60	0.29	10.96	23.35	110964.1	28.30	2.54	16.87	8.89	68371.3	29.34	5.61	10.46	13.27
Gravel	242.7	0.44	0.44			2677.7	0.68	0.68			11669.1	5.01	5.01		
Medium sand	4965.0	8.93	0.53	4.58	3.82	49093.3	12.52	2.98	5.84	3.70	20358.8	8.74	1.04	4.67	3.03
Fine sand	8733.6	15.72	2.67	0.98	12.06	98277.5	25.06	13.55	2.52	9.00	17935.5	7.70	2.94	1.37	3.39
Reef						15.3	0.00	0.00			25.0	0.01	0.01		
Coarse sand	10.9	0.02	0.02	0.00	0.00	188.3	0.05	0.05			1347.7	0.58	0.58		
Muddy gravel	5.7	0.01	0.00	0.01	0.00	943.5	0.24	0.09	0.15		2956.6	1.27	0.66	0.61	
Not classified	3680.8	6.62	0.41	3.11	3.10	16325.5	4.16	1.34	0.84	1.98	1818.9	0.78	0.07	0.30	0.42
<75 m	39498.6	71.1	1.20	23.54	46.34	319776.1	81.56	24.10	27.96	29.50	55824.2	23.96	5.35	6.40	12.21
75-100 m	11389.9	20.5	4.25	6.84	9.41	28561.6	7.284	1.57	3.14	2.57	28913.2	12.41	3.49	4.60	4.32
100-200 m	3934.6	7.08	0.42	2.27	4.39	40164.5	10.24	1.31	6.68	2.25	80008.0	34.33	10.95	15.02	8.37
>200 m	749.6	1.35	0.12	0.14	1.09	3598.5	0.918	0.09	0.37	0.46	68278.8	29.30	8.24	11.78	9.28
Total	55570.7		3332.2	18213.2	34025.3	392098.6		106129.0	149603.2	136366.4	233022.4		65314.7	88064.2	79643.5
%			6.00	32.77	61.23			27.07	38.15	34.78			28.03	37.79	34.18

░	▒	▓	█
<5%	5-10%	10-20%	>20%

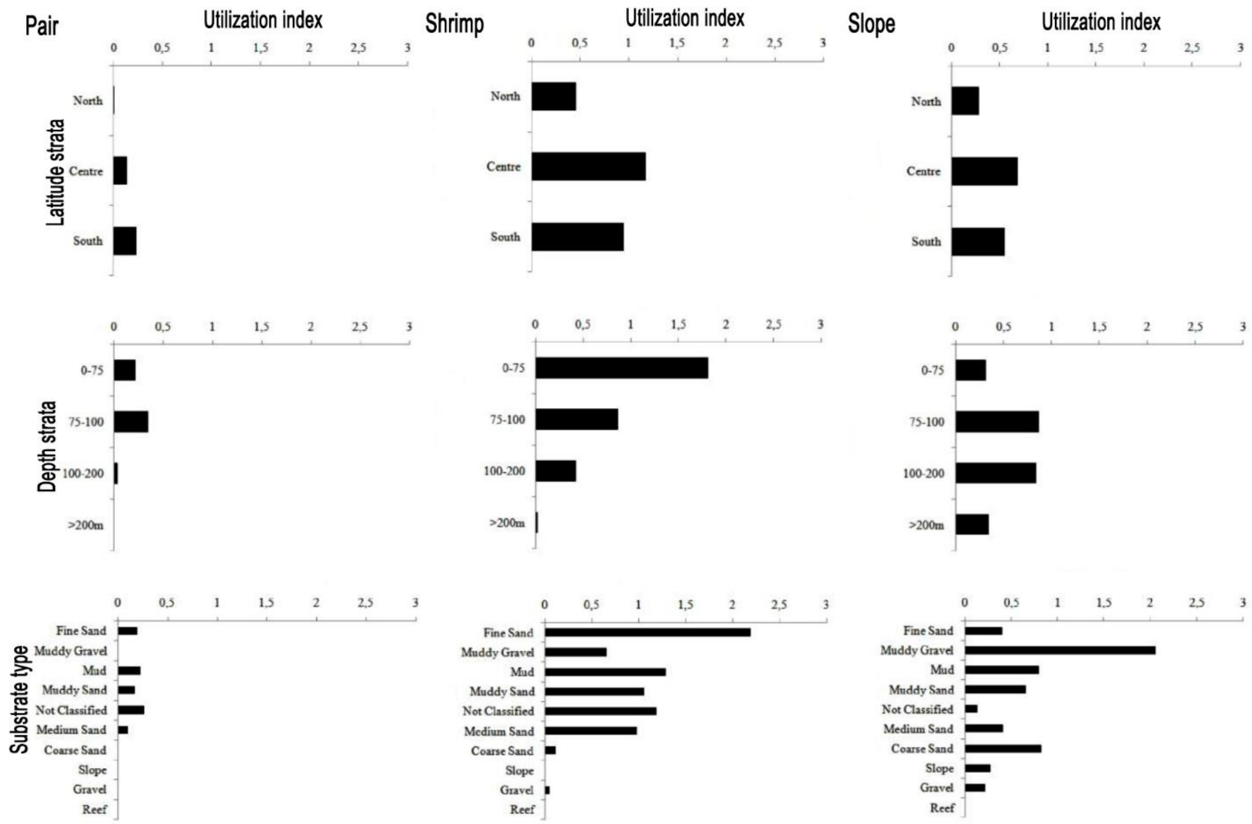

Figure 6. Utilization (UI = swept/available area) by pair, shrimp and slope trawling strategies of areas within different latitude and depth strata, and substrate types off southeastern and southern Brazil from 2003 to 2011. UI = 1 correspond to strata whose entire area was swept once during the study period.

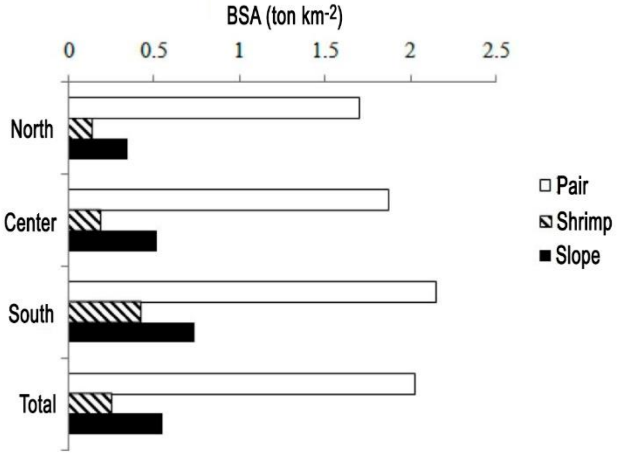

Figure 7. Index of Biomass-swept area (BSA) by fishing strategy (Pair, shrimp and slope), latitude strata and total.

pectively (*P* = 0.03, Fig. 8b), as opposed to shrimp trawling whose area swept ascended to a peak in 2006 decreasing thereafter.

Cumulatively all trawlers combined swept an area equivalent to the entire footprint after seven years of operations (Fig. 9a). Heavily trawled areas of the center and south sector were fully swept in four to five years, the former swept twice after nine years (Fig. 9a). Areas shallower than 100 m were fully swept in four years and swept twice in eight to nine years. Shelf break areas (100-200 m) were fully swept in seven years (Fig. 9b).

DISCUSSION

The spatial spread of the trawl fishery impact on benthic/benthopelagic environments off southeastern and southern Brazil was assessed from the analysis of effort distribution during a decade. Because fishing tracks were not known, estimated swept areas were aggregated in a 30’x30’cell grid which generated uncertainty about the precise area impacted, particularly in areas of low fishing activity (Gerritsen *et al*., 2013). Yet the analysis provided a preliminary assessment of the area of the continental margin likely demanded (and impacted) by Brazil’s largest industrial trawl fishing. Overall figures may be underestimated to a certain extent because the analyzed data set did not comprise the entire number of fishing operations that

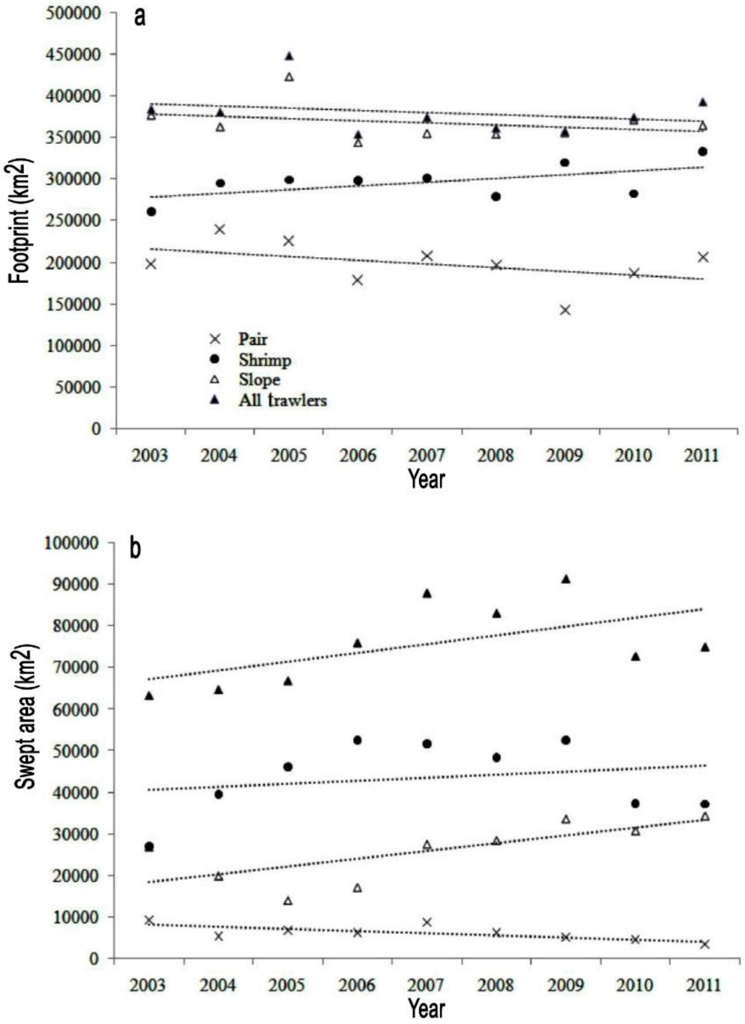

Figure 8. Footprint (a) and swept area (b) of the entire industrial trawling fleet off southeast/south of Brazil and the different fishing strategies (pair, shrimp and slope trawlers) per year.

took place in the study area during the study period. In addition, total area (and spatial impact) swept by pair trawlers were far more consistent for areas south of 24°S where trawlers operating from Santa Catarina harbors conduct most of their fishing activity. To the north, trawlers based on the harbors of São Paulo and Rio de Janeiro may add an important amount of impact, not taken into account in this study. The same limitation can be assumed for pair trawlers in the southern extreme (south of 29°S), where a fleet that operates off the Rio Grande harbor conducts annually nearly twice the number of fishing trips recorded in the Santa Catarina harbors. These shortcomings imply that impacts on both northern and southern extremes of the study area are likely larger than those estimated in this study (IBAMA/CEPERG, 2004, 2005, 2006, 2007, 2008, 2009, 2011a, 2011b, 2012).

The delimited footprint represents a scenario markedly different from that of previous periods of the trawl fishery development off Brazil, when operations beyond the outer shelf were rare and virtually restricted to scientific assessments (Perez *et al.*, 2001; Haimovici, 2007). From 2000 onwards, slope trawling greatly expanded partly as a result of government policies that stimulated the occupation of deep areas by foreign trawlers, and exploitation of a few export products such as the monkfish (*L. gastrophysus*) and the hake (*M. hubbsi*) (Perez *et al*., 2009b). By 2003, when most foreign vessels were terminating their operations off Brazil, over 270 national double rig and stern trawlers were already operating in the shelf break and upper slope areas, continuing the exploitation regime of the former species and the abundant codling *U. mystacea* (Perez & Pezzuto, 2006). Regardless of efforts to regulate trawling on slope areas, such expansion conti-

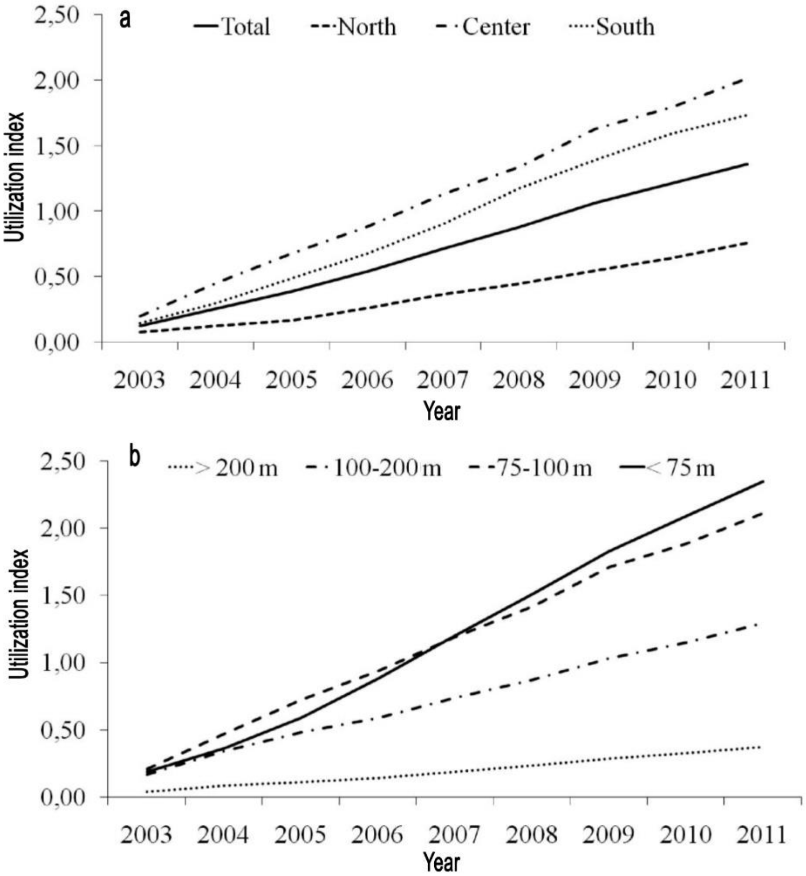

Figure 9. Total utilization index, by latitude strata (a) and depth strata (b) of the entire industrial trawling fleet off southeast/south Brazil per year.

nued uncontrolled to date and many of these trawlers may also operate in different shelf areas throughout the year (Perez *et al.*, 2009a; Dias & Perez, 2016).

Despite such fleet expansion process, coastal areas have remained essential for the trawl fishing activity and greatly impacted by it. A “core” area was outlined around two important nuclei where concentrations of valuable resources still account for an important fraction of annual landings and revenues of the trawling industry (Benincá, 2013). The northernmost one encompasses the continental shelf area of the, so called, Southeastern Brazil Bight (SBB, 22-28°S, *sensu* Matsuura, 1995) where double rig trawl fishing for penaeid shrimps (*Farfantepenaeus* spp. and *X. kroyeri*) historically developed since the 1960’s (D’Incao *et al.*, 2002). This area is bounded by a number of large estuarine and mangrove systems (Knoppers *et al.*, 2009) that are essential to early life stages of these shrimps and many other shelf species. During summer months (December-March) the dominating wind regime induce the subsurface shoreward intrusion of oceanic South Atlantic Central Waters (SACW) that enhances productivity in both pelagic and benthic systems and the availability of food for demersal fish and shellfish stocks (Borzone *et al.*, 1999; Sumida *et al.*, 2005; Rossi-Wongtschowski *et al.*, 2006).

The second nucleus of trawling activity was centered at the continental shelf off the Rio Grande do Sul State at the southern end of Brazilian EEZ. This is one of the most extensive shelf areas of Brazil’s continental margin, influenced by the runoff of the La Plata and Lagoa dos Patos estuaries and the input of colder waters from southern regions that flow northward principally during spring-winter months (Rossi-Wongtschowski *et al.*, 2007). Because these coastal and oceanic waters are nutrient-enriched, shelf primary and secondary productivity is greatly enhanced, sustaining dense fish and shellfish populations, some of them seasonally migrating from the Patagonian Shelf. This area long sustains the bulk of Brazil´s landings of demersal resources and a historic trawl fisheries directed at sciaenid fish (*M. furnieri*, *Macrodon atricauda*, *C. guatucupa*, *U. canosai*) and two coastal shrimps (*P. muelleri* and *A. longinaris*) (Haimovici *et al*., 2006).

Bottom habitats within this core area are formed by soft sediments, particularly mud and sand, where fishing productivity was highest (0.5-0.6 ton km^{-2}), particularly in the southern shelf area where up to 1 ton was landed per km^2, on average, during the study period. Yet trawling on these habitats cumulatively swept, in approximately six years, an area equivalent to 1.5-2.0 times the available surface, attaining extreme values (4 to more than 14 times) in some shallow areas. Considering that this core area has been exploited for at least 30 years (Perez *et al*., 2009a) it is possible that these are the most disturbed benthic habitats in the Brazilian continental margin, and that bottom trawling is their primary environmental pressure.

Besides overfishing, seabed disturbance produced by trawling, and its specific effects on invertebrates abundance and diversity (Kaiser *et al*., 2002; Lambert *et al*., 2011), could contribute to benthic habitat degradation and play a role on important biomass declines of commercial species that have taken place since the late 1970's (Haimovici, 1997; D'Incao *et al*., 2002). To what extent such ecological consequences are plausible, however, is currently uncertain but seems important to consider that despite them, the trawl fishery still critically rely on the core area for economic sustainability (Benincá, 2013). A comprehensive analysis exploring potential ecological drivers of overfishing, would require: a) considerations regarding the influence of spatial scale, b) intensity and frequency of seabed natural *vs* fishing disturbance, and c) patterns of recovery rates of benthic biota abundance and diversity in disturbed sand/ mud habitats (Kaiser *et al*., 2002).

An initial analysis refers to the fact that assessing the actual spread of the calculated swept area was not possible given the nature of the analyzed data. Thus for instance if a shelf area equivalent to the surface of one 30'x30' box was swept by trawling in six years, that could either be the result of a progressive occupation of 1/6 of the surface area per year, a regular increase of the area swept homogenously distributed over the box surface, or an intense trawling of a few localized smaller areas within the box surface area, leaving undisturbed an important fraction of this surface. Whereas in the first two hypotheses there could be enough time for recovery of benthic communities, neutralizing the effects of fishing disturbance, in the latter, such limited areas would be so frequently impacted that they could be held in a "permanently altered state" by the trawl fishing activity (Kaiser *et al*., 2002). This hypothesis, while more typical of the behavior of fishing fleets, would in fact imply in fewer ecological consequences than the former ones (Kaiser *et al*., 2002).

Secondly, benthic populations and communities are subjected to natural disturbances of different scales and frequencies (*i.e.*, predator feeding activities, tidal currents, storms), and have an inherent resilience to some of them. Trawl fishing must exceed these levels (*e.g.*, be more frequent) in order to cause significant ecological consequences in the long-term. In that sense, shallow soft-bottom habitats of the continental shelf tend to be frequently restructured by physical processes and its benthic communities may experience higher natural levels of disturbance than deeper sea habitats (Kaiser *et al*., 2006). That could explain a potential increased resilience of benthic communities within the trawl fishery core area in southeastern and southern Brazil, particularly in the heavily trawled shallow areas, which are often submitted to climatic and oceanographic conditions fluctuations throughout the year (Rossi-Wongtschowski *et al*., 2007; Knoppers *et al*., 2009).

Finally, the ecological effect of trawl disturbances is gear- and substrate-dependent. Communities inhabiting shelf sand and mud habitats were shown to exhibit important negative short-term impacts when trawled by scallop dredges, beam trawls and otter trawls (Kaiser *et al*., 2006). These impacts also required relatively long periods of recovery when disturbance was caused by beam trawls and dredges (200 days to more than eight years). In otter trawls, however, the effects tended to be short-lived (Kaiser *et al*., 2006) even in deeper areas (Kenchington *et al*., 2001). This gear is considerably lighter than the former ones, limiting its contact with the seabed to its otter doors, and may produce a seabed disturbance comparable to that produced by double rig and pair trawls widely used off Brazil. Whereas these results suggest somewhat reduced impacts of these trawls on the vast sand/mud southern shelf areas, in the northern grounds (north of 24°S), where gravel and biogenic beds may be submitted to trawling activity (not fully assessed by this study), more important ecological impacts may be expected. Before-after trawl experiments conducted with different gear types in areas covered by gravel or biogenic substrates have generally indicated that recovery of benthic communities to original states may take years (Kaiser *et al*., 2002; 2006).

Trawling impacts in the core area were primarily produced by the dominating shrimp trawling strategy. Over 300 vessels follow this strategy throughout the year combining operations both in the northern end of the core area, aiming at the pink- and bobtail-shrimps, and the southern shelf chiefly for coastal shrimps and flatfishes (Valentini & Pezzuto, 2006). In comparison with other strategies, these vessels used the most extensive shelf area, and disturbed more sand/mud habitat surface to produce less landed biomass. Combined with their highest fuel consumption and green-house gases emission rates (Port *et al*., 2016), highest production of indirect mortality through bycatch and discards (Perez *et al*., 2001) and the potential to overfish and deplete local stocks (D'Incao *et al*., 2002; Perez, 2002; Pezzuto & Borzone, 2004), double rig shrimp trawlers comprise the main stressors of demersal environments off southeastern and southern Brazil. Managing this economically and socially important activity towards sustainability, in a broad ecological sense, in conciliation with other fisheries and uses of the shelf areas, remains a critical task in the country's marine environmental agenda and will require complex solutions.

On the other hand, spatial exploitation of slope grounds has been moderate in relation to the vast available area. Within the limited core area, however, despite the high overall catch rate, a significant area was swept in association with elevated fuel consumption and CO_2 emissions (Port *et al*., 2016). Moreover, important short-term biomass reductions of key stocks such as the monkfish, codling, hake, wreckfish and others have been reported (Perez *et al*., 2009a). As generally attributed to deep-sea stocks (Koslow *et al*., 2000), these are less productive and resilient stocks than shelf ones (Perez, 2006). An expansion of slope trawl fishing footprint in the last decade could not be demonstrated neither ruled out considering the significant increase of the area swept by these trawlers. Overall, in light of the existing evidence, "freezing" the current footprint of the slope trawl fisheries, along with effort and/or fishing mortality limitations (Perez *et al*., 2009a), should be a desirable precautionary measure to ensure conservation of such fragile ecosystems of Brazilian deep con-tinental margin. This may turn out beneficial also for current and future developments of deep-sea oil exploration, whose fields partially overlap slope fishing grounds (Agência Nacional do Petróleo-ANP; www. anp.gov. br).

Jennings *et al*. (2012) analyzed the beam trawl fishery footprint in the North Sea concluding that critical impacts result from expansion of fishing effort from core areas to marginal, little impacted ones. They concluded that defining fishing grounds that exclude such less impacted marginal areas could substantially reduce habitat impacts. Delimiting the trawl fishery footprint off southeastern and southern Brazil and its main core areas comprised a first step towards assessing such marginal areas, for example, in the shelf-break and the lower slope below 500 m depths, providing preliminary information for future ecosystem-based fisheries management and marine spatial planning strategies. This process will largely benefit from the analysis of more precise geo-referenced effort data, such as those produced by VMS (Jennings & Lee, 2012; Gerritsen *et al*., 2013).

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