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Cumulative ecosystem pressures exerted by demersal fisheries in the Brazilian Meridional Margin: Hotspots and refuges

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A B S T R A C T

Demersal fishing operations exert, cumulatively, at least three forms of pressures over the benthic environment: mortality of megafauna (landed and discarded), discards of carrion back to the marine environment (also referred to as Predictable Anthropogenic Food Subsidies - PAFS) and disturbance of the seabed, by contact with bottom gear. This study presents a spatial synthesis of these forms of pressure on the Brazilian Meridional Margin (BMM, SW Atlantic) and their accumulated effect, in contribution to the development of effective space-based fishing management strategies. We analyzed landed catch, discards and effort of 2,125 fishing trips of industrial vessels operating double-rig trawlers, pair trawlers, stern trawlers, bottom longline and gillnets, monitored during 2018 in the main fishing harbors of Southern and Southeastern Brazil. All forms of pressure and the Accumulated Pressure Index (API) were represented spatially in a 20 × 20 nautical mile quads mesh grid. We demonstrated that nearly half of the BMM area was under high pressure. We also delimited fishing pressure hotspots in coastal and shelf areas mostly within the 'Brazilian Bight' region, between São Paulo and Santa Catarina states (24–29°S). Conversely, slope regions were found to be less demanded by demersal fishing, with both benthic ecosystems and demersal populations being barely disturbed. These were regarded as the main refuge areas for benthic and benthopelagic megafauna. Double-rig trawling was a major driver of pressure accumulating over half of total number of demersal fishing trips in 2018. Individual double-rig trawling operations also disturbed a seabed area far greater than the areas disturbed by the other fishing gear, and discarded the largest fraction (∼48%) of the produced mortality. Reducing the demersal fishing pressure on the BMM seems to be primarily concerned with abating the intensity of double-rig trawling, and/or diluting their effect through spatial management measures.

1. Introduction

Marine ecosystems provide a variety of services that are essential for human well-being, including the provision of natural resources (Daily et al., 1997; Palumbi et al., 2009; Barbier, 2017). Paradoxically, large-scale human activities developed to exploit marine resources often affect the 'health' of marine ecosystems, potentially weakening their capacity to provide such services to society. In the context of sustainable development, these activities are regarded as drivers of ecosystem change which, in order to be effectively managed, require (a) a complete assessment of the pressures they exert on the ecosystems, and (b) of the extent to which these ecosystems tend to change (i.e. are impacted) in response to such pressures. The DPSIR framework: Driver – Pressure – State – Impact – Response (Martins et al., 2012), can help in the process, as it provides a comprehensive approach to assessing these complex interactions.

Nearly the entire area of the world's ocean (97.7%) is potentially affected by anthropogenic activities such as oil and gas exploration, fishing, maritime transportation, and tourism among others (Halpern et al., 2015). These activities exert pressures cumulatively over marine spaces, generating multiple impacts on biotic and abiotic ecosystem components. The severity of such impacts depends on the vulnerability of different marine ecosystems to the different activities (Halpern et al., 2017). Often, however, when these activities coincide in space and time, the pressures they exert interact synergistically aggravating the overall environmental consequences (Crain et al., 2008). Because both ecosystem components and human activities tend to be heterogeneous in space, their spatial overlap may be discontinuous, forming 'hotspots' (i.

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e., nuclei of intensified cumulative pressures) interspersed by gaps. These gaps can be regarded as 'refuges' where marine ecosystems remain little impacted or virtually untouched. Mapping hotspots and refuges of human ecosystem pressures can improve the definition of space-based management priorities in the context of Marine Spatial Planning (MSP) and Ecosystem-Based Management (Halpern et al., 2008a, 2019).

Commercial fishing affects wide areas of the global ocean (Halpern et al., 2008b). Moreover, fishing operations targeting bottom-dwelling living resources, known as 'demersal fishing', are often regarded as 'destructive', ranking second among global threats to marine ecosystems (Halpern et al., 2007). That is because demersal fishing gear, including net, cables, otter boards etc., that contact the seabed disrupting the sediment structure, suspending sediments, imprinting scars on the substrate, and causing the loss of benthic epifauna and infauna diversity (Kaiser et al., 2002, 2006; Eigaard et al., 2016; Oberle et al., 2018; Schönke et al., 2022). Conducted over complex biogenic habitats, usually formed by stony corals and sponges, demersal fishing operations may drastically reduce biodiversity causing virtually irreversible degradation (Clark et al., 2016). In addition, as bottom fishing gear sweep the seafloor, demersal species biomass is removed, i.e., generating mortality of organisms, including a range of megafauna community components (here referred to fishes and invertebrates large enough to be captured by fishing gear), both targeted and non-targeted by the fishing activity (Chopin et al., 1996). The extent of this removal varies according to the amount of fishing effort, temporal and geographic distribution of fishing operations, and the efficiency and selectivity of the gear used (Piet et al., 2007). Its potential impacts span from declining population biomass to changes in community structures and functions (Salomon et al., 2010; Palomares et al., 2020). Finally, megafauna unwantedly caught by little selective bottom fishing gear, such as trawl nets, tend to be returned mostly lifeless to the marine environment as discards. In traditional fishing grounds, exploited over long time-periods, catch discards regularly supply additional amounts of organic matter (i.e., carrion) to the water column and seafloor environments. Oro et al. (2013) defined these inputs as Predictable Anthropogenic Food Subsidies (PAFS), capable of altering the structure of benthic and pelagic communities by favoring predators, scavengers and other ecosystem functions (Real et al., 2017).

Demersal fishing represents an important source of ecosystem pressure in the Brazilian Meridional Margin (BMM – Port et al., 2016). The region is located in the vicinity of South America's largest demographic and economic centers, integrating most anthropogenic marine activities of the country (Fig. 1). The BMM sustains nearly half of marine landed catches and over 80% of total oil and gas produced annually in Brazil, also being subjected to major environmental pressures (Halpern et al., 2008b; Perez et al., 2020). In that sense, the region is prioritized in the country's demand for integrated management through MSP (Douvere and Ehler, 2009; Carneiro, 2022), although drastically affected by the paucity of systematized and spatialized data on the pressures exerted by human activities (Polette and Vieira, 2009; Gandra et al., 2018).

Demersal fisheries in the BMM includes operations with bottom trawls, gillnets, and long-lines that jointly account for over 1/3 of the region's total annual landings (e.g. Valentini and Pezzuto, 2006). Demersal catches have been historically dominated by sciaenid fish, e.g. *Micropogonias furnieri*, *Umbrina canosai*, *Cynoscion guatucupa*, *Macrodon atricauda* and coastal shrimps, e.g. *Xiphopeneaus kroyeri*, *Artemesia longinaris*, *Penaeus paulensis* and *Penaeus brasiliensis* (Pezzuto and Mastella-Benincá, 2015). Since the late 1990's, demersal fishing fleets expanded their operations to the upper slope initiating fishing regimes on deep-sea fish, namely the codling *Urophycis mystacea*, the argentine hake *Merluccius hubbsi* and the monkfish *Lophius gastrophysus* (Perez et al., 2009). Throughout the past decades, however, many of these stocks underwent important biomass reductions due to excessive mortality exerted by demersal fishing (e.g., Perez et al., 2009; Haimovici and Cardoso, 2017); and there has been evidences of additional pressures on benthic ecosystems. Port et al. (2016) demonstrated that trawlers from Santa Catarina State operated over 100% of the available area of the BMM between 2003 and 2011, and over 60% of the available area was intensely swept during this period. Because this 'core area' had been under exploration by double rig trawlers for at least 40 years, Port et al. (2016) concluded that these were possibly the 'most disturbed benthic habitats in the Brazilian continental margin', and that bottom trawling was their primary environmental stressor. Despite these earlier results, the impact of demersal fisheries on benthic ecosystems of the BMM is not comprehensively dimensioned and represents an important gap of knowledge hindering the development of spatial management initiatives. Such an assessment would necessarily require a wider representation of the fishing fleets (e.g. operating from other fishing harbors) and demersal fishing methods (e.g. different types of trawls, gillnets, long-lines), and be conducted from the benthic ecosystem perspective, differentiating the multiple forms of pressures experienced from fishing operations and their spatial patterns.

This study analyses all demersal fishing activity in the BMM, producing a spatial synthesis of three forms of ecosystem pressures: mortality, disturbance of the seabed and generation of PAFS, through catch discards. We estimate total amounts of each pressure exerted by different fishing methods operated by all demersal fishing fleets active during one year, and map spatial patterns of pressure distribution delimiting areas submitted to greatest (hotspots) and lowest (refuges) cumulative pressures on the BMM. The study is part of a comprehensive analysis of the sustainable use of demersal resources off Southeast and South Brazil based on the DPSIR framework (Perez et al., 2022). Combined with a description of the benthic environmental setting (i.e., *State*), it represents a primary step towards the development of impact assessments on demersal populations and benthic habitats and communities (i.e., *Impact*) and the construction of an ecosystem-based spatial management regime for the demersal fisheries in the BMM (i.e., *Response*) (Perez et al., 2022). Overlaid to the information describing the spatial patterns of other marine anthropogenic activities these data layers can also support the implementation MSP initiatives in Brazil (Gandra et al., 2018).

2. Materials and methods

2.1. Study area

Demersal fishing fleets based in the ports of Southeast and South Brazil operate over the Brazilian Meridional Margin (BMM, *sensu* Alberoni et al., 2019), the southernmost sector of Brazilian Continental Margin, that extends from the Vitória-Trindade Seamount Chain (~20°S), to the southern border of the Brazilian EEZ (~34°S) (Fig. 1). It includes four sedimentary basins: Espírito Santo, Campos, Santos and Pelotas (Mohriak, 2003). The continental shelf is narrowest (40 km) in the northern extreme off Espírito Santo state, and widest (250 km) off southern São Paulo and Paraná states (~25°S) (Alberoni et al., 2019). Most of the shelf surface area (~60%) is covered by sand and mud, greatly favoring the operation of demersal fishing gear, such as trawls and gillnets. Off northern Rio de Janeiro and Espírito Santo states the shelf area is covered by more diversified substrates, including, sand, carbonate gravel, coralline algae and rhodolith beds (Bourguignon et al., 2018). The slope region (200–2000 m depths) is characterized by an irregular morphology that includes canyons, cones and terraces, associated with eroding and depositional processes of the along-shore flux of deep currents (Alberoni et al., 2019). The region is influenced by the southward flow of the subtropical Brazil Current (BC) and the Deep Western Boundary Current. These are boundary currents of the South Atlantic subtropical gyre system that overlay the shelf break and slope, carrying five water masses: Tropical Water (TW), South Atlantic Central Water, Antarctic Intermediate Water and North Atlantic Deep Water (Silveira et al., 2020). The continental shelf is influenced by subtropical shelf waters, formed from mixtures of TW advected from the BC, with

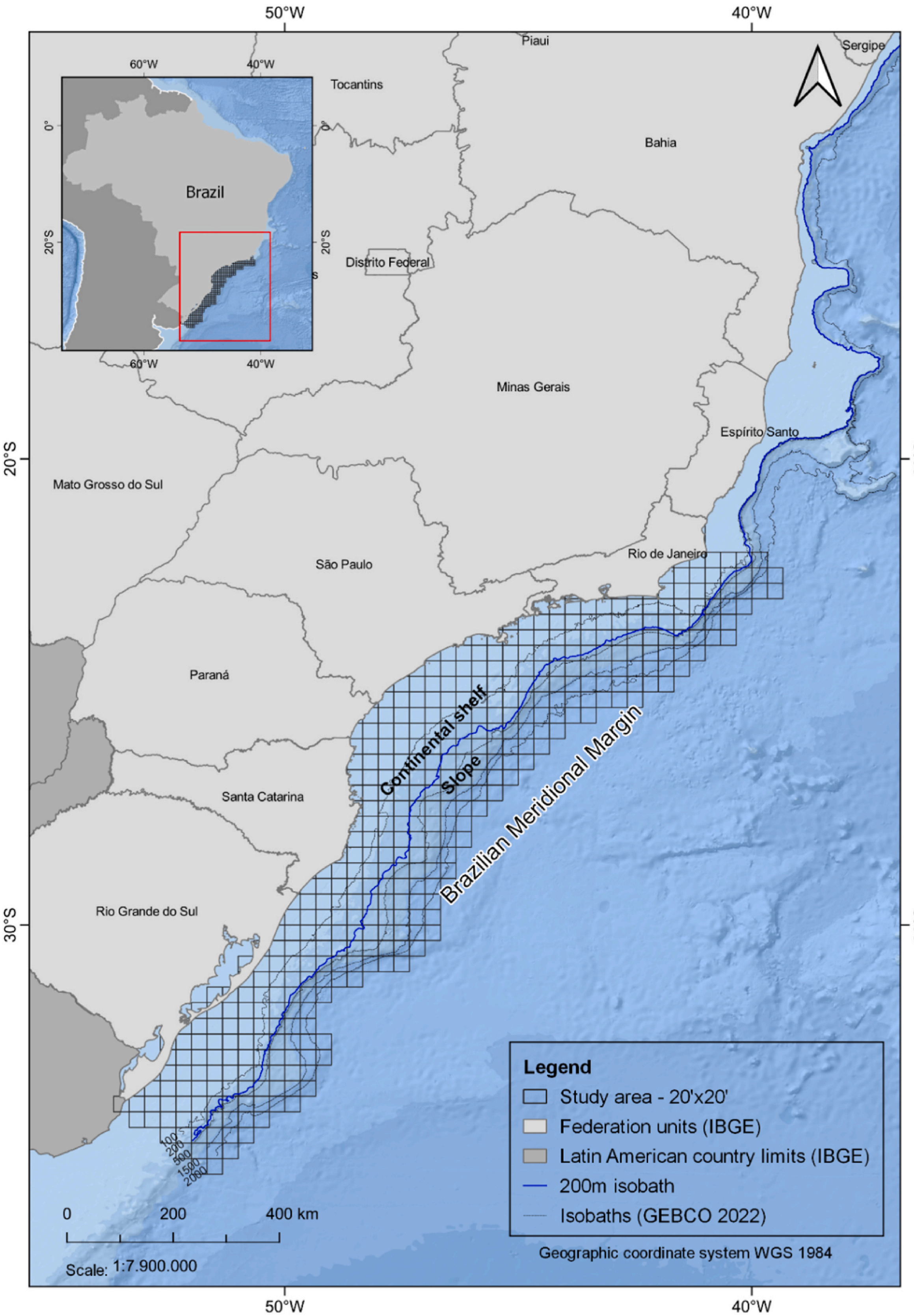

Fig. 1. Study area. Brazilian Meridional Margin (BMM) with study area divided by a 20 × 20 nautical miles quad mesh, total of 456 quads (1 quad ≈1,372 km^2).

freshwater discharges of the Rio de la Plata and Patos Lagoon systems. In association with latitude variation and the dynamics of distinct water masses, the BMM is a transition zone between subtropical and temperate faunas (e.g. Spalding et al., 2017; Pinheiro et al., 2018) that have enabled the development of demersal fisheries sustained by the exploitation of assorted subtropical and warm-temperate teleosts, elasmobranchs, crustaceans and cephalopod species (Martins and Haimovici, 2016).

2.2. Analyzed data

The analyzed data included landed catches, fishing effort and areas of operation of 2,125 fishing trips conducted in 2018 by vessels operating double-rig trawls, stern trawls, pair trawls (see Fishing methods illustrations in Supplementary Material S.1, Fig. 1) bottom gillnets, and bottom longlines (*sensu* He et al., 2021). Information was obtained through interviews with skippers at landing places in Rio de Janeiro, São Paulo, Paraná, Santa Catarina and Rio Grande do Sul states. Except for the Rio Grande do Sul state, interviews were carried on by fishing monitors from research institutions that participate of the 'Santos Basin Fishing Activities Monitoring Project', set out to support the environmental licensing processes of the offshore oil and gas exploration activities in Santos Basin. Landings in the Rio Grande do Sul state, were recorded and made available by the Institute of Oceanography of the Federal University of Rio Grande (FURG). Data collection in the different landing places were statistically designed to represent the total amount of fishing trips landed in 2018, but in most places data collection systems randomly covered distinct proportions of that amount. In that sense, a process of data expansion was applied to obtain estimations of total landings and effort measures. This procedure used a two-level stratified random sample (fishing harbor and fishing gear) and a Horovitz-Thompson classical estimator (Bolfarine and Bussab, 2005). These were unprecedented efforts to combine all demersal fishing data of this wide geographic area, only possible for the year 2018. Therefore, it has been considered the most comprehensive characterization of the 'recent' demersal fishing scenario produced in the country. Landings recorded in the subsequent years (2019–2022) in the states of Santa Catarina (UNIVALI/LEMA et al., 2023), São Paulo (IP, 2023), Paraná (FUNDEPAG, 2023), and Rio de Janeiro (FIPERJ, 2023), tend to show moderate increases but no indications of significant changes in fishing methods, catch composition or spatial patterns.

Areas explored during each fishing trip were assigned to a 20 × 20 nautical miles (nm) quad mesh (1 quad ≈1,372 km^2) (Fig. 1). The total reported effort and landed catch of each fishing trip were equally distributed throughout the visited quads, following the skippers' information on latitudinal, longitudinal and depth ranges of the fishing operations. These were the primary data used to estimate total mortality, disturbance of the seabed and the generation of PAFS, through catch discards (Fig. 2). Measuring these pressures also required information on fishing gear (e.g., gear dimensions) and fishing operations (e.g., discard rates) obtained from an extensive literature review and the adaptation of methods commonly applied in fishery science (e.g., swept area method). The effect of fishing methods on different types of pressures (disturbance of the seabed, total mortality and PAFS) were tested using the Kruskal-Wallis test and Dunn's test (Zar, 2010). An Accumulated Pressure Index (API) in each quad during 2018 was computed considering the quantified forms of environmental pressure over the benthic ecosystems weighed by the relative importance its potential impact, according to the judgement of experts (see below) (Kavadas et al., 2015; Innes and Pascoe, 2010).

In order to assess the effect of seafloor disturbance produced by demersal fisheries on benthic habitats, a substrate type map was built combining information from the Geological Oceanography Laboratory (UNIVALI) database, the geographic information system (GIS) of the Brazilian Continental Shelf maintained by the Geological Survey of Brazil (CPRM) and the cold-water corals database (Kitahara et al., 2008). This map included eight substrate classes (bioclasts, sand, sandy gravel, sandy mud, mud, muddy gravel, gravel, coral) spatially distributed using a Voronoi diagram. In addition, a digital bathymetry model with 490 m cell-size (GEBCO, 2021) was used to assess the distribution of fishing ecosystem pressure along depth zones of the BMM.

2.3. Estimating disturbance of the seabed

It was assumed that the seabed area 'swept' by a fishing gear is a proxy for seabed disturbance; i.e. the more a seabed surface is repeatedly subject to friction by a fishing gear, the higher is the level of physical disturbance. Disturbances potentially caused by the double-rig trawl,

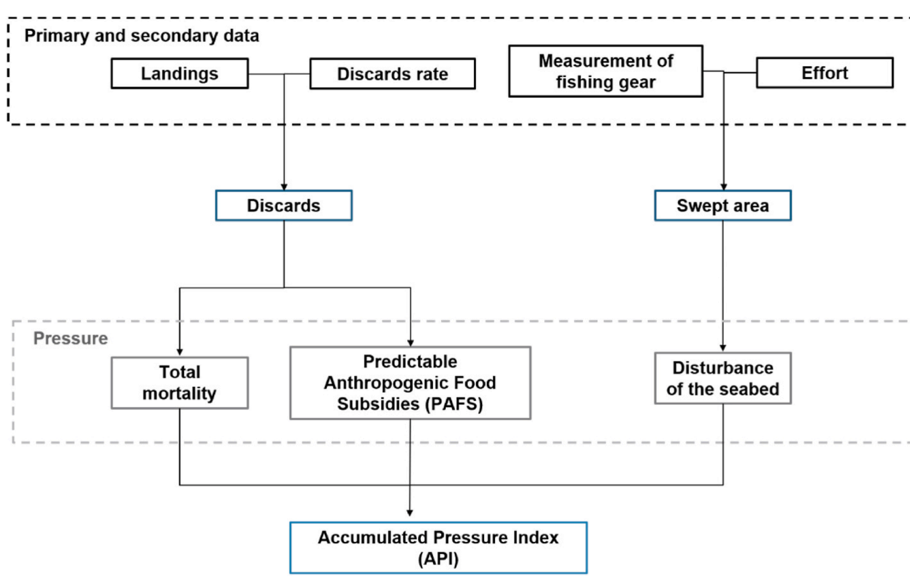

Fig. 2. Flowchart of primary and secondary data used for estimate three forms of pressure exerted by the demersal fisheries in the Brazilian Meridional Margin (BMM). Total discards are estimated from total landings and observed discard rates of different demersal fishing methods. Area swept during operations is estimated by fishing effort and specific fishing gear dimensions. Estimated pressures exerted by individual fishing trips were distributed over 20 × 20 nm quads. An Accumulated Pressure Index (API) of each quad was computed by summing normalized values all forms of environmental pressure produced by all fishing trips that visited each quad in 2018, weighed by the relative importance its potential impact.

stern trawl and pair trawl, were calculated and equally distributed over the area explored by fishing gear in each trip, using and adaptation of the 'swept area' estimate method (Sparre and Venema, 1998; Gunderson, 1993):

$$Sa_{ij} = r\left(n_{ij} \bullet d_{ij} \bullet \overline{v} \bullet HRl_i \bullet x\right) \quad \text{eq.1}$$

where the Sa_{ij} is area swept during the *i*-th fishing trip of the *j*-th vessel (in m^2), *r* is the number of trawl nets operated (where $r = 2$ in double rig trawls and r = 1 in other trawling methods), *n* is the number of trawls conducted during one day, *d* is the mean duration of each trawl (in hours). A mean constant trawl speed ($\overline{v}$) of 3.0 knots (5.6 km h^{-1}) was assumed to all trawling methods following previous studies in the region (Simões et al., 2003; Klippel et al., 2005; Santos et al., 2009). The length of the head rope (*HRl*) followed measurements made directly on trawl nets operated by different trawlers in the region and reported in the grey literature (unpublished reports - Correia, 2008; Pezzuto, 2015). Finally, the opening coefficient (*x*) is the fraction of the head rope length (*HRl*) effectively extended during the trawl. The value of $x = 0.56$ was adopted considering the operating performances of trawl nets analyzed by previous studies in the region (Haimovici and Fischer, 2007; Sant'Ana and Perez, 2016). Values of *HRl* used for the calculation of the *Sa* of different trawls were averages obtained by Monte Carlo simulations, considering the full set of values reported in the literature (see Supplementary Material S.2, Table 1).

Estimates of the area disturbed by bottom gillnets and bottom longlines were adapted from the "The Swept Area Seabed Impact" methods (SASI – Scheme presented in Supplementary Material, S.2, Fig. 2), developed by the Fisheries Management Council of New England (NEFMC, 2011). In gillnet fishing, the gear parts that can potentially cause disturbance to the seabed are the anchors, sinkers, anchoring cables, and the footrope. In the BMM, gillnets commonly operated are 15 mm diameter polyethylene threads, filled with an average of 300 g lead filaments per meter (Pio et al., 2012). The distance over which each net component moves over the sea floor is a function of the movements generated both during the fishing period and during the casting and retrieval processes. The disturbance area (*Aem*) potentially produced by gillnets on trip *i* of vessel *j*, was estimated, in km^2, using equations 2 and 3 below

$$Aem_{ij} = n_{ij} \bullet (2 \bullet (d_w \bullet l_w) + (d_l \bullet l_l)) \quad \text{eq.2}$$

$$n_{ij} = \frac{dp_{ij}}{\overline{T_i}} \quad \text{eq.3}$$

in which the number of fishing sets carried out (n_{ij}) result from the total number fishing days (dp_{ij}), divided by the average immersion time and duration of casting and retrieval operations of one fishing set ($\overline{T_i}$) (in hours). The parameters d_w and d_l refer to the distances (in km) that the anchors and end-weight or sinkers (*w*) and the gillnet (*l*) move laterally, perpendicularly to the nets. Values of l_w and l_l refer to the length (in km) of anchor cables and total gillnet distance used in a haul, respectively. Total gillnet lengths (l_l) and immersion times ($\overline{T_i}$) were extracted from previous descriptive studies on the gillnets used to capture the whitemouth croaker (*Micropogonias furnieri*), codlings (*Urophycis* spp.), monkfish (*Lophius gastrophysus*), and other demersal resources (Wahrlich et al., 2004; Pio et al., 2012; Occhialini et al., 2012). The summary of gillnet dimensions and immersion times for different fishing targets is presented in the supplementary material (S.2, Table 2). Net configuration and gear immersion periods used by the fleet that targeted *L. gastrophysus* and *M. furnieri* were considered when computing the disturbance area of fishing operations in outer shelf and slope (depth >150 m) and in inner shelf - coastal areas (depth <150 m), respectively. A mean length of anchor cables of 250 m (0.250 km) was considered for all gillnet configurations (Wahrlich et al., 2004). The mean extension of lateral movements of anchors and nets along the entire length of the fishing set was assumed to be 1 m ($d_w = d_l = 0.001$ km), following NEFMC (2011).

The methods used to calculate the area disturbed by longline fishing sets also used the disturbance area equation (*Aem*, eq. 2 and 3). The values of longline total length were extracted from fishing operations conducted by commercial vessels in the BMM (Haimovici et al., 2004). In these surveys, the main lines were made of approximately 9–13 km-long multifilament steel cables and 1 m-long secondary lines. An intermediate value between these extreme lengths was assumed for calculations using equation 2 ($I_l = 11.11$ km). The mean extension of lateral movements of main and secondary lines, as well as anchors, was also assumed to be 1 m (d_w and $d_l = 0.001$ km).

The total disturbance area calculated for each fishing trip of each fishing method was distributed equally along the quads visited by the fishing trip, as reported by the skippers. The total amount of area disturbed within each quad was computed by summing the disturbance areas accumulated in the quad during 2018. Finally, the Utilization Index (*UI*) of each quad, was calculated as the ratio between the total area disturbed and the total area available in the quad (~1,372 km^2). The *UI* was interpreted as a spatial measure of substrate disturbance intensity of demersal gear.

2.4. Estimating PAFS and total mortality of megafauna

In this study it was assumed that all biomass discarded by the demersal fishing vessels in the BMM during 2018 reached the benthic environment lifeless, contributing to organic matter inputs, here defined as Predictable Anthropogenic Food Subsidies (PAFS – Oro et al., 2013; Real et al., 2017). This biomass results from discard rates, which represent the average fraction of the total catch of a fishing operation that is discarded at sea. Discard rates vary according to the fishing gear configuration and selectivity, fishing motivations and targets, regional biodiversity, economic performance of fishing operations and management regulations (Kelleher, 2008). We considered this variability by compiling mean discard rates of double-rig, stern and pair trawl, gillnet and longline operations in different regions of the BMM, as reported in studies published between 1981 and 2020, added by some global values reported for these fishing methods (Supplementary Material, S.3, Table 3). For each fishing method (*m*) a median discard rate (*p*) (±95% Confidence Intervals) was estimated by extracting 1000 random values of normal distributions built using means and standard deviations of the reported rates (Supplementary Material, S.3, Table 3). PAFS (in kg) produced during the *i*-th trip of the *j*-th vessel operating the *m*-th method (D_{ijm}) were estimated using equation 4

$$D_{ijm} = \frac{L_{ijm} p_m}{(1 - p_m)} \quad \text{eq.4}$$

where L_{ijm} is the landed biomass (in kg) and p_m is the discard rate attributed to each fishing method (Heath and Cook, 2015; Perez-Roda et al., 2019). Total mortality (M_{ij}) was then computed as:

$$M_{ij} = L_{ij} + D_{ij} \quad \text{eq.5}$$

Discards and mortality were distributed equally along the quads visited by each fishing trip, as reported by the skippers. Total discards and mortality produced within each quad were computed by summing the values produced by each fishing trip recorded in the quad in 2018.

2.5. Estimating the Accumulated Pressure Index (API)

An Accumulated Pressure Index (API) was built to express the total amount of pressure exerted simultaneously by the demersal fisheries within each quad (*q*) on the BMM in 2018. The API sums the total amount of disturbance of the seabed (D_q), mortality (M_q) and discards (P_q) estimated for each quad, weighed by coefficients (v_d, v_m and v_p, respectively) that express their potential for pressing (i.e. modifying) the benthic ecosystem (equation (6)):

$$API_q = (D_q v_d) + (M_q v_m) + (P_q v_p) \quad \text{eq. 6}$$

D_q, M_q and P_q are normalized values of pressure, i.e., all varying from 0 to 1 (Eastman, 1997). Coefficients v_d, v_m and v_p were computed using expert's judgement (Kavadas et al., 2015; Innes and Pascoe, 2010) and an Analytic Hierarchy Process (AHP) (Saaty, 1977, 1980). Experts (n = 11) were asked to produce pair-wise evaluations of the forms of pressure exerted by demersal fisheries, where the contribution of one form of pressure to the overall change in the benthic ecosystem was rated in relation to the contribution of another form of pressure. Evaluations followed a pre-defined scale varying from 1 to 9 (Saaty, 1977). By choosing score 1 an expert considered that two forms of pressure contribute equally to modifications of the benthic ecosystem; by choosing 9 only one of the two forms of pressure compared were considered capable of ecosystem modification but not the other. Intermediate scores indicated that both forms of pressure compared could modify the benthic ecosystem, but to different extents. For example, one of them may be considered capable to contribute slightly more than the other (e.g. score 3 = 'weak contribution"), to have a 'strong' (e.g. score 5) or 'very strong' contribution (e.g. score 7) (Saaty, 1977). A comparison matrix (a_r) was built with the rates (s) provided by each respondent (r), representing the relative importance of each form of pressure in the lines (i) relative to each other in the columns (j):

$$a_r = \begin{vmatrix} 1 & s_{md} & s_{mp} \\ s_{dm} & 1 & s_{dp} \\ s_{pm} & s_{pd} & 1 \end{vmatrix}$$

Because only three rates were provided by the respondents; the remaining three rates in matrix a_r were filled considering that $s_{ij} = 1/s_{ji}$ (i.e., a 'reciprocal matrix'). The matrices produced by the eleven respondents were synthetized in one 'expert group' matrix through the geometric mean of individual s_{ij} values, considering that each respondent was equally capable of assessing priorities between the forms of pressure (Forman and Peniwati, 1998). In addition, the consistency of each respondent assessment was measured using the Consistency Ratio (CR) following Saaty (1991) (see details in Supplementary Material, S.4). Finally, v_d, v_m and v_p were expressed by eigenvectors of the 'expert group' matrix (Saaty, 1991).

The APIs and all forms of pressure (including UI) calculated for each quad in the BMM were represented spatially. Quad values were divided into five categories using the quantile method: 'very high', 'high', 'medium', 'low', and 'very low'. Demersal fishing 'hotspots' and ecosystem 'refuges' were delimited in the API spatial distribution following three criteria. Using the first criteria, quads classified into extreme categories were selected ('very high' and 'very low'). Then values of the selected quads were again divided into quantiles and only the extreme categories were selected (e.g. 'very very high' and 'very very low'). The second criteria involved defining the latitudinal range that encompassed the highest proportion of the area under the 'very high' and 'very low' categories (>40%), and selecting the quads of these categories enclosed within that latitudinal range. The third criteria repeated the second criteria but used depth range. The selected sets of 'very high' and 'very low' API quads were then merged, the former defining demersal fishing hotspots and the second defining ecosystem refuges.

3. Results

3.1. Fishing activity and spatial footprint

Demersal fishing operations during 2018 involved a total of 35,652 days at sea, calculated by summing all days at sea of all vessels operating during 2018. These operations covered an area of 437,668 km^2 (319 quads of the BMM) and landed 37,578 t of fish and shellfish (Table 1). Double-rig trawling and gillnet fishing operations made up, jointly, 86.1% of all fishing trips, 89.9% of total effort (in days at sea) and 72.8% of the landed catch in the period (Table 1). Double-rig trawlers and gillnet vessels also spread over wide extents of the BMM, with spatial footprints covering 99.1% and 86.8% of the total available area, respectively. Ecosystem pressures exerted by demersal fishing in the BMM during 2018 was significantly affected by fishing methods (Kruskal-Wallis test $p < 0.05$). Pairwise comparisons using Dunn's test indicated that all fishing methods differed significantly from each other in all forms of pressure (Dunn's $p < 0.05$, Fig. 3).

3.2. Disturbance of the seabed

The total area disturbed by demersal fishing in 2018 was estimated in 99,495 km^2, 15.9% of the total BMM study area. The numerous and extremely active double-rig trawl fleet (Table 1) was responsible for 91.1% of all disturbed area (90,648 km^2, Fig. 3). Pair trawlers ranked second, disturbing a much smaller area (6,555 km^2), and all other fishing methods contributed to less than 1.2% of all disturbed area (Fig. 3).

Disturbance of the seabed by demersal fishing concentrated on coastal and continental shelf areas (<200 m) of the BMM, between latitudes 24°S and 29°S (Fig. 4), as largely determined by double-rig trawling spatial patterns (Supplementary Material, S.5, Fig. 3C). In these areas the total surface disturbed by demersal fishing reached, on average, 64% of the area available area in the quads (UI, Fig. 4). In some highly disturbed areas, adjacent to the coastlines of Paraná and Santa Catarina States, the total disturbed surface reached maximum levels of 1.4 times the individual quad area (2,707 km^2) (Fig. 4). Seabed area disturbed by pair trawlers concentrated in the coastal areas off São Paulo, Paraná and Santa Catarina States (24°S - 27°S), and on mid-shelf off Rio Grande do Sul State, in the southern extreme of the BMM (32°S - 34°S) (Supplementary Material, S.5, Fig. 3B). A similar pattern was exhibited by gillnet vessels, whereas long liners concentrated over shelf break areas in central and northern sectors and stern trawlers in the southern extreme of the BMM (Supplementary Material 1, S.5, Figs. 3–4). Areas most intensely disturbed by demersal fishing in 2018 were covered by sandy and muddy substrates of Santos Basin, in the central sector of BMM (Fig. 5). Coraline bottoms in Santos Basin were also subject to moderate disturbance.

Table 1
Summary of demersal fishing activity in the Brazilian Meridional Margin (BMM), monitored during 2018 in the harbors of Southeaster and South Brazil. Footprint is the entire area of quads where each fishing method.

	Double-rig trawl	Pair trawl	Stern trawl	Gillnet	Long-line	Total
Fishing trips	1,102 (51.9%)	215 (10.12%)	34 (1.6%)	727 (34.2%)	47 (2.2%)	2,125
Days at sea	19,164 (53.8%)	2,431 (6.8%)	505 (1.4%)	12,877 (36.1%)	679 (1.9%)	35,656
Footprint (km^2)	433,539 (99.1%)	225,001 (51.4%)	231,861 (53.0%)	380,033 (86.8%)	257,928 (58.9%)	437,656
Landed catch (t)	13,031 (34.7%)	7,934 (21.1%)	1,883 (5.01%)	14,331 (38.1%)	397 (1.06%)	37,576
Mean seafloor disturbance (km^2/trip)	82.3	30.5	35.8	1.4	0.8	
Mean total mortality (t/trip)	22.5	56.8	90.38	25.24	10.87	
Mean PAFS (t/trip)	10.70	19.87	34.97	5.53	2.43	

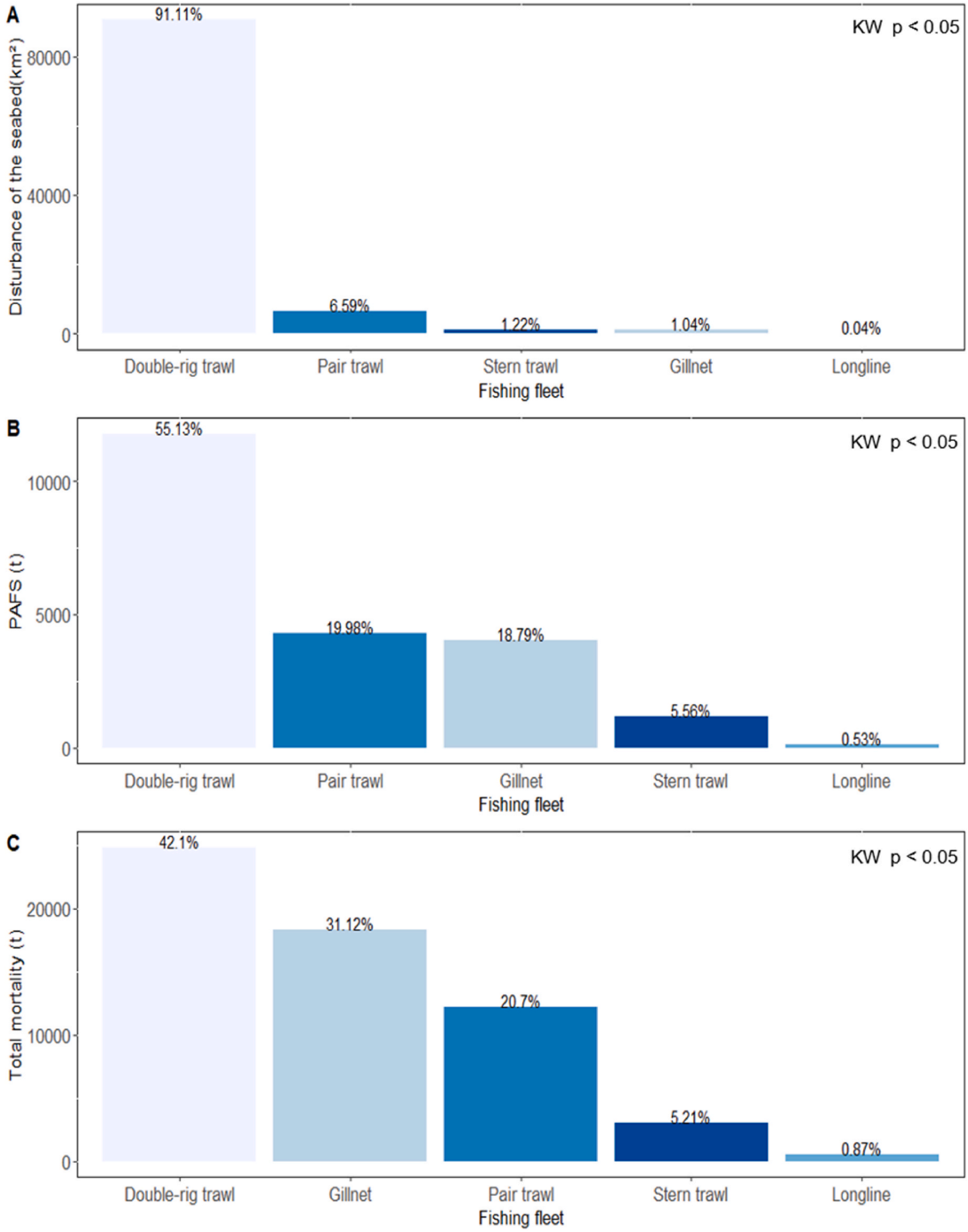

Fig. 3. Ecosystem pressures exerted by demersal fishing methods in the Brazilian Meridional Margin (BMM) during 2018. (A) Disturbance of the seabed (in km^2), (B) Predictable Anthropogenic Food Subsidies (PAFS) estimated from total discards (in tons), (C) total megafauna mortality (in tons). P-values of the Kruskal-Wallis non-parametric (KW) test are presented.

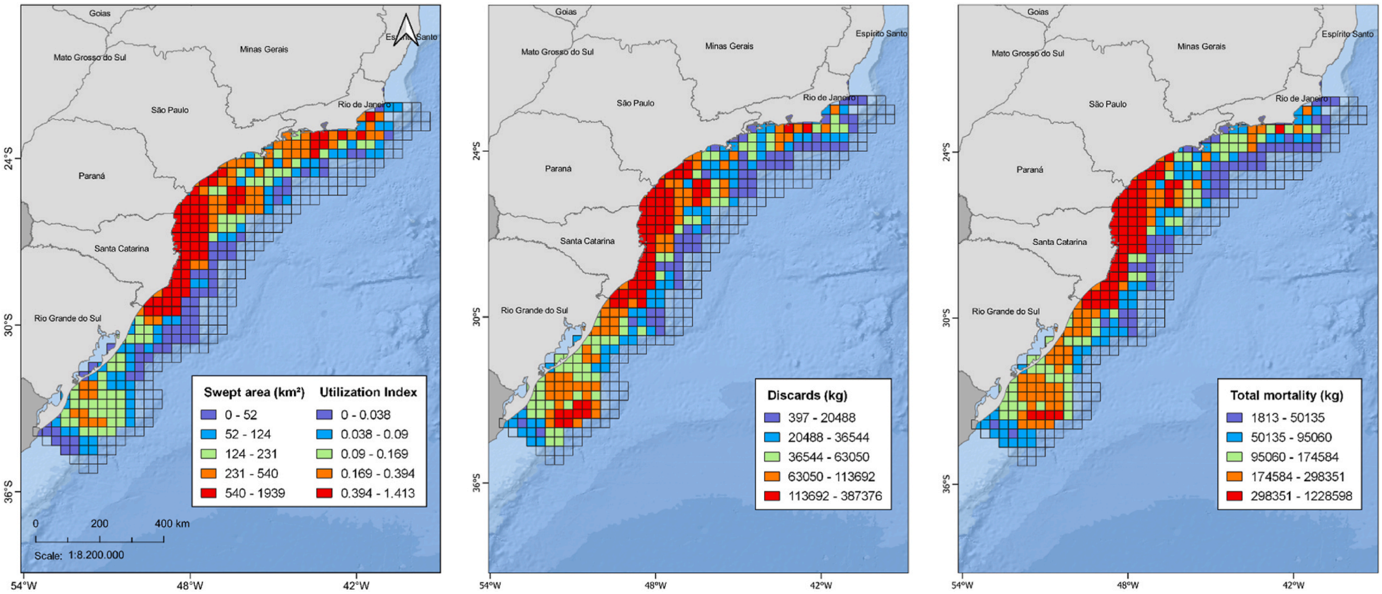

Fig. 4. Spatial distribution of three forms of ecosystem pressure exerted by demersal fishing in the Brazilian Meridional Margin (BMM) during 2018. Seabed disturbance area is represented by the area swept by fishing gear (in km^2) and by the Utilization Index (UI) expresses the ratio between the total area swept in one quad and the quad area (≈1,372 km^2). Predictable Anthropogenic Food Subsidies (PAFS) are represented by total organic discards (in kg). Total mortality is the sum of landed and discards catches (in kg). Values are expressed on a 20 nm × 20 nm quad mesh, classified in five categories.

3.3. Mortality and PAFS

The 2018 demersal fishery in the BMM produced an estimated total megafauna mortality of 58,962 t, of which 21,384 t (36.3%) was discarded to the marine environment as PAFS. Double-rig trawlers produced the largest mortality (24,821 t, 42.1% of total mortality) and the largest volume of discards (11,790 t, 55.1% of total discards) (Fig. 3). Less significant contributions to total mortality were also attributed to gillnet vessels (31.1%) and pair trawlers (20.7%), which produced similar volumes of discards (18.9% and 20.0%, respectively) (Fig. 3). Stern and pair trawlers discarded approximately 39% and 35% of the total mortality generated during each trip (Table 1); the contribution of the former to total PAFS is small, however, due to the reduced number of fishing trips in the period (Table 1).

The spatial distribution of PAFS and total mortality of megafauna were similar, as determined by the spatial patterns of dominant double-rig trawl and gillnet operations in 2018 (Fig. 4). Largest removals of megafauna biomass were recorded at coastal areas off southern São Paulo, Paraná and Santa Catarina states coinciding with the areas of highest effort concentration and disturbance of the seabed (Fig. 4). A reverse pattern was observed in a secondary nucleus of elevated mortality/discards in the outer shelf off Rio Grande do Sul, where lesser disturbed areas were (a) subject to great biomass removals (up to 328 tons per squad unit) and (b) received a great volume of discards (up to 142 tons per squad) (Fig. 4). Such a contrast is possibly the result of highest catch rates of demersal stocks observed in this southerly region, with landed catches as high as 186 tons per quad unit. The outer shelf and slope areas received less than 5% of the total discards in all the study coverage.

3.4. Accumulated Pressure Index (API)

In general, total mortality was perceived by experts as the most important form of pressure exerted by demersal fisheries in the BMM (weight 0.54) and the production of PAFS the least important (weight 0.12) (Table 2). Experts considered mortality over two times more important than disturbance of the seabed and over four times more important than the production of PAFS.

The API spatial distribution (dataset - Costa et al., 2023) retained the main spatial operational patterns of double-rig trawling and gillnet fishing in the BMM (Fig. 6). Almost half of the BMM surface area (127 quads) was considered under "high" and "very high" fishing pressure. A major demersal fishing 'hotspot' encompassed the extensive coastal and shelf areas (20–75 m depths) between 24.5°S (southern São Paulo) and 29.5°S (southern Santa Catarina) (Figs. 6 and 7). A secondary hotspot was defined in the narrow shelf adjacent to the southern Rio de Janeiro coastline (24°S). Ecosystem 'refuges' extended along most shelf break and slope areas of the BMM between 100 m and 1500 m isobaths (Figs. 6 and 7). A coastal refuge (depth <50 m) was exceptionally defined in northern São Paulo states (~24°S) (Figs. 6 and 7).

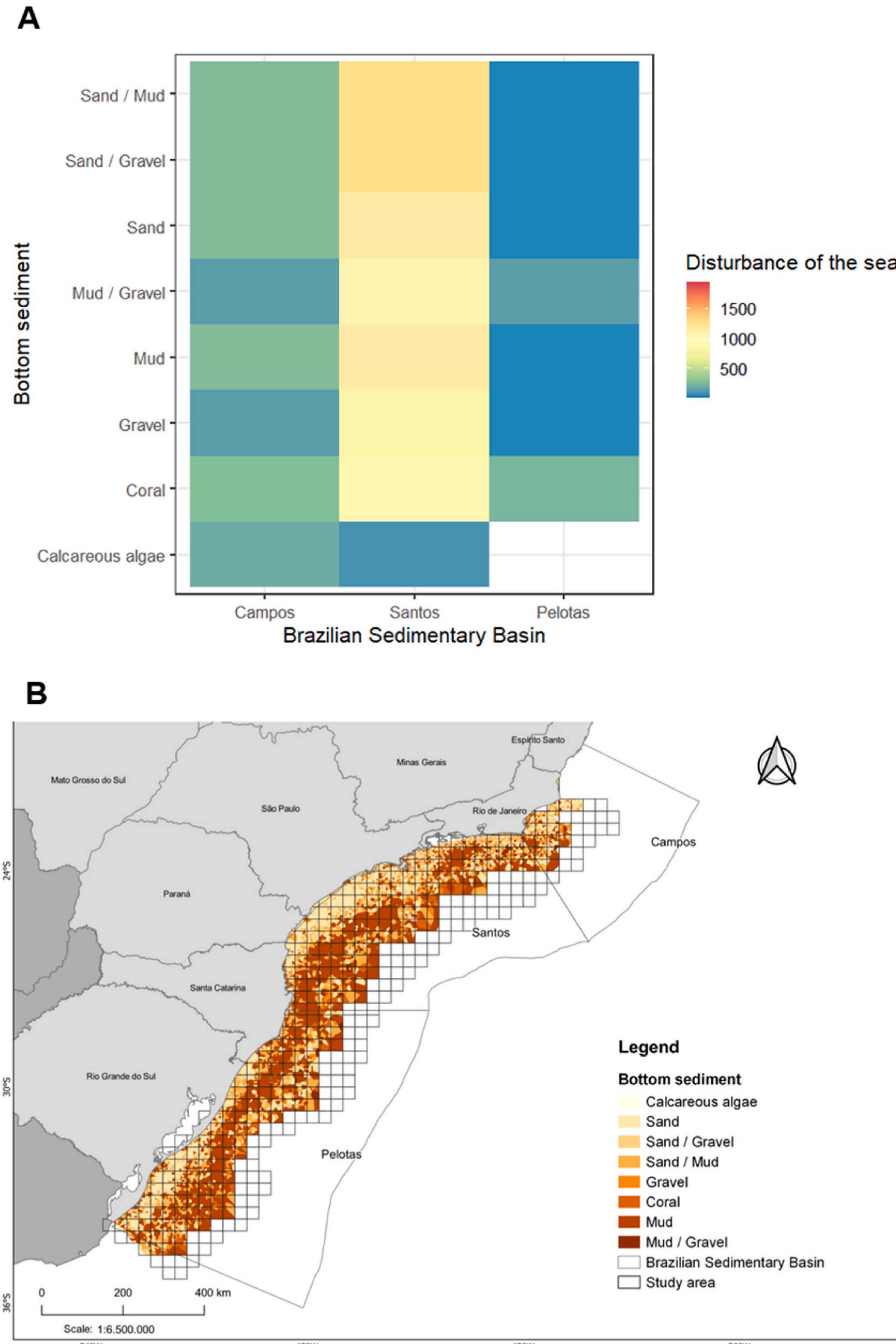

Fig. 5. Disturbance of the seabed. Heat map (A) expressing the area disturbed by demersal fishing (in km^2) within three sedimentary basins of the Brazilian Meridional Margin (BMM) and nine substrate types. The map (B) presents the spatial distribution of these substrate types in the BMM and the three sedimentary basins: Campos, Santos and Pelotas Basins.

Table 2
Expert group matrix expressing pair-wise comparisons of the forms of pressure exerted by demersal fisheries in the Brazilian Meridional Margin (BMM). Values in the matrix are geometrical means of scores chosen by 11 experts and reciprocal values. In the last column weights attributed to each form of pressure are shown (eigenvectors).

	Disturbance of the seabed	Total mortality	PAFS	Weights (eigenvectors)
Disturbance of the seabed	1.00	0.48	2.96	0.34
Total mortality	2.08	1.00	4.09	0.54
PAFS	0.34	0.24	1.00	0.12

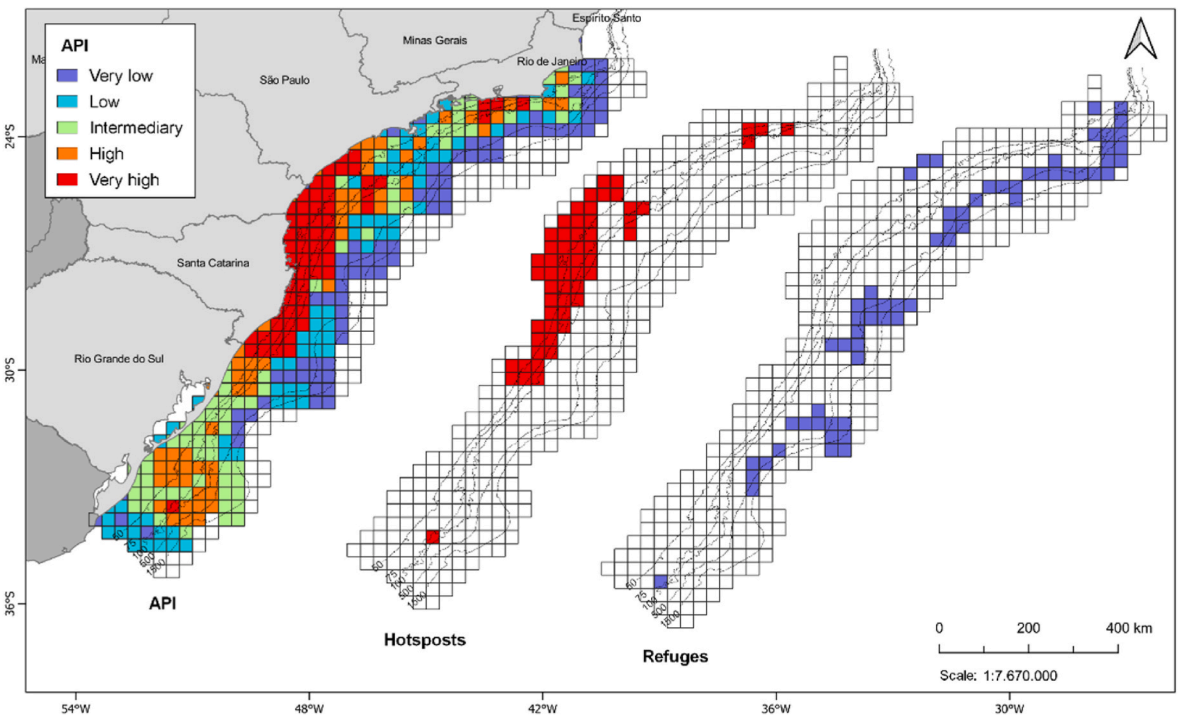

Fig. 6. Accumulated Pressure Index (API). Spatial distribution of the Accumulated Pressure Index (API) computed for the demersal fisheries in the Brazilian Meridional Margin (BMM) during 2018, and selected hotspots and ecosystem refuges. Values are expressed on a 20 nm × 20 nm quad mesh, classified in five categories.

4. Discussion

This study described spatial patterns of three forms of pressure exerted by demersal fishing in the BMM during 2018, delimiting nuclei of higher (hotspots) and lower (refuges) cumulative pressures. The analysis was limited by the relatively coarse spatial resolution of available data; i.e. often seabed areas affected by bottom fishing gear tend to be considerably smaller than the area contained within the 20 × 20 nm (e.g. Gerritsen et al., 2013). In addition, spatial patterns displayed by the different forms of pressure were broadly similar because they (a) tended to retain common spatial patterns of fishing effort (that also influences landings), and (b) were led by the overriding double-rig trawl and gillnet fishing operations. While from a pressure driver perspective these spatial patterns seem redundant, from an ecosystem perspective, however, they conveyed the multiple and diverse modifications underwent simultaneously by benthic ecosystems in the BMM. The redundancy of ecosystem pressures is a recurrent debate in studies that relate to the different uses of the ocean and spatial management (Halpern, et al., 2015; Ban and Alder, 2008). Marine areas that are permanently pressured by human activities have a high potential for environmental degradation (Lotze et al., 2006). In that sense, the spatial characterization of multiple and simultaneous pressures, as the ones generated by demersal fisheries, enables the differentiation of not only where seabed ecosystem is being modified, but also on the multiple nature of ecosystem modifications taking place (e.g. mortality, habitat destruction, etc.). In general, this produces a more refined understanding of ecosystem pressures that can improve impact assessments and the definition of spatial ecosystem management strategies (Maxwell et al., 2013).

4.1. Hotspots and refuges

Demersal fishing operations conducted in 2018 off southeast and south Brazil concentrated in coastal and shelf areas of the BMM. Main fishing pressure hotspots were located within the so-called ‘Brazilian Bight’ region (Matsuura, 1998), between São Paulo and Santa Catarina states (24–29°S). The region is a major fishing ground of penaeid shrimps (e.g. *Penaeus paulensis*, *P. brasiliensis*, *Xiphopenaeus kroyeri*), which have sustained valuable double-rig trawl fisheries since the 1960’s (Valentini and Pezzuto, 2006; Pezzuto and Mastella-Benincá, 2015). The decline of shrimps biomass since the 1980’s drastically affected this activity provoking an expansion of the trawl fleet to other shelf and slope areas, and the spreading of their fishing pressure to most BMM (Valentini et al., 2012; Perez and Pezzuto, 1998). Nonetheless, the traditional shrimp fishing grounds, off São Paulo, Paraná and Santa Catarina states remained heavily fished and subjected to extreme and continuous levels of pressure, not only in the forms of shrimp harvesting and seabed disturbance, but also by general megafauna mortality and

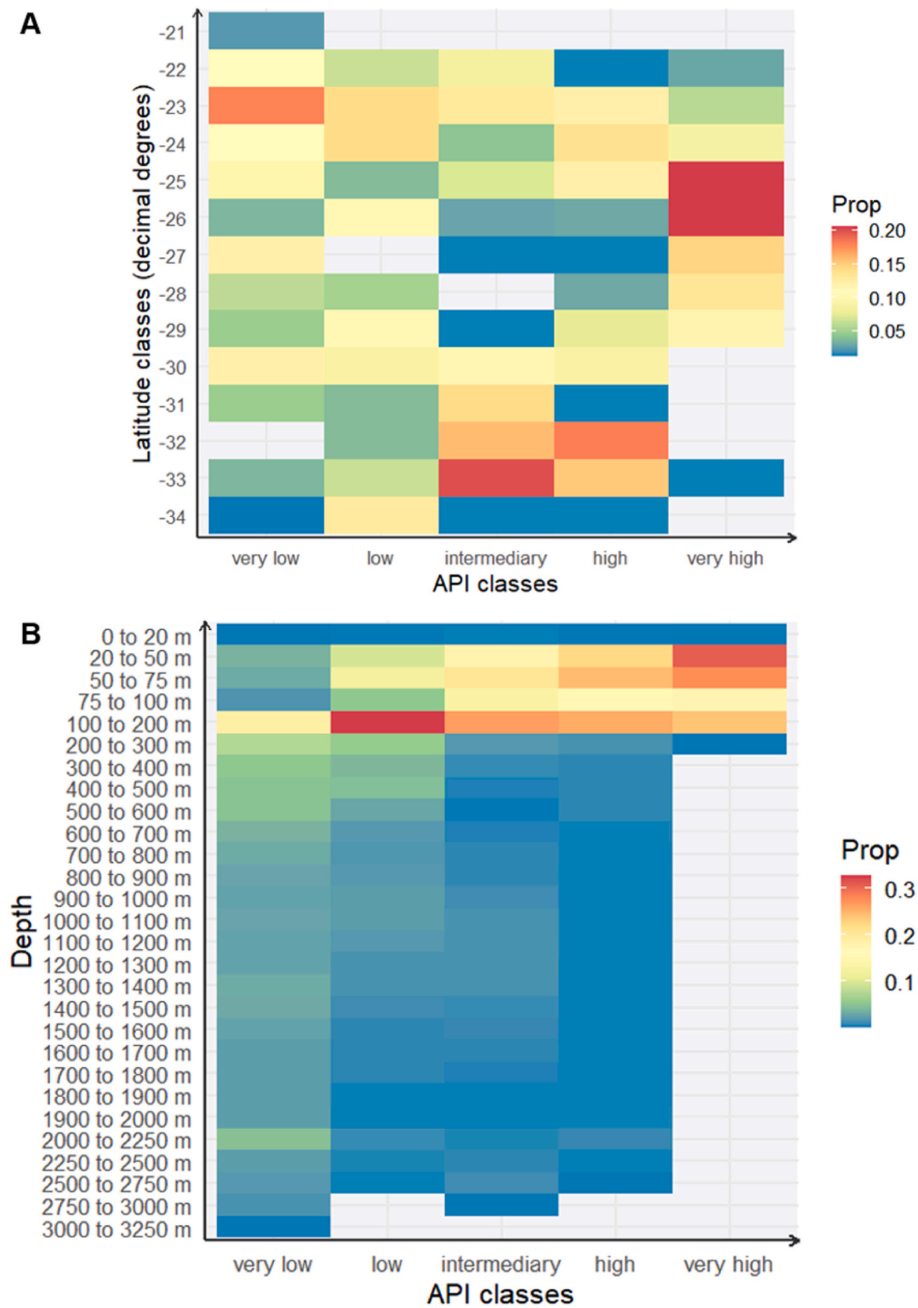

Fig. 7. Distribution of the Accumulated Pressure Index (API). Heat maps expressing the latitudinal (A) and bathymetric (B) distribution of the Accumulated Pressure Index (API) computed for the demersal fishing in the Brazilian Meridional Margin (BMM) during 2018. The legend presents the proportion of the area occupied by API classes.

massive production of PAFS (Valentini et al., 2012; Port et al., 2016; Rosso and Pezzuto, 2017). The area is characterized by high productivity and a seemingly high level of resilience to continuous pressure, which warrants it maximum priority for spatial management measures.

Slope areas of the BMM were shown to be under far less demersal fishing pressure. This spatial trend represents opportunities for conservation of benthic ecosystems, generally known to be less resilient; i.e. containing species that typically have greater longevity, late sexual maturity, slow growth rates, thus being less productive and more vulnerable to overfishing than coastal species (Morato et al., 2006; Cheung et al., 2005). However, the relatively low-pressure scenario evidenced in 2018 is not an evidence of entirely ‘pristine’ benthic ecosystems and populations. That is because the BMM slope area was affected by an important deep-sea fishing development process starting in the late 1990’s, wherein part of the demersal fishing fleet expanded their operation areas towards the upper slope (200–400 m depths) in search for profitable catches of finfish species (most notably the monkfish, *Lophius gastrophysus*, the argentine hake, *Merluccius hubbsi* and the codling *Urophycis mystacea*) (Dias and Perez, 2016; Pio et al., 2016; Port et al., 2016). Added to this process, between 2000 and 2008, over 35 foreign fishing vessels were licensed to operate gillnets, pots and bottom trawls in the region, under a Brazilian government deep-sea fishing development program, covering areas up to 1000 m-deep (Perez et al., 2009). All targeted stocks showed important signs of biomass reduction in the period, some of them to unsustainable levels (Perez et al., 2020). Also, some activities involving gillnet fishing for monkfish and trawling for deep-sea shrimps (Family Aristeidae) produced significant discards of fish and invertebrate species, including cold-water corals (Perez and

Wahrlich, 2005; Perez et al., 2015; Kitahara et al., 2020). After 2008, foreign vessels' operations ceased, virtually limiting demersal fishing to the upper slope areas (Perez et al., 2020). Since then, monkfish biomass has not recovered to the 2000's levels and less is known about deeper stocks (e.g. deep-sea shrimps and crabs) (Cardoso et al., 2022). Interestingly, however, a recent geophysical survey in one of the deep-sea shrimp fishing grounds revealed trawl marks that may have been printed by deep-sea shrimp trawlers over a decade before. This could evidence previous trawl-driven seabed disturbance and low recovery potential of the slope habitats to bottom trawling (Perez et al., 2023). The demersal fishing refuges delimited in the present analysis demonstrate that these areas have been poorly demanded by the fishing industry and their exclusion should be considered before any new deep-sea fishing activity is promoted in the region. Spatial measures in this direction should produce benefits that may extend beyond the protection of sensible ecosystems (e.g, cold-water coral reefs) (Magris et al., 2020), also becoming 'harvesting refugia" (*sensu* Schneider, 2018) for overfished shelf stocks of the BMM that may extend their distribution to deep slope grounds (Lauer and Reaka, 2022).

A few spatially-limited hotspots and refuges were evidenced also in the accumulated pressure analysis, not without relevant management implications. A hotspot off southern Rio de Janeiro state indicated concentrated demersal fishing pressure in a reduced continental shelf area and in the vicinity of a singular coastal refuge off northern São Paulo state (Fig. 6). This refuge coincides with a marine protected area network that comprises large trawling exclusion areas off the coast of São Paulo (Rolim and Avila-da-Silva, 2016). In the present analysis, this MPA network seems to be successfully reducing industrial fishing pressure, potentially contributing to the restoration of coastal habitats and populations, including reef fish biomass (Motta et al., 2021).

4.2. The effect of individual sources of ecosystem pressure

Hotspots of demersal fishing pressures on benthic ecosystems involved simultaneous contributions of increased levels of megafauna removal, disturbance of the seabed and inputs of carrion from discarded catches. Which of these sources of pressure have greater potential for significantly altering benthic ecosystems, however, is uncertain. Under the expert's perception, mortality was the most relevant form of pressure exerted by demersal fishing on the ecosystem, possibly because the consequences of biomass removals of studied species (e.g. overfishing) have been more commonly demonstrated than the ecosystem consequences resulting from other forms of pressure (e.g. Haimovici and Cardoso, 2017). However, because these studied species are only a small fraction of the overall species regularly caught and landed by the demersal fisheries (over 70 species), the levels of estimated total mortality may be causing impacts far greater than perceived. In fact, recent efforts to assess understudied stocks, historically neglected by fisheries management, have demonstrated that some have long been overfished (e.g. Hirota et al., 2022; Rodriguez et al., 2023). Also, because demersal stocks are often space-structured, spatial mortality patterns may concentrate on specific population strata (e.g. reproductive aggregations, nursery areas) aggravating population impacts.

In this study, the estimated seabed area disturbed by demersal fishing during one year in the delimited hotspots of the BMM (covering 40–140% of the quad areas) was comparable to other heavily trawled continental shelf areas of the Atlantic (Amoroso et al., 2018). This area was covered by sandy/muddy substrates, which tend to have cohesiveness and texture of sediments modified when subject to long-lasting bottom fishing (mainly trawling) (Oberle et al., 2018). Almeida and Vivan (2011) assessed the effects of these substrate alterations, as produced by double-rig trawls, on the diversity and abundance of benthic fauna of coastal trawling grounds off Santa Catarina, with inconclusive results. Worldwide regional assessments, however, suggest potential changes in functional groups, with large filter-feeding animals becoming more common in lightly trawled areas (e.g. refuges), while in areas under heavy trawling (e.g. hotspots) mobile animals, infaunal and scavenging invertebrates would predominate (Tillin et al., 2006). Biogenic habitats, which can be severely impacted by trawl fishing (Kaiser et al., 2002, 2006), were present in the slope areas of the BMM, where current demersal fishing activity was relatively low.

During 2018, 21,384 t of megafauna carrion were estimated to be returned to the sea in the BMM following demersal fishing operations, representing over 1/2 of their landed catch and over 1/3 of total fishing mortality. The ecosystem effects of such pressure on benthic ecosystem are little understood. Uncertain amounts were potentially consumed on the sea surface and water column by seabirds, pelagic fish and cetaceans (Matínez-Abraín, et al., 2002; Fondo et al., 2015), and only part of the total discarded volume reached benthic ecosystems on mostly coastal and shelf areas. Because these have been important demersal fishing grounds for over four decades (see above), catch discards in 2018 may have represented food inputs to benthic food webs long modified by such anthropogenic subsidies. Discarding unwanted catch back to the marine environment, supplies benthic food webs with carrion, eventually enhancing consumer populations, particularly benthic scavengers (Ramsay et al., 1997).

4.3. The effect of demersal fishing methods

Double-rig trawling was a major driver of pressure in the BMM first and foremost because of the elevated fishing effort, accumulating over half of total number of demersal fishing trips in 2018. Individual double-rig trawling operations also disturbed a seabed area far greater than the areas disturbed by the other fishing gear, and discarded the largest fraction (~48%) of the total fauna mortality. Originally introduced for coastal shrimp fisheries in the Brazilian Bight in the 1960's, this fishing method proved to be the most adaptable in the process of fishing expansion, whereby fishers have established multiple opportunistic fisheries in the continental shelf, shelf break and slope area (*e.g.*, Pezzuto and Mastella-Benincá, 2015; Dias and Perez, 2016). For at least a decade before this study (2003–2011), trawlers from Santa Catarina State were estimated to disturb the seafloor in a significant area of the BMM, and regarded as major drivers of ecosystem pressure (Port et al., 2016). Reducing the demersal fishing pressure on the BMM seems to be primarily concerned with abating the intensity of double-rig trawling, and/or diluting their effect through spatial management measures as demonstrated in the São Paulo MPA network (Rolim and Avila-da-Silva, 2016).

Industrial gillnet fishing has expanded in the BMM since the 1990's (Vasconcellos et al., 2014; Pio et al., 2016). In 2018, fishing operations were also spread over coastal, shelf and slope areas, accumulating high levels of mortality and discards, but disturbing a reduced seabed area. Whereas this estimated lower ecosystem pressure relies on assumptions about the area swept by gillnet footropes (and anchors, sinkers, anchoring cables) during fishing sets (NEFMC, 2011), the method tends to disturb far less seabed area than trawling, in general. On the other hand, gillnet fishing not only pressures benthic ecosystems through elevated megafauna removals, but also tends to produce high mortality rates (and discards) of sensible pelagic megafauna, including sea birds, sea turtles and cetaceans not considered in this study (Vasconcellos et al., 2014).

Stern and pair trawling operations can exert significant pressure on shelf benthic ecosystems, but their activity seem to be low in the BMM. Very few bottom longlining operations were recorded in shelf break areas of the BMM. Operations using this gear showed a lower potential for pressing benthic ecosystems, compared to the other demersal fishing methods, but in the past a larger fleet dedicated to unregulated fishing for the wreck fish (*Polyprion americanus*) depleted local stocks (Peres and Haimovici, 1998). In structurally-complex ecosystems (e.g. dominated by cold water coral communities), however, long-line fishing can drastically reduce the risk of habitat damage when compared to trawling (Pham et al., 2014). It is important to note that limiting/promoting the use of fishing methods that exert less pressure in spatially defined benthic ecosystems may become, in association with the reduction of effort of certain fishing methods, an effective initiative to reduce demersal fishing pressure in the BMM. This study presents an updated synthesis in support of management measures in that direction.

5. Conclusions

This study presents an updated synthesis of ecosystem pressures exerted cumulatively by demersal fishing on the benthic ecosystems of the BMM, as a first step in order to understand consequences of demersal fishing on the structure and functioning of benthic ecosystems. With a limited spatial resolution, it demonstrated that almost half of the total seabed area was under high or very high pressure in 2018, being not only affected by megafauna biomass removal, but also disturbed and enriched with allochthonous organic matter. It stressed the importance of particular coastal and shelf areas that have experienced extreme fishing pressures and demonstrated high levels of resilience. These areas can be regarded as 'productivity hotspots' (*sensu* Briscoe et al., 2016) that deserve priority in space-based management initiatives. It also highlighted opportunities to protect diverse and sensible benthic ecosystem at the slope regions of the BMM, and prevent future occupation by deep sea fishing expansion programs. It finally demonstrated that limiting the intensity and spread of double-rig trawling operations seems critical to reduce ecosystem pressure of demersal fishing, which represents a major challenge for regional fisheries management. The consideration of spatial patterns of ecosystem pressures exerted by fleets operating different fishing methods, combined with known spatial distribution of benthic ecosystem and demersal stocks, can be instrumental to reconcile objectives of sustained fishing productivity and conservation of benthic ecosystems of the BMM.

Authors' contributions

J.A.C.: Conceptualization; Investigation; Methodology; Formal analysis; Writing – original draft; Writing – review & editing.

R.S.: Conceptualization; Investigation; Methodology; Formal analysis; Writing – review & editing.

J.A.A.P.: Conceptualization; Supervision; Writing – review & editing; Project Administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The API spatial data reported in this paper are available in Mendeley Data, V1, doi: 10.17632/phj3kdzk3z.1

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ocecoaman.2023.106935.

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