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Under pressure: an integrated assessment of human activities and their potential impact on the ecosystem components of the Southern Brazilian continental shelf

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Economic activities in the South Brazilian Shelf (SBS) are concentrated on the coast, causing several impacts. To balance biodiversity and habitat conservation in coastal and marine areas with human activities relevant to society, it is important to identify and understand those sectors and pressures. We conducted an analysis to assess ecosystem risks from multiple drivers and pressures in the continental shelf that extends from the Southernmost point of Brazil (Chuí) to Cabo Frio cape, in Rio de Janeiro State. We used the Integrated Ecosystem Assessment (IEA) methodology, a framework for implementing ecosystem-based management grounded on five steps: scoping, indicator development, ecosystem assessment, risk analysis, and management strategy evaluation. This work presents the scoping step consisting of a semi-quantitative assessment identifying sector–pressure–ecological component pressure pathways. Subsequently, these pathways were scored using expert judgment supported by literature and data, regarding their level of overlap with each ecosystem component, frequency of occurrence, and degree of impact, enabling estimation of the magnitude of impact risk arising from each one of the sectors and pressures. The assessment involved 20 experts from multiple disciplines and backgrounds. To validate the results, we conducted a thorough literature review and engaged in further discussions with relevant stakeholders. As a result, 16 sectors and 19 pressures were identified as impacting 18 ecological components. Fishing, land-based industry, tourism and recreation, wastewater, and coastal infrastructure represented the main economic sectors impacting the area. The major associated pressures were the incidental catch of species, the introduction of contaminants and organic matter into the water, and the generation of waste. The most affected ecosystem components were, in turn, those located on or close to the coast, such as mangroves, saltmarshes, and rocky reefs while the preeminent impacted taxonomic groups were elasmobranchs, seabirds, reptiles, mammals, and bony fish. The literature review supported the expert assessment, and the stakeholders' workshop endorsed our findings. Additionally, this assessment highlights the need to implement public policies that focus on reducing the impact of the most influential sectors and pressures and the necessity of strengthening research and monitoring. Identifying these priorities for integrated coastal and marine management is crucial, and our research outcomes can be key in promoting regional ocean sustainability.

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The ocean provides an essential support system of resources for the development of human activities[1,2]. Even though this connection was initially limited to shallow coastal areas, as human needs increased and technology evolved, more distant and deeper parts of the ocean became accessible[3]. This achievement, nonetheless, came with a cost, often to the detriment of natural systems, and the sustainability of resources and ecosystem functions. Overall, continental shelves play a vital role in supporting economic activities, ecological systems, and human well-being in coastal regions[4]. They contain reserves of oil, gas, and minerals, resources vital for energy production, construction materials, and industrial processes[5]. Extensive fishing grounds are found on the continental shelf due to the presence of nutrient-rich waters and diverse marine ecosystems, making them important for global food security, as well as for aquaculture, commercial, and subsistence fishing[6,7]. Additionally, marine environments provide suitable opportunities for recreational and tourism activities that contribute to many local economies[8,9] and support important sites for scientific research and exploration. Major ports and harbors are located along the coastline and close to densely populated cities. Oceans and coastal areas, in particular, have been and continue to be, affected by a heavy burden of anthropogenic pressures[10,11]. The combination of natural and anthropogenic disturbances has altered coastal environments and led to the loss of species and reduction of ecosystem resources[12]. Although there is still a sense of disconnection between the marine system and human society, there is increasing understanding that they are intrinsically connected within a socio-ecological system[13]. As such, studies with integrated approaches provide a more realistic mechanism to identify sustainable ecosystem management strategies[14].

To balance the conservation of natural resources with intense coastal development and offshore use, ecosystem-based management (EBM) has been adopted as a strategy around the globe, from local and regional scales to large marine ecosystems. EBM can be defined as an integrated management perspective that aims to organize human activities in ecosystems, balancing the benefits of their use with the sustainability of the structures and processes that provide them[15,16]. This approach aims to incorporate different ecosystem aspects such as species management, habitat characterization, and human exploitation to minimize the risk of irreversible changes to natural communities and ecosystem processes[17,18]. Research studies employing EBM approach have been conducted to elucidate effective management strategies for natural resources. However, its execution has encountered difficulties due to the lack of scientific information[19–22].

To overcome this challenge and support EBM initiatives, the Integrated Ecosystem Assessment (IEA) approach was developed to guide a formal process of data synthesis and analysis. It allows for identifying socio-economic and biophysical attributes that maintain ecosystem structure and function, assesses human activities and their interdependence with the natural ecosystem, and, through recognition of trade-offs, evaluates management alternatives that will maintain or improve the coupled social-ecological system status quo[23,24]. In this way, the IEA seeks to provide information to qualify decision-making processes and management strategies for entire systems, taking into account interactions among ecosystem components and management sectors, as well as cumulative impacts of a wide spectrum of ocean-use sectors[25]. This approach consists of a continuous process, allowing for improved understanding and feedback between stakeholders (policymakers, researchers, citizens, industry, etc.) over time, and has already been utilized in open water, shallow water, and deep water biomes[26–28].

In Brazil, the economic growth peaks of the last decades were based on industrialization concentrated in the coastal areas, together with tourism development and urban growth[29]. This strong association produced vigorous territorial, populational, and economic dynamics, causing environmental, social, and economic impacts and conflicts[30,31]. In order to meet the goals of adaptive EBM of socio-eoclogical systems, it is vital that we have the best possible knowledge on these interactions[32].

Therefore, the aim of this study is to improve the understanding of the Brazilian marine and coastal social-ecological system through the novel application of IEA in Brazilian territory. We present a synthesis of the interactions between economic sectors, their pressures, and the affected ecological components in order to identify those that present high-impact risks to marine ecosystems in the southern continental shelf, and, therefore, priority areas for management action.

For the first step of the IEA framework, an adaptation of the ODEMM (Options for Delivering Ecosystem-based Marine Management) approach was applied[27]. This work was developed as part of a collective research effort developed within the scope of Mission Atlantic Project (MA - https://missionatlantic.eu). MA is an EU-funded project that will map and assess the present and future status of the Atlantic marine ecosystems under the influence of climate change and exploitation through the adoption of a unified methodology for carrying out IEAs in seven case study areas on the Atlantic.

Results

For the South Brazilian Shelf (SBS) (Fig. 1), 16 sectors and 19 pressures were considered as potentially impacting 18 ecological components. Reviewing the interactions led to the identification of 2348 (42.9%) established linkages out of 5472 potential connections[33]. The main components of the linkage framework are illustrated in Fig. 2.

The most linked sectors were coastal activities, such as (the lack of) wastewater treatment and coastal infrastructure (Fig. 3C), which is mainly due to the presence of several large coastal cities in the SBS area. Fishing is not restricted to the coastal zone, and as such, impacts a larger number of ecological components ($n = 17$), leading to a relatively high proportional connectance (Fig. 3C). As many fishing impacts are acute, this leads to the highest risk score for a single sector (Fig. 3C).

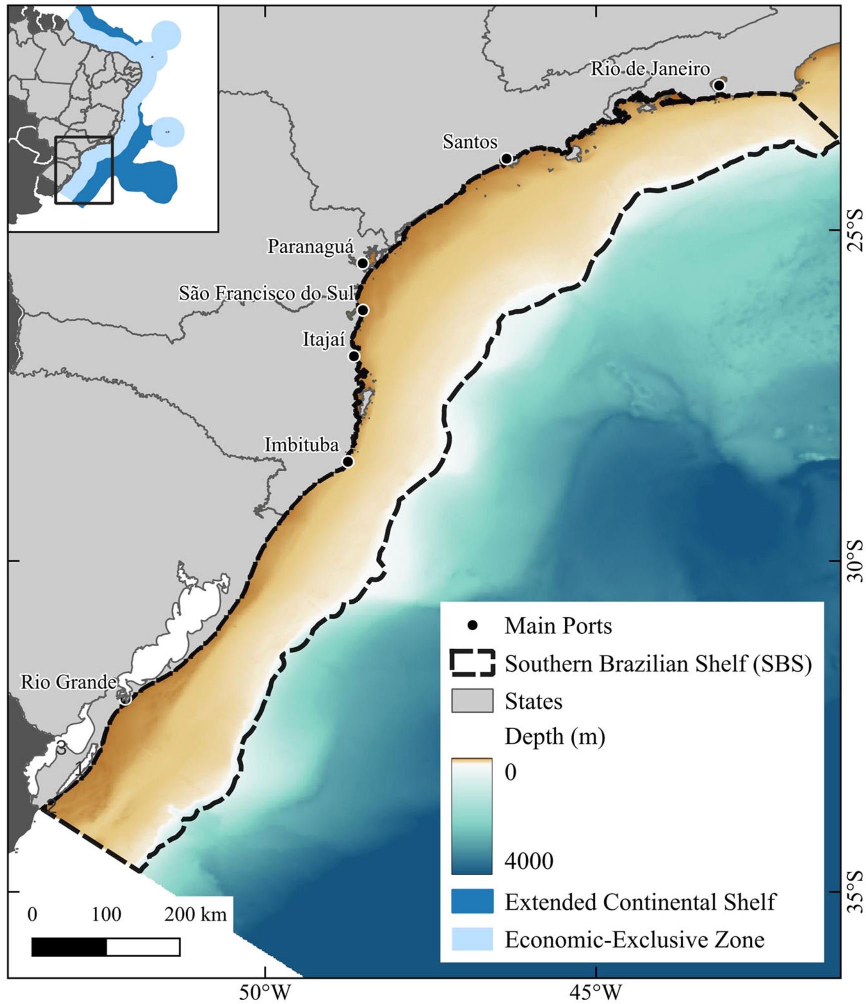
Even though looking at connectance is useful to identify the connectedness or centrality of particular components, it does not provide information on magnitude or risk. The land-based industry, for instance, presented a relatively low proportional connectance but was ranked as the third most impactful sector considering the summed impact risk (Figs. 2 and 3C). Tourism, shipping, and the aggregates sectors, on the other hand, have higher proportional connectance but scored lower on the summed Impact Risk. The oil and gas (non-renewables) sector was linked to most pressures and ecosystem components. However, as this assessment only focuses on current existing 'business as usual' pressures, consequences of potential oil spill accidents were not considered in the analysis, thus having a low impact risk (Fig. 3C).

Analyzing overall impact risk, fishing is the most impactful sector and has the highest relative contribution to impact risk (~66%—Table 1). Land-based activities (merging of agriculture, land-based industry, and wastewater treatment, due to their common source) are responsible for 16.55% of the summed total risk. Coastal infrastructure, Shipping, Tourism, and recreation round out the top five sectors, which altogether account for 96.29% of the summed impact risk.

Regarding the pressures, litter was identified as the one having the most links, both with the sectors causing this pressure and impacting ecological components (Fig. 2). However, bycatch was the highest contributor to sum risk (Table 2). Other fishing-related pressures, such as species extraction and incidental loss of species also highly contributed to the sum risk (both account for over 31.27%). The introduction of contaminating compounds had high proportional connectance (15.6% of the total links) and had a major relative contribution to sum risk (16.20%). Input of organic matter is also featured in the main pressures in the case study.

The ecosystem components most affected by sectors and pressures, as revealed by summed impact risk scores, were those that are targeted by fishing: demersal and pelagic fish and elasmobranchs (Fig. 3A). Shelf rock and reef, and mangroves had relatively low proportional connectance, but high average Impact Risk due to the pressures being persistent and widespread. Shallow sediment, on the other hand, was the only ecological component that was shown to be impacted by all the sectors and pressures analyzed; however, due to the low average Impact Risk score, it did not stand out from other ecosystems.

Fig. 1 | Map of the South Brazilian Shelf (SBS). The insert shows the case study related to the borders of the Brazilian continental shelf (dark blue) and the Economic Exclusive Zone (light blue).



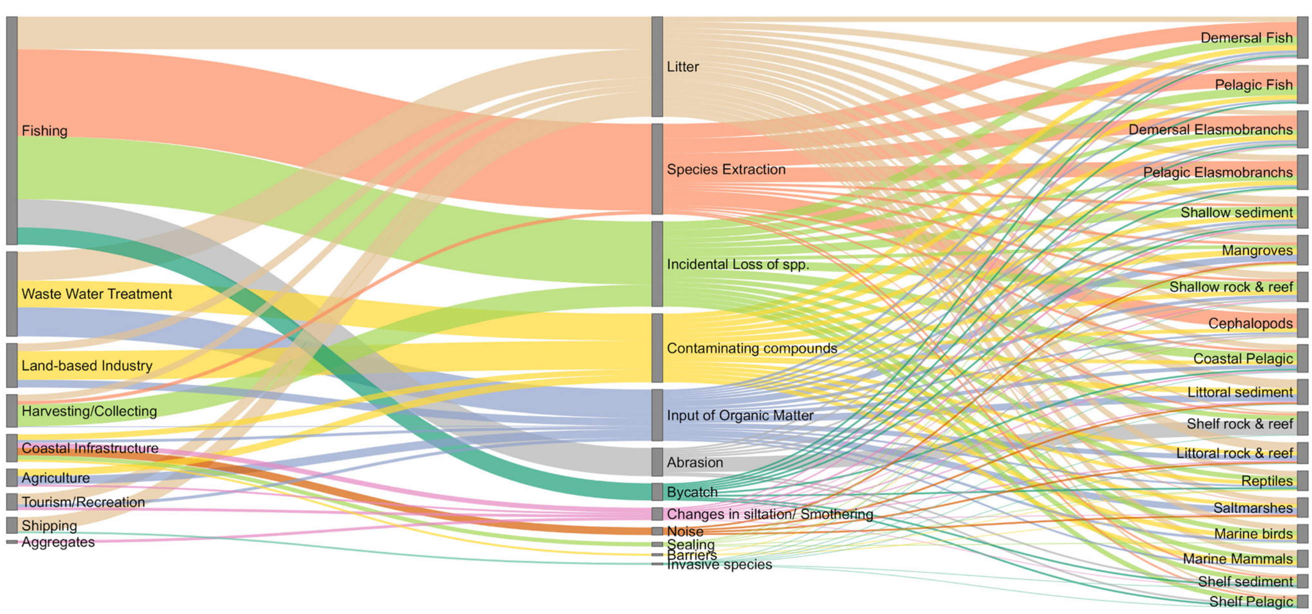


Fig. 2 | Sankey diagram of linkages between sectors (left), the pressures these exert (middle), and the ecological components they impact (right). The width of lines (color-coded according to pressures) represents the Impact Risk score (product of overlap, frequency, and degree of impact). Sectors that have a low number of linkages are not represented in this figure.

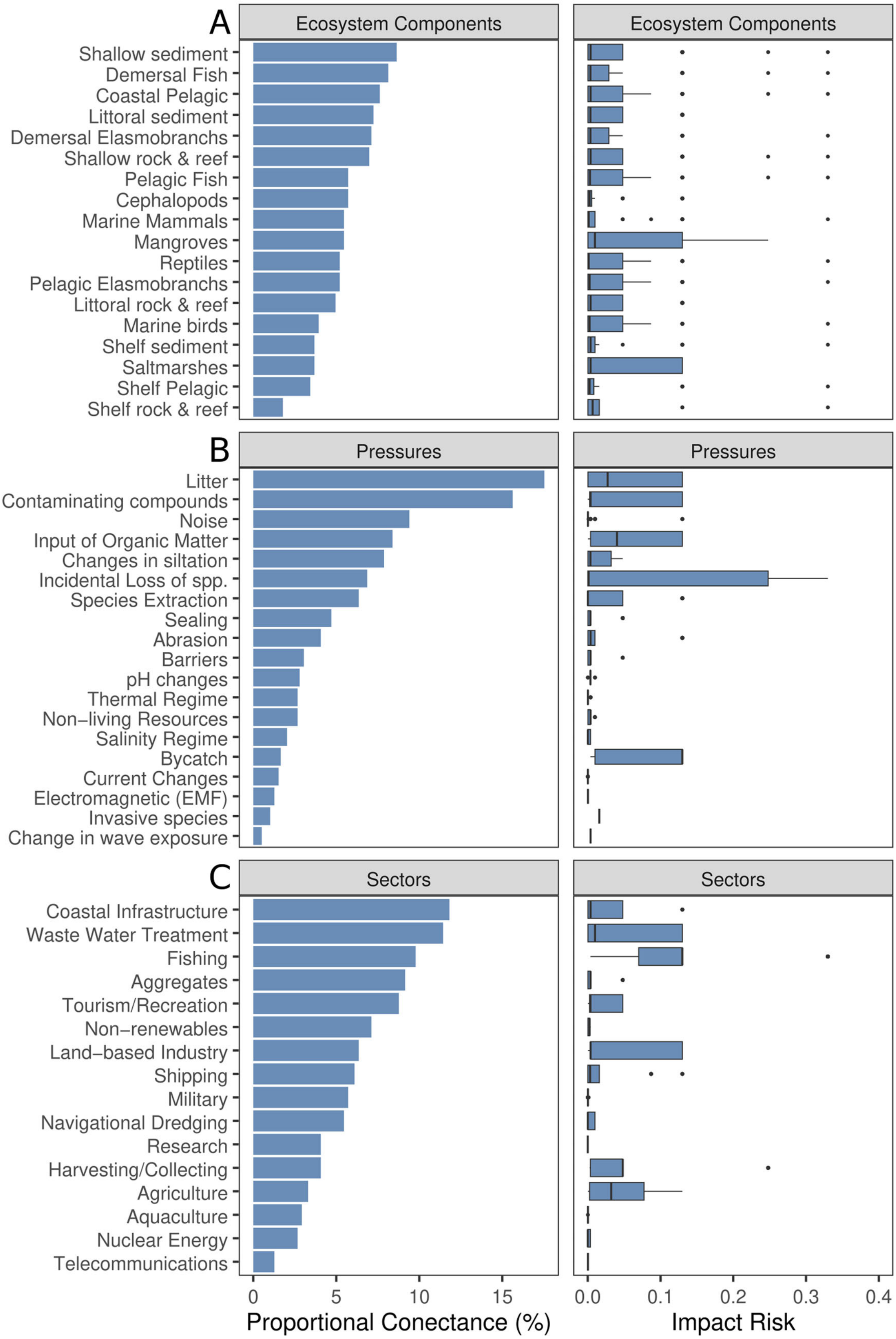


Fig. 3 | Proportional Connectance and Impact Risk. Percent proportional connectance (left) and boxplots showing Impact Risk (right) of ecosystem components (**A**), pressures (**B**), and sectors (**C**). Components are ordered according to proportional connectance. In the boxplots, thick black vertical lines are median values, box lengths represent 25% quartiles, whiskers represent 1.5 times the interquartile range, and black dots represent outliers.

Table 1 | The relative contribution of the five most impactful sectors to total impact risk

Sector	Relative contribution (%)
Fishing	66.03
Land-based activities	16.55
Coastal infrastructure	6.85
Shipping	3.68
Tourism and recreation	3.18

In this case, the category "land-based activities" comprises agriculture, land-based industry, and wastewater treatment.

Table 2 | The six most impactful pressures based on their relative contribution to the total impact risk score

Pressure	Relative contribution (%)
Bycatch	22.34
Species extraction	19.40
Introduction of contaminants	16.20
Litter	15.71
Incidental loss of species	11.87
Input of organic matter (N and P)	11.79

A detailed display of individual scoring of each combination of the sector–pressure–ecological component, and assessment results (connectance, average Impact Risk, and sum Impact Risk by sector, pressure, and ecological component) are available as supplementary material.

Reviewing the supporting data and knowledge, most of the linkages assigned were categorized as coming from Specific Expertise ($n = 233$, 30%), followed by Regional Literature ($n = 225$, 29%), Global Literature ($n = 203$, 25%) and Regional Data-Monitoring ($n = 115$, 15%), while No Specific Expertize was associated with a low number of linkages ($n = 11$, <1%) (Fig. 5). The highest impact risk categories, such as fishing and species extraction, are associated with a robust knowledge quality and hence a high confidence level (Fig. 4). However, there are still some gaps. Monitoring bycatch would be essential to reduce its impact on ecosystems and species groups. Also increasing research and data collection on shipping and tourism would also be an important step to better understand these sectors' influence on the study area.

Participants at the stakeholder workshop were satisfied with the assessment categories and supportive of the results presented. Stakeholders confirmed the outputs largely reflected their understanding of the system. They also identified the need for a full IEA cycle development, with further assessment of the impact magnitude of top pressures and sectors. Furthermore, there was a general interest in evaluating how the impacts on the ecosystem might affect the economic activities in this region.

The fisheries group notably indicated the need to strengthen the institutions related to sector management, in addition to deepening and expanding the number of the assessed fished stocks, since official statistics are absent, incomplete, or hard to find. The group also suggested breaking down the sector analysis into better-detailed categories: illegal, off-season/out of the closed season, lacking assessment, and threatened species (or according to their vulnerability status). The necessity for revision of the fishery's legal framework was also highlighted, aiming at the debate and improvement of fisheries legislation.

The group focusing on coastal issues (land-based industry, wastewater treatment, and coastal infrastructure) raised that one of the main problems faced in the case study region is erosion, a pressure not included in the current assessment, which focuses on marine/at-sea pressures. The coastal management framework, as well as the Brazilian guidelines on coastal interventions, were also discussed. The group also suggested that interactions and discussions among sectors should be stimulated to further develop multidisciplinary research and better understand how these impacts act on ecosystems in the land-sea interface, providing better subsidies for policy integration, encompassing river basins, coastal management, and marine spatial planning. Scenario projection, including the effects of climate change, was also suggested.

The tourism and recreation group pointed out the need to reinforce land-use monitoring in coastal areas. Visitors in marine protected areas and a growing number of tourists in small boats were identified as the main emerging issues for the sector. Some participants warned that the results associated with tourism should be differentiated from pressures generated by real estate expansion. The group also suggested the addition of "suppression of habitats" as pressure in further studies.

Amongst the most common global considerations for the South Brazilian Shelf was the need for increasing both human resources and financial investments in management bodies; the development and implementation of monitoring systems (i.e., for fish stocks, erosion, conservation efforts, marine protected areas); better understanding of the governance processes associated with these sectors; capacity building of managers; the establishment of partnerships; and the development of more integrated management in conjunction with a marine spatial planning process.

A survey conducted at the end of the workshop regarding the participants' expectations of the event revealed that the majority (95%) considered them as fully met. Stakeholders' questions and suggestions, alongside other important issues raised during the workshop, such as climate change, will be taken into consideration in the next stages of the study, strengthening the process, and facilitating the next steps in the IEA cycle (e.g., indicators development and scenario projection).

Discussion

As observed in other densely populated coastal areas, several and sometimes conflicting socioeconomic activities, herein described as sectors, co-exist generating intricate connections and a wide range of potential impacts that affect diverse ecosystem components[26]. In order to manage and/or mitigate these effects, one must first document, assess, and characterize the existing pressures[34,35].

For the first time, this study documents the initial steps of an applied IEA, detailing a linkage framework and risk assessment used to identify the interactions between economic sectors and the pressures they create on the marine ecosystem in the Southern Brazilian continental shelf (SBS).

Our analysis indicates that multiple sectors and pressures impact several ecosystem components. Fishing poses a major risk. Surely, the current fishing practices interact and act in almost all ecosystem components analyzed in this study due to the significant numbers of vessels that operate and land in the study area (Fig. 1) with highly varied characteristics, types of fishing gear (e.g., trawlers, gillnetters, purse seiners, longlines) and target species[36–38]. In fact, as emphasized by the stakeholders, the management of fisheries resources and the improvement of fisheries legislation is urgent for the SBS. Commercial fishing in this region holds significant economic importance due to its higher biological productivity compared to other areas within the Brazilian EEZ[39,40]. It also serves as a primary center for fishing fleets, involving numerous stakeholders engaged in traditional fishing activities. Nevertheless, it is crucial to highlight the importance of such an analysis that indicates that while fishing is at the top, it is not alone, and other relevant pressures exist and interact with it in various ways.

The study revealed that among the assessed pressures in the SBS, litter was the most prevalent and highest impact. This is perhaps not surprising, as litter is simultaneously connected to land-based, coastal, and marine activities, and can travel and affect multiple ecosystem components. Generally, pressures (e.g., species extraction, introduction of contaminating compounds) were primarily concentrated in benthic habitats and close to the coast, since shallow ecosystems (e.g., shallow sediment, shallow rock and reef, mangroves) and species groups that inhabit them (e.g., demersal fish) are among the most threatened ecological elements.

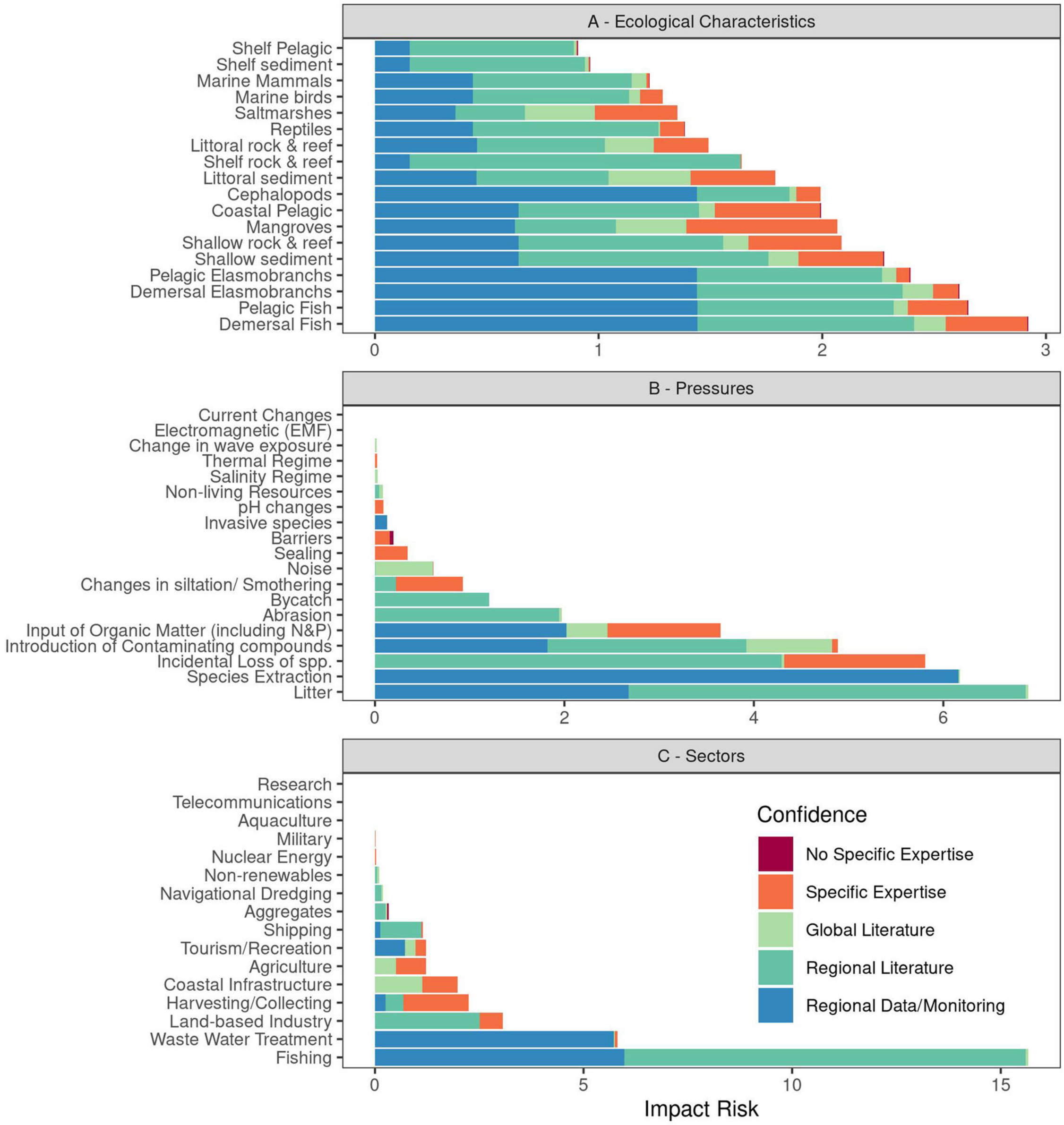


Fig. 4 | Impact Risk and Confidence. Summed risk of Impact by ecosystem components (**A**), pressures (**B**), and sectors (**C**), where the bars are colored according to confidence level categories: (i) no specific expertise, (ii) specific expertise, (iii) global lite literature, (iv) regional literature, and (v) data regional monitoring.

These findings highlight the direct linkage between coastal human activities and impacts on the benthic communities, a well-known relationship that includes hypoxia, eutrophication, sedimentation, and dominance issues, among others[41,42]. Furthermore, when widely spread, these pressures can induce changes in the ecosystems[43]. Literature shows that the resuspension of contaminants and input organic matter (mostly N and P) after dredging, for instance, has led to decreasing biomass and weakened phenology[44].

Similarly to what was found in other cases in the Atlantic Ocean where the IEA was applied (e.g., South Africa, Ireland, and oceanic islands in the South-Mid Atlantic Ridge)[26–28], our results also suggest that land-based activities (wastewater, land-based industry, coastal infrastructure, agriculture) are a major source of risk in the region, which is mainly due to the presence of several large cities located in the coastal zone in the SBS area. Insufficient or non-existent wastewater treatment facilities demonstrate a high degree of connections and contribute to the high-risk scores associated with contaminants and organic matter inputs.

It is recognized that semi-quantitative studies often come under fire for being subjective, and, in this sense, the use of a documented standardized approach helps to minimize such subjectivity. Both IEA and EBM require a broad, holistic, and integrative understanding of the system. In such cases, semi-quantitative approaches are necessary as the only available way to include all aspects of the system and not limit findings to those for which good knowledge and available data exist. In these cases, expert judgment coupled with stakeholder knowledge is an invaluable tool, allowing maximization of prior and experiential knowledge and incorporation of broader perspectives and understanding[45]. In our case, virtuality, although limiting with regard to the fluidity of interaction between stakeholders, enabled broader participation, recording, and subsequent consultation for transcription of the results.

Studies that cover a large geographical area and a diversity of factors may have difficulty in finding specific data or literature to support them. Conversely, the results detailed herein were well supported by a combination of sources of information, including academic expertize, scientific literature, and monitoring data, all of which provide a high level of confidence in the results.

The effectiveness of ecosystem assessment frameworks in accurately assessing marine environmental status depends on the sharing of knowledge between researchers and policymakers[1,46]. Reinforcing the findings, the described relationships were also identified and validated by the stakeholders, illustrating that the outcomes reflect the intuitive and regional understanding of the SBS socio-ecological system. Local stakeholders' perceptions and experts' knowledge have previously been shown to efficiently and effectively reduce uncertainty when prioritizing pressures and areas in risk assessments[47–49]. An important additional effect of such analysis is the ability to highlight areas that may have risks associated with them but that have gaps in data availability[50]. This helps to direct future priorities for research and monitoring, and thus avoid unintended impacts or consequences.

The adoption of this particular methodological framework favored the synthesis and systematization of the empirical and traditional knowledge about the marine socio-ecological system of the SBS. The present study, therefore, gathered through a standardized framework all the previously sparse and counter-dispersed information, along with the identification of the main threats to marine and coastal ecosystems in the study area. This is particularly relevant in a data-poor situation[51], as in the SBS, where the absence of robust measured data is routinely used as a justification for poor management. Although areas such as the Southern Brazilian Shelf indeed need focused effort on investigation and monitoring (which was also highlighted in the stakeholders' meeting), the adoption of a standard methodological scheme like the one presented in this research improved our understanding of the area and provided scientific background for better regional governance.

The need for a multisectoral management approach is strongly endorsed by the results presented herein, showing that ecological components in SBS are affected by a combination of coastal and marine sources of impact. Additionally, the stakeholders independently identified the same need for deeper cooperation among institutions and better legal regulation of ongoing activities[50]. To this extent, integration and engagement of different sectors provide an important participatory arena, critical for policy development and legitimacy of management measures. Thus, the current research provides a relevant starting point for a concrete ecosystem-based coastal and marine management action and informs the development of multisectoral policies and marine spatial planning processes[33].

Methods

Study area

The South Brazilian Shelf (Fig. 1) comprises the Rio Grande and the Southeastern Brazil ecoregions as described by the Marine Ecoregions of the World—MEOW5[52]. It extends from the southernmost point of Brazil (Chuí) to the Cabo Frio Upwelling System (CFUS), in Rio de Janeiro state (northern limit). The eastern boundary is defined by depth, covering from the continental shelf (depth <200 m) to the coastline. SBS overlaps with focal sedimentary basins of the Brazilian Oil and Gas Agency (ANP; http://geo.anp.gov.br/mapview), responsible for regulation, contracting, and oversight of commercial activities in the oil industry, and the South Brazil Bight (SBB) region[53].

The economic activities on the South Brazilian Shelf are concentrated on the coast[30], where a diversity of uses have been established, mirroring the situation around the world. The main economic sectors and activities in the area are the oil and gas industry, fishing, tourism and recreation, provision of wastewater services, and coastal infrastructure. In the SBS, the main industrial fishing fleets (according to the number of vessels) are otter-trawls, gillnets and traps (for bottom fisheries) and purse-seining, gillnets and surface longlines (for pelagic fisheries)[53–55].

Integrated ecosystem assessment

Integrated Ecosystem Assessments (IEAs) is a framework that employs a range of tools to support ecosystem-based management, with the particular capacity to adapt itself to the regional management context in which it is undertaken, data availability, and the focus of the study[56]. The full cycle of an IEA consists of five iterative steps[25]: Scoping, Development of indicators, Risk analysis, Management scenarios, and Assessment. Here, we present the details and outcomes of the initial risk assessment and scoping stage, collecting information about the state of ecosystems, and pressures exerted by human activities (Fig. 5).

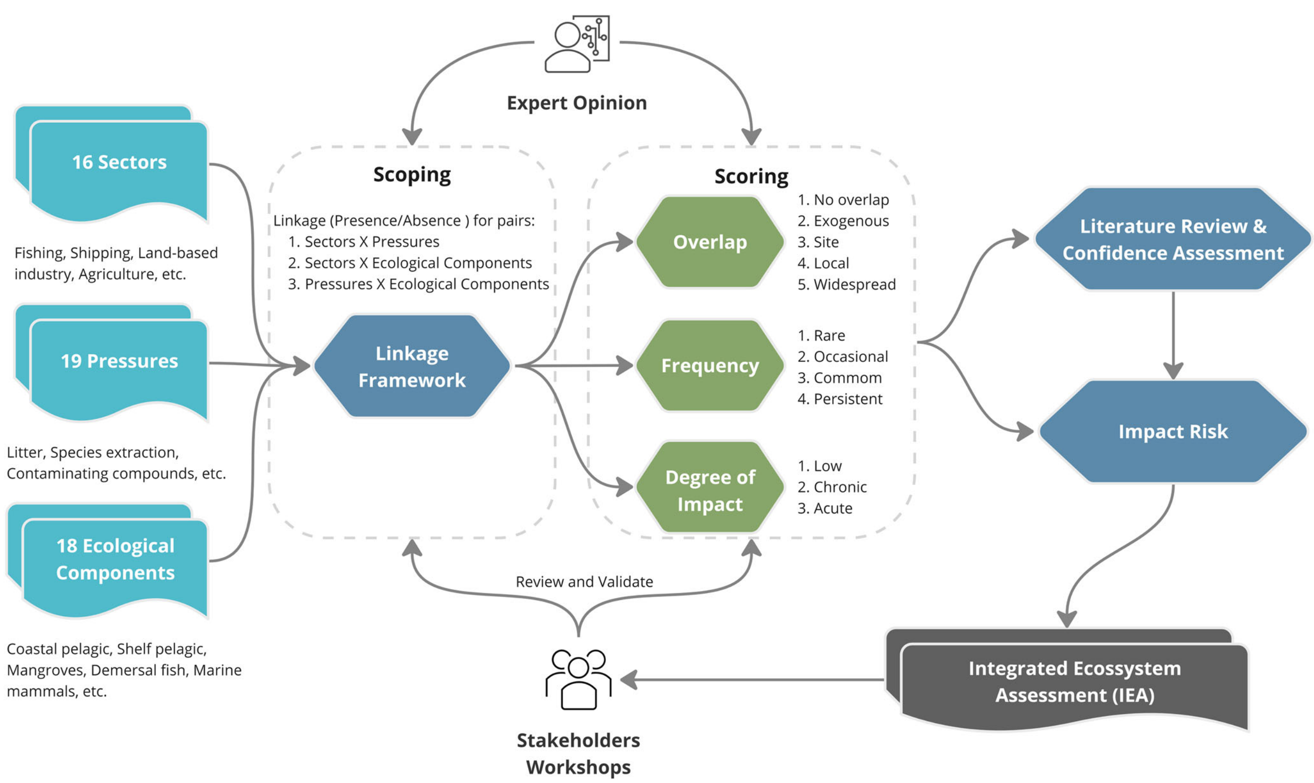


Fig. 5 | Integrated Ecosystem Assessment (IEA) framework applied for the SBS case study. Scoping and risk assessment contribute to various stages of the overall IEA.

Scoping. Conceptual models are valuable tools to facilitate the appropriate representation of complex social-ecological systems, depicting components, processes, and interactions[57,58]. This first step of the IEA consists of identifying ecosystem-relevant sub-components[25]. Thus, it involves the identification of all relevant human-related activities affecting the ecosystem and the pressures they create on ecosystems and their sub-components. Therefore, in order to identify the relationships between economic sectors, pressures, and ecological components of the SBS social-ecological system, we performed a semi-quantitative risk assessment[34]. An initial list of sectors, pressures, and ecological components was developed as a part of the Mission Atlantic project, adapting and building upon the ODEMM and AQUACROSS approaches[27,59] in order to allow further comparison among different ecosystems, including the Mission Atlantic case studies[33]. Regional adaptations to the SBS case study consisted of the removal of some sectors and ecological components that were not representative within the area (e.g., renewables and deep-sea ecosystems, respectively). The whole scoping process consisted of Linkage Chain Network Development, Pressure Assessment, Risk Assessment, Bibliographic Review, and Stakeholder Validation.

Linkage chain network development. The first step in developing the risk assessment framework was identifying the critical components comprising the social-ecological system, and their interactions. In order to do so, we established linkage matrices: (1) relating different economic sectors and human activities with pressures; (2) connecting pressures with ecological components affected by them; and (3) associating the economic sectors and human activities to the ecological components. Each cell in the matrix describes the potential for impact on an ecological component from a sector, wherein the pressure is the mechanism through which a direct impact occurs, the so-called linkage chain[34]. This stage focuses on connections among sectors, pressures, and ecological components that are regionally relevant and currently established[60–62]. The list of sectors, pressures, and ecological components identified as relevant to the SBS study area is presented in Table 3. For a full description of sectors, pressures, and ecological components, see Supplementary Tables 1–3.

To ensure a broad and comprehensive perspective, a series of expert opinion panels were conducted to ascertain the presence/absence of interactions between the assessed variables in the framework (Table 1). The panels consisted of 20 experts from three different institutions (Federal University of Santa Catarina—UFSC, University of São Paulo—USP and Institute of Sea Studies Almirante Paulo Moreira–IEAPM) with many different disciplinary backgrounds to ensure the inclusion of diverse knowledge and perspectives (see Supplementary Table 4).

Each of the 5472 potential linkages between the components was examined to establish which direct connections between the sectors, pressures, and ecological components occurred within the SBS. This process was informed by expert knowledge, and, when available, incorporated quantitative and qualitative data described in specific bibliographic references that support the connections. The metadata of the consulted bibliographic material was stored in the project's relational database for further consultation and validation.

Pressure assessment. After the linkages were identified, the relative importance of these connections was established through scoring each linkage chain. Scores were assigned using three criteria: (1) spatial extent, which takes into account if pressure occurs widespread, at local, or at site scale; (2) frequency of occurrence, which classifies pressures as persistent, common, occasional, or rare; and (3) degree of impact (DoI), describing if the pressure is acute/severe, chronic or low (Table 4). Standardized values for each level of the three criteria were then applied[34], and each qualitative category classified was replaced by the respective standardized quantitative value (Table 4). The score values are derived from expert judgment and supplemented by the best available knowledge[27,60], thereby representing a reliable measure.

Table 3 | Sectors, pressures, and ecological components relevant to the Southern Brazilian Shelf

Sectors	Pressures	Ecological components
Aggregates	Abrasion	Cephalopods
Agriculture	Barriers	Coastal Pelagic
Aquaculture	Bycatch	Demersal Elasmobranchs
Coastal Infrastructure	Change in wave exposure	Demersal Fish
Fishing	Changes in siltation/ Smothering	Littoral rock & reef
Harvesting/Collecting	Current Changes	Littoral sediment
Land-based Industry	Electromagnetic (EMF)	Mangroves
Military	Incidental Loss of species	Marine birds
Navigational Dredging	Input of Organic Matter (N&P)	Marine Mammals
Non-renewables	Introduction of Contaminating compounds	Pelagic Elasmobranchs
Nuclear Energy	Invasive species	Pelagic Fish
Research	Litter	Reptiles
Shipping	Noise	Saltmarshes
Telecommunications	Non-living Resources	Shallow rock & reef
Tourism/Recreation	pH changes	Shallow sediment
Waste Water Treatment	Salinity Regime	Shelf Pelagic
	Sealing	Shelf rock & reef
	Species Extraction	Shelf sediment
	Thermal Regime	

Risk assessment (also called scoring phase—Fig. 5). The final stage of the Scoping phase of the IEA was the risk assessment. The values assigned during the Pressure Assessment were used to calculate Impact Risk (IR), which is a function of the Overlap Score, Frequency Score, and Degree of Impact (DoI) Score:

$$IR = Overlap\ Score \times Frequency\ Score \times DoI\ Score$$

Impact Risk (IR) is understood as the likelihood of an adverse environmental impact caused by a sector/pressure[14,34,61]. For this work, we focused on synthesizing the current status of sectors and pressures acting on the coastal and marine ecosystems of the study area. Risk values were log-transformed for better comparison. Sum risk was used to rank IR and verify the relative contribution of each group to the overall risk score. Even though the number of impact chains might influence summation, the cumulative risk was of interest here, and we opted to use it in the ranking process to avoid methodological bias[26,33]. We then represented the relationship between sectors, ecological components, and pressures using network plots connecting the interactions (Sankey plots).

In addition, 'Proportional Connectance' values were calculated as the number of linkages associated with each sector/pressure/ecological component divided by the total number of linkages. These values reveal how 'connected' each of the assessed linkage chains are[33]. Computation was based on the script developed in 'R' for the Mission Atlantic project (https://github.com/missionatlantic/MissionAtlantic-RISK-Analysis).

Bibliographic review. Throughout the assessment a data search and a bibliographic review were performed in order to support the process. Approximately 223 documents were reviewed and used to support the establishment of links and scoring of those linkages. Previous research that described the impacts of different sectors on ecological components of the SBS study area was used to support and strengthen the expert

Table 4 | The criteria and categories used to evaluate each linkage chain and the numerical risk scores assigned to each category[40]

	Class	Description	Metric	Thresholds	Value
Spatial extent	Widespread	The spatial extent of overlap between a sector/pressure and an ecological component.	Spatial overlap (%)	>50	1.00
	Local			5<but <50	0.37
	Site			<5	0.03
	No overlap			0	0.00
Frequency	Persistent	How often a sector/pressure and ecological component interaction occurs measured in months per year.	Months per year	12	1.00
	Common			8	0.67
	Occasional			4	0.33
	Rare			1	0.08
Degree of impact	Acute	A severe impact over a short duration. An interaction that kills a large proportion of individuals and causes an immediate change in the ecological components.	Severity per interaction	1.00	1.00
	Chronic	An impact that could have detrimental consequences if it occurs often enough or at high enough levels.		0.125	0.13
	Low	Never cause a high level of mortality or habitat loss.		0.01	0.01

The section "Overlap (%)" represents the percentage of occurrence of a given sector–pressure within an ecological component, "Months per year" corresponds to the number of months on which pressure occurs, and the sections "Severity per interaction" (severity of the interaction where overlap occurs) and "Standardized value" contains scores pre-established to calculate impact risk (IR). Linkage chains from the framework that are non-existent for the SBS were attributed "No overlap" category.

assessment. Subsequently, a confidence level was assigned to each linkage chain according to the degree of information available, ranging from No Specific Expertize (very low confidence), passing through Specific Expertize, Global Literature, Regional Literature, to Regional Data and Monitoring for the SBS study area (very high confidence). The category assigned to the score depended on the available data. For the fishing sector, for instance, there is data monitoring on a regional level, and regional literature. For harvesting/collecting, on the other hand, because there is little monitoring, we had to rely more on regional literature and specific expert opinion.

Stakeholder validation. The results of the scoping processes were presented to stakeholders in a dedicated workshop. Participants were selected to represent the different human activities considered by the analysis. At the workshop, the results were presented, discussed, and validated with participants. Due to the Sars-Covid-19 pandemic, the stakeholders' workshop had to be carried out online. Thirty-five regional stakeholders were invited, and a total of 29, from diverse backgrounds and institutions attended the workshop. There were 21 representatives from government institutions—tourism, infrastructure, fisheries, mariculture, conservation, water, defense; 4 from NGOs, 1 from the fishing industry, 1 from tourism (economic sector), and 2 researchers.

The meeting started with a presentation of the Mission Atlantic project, followed by an explanation of the methodology and the initial results, including all sectors, pressures, and ecological components, highlighting the main sectors responsible for the most relevant pressures in the SBS. Participants were canvassed to see if there were any missing sectors, pressures, or components that should be included in the assessment. Afterwards, a round of questions and discussion was conducted. The participants were then split into three breakout groups according to their expertise to discuss further the most impactful sectors identified in the risk assessment:

a. Fisheries
b. Land-based industry, wastewater treatment, and coastal infrastructure (grouped due to their common land-based origin)
c. Tourism and recreation

Lastly, the main points debated in the breakout groups were presented in plenary, and further discussions were developed to identify knowledge gaps, and discuss management objectives, demands, and emerging issues.

Data availability

The Scoping data that support the findings of this study and R scripts used are available in/from https://github.com/gandrat/ODEMM. An online, interactive version of the linkage framework is also available at https://rpubs.com/gandra/ODEMM-SBS.

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Author contributions
MS and GS wrote the manuscript. TG was the main responsible for data analysis and figures. MS and MAG are the coordinators of the South Brazilian Shelf case study in the Mission Atlantic Project. DP contributed to method development. All authors contributed to the scoping, scoring, and risk assessment phases, participated in the stakeholders' workshop, contributed to the manuscript revision, and read and approved the submitted version.

Competing interests
The authors declare no competing interests.

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