frontiers
in Ocean Sustainability

TYPE Original Research
PUBLISHED 24 April 2026
DOI 10.3389/focsu.2026.1721755

OPEN ACCESS

EDITED BY
Natalie Prinz,
University of Waikato, New Zealand

REVIEWED BY
Inês Gomes,
Universidade dos Açores, Portugal
Jian Chen,
University College London,
United Kingdom

*CORRESPONDENCE
Ana C. Suhett
✉ anaclarasuhett@gmail.com

RECEIVED 09 October 2025
REVISED 12 March 2026
ACCEPTED 23 March 2026
PUBLISHED 24 April 2026

CITATION
Suhett AC, Ferrari DS, Floeter SR, Liedke AM, Gandra TBR, Rodrigues AR, Pinheiro HT, Macieira RM, Gasparini JL, Giglio VJ, Gasalla MA and Ferreira CEL (2026) Assessing ecosystem risk from human activities in an Atlantic oceanic island. *Front. Ocean Sustain.* 4:1721755. doi: 10.3389/focsu.2026.1721755

Assessing ecosystem risk from human activities in an Atlantic oceanic island

Ana C. Suhett[1,2]*, Débora S. Ferrari[3], Sergio R. Floeter[3], Ana M. Liedke[3], Tiago B. R. Gandra[4], Amanda R. Rodrigues[5], Hudson T. Pinheiro[6], Raphael M. Macieira[7], João L. Gasparini[7,8], Vinicius J. Giglio[9], Maria A. Gasalla[5] and Carlos E. L. Ferreira[2]

[1]Programa de Pós-Graduação em Ecologia, Universidade Federal do Rio de Janeiro, Rio de Janeiro, RJ, Brazil, [2]Reef System Ecology and Conservation Lab, Department of Marine Biology, Universidade Federal Fluminense, Niterói, RJ, Brazil, [3]Marine Macroecology and Biogeography Lab, Universidade Federal de Santa Catarina, Florianópolis, SC, Brazil, [4]Federal Institute of Education, Science and Technology of Rio Grande do Sul (IFRS), Rio Grande, RS, Brazil, [5]Fisheries Ecosystems Laboratory (LabPesq), Oceanographic Institute, University of São Paulo, São Paulo, SP, Brazil, [6]Center for Marine Biology, University of São Paulo, São Sebastião, SP, Brazil, [7]Departamento de Oceanografia e Ecologia, Universidade Federal do Espírito Santo, Vitória, Espírito Santo, Brazil, [8]Instituto de Biodiversidade e Sustentabilidade, Pós-Graduação em Ciências Ambientais e Conservação, Universidade Federal do Rio de Janeiro, Macaé, RJ, Brazil, [9]Universidade Federal do Oeste do Pará, Campus Oriximiná, Santarém, PA, Brazil

The increasing intensification of anthropogenic pressures on remote sites such as oceanic islands highlights the need for integrated approaches to marine management and conservation. Here, we applied an Integrated Ecosystem Assessment (IEA) using Options for Delivering Ecosystem-Based Marine Management (ODEMM) framework to identify and quantify ecological risks associated with five socioeconomic sectors (fishing, military activities, shipping, tourism, and research), at Trindade and Martin Vaz Islands (Southwestern Atlantic). Through a structured expert elicitation process involving stakeholders, we constructed a matrix of linkages between sectors, pressures, and ecological components. Each impact chain (sector → pressure → ecological component) was scored based on spatial overlap, frequency, and degree of impact and combined multiplicatively to estimate Impact Risk (IR). We identified 515 impact chains, with fishing emerging as the dominant risk vector, particularly affecting pelagic fish, shallow reefs, and sedimentary habitats. Network-level proportional connectance analysis revealed high connectivity for military and shipping sectors, though with lower overall risk intensity. Although the creation of marine protected areas (MPAs) has been a step forward, our results reveal that the absence of management and enforcement plans limits their effectiveness. We recommend strengthening fisheries enforcement, expanding MPAs to include critical habitats, and adopting continuous ecological risk assessments as a basis for adaptive management strategies. Our findings demonstrate the applicability of IEA–ODEMM in data-limited, remote systems and provide a transparent, replicable framework to prioritize management actions and strengthen adaptive governance in oceanic island ecosystems facing cumulative human pressures.

KEYWORDS

anthropogenic impacts, ecosystem-based management, Island, marine ecosystems, marine pollution

1 Introduction

1.1 Background: cumulative impacts

Human activities have driven widespread degradation in marine ecosystems, leading to alarming worldwide biodiversity loss (McCauley et al., 2015; Halpern et al., 2020). Unsustainable economic activities are a major factor in this decline, with global change, overfishing, sedimentation, and chemical pollution further accelerating habitat destruction (Manes et al., 2021). Loss of biodiversity means decreased levels of redundancy and increasing reliance on a few key species to fulfill crucial roles to maintain ecosystem services functionally (Villasante et al., 2016). However, a current challenge has been to elucidate the complex trade-offs between economic development and environmental sustainability, particularly the role of economic activities as stressors contributing to biodiversity decline. As human uses of the oceans continue to expand and diversify, it becomes increasingly challenging for managers and policymakers to monitor anthropogenic impacts. Establishing sustainable standards to promote more effective coastal management remains challenging (Blasiak et al., 2014; Halpern et al., 2020).

Socio-ecological assessment methods are inherently complex and require significant expertise. Tools such as the Ocean Health Index and the UN Sustainable Development Goals (SDGs) offer guidelines for evaluating sustainability at a global scale; however, a clear method for translating these broad criteria into smaller contexts, such as specific coastal areas, smaller nations, or even insular environments, is still lacking. This process, referred to as "localization," remains a critical challenge (Delgado-Serrano et al., 2015).

1.2 Integrated ecosystem assessment and risk tools

Integrated Ecosystem Assessment (IEA) is a practical management tool that comprehensively evaluates ecosystems. It utilizes the Ecosystem-Based Management (EBM) approach, incorporates biological and socioeconomic factors, and involves stakeholder participation in the evaluation process. IEA enables assessment of the ecosystem's current condition (Hill et al., 2020). The IEA includes toolkits that can be applied to different target assessments (Levin et al., 2009). Due to its ability to integrate socioeconomic and biological factors, risk assessment is the most frequently demanded strategy while utilizing the IEA (Battista et al., 2017).

This study applies the ODEMM (Options for Delivering Ecosystem-Based Marine Management) framework, which is an IEA tool specifically designed for marine ecosystem risk assessment (Robinson et al., 2014). The ODEMM framework provides a structured approach to evaluate the relationships between human activities (sectors), the pressures they generate, and the ecological components they affect. Risk assessments are a tool for identifying, evaluating, and conveying the potential harm that human activities may pose to the marine environment. It should be noted that different risk assessment methods exist and do not all follow the same framework. The present method semi-quantifies cumulative pressures rather than explicitly modeling interactions among ecosystem components. The process consists of three steps: (i) defining key components for the assessment based on the study area; (ii) developing linkage matrices that link identified sectors, pressures, and ecological components; and (iii) quantifying risk in each impact chain. Assessments and interactions with stakeholders are crucial components of the IEA process. The IEA can be used to assess the probability and effects of a destructive event occurring in sequence, as well as how human activities affect sustainable development objectives (Borja et al., 2016). In the marine realm, IEA has been successfully applied in many environments, mainly those severely impacted, encompassing open-ocean deep-sea biomes (Rodrigues et al., 2023) and shallow waters (Scherer et al., 2024). However, few studies have used remote sites like oceanic islands as research models employing the IEA (Rodrigues et al., 2023; Gomes et al., 2025).

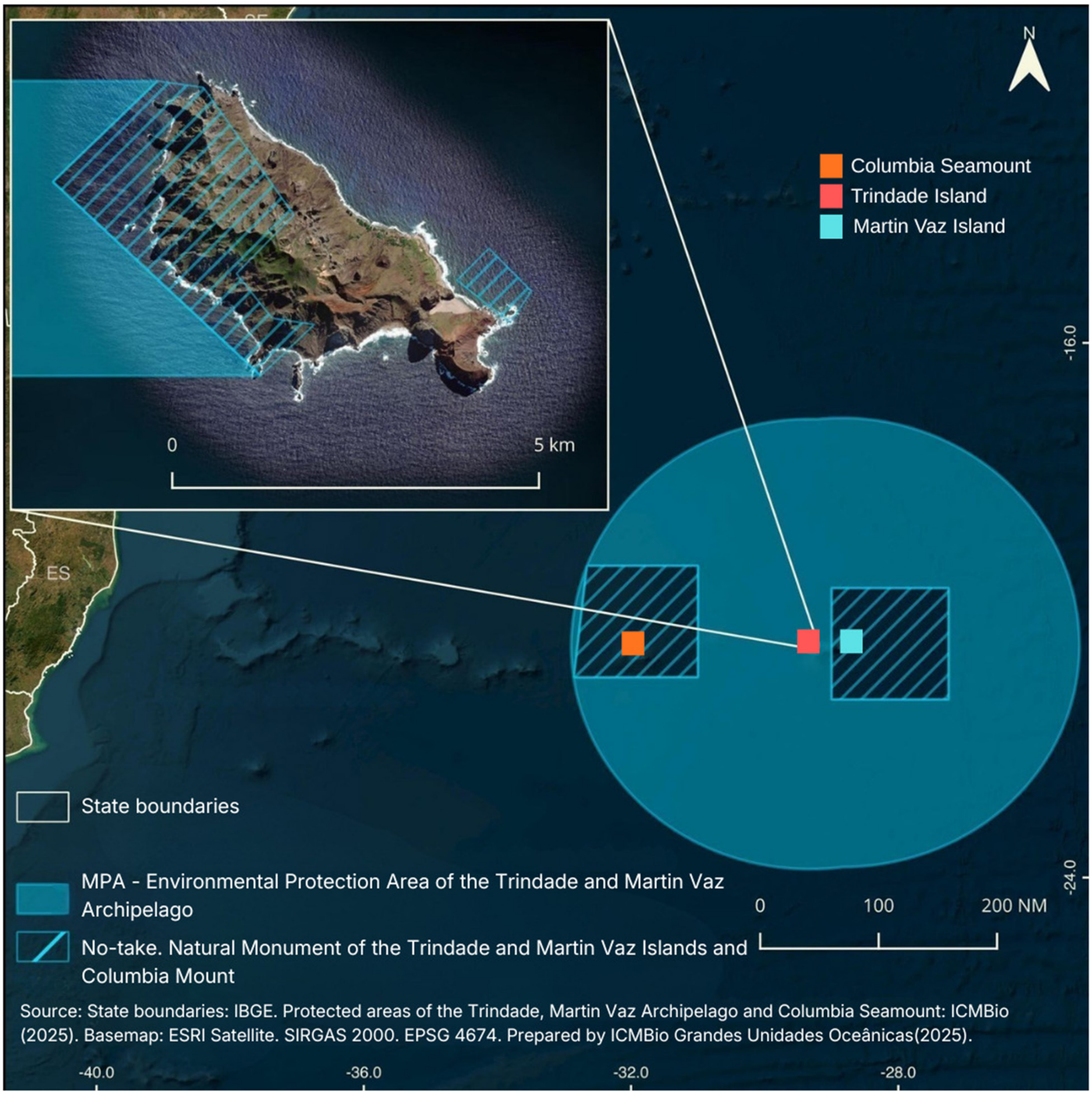
1.3 Oceanic islands under the integrated ecosystem assessment (IEA) framework

Due to their isolation, reefs at oceanic islands generally have a high biomass of meso- and top predators, such as sharks and groupers, compared to coastal areas where human impacts act synergistically (Morais et al., 2017; Pinheiro et al., 2011). However, in the current scenario, even isolated oceanic islands are not safe from overfishing and pollution (Halpern et al., 2015). Due to their high endemism and relatively low species richness and functional redundancy, these reef systems are more vulnerable to short-term impacts than coastal reefs (Morais et al., 2017; Pinheiro et al., 2011; Gasparini and Floeter, 2001). The IEA offers flexibility to address management challenges at various scales, from local coastal areas to global ecosystem evaluations, making it versatile across diverse contexts. It aligns seamlessly with global sustainability initiatives, such as the UN Sustainable Development Goals, facilitating the integration of local and regional policies with overarching global objectives. Moreover, the IEA encourages collaborative governance by involving stakeholders, fostering inclusive decision-making processes that account for ecological, social, and economic dimensions. The objective of this study was to identify and quantify the main anthropogenic pressures affecting the marine ecosystem of Trindade Island using the IEA–ODEMM framework, evaluate their relative risk, and provide management-relevant insights for conservation planning on remote oceanic islands.

2 Materials and methods

2.1 Study area

Trindade Island is a small volcanic island with an area of ~10.4 km^2. It is situated ~1,200 km off the southeastern mainland region of Brazil (Figure 1). The island is part of the Trindade and Martin Vaz Archipelago and represents one of the most isolated oceanic environments under Brazilian jurisdiction. Trindade Island hosts one of the major nesting grounds for the green sea turtle (*Chelonia mydas*) (Almeida et al., 2011), harbors the highest global diversity of calcareous algae (Sissini et al., 2017), and exhibits a high



Source: State boundaries: IBGE. Protected areas of the Trindade, Martin Vaz Archipelago and Columbia Seamount: ICMBio (2025). Basemap: ESRI Satellite. SIRGAS 2000. EPSG 4674. Prepared by ICMBio Grandes Unidades Oceânicas(2025).

FIGURE 1
Location of Trindade Island and the Vitória-Trindade Chain region (area delimited by the red rectangle). ES – Southeastern Brazilian state. Offshore dotted lines indicate the delimitation of the Exclusive Economic Zone and the study site. The area in green corresponds to the two no-take areas on the island: the Trindade Monument and the Parcel das Tartarugas.

level of fish endemism (Pinheiro et al., 2015, 2018). The Trindade Island Oceanographic Post (POIT) was established in 1950 by the Brazilian Navy and has since then provided critical oceanographic information to navigators. Currently, only military personnel and researchers are authorized to stay on the islands, where there is a permanent presence of these two groups. Approximately 200 people per year—military and researchers—visit the island. Trindade Island and surrounding waters are protected through two marine protected areas (MPAs) (Figure 1). The MPAs include the no-take natural monument of the Trindade and Martin Vaz Islands and Columbia Seamount (IUCN Category III) and the partially protected MPA Environmental Protection Area of the Trindade and Martin Vaz Archipelago (IUCN Category V). The area considered for the application of the IEA extends from the coastline to 370 km offshore, corresponding to the limits of the Exclusive Economic Zone (Figure 1).

2.2 Key concepts

2.2.1 Terminology

To ensure conceptual consistency throughout the manuscript and avoid ambiguity among commonly used terms in ecosystem risk assessments, key concepts adopted in this study are defined below according to the IEA–ODEMM framework in Table 1.

TABLE 1 Glossary of key concepts and terminology applied in the IEA–ODEMM assessment.

Sector	A human activity or socio-economic domain capable of generating pressures on the marine environment (e.g., fishing, navigation/shipping, military activities, tourism, research).
Pressure	A mechanism through which a sector exerts stress on ecological components, including physical pressure, extraction, pollution, or noise.
Ecological component	A biological group, habitat, or ecosystem element potentially affected by pressures (e.g., pelagic fish, seabirds, reef habitats, marine mammals).
Impact chain	A complete causal pathway linking a sector to a pressure and an ecological component (sector → pressure → ecological component).
Impact matrix	A structured representation of all potential sector–pressure–component relationships considered in the assessment.
Impact risk (IR)	A semi-quantitative score representing the magnitude of potential impact, calculated as the product of spatial overlaps, frequency of occurrence, and degree of impact following the IEA–ODEMM methodology.
Proportional connectance (PC)	A network-level metric describing the density of realized impact chains relative to the number of all possible linkages within the assessment framework.

These definitions are included to standardize terminology, avoid ambiguity, and facilitate interpretation of the sector–pressure–ecological component relationships analyzed in this study.

2.3 IEA–ODEMM framework

2.3.1 The scoping phase

The Driver-Pressure-State-Impact-Response (DPSIR) method, which systematically arranges the linkages between the three components of the assessment, served as the foundation for this system (Piet et al., 2015; Robinson et al., 2014). The scope phase involved organizing information about Trindade Island by building a comprehensive list of pressures, sectors, and ecological components. To accomplish this, a committee was formed, consisting of nine experts who have in-depth knowledge of the studied system and experts in the IEA approach. Linkage scores were assigned through a structured expert elicitation process. A panel of nine experts, selected at the beginning of the study, evaluated all sector–pressure–ecological component linkages using the predefined criteria described in Table 2 (spatial overlaps, frequency, and degree of impact). Scores were initially attributed individually and subsequently discussed during a validation workshop. When differences occurred, experts clarified their reasoning, and scores were adjusted through moderated discussion to reach a consensual value consistent with the assessment criteria. Expert bias was mitigated through the use of standardized scoring criteria and the separation between stakeholders providing contextual information and experts responsible for score attribution. The selection of pressures, sectors, and ecological components was adapted from previous studies and is presented in Table 3 (e.g., Rodrigues et al., 2023; Scherer et al., 2024).

2.3.2 Scoring phase and impact risk

To identify impact pathways, we developed an impact matrix representing the relationships among economic sectors,

TABLE 2 Criteria for pressure assessment, their respective scores, and definitions.

Criteria	Scores and definitions			
(I) Spatial overlaps Spatial extent of overlaps between a pressure and an ecological component	**No (score = 0):** No overlaps between sector-pressure-ecochar	**Site (0.03):** Sector overlaps an ecological component, but less than 5%	**Local (0.37):** Sector overlaps an ecological component by more than 5% but less than 50%	**Widespread (1.00):** Sector overlaps an ecological component by 50% or more
(II) Frequency Timing of the interaction measured in months per year (i.e., between a given sector, pressure, characteristic pathway)	**Rare (0.08):** Pressure introduced via sector up to 1 month a year	**Occasional (0.33):** Pressure introduced via sector up to 4 months a year	**Common (0.67):** Pressure introduced via sector up to 8 months a year	**Persistent (1.00):** Pressure introduced via sectors throughout an entire year
(III) Degree of impact The severity of an ecological characteristic to a pressure – regardless of extent or frequency	**Low (0.01):** Never causes high levels of mortality or habitat loss/never causes a noticeable effect for the ecosystem component of interest in the area of interaction	**Chronic (0.13):** Impact could have detrimental consequences if it occurs often enough/ at high enough levels	**Acute (1.00):** Severe impact over a short duration. An interaction that kills a large proportion of individuals and causes an immediate change in the ecological component	

All criteria were applied for each impact chain. Data adapted from Robinson et al. (2014).

TABLE 3 Sectors, pressures, and ecological components identified within the study area.

Sectors	Pressures	Ecological components
Fishing	Litter	Shallow rock & reef
Military	Species extraction	Shelf rock & reef
Shipping	Bycatch	Pelagic fish
Research	Contaminants	Shelf sediment
Tourism	Noise	Littoral sediment
	Invasive species	Littoral rock & reef
	Organic matter/NP	Coastal pelagic
	Incidental loss	Shelf pelagic
	Siltation/Smothering	Demersal pelagic
	pH changes	Shallow sediment
	Wave exposure	Oceanic pelagic
	Abrasion	Slope rock & slope sediment
	Electromagnetic (EMF)	Deep sea & demersal Elasmobranchs
	Light pollution	Pelagic elasmo
	Sealing	Seabirds
		Cephalopods
		Reptiles
		Deep-sea fish
		Marine mammals
		Deep sea rock & reef
		Deep sea sediment

human activities, the pressures they generate, and the ecological components affected. Each cell of the matrix corresponds to a sector–pressure–ecological component linkage, defined as an impact chain (Scherer et al., 2024). For example, the shipping sector may generate the pressure *noise*, potentially affecting marine mammals.

During the pressure assessment phase, each connection was evaluated to estimate the magnitude of its potential effect and the risks associated with different sector–pressure–ecological component combinations (Robinson et al., 2014). Impact Risk (IR) was calculated using the scores assigned during this assessment, based on the product of Overlaps Score, Frequency Score, and Degree of Impact (DoI). IR represents the probability of a negative environmental effect resulting from a given sector or pressure.

Linkage scores were assigned through a structured expert elicitation process following the IEA–ODEMM framework. Each expert independently evaluated all sector–pressure–ecological component combinations using predefined criteria (spatial overlap, frequency, and degree of impact), ensuring consistency with the scoring scales described in Table 2.

Individual scoring was conducted prior to group discussion to minimize social bias and anchoring effects. Subsequently, a facilitated workshop was held to review discrepancies and clarify interpretations of the criteria. Discussions were moderated by the lead author to ensure equal participation and adherence to the methodological protocol.

When consensus was achieved, the agreed value was recorded as the final score. When disagreement persisted after discussion, the final score was determined as the median of the individual scores. The median was selected because it is robust to extreme values and appropriate for semi-quantitative ordinal scales, thereby maintaining coherence with the defined scoring system. This procedure ensured that all linkage scores were derived using a single, consistent rule. No weighting was applied to individual experts, and all participants contributed equally to the final scores.

$$IR = Overlaps\ Score\ x\ Frequency\ Score\ x\ Degree\ of\ Impact\ Score$$

The connectance values were determined by dividing the total linkages in the ecosystem region by the number of linkages associated with each sector, pressure type, and ecological component and expressed as a percentage (Pedreschi et al., 2019). This indicator looks at the connectance of the evaluated connection chains rather than the intensity or potential key pathways (Pedreschi et al., 2019).

Each impact chain was evaluated through a confidence classification based on the type and robustness of the information supporting the relationship between pressures and ecological components. Links supported by consistent or long-term regional monitoring data were assigned higher confidence levels, as these sources provide stronger empirical evidence and reduce uncertainty regarding the ecological response to the associated pressure. In contrast, lower confidence levels were attributed to relationships supported by limited information, particularly when available studies did not clearly demonstrate causal effects.

The four-level confidence framework adopted in this study serves as a descriptive indicator of the strength of the evidence underlying each impact chain. Its purpose is to qualitatively characterize the reliability of the available information rather than to provide a quantitative measure. Therefore, these confidence levels were not incorporated into uncertainty propagation, as they represent the quality and type of supporting evidence rather than statistical variability in the analysis.

2.3.3 Stakeholder and expert elicitation process

A workshop with stakeholders was conducted to support the impact and risk scoring process. Nine experts participated, representing three main stakeholder categories: academic researchers with expertise in marine ecology and ecosystem services ($n = 5$), environmental managers ($n = 2$), and operational stakeholders associated with on-island activities, including the Brazilian Navy ($n = 2$). Participants were selected based on their professional experience, long-term engagement with Trindade Island, and familiarity with local socio-ecological dynamics. Individual scores for sector–pressure–ecosystem component linkages were first assigned independently following the IEA–ODEMM framework to minimize group influence and subsequently discussed collectively to clarify assumptions and resolve discrepancies. Final scores were derived using a consensus-based approach, adopting the sum of individual scores when disagreement persisted. Potential conflicts of interest related to the military presence on the island were managed through balanced stakeholder representation, anonymous individual scoring prior to group discussion, and moderation by the research team; military participants contributed operational knowledge but did not influence final scoring decisions. Formal ethical approval was not required, as no personal data were collected, participation was voluntary, and all inputs were aggregated and anonymized in accordance with best research practices and data protection standards.

The analyses were adapted from Pedreschi et al. (2019) and are available on https://github.com/gandrat/ODEMM.git. To improve the visualization between the links of the impact chain, a Sankey diagram was created using the R packages *Igraph* (Csardi and Nepusz, 2006) and *Ggplot2* (Wickham, 2016). Maps were created using the software QGIS (QGIS Development Team, 2025).

3 Results

3.1 Network size and composition

We identified a total of 515 potential impact chains connecting five sectors (fishing, military, research, tourism, and shipping), 15 pressures, and 23 ecological components (Figure 2 and Supplementary Table S1).

3.2 Proportional connectance and linkages

The sectors with the most pronounced overlapping effects were fishing and shipping (Supplementary Figure S1). Litter, species extraction, and bycatch are all common pressures associated with fishing, whether it is for recreational or industrial purposes. Additionally, at the site and local level, activities from the military and research sectors were stronger. The degree of impact was low in most of the analyzed impact chains. The fishing, shipping, and military sectors presented two impact classifications: low and chronic. Shipping, however, had fewer linkages with the bulk of ecological components, with a critical influence on litter production (Supplementary Figure S2). The fisheries sector had the highest number of ecological components exposed to persistent pressures (Supplementary Figure S3).

3.3 Impact risk (IR)

Fishing posed the highest risk (IR total - 4.42—Supplementary Table S2). Despite this score, the sectors with the largest proportional connectivity, both with 29.1%, were the military and shipping (Figure 3). When compared to fishing, the risk effect for the military and shipping was comparatively lower. Military and shipping sectors had similar scores regarding the overall number of linkages, the number of impacted ecological components, and pressures (Figure 3). Pelagic fish, shallow rock and reef, littoral sediment, and shelf sediment were the ecological components with the highest risk based on impact risk.

3.4 Confidence level

The majority of impacts had a moderate degree of confidence, i.e., supported by the literature (Figure 4). The results were consistent with expert expectations expressed during the validation workshop of the analyzed impact chains. Neritic areas, among all, were in the top ranking of the discussions. Among the impact risk chain, fishing was considered the most significant. Bycatch has an important effect on seabirds (Bugoni et al., 2008), sharks (Pinheiro et al., 2010). The analysis indicated the need for further research specifically addressing fishing practices.

4 Discussion

4.1 Key risk drivers

This study employed an integrated ecosystem approach to evaluate the impact risk associated with five predefined sectors contributing to cumulative impacts on Trindade Island: fishing, shipping, military activities, tourism, and scientific research. The combination of the Integrated Ecosystem Assessment (IEA) and Options for Delivering Ecosystem-Based Marine Management (ODEMM) frameworks proved effective for comparing sectoral impacts, offering flexibility and adaptability to data-scarce, remote environments. Holistic identification and semi-quantitative risk assessment highlighted fishing as the dominant sector in terms of environmental impact. The high risk was attributed to both small-scale (hook-and-line and spearfishing along rocky reefs) and industrial fishing activities (longline fishing near the island, Martin Vaz reefs, and across the Vitória-Trindade Chain). The lack of fisheries monitoring exacerbates these impacts. Similar findings have been reported in other oceanic contexts, such as the Celtic Sea (Pedreschi et al., 2019), Southern Africa (Skein et al., 2022), and Ascension Island (Ferrari et al., 2023), where recreational fishing contributed to biodiversity declines (Guabiroba et al., 2020; Hardman et al., 2022; Ferrari et al., 2024).

Military activities represent a relevant proportion of pressure linkages in the impact network in Trindade Island, particularly due to their persistent presence and overlaps with ecological components. The regular transit of military personnel contributes to pressures such as noise pollution, trampling of coastal habitats, and infrastructure development. Although the impact risk score of military activities was lower than fishing, the widespread nature of their interactions with ecological components suggests the potential for cumulative or synergistic impacts. These findings highlight the importance of integrating military personnel as key stakeholders into management processes and developing guidelines that minimize ecological pressure.

Shipping activities, including vessel traffic and maritime transport, emerged as a highly connected sector, with influence on pressures such as marine litter and underwater noise. The accumulation of plastics and other debris on Trindade Island beaches (Andrades et al., 2018) and reefs (Pinheiro et al., 2023) is likely intensified by maritime operations, which contribute through waste discharge. Given the intensification of shipping traffic globally (Deng and Mi, 2023), it is essential that management

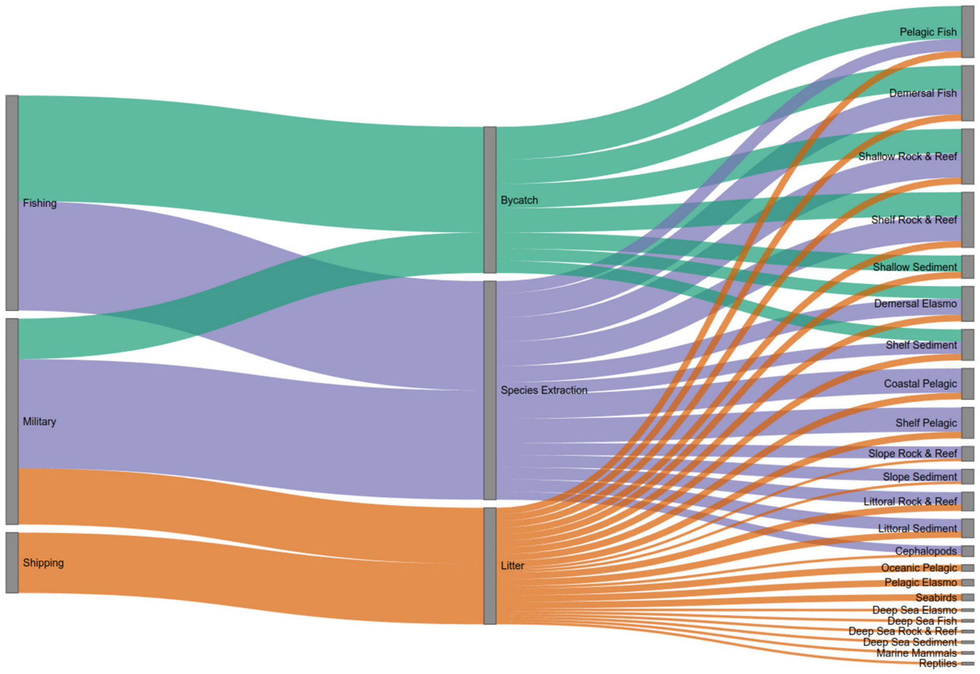


FIGURE 2
Sankey graphic showing linkages between three principal sectors, pressures, and ecological components. The three sectors were selected because they exhibited the highest connectivity and impact risk. The bars show how much of a proportional connectance. The impact chains are arranged so that the bars are ranked in descending order. The line widths in the diagram correspond to the Impact Risk Score, calculated based on the results of overlaps, frequency, and degree of impact.

initiatives incorporate strategies to monitor and mitigate shipping-related impacts, including waste management protocols, speed regulations, and restrictions in ecologically vulnerable zones.

Risk scores revealed that pelagic fish, shallow rocky reefs, littoral sediments, and shelf sediments were among the most impacted ecological components, indicating broad exposure to multiple persistent pressures. These components have relevant roles in ecosystem functioning, including nutrient cycling, trophic relationships, and key habitats (Wolfe et al., 2021). Despite their importance, current conservation strategies overlook their protection, especially in deeper or soft-bottom areas such as shelf sediments, which are typically excluded from no-take zones. Management efforts should prioritize these high-risk components by incorporating habitat-specific measures that address cumulative threats such as litter deposition, species extraction, and habitat alteration across both benthic and pelagic realms.

4.2 Management implications

Although the establishment of the Trindade mosaic of MPAs in 2018 represents an important conservation advance, its effectiveness remains limited. Critical shallow reef habitats of Trindade Island were excluded from protection, while vast open-ocean zones of comparatively lower biodiversity were prioritized (Giglio et al., 2018). Furthermore, most Brazilian MPAs still lack comprehensive management plans, enforcement capabilities, and performance metrics (Patrizzi et al., 2025), raising concerns about their real conservation outcomes. These findings reinforce that the mere creation of MPAs is insufficient to ensure effectiveness without effective management implementation and long-term monitoring. The success of MPAs is strongly linked to their active enforcement and duration of protection (Ferrari et al., 2023; Tardin et al., 2025). To strengthen management on Trindade Island, we recommend the following actions: (1) Developing participatory management plans involving local stakeholders (fisheries sector, military personnel, researchers, environmental managers); (2) Implementing continuous fisheries monitoring programs, supported by technologies such as drones, satellite imagery, and programs like PREPS (National Program for Satellite Tracking of Fishing Vessels); (3) Expanding protected areas to include critical shallow reef habitats currently left outside conservation boundaries; and (4) Establishing clear performance indicators to regularly assess MPA effectiveness. To enhance the operational relevance of our findings, we explicitly linked the highest-risk chains and most exposed ecological components to concrete management actions, their expected mechanisms of risk reduction, and measurable indicators for evaluation (Table 4). This mapping illustrates how the cumulative risk assessment can directly inform enforcement priorities, MPA design, and monitoring strategies.

The scientific community has increasingly debated the design of recent MPAs in the region. While open-ocean zones were prioritized, nearshore habitats hosting higher species richness and endemism remain unprotected. Moreover, most pressures, such as those associated with fishing, extend across the entire Exclusive Economic Zone of Trindade Island. These results highlight the crucial role of ecological connectivity, particularly

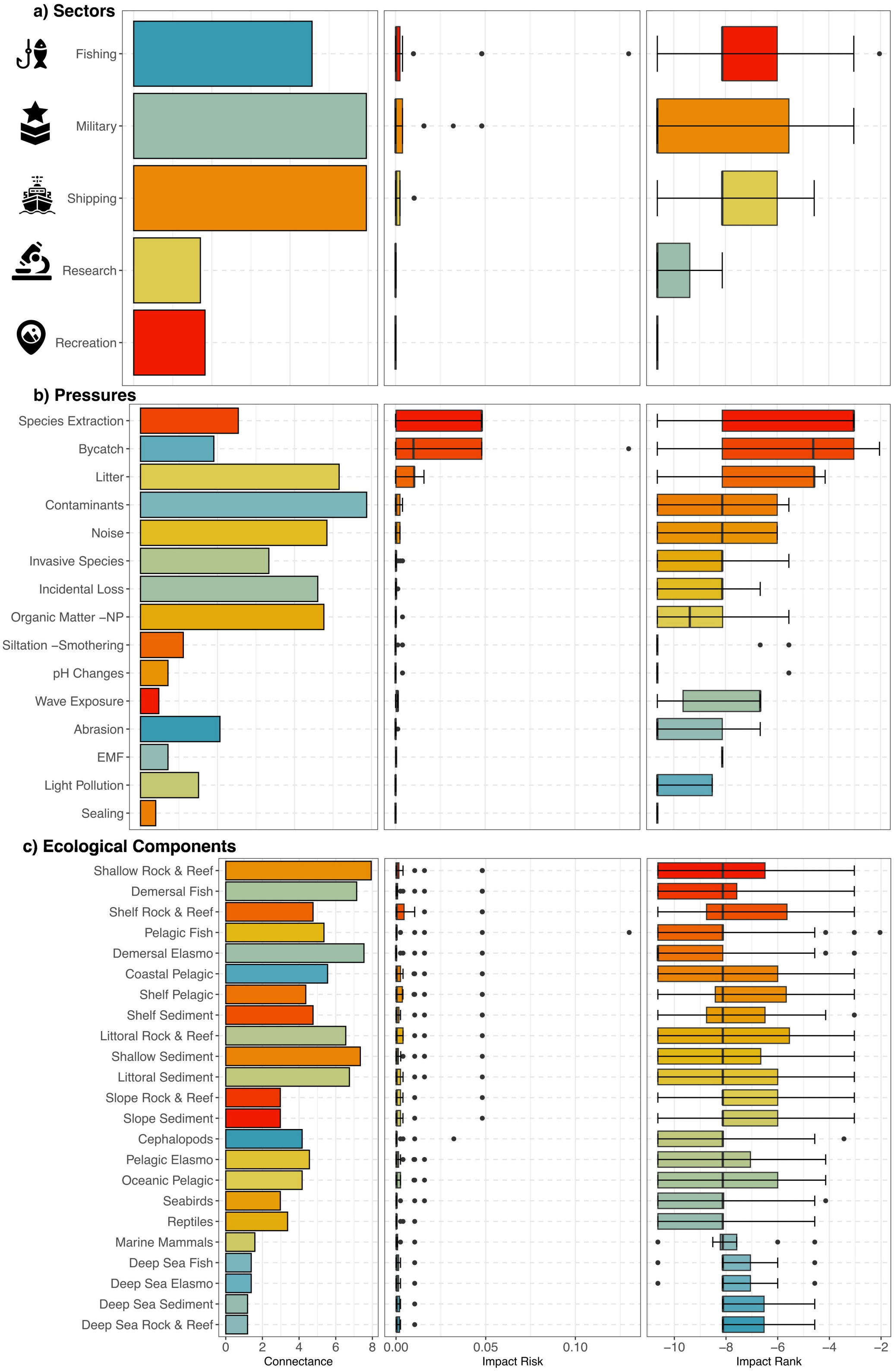


FIGURE 3
Impact risk index per ecological components, pressures and sectors. **(A)** Sectors, **(B)** Pressures, **(C)** Ecological Components. *The black dots are outliers*. Elasmo, elasmobranch. EMF, Electromagnetic fields.

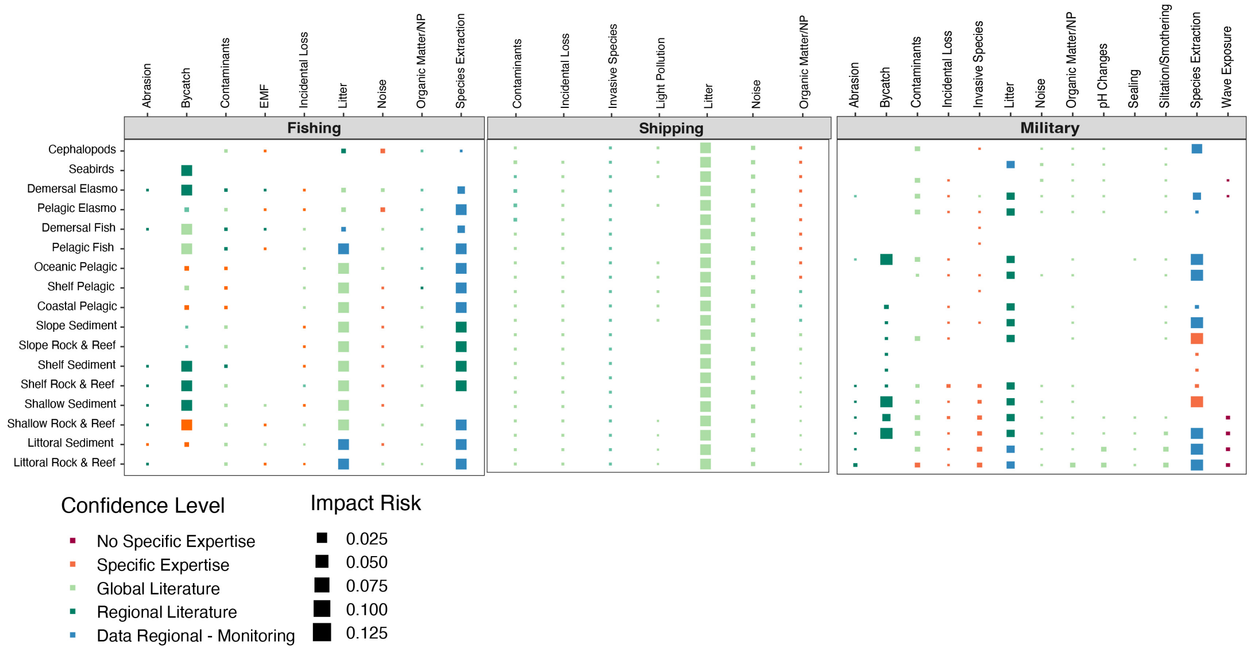


FIGURE 4
Distribution of cumulative impact risk across economic sectors according to the confidence level of the supporting evidence. Bars represent the total summed impact risk for each sector (fishing, military activities, shipping, research, and tourism/recreation), while colors indicate the type of evidence supporting each sector–pressure–ecological component linkage: regional monitoring data, regional literature, global literature, specific expertise, and no specific expertise. This classification reflects the robustness of the information used to evaluate each impact chain.

TABLE 4 Management actions linked to top-ranked risk chains and ecological components identified in the IEA-ODEMM assessment of Trindade Island.

High-risk sector–pressure–ecological component	Management action	Expected mechanism of risk reduction	Measurable indicator for evaluation
Fishing – Bycatch – Seabirds (e.g., *Pterodroma arminjoniana*, *Fregata ariel*)	Temporal restrictions for fishing; and modification of fishing gears	Reduction of incidental capture during peak foraging and breeding periods	Bycatch rate (individuals per fishing effort); seabird mortality records
Fishing – Bycatch – Sea turtles (*Chelonia mydas*, *Dermochelys coriacea*)	Mandatory bycatch mitigation measurements; and enhanced fisheries surveillance	Physical reduction of sea turtle interactions with fishing gear	Number of sea turtle bycatch events; strandings associated with fishing
Fishing – Species extraction – Reef fish (shallow rock and reef habitats)	Strengthening fisheries enforcement and monitoring programs	Decrease in extraction pressure and recovery of exploited populations	Fish biomass and size structure; number of enforcement actions
Navigation / Shipping – Litter – Coastal and pelagic habitats	Implementation of waste management protocols and vessel regulation	Reduction of marine debris input from maritime activities	Beach and reef litter density (items·m^2); plastic composition surveys
Navigation / Shipping – Noise – Marine mammals	Regulation of vessel speed and navigation routes in sensitive areas	Decrease in chronic acoustic pressure and collision risk	Underwater noise levels (dB); marine mammal sighting and interaction records
Military activities – Trampling and infrastructure – Coastal habitats	Development of environmental guidelines and training for military personnel	Reduction of physical pressure and habitat degradation	Area of disturbed habitat; compliance with environmental protocols
Multiple sectors – Cumulative pressures – Pelagic fish	Expansion of MPAs to include critical pelagic habitats	Spatial reduction of Overlaps pressures across trophic levels	Pelagic fish abundance and diversity indices
Multiple sectors – Cumulative pressures – Littoral and shelf sediments	Inclusion of soft-bottom habitats in MPAs	Protection of benthic habitats from chronic pressure	Benthic diversity indices; sediment condition metrics

MPAs, marine protected areas.

between Trindade, Martin Vaz, and the Vitória-Trindade Chain (Simon et al., 2021). Historical data reveal that Trindade connectivity with coastal habitats has been shaped by sea-level fluctuations, with the Vitória-Trindade Chain functioning as stepping-stones for marine organisms (Pinheiro et al., 2018; Macieira et al., 2015). The high endemism and reduced genetic diversity found in local populations further stress the need to prioritize management strategies based on maintaining connectivity and safeguarding evolutionary processes. Although impact assessments primarily identify current pressures, they also offer strategic insights for guiding management interventions and evaluating potential future developments (Copping, 2020).

4.4 Limitations and future work

While this study successfully identified the main pressures affecting Trindade Island, it is constrained by the absence of long-term temporal analyses and explicit modeling of cumulative impacts. Future initiatives should incorporate the spatial modeling of pressures using geographic information systems and the analysis of cumulative and synergistic impacts. Such data should be obtained through remote environmental monitoring programs to detect real-time changes and trends. We identified key anthropogenic pressures, the associated pressures they generate, and the ecological components affected, providing a basis to evaluate and implement targeted mitigation strategies. Advancing into the next phases of the ODEMM framework such as vulnerability assessments and evaluations of ecosystem service impacts (Levin et al., 2009; Knights et al., 2015) will be crucial for informing adaptive management practices. By applying an integrated ecosystem assessment approach, this study prioritized human-induced risks affecting Trindade Island marine ecosystems, highlighting fishing as the dominant threat, followed by military activities and maritime transport. Strengthening environmental governance through effective enforcement, adaptive MPA design, participatory decision-making, and cross-sectoral integration is vital for ensuring long-term ecological resilience.

Regional approaches complementing local management efforts particularly recognizing the importance of connectivity across the Vitória-Trindade Chain will be essential to conciliate biodiversity conservation, ecosystem functionality and human uses of the island. In a context of increasing anthropogenic pressures and climate change, embracing integrated, science-based management frameworks such as IEA-ODEMM is critical for guiding future public policies and ensuring the sustainable conservation of Brazilian oceanic islands.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

AS: Methodology, Formal analysis, Writing – original draft, Software, Data curation, Visualization, Investigation, Validation, Resources, Project administration, Supervision, Funding acquisition, Writing – review & editing, Conceptualization. DF: Formal analysis, Writing – review & editing, Data curation, Conceptualization. SF: Funding acquisition, Resources, Data curation, Writing – review & editing, Conceptualization. AL: Writing – review & editing, Conceptualization. TG: Writing – review & editing, Methodology, Formal analysis. AR: Conceptualization, Data curation, Writing – review & editing. HP: Data curation, Conceptualization, Writing – review & editing, Investigation. RM: Conceptualization, Writing – review & editing, Data curation. JG: Data curation, Writing – review & editing, Conceptualization. VJG: Formal analysis, Data curation, Writing – review & editing, Conceptualization. MG: Methodology, Software, Investigation, Validation, Resources, Project administration, Supervision, Funding acquisition, Writing – review & editing, Conceptualization. CF: Validation, Data curation, Visualization, Formal analysis, Supervision, Writing – review & editing, Funding acquisition, Conceptualization.

Funding

The author(s) declared that financial support was received for this work and/or its publication. This study was funded by Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), through the Long Term Ecological Research in Brazilian Oceanic Islands (PELD-ILOC) (grant 441327/2020-6 -CELF/PI). AS was funded by CNPq through a MSc scholarship. HP was funded by Fundação de Amparo à Pesquisa do Estado de São Paulo (grant 2019/24215-2 and 2021/07039-6). DF, AR, AL, MG, TG, and SF acknowledge the support received from Project MISSION ATLANTIC -the European Union's Horizon 2020 Research and Innovation (grant #862428). MG, SF, HP and CF received productivity grants from Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq-Brazil; 310906/2023-7 and 310219/2023-0, respectively).

Acknowledgments

We are grateful to the Projeto Ecológico de Longa Duração das Ilhas Oceânicas Brasileiras (PELD-ILOC), the Brazilian Navy (PROTRINDADE), and the Mission Atlantic Project. DF, AR, AL, MG, TG, and SF received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 862428 (Mission Atlantic - SOMAR Group). This output reflects only the author's view, and the Research Executive Agency (REA) cannot be held responsible for any use that may be made of the information contained therein.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that generative AI was not used in the creation of this manuscript.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/focsu.2026.1721755/full#supplementary-material

SUPPLEMENTARY FIGURE S1
Spatial extent of overlaps between a pressure and an ecological component. The values for each classification are detailed in Table 1. S, Site; W, Widespread, and L, Local.

SUPPLEMENTARY FIGURE S2
Frequency of impact. Timing of the interaction is measured in months per year (i.e., between a given sector, pressure, and characteristic pathway). The values for each classification are detailed in Table 1. R, Rare; O, Occasional; C, Common; P, Persistent.

SUPPLEMENTARY FIGURE S3
Degree of impact: generic sensitivity of an ecological characteristic to a pressure regardless of extent or frequency. The values for each classification are detailed in Table 1. L, Low; C, Chronic.

SUPPLEMENTARY TABLE S1
All links created for Ilha da Trindade in the linkage framework phase.

SUPPLEMENTARY TABLE S2
Rankings of descriptors identified by the summed (IR) and their proportional connectance (PC) and sum and average risk scores for sectors. Eco Com, Ecological Components.

References

Almeida, A. P., Moreira, L. M. P., Bruno, S. C., Thomé, J. C. A., Martins, A. S., Bolten, A. B., et al. (2011). Green turtle nesting on Trindade Island, Brazil: abundance, trends, and biometrics. *Endang. Species Res.* 14, 193–201. doi: 10.3354/esr00357

Andrades, R., Santos, R. G., Joyeux, J.-C., Chelazzi, D., Cincinelli, A., and Giarrizzo, T. (2018). Marine debris in Trindade Island, a remote island of the South Atlantic. *Mar. Pollut. Bull.* 137, 180–184. doi: 10.1016/j.marpolbul.2018.10.003

Battista, W., Karr, K., Sarto, N., and Fujita, R. (2017). Comprehensive Assessment of Risk to Ecosystems (CARE): a cumulative ecosystem risk assessment tool. *Fish. Res.* 185, 115–129. doi: 10.1016/j.fishres.2016.09.017

Blasiak, R., Anderson, J. L., Bridgewater, P., Furuya, K., Halpern, B. S., Kurokura, H., et al. (2014). Paradigms of sustainable ocean management. *Mar. Policy* 48, 206–211. doi: 10.1016/j.marpol.2014.03.021

Borja, A., Elliott, M., Andersen, J. H., Cardoso, A. C., Carstensen, J., Ferreira, J. G., et al. (2016). Overview of integrative assessment of marine systems: the ecosystem approach in practice. *Front. Mar. Sci.* 3:20. doi: 10.3389/fmars.2016.00020

Bugoni, L., Neves, T. S., Leite, Jr. N. O., Carvalho, D., Sales, G., Furness, R. W., et al. (2008). Seabird bycatch in the Brazilian pelagic longline fishery and a review of capture rates in the southwestern Atlantic Ocean. *Endanger. Species Res.* 5, 137–147. doi: 10.3354/esr00115

Copping, A. E. (2020). "Marine renewable energy: environmental effects and monitoring strategies," in OES-Environmental 2020 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World, eds. A. E. Copping and L. G. Hemery (Report for Ocean Energy Systems (OES)), 18–26. doi: 10.2172/1632880

Csardi, G., and Nepusz, T. (2006). The igraph software package for complex network research. *InterJournal Complex Systems* 1695. https://igraph.org

Delgado-Serrano, M. M., Oteros-Rozas, E., Vanwildemeersch, P., Ortíz-Guerrero, C., London, S., and Escalante, R. (2015). Local perceptions on social-ecological dynamics in Latin America in three community-based natural resource management systems. *Ecol. Soc.* 20:24. doi: 10.5751/ES-07965-200424

Deng, S., and Mi, Z. (2023). A review on carbon emissions of global shippingl. *Mar. Dev.* 1:4. doi: 10.1007/s44312-023-00001-2

Ferrari, D. S., Floeter, S. R., Leprieur, F., and Quimbayo, J. P. (2023). A trait-based approach to marine island biogeography. *J. Biogeogr.* 50, 528–538. doi: 10.1111/jbi.14549

Ferrari, D. S., Nunes, L. T., Jones, K. L., Ferreira, C. E. L., and Floeter, S. R. (2024). Thermal tolerance as a driver of reef fish community structure at the isolated tropical Mid-Atlantic Ridge Islands. *Mar. Environ. Res.* 199:106611. doi: 10.1016/j.marenvres.2024.106611

Gasparini, J. L., and Floeter, S. R. (2001). The shore fishes of Trindade Island, western South Atlantic. *J. Nat. Hist.* 35, 1639–1656. doi: 10.1080/002229301317092379

Giglio, V. J., Pinheiro, H. T., Bender, M. G., Bonaldo, R. M., Joyeux, J. C., Ferreira, C. E. L., et al. (2018). Large and remote marine protected areas in the South Atlantic Ocean are flawed and raise concerns: comments on Soares and Lucas (2018). *Mar. Policy* 96, 13–17. doi: 10.1016/j.marpol.2018.07.017

Gomes, I., Serrano, D., Pham, C., and Afonso, P. (2025). Remote but not isolated: an integrated ecosystem assessment across the marine ecosystem of the Azores. *Ecol. Indic.* 181:114409. doi: 10.1016/j.ecolind.2025.114409

Guabiroba, H. C., Santos, M. E. A., Pinheiro, H. T., Simon, T., Pimentel, C. R., Vilar, C. C., et al. (2020). Trends in recreational fisheries and reef fish community structure indicate decline in target species population in an isolated tropical oceanic island. *Ocean Coast. Manage.* 191:105194. doi: 10.1016/j.ocecoaman.2020.105194

Halpern, B. S., Frazier, M., Potapenko, J., Casey, K. S., Koenig, K., Longo, C., et al. (2015). Spatial and temporal changes in cumulative human impacts on the world's ocean. *Nat. Commun.* 6:7615. doi: 10.1038/ncomms8615

Halpern, B. S., Kroodsma, D. A., Selkoe, K. A., Brown, C. J., Longo, C., Lowndes, J. S., et al. (2020). Recent pace of change in human impact on the world's ocean. *Sci. Rep.* 10:13406. doi: 10.1038/s41598-019-47201-9

Hardman, E., Thomas, H. L., Baum, D., Clingham, E., Hobbs, R., Stamford, T., et al. (2022). Integrated marine management in the United Kingdom overseas territories. *Front. Mar. Sci.* 8:643729. doi: 10.3389/fmars.2021.643729

Hill, N. A., et al. (2020). Cumulative impacts across marine ecosystems. *Glob. Change Biol.* 26, 289–302.

Knights, A. M., et al. (2015). A risk-based approach to cumulative effects assessment. *ICES J. Mar. Sci.* 72, 107–117. doi: 10.1093/icesjms/fsu167

Levin, P. S., Fogarty, M. J., Murawski, S. A., and Fluharty, D. (2009). Integrated ecosystem assessments: developing the scientific basis for ecosystem-based management of the ocean. *PLoS Biol.* 7:e1000014. doi: 10.1371/journal.pbio.1000014

Macieira, R. M., Simon, T., Pimentel, C. R., and Joyeux, J. C. (2015). Isolation and speciation of tidepool fishes as a consequence of Quaternary sea-level fluctuations. *Environ. Biol. Fish.* 98, 385–393. doi: 10.1007/s10641-014-0269-0

Manes, S., Costello, M. J., Beckett, H., Debnath, A., Devenish-Nelson, E., Grey E.-A., et al. (2021). Endemism increases species' climate change risk in areas of global biodiversity importance. *Biol. Conserv.* 257:109070. doi: 10.1016/j.biocon.2021.109070

McCauley, D. J., Pinsky, M. L., Palumbi, S. R., Estes, J. A., Joyce, F. H., Warner, R. R., et al. (2015). Marine defaunation: animal loss in the global ocean. *Science* 347:1255641. doi: 10.1126/science.1255641

Morais, R. A., et al. (2017). Food-web structure of oceanic reefs. *Coral Reefs* 36, 779–790.

Patrizzi, N. S., Giglio, V. J., Rolim, F., and Barros, F. (2025). Beyond area-based targets: emerging trends in coastal and marine protection in Brazil. *Ocean Coast. Manag.* 261:107509. doi: 10.1016/j.ocecoaman.2024.107509

Pedreschi, D., Reid, D. G., Gerritsen, H., van der Meer, Y., del Mar Otero, M., Smelt, I., et al. (2019). Integrated ecosystem analysis in Irish waters: providing the context for ecosystem-based fisheries management. *Fish. Res.* 209, 218–229. doi: 10.1016/j.fishres.2018.09.023

Piet, G. J., et al. (2015). An integrated ecosystem assessment framework. *ICES J. Mar. Sci.* 72, 1–12.

Pinheiro HT, Ferreira CEL, Joyeux J-C, Santos RG, and Horta PA (2011). Reef fish structure and distribution in a south-western Atlantic Ocean tropical island. *J. Fish Biol.* 79:1984–2006. doi: 10.1111/j.1095-8649.2011.03138.x

Pinheiro HT, Mazzei E, Moura RL, Amado-Filho GM, Carvalho-Filho A, Braga AC, Costa PAS, Ferreira BP., et al. (2015) Fish biodiversity of the Vitória-Trindade seamount chain, southwestern Atlantic: an updated database. *PLoS ONE* 10:e0118180. doi: 10.1371/journal.pone.0118180

Pinheiro HT., Martins AS., and Gasparini JL (2010) Impact of commercial fishing on Trindade Island and Martin Vaz Archipelago, Brazil: characteristics, conservation status of the species involved and prospects for preservation. *Braz. Arch. Biol. Technol.* 53, 1417–1423. doi: 10.1590/S1516-89132010000600018

Pinheiro, H.T., Rocha, L. A., Macieira, R. M., Carvalho-Filho, A., Anderson, A. B., Bender, M. G., et al. (2018). South-western Atlantic reef fishes: zoogeographic patterns and ecological drivers reveal a secondary biodiversity center in the Atlantic Ocean. *Divers. Distrib.* 24, 951–965. doi: 10.1111/ddi.12729

Pinheiro, H. T., MacDonald, C., Santos, R. G., Ali, R., Bobat, A., Cresswell, B. J., et al. (2023). Plastic pollution on the world's coral reefs. *Nature* 619, 311–316. doi: 10.1038/s41586-023-06368-0

QGIS Development Team (2025). *QGIS Geographic Information System*. Open Source Geospatial Foundation Project. Available online at: http://qgis.osgeo.org

Robinson, L. A., Culhane, F. E., Baulcomb, C., Bloomfield, H., Boehnke-Henrichs, A., Breen, P., et al. (2014). *Towards Delivering Ecosystem-based Marine Management: The ODEMM Approach*. ODEMM Project Deliverable 17, European Commission.

Robinson, L. A., Culhane, F. E., Baulcomb, C., Bloomfield, H., Boehnke-Henrichs, A., Breen, P., et al. (2014). Towards delivering ecosystem-based marine management: the ODEMM approach. *Deliverable* 17, 1–96.

Rodrigues, A. R., Floeter, S. R., Gomes, V., Ferrari, D. S., Giglio, V. J., Silva, F. C., et al. (2023). Integrated ecosystem assessment around islands of the tropical South Mid Atlantic Ridge. *Front. Mar. Sci.* 10:1001676. doi: 10.3389/fmars.2023.1001676

Scherer, M. E., Sardinha, G. D., Souza, V., Gandra, T. B. R., Floeter, S. R., Liedke, A. M., et al. (2024). Under pressure: an integrated assessment of human activities and their potential impact on the ecosystem components of the Southern Brazilian continental shelf. *npj Ocean Sustain.* 3:9. doi: 10.21203/rs.3.rs-2661929/v1

Simon, T., Pinheiro, H. T., Santos, S., Macieira, R. M., Ferreira, Y. S. S., Bernardi, G., et al. (2021). Comparative phylogeography of reef fishes indicates seamounts as stepping stones for dispersal and diversification. *Coral Reefs* 40, 1121–1135. doi: 10.1007/s00338-021-02178-8

Sissini, M. N., Oliveira, M. C., Bastos, E. O., Amado-Filho, G. M., and Bahia, R. G. (2017). "Macroalgas da Ilha da Trindade," in *PROTRINDADE:10 anos pesquisa* (Brasília: SECIRM), 99–108.

Skein, L., Sink, K. J., Majiedt, P. A., van der Bank, M. G., Smit, K. P., and Shannon, L. J. (2022). Scoping an integrated ecosystem assessment for South Africa. *Front. Mar. Sci.* 9:975328. doi: 10.3389/fmars.2022.975328

Tardin, R., Maricato, G., Kiszka, J. J., Cantor, M., Maciel, I., Melo-Santos, G., et al. (2025). Optimistic climate mitigation scenario halves projected range loss in a neotropical dolphin. *Ocean Coast. Manage.* 269:107800. doi: 10.1016/j.ocecoaman.2025.107800

Villasante, S., Guyader, O., Pita, C., Frangoudes, K., Macho, G., Moreno, A., et al. (2016). *Social Transformation of Marine Social-ecological Systems.* ICES Science Fund Report. International Council for the Exploration of the Sea (ICES).

Wickham, H. (2016). *ggplot2: Elegant Graphics for Data Analysis.* New York, NY: Springer-Verlag. Available online at: https://ggplot2.tidyverse.org.

Wolfe, K., Anthony, K., Babcock, R. C., Bay, L., Bourne, D. G., Burrows, D., et al. (2021). Priority species to support the functional integrity of coral reefs. *Oceanogr. Mar. Biol.* 59, 1–47. doi: 10.1201/9780429351495