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Research article

Networks of interactions between Marine Protected Areas and their effects on the conservation of the South American sea lion and the Southern right whale in the Western South Atlantic Ocean

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ABSTRACT

Marine protected areas (MPAs) are key for biodiversity conservation and natural resource management, contributing to ecosystem services. However, fixed MPA boundaries present challenges for species with large geographic ranges, such as marine mammals. It is essential to evaluate the role of international MPA networks in protecting species like the South American sea lion (*Otaria flavescens*) and the Southern right whale (*Eubalaena australis*), whose distribution spans the southern coasts of Brazil, Uruguay, and Argentina. MPA networks can benefit from manager interactions through information exchange, knowledge sharing, and joint management strategies, addressing socio-environmental issues more effectively. In this study, we used graph theory and complex network analysis to investigate the structure of interactions among 27 MPAs based on interviews with managers across the three countries. Our findings reveal that interactions are limited to within-country networks, with no transboundary cooperation for the conservation of *O. flavescens* and *E. australis*. The networks showed low density, with geographic and hierarchical proximity influencing interaction likelihood. Management networks were generally broader than species-specific biological networks. Although our study is limited by its reliance on self-reported data and the absence of direct geospatial validation, the findings underscore critical governance gaps and emphasize the urgent need for enhanced international collaboration in the conservation of marine megafauna in the South Atlantic. Strengthening both national and transnational networks of MPAs is essential to ensure the effective protection of migratory marine species.

1. Introduction

Marine Protected Areas (MPAs) are managed spaces aimed at conserving the biodiversity and productivity of oceans, playing a critical role in preserving ecosystem services (WCPA, 2008; Balbar, 2019). Over the past few decades, there has been a global increase in both the quantity and extent of MPAs, reaching 8.17 % of the world's ocean area in 2023 (IUCN; UNEP-WCMC, 2023). Studies emphasize their

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effectiveness in maintaining, restoring, and promoting the growth of marine populations, as well as in mitigating biodiversity loss, if well enforced (Almany et al., 2009; Gaines et al., 2010; Speed et al., 2018). Protected areas (PAs) constitute social-ecological systems involving interactions among various stakeholders (Maciejewski; Cumming, 2015).

Defining the boundaries of MPAs poses challenges for species with transboundary distribution, as they are subject to different pressures and conservation approaches across different countries. This is exemplified by the South American sea lion (*Otaria flavescens*) and the Southern right whale (*Eubalaena australis*), whose ranges extend along the southern coasts of Brazil, Uruguay, and Argentina in the western South Atlantic Ocean (Jefferson et al., 1993). These waters harbor a highly diverse marine ecosystem, home to many fish species, multiple invertebrate assemblages, and other marine megafauna such as dolphins and sea turtles, with habitats ranging from estuarine systems to rocky reefs and sandy beaches (Miloslavich et al., 2011; Pinheiro et al., 2018; González Carman et al., 2016). In this context, the establishment of functional MPA networks—rather than isolated units—is crucial to ensure coordinated conservation efforts for wide-ranging species (Hoyt, 2018).

In the Atlantic Ocean, the South American sea lion is distributed from southern Argentina to southern Brazil, including the Falkland Islands (King, 1983). The species exhibits two distinct breeding areas along its distribution on the Atlantic coast: (1) along the coast of Uruguay at Isla de Lobos, Cabo Polonio, and La Coronilla (Vaz-Ferreira, 1982; Túnez et al., 2006, 2008); and (2) in Argentina, along the Patagonian coast, from Punta Bermeja to Tierra del Fuego (Cappozzo Perrin, 2009). In Brazil, there are no reproductive colonies; however, individuals, primarily juveniles and subadult (Rosas et al., 1994; Sanfelice et al., 1999; Procksch et al., 2020), undertake seasonal movements to feeding and resting areas, such as Ilha dos Lobos and Molhe Leste de São José do Norte in southern Brazil (Sanfelice et al., 1999; Pavanato et al., 2013; Procksch et al., 2020).

Whales are known to migrate to warmer, shallower waters during the breeding season, where environmental conditions provide physiological benefits to calves, such as thermal regulation before the development of blubber (Roman et al., 2025). The Southern right whale exemplifies this pattern, feeding at high latitudes during summer and calving at mid- and low-latitudes in winter (Bannister et al., 1999; Palazzo Jr. & Flores, 1998; Payne, 1986). Important breeding areas include Península Valdés in Argentina (Payne et al., 1990; Rowntree et al., 2020) and Santa Catarina, Brazil (Groch et al., 2005; Pires Renault-Braga et al., 2018). Recognizing this, the Environmental Protection Area (APA, in Portuguese) Baleia Franca in Santa Catarina and the Peninsula Valdes MPA in Argentina were established to protect the species and its habitat. The Uruguayan coast is also considered a significant winter aggregation area (Costa et al., 2007).

This biological connectivity is supported by currents like the South Equatorial Current, a major oceanographic feature in the South Atlantic that plays a fundamental role in enhancing marine productivity supporting highly productive ecosystems along the migratory routes of these species. However, the ecological connectivity fostered by ocean currents also facilitates the spread of anthropogenic pressures, including illegal fishing, plastic pollution, unregulated coastal development, and climate change, that threaten the sustainability of these marine ecosystems. In this context, coordinated international cooperation among environmental authorities is essential to address these shared challenges and to ensure the long-term protection of migratory species and the ecosystems they depend on.

Migration, seasonal movements, and the presence of transient or visiting animals can have significant implications for the conservation of populations and groups of these marine mammals that cross international borders (Bearzi et al., 2011; Genov et al., 2016). Therefore, the establishment of MPAs can be highly effective in biodiversity conservation and the maintenance of native populations in their natural habitat (Laffoley et al., 2019; Maestro et al., 2019). Networks of MPAs, as opposed to individual MPAs, demonstrate greater efficiency in achieving ecological, economic, and social management objectives (Grorud-Colvert et al., 2014) because they operate cooperatively, facilitating the exchange of knowledge and effective conservation strategies (Katz, Martin, 1997; Alexander Armitage, 2015). The interactions among MPAs are influenced by geographic distance and their affiliation with the same level of government jurisdiction. MPAs in proximity tend to interact more frequently facilitating cooperation, specially when they are administered by the same legal institution, as shared management structures foster increased interaction (Maciejewski and Cumming, 2015).

In the context of South America, Brazil has the National System of Conservation Units (SNUC, in Portuguese), which addresses the creation and management of PAs and categorizes them not only based on the degree of resource protection but also according to the area's protection objectives (Brasil, 2000; Rylands, Brandon, 2005). Uruguay's National System of Protected Areas (SNAP, in Spanish) initiated in 2005, and currently comprises six federal MPAs (Ministerio de Ambiente, 2023). Argentina, conversely, has 65 coastal and/or marine protected areas in a multi-jurisdictional management strategy, with some areas under national jurisdiction (the National System of MPAs, SNAMP in Spanish), areas managed by the provinces, and areas with international designations (e.g. biosphere reserves, RAMSAR sites, among others, https://ampargentina.org).

However, for these MPAs to achieve their conservation goals related to migratory species, coordinated efforts among countries are required. This coordination faces significant challenges arising from complex geopolitical, economic, and legal issues that hinder cooperation despite ecological connectivity. Nonetheless, successful examples demonstrate that strong governance and shared objectives can enable effective collaboration. For instance, Dogger Bank -a large sandbank in the shallow North Sea shared by the UK, Netherlands, Germany, and Denmark-illustrates this. Despite economic conflicts among these countries concerning renewable energy, fisheries, and conservation interests, scientific input, stakeholder engagement, and intergovernmental steering groups have facilitated cross-border fisheries management proposals (Mackelworth et al., 2019). This case highlights the potential for overcoming conflicts through integrated governance and cooperative frameworks to protect ecologically connected marine areas.

Understanding the structure and interaction patterns within the network of MPAs is paramount for comprehending the relationships between actors involved in management (Bodin et al., 2006). In this study, this structure is represented by complex networks -a graph with non-trivial topographical arrangement-formed by nodes (MPAs) and edges (representing interactions among managers) (Barabási, 2009), allowing the modeling and quantification of these interactions and the resulting structure (Degenne, Forsé, 1999).

This study aimed to enhance the efficacy of existing conservation strategies for species with transnational distributions, such as the South American sea lion and the Southern right whale. To accomplish this goal, we assessed the collaborative dynamics among MPAs across Argentina, Uruguay, and Brazil. Through an application of graph theory and complex network analysis, we examined the interactions within and between these MPA networks, based on information from interviews conducted with managers from all three countries.

2. Methodology

2.1. Study area

The study area was defined by the distribution of the South American sea lion and the Southern right whale in the Western South Atlantic Ocean, specifically along the southern coast of Brazil, Uruguay and Argentina, including several MPAs distributed in this region (Fig. 1).

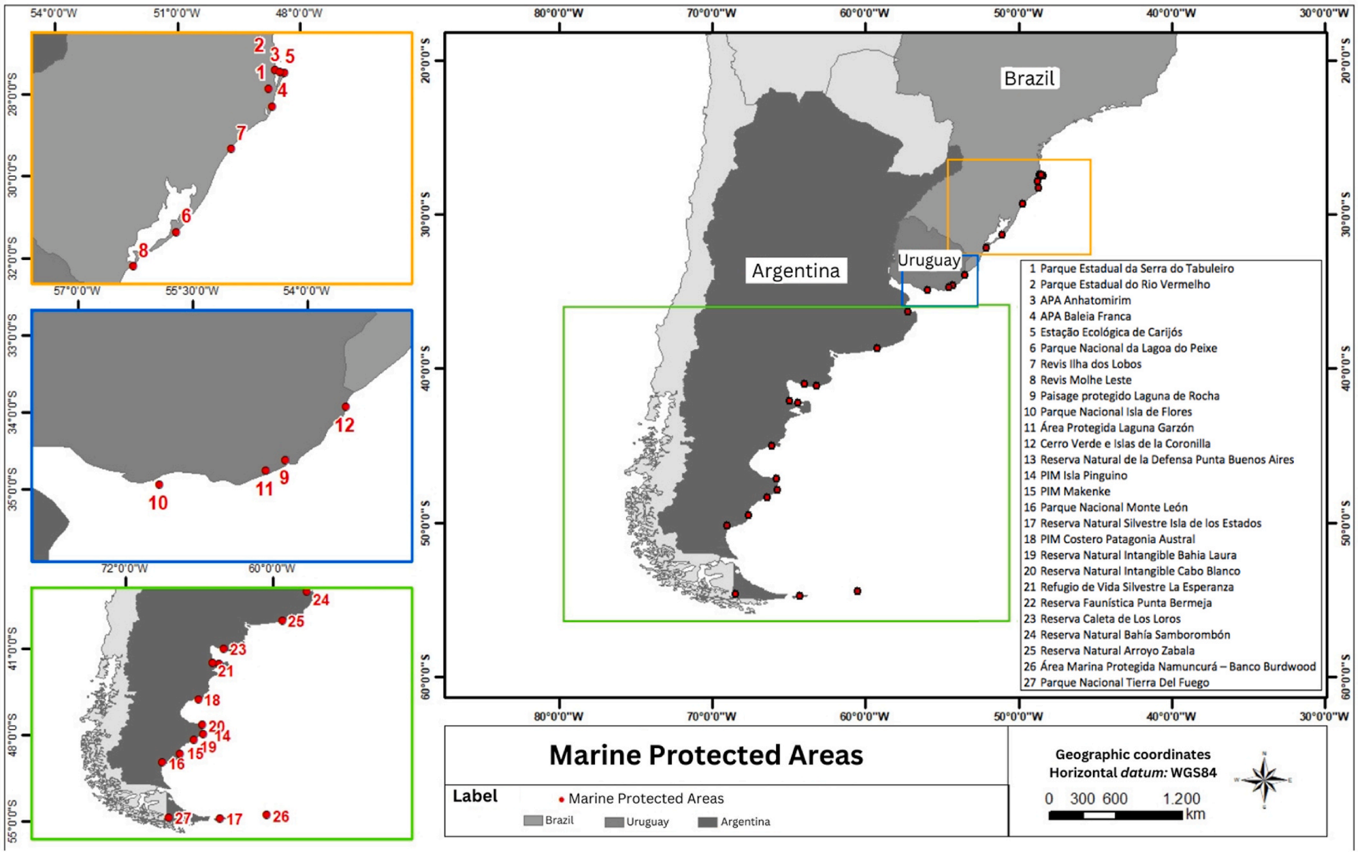

Fig. 1. Geographical location of the 27 Marine Protected Areas (MPAs) for which managers responded to the questionnaire, located in regions predominantly inhabited by South American sea lions and Southern right whales, the focus of research on interaction networks between MPAs. The 27 MPAs were identified using numbers from 1 to 27.

2.2. Data collection

A single standardized questionnaire was developed and applied consistently across the three participating countries. Distribution was conducted primarily via email and, when possible, complemented by structured phone interviews to clarify questions and ensure data quality. Follow-up reminders were sent to all selected MPAs to maximize participation and reduce non-response bias. Data collection occurred between September 2018 and July 2022, resulting in a high response rate of 87 % (27 responses out of 31 MPAs contacted - Supplementary Material 1). It is important to note that the data represent a cumulative cross-sectional overview for this period and do not aim to compare trends over time. The survey targeted MPAs within the marine domain, including both coastal sites encompassing terrestrial and marine ecosystems, and those composed solely of marine environments. In this sense, a species was considered associated with an MPA when confirmed records or seasonal occurrences were reported either within its boundaries or in adjacent marine areas. It is important to note that Uruguay has only six MPAs, and two of them do not encompass the focal species of this study. Therefore, the responses (four MPAs) obtained from Uruguay cover all relevant MPAs, making the sample representative within its national context, despite natural differences in territorial size and number of MPAs among the three countries. For visual representation of the interaction network, MPAs were assigned numerical identifiers (IDs), as detailed in Supplementary Material 2. These include MPAs whose managers responded directly to the questionnaire (ID 1–27) and those referenced by respondents (ID 28–72). Although some of the latter are not coastal or marine, they were included due to their relevance to the broader interaction network. The 31 original MPAs were selected based on their geographic relevance to the distribution of the two focal species and served as institutional, not georeferenced, sampling points identified through purposive sampling.

2.3. Definition of networks

This study investigates two distinct yet complementary networks. The first, referred to as the biological network, captures interactions related to the production and exchange of ecological knowledge for both species.,The second, the management network, represents cooperative efforts among MPAs involving administrative and operational activities (Table 1). Both networks were derived from responses to a structured questionnaire (Supplementary Material 1). Interaction strength was assessed based on mode, frequency, and perceived relevance of the interactions.

In the network framework, nodes represent individual MPAs and edges indicate the presence and intensity of interactions. Management interactions include joint initiatives such as administrative collaboration, shared training, legal frameworks, and informal communication. Biological interactions refer to cooperation in research activities supporting species conservation and population management.

Interaction mode was scored as: 1 = remote, 2 = in-person, 3 = formalized; frequency as: 1 = rare, 2 = occasional, 3 = frequent; and relevance as: 1 = low, 2 = moderate, 3 = high. The total interaction strength was calculated by summing the scores for each dimension. All edges were considered undirected, representing non-directional links between MPAs.

Thus, we obtained the interaction matrices that illustrate the strength of the connections between the MPAs with which we built the respective biological and management networks, one for each country (Brazil, Uruguay and Argentina).

Table 1
The categories of interaction used in the questionnaire for the management network and for the biological network (for both species *O. flavescens* and *E. Australis*).

Networks	Questions
Management	Vehicle (land or water) Team Volunteer or temporary programs Equipment WhatsApp Group Other social medias groups Formal Training (conducted after taking office) Previous Professional Training (conducted before taking office) Environmental Education Programs Public Use Programs Research Program Joint Species Protection Program Joint Publications (brochures, booklets, books, official reports, investigations, manuals, others) Collective External Funding Sources (international fund, NGO, etc.) Financial Resources per Specific Legislation (entrance fees, payment for environmental services, others) Participation in Management Councils Participation in Forums or Working Groups NGO Support for Management (same NGO) Fisheries Legislation (if there is legislation regulating fishing jointly with other MPAs) Joint Inspection Program "Sister" MPA Program (program to bring together Protected Areas with the same theme and relevance) Database Sharing (any type of data) Participation in Conflict Resolution in another MPA
Biological *Otaria flavescens* *Eubalaena australis*	Genetic studies Behavioral studies Ecological studies Morpho-physiological studies Stranding monitoring (sweep) Studies on conflicts with human activities Ethnobiological studies Analysis and classification of threats (Red List, according to IUCN)

2.4. Data analysis

To analyze the structural properties of the networks, we calculated key graph metrics—density, diameter, transitivity, modularity, degree centrality, betweenness centrality, and eigenvector centrality—using the *igraph* package (Csardi and Nepusz, 2006) in R version 3.6.0 (R Core Team, 2023). Network visualizations were produced using the Fruchterman–Reingold force-directed layout algorithm (Fruchterman and Reingold, 1991), which positions nodes based on the strength and number of their connections, placing highly connected nodes toward the center of the graph.

Topological metrics such as centrality and modularity were used to identify key actors and cohesive subgroups within the networks. Although spatial proximity among MPAs was qualitatively considered, no GIS-based spatial analysis was conducted. The geometric layout of the graphs reflects interaction strength, not geographic position.

2.4.1. Network connectivity

To assess how well-connected the networks are, we calculated network density, defined as the proportion of observed interactions relative to all possible interactions (Bodin & Prell, 2011; Janssen et al., 2006). Network diameter measures the geodesic distance between the two most distant nodes, indicating the maximum number of steps required to traverse the network (Newman, 2018). This calculation incorporates edge weights, and the output of the function indicates the maximum distance between any two nodes in the network. Transitivity quantifies clustering within the network, representing the probability that two nodes connected to a common node are also connected to each other, thus forming a triangular structure (Rodrigue, 2020).

2.4.2. Network modularity

Modularity was used to detect cohesive subgroups (modules): clusters of nodes that interact more frequently with each other than with the rest of the network (Newman and Girvan, 2004; Pons and Latapy, 2005). In the graphical representations, isolated nodes were removed to enhance the visualization of these subgroups.

2.4.3. Network centrality

Three centrality measures were calculated to highlight different aspects of nodes: 1) Degree centrality reflects the number of connections each node has in a network (Newman, 2018). By analyzing the overall degree centrality, calculated as the total number of interactions per node, we identified the factors that contributed most and least to MPA connectivity. 2) Betweenness centrality measures a node's influence on the flow of information within the network (Freeman et al., 1979). In this study, node size was scaled according to betweenness values, highlighting 'key MPAs' that act as bridges between network branches, essential for network structure and function. Key nodes vary depending on the context and purpose (Li et al., 2020); here, we refer to them specifically as 'key MPAs' occupying structurally important positions in the network. 3) Eigenvalue centrality highlights an MPA's influence on others (Llopis-Albert et al., 2015), with values calculated using the eigen_centrality function, reflecting the importance of each node's neighbors.

3. Results

Out of the 31 MPA managers contacted, 27 responded to the questionnaire (response rate of 87 %). Fifteen were MPAs from Argentina (55,56 %), eight from Brazil (29,63 %) and four from Uruguay (14,81 %) (Fig. 1, Supplementary material 2). These four responses include all relevant Uruguayan MPAs with the target species, ensuring representative coverage within that national context.

Of the 27 MPA managers who responded to the questionnaire, none of them mentioned the existence of interactions at the international level. This resulted in three distinct and unconnected networks, one for each country, in which only internal interactions could be observed. The total number of MPAs was 72, equivalent to 72 nodes (i.e., the 27 MPAs where the interviewed managers work plus 45 MPAs/PAs with which the managers interact with) (Fig. 2).

Some managers (n = 5) reported that their MPAs do not interact with other MPAs (REVIS Molhe Leste in Brazil; and PIM Isla Pingüino, Reserva Natural Arroyo Zabala, Área Marina Protegida Namuncurá – Banco Burdwood I, and Parque Nacional Tierra Del Fuego, in Argentina).

3.1. Hierarchical level and geographical proximity

The MPAs were categorized based on their level of government jurisdiction as follows: 48,6 % (n = 35) were federal/national, 44,4 % (n = 32) state-level, and about 2,8 % (n = 2) municipal. Additionally, 4,2 % (n = 3) were inter-jurisdictional MPAs (State and national administration), present only in Argentina. Uruguayan MPAs are all national, while Brazilian MPAs include federal, state, and municipal categories. Although Argentina has municipal MPAs, only national, provincial, and inter-jurisdictional categories were included in this study. Federal/national MPAs interacted mainly with other federal/national MPAs (47 interactions), followed by state MPAs (11) and inter-jurisdictional MPAs (3). State-level MPAs showed a higher level of interaction with other state-level MPAs (30), followed by 16 interactions with federal/national MPAs, 8 with inter-jurisdictional level and only one with a municipal level. The inter-jurisdictional level format is mixed, with provincial administration (through provincial agencies) and national administration (through the National Parks Administration) and exhibits a higher number of interactions with federal/national MPAs (17), followed by

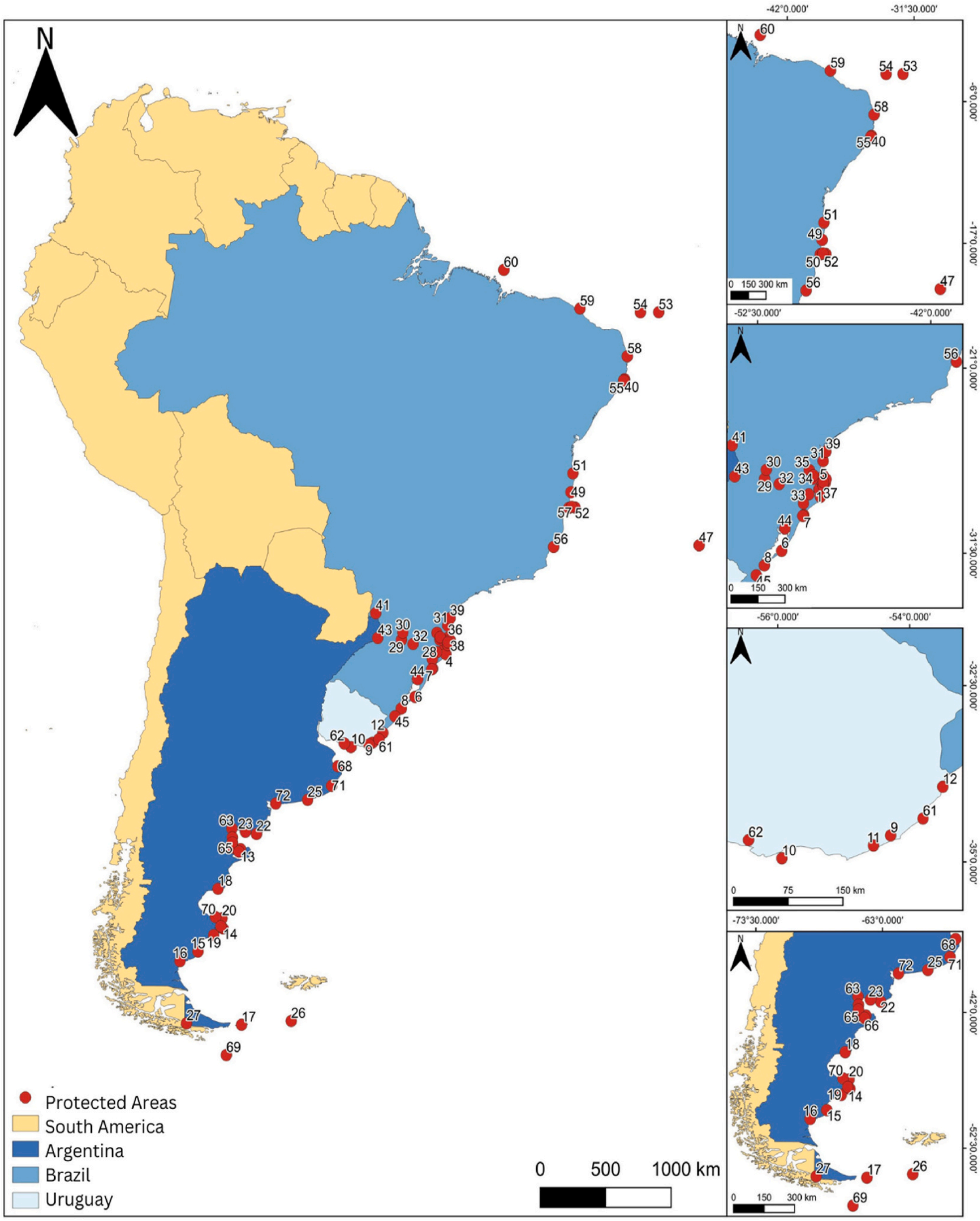

Fig. 2. Geographic location of the 72 Protected Areas (PAs) on the southern coast of South America (nodes 1 to 27 represent the Marine Protected Areas whose managers' responded questionnaire, and nodes 28 to 72 represent other PAs mentioned by those managers). The identification (ID) for each PA is shown in Table S1.

state-level MPA's (3). Despite being a small category, interjurisdictional MPAs had notable interactions among themselves (4), considering there are only 3 in this level. Therefore, the census proposed by the study supports the hypothesis that MPAs interact more with those of the same hierarchical or jurisdictional level (Gruby et al., 2021). The sole municipal-level MPA surveyed (Molhe Leste Wildlife Refuge) had no interactions with other MPAs and faced challenges in management and response quality due to the absence of a directly responsible administrator.

Our results also show that MPAs within the same state or region tend to interact more with each other, except in Uruguay. In Brazil, most interactions occurred among MPAs within the same state (37), while MPAs in southern Brazil interacted with 14 MPAs from other regions of the country. In Uruguay, the number of interactions between MPAs within the same state was equal to the number of interactions between different states (4). In Argentina, interactions were predominantly among MPAs from the same Patagonian region (26), followed by interactions among MPAs within the same state (19). Interactions between MPAs from Patagonia and PAs from other regions of the country were less frequent (6). It is important to note that the distances between MPAs are well known and validated using official political maps and location data, which supports our qualitative assessment of proximity.

3.2. Factors that most connect and least connect MPAs

Based on centrality measures, the type of interactions driving connectivity within countries was identified (Table 2). In Brazil, 'WhatsApp Groups' and 'Data Sharing' had the highest connectivity, with 50 and 26

Table 2
Factors that most connect and least connect MPAs for Brazil, Uruguay and Argentina.

Factor	Brasil	Uruguai	Argentina
WhatsApp Groups	50	0	29
Data Sharing (any type of data)	26	1	50
Groups on other social networks	18	0	18
Research Program	18	0	5
External collective financing sources (international fund)	17	0	1
Participation in Forums or working groups	12	0	3
Vehicle (land or water)	11	2	9
Equipment	11	0	5
Environmental Education Programs	10	0	3
Joint species protection program(s)	10	0	4
Volunteer or temporary programs	9	0	4
Joint publications	9	0	1
Financial resources through specific legislation	9	0	4
Beach stranding monitoring (sweeping)	9	6	6
Behavior studies	8	1	2
Ecology studies	8	6	9
Morpho-physiological studies	8	0	1
Threat analysis and classification	4	0	0
Formal training (conducted after being in the position)	3	0	21
Public Use Programs	3	0	2
Participation in Boards - Managers	3	0	5
NGO support for management (same NGO)	3	4	1
Genetic studies	3	0	10
Staff/team	1	2	10
Previous Professional Training	1	0	5
Joint inspection program	1	0	3
Fishing legislation	0	6	2
"Sister" MPA program	0	0	1
Participation in conflict resolution in another MPA	0	0	6
Studies on conflicts with human activities	0	0	1
Ethnobiological studies	0	0	0

points respectively. 'WhatsApp Groups' referred to communication and interaction through instant messaging groups, possibly used for information exchange and coordination of actions among participants, consultations, questions, and requests for support as well. 'Data Sharing' represented the exchange of information and data among stakeholders, which could contribute to better management and evidence-based decision-making. Argentina followed a similar pattern, with 'Data Sharing' at 50 points, 'WhatsApp Groups' at 29 points, and 'Formal Training' at 21 points, indicating interactions related to the joint training of professionals working in protected areas, seeking to improve their skills and knowledge. 'Genetic Studies' and 'Staff/Team' also scored relatively high with 10, indicating a strong focus on sharing genetic studies and staff working/collaborating in more than one MPA. Uruguay had lower connectivity, with 'Beach Stranding Monitoring' and 'Fishing Legislation' each scoring 6 points, highlighting common monitoring and joint fishing regulation efforts.

3.3. Connectivity and modularity of the networks

As no cross-country interactions were observed, the management and biological networks were analyzed separately within each country. Connectivity and modularity metrics are detailed in Table 3.

In Brazil, the management network for MPAs consists of 41 nodes connected through 60 edges, with low overall connectivity (density of 0.07), indicating infrequent interactions among MPAs. The modularity score of 0.51 suggests moderate subgroup division (Fig. 3), with some groups coordinating better. By individually analyzing the biological networks for the species of *O. flavescens* and *E. australis*, both networks showed higher densities (0.18 and 0.20 respectively), suggesting that MPAs work with some level of cooperation when addressing the conservation of these species compared to their general management. However, these biological networks had a lower number of nodes with very low modularity (Figs. 4 and 5), indicating little to no subgroup division.

In Uruguay, the management network is highly interconnected (density of 0.53) with fewer nodes and edges, indicating a compact and collaborative structure with only one subgroup. The biological network for sea lions also shows a relatively high density (0.33), without transitivity, meaning indirect connections (a node connecting through another node) are absent. There was no data reported for the Southern

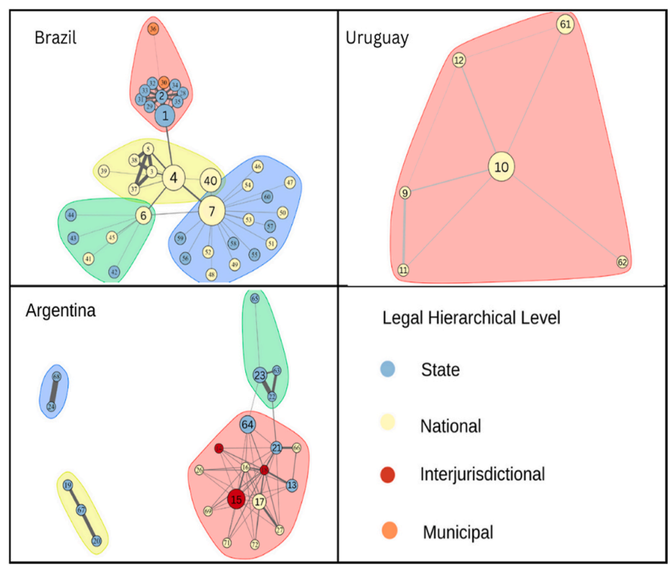

Fig. 3. Subgroups for the management networks of marine protected areas in southern Brazil, and the coasts of Uruguay and Argentina. Node size and edge thickness are proportional to betweenness centrality and interaction strength values, respectively. Node identification can be found in Table S1. Background shading colours indicate subgroups that are more connected (or only connect) to each other than to other nodes in the network.

Table 3
Number of nodes and edges, density, transitivity, diameter, subgroups, and modularity of the management and biological networks related to the Marine Protected Areas of southern Brazil, Uruguay and Argentina.

COUNTRY	NETWORK			CONNECTIVITY			MODULARITY	
		Nodes	Edges	Density	Transitivity	Diameter	Subgroups	Modularity
BRAZIL	Management	41	60	0.07	0.15	74	5	0.51
	Biological *Otaria flavescens*	10	8	0.18	0.60	54	6	0
	Biological *Eubalaena australis*	10	9	0.20	0.53	96	5	0
URUGUAY	Management	6	9	0.53	0.50	24	1	0
	Biological *Otaria flavescens*	6	5	0.33	0.00	32	1	0
	Biological *Eubalaena australis*	–	–	–	–	–	–	–
ARGENTINA	Management	24	63	0.23	0.56	127	5	0.60
	Biological *Otaria flavescens*	21	19	0.09	0.13	50	10	0.68
	Biological *Eubalaena australis*	17	6	0.04	0.75	15	13	0.46

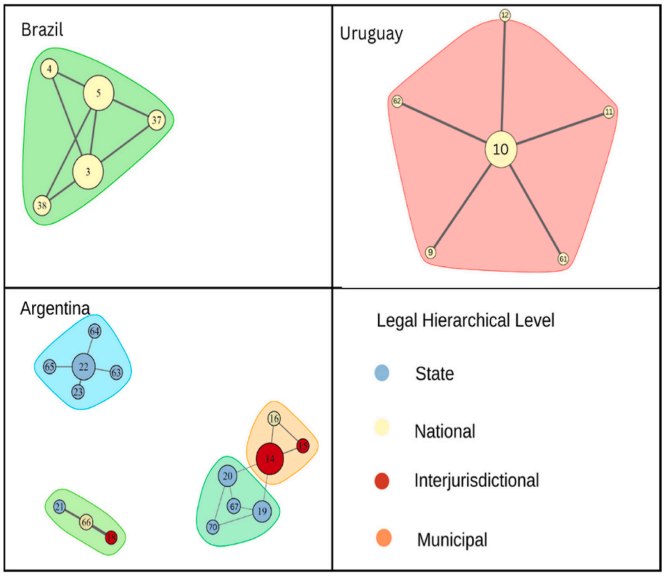

Fig. 4. Subgroups for the biological networks focusing on the species *Otaria flavescens* for the marine protected areas in southern Brazil, and the coasts of Uruguay and Argentina. Node size and edge thickness are proportional to betweenness centrality and interaction strength values, respectively. Node identification can be found in Table S1. Background shading colours indicate subgroups that are more connected (or only connect) to each other than to other nodes in the network.

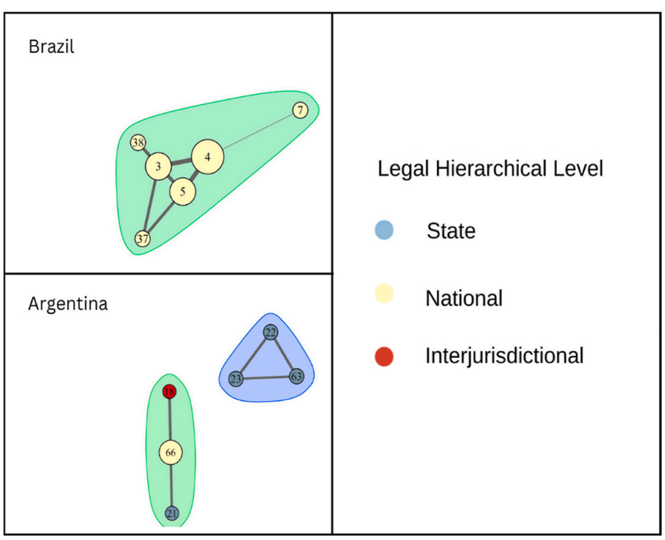

Fig. 5. Subgroups for the biological networks focusing on the species *Eubalaena australis* for the marine protected areas in southern Brazil and the Argentine coast. Node size and edge thickness are proportional to betweenness centrality and interaction strength values, respectively. Node identification can be found in Table S1. Background shading colours indicate subgroups that connect more (or only) to each other than to other nodes in the network. The absence of the Uruguayan network is due to the lack of interaction between managers at the moment of interviews.

right whales.

Argentina's management network has moderate connectivity (density of 0.23) and high modularity (0.60), showing distinct, independent management groups. The sea lion network has a low density (0.09), indicating fewer connections among the nodes, and a high modularity (0.68), reflecting strong subgroup division. The Southern right whale network, with the lowest density (0.04), has high transitivity (0.75), suggesting tightly knit clusters where connections exist.

3.4. Network centrality

Centrality analysis of management networks revealed that certain MPAs were crucial in connecting the networks (Fig. 6). Identifying "key MPAs" (nodes with the largest sizes) is valuable for optimizing network structure and function. These key MPAs indicate critical points needing support, highlighting those facing significant logistical, functional, and management challenges. Centrality metrics are detailed in Table 4.

In Brazil's management network, REVIS Ilha dos Lobos (node 7) is central, with the highest degree centrality (DC = 19) and betweenness centrality (BC = 471). Degree centrality measures the number of direct connections a node has, indicating that REVIS Ilha dos Lobos interacts frequently with various other MPAs, exhibiting higher versatility by engaging in numerous collaborative conservation activities. Betweenness centrality quantifies the number of times a node acts as a bridge along the shortest path between two other nodes, suggesting this node frequently interacts with various MPAs and acts as a crucial bridge in facilitating communication and resource flow. APA Anhatomirim (node 3) and ESEC de Carijós (node 5) also show significant influence, each with an eigenvalue centrality (EC) of 1.0. This metric highlights nodes that are not only directly connected to many others but also connected to those that are themselves central, emphasizing their importance in the spread of information and influence throughout the network (Fig. 6).

In the Uruguay management network, Parque Nacional Isla de Flores (node 10) exhibits the highest degree and betweenness centrality (DC = 5.0 and BC = 7), highlighting its role as a key hub and connector within the network.

In Argentina, PIM Makenke, Parque Nacional Monte León, Reserva Natural Silvestre Isla de los Estados, and PIM Costero Patagonia Austral (nodes 15, 16, 17, and 18 respectively) register the highest degree centrality (DC = 15). This establishes them as central operational points within the network. Their high centrality indicates a strong capability to mobilize resources, coordinate activities, and disseminate critical information across the network.

In the biological networks for *O. flavescens,* key nodes varied by country. In Brazil, REVIS Ilha dos Lobos and ESEC de Carijós were central, playing significant roles in biological interactions. Uruguay's Parque Nacional Isla de Flores was also a central hub. In Argentina, Reserva Faunística Punta Bermeja had the highest degree centrality, indicating many direct interactions, while PIM Isla Pingüino had high betweenness centrality, highlighting its role as a crucial connector. Área Natural Protegida Península Valdés had the highest eigenvalue centrality, indicating strong influence over connected nodes.

For *E. australis* in Brazil, APA Anhatomirim and ESEC de Carijós showed high degree and eigenvalue centrality, confirming their pivotal roles. APA Baleia Franca exhibited the highest betweenness centrality, highlighting its intermediary role in connecting diverse nodes. In Argentina, Reserva Faunística Punta Bermeja was again prominent, alongside Reserva Caleta de Los Loros, with high degree centrality, while Área Natural Protegida Península Valdes's high betweenness centrality underlined its important bridging role in the network.

4. Discussion

Networks of interactions between MPAs targeting the conservation of *O. flavescens* and *E. australis* in the western South Atlantic Ocean showed no transboundary interactions during the 2018–2022 survey period, despite the recognized need for cross-country cooperation for migratory species (Wilkinson et al., 2004). This highlights the urgent need for enhanced international cooperation between MPAs. The lack of cross-border collaboration among MPAs may stem from multiple barriers, including differences in conservation policies, legal and administrative frameworks, institutional cultures, and stakeholder engagement, in addition to resource limitations (Costello and Molina, 2021). Addressing these multidimensional challenges is crucial to improving cooperation for the conservation of migratory species. Our findings

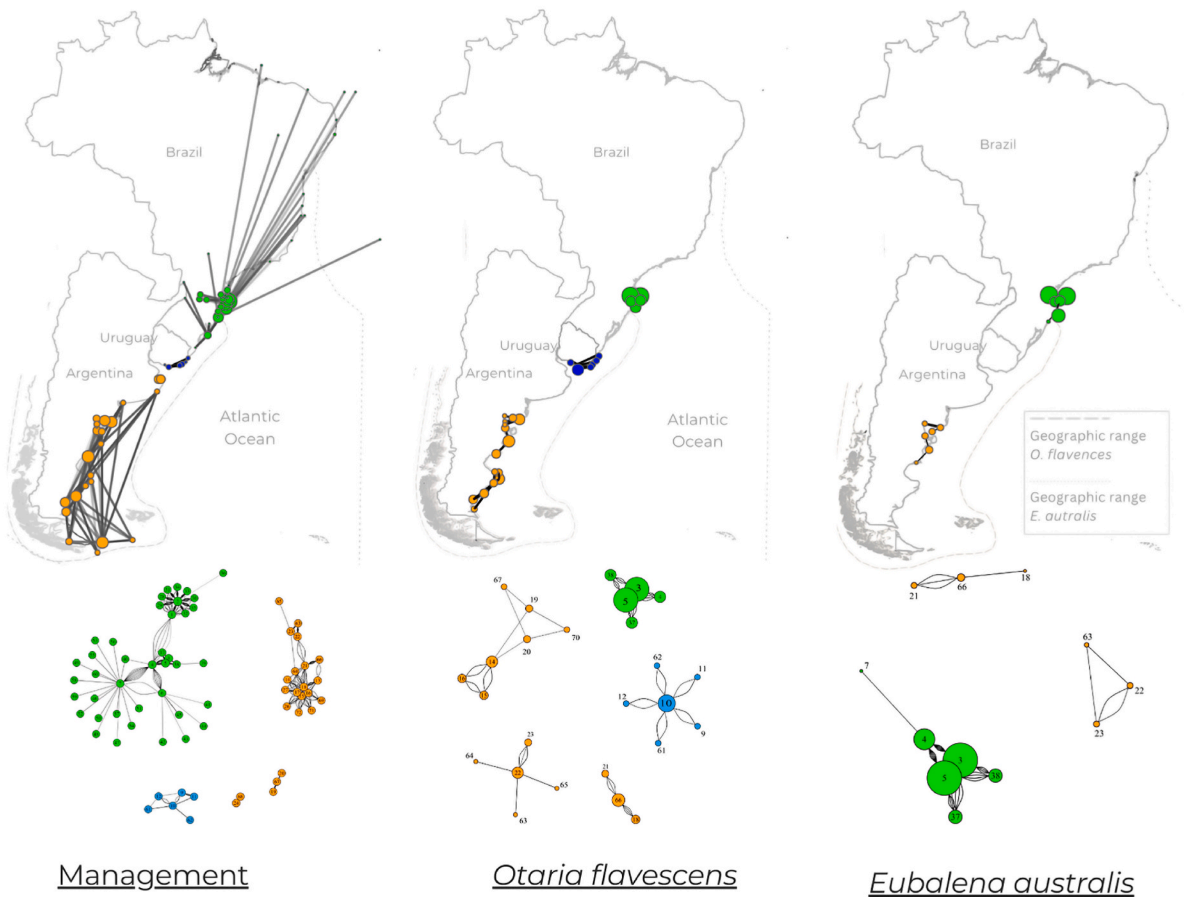

Fig. 6. Management and biological networks for marine protected areas in southern Brazil and the coasts of Uruguay and Argentina. Node size and edge thickness are proportional to betweenness centrality values and interaction strength, respectively. Green nodes are from Brazil, blue nodes are from Uruguay and orange nodes are from Argentina. Maps indicate the location of MPAs in each country. Node identification can be found in Table 2.

suggest that low-cost, accessible tools, such as messaging apps (e.g. WhatsApp) and digital platforms, can support early steps toward international collaboration, especially in contexts where formal agreements remain limited. We acknowledge that this absence of transboundary cooperation is both an important result and a limitation of this study, as it constrains the depth of the regional conservation analysis but simultaneously identifies a clear gap that future efforts should address.

Analyzing the networks of each country separately, it was observed that the management interaction network is broader, with significantly more interactions than the biological networks. This likely reflects the broader applicability of administrative collaboration—such as resource sharing, personnel management, or legal procedures—which is often easier to establish than scientific partnerships that require aligned research goals, technical capacity, and long-term funding. This finding suggests that MPAs may more readily engage in general administrative cooperation than in coordinated scientific monitoring. A dual-track approach could be considered, where broad management collaboration is accompanied by targeted thematic networks focusing on species-specific research and conservation.

The jurisdictional hierarchy of MPAs influenced their interactions, particularly in federal/national and state MPAs, often managed by the same governing body within each country. The municipal-level MPA Molhe Leste Wildlife Refuge in Brazil, located in a key South American sea lion area (Rosas et al., 1994; Pavanato et al., 2013), is isolated from other MPAs, which may hinder regional conservation strategies. In Argentina, interjurisdictional MPAs are jointly managed by national and provincial authorities, leading to more interactions between PIM managers and those overseeing national or state parks.

Our results indicate that MPAs located within the same country or region are more likely to interact with one another (Fig. 6), supporting the hypothesis that geographical proximity enhances interactions and strengthens administrative, socioeconomic, and environmental connections between MPAs, as documented in previous studies (Maciejewski & Cumming, 2011). Protected areas that are geographically close to each other are more likely to share similar social and environmental issues, increasing the chances of connectivity (Jones et al., 2009; Gerber et al., 2013; Bodin, 2017; Zapelini et al., 2024). In Brazil, the Instituto Chico Mendes de Conservação da Biodiversidade (ICMBio), the environmental body responsible for proposing, implementing, managing, and protecting federal PAs, has established Integrated Management Centers (CMI) to promote the integrated management among geographically proximate protected areas. This strategy is consistent with our findings and leverages pre-existing connections, as evidenced by the formation of modularity subgroups. A clear example is the cluster formed by APA Anhatomirim, ESEC Carijós, RESEX Pirajubaé, and REBIO do Arvoredo (Fig. 3), all of which are part of the Florianópolis CMI in the state of Santa Catarina).

In addition to spatial proximity, digital communication has become essential for overcoming distance limitations. Social networks, especially WhatsApp groups, facilitate connections among MPA managers, promoting interactions across regions. In Brazil and Argentina, WhatsApp groups based on MPA hierarchies (federal and state levels) enable broader communication. For example, in southern Brazil, there are groups for state and federal MPAs, fostering interactions with northern and northeastern regions. In Argentina, these groups primarily exist at the state level.

We found that the MPA networks in Brazil and Argentina exhibit low density, one of the topological metrics commonly used to assess network

Table 4
Marine protected areas showing the highest value of centrality metrics (degree centrality (DC), betweenness centrality (BC), eigenvalues centrality (EC)) in the management and biological networks in the southern region of Brazil and the coasts of Uruguay and Argentina. Acronyms: APA = Environmental Protection Area, REVIS = Wildlife Refuge, PIM = Interjurisdictional Marine Park, ESEC = Ecological Station.

	NETWORK	CENTRALITY		
		Degree Centrality	Betweenness Centrality	Eigenvalues Centrality
BRAZIL	Management	REVIS Ilha dos Lobos (node 7); DC = 19.0	REVIS Ilha dos Lobos (node 7), BC = 471	APA Anhatomirim (node 3), ESEC Carijós (node 5); EC = 1.0
	Biological *Otaria flavescens*	APA Anhatomirim (node 3) e ESEC Carijós (node 5); DC = 5.0	APA Anhatomirim (node 3) e ESEC Carijós (node 5), BC = 1.5	APA Anhatomirim (node 3), ESEC Carijós (node 5); EC = 1.0
	Biological *Eubalaena australis*	APA Anhatomirim (node 3) e ESEC Carijós (node 5); DC = 5.0	APA Baleia Franca (node 4); BC = 4.0	APA Anhatomirim (node 3). ESEC Carijós (node 5); EC = 1.0
URUGUAY	Management	Isla de Flores National Park (node 10); DC = 5.0	Isla de Flores National Park (node 10), BC = 7.0	Protected Landscape Laguna de Rocha (node 9); EC = 1.0
	Biological *Otaria flavescens*	Isla de Flores National Park (node 10); DC = 5.0	Isla de Flores National Park (node 10), BC = 10.0	Isla de Flores National Park (node 10), EC = 1.0
ARGENTINA	Management	PIM Makenke (15), Monte León National Park (16), Isla de los Estados Natural Wildlife Reserve (17), PIM Costero Patagonia Austral (18); DC = 15	PIM Makenke (node 15), BC = 51.6	Punta Bermeja Fauna Reserve (node 22) EC = 1.0
	Biological *Otaria flavescens*	Punta Bermeja Fauna Reserve (node 22); DC = 5.0	PIM Isla Pingüino (node 14); BC = 8.5	Península Valdés Natural Protected Area (node 66); EC = 1.0
	Biological *Eubalaena australis*	Punta Bermeja Fauna Reserve (node 22), Caleta de Los Loros Reserve (node 23); DC = 3.0	Península Valdés Natural Protected Area (node 66); BC = 1.0	Punta Bermeja Fauna Reserve (node 22). EC = 1.0

connectivity. This low density is expected in real-world networks, where the typical structure tends to be sparse rather than dense (Faust, 2006). In such networks only a small fraction of the possible connections actually exist, limiting knowledge exchange among managers (Janssen et al., 2006). In contrast, the network in Uruguay showed high density, which is expected in networks with a small number of nodes. When the number of nodes is low, even a few edges can result in high network density, as the denominator (maximum possible connections) is relatively small. This metric is important for management of MPAs because while high densities can homogenize information (Bodin Norberg, 2005), low densities such as those found here, may hinder progress, data exchange, and the maintenance of collaborative processes (Bodin Crona, 2009). Network diameter, defined as the longest shortest path between any two nodes in a network, serves as an indicator of overall communication efficiency (Newman, 2010; Borgatti et al., 2009). A larger diameter suggests slower or less efficient information flow across the network. In our analysis, Argentina exhibited the highest network diameter, indicating lower connectivity and longer paths for potential interaction between MPAs. Brazil also showed relatively high diameter values, which may be attributed to its large geographic extent and the high number of MPAs, which increases the number of potential but not necessarily realized connections. In contrast, Uruguay's network, composed of fewer MPAs with more frequent interactions, displayed a smaller diameter, reflecting more efficient communication within a compact national system.

In Argentina, the management and biological networks of *O. flavescens* show well-defined subgroups with minimal overlap, likely influenced by geographical proximity. These subgroups, all within the same state but varying in hierarchy, may lead to isolated decision-making and limited integration with other MPAs. Ideally, greater integration between MPAs would be preferable (Bodin et al., 2006). In contrast, Uruguay's network exhibited zero modularity, meaning that nodes were not organized into distinct communities. This homogeneous structure may be explained by the small number of MPAs, the country's limited geographic scale, and the high level of connectivity among MPAs, which together favor more centralized and cohesive communication among managers. The absence of subgroups in Uruguay's network likely reflects both the reduced number of protected areas and a more streamlined national context, where jurisdictional and administrative fragmentation is less pronounced compared to Brazil and Argentina. As noted by Barabási (2016), a modularity value of 0 indicates an absence of community division, which in this case may facilitate more effective interaction within a unified network. Brazil's biological networks displayed a similar pattern, also showing modularity values of zero.

Betweenness centrality identifies key MPAs in communication networks. In Brazil, ESEC Carijós and APA Anhatomirim play pivotal roles in South American sea lion research, collaborating with other MPAs. Argentina's network is divided into small components, with PIM Isla Pingüino standing out for its interactions.APA Baleia Franca in Brazil, dedicated to Southern right whale conservation, fosters collaboration among MPAs, consequently, it serves as a benchmark for other MPA that also conduct research on the Southern right whale, similarly to Peninsula Valdés NPA in Argentina. Uruguay's Isla de Flores National Park is crucial for connecting MPAs, being the only MPA that has connections with all other MPAs, thus responsible for facilitating the flow of information, while PIM Makenke in Argentina acts as a central facilitator in the management network.

Even in MPAs, conservation faces challenges: in Brazil, REVIS do Molhe Leste has intense pressure from sea lion–fishery interactions (Rosas et al., 1994; Machado et al., 2015; Ramos et al., 2023), while in the Baleia Franca APA, local fishers have reported altering practices to avoid conflicts with migrating whales (Zappes et al., 2013). A previous study highlighted the overlap between *O. flavescens* and fishing vessels from Uruguay, and there may also be spatial conflicts on the Argentine side (Riet-Sapriza et al., 2013). Strengthening cooperation among MPAs could help mitigate such conflicts by fostering joint actions with fishers and improving understanding of species' distributions, population dynamics, and human-wildlife conflicts. Additionally, the ongoing panzootic of Highly Pathogenic Avian Influenza (HPAI) A(H5N1), which has killed over 24,000 South American sea lions in 2023 (Plaza et al., 2023), highlights the urgent need for collaboration across countries, particularly as the virus has now been detected in Brazil (MMA, 2023). Lessons from neighboring countries could be critical in preventing high mortality rates in Brazil. This further emphasizes how multinational cooperation can help share data, improve responses to emergencies, and enhance disease monitoring capabilities.

Whales and pinnipeds were heavily hunted in the past, but today other threats have become a constant danger to marine megafauna, such as the ingestion of solid waste (Nascimento et al., 2023) and fishing interaction (Bjørge et al., 2002). In Brazil, during the winter and spring months when sea lions migrate from breeding colonies in Uruguay (Machado et al., 2016), fishers frequently hold negative views of the animals due to the damage they cause to fishing nets (Pont et al., 2015). In Uruguay, industrial bottom trawling represents a threat to the South American sea lion, with estimates indicating that mortalities of the species account for about 0.8 % (IC: 0.4–1.6 %) of the local population (Franco-Trecu et al., 2019). Whales are at risk from ship collisions (Panigada et al., 2006) and entanglement in fishing gear (Dawson, 1991), particularly monofilament gillnets, as seen in 97.4 % of Southern right whale entanglement cases (Groch et al., 2015). In Santa Catarina, artisanal fisheries increase the risk of whale entanglement, emphasizing the need for ongoing monitoring of whale populations and fishing activities (Zappes et al., 2013).

Hoyt (2011) emphasized the importance of coordinated MPA networks specifically dedicated to cetacean protection. Ensuring ecological connectivity for transboundary species requires not only spatial planning but also institutional collaboration among MPA managers. Notable international examples highlight effective models of cross-border cooperation. In the Mediterranean, the MedPAN network brings together over 110 MPA management institutions from 21 countries, facilitating joint conservation strategies and harmonized monitoring for mobile species such as cetaceans and marine turtles (UNEP/MAP, 2020; Gallon et al., 2019). Similarly, in the North-East Atlantic, the OSPAR Convention serves as a legally binding framework among 15 governments and the European Union, promoting coordinated monitoring and common strategies for marine protection (OSPAR Commission, 2023). However, Geijer and Jones (2015) argue that MPA networks alone may be insufficient to address key threats to migratory whales, such as ship strikes. Their analysis of the Mediterranean fin whalesuggests that that broader sectoral approaches—particularly through the International Maritime Organization—are necessary to regulate shipping activities across ecological scales that transcend administrative boundaries.

Beyond MPA-focused initiatives, agreements like ASCOBANS (Agreement on the Conservation of Small Cetaceans of the Baltic, North East Atlantic, Irish and North Seas), which demonstrates how formalized, legally supported cooperation can address the challenges of managing wide-ranging species. The agreement fosters coordination across range states through a Conservation and Management Plan that includes habitat protection, research, pollution mitigation, and public awareness (ASCOBANS, 2024). Together, these examples illustrate the need for a multi-dimensional governance strategy that combines spatial protection through MPAs with broader institutional and sectoral coordination. For the Western South Atlantic, where transboundary cooperation remains limited and threats are diverse, such integrated frameworks could significantly enhance conservation outcomes for species like the Southern right whale and the South American sea lion.

Building on these international examples, regional initiatives have also emerged to improve cooperation for marine mammal conservation in the South Atlantic. One such proposal is the South American MPA Network for whale conservation, originally proposed by Palazzo (2003), which aims to strengthen collaboration in the management of MPAs and promote coordinated actions for the protection of cetacean habitats. This initiative would also support the broader goal of establishing the South Atlantic Whale Sanctuary, a proposal led by Brazil since the 50th meeting of the International Whaling Commission (IWC). The sanctuary seeks to provide a safe zone for whales, free from threats such as whaling, bycatch, ship strikes, and pollution. Despite multiple submissions, the proposal has not yet been formally adopted due to persistent opposition from some member states (Marcondes, 2020).

More recently, on September 15, 2023, the IUCN Marine Mammal Protected Areas Task Force identified and mapped 33 new Important Marine Mammal Areas (IMMAs) in the Western South Atlantic, ranging from the Guianas to the southern tip of Argentina. Although IMMAs are not legally protected zones, they are science-based tools that help identify priority areas for marine mammal conservation (IUCN Marine Mammal Protected Areas Task Force, 2023). These designations present a valuable opportunity to guide future MPA expansion and inform the development of effective transboundary networks. Future research should seek to integrate ecological impact assessments with network analysis to better understand how existing and proposed MPAs meet the conservation needs of species like the Southern right whale and the South American sea lion.

This study is not without limitations. Our results are based on self-reported data from MPA managers, and the nature of social network data may be influenced by subjective interpretation of interaction intensity. While self-reported data can introduce potential biases—such as recall errors or social desirability effects—this approach remains widely accepted in socioecological research for its practicality and ability to capture nuanced institutional perspectives (Rosenman et al., 2011; Corneille and Gawronski, 2024). We took active steps to minimize these limitations by using a standardized questionnaire, conducting follow-up reminders, and supplementing with phone contacts where needed. Future studies could complement this method with additional observational studies. The proximity between MPAs was inferred from jurisdictional and qualitative descriptors, and no formal GIS analysis was performed. This methodological choice was consistent with the study's primary focus on institutional interactions rather than spatial clustering. Also, this study data provide a cumulative cross-sectional perspective for 2018–2022, without assessing temporal trends. Future research could build on this baseline to analyze changes in MPA interactions over time. Despite these constraints, the findings underscore the importance of understanding MPA network connectivity to guide regional conservation planning. Implementing transboundary conservation measures involves dealing with multiple and diverse economic, political and socio-environmental conditions and drivers that affect the quality and capacity for effective governance and the potential for collaboration between countries (Mason et al., 2020; Lim, 2016). In this way, MPAs network analysis offers a valuable tool for informing decision-makers and supporting more effective collaboration among protected areas. The insights from this study can contribute to public policies aimed at enhancing the integrated management of coastal and marine ecosystems, in alignment with global conservation frameworks such as the Convention on Biological Diversity (CBD) and the United Nations Sustainable Development Goals (SDGs). The ongoing UN Decade of Ocean Science for Sustainable Development (2021–2030) provides a timely platform to foster international cooperation and engage stakeholders in restoring and sustaining ocean health (Lee et al., 2020).

5. Conclusion

This research is important because it provides a regional perspective on the institutional connectivity (or lack thereof) between Marine Protected Areas in the Western South Atlantic Ocean, offering novel insights into the structural and governance gaps that hinder effective conservation of migratory marine mammals. By applying social network analysis, the study identifies interaction patterns, central actors, and opportunities for improved integration among MPAs.

The main findings reveal the absence of transboundary collaboration, low-density national networks, and the influence of both geographical and hierarchical proximity on interaction likelihood. It also shows that general management issues tend to promote more collaboration than species-specific initiatives. Technology has proven to be an ally in social interaction between managers through the use of WhatsApp groups and shared databases, but many MPAs managers have yet to adopt the use of this technology as an interaction facilitator.

Southern right whales and South American sea lions continue to face anthropogenic threats, underscoring the importance of strengthening

MPA networks and implementing coordinated management strategies. Although based on self-reported data and qualitative proximity assessments, the study offers valuable insights to inform public policy and strengthen MPA networks in support of broader conservation goals. Enhancing cooperation among MPAs is essential for advancing marine mammal conservation and aligning local actions with international commitments to ocean governance.

CRediT authorship contribution statement

Lorena Oliveira do Nascimento: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Cleverson Zapelini:** Writing – review & editing, Validation, Supervision, Formal analysis, Conceptualization. **Julián Olaya-Restrepo:** Writing – review & editing, Visualization. **Ana Cinti:** Writing – review & editing, Validation. **Guillermo Chalar:** Writing – review & editing, Validation. **Rodrigo Machado:** Writing – review & editing, Validation. **Alexandre Schiavetti:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Formal analysis, Conceptualization.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2025.126679.

Data availability

Data will be made available on request.

References

Alexander, S.M., Armitage, D., 2015. A social relational network perspective for MPA science. Conserv. Lett. 8 (1), 1–13. https://doi.org/10.1111/conl.12090.

Almany, G.R., Berumen, M.L., Thorrold, S.R., Planes, S., Jones, G.P., Srinivasan, M., 2009. Connectivity, biodiversity conservation and the design of marine reserve networks for coral reefs. Coral Reefs 28 (2), 339–351. https://doi.org/10.1007/s00338-009-0484-x.

ASCOBANS, 2024. Agreement on the conservation of small cetaceans of the Baltic, North East Atlantic, Irish and North Seas. Available at: https://www.ascobans.org/en/legal instrument/ascobans. (Accessed 16 April 2025).

Bannister, J.L., Pastene, L.A., Burnell, S.R., 1999. First record of movement of a southern right whale (*Eubalaena australis*) between warm water breeding grounds and the Antarctic Ocean, south of 60° S. Mar. Mamm. Sci. 15 (4), 1337–1342. https://doi.org/10.1111/j.1748-7692.1999.tb00895.x.

Barabási, A.-L., 2009. Scale-free networks: a decade and beyond. Science 325 (5939), 412–413.

Barabási, A.L., 2016. Network Science. Cambridge University Press, Cambridge.

Bearzi, G., Bonizzoni, S., Gonzalvo, J., 2011. Mid-distance movements of common bottlenose dolphins in the coastal waters of Greece. J. Ethol. 29 (2), 369–374. https://doi.org/10.1007/s10164-010-0245-x.

Bjørge, A., Bekkby, T., Bryant, E., et al., 2002. Interactions between harbour seals, Phoca vitulina, and fisheries in complex coastal waters explored by combined Geographic Information System (GIS) and energetics modelling. ICES Journal of Marine Science 59 (1), 29–42. https://doi.org/10.1006/jmsc.2001.1137.

Bodin, Ö., 2017. Collaborative environmental governance: achieving collective action in social-ecological systems. Science 357 (6352), eaan1114. https://doi.org/10.1126/science.aan1114.

Bodin, Ö., Crona, B., Ernstson, H., 2006. Social networks in natural resource management: what is there to learn from a structural perspective? Ecol. Soc. 11 (2). http://www.jstor.org/stable/26266035.

Bodin, Ö., Crona, B.I., 2009. The role of social networks in natural resource governance: what relational patterns make a difference? Glob. Environ. Change 19 (3), 366–374. https://doi.org/10.1016/j.gloenvcha.2009.05.002.

Bodin, Ö., Norberg, J., 2005. Information network topologies for enhanced local adaptive management. Environ. Manag. 35, 175–193. https://doi.org/10.1007/s00267-004-0036-7.

Brasil, 2000. Lei Federal No 9.985, de 18 de julho de 2000. Regulamenta o art. 225, § 1o, incisos I, II, III e VII da Constituição Federal, institui o Sistema Nacional de Unidades de Conservação da Natureza e dá outras providências. Available at: https://www.planalto.gov.br/ccivil_03/leis/l9985.htm. (Accessed 20 May 2023).

Borgatti, S.P., Mehra, A., Brass, D.J., Labianca, G., 2009. Network analysis in the social sciences. Science 323 (5916), 892–895.

Cappozzo, H.L., Perrin, W.F., 2009. South American Sea lion: otaria flavescens. In: Encyclopedia of Marine Mammals. Elsevier, pp. 1076–1079. https://doi.org/10.1016/B978-0-12-373553-9.00244-3.

Corneille, O., Gawronski, B., 2024. Self-reports are better measurement instruments than implicit measures. Nature Reviews Psychology 3 (12), 835–846. https://doi.org/10.1038/s44159-024-00376-z.

Costa, P., Franco-Trecu, V., Ott, P.H., et al., 2007. Distribution and habitat use patterns of southern right whales, Eubalaena australis, off Uruguay. J. Cetacean Res. Manag. 9 (1), 4–51. https://doi.org/10.47536/jcrm.v9i1.691.

Costello, C., Molina, R., 2021. Transboundary marine protected areas. Resour. Energy Econ. 65, 101239. https://doi.org/10.1016/j.reseneeco.2021.101239.

Csardi, G., Nepusz, T., 2006. The igraph software package for complex network research. InterJournal, Complex Systems 1695 (5), 1–9.

Degenne, A., Forsé, M., 1999. Introducing Social Networks. Sage.

Faust, K., 2006. Comparing social networks: size, density, and local structure. Advances in Methodology and Statistics 3 (2). https://doi.org/10.51936/sdbv3216.

Franco-Trecu, V., García, D., Suárez, N., et al., 2019. Marine mammal bycatch by the industrial bottom trawl fishery at the Río de la Plata Estuary and the adjacent Atlantic Ocean. Latin American Journal of Aquatic Research 47 (1), 89–101. https://doi.org/10.3856/vol47-issue1-fulltext-10.

Freeman, L.C., Roeder, D., Mulholland, R.R., 1979. Centrality in social networks: II. Experimental results. Soc. Netw. 2 (2), 119–141. https://doi.org/10.1016/0378-8733(79)90002-9.

Fruchterman, T.M.J., Reingold, E.M., 1991. Graph drawing by force-directed placement. Software Pract. Ex. 21 (11), 1129–1164. https://doi.org/10.1002/spe.4380211102.

Gaines, S.D., White, C., Carr, M.H., Palumbi, S.R., 2010. Designing marine reserve networks for both conservation and fisheries management. Proc. Natl. Acad. Sci. U. S. A 107 (43), 18286–18293. https://doi.org/10.1073/pnas.0906473107.

Geijer, C.K.A., Jones, P.J.S., 2015. A network approach to migratory whale conservation: are MPAs the way forward or do all roads lead to the IMO? Mar. Pol. 51, 1–12. https://doi.org/10.1016/j.marpol.2014.06.002.

Gallon, S., Sourbes, L., Neveu, R., Romani, M., Canals, P., 2019. Towards transboundary monitoring and conservation of mobile species within the MedPAN network. In: *Rapp. Comm. Int. Mer Médit.*, CIESM Congress, vol. 42.

Genov, T., Centrih, T., Wright, A.J., Pleslić, G., 2016. Mid-distance re-sighting of a common bottlenose dolphin in the northern Adriatic Sea: insight into regional movement patterns. J. Mar. Biol. Assoc. U. K. 96 (4), 909–914. https://doi.org/10.1017/S0025315415001241.

Gerber, E.R., Henry, A.D., Lubell, M., 2013. Political homophily and collaboration in regional planning networks. Am. J. Polit. Sci. 57 (3), 598–610. https://doi.org/10.1111/ajps.12011.

González Carman, V., Mandiola, A., Alemany, D., Dassis, M., Seco Pon, J.P., Prosdocimi, L., Ponce de León, A., Mianzan, H., Acha, E.M., Rodríguez, D., 2016. Distribution of megafaunal species in the Southwestern Atlantic: key ecological areas and opportunities for marine conservation. ICES Journal of Marine Science 73 (6), 1579–1588. https://doi.org/10.1093/icesjms/fsw019.

Groch, K.R., Palazzo, J.T., Flores, P.A.C., Adler, F.R., Fabian, M.E., 2005. Recent rapid increases in the right whale (Eubalaena australis) population off southern Brazil. Lat. Am. J. Aquatic Mamm. 4 (1), 41–47. https://doi.org/10.5597/lajam00068.

Groch, K.R., Flores, P.A.C., Kolesnikovas, C.K.M., et al., 2015. Collisions between vessels and southern right whales (*Eubalaena australis*) in the Brazilian coast. In: Abstracts of the 21st Biennial Society for Marine Mammalogy Conference, San Francisco, pp. 13–18.

Grorud-Colvert, K., Claudet, J., Tissot, B.N., Caselle, J.E., Gleason, M., Lester, S.E., et al., 2014. Marine protected area networks: assessing whether the whole is greater than the sum of its parts. PLoS One 9 (8), e102298. https://doi.org/10.1371/journal.pone.0102298.

Gruby, R.L., Gray, N.J., Fairbanks, L., Havice, E., Campbell, L.M., Friedlander, A., Oleson, K.L.L., Sam, K., Mitchell, L., Hanich, Q., 2021. Policy interactions in large-scale marine protected areas. Conserv. Lett. 14 (1), e12753. https://doi.org/10.1111/conl.12753.

Hoyt, E., 2011. Marine Protected Areas for Whales, Dolphins and Porpoises. Earthscan. Taylor & Francis, New York, NY.

Hoyt, E., 2018. Marine protected areas. In: Encyclopedia of Marine Mammals. Elsevier, pp. 569–580.

IUCN Marine Mammal Protected Areas Task Force, 2023. Final Report of the 9 Th IMMA Workshop: Important Marine Mammal Area Regional Workshop for the South West Atlantic Ocean, 5-9 December 2022.

Janssen, M.A., Bodin, Ö., Anderies, J.M., Elmqvist, T., Ernstson, H., McAllister, R.R.J., et al., 2006. Toward a network perspective of the study of resilience in social-ecological systems. Ecol. Soc. 11 (1), 15. https://doi.org/10.5751/ES-01462-110115.

Jefferson, T.A., Leatherwood, S., Webber, M.A., 1993. Marine Mammals of the World. Food & Agriculture Org.

Jones, T., Caro, T., Davenport, T.R.B., 2009. Maintaining Ecological Connectivity Between the Protected Areas of south-central Tanzania: Evidence and Challenges. Anglia Ruskin University, Cambridge, UK.

Katz, J.S., Martin, B.R., 1997. What is research collaboration? Res. Pol. 26 (1), 1–18. https://doi.org/10.1016/S0048-7333(96)00917-1.

King, J., 1983. Seals of the World. Cambridge University Press, Cambridge.

Laffoley, D., Baxter, J.M., Day, J., Wenzel, L., Zischka, K., O'Leary, B.C., 2019. Marine protected areas. In: World Seas: an Environmental Evaluation. Elsevier, pp. 549–569. https://doi.org/10.1016/B978-0-12-805052-1.00027-9.

Lee, K.-H., Noh, J., Khim, J.S., 2020. The Blue Economy and the United Nations' sustainable development goals: challenges and opportunities. Environ. Int. 137, 105528. https://doi.org/10.1016/j.envint.2020.105528.

Li, Y., Fan, Y., Wang, H., Deng, Y., Di, Z., Havlin, S., 2020. Key node ranking in complex networks: a novel entropy and mutual information-based approach. Entropy 22 (1), 52. https://doi.org/10.3390/e22010052.

Lim, M., 2016. Governance criteria for effective transboundary biodiversity conservation. Int. Environ. Agreements Polit. Law Econ. 16, 797–813. https://doi.org/10.1007/s10784-015-9296-3.

Llopis-Albert, C., Palacios-Marqués, D., Soto-Acosta, P., 2015. Decision-making and stakeholders' constructive participation in environmental projects. J. Bus. Res. 68 (7), 1641–1644. https://doi.org/10.1016/j.jbusres.2015.02.010.

Machado, R., Oliveira, L.R., Montealegre-Quijano, S., 2015. Incidental catch of South American sea lion in a pair trawl off southern Brazil. Neotropical Biology and Conservation 10 (1), 43–47. https://doi.org/10.4013/nbc.2015.101.06.

Machado, R., Ott, P.H., Moreno, I.B., et al., 2016. Operational interactions between South American sea lions and gillnet fishing in southern Brazil. Aquat. Conserv. Mar. Freshw. Ecosyst. 26, 108–120. https://doi.org/10.1002/aqc.2554.

Maciejewski, K., Cumming, G.S., 2015. The relevance of socioeconomic interactions for the resilience of protected area networks. Ecosphere 6 (9), 1–14. https://doi.org/10.1890/ES15-00022.1.

Mackelworth, P.C., Teff, Seker Y., Vega Fernández, T., Marques, M., Alves, F.L., D'Anna, G., Fa, D.A., Goldborough, D., Kyriazi, Z., Pita, C., Portman, M.E., Rumes, B., Warr, S.J., Holcer, D., 2019. Geopolitics and marine conservation: synergies and conflicts. Front. Mar. Sci. 6, 759. https://doi.org/10.3389/fmars.2019.00759.

Maestro, M., Milchakova, N., Brkljacic, M., 2019. Marine protected areas in the 21st century: current situation and trends. Ocean Coast Manag. 171, 28–36. https://doi.org/10.1016/j.ocecoaman.2019.01.008.

Marcondes, D., 2020. Conservationist geopolitics: brazilian foreign policy and the South Atlantic Whale Sanctuary. Mar. Pol. 120, 104054. https://doi.org/10.1016/j.marpol.2020.104054.

Mason, N., Ward, M., Watson, J.E.M., Venter, O., Runting, R.K., 2020. Global opportunities and challenges for transboundary conservation. Nature Ecology & Evolution 4, 694–701. https://doi.org/10.1038/s41559-020-1160-3.

Miloslavich, P., Klein, E., Díaz, J.M., Hernández, C.E., Bigatti, G., Campos, L., Artigas, F., Castillo, J., Penchaszadeh, P.E., Neill, P.E., Carranza, A., Retana, M.V., Díaz de Astarloa, J.M., Lewis, M., Yorio, P., Piriz, M.L., Rodríguez, D., Yoneshigue-Valentin, Y., Gamboa, L., Martín, A., 2011. Marine biodiversity in the Atlantic and Pacific coasts of South America: knowledge and gaps. PLoS One 6 (1), e14631. https://doi.org/10.1371/journal.pone.0014631.

MMA, 2023. Avian influenza report, August 16, 2023. Available at: https://www.gov.br/icmbio/pt-br/assuntos/centros-de-pesquisa/cemave/destaques/gripe-aviaria/informes-epidemiologicos-1/06_informe_influenza-aviaria_16_08_2023.pdf. (Accessed 25 October 2023).

Newman, M.E.J., 2010. Networks: an Introduction. Oxford University Press.

Newman, M.E.J., 2018. Network structure from rich but noisy data. Nat. Phys. 14 (6), 542–545. https://doi.org/10.1038/s41567-018-0076-1.

Newman, M.E.J., Girvan, M., 2004. Finding and evaluating community structure in networks. Phys. Rev. 69 (2), 026113. https://doi.org/10.1103/PhysRevE.69.026113.

Nascimento, L.O., Barreto, J., de Oliveira Gomes, L.E., Bomfim, L.N.S., Martins, A.S., 2023. Solid waste ingestion by marine megafauna on Southeast Brazilian coast. Mar. Pollut. Bull. 190, 114821. https://doi.org/10.1016/j.marpolbul.2023.114821.

OSPAR Commission, 2023. About OSPAR. Available at: https://www.ospar.org/about. (Accessed 16 April 2025).

Palazzo, J.T., 2003. Building a Marine Protected Areas Network to Protect Endangered Species: Whale Conservation as a Tool for Integrated Management in South America.

Palazzo Jr, J.T., Flores, P.A. de C., 1998. Right whales Eubalaena australis in southern Brazil: a summary of current knowledge and research needs. In: International Whaling Commission Workshop on the Comprehensive Assessment of Right Whales: a Worldwide Comparison, Cape Town, South Africa.

Panigada, S., Pesante, G., Zanardelli, M., Capoulade, F., Gannier, A., Weinrich, M.T., 2006. Mediterranean fin whales at risk from fatal ship strikes. Mar. Pollut. Bull. 52, 1287–1298. https://doi.org/10.1016/j.marpolbul.2006.03.014.

Pavanato, H., Silva, K.G., Estima, S.C., Monteiro, D.S., Kinas, P.G., 2013. Occupancy dynamics of South American sea-lions in Brazilian haul-outs. Braz. J. Biol. 73, 855–862. https://doi.org/10.1590/S1519-69842013000400023.

Payne, R., 1986. Long term behavioral studies of the southern right whale (*Eubalaena australis*). Rep. Int. Whal. Comm. 10, 161–167.

Payne, R., et al., 1990. Population size, trends and reproductive parameters of right whales (*Eubalaena australis*) off Peninsula Valdes, Argentina. Rep. Int. Whal. Comm. 271–278.

Pires Renault-Braga, E., et al., 2018. Area usage estimation and spatiotemporal variability in distribution patterns of southern right whales, Eubalaena australis, of southern Brazil. Mar. Ecol. 39 (3), e12506. https://doi.org/10.1111/maec.12506.

Pinheiro, H.T., Rocha, L.A., Macieira, R.M., Carvalho-Filho, A., Anderson, A.B., Bender, M.G., Di Dario, F., Ferreira, C.E.L., Figueiredo-Filho, J., et al., 2018. South-western Atlantic reef fishes: zoogeographical patterns and ecological drivers reveal a secondary biodiversity centre in the Atlantic Ocean. Divers. Distrib. 24, 951–965. https://doi.org/10.1111/ddi.12729.

Pont, A.C., Marchini, S., Engel, M.T., et al., 2015. The human dimension of the conflicts between fishermen and sea lions in southern Brazil. Hydrobiologia 770, 89–104. https://doi.org/10.1007/s10750-015-2576-7.

Pons, P., Latapy, M., 2005. Computing communities in large networks using random walks. In: International Symposium on Computer and Information Sciences. Springer.

Plaza, P., Gamarra Toledo, V., Rodríguez Eugui, J., Rosciano, N., Lambertucci, S.A., 2023. Pacific and Atlantic Sea lion mortality caused by highly pathogenic avian influenza A(H5n1) in South America. Available at: SSRN: https://ssrn.com/abstract=4611782, 10.2139/ssrn.4611782.

Procksch, N., et al., 2020. The northernmost haulout site of South American sea lions and fur seals in the western South Atlantic. Sci. Rep. 10 (1), 20008. https://doi.org/10.1038/s41598-020-76755-2.

R Core Team, 2023. A language and environment for statistical computing. Available at: https://www.r-project.org/. (Accessed 16 March 2023).

Ramos, K.L., Machado, R., Zapelini, C., de Castilho, L.C., Schiavetti, A., 2023. Knowledge, attitudes and behavioural intentions of gillnet fishermen towards the South American sea lion in two marine protected areas in southern Brazil. Ocean Coast Manag. 242, 106673. https://doi.org/10.1016/j.ocecoaman.106673.

Rodrigue, J.P., 2020. The Geography of Transport Systems, fifth ed. Routledge, New York, NY.

Roman, J., Abraham, A.J., Kiszka, J.J., Harrison, A.-L., Palacios, D.M., Torres, L.G., Rayment, W., Zerbini, A.N., Kennedy, A.S., Costa, D.P., 2025. Migrating baleen whales transport high-latitude nutrients to tropical and subtropical ecosystems. Nat. Commun. 16, 2125. https://doi.org/10.1038/s41467-025-56123-2.

Rosas, F.C.W., et al., 1994. Seasonal Movements of the South American Sea Lion (*Otaria flavescens*, Shaw) off the Rio Grande do Sul Coast, Brazil.

Rosenman, R., Tennekoon, V., Hill, L.G., 2011. Measuring bias in self-reported data. Int. J. Behav. Healthc. Res. 2 (4), 320–332. https://doi.org/10.1504/IJBHR.2011.043414.

Rowntree, V.J., Payne, R.S., Schell, D.M., 2020. Changing patterns of habitat use by southern right whales (*Eubalaena australis*) on their nursery ground at Península Valdés, Argentina, and in their long-range movements. J. Cetacean Res. Manag. 133–143. https://doi.org/10.47536/jcrm.vi.298.

Rylands, A.B., Brandon, K., 2005. Unidades de conservação brasileiras. Megadiversidade 1 (1), 27–35.

Riet-Sapriza, F.G., Costa, D.P., Franco-Trecu, V., Marín, Y., Chocca, J., González, B., Beathyate, G., Chilvers, B.L., Hückstadt, L.A., 2013. Foraging behavior of lactating South American sea lions (*Otaria flavescens*) and spatial–temporal resource overlap with the Uruguayan fisheries. Deep-Sea Res. Part II Top. Stud. Oceanogr. 88–89, 106–119. https://doi.org/10.1016/j.dsr2.2012.09.005.

Sanfelice, D., Vasques, V.C., Crespo, E.A., 1999. Ocupação sazonal por duas espécies de otariidae (Mammalia-Carnivora) da reserva ecológica da Ilha dos Lobos, Rio Grande do Sul, Brasil. Iheringia. Série Zool. 87, 101–110.

Speed, C.W., Cappo, M., Meekan, M.G., 2018. Evidence for rapid recovery of shark populations within a coral reef marine protected area. Biol. Conserv. 220, 308–319. https://doi.org/10.1016/j.biocon.2018.01.010.

Túnez, J.I., Centrón, D., Capozzo, H.L., Cassini, M.H., 2006. Geographic distribution and diversity of mitochondrial DNA haplotypes in South American sea lions (Otaria flavescens) and fur seals (Arctocephalus australis). Mamm. Biol. 72 (4), 193–203. https://doi.org/10.1016/j.mambio.2006.08.002.

Túnez, J.I., Capozzo, H.L., Cassini, M.H., 2008. Regional factors associated with the distribution of South American fur seals along the Atlantic coast of South America. ICES Journal of Marine Science 65 (9), 1733–1738. https://doi.org/10.1093/icesjms/fsn168.

UNEP/MAP, 2020. MedPAN: the network of marine protected area managers in the Mediterranean. United Nations environment programme/Mediterranean action plan. Available at: https://www.unep.org/unepmap/what-we-do/MSSD/MedPAN. (Accessed 16 April 2025).

Vaz-Ferreira, R., 1982. Otaria flavescens (Shaw), South American sea lion. Mammals in the Seas 4, 477–495.

WCPA, I., 2008. Establishing Resilient Marine Protected Area Networks—Making it Happen. IUCN-WCPA, Washington DC.

Wilkinson, T., et al., 2004. Marine species of common conservation concern: protecting species at risk across international boundaries. In: Proceedings of the Fifth International SAMPAA (Science and Management of Protected Areas) Conference. British Columbia. Vic.

Zapelini, C., Souza, D.S., Santana, R.O., Olaya-Restrepo, J., Schiavetti, A., 2024. Environmental, social, and management aspects in a hotspot: interaction networks between marine protected areas. Ocean Coast Manag. 251, 107068. https://doi.org/10.1016/j.ocecoaman.2024.107068.

Zappes, C.A., Silva, C.V., Pontalti, M., Danielski, M.L., Di Beneditto, A.P.M., 2013. The conflict between the southern right whale and coastal fisheries on the southern coast of Brazil. Mar. Pol. 38, 428–437. https://doi.org/10.1016/j.marpol.2012.07.003.