



Understanding socioecological interaction networks in Marine Protected Areas to inform management

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ABSTRACT

The concept of ecosystem services has become increasingly important in understanding the interactions between humans and nature and the associated implications in terms of human well-being. Despite growing interest in ecosystem services research, knowledge of their ecological underpinnings and their integration with socio-economic and management components remains limited. In this study, we propose a multi-layered network approach to assess the connection between ecological components, ecosystem functions and societal uses and benefits, management actions, and global change impacts in four Marine Protected Areas (MPAs) in Spain. An interaction matrix between all relevant components in the MPAs was built based on scientific knowledge, published records, and validated in stakeholder workshops. Then, we applied network analysis to explore the emergent properties of the network of connected elements in the MPAs. For example, habitat foundation species, such as kelp or seagrasses, were central to the networks and concentrated most connections with other ecological, social, and management components. The positive-negative index showed that human activities often had negative indices, ecological components had positive indices, and management, mitigation action, and infrastructure had variable effects across MPAs. Betweenness identified the foundation species or the scientific community as playing a key role in facilitating connections across the network in MPAs. This research provides valuable insights into the complex interactions between ecosystems, human activities, ecosystem functions and services, and management opportunities for coastal MPAs, with important consequences for the local management of the areas.

1. Introduction

Coastal ecosystems support a substantial proportion of global biodiversity and play a significant role in the well-being of societies by regulating the local climate, providing food, and preserving cultural values and recreational opportunities (Barbier, 2017). Nevertheless, coastal ecosystems are threatened globally by ever-increasing environmental pressures, including global change (IPBES, 2019). The consequences of increased temperatures, extreme weather events, and changes in rainfall regimes have already been reported as the drivers

responsible for most of the global increase in cumulative impacts in the marine environment (Bryndum-Buchholz et al., 2019). The combined effects of climate change and local stressors could have cumulative impacts on marine ecosystems with direct effects on human well-being through the loss of ecosystem services (Simeoni et al., 2023). In this context, it is important to focus on local management actions that contribute to increasing the resilience of marine ecosystems (Roberts et al., 2017) and provide ecosystem services in the future.

Marine Protected Areas (MPAs) are globally recognized instruments for safeguarding biodiversity, maintaining marine ecosystem health,

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and supplying ecosystem services (Di Franco et al., 2016; Zhang et al., 2019). In the European Union, MPAs cover 12% of the EU Seas; however, not all of them are effectively managed, and less than 1% are strictly protected (Di Cintio et al., 2023). MPAs are promoted and designated for different purposes, such as conserving marine biodiversity (Sala et al., 2021), improving fisheries management (Cabral et al., 2019), safeguarding ecosystem services provision (Di Franco et al., 2016), including recreational activities (de Juan et al., 2021), and achieving a combination of these goals (Ospina-Alvarez et al., 2020). Their governance is also remarkably diverse, ranging from co-management and community-based to state-led MPAs (Jones et al., 2013). While MPAs have the potential to improve both human well-being and biodiversity conservation (Ban et al., 2019), by providing positive ecological and social outcomes, their long-term success often depends not only on the acceptance and support of local communities, but also on the conflicts generated between the interests of multiple users (Ban et al., 2017; Bennett and Dearden, 2014; Edgar et al., 2014).

For these reasons, MPAs provide an ideal context for the study of interactions between ecological, socioeconomic, and legislative frameworks. However, knowledge on their ecological underpinnings and their integration with socioeconomic and management components remains still largely limited (Bennett, 2017). The characterization of human-ocean relationships is complex, as multiple aspects must be considered simultaneously. These aspects include the non-linear interaction between humans and the biological systems in which they are embedded (Koch et al., 2009), the translation of these interactions into the flow of services from nature to people (Potts et al., 2014), and the different human uses that can generate conflicts between social actors (Agardy et al., 2003). Multidisciplinary methods that integrate information from diverse sources are needed. The combination of scientific and end-user knowledge allows the integration of multiple perspectives over a complex socio-ecological system, such as MPAs. Multidisciplinary working groups can produce semi-quantitative databases that can be analyzed with advanced statistical methods, such as network analysis, to identify the emergent properties of a system of connected actors.

Graph theory is defined as the mathematical study of the interaction of a system of connected elements (Berge, 1962). The analysis of networks using Graph Theory can be described as the analysis of existing relationships (i.e., edges) between different elements (i.e., nodes) contained in a network. Therefore, it can be used to explore the relationships between ecological and social components and explain the emergent properties of complex MPA systems (Borgatti et al., 2009). Networks provide a quantitative view of the multiple factors involved in the connection of the entities within a system through the quantity and quality of edges, and allow the identification of critical nodes within the network (Scott, 1988). Additionally, social-ecological systems can be interpreted as a network of overlapping layers, known as multi-layered or multi-level networks (Pilosof et al., 2017). Multi-layered networks have two or more layers that represent distinct types of interactions, species communities, social actors, etc.

Studying MPA systems through a multi-layered approach has the potential to account for the interdependencies between complex human and ecological dynamics that underpin important environmental problems. Network analysis has been previously employed in various contexts, including the examination of trophic interactions (Pérez-Matus et al., 2017), the investigation of spatial connectivity regarding species composition (de Juan et al., 2023), and the exploration of transport, dispersion, and connectivity within marine fauna and flora (Pastor et al., 2022). Additionally, it has been applied in the assessment of marine system management (Ospina-Alvarez et al., 2020) and to analyze the traceability of global seafood trade on an international scale (Ospina-Alvarez et al., 2022). However, despite these diverse applications, its use in the study of complex socio-ecological systems within marine and coastal environments is still in its early stages (although notable exceptions exist, as evidenced by Bruzese et al., 2022; Ruiz-Frau et al., 2020; Tuda et al., 2021).

This study focuses on four MPAs in Spain to illustrate the application of network analysis to explore complex interactions between the environmental, ecological, and social and ecological components of a coastal system and interpret the interactions from a management perspective. The application of network analysis allows the identification of relevant components in the MPA owing to the quantity and quality of connections (i.e., edges in the network) among components (i.e., nodes in the network); and these network interactions are highly context specific. The four MPAs are characterized by distinct environmental contexts and management schemes: the Cabo de Gata-Níjar Natural Park, the Marine Reserve of Fishing Interest of Os Miñarzos, and two Maritime-Terrestrial National Parks, the Atlantic Islands of Galicia, and Cabrera Island. Taking advantage of the variable context offered by the MPAs under study, we explore the applicability of the network analysis to understand the specific socio-ecological interactions that emerge in MPAs. This analysis potentially has implications for the assessment of the effectiveness of the MPA and for how policymakers identify actions to deal with local conflicts in the case study.

2. Methods

2.1. Study areas

The four MPAs were in geographical areas with distinctly different ecological features and had varying degrees of protection and restrictions as part of their management regimes. This selection allowed to explore the capacity of the network analysis to capture interactions in different ecological, social, and institutional contexts. The case studies included two MPAs located on the northwestern Atlantic coast of Spain and two MPAs in the Mediterranean (Fig. 1). Two of the MPAs were established as National Maritime-Terrestrial Parks (NMTP), which is the highest form of protection under Spanish regulations (i.e., these figures have the most complete mechanisms for the management of uses and protection of ecosystems), one MPA is a Natural Park (NP), and the fourth is a marine reserve of fishing interest (Table 1).

The Cabo de Gata-Níjar Natural Park (CGN-NP) covers 506.4 km², including a marine reserve of 120 km² in the Andalusia region in southern Spain and the Mediterranean Sea (Fig. 1). It represents the largest protected coastal stretch in Spain and includes extensive meadows of *Posidonia oceanica* and *Cymodocea nodosa*. The NP was created in 1995 (under Council Regulation (EC) 1626/94) to extend the existing Natural Park (CGN-NP) (declared in 1987, which includes 386.4 km² of land and 73.59 km² of internal waters). Six integral reserve areas totaling 46.5 km² were defined, where extraction and recreational activities were prohibited. 7500 inhabitants permanently live in the NP, concentrated in small coastal villages, where artisanal fisheries represent the main economic activity. The human population increases in summer and is associated with tourism, which is a relevant sector for the economy of the area. The CGNP, belonging to the Natura 2000 Network, has been declared SPAMI, is included in the MedPan network, and has also been declared a biosphere reserve by UNESCO.

The Maritime-Terrestrial National Park (MTNP) of Cabrera was officially established in 1991 through a process initiated by conservation organizations. The MTNP is located on a small island in the SE southeast of the island of Mallorca, in the Mediterranean (Fig. 1), and has a total area of 90,800 ha, of which approximately 89,000 ha is marine, including coralligenous bottoms and *Posidonia oceanica* seagrass meadows. A limited number of artisanal fishery licenses have been issued, with trammel netting being the main activity. Coastal uses such as beach use or diving are restricted to dedicated areas. Visitors can access the MTNP either through a commercial ferry or by private boat, previously requesting a permit. A limited number of daily permits were issued.

The Cíes Islands (MTNP Islas Atlánticas de Galicia) constitute an archipelago in the northwest of the Iberian Peninsula (Fig. 1). The total area is 3091 ha, with 433 ha of terrestrial area and 2658 ha of marine



Fig. 1. Geographical positions of the four case studies. The map shows the MPAs locations: RMIP Os Miñarzos on the Lira Coast in the Atlantic Ocean; MTNP Islas Atlánticas de Galicia (Cíes Islands) in the Atlantic Ocean; CGN-NP Cabo de Gata-Níjar on the coast of Andalusia in the Mediterranean Sea; and MTNP Archipiélago de Cabrera (Cabrera Islands) in the Balearic Islands and, also in the Mediterranean Sea.

Table 1

Main geographic, demographic, and management characteristics of the selected Marine Protected Areas.

MPA	Location	Management type	Permanent Population	Annual tourists	Main economic activities	Area
MTNP Islas Atlánticas Galicia	NW Spain. Atlantic	National Maritime-Terrestrial Park	4	330,000 (2022)	Tourism Artisanal fisheries	26.58 km ² marine 4.33 km ² terrestrial
RMIP Os Miñarzos	NW Spain. Atlantic	Marine Fishing Reserve	0	0	Artisanal Fisheries	20.74 km ² (1.40 km ² integral reserve)
CGN-NP Cabo de Gata-Níjar	Mediterranean Sea	Natural Park	7500	192,000 (2010)	Tourism Artisanal fisheries	120.12 km ² marine 375.00 km ² terrestrial
MTNP Archipiélago de Cabrera	Mediterranean Sea	National Maritime-Terrestrial Park	0	185,000 (2011)	Tourism Artisanal fisheries	84.8 km ² marine 15.69 km ² terrestrial

area, including kelp forests and coastal lagoons. Artisanal fisheries have historically represented an important economic activity in the area throughout recent history, with approximately 500 fishing ships vessels currently operating on the archipelago. The Cíes Islands are not permanently inhabited. However, they were visited by more than 330,000 tourists in 2022, mainly sun and beach users, as well as practitioners of active tourism initiatives. The islands were declared a Natural Park by Royal Decree in 1980, and the management plan was approved in 1999. The MTNP of the Atlantic Islands of Galicia was created in 2002. In 2018, the Rector Plan for the Use and Management of National Parks was approved. The islands are also part of the Galician

Natura 2000 Network Master Plan, which includes protection tools, such as the Special Protection Area for Birds and the Special Conservation Area.

The Os Miñarzos Marine Reserve of Fishing Interest (RMIP), located in the northwest of the Iberian Peninsula (Fig. 1), covers 2074 ha of the underwater area. It was established by the decree of the Galician Regional Government in 2007 after a 5-years process in which artisanal fishers were actively involved, leading to a system of co-management within the reserve, resulting in greater acceptability and compliance with the rules. This initiative emerged from the severe impact of the Prestige oil spill in 2002 on artisanal fisheries (de Oliveira, 2013).

Despite the lack of public funding, the creation of the RMIP successfully built a common vision of a sustainable future for the reserve and associated coastal communities. The main fisheries in the reserve target invertebrates (e.g., clams, octopus, crabs, sea urchins) and fish. Scientific activities were allowed within the reserve; however, recreational fishing, diving, and other activities were only allowed outside the reserve area, but only scientific activities are allowed within. Tourist uses were negligible.

2.2. Construction of interaction matrices

To identify and capture the relationships between ecological, social, and institutional elements in the case studies, we used an adaptation of the Ecosystem Services (ES) cascade framework by Haines-Young and Potschin (2010). The ES cascade approach is particularly well-suited for establishing links between the ecological elements, functions, and services they provide and the social components in a system. We modified and expanded the original framework to include the effects of management and the impact of climate change on the system. Two main elements can be distinguished in the cascade approach: the different components in the system, and the interactions between them. Therefore, this approach is well-suited to feed a Network Analysis by indicating the nodes (i.e., components) and edges (i.e., interactions) in the system. In this study, we considered five major component categories (Table 2) and three types of potential interactions. The interactions between the different components could be of an ecological, social, or manageable nature. The ecosystem service component is not considered in the matrix because it is extracted from the relationship between ecosystem functions and social actors (Bennett et al., 2015). The inclusion of the three components (function, service and human activity) would generate redundancy in the matrix.

For each case study, a list of specific components based on the biophysical context and the main actors in the MPA was developed. Between four and ten components within each of the four categories were identified for each category in each protected area. The total number of components per area was limited to the most relevant ones to avoid complex networks that are difficult to interpret. Therefore, a maximum of 31 ecological, environmental, and socio-economic components were identified in each MPA. A fraction of these components was kept common to all areas to guarantee the existence of connecting elements between the four networks (e.g., policy actors).

A square matrix that included the weight and direction of the

Table 2

The socio-ecological components of the MPA are classified into one of the five categories.

Categories	Definition	Examples
Ecological components	The structural biophysical components that either provide key ecological functions or are species/habitats of conservation interest	Fish diversity, seagrass meadow, kelp forest, charismatic species
Ecosystem functions	The biological processes that underpin the supply of ecosystem services	Habitat provision, nutrient cycling, coastal protection, carbon sequestration
Social Actors	Social groups that interact with the ecological components at distinct levels, whether it be for use, management, or enjoyment	Use: small-scale fisher Management: area manager or decision maker Enjoyment: sun and beach tourism
Human interventions	Human actions whose purpose is to manage activities in the protected area to minimize negative effects on the biophysical components.	Regulation, enforcement, mitigation actions, MPA infrastructure
Global change	the main drivers of global change on marine ecosystems	Warming, ocean acidification, extreme weather events

interactions between the different components was built for each area. The connections between the different components could be directed, weighted, and signed (positive or negative). The connections between components in the matrix were assigned on a scale of -1 to 1 (i.e., -1 , 0 , 1), where -1 corresponds to a negative interaction, 1 corresponds to a positive interaction, and 0 indicates a neutral interaction. In general, connections were considered unidirectional relationships and were only considered in both directions when the relationship between components made sense (Table 3). Only direct relationships that were evident between two nodes were represented. Indirect relationships derived from chain relationships were not considered in this study. Global change components were forced to interact only with ecological components, with effects assumed to be negative (based on general global patterns in the literature).

2.3. Validation of interaction matrices

The matrices were elaborated based on the information obtained from the bibliography, reports, and small interviews with experts on MPAs. Once the matrices were developed, working groups were organized for validation, except for Cabrera MPA, owing to project-logistic constraints. The working groups included representatives from different sectors considered in the case study system (e.g., administration and management, research, fishing, and NGO representatives). In each of these working groups, questions and doubts were raised about specific interactions in the network to corroborate, validate, or modify certain information contained in the matrix. Each sector initially focused on analyzing specific relationships between the components most related to their role in the MPA; for example, researchers focused on validating interactions between ecological components and ecosystem functions. Roundtables were then arranged to reach a final consensus on the interactions between the components. The functioning of the roundtables focused on generating small discussions in such a way that all points of view of the attendees were considered to encourage participation and obtain a result with the highest possible degree of consensus. Once the roundtables were completed, consensus information was used to correct the matrices if necessary; in this way, a final matrix of interactions (direction and sign) between the components was obtained.

2.4. Analysis of networks and calculation of centrality measures

After validating the matrices of interacting components, a multi-layer approach was used to conduct a network analysis that assessed the connection between ecological components, ecosystem functions, social actors, and management actions in each protected area. First, a network graph was constructed using four case studies to identify commonalities across areas. Individual networks were then conducted for each case study to identify local properties in the management system. The climate change components were only considered in the global network, which includes the four case studies; this component was excluded from the individual networks. This exclusion was made because climate change impacts cannot be managed locally, and the objective of local networks is to highlight those components that are susceptible to being managed.

An adjacency matrix with weights was constructed for all nodes in all categories, which was represented as a graph using R language and environment for statistical computing and the *igraph* package. In a network of connected elements, it is possible to determine which element is most important by calculating a series of centrality measures. Centrality measures (i.e., degree, eigenvector, and betweenness) were selected because they are known to be effective for identifying emerging patterns in ecological and social systems (de Juan et al., 2021; Ospina-Alvarez et al., 2020). The eigenvector centrality network metric considers not only the number of connections a node has (i.e., its degree or strength) but also the centrality of the vertices to which it is

3. Results

3.1. Cabo de Gata-Níjar Natural Park

In Cabo de Gata-Níjar, the network analysis arranged components in two clusters that reflect different socio-ecological dynamics occurring in the MPA (Fig. 2); one is organized around the marine species and biological communities that directly or indirectly support ecological functions, such as carbon sequestration, nutrient recycling or productivity; a second cluster reflects the negative relationships associated with diverse stakeholders' groups, led by recreational fishers, but also active tourists' and MPA managers.

The network clearly shows a positive role (i.e., a high positive-negative index of the nodes, Fig. 2) of marine phanerogams (*Posidonia* and *Cymodocea*) as these species are key supporters of ecological functions, including the provision of habitat for fish and invertebrates. In this sense, *Posidonia* and fish and invertebrate diversity occupy a central position in the network, reflecting their relevance as nodes connected to many other nodes in the network, and shows the highest positive index (i.e., these connections are mainly positive).

Recreational fisheries and MPA managers represent groups with the most central position in the network and, particularly recreational fishers, are negatively affected by regulation, enforcement, and mitigation actions. Despite NGOs have a marginal position in the network, they do have connections (i.e., high eigenvector value) with other actors (e.g., negative with the hospitality sector and positive with mitigation actions). Sun and beach tourism, despite having a low eigenvector value (i.e., the number of connections and centrality of the nodes it is connected to is not high), presents a central position in the network and is positively related to all key marine species (*Posidonia* and seabirds) and

negatively affected by recreational fishers. Active tourism also has a central position in the network and a high betweenness index (Fig. S1), indicating their role in channeling connections among the components in the network, e.g., seabird diversity, active tourism, mitigation actions.

3.2. Cabrera National Park

In Cabrera Island MPA, the biological components adopt a highly central position in the network, denoting their importance as the basis for the system (Fig. 3). They show high eigenvector values and the most positive indices, in particular *Posidonia oceanica*, which also has high betweenness, indicating its role in structuring the network (Fig. S2) and in connecting many nodes of the network. The grouper (*Epinephelus marginatus*), despite being a key species in the area, has a marginal position in the network with a low positive-negative index. Our results also show the marginal importance of the ecosystem function "carbon sequestration" and "coastal protection" within the network.

The scientific community plays a central position in the network with one of the highest eigenvector values and a high positive index, which denotes the importance of this component by the number of positive connections with other central nodes. The NGOs and MPA managers have a similar high eigenvector value, however, their positive index is lower than the scientific community. In this network, MPA infrastructure and awareness rising, despite positively affecting beach users, have a marginal role in the network.

Small-scale fishers and sun and beach users do not have a central position in the network, but these actors have a high eigenvector and the most negative index of all components. As reflected through the network, this is because both groups are the ones most affected by the different human intervention components (e.g., mitigation actions,

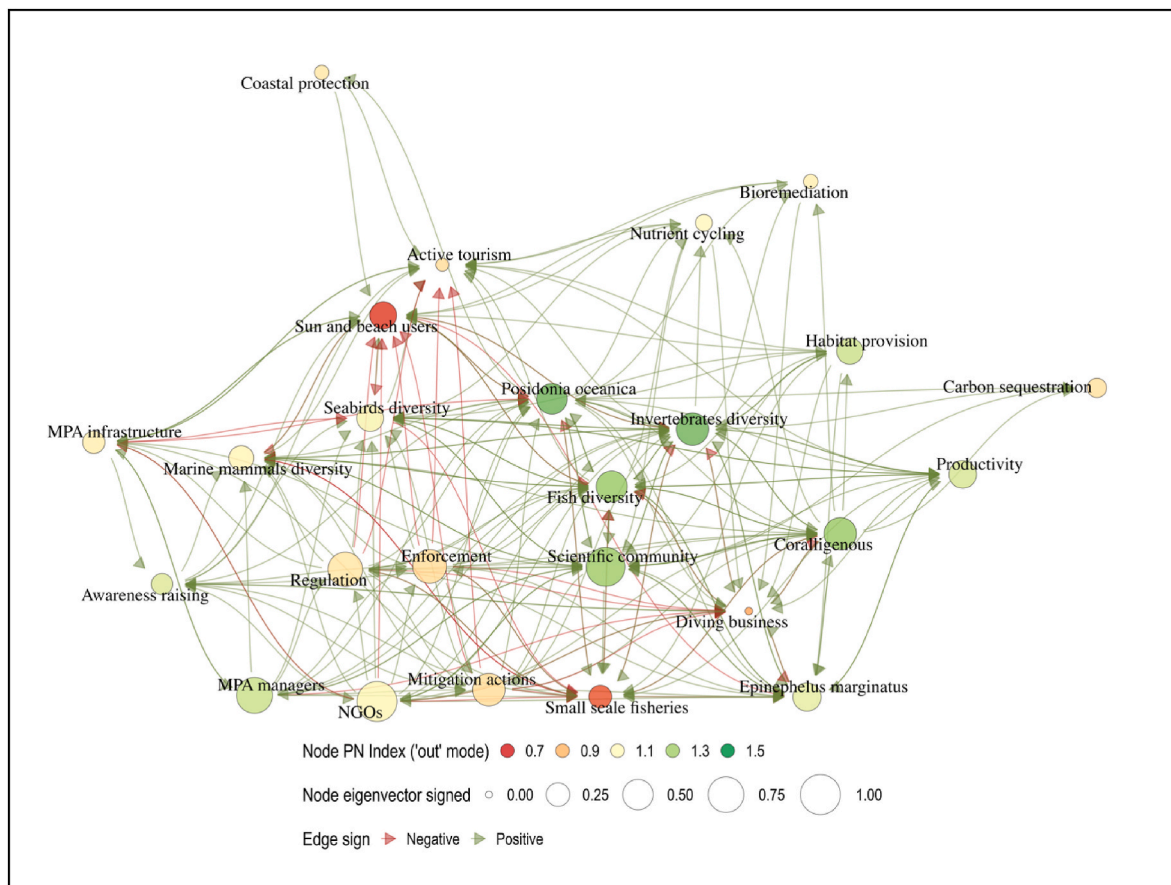


Fig. 3. –Network of the positive-negative index in Cabrera Islands MPA. Node color denotes the positive-negative score, based on the average of the effects the node has over other nodes, and the edge color is related to the positive (green) or negative (red) link between nodes. The node size represents the Eigenvector centrality.

regulation, enforcement) and, at the same time, are the social groups that have the most negative effects on the biological components of the system. Active tourism and diving are negatively influenced by MPA regulation and mitigation actions; however, these actors do not appear to have a relevant role in the network. Sun and beach tourism are related to the coastal ecosystem components (Posidonia and seabirds) and marginally by MPA infrastructure, awareness, and marine mammals. Small-scale fishers on the other hand are more related to fish and fish diversity (positive) and regulation, enforcement, and mitigation actions (negative). Also, it is important to note the negative interaction between marine mammals and fishers.

3.3. Cíes Islands National Park

The results obtained for Cíes Islands MPA (Fig. 4) denote two main clusters in the network: one organized around the marine resources directly or indirectly exploited by small-scale fisheries or enjoyed by diving activities, and another one centered in the landscape of the MPA. Active tourism has a central position in the network, and it has a high betweenness, acting as a connector of nodes through the network (Fig. S3). Benthic invertebrates and the fish community show high eigenvector values and positive indices reflecting their key roles in the network (e.g., as key components of the trophic network), which channels energy towards the fishing activity. Seabirds also have high eigenvector but have a lower positive index and are more related to the landscape cluster. Other biotic (e.g., kelp and marine mammals) and ecosystem functions (e.g., nutrient cycling and coastal protection) are marginal in the network.

MPA managers and the scientific community adopt a central position in the network, connecting the two identified clusters of nodes. Both

components show high eigenvector values and a positive index. NGOs show a lower positive index and are more related with the landscape cluster and the interaction with the touristic activity than to the marine resources-based portion of the network.

The social activities showing a central position in the network, and with the most negative outgoing links, are small scale fisheries and active tourism, that not only interact negatively between them but also impact several biological components and other social actors. The low values of the positive-negative index (i.e., in average, the negative connections prevail) of these activities allow inferring interactions that may potentially lead to conflicts between users (e.g., between small scale fisheries and active tourists, divers or MPA managers and between beach users and NGOs). As expected from the nature of the national park protection figure, regulation and enforcement display a relevant and positive role in the network (Fig. 6). By contrast, mitigation actions exert a negative impact over stakeholders operating in the Cíes Islands MPA.

3.4. Os miñarzos fishing reserve

The Os Miñarzos MPA is characterized by having small-scale fisheries in a central position, but with a neutral positive-negative index (Fig. 5). Fish diversity, habitat provision, shell-fishers and the scientific community are also in a central position and have a high eigenvalue.

The network reflects a conflict between recreational and commercial fishers, being recreational fishers one of the nodes with a more negative index. Sun and beach tourism also have a negative index; however, this component has a marginal position in the network.

The Os Miñarzos MPA is characterized by a high diversity of habitats and species, which is reflected by the central position of the habitat components, with positive connections with other components, in

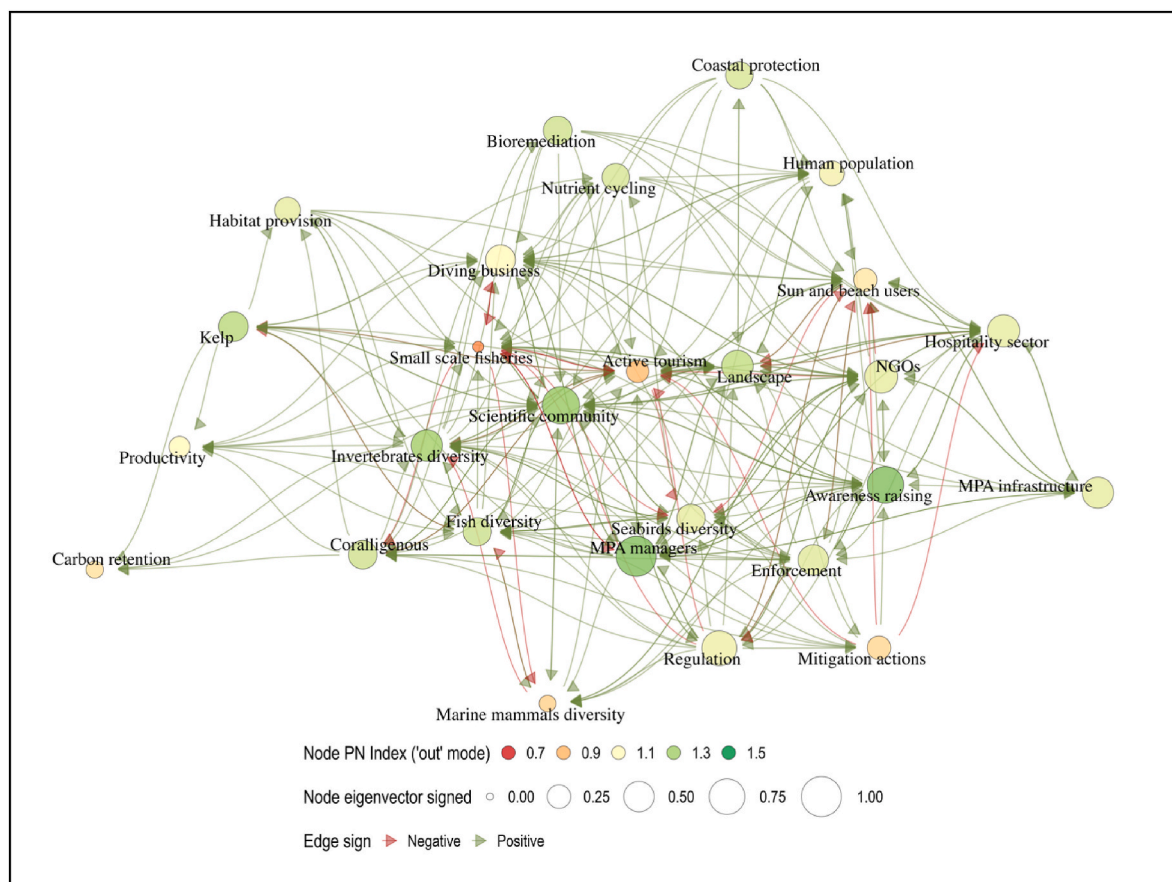


Fig. 4. –Network of the positive-negative index in Cíes Islands MPA. Node color denotes the positive-negative score, based on the average of the effects the node has over other nodes, and the edge color is related to the positive (green) or negative (red) link between nodes. The node size represents the Eigenvector centrality.

particular fish and invertebrate diversity, productivity, and coastal protection. This is evidenced in the betweenness metric (Fig. S4), as shell-fishers, artisanal fisheries, fish diversity and habitat provision have a high index, being important architects of the network (i.e., influencing the flow of information between pairs of nodes). It is important to note the role of marine mammals, that, despite having a marginal position in the network, have a negative index, due to negative interactions with fish diversity and small-scale fishers that then propagate through the network.

3.5. Global network

The group of nodes under the category “ecological components,” has the highest averaged positive index in the four MPAs, whereas the group of nodes “social actors,” in general, has the lowest scores (Fig. 6). The average positive-negative index for the group of components termed “interventions” (e.g., regulation and enforcement) has a high variability amongst MPAs. The average betweenness presents a high variability amongst components and MPAs, and between components of the same group in a single MPA (Fig. 6). For example, whereas in Cabrera and Cíes Islands MPAs, the scientific community emerges for having high betweenness, in Os Miñarzos and Cabo de Gata-Níjar MPAs the social actors with the highest betweenness are shell-fishers and active tourism, respectively.

The global network (Fig. 7) evidence a consistent positive role of the ecological components across the four MPAs, while climate change drivers have a marked negative effect on the MPA networks. The principal functions flowing from the biological components, are habitat provision and productivity, which connect to social actors that tend to show negative values of the positive-negative index and low eigenvector

values. The scientific community, the regulation and then enforcement, all have a high eigenvector value, denoting the importance of these three components for the MPAs. However, while the scientific community has a positive role in the network, the regulation and enforcement tend to have negative indices, reflecting conflicts with uses in the areas.

4. Discussion

4.1. Network analysis for understanding complex socio-ecological systems

The network analysis applied to four socio ecological MPA systems in Spain highlights the flow of connections between elements, the magnitude of the influence of one element on another, and the positive or negative sign of this interaction. The observed connections revealed by this analysis are complex and allow identifying patterns that may not be visible through other approaches or analyses (Ospina-Alvarez et al., 2020; 2022). For example, the habitat foundation species characteristic of the case studies, such as kelp or seagrasses, are central in the network and have a high eigenvalue as they concentrate most connections with other ecological components, but also with the human actors and management actions; many of these components also central in the network. The positive-negative index indicates whether a node has an overall negative, neutral or positive influence according to the sum of the connections with other nodes in the network; human activities often had negative indices, ecological components had positive indices, and management, mitigation actions and infrastructure had variable effects across MPAs. Betweenness identifies the foundation species or the scientific community as having a key role in facilitating connections across the network in some MPAs. On the other hand, the network graph also evidences the components that, having a marginal position in the

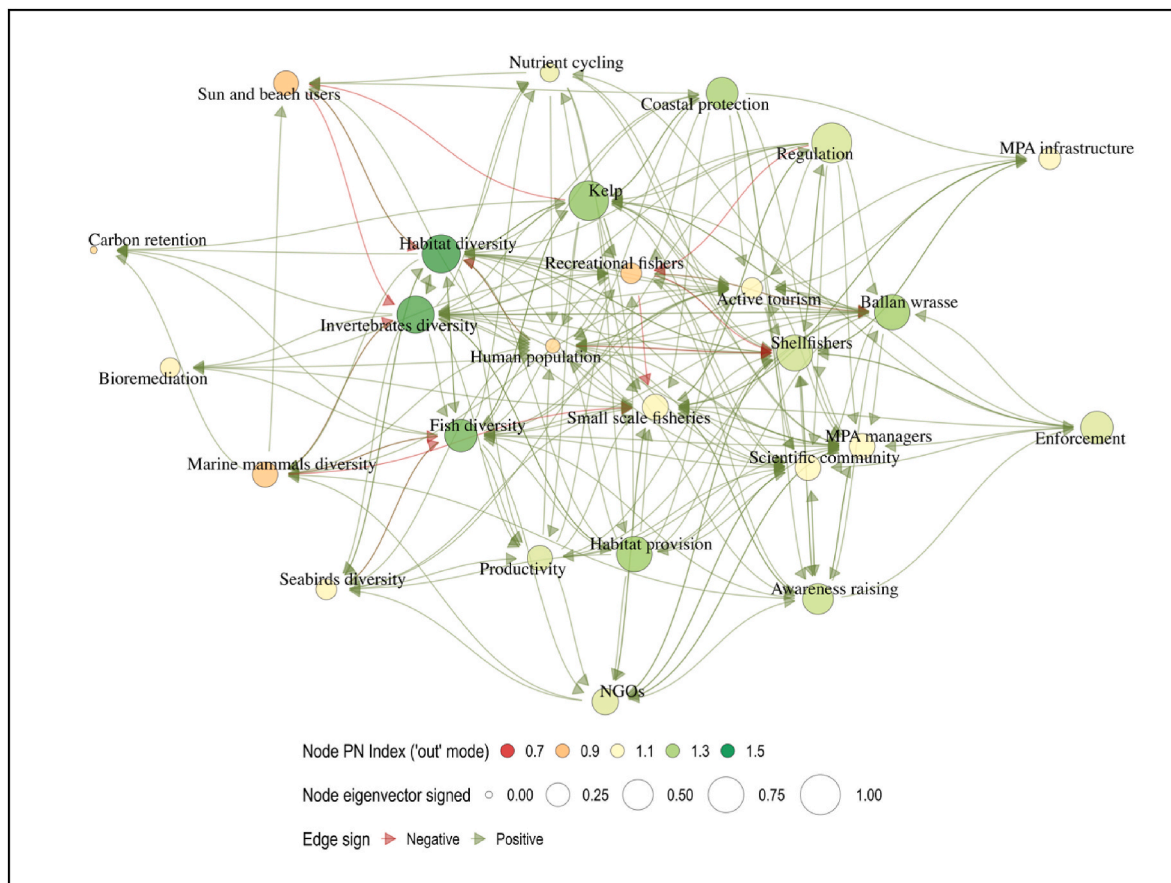


Fig. 5. –Network of the positive-negative index in Os Miñarzos MPA. Node color denotes the positive-negative score, based on the average of the effects the node has over other nodes, and the edge color is related to the positive (green) or negative (red) link between nodes. The node size represents the Eigenvector centrality.

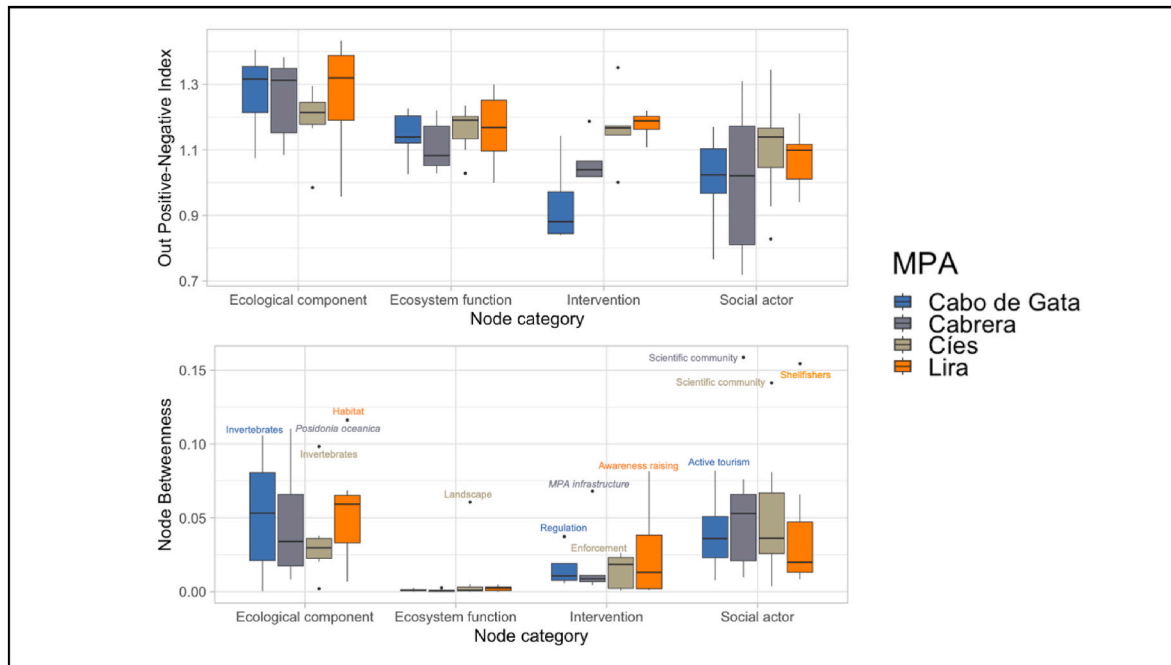


Fig. 6. Average Negative-Positive Index (PN; upper graph) and average betweenness (bottom graph) for each main components in the network (i.e., ecological component, ecosystem function, intervention, and social actor) of the four MPAs.

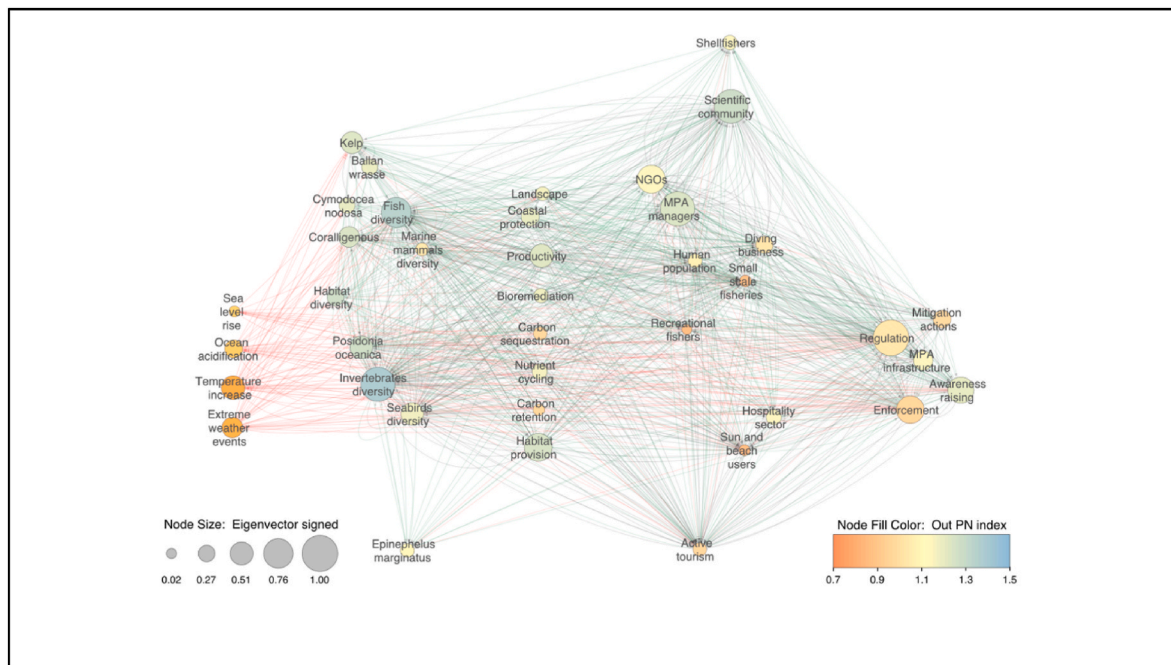


Fig. 7. Meta-network including the four MPAs and the climate change components. The node size represents the Eigenvector value and the node and edge color the positive-negative score of the node based on its average effects on the other nodes.

network, do not play a key role in the interaction between components, such as mitigation actions in the four MPAs.

4.2. The interaction between environmental, ecological, and social components in the MPA

The results obtained for the climate change nodes in the global network indicate that, even if only direct relationships with the ecological components are established, they manage to spread their

negative effect throughout the network. On the other hand, the ecological components, particularly the habitat foundation species (e.g., seagrass and kelp), propagate their positive effects through the network, consolidating their role as an umbrella conservation target species. Focusing on individual networks, the central nodes belong mostly to the categories of ecological components and social actors. However, the effect of some of these components has a limited (or localized) influence and does not spread throughout the network. This is the case for small-scale fishers in Cíes Islands, where the dark red color and the small size

of the node indicates that its negative influence does not spread directly throughout the network even though it is the node with the most interactions. On the other hand, the MPA managers' node in Cabo de Gata-Níjar is large and pale yellow, which shows its greater propagation of effects within the network, which are slightly negative. The ecological functions are positioned in the margins of the networks. This pattern might be since, for this study, only direct interactions have been considered, i.e., the effect that these nodes can generate on any of the social actors has not been considered, as these interactions are sometimes complicated to relate. For example, the effect of carbon storage on small-scale fisheries is not either direct or evident, although carbon storage will have a positive impact on societies at large scale through its contribution to climate change mitigation (Macreadie et al., 2021). The nodes that best propagate their influences through the network are identified by the betweenness centrality measure, which is the case of the scientific community in both Cabrera Island and Cíes Islands National Parks and end-users such as shell fishers and active tourism in Os Miñarzos and Cabo de Gata-Níjar, respectively. This has relevant implications suggesting scientific communities are connected to many elements in the networks of the two national parks, whereas small-scale fisheries in the fishing reserve and tourism in Cabo de Gata coastal Natural Park are the actors with wider influence in the network.

4.3. Specific features of individual networks

The Cabo de Gata-Níjar MPA is home to a variety of Mediterranean communities influenced by the Atlantic waters, which gives them a high biogeographical value (Moreno et al., 2001). Seagrass (*P. oceanica*), algae, and various species of invertebrates and vertebrates populate the reserve (Moreno et al., 2001). It is therefore to be expected that the ecological components are of foremost importance, as well as the existence of diverse relationships between social actors, since the MPA encompasses a coastal strip of 60 km. Along this coastal strip there are many social actors with direct relations to the MPA, including beach users, active tourism, the hotel and catering sector, artisanal and recreational fishers. Among these, the scientific community, and the resident population have the highest net positive interactions, reflecting that these two groups have the least conflicts with other actors within the network. On the other hand, NGOs and recreational fishers spread their negative effects throughout the network. In Cabo de Gata-Níjar, the compliance with the measures and mitigation actions are nodes with a low positive influence within the network, which may be due to the lack of resources and measures in recent years to mitigate impact of summer tourism. This last reflects on the crucial importance of locally based management actions to balance both conservation actions and recreational activities.

In Cabrera MPA, the biological components also adopt a highly central position in the network, denoting their importance as the basis for the system, in particular *Posidonia oceanica* that in the MPA is in a good environmental status (Marbà et al., 2002). This good status is reflected in the role of the seagrass meadow in structuring the network, indicated by a high betweenness index, and it is consistent with the numerous ecosystem functions they provide (e.g., habitat provision and productivity emerge as the most relevant in this network) (Boudouresque et al., 2006). On the other hand, the grouper is a charismatic species in the area, illustrated through the outgoing links to the different human components; however, it has a marginal role in the network. This is most likely because it does not play a functional role comparable to that of *Posidonia*. The ecosystem functions carbon sequestration and coastal protection also have a marginal importance in the network, despite being key functions of *Posidonia* meadows (Campagne et al., 2015). This might be because while habitat provision and productivity have outgoing links to both the ecological and the social components, the links stemming from carbon sequestration and coastal protection are only indirectly transmitted to society. Focusing on the social actors, the scientific community also plays a central position in the

network, having a high positive index, while NGOs and MPA managers have a similar crucial importance but the positive index being lower. The Cabrera Island National Park is the first large Maritim National Park in the Spanish Mediterranean, which places this area in the spotlight of scientific studies in the region. Human activities do not have a central position in the network, probably because in Cabrera Islands human uses are limited and there is no permanent population. Nevertheless, we identified small-scale fishers and sun and beach users as having an important negative role in the network. This is because both groups are the ones most affected by the different human intervention components (e.g., mitigation actions, regulation, enforcement) and, at the same time, are the groups that have the most negative effects on the biological components of the system.

Cíes Islands MPA are embedded in a productive upwelling system and hosts diverse benthic and pelagic communities (Fernández et al., 2020). Accordingly, most ecological components exhibit positive effects on the network, and the landscape of the MPA acts as an element of attraction for tourists. Nevertheless, three negative interactions are observed related to fish diversity on kelp, and marine mammal diversity on fish and invertebrate diversity. Dolphins, the most abundant marine mammals in the MPA are known to feed intensively on fishes and cephalopods (Silva, 1999) and recent studies conducted in the MPA show that the observed decline, and even collapse of the golden kelp *Laminaria ochroleuca* is related to high grazing rates of fishes (Barrientos et al., 2022). The dominant rocky nature of the benthic substrate and the local extinction of *Z. marina* and *Z. noltei* meadows at the end of the last century, explains the low relevance of the carbon retention function in this ecosystem. Seabirds also have a central position in the network, as the breeding colonies of seabirds constitute one of the most outstanding natural values of the National Park (Otero et al., 2015). Social actors have a similar importance in the network. Active tourism or diving companies have a positive net effect on the network as they are not overcrowded activities in the area and contribute to the dissemination of the natural values of the archipelago, having a positive perception. Through the workshops, it was possible to identify conflicts in relation to the perception of boating activities (included in the active tourism node) due to their impact on marine biodiversity, but also due to the overlapping of uses with the fishing sector in the marine space. In fact, the artisanal fishers exert a certain negative influence on the network. However, this result should be linked to disagreements in the current management of fishing activity in the Cíes Islands MPA. For example, the fishing sector does recognize the existence of conflicts with nautical tourism, even indicating the need to establish a temporal or spatial zoning for the different activities. On the other hand, the sectors most intricately linked to environmental protection express the need to reduce the impact of fishing gear on the seabed, the accidental capture of seabirds and even cetaceans, proposing a zoning of the area. At the same time, the MPA managers expressed the need to increase communication channels with the fishing sector to facilitate the co-management of fishing resources, given that the management of the MPA and fishing activity is currently conducted by different administrations.

In Os Miñarzos MPA, the upwelled nutrient-rich waters result in high fish production, together with the presence of seabirds and cetacean communities. This oceanographic process explains the perception of productivity as the most relevant ecosystem function component. The local participatory process of MPA creation was mediated by scientists and NGOs (Villasante et al., 2021), explaining the relevance of these groups in the network, particularly awareness-raising having a high betweenness. On the other hand, there is a positive influence of shellfish gatherers and artisanal fishers on the MPA network, as the creation of the area was supported by the local ecological knowledge of fishers (Villasante et al., 2021). Indeed, the relationship extends to recreational fishing, which is embedded as a human welfare service and which acts as an active driver of progress in the area (Pita et al., 2022). The exclusion of part of the collective (spear fishers, and de facto boat fishers) on the MPA planning process, would explain their negative perception of the

regulations and their enforcement (Pita and Villasante, 2019). Active tourism also generates a dynamization factor, not only through marine tourism, but also through other nautical activities in the Os Miñarzos area. Despite the number, relevance, and positive assessment of the relationships of the actors involved in the Os Miñarzos MPA, it is worth highlighting the negative relationships identified between some of them (e.g., between commercial and recreational fishers), which should be understood because of competition for access to the area. Some of the activities were also perceived as negative for the ecological components; for example, artisanal fishers had a negative interaction with mammals, due to the impacts derived from fishing; and summer beach users traditionally collect clams having a negative effect invertebrate diversity, and in consequence, on shell fishers.

5. Conclusions

The variability observed in the connections established between components in the four MPAs, characterized by different creation processes, human activities, and ecological and environmental contexts, highlight the need to understand the specific socio-ecological interactions emerging in each MPA. Certain common patterns were observed, e.g., positive effects of ecological components, as the basis for ecosystem service provision, and negative effects of climate change, propagating throughout the MPA networks. However, the consequences of local human activities are highly context-specific, and this was evidenced by the variable effects that social actors, management, and interventions have on the four MPAs. The interpretation of this variability has important consequences for the local management of the areas, and MPA managers and decision makers must be aware of the particularities of each case study to adjust the management plans. The regular organization of workshops and roundtables with key actors in the area would allow to monitor changes in the system after implementing management actions. Non-obvious and subtle changes that may occur after the adjustment of regulatory measures can be evidenced by the application of network analysis. Network analysis is a consolidated approach in ecological sciences and now emerges as an effective tool to identify interactions and conflicts between components of a socio-ecological system, as well as key components for the functioning of this system. Future recommendations for the development and application of this technique to support marine management and conservation plans focus on the need to integrate all components of a system. A weak integration implies partial views of the system. This matrix-based method allows “to co-create” the framework, integrating scientific, expert, and traditional knowledge. The network only reflects the interactions between the components that one includes. Therefore, to have representative non-biased networks is crucial to do a comprehensive job when deciding the elements to include and the integration of all relevant actors. As a result, the network of socio-ecological components is solid, but easy to implement and to visualize, a crucial characteristic if the method is intended to be used by decision-makers. Moreover, this approach can be replicated across MPA in the region so then outputs are comparable.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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