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Analysis of the causes and consequences of major concern on biodiversity change in the Gulf of Oristano Area (Sardinia, Italy)

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Abstract

The Gulf of Oristano Area, located on the central-western coast of Sardinia (Italy, Mediterranean Sea), is a highly diverse and ecologically valuable region. This area features a mosaic of habitats, supports rich biodiversity, and sustains traditional fishing practices. It is also protected under various international and EU conservation frameworks. However, despite its ecological importance, the Gulf Area faces growing pressures from human activities such as overfishing, eutrophication, habitat loss, and the introduction of non-native species. This study applies a bow-tie risk analysis framework to identify key drivers, pressures, and consequences associated with three central ecological events: species decline and loss, habitat change, and increased competition with non-native species. Stakeholder consultations and standardized classification systems inform the assessment, highlighting the interplay between legal fishing, tourism, aquaculture, pollution, and infrastructure development. The analysis identifies both prevention and mitigation measures, such as spatial planning, environmental monitoring, citizen science, and sustainable tourism and fisheries initiatives. While the environmental regulation of the Gulf of Oristano Area provides a basis for ecosystem protection, persistent challenges—such as enforcement, fragmented governance, and low stakeholder engagement—hinder effectiveness. To ensure ecological integrity and socio-economic resilience in the central-western Sardinian coast, this study underscores the need for strengthened integrated coastal zone management, alignment with EU strategies, and investment in adaptive and participatory conservation approaches.

Keywords: species decline, biodiversity, conservation, habitat change, non-native species

Introduction

The Gulf of Oristano Area (Italy, Mediterranean Sea), located on the central-western coast of Sardinia, extends from Is Arenas beach (40°03'58.4"N 8°28'29.3"E) in the north to Porto Palma in the south (39°40'06.6"N 8°27'33.1"E; Fig. 1). This region encompasses a complex and ecologically rich system, including the Gulf of Oristano itself (approximately 150 km², with a maximum depth of 24 meters), several connected lagoons and salt marshes (covering a total area of 46 km²), a Marine Protected Area - “Penisola del Sinis – Isola di Mal di Ventre” (approximately 260 km²), as well as a wide stretch of open sea (extending up to 20 mi offshore). Among the most prominent lagoon systems are Cabras, Santa Giusta, S’Ena Arrubia, Corru S’Ittiri, San Giovanni–Marceddì, and Mistras. The entire lagoon system hosts a variety of coastal habitats, many of which are protected under the EU Habitats and Birds Directives. These coastal lagoons are shallow (0.5–2 m), predominantly eutrophic water bodies affected by anthropogenic nutrient loading and freshwater reduction from upland sources. As a result, they have undergone environmental degradation, with frequent dystrophic crises leading to benthic and fish mortality events (Murenu et al., 2004; Magni et

al., 2005, 2008b). The Mistras Lagoon, however, stands out as an oligotrophic system with sandy, low-organic sediments, no riverine input, and negligible anthropogenic pressure, making it ecologically distinct from other Sardinian lagoons (Specchiulli et al., 2018; Gravina et al., 2020; Magni and Gravina, 2023). The adjacent Sinis Peninsula hosts the “Penisola del Sinis – Isola di Mal di Ventre” Marine Protected Area (hereinafter Sinis MPA), established in 1997 (Decree 12/12/1997), one of the largest MPAs in Italy, covering more than 26,000 ha and about 30 km of coastline. This multiple-use MPA is divided into three zones with different levels of protection: two no-entry/no-take zones (Zone A – 1.5% of the total area), two high-protection areas (Zone B – 4%), and a broader buffer area (Zone C – partial protection, 94.5%; Fig. 1 and Fig. 2). Despite its protected status, the Sinis MPA continues to experience significant fishing pressure. While earlier data reported 94 boats and 199 licensed professional fishers (Casola et al., 2014), the fleet currently consists of fewer than 80 professionals, along with over 250 recreational fishing licenses issued annually. Small-scale fisheries target different species depending on habitat: in lagoon environments, catches primarily focus on grey mullets (*Mugilidae*), whereas offshore and coastal waters are more associated with species such as European seabass (*Dicentrarchus labrax*), gilt-head seabream (*Sparus aurata*), and common dentex (*Dentex dentex*), which are of high commercial value. Additionally, fish and mussels aquaculture is present in the central part of the Gulf. The area is also critical for the conservation of vulnerable and endangered species that have experienced sharp population decline due to a combination of anthropogenic and environmental pressures. The edible sea urchin *Paracentrotus lividus* has been intensely harvested in coastal waters, leading to significant reductions in population densities and shifts in size structure, with larger individuals becoming increasingly rare (Camedda et al., 2011; Farina et al., 2020; Ruberti et al., 2023). These impacts are particularly evident even within MPA boundaries, where enforcement remains challenging (Coppa et al., 2021). Similarly, *Patella ferruginea*, a critically endangered Mediterranean limpet and an indicator of healthy intertidal environments, persists at very low densities in the MPA, with the island of Mal di Ventre and San Marco Cape hosting the only known local populations, despite over two decades of protection (Coppa et al., 2012; Coppa et al., 2013; Marra et al., 2016). Studies have shown that the current level of protection in the intertidal zone is insufficient to halt ongoing declines, highlighting the need for targeted conservation actions (e.g. Coppa et al., 2016). In addition, *Pinna nobilis*, the endemic fan mussel of the Mediterranean Sea, is suffering a dramatic mass mortality event, first detected in Spain in 2016 and subsequently spreading across the entire basin (Vázquez-Luis et al., 2017; Cabanellas-Reboredo et al., 2019). These events are driven by a combination of pathogens including *Haplosporidium pinnae*, *Mycobacterium spp.*, and *Rhodococcus erythropolis*, and exacerbated by the increasing of temperature and pollution (Scarpa et al., 2020). These losses represent a major blow to the benthic biodiversity and ecosystem functioning of the study area and its associated habitats. The ecological integrity of this area is also threatened by land-based pressures such as intensive agriculture and livestock farming, which contribute to pollution and eutrophication in coastal waters (Magni et al., 2006). Historical mining activities in the southern catchment area, particularly affecting the Marceddì lagoon, have left a legacy of environmental stress (Cucco et al., 2006; Magni et al., 2006). Moreover, infrastructural developments like dredging and port construction have altered sediment dynamics, influencing the distribution and health of *Posidonia oceanica* meadows, which still cover about 70% of the Gulf seabed (De Falco et al., 2000, 2008; Como et al., 2008). In addition to these land-based and infrastructural pressures, seasonal human activities—particularly tourism—also contribute to environmental stress. Although the central-western coast of Sardinia receives fewer visitors than other parts of the island, tourist numbers increase in summer, as in many marine areas, leading to localized impacts on coastal ecosystems (Simeone et al., 2012; Coppa et al., 2023). The region is nonetheless recognized for its high naturalistic value and supports important activities such as eco-tourism and birdwatching, especially in Ramsar-listed sites. However, conservation efforts occasionally face social challenges: for instance, the presence of piscivorous birds,

particularly cormorants, has sparked conflict between fishers and conservationists due to concerns over fish stock depletion in the lagoons (Buttu et al., 2013). The governance of the Sinis MPA reflects a decentralized model common in Italy, with the Cabras Municipality acting as managing authority. The mayor serves as the MPA president, appointing a directorand supported by a small team. Enforcement responsibilities are shared among the Coast Guard, Local Police, and Forestry Police (Decree 20/07/2011, n. 188). The regulatory framework of the Sinis Marine Protected Area (MPA) has been progressively strengthened to improve environmental protection and sustainable management. Since its establishment in 1997, successive regulations have clarified permitted activities, introduced enforcement mechanisms, and defined user fees, reflecting a growing commitment to effective governance and ecological conservation. All the components of the Gulf of Oristano Area—including lagoons and salt marshes, the gulf itself, the MPA, and the adjacent open sea—together form a highly diverse yet vulnerable socio-ecological landscape, where the interplay between ecological processes, traditional fisheries, conservation priorities, and fragmented management creates complex trade-offs. Applying risk analysis tools such as bow-tie diagrams could support communication of key cause-effect pathways behind biodiversity loss, eutrophication, and fish stock depletion, while also identifying strategic leverage points for integrated coastal zone management in a changing climate and socio-economic context.

Methodology

In our study, three central events referring to significant changes in ecological state and biodiversity are considered in the bow-tie risk analysis framework: 1) Species decline and loss; 2) Habitat change; 3) Increased competition with non-native species. On the left-hand side, the bow-tie analyses list ACTIVITIES affecting the environment and anthropogenic PRESSURES through which human activities impact marine ecosystems, and the PREVENTION MEASURES aimed at reducing these pressures. On the right side, the analysis presents the corresponding MITIGATION MEASURES, and the CONSEQUENCES of ecological and biodiversity status change. To operationalise the tool across European seas, a standardised vocabulary and classification of each element is applied following the Elliott et al., in preparation. In both Figure 3 and Table 1, letters and numbers are used to identify prevention and mitigation measures: letters indicate actions addressing tourism-related impacts, while numbers refer to those targeting impacts from fishing activities. The prevention measures are decoded as follows: a) Spatial and temporal planning - Ctrl1.3.2; b) Tourists and parking fees - Ctrl5.2; c) EU policy on single use plastic, deposit system - Ctrl4.1; d) Regulation of tourism and activities - Ctrl1.3; 1) Monitoring of maritime regulated uses and tourism activities - Ctrl3.1; 2) Spatial planning - Ctrl1.3.2; 3) Regulation of fishing activities - Ctrl1.3; 4) MPAs implementation - Ctrl1.3.5; 5) Information availability and co-working - Ctrl3.5; 6) Participatory approach - Ctrl6.2; 7) Noise pollution assessment - Ctrl3.2. The mitigation measures are defined as follows: a) Development of a regional strategy for Blue Economy and Blue Tourism - Ctrl4.3.6; b) Legislation and monitoring of impacts on the environment and local populations - Ctrl4.1 and/or Ctrl4.3 + Ctrl3.1; c) Green infrastructures - Ctrl2.2; d) Diversification of touristic resources: naval, historic, cultural and heritage values - Ctrl6.3; e) Local legislation and subsidies to shellfisheries/fisheries - Ctrl4.2 and Ctrl5.1; f) Encouraging citizen actions and recording environmental changes - Ctrl6.2; g) Visiting with nature guides, education, birdwatching activities and competition - Ctrl6.4 and/or Ctrl6.1; h) Carrying capacity in distributing people along coast, restricted areas, visiting periods, game fishing periods - Ctrl1.3.1; i) Installation of paths and fences in dunes - Ctrl1.3; 1) Diversification of touristic resources: naval, historic, cultural and heritage values - Ctrl6.3; 2) Fishing e-commerce development - Ctrl2.2; 3) Development of sustainable fishing models - Ctrl4.3; 4) Awareness programmes - Ctrl6.5; 5) Monitoring impacts on the environment and local populations - Ctrl3.1.

Results of bow-tie analysis

The primary topics related to biodiversity loss in the Gulf of Oristano Area have been identified through consultations with key stakeholders, including managers of protected areas, fisheries associations, researchers, local private sector (e.g. hospitality, commerce, trade), schoolteachers, enforcement bodies and subject-matter experts and NGOs. The three central events in our bow-tie analysis (Fig. 3) highlight different patterns of biodiversity loss. Habitat changes in the Gulf of Oristano, its associated lagoons, and the adjacent MPA, along with the decline of ecologically and commercially important species, are linked to human activities such as nutrient runoff and overfishing. In addition, the increasing spread of non-indigenous species—often unintentionally introduced through aquaculture activities and the transport of farmed organisms—has intensified competition with native species, further accelerating their decline. This event serves as an example of rapid, unmanaged biodiversity loss with uncertain recovery potential. A detailed analysis of these events is presented using the bow-tie framework below.

Species decline and loss

The Gulf of Oristano Area represents a biodiversity hotspot for Mediterranean flora and fauna, including numerous protected and endemic species (Como et al, 2008, Coppa et al., 2016, Coppa et al., 2021; Magni and Gravina, 2023). However, this ecological richness is under mounting pressure from a wide array of anthropogenic activities leading to species decline and local extinctions. Among the most critical threats is overharvesting (A4.1, A4.4), both legal and illegal, which significantly impacts key species such as the sea urchin *Paracentrotus lividus* (Farina et al., 2020; Coppa et al., 2021; Ruberti et al., 2023), and the critically endangered limpet *Patella ferruginea* (Coppa et al., 2012; Coppa et al., 2013; Marra et al., 2016). Unregulated or poorly enforced fishing practices, including IUU (Illegal, Unreported, and Unregulated) fishing and ghost fishing (P3.1, P3.3), continue to deplete natural stocks and damage sensitive habitats. Industrial, artisanal, and recreational fisheries (A4.1) exert simultaneous pressure across coastal and lagoon systems, leading to cascading ecological effects such as trophic imbalances and reduced reproductive success in overexploited species. Concurrently, aquaculture activities (A5.1, A5.2), particularly fish farming in the central Gulf, contribute to nutrient pollution (P3.2), increase disease transmission risk to wild populations, and facilitate the introduction of non-native genetic stocks, potentially undermining local biodiversity (Magni et al., 2008b; Sinerchia et al., 2009; Como et al., 2018). Coastal urbanization and infrastructure development (A7.1, A8.1) amplify habitat fragmentation and contribute to wildlife disturbance (P1.5; Como et al., 2007), while overcrowding during the tourist season (A8.2) adds further stress to nesting birds, foraging fish, and intertidal species (Iorio and Corsale, 2010). Noise and light pollution (P3.5, P3.6) from boating, nightlife, and urban centers disrupts behavioral patterns in sensitive taxa, including migratory birds and nocturnal marine fauna, with long-term implications for population viability (Corrias et al., 2023). Pollution—originating from sewage discharge, littering, and agricultural runoff (P3.1, P3.4)—deteriorates water quality and introduces toxic substances into food webs, weakening immune systems and increasing mortality among aquatic organisms (e.g. heavy metals, Magni et al., 2006; organic over-enrichment, Magni et al., 2008b,c; plastics, de Lucia et al., 2014). Even species that were once widespread and abundant across the Mediterranean basin, such as *Pinna nobilis*, have proven particularly vulnerable to combined pressures, including pathogenic outbreaks exacerbated by environmental degradation (Scarpa et al., 2020). To address these ongoing declines, a combination of prevention and mitigation measures has been introduced or proposed. Regulatory controls on tourism and fishing activities (Ctrl1.3), visitor fees (Ctrl5.2), and spatial planning tools aim to limit direct human disturbance. The implementation of EU policies on single-use plastics (Directive (EU) 2019/904) and deposit-return systems (Ctrl4.1) seeks to reduce marine litter and pollution. Monitoring programs (Ctrl3.1), noise assessments (Ctrl3.2), and participatory management approaches (Ctrl6.2) are increasingly

recognized as essential for adaptive conservation strategies. Within the Sinis MPA, efforts are underway to enforce restrictions, share information (Ctrl3.5), and promote awareness through citizen science, educational programs, and nature-based tourism (Ctrl6.1, Ctrl6.4, Ctrl6.5). Mitigation efforts include green infrastructure development (Ctrl2.2), subsidies for sustainable fisheries and shellfish farming (Ctrl4.2, Ctrl5.1), and the promotion of eco-labels and fishing e-commerce (Ctrl2.2) to support economic alternatives. The diversification of tourism (Ctrl6.3)- highlighting the historical, and cultural heritage—helps redirect pressure away from ecologically fragile zones. Despite these measures, significant challenges remain. Species loss impacts not only the ecological integrity of the area (C1.5) but also its socio-economic foundations. Declining biodiversity threatens nature-based tourism income (C2.2), drives up municipal costs for beach cleaning and dune protection (C2.1), and contributes to the rise of black markets for marine products (C2.6). Without continued investment in enforcement, monitoring, and community engagement, the risk of "paper parks"—protected areas that fail to achieve real conservation outcomes—will persist (Pieraccini et al., 2017). The long-term protection of the Gulf of Oristano Area depends on practical actions, stronger cooperation between authorities and local communities, and a shared commitment caring for the area's natural resources.

Habitat change

The coastal landscape of the Gulf of Oristano Area is a semi-natural system shaped by the interaction of natural dynamics and centuries of human activity. Coastal dune systems, shallow marine zones, and lagoonal wetlands historically supported traditional fisheries, agriculture, and seasonal tourism. However, over the last decades, intensification and diversification of anthropogenic pressures have led to significant ecological and habitat alterations. Dune systems along the Sinis Peninsula and southern shorelines, partially stabilized through historical vegetation planting, are particularly vulnerable to physical disturbance (P2.1) and physical loss (P2.2). Unregulated recreational access and overcrowding (A8.2) during peak tourist seasons lead to trampling of dune vegetation and the formation of informal paths, resulting in erosion, dune destabilization, and fragmentation of native vegetation (Simeone et al., 2012; Pinna et al., 2015). Illegal off-road driving and informal parking areas have further exacerbated this degradation. These forms of physical disturbance reduce the natural resilience of the coastline to storm surges and sea-level rise (Hanley et al., 2014). Similarly, boat anchoring (A8.2) in sensitive nearshore zones contributes to the physical destruction of seagrass beds (P2.1), including *Posidonia oceanica* meadows, leading to the deterioration of nursery habitats, carbon storage capacity, and biodiversity functions (C1.5, C2.5; Milazzo et al., 2004). Within lagoon ecosystems—such as Cabras and Santa Giusta—pressures from artisanal fisheries, aquaculture-related traffic (A4.1), and unregulated resource extraction (A4.4, IUU fishing) cause seabed scouring (P2.1) and habitat degradation (P3), resulting in declining fish stocks and loss of ecosystem services, with direct impacts on local fisheries (C2.2) and harbor infrastructure development (C2.1; Como et al., 2007). The inadequate management of waste (A7.3)—particularly during the summer tourist peak—further compromises ecological integrity (Simeone et al., 2012). Dumping and pollution in coastal and wetland areas degrade water quality, reduce habitat value, and diminish the sense of place (C3.3) and landscape/seascape quality (C1.4, C3.2; Newton et al., 2020). These cumulative impacts also reduce real estate value (C2.3), threaten tourism income, and hinder spatial planning (C2.6) by generating land-use conflicts and fragmentation (Sahavacharin et al., 2022). To counteract these threats, a number of prevention and mitigation measures are being implemented or proposed. Spatial and temporal planning (Ctrl.1.3.2), combined with visitor fees and parking controls (Ctrl.5.2), aims to regulate tourist numbers and pressure. Installation of dune footpaths and fences (Ctrl.1.3) seeks to protect vegetation from trampling, while restrictions on anchoring in marine protected areas (MPAs, Ctrl.1.3.5) help limit physical seabed damage. The development of sustainable fishing

models (Ctrl.4.3) and e-commerce for local products (Ctrl.2.2) supports traditional economies while reducing environmental impact. Broader policies—such as the EU directive on single-use plastics and the deposit-return system (Ctrl.4.1)—help address chronic waste problems. Monitoring programs (Ctrl.3.1) and citizen science initiatives (Ctrl.6.2) are critical for tracking environmental changes and increasing public participation (Conrad & Hilchey, 2010; Dickinson et al., 2012). Educational efforts, including nature-based tourism, guided visits, and birdwatching (Ctrl.6.4), raise awareness of the ecological value of the area and reduce uncontrolled use (Wolf et al, 2019). In parallel, the diversification of tourism activities to include cultural and historical assets (Ctrl.6.3) helps distribute visitor flows and reduce pressure on fragile natural sites. The Natura 2000 Priority Action Framework (2021–2027) provides strategic support for key actions: (i) eradication of invasive species, (ii) installation of sand capture and stabilization structures (Ctrl.2.2.14), and (iii) habitat restoration plans for priority dune and wetland species, and also indicates relevant funding channels (e.g. LIFE, Interreg) for their implementation. These measures are essential for maintaining the ecological function and resilience of protected habitats. In the absence of continued and well-coordinated management—including enforcement of protected area regulations and transboundary cooperation—the degradation of habitats in the Gulf of Oristano Area could accelerate. This would lead to loss of biodiversity (C1.5), decline of economic sectors linked to the Blue Economy (C2.5), increased costs for habitat restoration, and eventual loss of both natural and cultural values that define the region (C3.1, C3.3). The integration of land-sea planning, stakeholder engagement, and adaptive management is essential to protect this unique Mediterranean coastal and lagoonal landscape.

Increased competition with non-native species

The ecological balance of the Gulf of Oristano Area is increasingly threatened by the spread of non-native species—an issue closely linked to marine aquaculture (A5.1) and maritime activities such as vessel traffic and shellfish translocations. These human-mediated vectors often lead to the accidental introduction of invasive organisms, which can establish themselves in new environments and compete with native species for space and resources, exerting growing pressure (P1.1) on local biodiversity (Bax et al., 2003; Gentili et al., 2021). This problem is particularly acute in shallow coastal and lagoon habitats, where environmental conditions often favour the success of opportunistic or generalist invaders. A notable example is the Asian date mussel (*Arcuatula senhousia*), first recorded in the Santa Giusta and Marceddì lagoons in 2009. Likely introduced through shellfish farming operations or ballast water discharge, this fast-growing bivalve—originally from the Indo-Pacific—has since spread widely across the Mediterranean. In Oristano, it colonizes soft sediments, forming dense mats that modify the seabed, displace native bivalves, and disrupt nutrient cycles and benthic food webs (Como et al., 2018). Another significant invader is the comb jelly *Mnemiopsis leidyi* Agassiz, 1865, a zooplanktivorous predator of fish and bivalve eggs and larvae. Native to the temperate and subtropical coastal and estuarine waters of the western Atlantic, *M. leidyi* has shown a remarkable capacity for dispersal. It is listed among the world's 100 worst invasive species by the IUCN (Lowe et al., 2000), and since the 1980s has been recorded along European coasts and transitional waters. It is now considered part of the alien fauna of the Mediterranean (Zenetos et al., 2010) and is included in the "Black List" of 47 invasive species in the region (Otero et al., 2013). Its presence in Sardinia was first reported in the S'Ena Arrubia lagoon in 2015 (Diciotti et al., 2016). This species poses a serious threat to the pelagic food web due to its predation on zooplankton and early developmental stages of commercially important species. Equally alarming is the silent spread of the aquatic plant *Eichhornia crassipes*—commonly known as water hyacinth—within Italian inland and transitional waters, including those in Sardinia. Originally from the Amazon basin, this fast-growing floating macrophyte is among the most aggressive aquatic invaders globally. In areas experiencing high nutrient loads, altered hydrology, and habitat disturbance—conditions present in

parts of the Oristano lagoon complex—*E. crassipes* can form dense surface mats. These drastically reduce light penetration, deplete oxygen levels, and alter water flow, leading to significant ecological degradation. Its presence further exacerbates eutrophication and compromises the ecological integrity of freshwater and brackish habitats (Brundu et al., 2013). In addition to its ecological impacts, *E. crassipes* is known to impede fishing and aquaculture operations, block irrigation systems, and create favourable conditions for disease vectors, raising One Health concerns. Furthermore, recent monitoring activities in the Oristano area, particularly in the Sinis Peninsula and lagoon systems, have confirmed the presence of other notable invasive species (Vencato et al., 2024). Among them is the green alga *Caulerpa cylindracea*, known for its ability to overgrow native seagrass meadows and alter sediment dynamics, as well as the crab *Percnon gibbesi*, which competes with native decapods and disrupts rocky shore ecosystems (Klein et al., 2008; Stasolla et al., 2016). Additionally, past observations have recorded the blue crab *Callinectes sapidus*, a large, aggressive predator that threatens local shellfish populations and fisheries; the stinging box jellyfish *Carybdea marsupialis*; and the cornetfish *Fistularia commersonii*, a fast-moving Indo-Pacific predator that preys on small native fish, contributing to trophic imbalances. Also observed are *Asparagopsis taxiformis*, a red alga that releases bioactive compounds harmful to native communities, and the ascidian *Styela plicata*, a fouling organism often found on artificial substrates such as aquaculture equipment, which can outcompete native filter feeders (Coppa et al., 2020). These cases clearly demonstrate how a single invasive species—or a combination of them—can trigger cascading ecological impacts once introduced via human activities. These changes undermine the conservation status of protected areas (C1.5), contributing to the phenomenon of “paper parks,” where legal protection exists but fails to deliver real ecological outcomes (Otero et al., 2013). Moreover, the presence of invasive species raises One Health concerns (C3.2): they can act as carriers of pathogens or parasites, posing risks not only to native fauna and aquaculture stocks, but also indirectly to human health and local economies (Dunn & Hatcher, 2015; Najberek et al., 2022). To tackle this complex challenge, a mix of prevention and mitigation strategies is essential. Spatial and temporal planning (Ctrl1.3.2) can help regulate the location and intensity of aquaculture activities to minimize the risk of ecological disturbance and species escapes. Improving information exchange and institutional cooperation (Ctrl3.5) is crucial for early detection and coordinated responses, particularly in protected areas and Natura 2000 sites. On the mitigation side, regular environmental monitoring (Ctrl3.1)—especially of species composition in high-risk areas—helps track the spread of non-native organisms. Citizen science initiatives (Ctrl6.2) can strengthen surveillance efforts and involve local communities in early response actions. Public awareness campaigns (Ctrl6.5) are also vital, educating aquaculture operators, fishers, and tourists on the risks of invasive species and the importance of biosecurity practices. Although eradicating established non-native species is rarely feasible, these integrated actions aim to contain their spread, reduce their impacts, and strengthen the resilience of native ecosystems. Promoting ecologically responsible aquaculture within a broader framework of integrated coastal zone management will be key to safeguarding the biodiversity and natural heritage of the Gulf of Oristano Area in the face of increasing biological invasions.

Conclusions

The Gulf of Oristano Area is a highly diverse but vulnerable socio-ecological area, where the interplay between traditional uses, conservation needs, and compliance issues presents complex management challenges. The bow-tie analysis proved useful in clarifying the relationships between human activities, environmental pressures, and biodiversity outcomes, while also identifying key control measures for both prevention and mitigation. Addressing biodiversity loss in this context requires stronger coordination between institutional levels, integration of existing regulatory tools, and more active stakeholder participation. Particular attention should be given to improving

monitoring, enhancing local enforcement capacity, and promoting sustainable economic alternatives, such as low-impact tourism and eco-certified fisheries. Potential escalation factors—such as declining financial support (E1), reduced societal engagement (E2), and political shifts away from environmental priorities (E3)—may compromise long-term conservation goals. Maintaining alignment with EU strategies like the Green Deal and Blue Economy framework is essential to ensure the resilience of ecosystems and the communities that depend on them.

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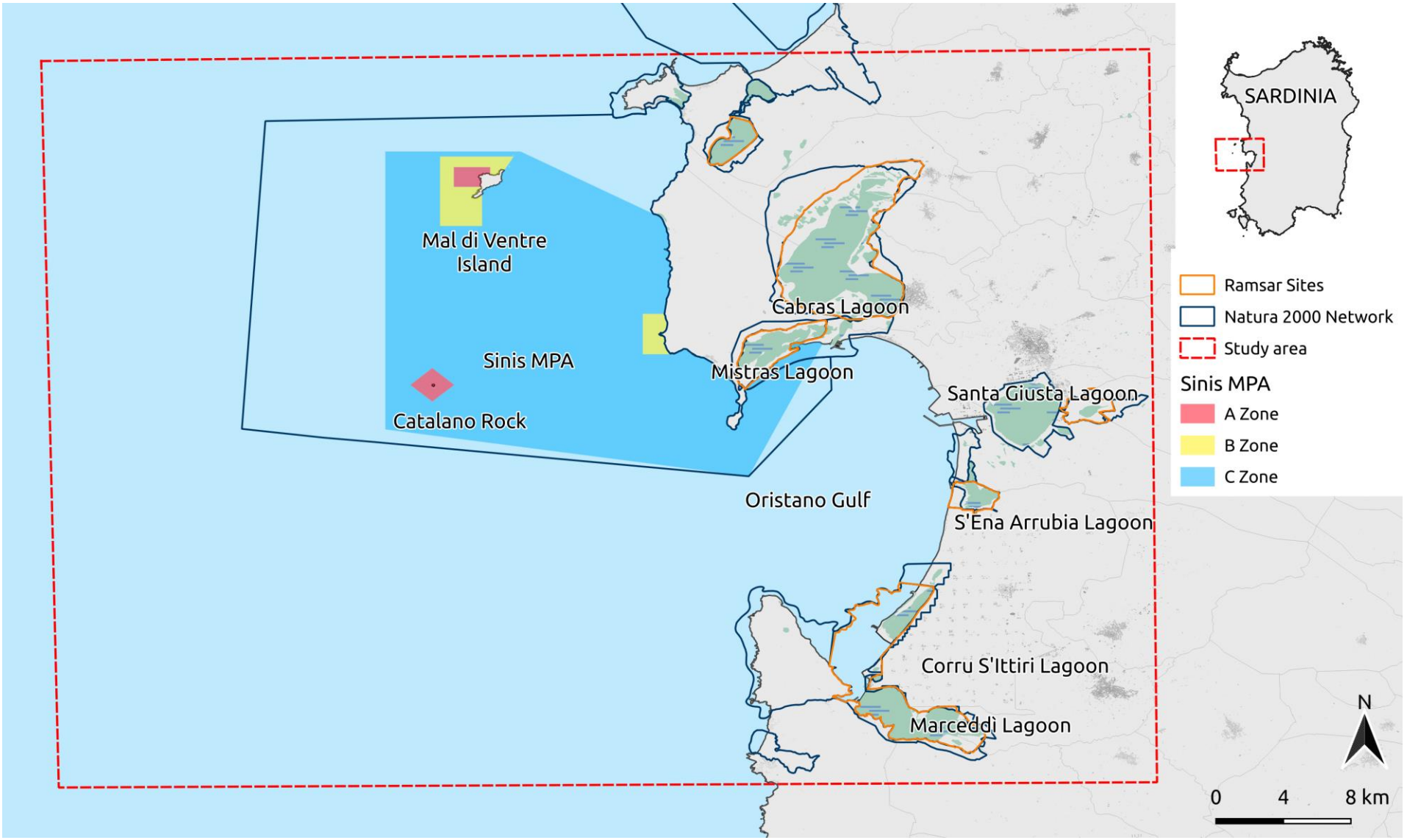

Fig. 1. Main characteristics of the Study area. The figure shows wetlands of international importance designed under Ramsar Convention, Natura 2000 sites, and the zoning of the Marine Protected Area.

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Fig. 2. Photo of Mal di Ventre island. This island is among the most significant ecological and conservation sites in the Study area. Photo by Giorgio Massaro.

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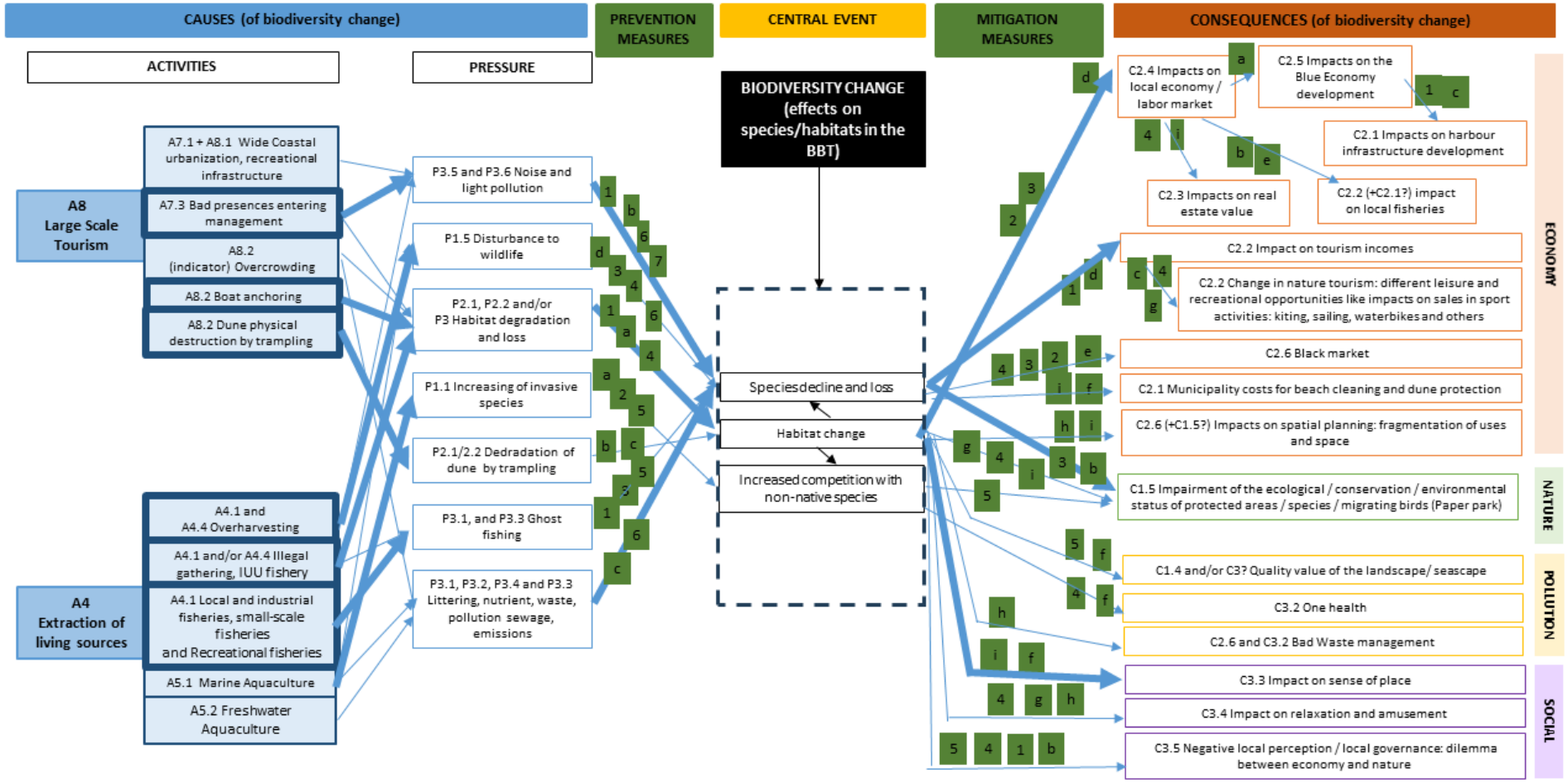

Fig. 3. Bow-tie diagram of three largest biodiversity loss processes. Bold arrows represent stronger connections between causes, impacts, and consequences. Letters and numbers are used to identify prevention and mitigation measures. (see text in Methodology for coding).

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	PREVENTION MEASURES		MITIGATION MEASURES
a	Spatial and temporal planning	**a**	Development of a regional strategy for Blue Economy and Blue Tourism
b	Tourists and parking fees	**b**	Legislation and monitoring of impacts on the environment and local populations
c	EU policy on single use plastic, deposit system	**c**	Green infrastructures
d	Regulation of tourism and activities	**d**	Diversification of touristic resources: naval, historic, cultural and heritage values
1	Monitoring of maritime regulated uses and tourism activities	**e**	Local legislation and subsidies to shellfisheries/fisheries
2	Spatial planning	**f**	Encouraging citizen actions and recording environmental changes
3	Regulation of fishing activities	**g**	Visiting with nature guides, education, birdwatching activities and competition
4	MPAs implementation	**h**	Carrying capacity in distributing people along coast, restricted areas, visiting periods, game fishing periods
5	Information availability and co-working	**i**	Installation of paths and fences in dunes
6	Participatory approach	**1**	Diversification of touristic resources: naval, historic, cultural and heritage values
7	Noise pollution assessment	**2**	Fishing e-commerce development
-		**3**	Development of sustainable fishing models
-		**4**	Awareness programmes
-		**5**	Monitoring impacts on the environment and local populations

Tab. 1. Prevention and mitigation measures. Letters indicate actions addressing tourism-related impacts, while numbers refer to those targeting impacts from fishing activities.